An MIT Energy Initiative Workshop Report

MIT-CSIS ENERGY-WATER-LAND NEXUS WORKSHOP

May 6–7, 2013

MITei Massachusetts Institute of Technology CSIS CENTER FOR STRATEGIC & INTERNATIONAL STUDIES

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PREFACE

About the MIT-CSIS Energy-Water-Land Nexus Workshop

The availability of water and land resources is increasingly recognized as one of the next big issues facing the energy industry. On May 6 and 7, 2013, the MIT Energy Initiative (MITEI) held an Energy-Water-Land Nexus Workshop at the Center for Strategic International Studies in Washington, DC. The goal for the workshop was to develop a research agenda around the energy-water-land nexus, and to identify the important challenges to be addressed through university, industry, and government collaboration. The workshop was hosted by MITEI's Director, Professor Robert Armstrong, and Dr. Francis O'Sullivan, MITEI Director for Research and Analysis. The workshop brought together the expertise and insights of nearly 200 researchers from many of the 13 universities that have been partners in BP's Energy Sustainability Challenge (ESC) program, along with other leading experts with knowledge and understanding of the technology, economics, policy, and systems issues that accompany the energy-water-land nexus. This event grew out of the ESC program, a multi-year, multi-university research program, funded by MITEI Founding Member BP.

About the ESC

In 2010, BP initiated the ESC Program to study the linkages between energy production, energy use and natural resources — particularly water, land, and minerals. The central goal of ESC has been to address the question: How will natural resource constraints affect the way we produce and use energy in the future? This work was motivated by the realization that future commercial and policy decision making on issues concerning the energy-water-land nexus needed a very strong technical base of understanding. BP's ESC Program, in collaboration with 13 university research partners, including MIT, Princeton, San Diego, Berkeley, Illinois, Texas, Tsinghua, Sao Paolo, and Cambridge University, has worked to develop this enhanced technical understanding of the issues pertaining to the energy-water-land nexus. Findings have been made available to practitioners through peer-reviewed journal publications and a series of BP-published handbooks, as well as through a range of tools and models. For more information about BP's ESC Program, visit http://www.bp.com/energysustainabilitychallenge.

About MITEI

MITEI pairs MIT's world-class research teams with key players across the innovation spectrum to help accomplish two important goals: improving today's energy systems and transforming tomorrow's global energy marketplace. MITEI is also a resource for industry, policy makers, and the public — providing unbiased analysis and service as an honest broker for industry and government. MITEI's educational offerings combine depth with multidiscipline breadth, making MIT's campus an energy-learning laboratory. Through research, analysis, and education, MITEI is working to find answers that reinvent our energy world. For more information about MITEI, visit http://mitei.mit.edu.

ACKNOWLEDGMENTS

MITEI wishes to thank BP and the Center for Strategic International Studies for their generous support of the MIT-CSIS Energy-Water-Land Nexus Workshop. MITEI also thanks the moderators, panelists, and participants who filled this day-and-a-half program with spirited discussion, thought-provoking debate, and substantive information.

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INTRODUCTION

Francis O'Sullivan and Raanan Miller, MIT Energy Initiative

Population growth and rising income levels will present a major challenge for mankind in meeting the world's growing energy needs over the coming decades. The scale of the challenge is especially apparent when the expanding energy demand is viewed in the context of the finite, increasingly expensive, and carbon-polluting fossil resources that support the majority of today's energy supply. The simple availability and cost of energy resources are just part of an even more complex story. Contemporary energy production is dependent on other natural resources, particularly water, land, and non-energy resource minerals. Serious questions arise regarding the ways that this expanding energy demand will impact these resources going forward. The energy system's impact on water, particularly fresh water, and land is further complicated by climate change, which is affecting fresh water availability and land productivity across multiple spatial scales, and which is, of course, ultimately being driven by carbon emissions from the energy system.

Although much of the contemporary discussion regarding the energy-water-land nexus is focused on future challenges, many parts of the world are seeing water and land resources that are already stressed, impacting our ability to produce energy. The 2014 US National Climate Assessment report highlights how climate change is negatively affecting both water availability and land productivity across the United States. It points out that, for the case of water particularly, droughts and increasing stress levels are already impacting our nation's ability to produce energy. The report also highlights the risks to the energy infrastructure that are emerging as a result of climate change.

Other regions of the world are also facing challenges today at the energy-water-land nexus. Dramatic economic growth coupled with China's expanding and migrating population is placing an increasingly greater demand on its energy system and on the limited fresh water resources in the eastern regions of the country. Unconventional gas production has recently provided a tangible example of an energy-water conflict in China. While much of China is arid, competing water demand from non-energy users might prompt the government to place limits on the amount of unconventional gas resource in the Szechwan Basin that can be exploited over the coming years.

Given that in almost every conceivable future scenario global energy demand increases, it is likely that energy-related water demand also will grow. If current fossil-based energy pathways and technology paradigms continue to dominate supply as analysis suggests, then energy's water needs will likely rise faster than demand for energy itself, given that future production will be forced to move to lower-quality, more water-intensive, "unconventional" resource types. In important energy-producing regions which are already — or projected to become — water stressed, it seems likely that, in the future, energy production's water demands will come into greater conflict with the water demands of other sectors, particularly those of agriculture and municipalities. As it was made clear during the workshop, history teaches that crises relating to natural resources are rarely addressed effectively in a proactive, forward-looking manner. A crisis typically needs to materialize before meaningful policy action is taken. It seems very likely that this scenario will play out in the case of water for energy, particularly in countries without central control and overarching regulatory structures for water management, and where non-energy water users represent powerful regional political constituencies.

As such, the energy sector must proactively focus on reducing its water intensity. This is especially necessary given the likelihood of increased conflict surrounding access to water resources; the likelihood that effective policy will not be implemented nor regulatory action taken prior to a crisis manifesting, see Session 4; and the energy sector's (sometimes) limited political influence relative to other major water users. Fortunately, technology can provide an effective pathway to lower water intensity. These technologies must also be economically compelling for them to be adopted. Today, technologies exist that can dramatically reduce the water requirements of major energy pathways; however, in many instances, the relative economics of these solutions means that operators choose not to implement them. Take, for example, thermal-based electricity generation. Today's thermal plants (particularly in the United States) use once-through or tower-cooled systems to shed heat as part of their thermodynamic cycles. These systems have varying levels of water intensity, but this demand could be eliminated almost entirely by using dry-cooling systems that replace water with air as the cooling medium. Unfortunately, this technology is more expensive than conventional cooling, and therefore, it is only used when no other option exists. An example of this is in South Africa, where dry-cooling has been adopted specifically to eliminate power plants' need for water in an already highly water-stressed environment. The South Africa example demonstrates that water intensity can be massively reduced at scale, albeit by accepting an economic penalty. Nevertheless, the option exists and emerging advances in materials technology and surface engineering have the potential to significantly improve the economic attractiveness of these systems.

The extraction and processing of fossil fuels is another area in which technology could significantly mitigate water demand. An important example of this relates to hydraulic fracturing and the reservoir stimulation techniques that are being widely applied to unconventional oil and gas resources today. Hydraulic fracturing, see Session 7, requires very large volumes of water, often fresh water, and although on a full life cycle basis, the water volume actually consumed by fracturing is not extremely high, the impulsive nature of the process's water needs places very significant temporary demands on local water resources.

Technology can effectively mitigate many of the water issues associated with fracturing, and work is already ongoing that is focused on developing fracturing technologies that do not need fresh water, or that use entirely non-aqueous fluids. Research is also ongoing to design novel water filtration and treatment systems that allow for extensive recycling of hydraulic fracturing wastewaters. As in the power plant cooling technology case, many of these newer, less fresh water-intensive hydraulic fracturing techniques are currently not as economically attractive as more fresh water-intensive alternatives. Nevertheless, should it prove possible to improve the economics through further innovation and greater adoption at scale, it seems likely that the fresh water demands of the hydraulic fracturing process can be significantly reduced, if not entirely eliminated.

The examples of the water intensity-reducing technologies described here are just two vignettes from a much broader body of research and innovation focused on reducing the water needs associated with meeting today's and tomorrow's energy needs. These examples demonstrate that, through both fundamental and applied research, technical solutions for reducing energy's water needs can be found. However, these examples also suggest that more research is needed for these technologies to become economically compelling, and to make them the *de facto* choice for the industry. If that can be achieved, it may be possible to significantly reduce the fresh water demands of energy production. Doing this would help the energy sector and it would also help alleviate broader water conflict in water-stressed regions that are also important energy-producing areas.

Key Issues and Themes

SECTION 1 THE ENERGY SUSTAINABILITY CHALLENGE

Keynote Address: Dr. Ellen Williams, BP

Keynote: Emphasized Points

Impact of Increasing Energy Demands on Natural Resources

The world's population is increasing; it is expected to reach nine billion people by mid-century, and perhaps as many as ten billion by the end of the century. Each person will desire an improved quality of life and access to an increased level of resources. However, with finite resources, there is concern about whether the water, land, and energy that is needed to sustain this population will be available. With regard to energy, BP sees a vast increase in the need for primary energy of all sorts in developing countries. A significant amount of that energy will be used for generating power. While renewables, hydropower, and nuclear power will increase their shares dramatically, they are starting from a small base. Therefore, given today's trends, even by 2030, the world will still be burning coal, gas, and oil.

ESC analysis finds that issues surrounding energy and natural resources, such as water, minerals, and land, can be managed with good governance and good policy. However, the impacts of climate change are not so clear. Most of the issues regarding resource use for land and water are very regional, and it is suspected that climate change impacts also will vary dramatically by region. In terms of land, across the world there are disparities in the availability of fertile land for people to use for food or for biofuels production. For example, northern Africa has very little fertile land while northern Russia has very high carbon content in its soil. Similarly, water resources are highly variable across the world. The areas that are going to have growing populations in the next 20 years are almost certainly going to see an increase in water scarcity. Various regional responses to resource stresses are going to lead to different choices and different decisions about energy use. But these resource stresses will not actually drive major changes in the world's decisions concerning the use of energy. Good, solid technical information is needed to help the world make sound decisions about how to manage its resources. Facts are needed to provide policy makers with the information to make decisions that position the world on the right path going forward.

ESC analysis has identified opportunities for the world to reduce the impacts of energy production on fresh water resources. The four key approaches for improvement are:

- Replacement — using something other than fresh water whenever possible.
- Reuse — using the same water over and over again rather than withdrawing a new batch of water for the multiple strands of a process.
- Recycling — taking the water that has been used, treating it to a level that is useful for some other purpose such as irrigation, and releasing it as recycled water.
- Regional responsibility.

Water for Energy and Energy for Water

Water is the biggest issue in energy production after climate change. Globally, around 4,000 cubic kilometers of fresh water are withdrawn for human use annually; 70% of this is for agriculture and around 12% for power generation. The share of water withdrawals for extracting fossil fuels — coal, gas, and oil — is less than about 0.5% of the world's total fresh water withdrawals.

Often, in discussions about water, consumption and withdrawal concepts are confused. In 2009, the world withdrew around 450 cubic kilometers of fresh water for power production. But because a significant fraction of that was used in once-through cooling and was then returned to the ecosystem, the amount consumed was actually relatively small, only around 16 cubic kilometers.

Energy use for water, which relates to the amount of energy needed to source and supply water in the required quantity to users and the amount of energy needed to treat and release used water, represents about 2% of the global primary energy and around 6% of global electricity use.

Water Use in Oil Production

In oil production, water is used to maintain sufficient overpressure to extract oil from a reservoir. Briny water, called produced water, is often recovered along with the oil. The produced water is typically recycled back to a second well along with additional water sufficient to meet pressure requirements. It is pumped down to increase the pressure of the reservoir, which constitutes a secondary production. Ultimately, as it becomes harder and harder to get oil out of the rock, techniques such as creating water floods using different types of chemicals or injecting CO_2 along with the water are used to increase the recovery of oil. This produces a cycle of water being pumped underground to increase the pressure and drive the oil out. The result is a limiting case in which at least one barrel of some type of water needs to be put back in the ground to replace the pressure loss due to every barrel of oil that is taken out of the ground. One barrel per barrel is considered a canonical number for the water use needed in oil extraction. However, none of this water needs to be fresh.

It is not uncommon for the amount of produced water to vastly exceed the amount of oil that is extracted from the ground in mature wells. A responsible operator will mix in additional replacement water that can be fresh or non-fresh water, or even salty water from the ocean. The amount of fresh water used in the process per barrel of oil produced is a metric used to tabulate and understand water usage in oil production.

It is difficult to obtain industry information about the amount of fresh water that is used in the production of oil. Ninety percent of the world's oil reserves are owned by national oil companies that produce 80% of the world's oil. These companies generally have little motivation to release information on their processes. Yet, the broad practices of oil companies across the world can still be studied. For example, in Canada, over the last 20 years, there has been a significant increase in the amount of produced water coming out with oil necessitating a significant increase in the amount of water that is injected into the ground. But with practicing more reuse and replacement tactics, the industry has managed to control the fresh water consumption to around 1.5 barrels of water per barrel of oil. In Texas, less than 0.5 barrel of fresh water is injected to produce one barrel of oil, while in the Middle East, saline water is primarily used for injection. In all deep sea oil production, when additional water is needed, seawater is used, and the fraction of fresh water used is very small. As such, it is possible to reduce the amount of fresh water used for oil production if there are appropriate incentives to do so.

Irrigation and Biofuels

Worldwide, only 20% of cropland is irrigated. This is surprising considering that the vast quantity of water withdrawn in the world is used in irrigation. Most crops worldwide are grown with partial or no irrigation. It is important to use irrigation water, not the total crop water used, as a water-intensity factor in growing crops for biofuels, as well as crops for food.

Crop yield as well as fuel yield must be considered when assessing the number of liters of fuel that can be obtained from a ton of any given crop. In addition, water requirements are not constant throughout the year. Often, water requirements are highest at the early part of crop growth. Typically in biofuel plantations at commercial scale, if the crops are not totally rain fed, then less than 10% of the crop's water need is provided via irrigation that results in fresh water intensities of 10,000 cubic meters per terajoule.

The water intensities for fuel production for primary energy like oil are tens of cubic meters per terajoule. For electricity generation, in terms of consumption, they are in the hundreds of cubic meters per terajoule. For withdrawals, it is on the order of tens of thousands of cubic meters per terajoule, which is limited by the heat capacity of water and the efficiency of each specific plant. If the amount of water that is withdrawn across the world for irrigation is divided by the number of food calories that people eat across the world, the result would likely be up to about 100,000 cubic meters per terajoule of the calories consumed. The amount of energy that is consumed by food production is actually a big number.

Temperature and Climate Change

The International Energy Agency (IEA) estimates that, without policy, we are heading for a 6°C temperature increase by the end of the century. The IEA new policy scenario, which is more optimistic, shows a tapering off of CO_2 emissions, resulting in only a 4°C temperature rise by the end of the century. The IEA has also projected the requirements necessary in terms of changes in the energy mix to cap the temperature increase by the end of the century at 2°C. To achieve this, there must be more nuclear energy capacity, more fuel switching away from carbon-intensive fossil fuels such as coal, and an increased use of renewables — as well as a wider use of carbon capture, along with energy storage and improvements in efficiency.

Workshop Directions

This workshop tackled topics that span the areas of water and hydrocarbons, and water and electricity. Issues of governance and the impact that climate change will have on our ability to extrapolate into the future and make plans were discussed. It included a discussion of how to manage production across the entire energy spectrum — from fossil fuels to other sources of energy — in a way that minimizes impacts on the other aspects of natural resources throughout the world.

SECTION 2 CLIMATE CHANGE AND WHAT IT MEANS FOR REGIONAL WATER RESOURCES AND LAND AVAILABILITY

Session Keynote: Dr. John Reilly, MIT Joint Program

Session Summary

This session framed some of the key issues related to climate change and its impact on regional water resources and land availability. The link between energy, climate, water, and land was explored, and the need for better tools and models to enable improved decision making and planning was emphasized. A number of specific models and their application to several scenarios were analyzed.

Keynote: Emphasized Points

Key Challenges to Addressing Climate Change

Current climate models need to be improved, and uncertainties reduced, to avoid misleading conclusions, such as for example, making erroneous precipitation projections. Current models also infer uncertainty from actual policy implementation, long-term climate sensitivity, and variability in climate initial conditions and lead to widely variable outcomes. Future models must have the ability to reduce uncertainty, and be able to accommodate multiple initial conditions. Today's climate models though are still useful for identifying trends. For example, in the United States, climate change will make arid regions drier, while far northern regions will see significant increases in rainfall.

Improved global datasets are also needed to better facilitate climate change analysis. At present, much of this needed data are held confidentially by companies or countries and is often seen as a national security issue, which makes it difficult to procure the needed data.

The cost of solving the climate problem, at least in terms of food prices, may become an inequity that is borne by poor consumers around the world. While it is expected that incomes will increase, the food budget share of incomes will also likely increase due to higher food prices. If carbon prices were to be placed on energy, agriculture would have to consider nitrous oxide and methane emission, which will add significant cost. The gain in avoided damage will be offset by the increased cost of energy and mitigation in the agricultural sector. Over the course of history, food prices, despite some recent increases, have been declining. Adding in carbon sequestration and biofuels will drive food prices higher, up to 80% higher over the course of the century.

Our ability to expand water use for agriculture in response to climate change and water stress is limited by our desire to restore watersheds and water ecosystems. Given limited water supply, efforts to improve ecosystem performance lead to competition with water for irrigation or other uses.

Mitigating Climate Change

We cannot wait and must prepare for climate change using the data that are available today while making qualified assumptions about uncertainty and risk and considering the dynamic nature of climate. Plans must also be in place to prepare for a range of different scenarios.

It is important to get nations to understand that they share a common interest in managing water, land, and energy. In the United States, a significant amount of work has been facilitated under the Intergovernmental Panel on Climate Change (IPCC), documenting best practices for accounting and mitigation of greenhouse gas (GHG). A similar set of data is needed on land and water resources.

Efforts to mitigate climate change by reducing GHG emissions will likely result in higher energy costs, as indicated by models developed by Dr. Reilly in conjunction with the Environmental Protection Agency (EPA) that investigated temperature rise and radiative forcing levels resulting from several policy and energy source choices. A scenario without a policy penalizing carbon emissions showed high radiative forcing levels and a fuel mix dominated by coal, oil, and natural gas. Scenarios focused on stabilizing or reducing radiative forcing in the atmosphere through the use of non-consumptive energy sources, e.g., energy efficiency as well as renewable sources, or the combination of conventional fossil fuels with carbon capture indicated higher energy costs.

Panel Discussion: Emphasized Points

- It is important to understand the spatial pattern of cropland expansion to determine the impact on potential biodiversity loss. Carbon loss of these converted lands could have a significant impact on climate. There is a need for sustainable scenario development and data is needed for all Earth models. Underlying concerns need to be addressed in the models considering how emissions targets are met while still feeding the world and also protecting biodiversity, ensuring ecosystem services, and providing food security.

- The current land use data, while noting where the cropland is located, does not contain crop management related information, such as the irrigation requirements, the type of crops that are being planted, and their harvest schedules. While there is information on socioeconomic data at a regional or country level, many of the processes that have been considered for land use are happening at the gridded scale. Therefore, socio-economic data at this gridded scale would be especially useful.

- The ability to predict or simulate regional patterns of precipitation is far more limited than the ability to simulate global fields, or the ability to simulate temperature at nearly any spatial scale. It is very difficult to predict the amount of precipitation that will occur, as well as the availability of water at the regional level as they both depend on processes that are not well represented in climate models. These include cloud and aerosol processes as well as surface features like orography, which — unless the climate system is being simulated at high spatial resolution — is difficult to represent. Predictions are influenced quite critically in many parts of the world on the vegetation that is actually on the landscape and the spatial configuration in which it exists. There is the potential to change regional climates and regional precipitation by changing either the arrangement or the actual vegetation that is growing on the landscape.

- Most physically based models do not simulate land use; they simulate land cover due to the evolution of terrestrial ecosystems. This represents an interaction between the climate and the history of the landscape. However, what is actually there is as much an economic, policy, and cultural issue as it is a physical question. Today's world has about as much agriculture as it does forest globally. It is quite easy to create scenarios in which land that is used for human services, whether for energy or for crops, vastly exceeds the amount of land that is natural and available for those services. It is critical to understand the evolution of the demand for those services and the factors that affect the growth of demand, just as much as it is to understand the interaction of the climates and the physical nature of those resources. It is also important to understand the people, economic activity, and the technology choices that are either likely or that can be envisioned.

- The early stages of an integrated Earth system modeling collaboration have established that the choice of mitigation policy affecting land cover is largely determined by whether terrestrial carbon has a price or not.

- Given the complexity of the systems being analyzed, the sequence of events will not be "predict then act," which many scientists, as quantitative analysts, would prefer. It is much more likely that the sequence will be "act, then learn and adjust" with an iterative process of learning that is underpinned by an evolution in modeling and scientific understanding. What is important is to break free from the trap of waiting 10 years for a better model.

- The way that natural resource decisions are made must change. The models should be used more as a guide for thinking about the future in a structured way so that the most salient inherent scientific uncertainties can be addressed. The models and the evolution of the modeling capacity must be augmented by measurement and indicator systems so the quality of the decisions can be adjusted and improved.

SECTION 3 GLOBAL CHANGE AND THE CHALLENGES OF SUPPORTING A GROWING PLANET

Session Keynote: Dr. Thomas Hertel, Purdue University

Session Summary

The session on global change and the challenges of supporting a growing planet provided an overview of factors that will shape global sustainability outcomes from today to 2050. These factors include population and income growth; future food prices; energy prices as a driver for land use; competition between agriculture, fuel, and environmental services; and the need for better shared data.

Keynote: Emphasized Points

Population and Income

Today, the relative importance of population and income growth is changing. Although the projected two billion person increase in worldwide population by 2050 is often met with alarm, this increase represents a remarkable slowdown in population growth rate from historic figures. Income levels, at the same time, are rising, and they are growing fastest in low-to-middle income economies (China, Brazil, India, and parts of Africa). This income growth is translating into a rapid increase in per capita food demand that may have a significant impact on global environmental and food security.

Over the past 45 years, total global crop production has expanded by 200%, but the land area in use has only increased by about 20%. Slower population growth now means that, over the coming years, the amount of cropland needed to meet the near- to medium-term food needs could actually decrease, if factors such as global income patterns remain constant. This scenario, however, is not very realistic, as recent fast growth in low- and middle-income levels across emerging economies has and will likely continue to drive greater demand for food over the medium term. This fact coupled with predictable moderation in crop yield improvement rates, means that the total cropland need will at the very least remain static, and more likely grow to mid century.

Future Food Prices

Future food prices will be driven by the rate of technological progress; investment in R&D to enhance productivity is a critical factor. If the increases in total factor productivity (TFP) levels seen over the past 20 years can be maintained over the coming decades, there will be little need for cropland expansion out to 2050. In fact, if historical TFP improvement rates could be maintained toward 2050, it could result in a significant decline in global food prices. Modeling by MIT's Marc Baldo and Hertel indicates that a decrease of as much as 50% in global crop prices could occur under such a scenario. This analysis, however, excludes important barriers to continued high levels of TFP improvements, including the impacts of climate change, and does not account for the impact of a major expansion in biofuels production.

Energy Prices and Land Use

Energy prices will play a major role in shaping global land use over the coming decades. Cheaper energy will yield lower-cost intensification and reduced land requirements, since low energy prices generally lead to lower fertilizer and irrigation costs. With lower electricity costs, water availability can be increased, as groundwater pumping and long-distance conveyance will become less expensive. Today, more than 40% of crop output comes from the 20% of cropland that is irrigated. Growth in irrigated agriculture has played a key role in feeding the world, and this has been done with only a modest increase in land area requirements. Going forward, the availability of irrigation will depend on both energy prices and water availability. If future production expansion is constrained to rain-fed agriculture, the resulting lower yields will drive a need for greater land use.

Interest in biofuels is directly related to oil prices. High oil prices drive market-based integration of agriculture and energy, and expansion of biofuels. At higher oil prices, renewable fuel standards will be popular, less costly to meet, and more likely to be sustained. With low oil prices, given the higher cost of biofuels, interest in biofuels will diminish.

Competition between agriculture, fuel, and environmental services

As the world's population growth slows and people become wealthier, the growth in demand for food will moderate, but the demand for environmental services from land (parks, biodiversity, and carbon sequestration) will grow. As an example, in China, tensions have risen over whether to set land aside for parks or to continue to use the land for agriculture.

Adaptation to Climate Change

Climate change affects global land use. The development of temperature and drought resistant crop varieties and other mitigating approaches that enable historical crop yield growth rates to be maintained even in the face of higher temperatures and reduced precipitation are critical, and will require significant investment. This investment will not only result in higher yields, but also could result in lower prices, and improved food security. The development of these newer crops will also reduce the need for future land conversion, which will save considerable emissions.

Conclusions

Research over the past decade has greatly increased our knowledge and understanding regarding the challenge of supporting the growing planet. However, there remains much to be done in terms of understanding both the fundamental science of global change and the potential impacts of various policy and regulatory approaches to dealing with the issue. One area where major near-term progress could be made that would help move the state of knowledge forward is linked to data. Contemporary research efforts often suffer for lack of access to data even though that data may exist. These hurdles could be overcome if the global change research community focused on coordinating data more effectively, similarly to how on a small scale, the Global Trade Analysis Project has achieved this.

Panel Discussion: Emphasized points

- Population and income level increases will lead to a shift in food consumption. Food production increasingly will take place in locations that are not near the points of consumption. This has numerous policy implications for international trade policy as well as for the governance of the international trading system. This will lead to growing concern at the national level about food security unless the international trading system can ensure dependable trade in food and commodities.

- One of the major problems with models is that they are generally based on economics and not political economy. They assume it is basic underlying economics — supply, demand, costs, and prices — that, for example, drive deforestation. However, there is fairly strong evidence that a great deal of deforestation, and particularly the expansion into tropical rain forests, has been driven by political economic factors that models based on economics alone do not capture. Such political factors include the ability to influence government, or the ability to obtain permits through unofficial or illegal means, such as cronyism or outright bribery.

- From the point of view of land, it is important to consider the types of livestock production. Chicken, pork, and dairy have much less need for land per kilogram of protein or per calories produced than beef. About 60% of global agricultural land is used for beef production that provides less than 5% of the world's protein and less than 2% of calories.

- Greater detail and a higher degree of local scalability are needed in today's models. This will result in more complex models that can be cumbersome to apply.

- Attention must be paid to policy and institutional frameworks, incentives in each geographical location, the role of local enterprises and nongovernment organizations, and adaptations of new technologies to improve the access and efficiency of services provided in developing countries.

SECTION 4 THE GOVERNANCE OF WATER IN RESOURCE-STRESSED REGIONS – CASE STUDIES ON THE US SOUTHWEST, CHINA, AND THE MIDDLE EAST

Session Summary

This session focused on governance of water in resource-stressed regions and included two keynote presentations. The first presentation by Dr. Barton Thompson focused on governance of water in the Western United States and the need to live with inefficient institutions. It also evaluated the ability of the Western United States to respond and adapt to the combination of increasing demand and less reliable water supply. The second presentation by Dr. David Victor outlined his political theory of water governance as a way to explain the lack of a rational approach to water resource management. He illustrates his theory through examples from the Middle East, China, and the Southwestern United States.

Session Keynote: Dr. Barton Thompson, Stanford University

Keynote: Emphasized Points

Institutional Weaknesses

Traditional water institutions in the Western United States are challenged by a combination of increasing demand due to high population growth rates and a less reliable water supply due to climate change. In their early history, Western water institutions were successful at encouraging rapid allocation and use of water, but did not adequately address issues of reallocation, changing supply conditions, and unsustainable withdrawals. Western water institutions are afflicted by problems of fragmentation, inefficient adherence to relatively strict temporary prioritization, heterogeneity, inflexibility, and an inherently ineffective and incomplete regulatory structure. Multiple geographic units often govern a single water system, and different governmental agencies in the same geographic space may be responsible for different aspects of water management. This makes coordinated governance extremely challenging. Furthermore, historic appropriation still dominates water allocation in the West. Institutional weaknesses also make it difficult for Western water users and managers to adapt to new demands and challenges. Rather than acquiring needed water from willing sellers, new and expanding water users are pushed to the back of the priority queue owing to the first-in-time, first-in-right temporal priority doctrine. As such, climate change imposes disproportionate risk on the relatively arbitrary class of "junior" water users.

Overcoming/Working around Institutional Weaknesses

Users, managers, and stakeholders in the Western United States have tried to meet water-related resource challenges in several ways in the past. In the first approach, users and managers lobby state legislatures to reform water institutions to provide for greater flexibility, sustainability, integration, and foresight — e.g., by adopting institutions that better promote the marketability of water rights, or by prohibiting long-term groundwater overdrafting. While legislative change has and continues to take place, change is slow and is likely to remain slow for political reasons.

A second approach is through judicial reform, where water users and stakeholders use lawsuits either to change the institutions through judicial mandate or to encourage more rapid legislative or administrative change. In another approach, water users and managers try to exploit interstitial pockets of flexibility in existing legal institutions. Water users also can engage in localized "reordering" of water institutions through private contracts, judicial settlements, or control over local water organizations. Finally, water managers can construct overlays designed to solve institutional problems without changing the underlying institutions themselves. While each of these approaches for overcoming traditional institutional weaknesses has been and can be successful in particular settings, all have limited applicability and can sometimes even be counterproductive.

The most common approaches to addressing the weaknesses of Western water institutions are "workarounds" which entail finding local pockets of flexibility, engaging in localized reordering, and adding institutional overlays. All have limited scope and their own problems. These workarounds may impede future reform and can result in additional inefficiencies.

The only answer to current institutional weaknesses is fundamental legislative or judicial reform, which will likely only occur when the cost of the weakness outweighs the cost of the reform. As such, reforms probably will continue to be implemented late in the process, leading to significant inefficiencies.

Session Keynote: Dr. David Victor, University of California, San Diego

Keynote: Emphasized Points

A Political Theory of Water Governance

In most countries, fresh water resources are under increasing stress. While the sources of stress are many, the energy industry plays a particularly important role. The energy industry is the world's second largest net user of fresh water (agriculture is first) as it is the largest source of water withdrawals in some regions, notably in the United States — mostly in the form of cooling water that is returned (a bit warmer) after use. For both use and withdrawal, policy makers are scrutinizing more closely the many impacts that the energy industry has on water. Worldwide, there are significant variations in how policy makers treat different sectors even when they draw upon the same resources.

Four key points were emphasized throughout the session. First, even though there is tremendous technical potential for reducing energy and other industrial impacts on water resources, actually realizing these potentials will hinge on governance. Secondly, societies tend to ignore water stresses until they become acute and have a strong bias in favor of "command and control" regulation over more flexible markets, which is deeply rooted in human cognition and political economy. Third, there is tremendous promise in popular new ideas for water governance — notably integrated water resources management. Fourth, while the political challenges for efficient governance are significant when focusing on water quantities, the problems are likely to become much greater as jurisdictions focus on water quality aspects such as temperature, pollution loads, seasonal flows, and complex interactions between the uses of fresh water for human and natural purposes. These "governance" factors are likely to explain why real world outcomes in fresh water management could be radically different from the economically optimal potential.

The session also examined how societies identify problems and mobilize the resources needed to govern them. Crisis-mode decision making was found to actually help political systems address some of their greatest challenges. A simple model of political economy — which informs the timing of policy responses and the choice of policy instrument — was used to illustrate the evolution of water policy in three macro regions of the world: China, the arid Middle East, and the Southwestern United States. Finally, the presentation looked to the future and the possible use of new governance systems such as Integrated Water Resources Management (IWRM) across basins and industries.

Illustrations and Case Studies

Many regions in the world are facing severe and growing challenges in water supply. Those challenges are particularly notable in the portions of the world — such as China and India — that are growing most rapidly. Climate change will likely make these problems even more severe. A warmer world is likely to be a wetter world overall, but the distribution of fresh water supplies is likely to change radically. River basins that depend on high-altitude snowpack — including the basins in China, India, and the Southwestern United States that are already under stress — are likely to fare worse as the climate warms. The three regions — the Middle East, China, and the Southwestern United States — face severe water shortages (and problems of water quality) and thus are good test beds for illustrating how water governance evolves.

Middle East

In the Middle East, countries have managed water resources in a number of radically different ways that offer insight into the central role or lack of central role of their public institutions. The failure of public services in many of these countries has led to the rise of private markets. To some observers, water is the centerpiece of Middle Eastern politics while others hold that water is structurally insignificant to most of the political forces at work in the region. There is little doubt that across the region pressures on water resources are mounting and that they are likely to increase with climate change. Eight of the 11 countries in the region are considered water scarce, and two are water stressed.

Governments in the Middle East have focused on large supply-side projects such as desalination and dam construction and less on an adaptive approach that emphasizes managing water demand and improving efficiency in water use. Each country has different problems and has handled them with varying degrees of success depending on their public administrations. Some of the key water governance challenges include limited enforcement of water policies; overlapping responsibilities between different institutions with unclear roles; unclear legislative and regulatory frameworks at the national level, which creates coordination problems at the regional and local levels; lack of an effective strategy to manage water demand growth; inadequate human resources capital in government agencies; and insufficient awareness of water issues among the general population. In the predominantly Muslim countries, Islamic principles that address water resources present a unique challenge to solving the water-scarcity issue, as the Qu'ran states that "water is a gift of God and in principle belongs to the community" and all individuals and domesticated livestock have a right of access.

China

China's water supply is dominated by two central issues — the rising demand from rapid growth in industry, urban populations, and agriculture, and a highly uneven spatial distribution of water resources. The northern parts of the country are generally arid and the south is much wetter. Total water use in China is dominated by agriculture. However, as China's economy grows, industrial output is increasingly more profitable than agricultural output, so water resources will be transferred to industrial purposes.

Fragmentation is a challenge in large countries like China. In fact, several ministries and commissions oversee water management in China. The fragmented nature of China's water governance, both regionally and nationally, has led to problems such as inefficient and ineffective pricing of urban water, conflicting competencies between government bodies, poor delineation of duties, and a lack of coordination. While laws are in place to manage some of these issues, few have been effectively implemented.

The Southwestern United States

Since the previous session focused solely on the Western United States, this speaker only emphasized two points about this geographical area — fragmentation of authority and the practical impact of market incentives in a system where property rights are not fungible. The basic allocation of water in the Southwestern United States comes from a series of overlapping institutions. One is the fundamental allocation of private, surface water rights mainly through the doctrine of prior appropriation. Another is the sharing of water resources of the major inter-state river. A third is the allocation of those river sources between the United States and Mexico. As the demands for water have changed — in particular with the huge surge in demand for water in California — new hybrid markets have emerged on top of these basic institutional arrangements. In the hybrid market — where transaction costs for developing trades are high and most existing users face no incentive to trade away their established rights — prices form in different ways, and ironically, this approach most likely results in excessive amounts of technological innovation.

Implications for the Future

There is a need for major reforms to water governance. There are at least four major kinds of pressure for reforms in the allocation and protection of water resources: localization, adaptive management, ecosystem services, and integrated water resources management. Localization is possible, as many political systems are shifting authority to local levels and local rule makes it easier for interests to control outcomes. However, the other three do not map as well with the political interests and administrative capabilities needed to translate these ideas into practice.

Real-world outcomes will be structurally biased away from optimal allocation of resources. A new line of research might be opened to explore second-best outcomes that will be most consequential for various industries, including the energy industry. To get started on such research, here is a short list of standard assumptions that might be applied when building models that allow for the more real-world portrayal of water-related decision making:

- Differential pricing across sectors of the economy, with early incumbents (e.g., agriculture) enjoying the lowest prices and later entrants (e.g., most of industry, especially new firms) facing higher prices.

- Persistent use of command-and-control regulation rather than markets (or social planner perspectives), reflecting the reality that well-organized interests often prefer command arrangements that are more readily controlled.

- Hybrid markets rather than pure markets in which all trades are fungible. Hybrid markets are thin and marked by high transaction costs.

- A system that self-adjusts not in response to all evidence of scarcity and poor performance — as the advocates of adaptive management argue would be best — but in punctuated form in response to crisis.

SECTION 5 WATER AND ELECTRICITY

Session Keynote: Dr. Bryan Hannegan, EPRI

Session Summary

This session explored some of the present and future challenges faced by the electric power sector due to water availability constraints. It also highlighted some of the research required to assess and reduce vulnerabilities to water shortages.

Keynote: Emphasized Points

Water Access Challenges for Electric Power

A fairly well resolved picture of water use across the United States is provided by a 2011 Electric Power Research Institute (EPRI) publication on water use for electricity generation and other sectors.[1] It indicates that the three largest components of water withdrawal are for agriculture, thermoelectric cooling, and municipal demand. Agricultural and thermoelectric cooling water withdrawals are the dominant components of the total fresh water withdrawal nationwide at 36% and 40%, respectively. Yet, despite being one of the largest users of water on a withdrawal basis, electric power is frequently assigned the lowest priority for water allocation after residential, commercial, industrial, and agricultural uses. As those competing uses grow, it is increasingly likely that water availability will become a major issue for the electric power industry in the next decade and beyond. In fact, siting of new plants is already constrained by access to cooling water, especially fresh water.

Managing the Energy-Water Nexus

Managing the energy-water nexus is a broader discussion than simply identifying the ways that electric power plants can reduce their water intake. Strategic challenges and opportunities for the electric sector lie in its ability to use less water for power production as well as less energy for water production, the treatment of wastewater to minimize environmental impacts, and making it available for reuse.

Using less water for power production: The power sector's water use efficiency increased quite significantly from 1950 to 2005, with an approximately 50% decrease in gallons of water used per megawatt hour of power. Fresh water withdrawals (billion gallons per day) have remained relatively constant since the 1970s despite a large increase in generation, reflecting the move from once-through cooling systems, which were dominant prior to the 1970s, to recirculating wet-cooling systems, with much lower water withdrawals per unit of electricity generated. Today, most new plants use some form of wet recirculating cooling system.

1 Water Use for Electricity Generation and Other Sectors: Recent Changes (1985–2005) and Future Projections (2005–2030), EPRI, Palo Alto, CA, 20011.

There are four major strategies for reducing fresh water use in new thermoelectric generation involving: the use of degraded water sources; the use of dry or hybrid cooling; increasing thermal conversion efficiencies; and water recycling within plants. Each of these options has been used to varying degrees, depending on local water resources and costs. However, even with these improvements, there still exists a great need for further novel water treatment and waste heat concepts to improve efficiency and reduce water usage.

Using less energy for water production, treatment, and use: Water and wastewater conveyance and treatment consume approximately 3.3% of US electricity. Most wastewater plants are 30 to 50 years old, using inefficient technology. There is an opportunity to update wastewater plants, which will subsequently equate to less energy for wastewater treatment. More energy-efficient water desalination is another area for significant innovation.

Minimizing Environmental Impacts

The ability to continue existing withdrawals may be limited by environmental constraints, particularly the protection of aquatic life. Therefore, it cannot be assumed that an existing supply will be present indefinitely. Maintaining sustained water availability while minimizing environmental impacts is, therefore, critical, especially in some regions of the country. In fact, to minimize environmental effects, many power plants have been operating for years on nontraditional or degraded water sources, particularly treated sewage effluent. Treated sewage effluent has been the most attractive source, because of its year-round availability, inexpensive price (although prices are increasing), relatively low cost of treatment, and minimal impacts to power plant operation. However, this treated water source is being secured in some areas of the country for use in irrigation and groundwater recharge, which limits its availability for power plant cooling and other applications.

Conclusions

As populations and the economy grow amid a fixed, finite, and increasingly scarce water resource, climate variability, including drought, may limit the ability of all users to meet the full extent of their withdrawals. Meeting the challenges and realizing the opportunities will require a more systematic dialogue on sustainable water resource management driven by collaborative decision making across multiple societal and economic sectors. However, the tools for this dialogue are only now being assembled. As such, there is much work to be done in the coming years.

SECTION 6 THE FUTURE OF BIOFUEL AND FOOD PRODUCTION IN THE CONTEXT OF CLIMATE CHANGE AND EMERGING RESOURCE STRESSES

Session Keynote: Dr. Heather Youngs, Energy Biosciences Institute, UC Berkeley, CA

Session Summary

This session highlighted the need for better metrics and data to accurately determine the impact of the expansion of bioenergy on water resources and the environment. Examples were provided of some of these metrics, such as water footprint, which can be misleading if not applied correctly.

Keynote: Emphasized Points

The Water Footprint and the Need for Improved Metrics

Concern is often heard about the adverse impacts that expanding bioenergy production may have. These include: the size of the water footprint for bioenergy feed stocks relative to that of fossil fuel sources; the unsustainable water use that irrigation for bioenergy will create; the decrease in water quality from biofuel industry expansion; competition with food and forest for water for expansion of bioenergy feed stocks; and exacerbation of water scarcity associated with climate change with the expansion of the bioenergy sector. The question is how valid are these concerns? To answer this, better metrics are needed.

The GHG emission footprint has been a powerful tool to normalize impact at a global level. Water impacts, on the other hand, have a very local nature, and the widely used water footprint metric, which is effectively a measure of productive water use, does not, in fact, encompass the broader and important impacts of bioenergy on water. A water footprint shows that, for a gallon of water going into the system, there are a certain number of "miles traveled" coming out. But it tells nothing about the impact of that use on the water system. From a water footprint, one cannot tell whether rainfall or just irrigation water has been considered, or the source of the data; whether the data are modeled or measured; and whether evapotranspiration considerations have been included. These and other factors mean that the water footprint is not a transparent measure. For full impact assessment, the volume of water used must be considered, along with the impact of taking the water out of the system. To obtain a more complete picture, a full water balance and surface flow analysis should be performed.

Water Balances and Surface Flows Can Drive Policy

A full water balance analysis provides a more complete picture of the water system, explaining what happens with water in the system when vegetation or practices are changed.

This idea of using water balances and surface flows made its way into policy in South Africa. In the 1970s, there was a concern over changes in water flow due to the increased number of plantations that were being created for wood production — woody biomass production for forest use. The South African government required that plantation owners facilitate a crude water balance and apply for a permit to effectively use that water. By the late 1990s, this edict grew into a national water act that included other provisions.

One of the new strategies was to categorize the catchments in terms of vulnerability and their social/ethical goals, and the need for biophysical, economic, and social components to the environmental assessment. In South Africa, the water use license extends for 40 years due to the nature of the plantations. They are reviewed every five years to take into account new practices and new information. The process is transparent to the public and the allocation of water is discussed. This policy has not prevented economic activity, though it might have curtailed some in a rational way. This interesting example, which deserves more study, highlights the benefits of starting with an initial policy, driven by relevant metrics. Even if the initial policy is not perfect, it will get users engaged and points them in the right direction. A policy can be refined as more is learned about the different stakeholders involved.

The Need for Careful Context-based Analysis

Back-of-the-envelope estimates often lead to erroneous conclusions, as do calculations that make assumptions that are not borne out in actual usage scenarios and tend to be either over optimistic or pessimistic. Other common errors include highly resolved estimates that give the appearance of highly articulated data, but are erroneous. As an example, if one were to look at an irrigated cornfield in California next to an ethanol plant, it might be assumed that its irrigated corn is supplying the ethanol plant. The reality, on the other hand, may be that the plant is importing corn ethanol from the Midwest, and the cornfield is being used to feed cows that are then sold for protein. Therefore, the actual water footprint depends on the location of the source of the corn, and this cannot be determined from the obvious data.

Conclusions

Water use estimates in bioenergy production are highly variable, and water requirements for biomass production vary significantly by crop type, region, and methodology of analysis. Water impact analysis is especially prone to errors. A full water balance analysis should be conducted for bioenergy systems within the specific context of the entire watershed. Water impacts should not be condensed into convenient, weighted parameters. There needs to be agreement on a better set of reference systems and metrics, which should lead to a discussion about balancing ecological and socioeconomic goals.

SECTION 7 WATER AND CONTEMPORARY HYDROCARBON PRODUCTION

Session Keynote: Dr. Francis O'Sullivan, MIT

Session Summary

This session addressed water use in contemporary hydrocarbon production. The discussion was particularly focused on hydraulic fracturing. This process has had a profound impact on the North American energy sector over the past decade, opening up as it has vast amounts of oil and gas resources in low permeability formations that were previously considered unrecoverable.

Keynote: Emphasized Points

US Gas Resources

The past decade has seen tremendous change in the North American energy sector. Increased production of oil and natural gas in the United States has been driven largely by the extraction of "unconventional" resources of natural gas, oil, and other hydrocarbons locked inside tight sandstones, shales, and other low-permeability formations. These rocks were long known to contain hydrocarbons and to have served as source rocks for many conventional oil and gas production fields. Because of their low porosity and permeability, however, the gas and oil in them were generally viewed as unrecoverable, at least at prices comparable to those of recent decades.

The impacts that the unlocking of unconventional oil and natural gas resources have had on estimates of recoverable resources and production have been profound. Numerous countries, including Algeria, Argentina, Australia, Brazil, Canada, China, France, Libya, Mexico, Poland, Russia, South Africa, the United States, and Venezuela, are estimated to possess at least ~3 x 10^{12} m^3 (~100 Tcf, trillion cubic feet or 1x10^{14} ft^3) of recoverable shale gas. Global estimates for recoverable shale gas are ~206 x10^{12} m^3, at least 60 years of current global usage in 2013, and global estimated shale oil resources are now 345 billion barrels. In the United States, mean estimates for the technically recoverable shale gas resource doubled to 600–1000 Tcf (17–28 x 10^{12} m^3) in 2013, and the technically recoverable shale oil resource rose by 40% or 58 billion barrels (Bbbl; one barrel=42 US gallons). These substantial resource estimates remain best guesses because large-scale production of shale and other unconventional resources is still in its infancy.

Hydraulic Fracturing

The unlocking of unconventional oil and gas resources has been made possible through advancements in hydraulic fracturing and horizontal drilling technologies. Drilling occurs kilometers underground and to horizontal distances of 2km or more, tracking shale, sandstone, and other formations as narrow as 30m thick. After horizontal drilling, wells are hydraulically fractured. From ~8,000 to 80,000 m^3 (2–20 million gallons) of water, proppants such as sand and chemicals are pumped underground at pressures sufficient to crack impermeable rock formations (10,000–20,000 psi). The fractures induced by high-pressure, high-volume fracturing provide the hydraulic conductivity necessary to allow natural gas and oil to flow from the formation to the well and then up through the well to the surface.

Water is an ideal working fluid for the type of fracturing needed in today's unconventional operations. It allows for the creation of long narrow fractures that provide extensive fracture surface area in the low-permeability formations now being exploited. This is in contrast to older fracturing applications in which wider, massively propped fractures were the objective of stimulation treatments, primarily for managing near-wellbore pressure and skin-effect issues in conventional reservoirs.

Environmental Issues and Water Intensity

Public concerns about the environmental impacts of hydraulic fracturing have accompanied the rapid expansion in fracturing operations over the past decade. These concerns include the potential for ground and surface water pollution, local air-quality degradation, fugitive GHG emissions, induced seismicity, ecosystem fragmentation, and various community impacts. Many of these issues are not unique to unconventional oil and gas production. However, the scale of hydraulic fracturing operations is much larger than in the past. Moreover, extensive industrial development and high-density drilling is occurring in areas with little or no previous oil and gas production, often literally in peoples' backyards.

Estimating Recovery

A central issue when estimating the water intensity of hydraulic fracturing operations is being able to assess how much energy a fractured well will yield over its lifetime following a fracture treatment. Unfortunately, this is an exceptionally difficult question to answer. A range of "production analysis" techniques, both empirically and analytically derived, exist to estimate ultimate recovery. These have been designed over the years based on data from conventional wells, and unfortunately they do not work well with hydraulically fractured unconventional wells.

The most widely used and misused production analysis technique is the Arps equation, which is effectively a semi-sophisticated form of curve fitting. This equation can be derived analytically for wells with specific flowing characteristics. Unfortunately, these conditions are generally not met with unconventional wells and so using the Arps equation to estimate the ultimate recovery from such wells leads to erroneous recovery estimates. This had a knock-on effect for assessing water intensity since any overestimation of recovery will result in an underestimation of life-cycle water intensity of energy produced from a hydraulically fractured well.

There Is No Typical Shale Well

Along with the issues of assessing ultimate recovery from shale wells, it is also important to understand that unconventional well productivity tends to differ considerably, even over very small spatial resolutions, despite having similar physical specifications and being subject to similar hydraulic fracturing treatments. What this means is that there is no typical shale well, and therefore when energy intensity and water intensity are considered, the interplay and intra-play variability in well productivity must be considered.

Life Cycle Intensity

The typical (mean) life-cycle water intensity of oil and gas produced following hydraulic fracturing treatments is between five and seven liters per gigajoule. Relative to other, major contemporary energy pathways, this remains a relatively modest intensity. However, when considering life-cycle water intensity data for unconventional oil and gas, it is also very important to appreciate that the life-cycle numbers mask a dramatic temporal asymmetry in energy production versus water consumption. A well might take 30 years to produce all its energy, but all the water needed to fracture it is consumed in one day. This fact means that while unconventional wells may not have dramatic life-cycle water intensities, fracturing them can still place large impulsive demands on localized water resources. Additionally, if the lifetime of a fractured well happens to be shortened owing to economic or technical decisions, then the actual water intensity of any energy produced will be higher than suggested by the 30-year figure. For example, if a typical shale well flows for only 4–5 years, then its water intensity will be closer to 20 liters per gigajoule, or 4X the 30-year case.

Along with assuming long and productive well lifetimes, many assessments of the water intensity of unconventional oil and gas have failed to account for the potential of "refracturing," where a producing well is re-stimulated in order to boost production. The decision to refracture is typically driven by economic factors, and will be undertaken if the stimulation is likely to increase the economic value of the well. From a water intensity perspective, refracturing has important implications in that it is likely to significantly increase the life-cycle water intensity of the energy produced from that well. This is due to the fact that while refracturing does stimulate additional production, it is not enough to compensate for the additional water without increasing overall water intensity.

Panel Discussion: Emphasized points

- The life-cycle water intensity of unconventional oil and gas production is relatively modest compared to many conventional energy pathways assuming the wells flow for 20–30 years; however, the asymmetry of energy production versus water use means that large-scale development activities can lead to significant stress on local water resources.

- Increasingly, industry is looking to move away from fresh water-based fracture fluids and toward chemistries that can function with lower-quality influent water, particularly water with higher salinity levels, which can enable higher levels of recycling in the field.

- Buoyant proppants, which make the fracture fluid chemistry a lot simpler, and even more robust with respect to salinity and other pollutants in the water, represent an exciting recent technology development. A method called channel fracturing, which uses less water and proppant, is also under active development.

- Unconventional, or shale gas, wells are unusual in that the water production actually decreases as a function of time, while in conventional reservoirs, water production goes up as a function of time. This changes the water-handling situation with greater opportunity for reprocessing and reuse of flowback water in the field. Today, water recycling practices vary dramatically by region, often due to the relative expense of disposal versus recycling. Nevertheless, regulators and the industry do appear to be moving toward higher overall levels of recycling than had been the case previously.

- There is a need for better fracture stage selection. A fracture should only be placed where it will increase well productivity. If better fracture stage selection is employed, one-third less water will be used in the typical well.

- Except in very arid regions water availability and usage is not the most significant environmental issue associated with unconventional oil and gas. A much greater concern is the potential for negative ground and surface water impacts arising from the mishandling of flowback water.

SECTION 8 DEFINING THE RESEARCH AGENDA FOR THE ENERGY-WATER-LAND NEXUS

Session Summary

This session started with a presentation by a Department of Energy (DOE) representative on initiatives in the Energy-Water-Land Nexus. After this presentation, thought leaders synthesized key points from the workshop and provided a perspective on developing a research agenda around the nexus, identifying problems that should be addressed through university, industry, and government collaboration. These key points and challenges are captured in the conclusions section of this workshop report.

DOE Initiatives: Emphasized Points

There are two initiatives at DOE related to the energy-water-land nexus. The first is a report on US energy sector vulnerabilities to climate change and extreme weather being developed as part of a broader White House initiative on climate change adaptation. The second is a working group that focuses on the energy-water component. This group consists of 80 individuals representing more than 20 programs across the department from agencies like ARPA-E, the Office of Science, and R&D program offices, that reviews what has been done and what needs to be done in this space. The goal is not just to identify work that DOE can do to leverage its expertise and resources, but to determine how to leverage the common interests that lie across the federal government and beyond. In addition, the working group will be looking at opportunities for improved research and technologies to determine the enabling policy framework needed to move both the innovative information and technology ideas into the marketplace. This working group is organized to focus on three principal areas:

- **Better Monitoring and Modeling:** There is a need for improved monitoring of information about water use and water availability as well as better forecasting. Issues that need to be addressed include the effects of climate change and the effects of energy technology deployment scenarios, particularly with regard to the water footprint. This group is focused on establishing effective decision support tools.

- **Cooling Technologies:** Cooling technologies and the feasibility of implementing power plants that are more water efficient is being studied. This team is looking at ways to take advantage of waste heat through combined heat and power, as well as ways to reduce the water needs for cooling itself and to capture, reuse, and recycle water wherever possible. In this area, cost is a concern and efforts to bring costs down are important.

- **Water for Fuels and Hydraulic Fracturing:** Work is ongoing that is investigating turning wastewater streams into a useful resource. The focus is on how to take advantage of produced water to address both the needs of the industry itself as well as potentially producing water for other sectors that could use that water. The team is studying ways of using less fresh water in the hydraulic fracturing process. This could involve a reuse of fresh water, or migrating toward non-water based hydraulic fracturing approaches. Since these methods will cost more, identifying approaches to lower costs is a priority. This team is also examining the variation in terms of water needs for different potential bio-crops. How does one make advancements in terms of reducing or producing a more drought tolerant bio-crop? How does one reduce the water intensity of the conversion process to create those fuels?

DOE is starting a fourth group looking to improve the energy efficiency in wastewater treatment in large part through improved membrane technologies and more efficient pumps. The current characterization is that about 70% to 80% of the cost of wastewater treatment plants is associated with energy, so reducing the energy footprint is important.

Another future effort will focus on energy assurance for water infrastructure. Recent climate events, like Hurricane Sandy, have underscored the interdependency between water and energy. Some of the world's largest wastewater treatment plants went offline because they did not have electricity due to these events. The team will be studying ways to build greater assurance into energy generation and energy for wastewater treatment in the future.

WORKSHOP CONCLUSIONS

The MIT-CSIS Energy-Water-Land Nexus workshop focused on identifying the key challenges facing the energy-water-land nexus over the coming decades, and the research agenda needed to help address them. As part of the event, the many factors affecting the relationship between energy, water, and land were discussed including drivers such as population and income growth, particularly in Africa and Asia. The ever-growing impacts of climate change were also described, especially in terms of how they relate to local and regional water availability and crop productivity. Combined, the growing demand for energy, water, and land resources along with the impacts of climate change suggest greater resource stress and the potential for resource-linked crises across many regions of the world over the coming years.

The issue of society's ability to manage these emerging challenges was also discussed. The point was made that historically, society has tended to find it difficult to proactively prepare for crises, tending instead to react once a crisis manifests itself. This experience suggests an effective and coordinated approach to managing any impending challenges at the energy-water-land nexus may be difficult to achieve, even if a proactive approach would be economically attractive. However, the workshop also highlighted that there is much to be optimistic about regarding the future evolution of energy's relationship with water and land resources.

Throughout the event, it was made clear that technology offers a pathway to reducing the strong contemporary dependence of energy production on water and land, along with also providing mechanisms for mitigating many of the negative environmental impacts on water and land associated with energy production. Although technology does offer great potential, if that potential is to be realized, technology cost reductions must be achieved, since cost will ultimately drive adoption in most settings, and today many technically superior options are still too expensive.

Along with the need for research and development on reducing technology costs, a range of other recommendations — some very broad and some specific — emerged over the course of the workshop. The key themes of the recommendations related to: data, its nature and the availability; technology pathways to lower the water intensity of energy production; and regulation and the design of policy and governance structures to mitigate challenges arising in regard to resource stresses and competing resource demands. Along with identifying areas for further work, workshop participants also commented on the stakeholders that should be involved in these efforts, including government entities, academia, and industry.

It was asserted throughout the workshop that access to data is often a barrier to those studying issues related to the energy-water-land nexus. Either data simply does not exist or it is not available broadly to investigators. A strong recommendation from the workshop was that wherever possible the sharing of existing data among researchers should be encouraged and that where possible, data format standards should be established to enable this sharing.

The workshop also heard about extensive ongoing efforts focused on developing more sophisticated modeling capabilities that can provide deeper insight into future water and land resource dynamics. Of course, the efficacy of these tools is based in many instances on the input data available. Therefore, current data gaps mean these tools are not yielding the value they could. Given that, the workshop recommended that increased efforts be placed on identifying today's data gaps and on the acquisition of the needed data to fill these gaps and broaden the database where necessary. It was also emphasized that in all cases it is important that government, academic, and industry stakeholders look to collaborate to the greatest extent possible to address these data challenges.

Regarding technology and its role in helping reduce the water and land demands associated with energy, the workshop highlighted that many technical pathways exist or are emerging that can mitigate the water and land impacts associated with energy production. Innovative membrane technologies that are available for reducing the salinity and other contaminants in produced water, and closed-loop cooling systems are two examples. The workshop, however, also emphasized that in many cases the challenge surrounding the technical solutions relate to their economics rather than their fundamental science and engineering, and that cost is often a gating factor for the energy industry in adopting newer, less water-intensive solutions. The workshop recommended that further effort be placed on improving the economics of today's most water-efficient technologies in order to make their adoption more commercially compelling. The workshop also recommended that continued and indeed expanded support be provided for the development of emerging technologies with the potential to yield a step change in the energy-water and energy-land relationships. Advanced water treatment and desalination techniques were singled out as a particularly important example owing to increasing climate-linked disruption to water availability in many regions and the ability for these technologies to enable the decoupling of fresh water usage from energy production.

Beyond data and technology, the issue of regulation and governance at the energy-water-land nexus was highlighted as a major challenge throughout the workshop. The point was made that as stresses on water and land resources increase owing to demographic, economic and climate change factors, the potential for conflict between energy and other resource users increases. It was also mentioned that in some extreme circumstances conflict over water and land resources could lead to future failed states, highlighting the geopolitical significance of dynamics at the energy-water-land nexus. Even in more stable regions, increased stresses on water and land over the coming decades will result in impacts that will be consequential for the energy sector. In particular, given contemporary water governance paradigms in regions like the United States, it is unlikely that the energy sector will have the political influence to defend its current water access should stresses increase, particularly if juxtaposed to the influence of the agricultural and municipal sectors. This message highlights how a transition to less water-intensive technologies and practices by the energy sector now represents an important operational risk mitigation step for the coming decades.

Overall, the workshop clarified the dynamics that are now emerging regarding water and land stresses in many regions of the world and how these intersect with energy. The uncertainty surrounding these dynamics was emphasized and the need for improved data and more effective modeling was articulated. The very significant reductions in energy production's water intensity that is possible in particular with technical solutions available today was highlighted; however, the need for the reduction of costs in order to spur adoption by industry was also addressed. Finally, the workshop described the complex regulatory tapestry that pertains to the energy-water-land nexus. This helped shed light on the risks that increasing stresses on, and competition for, water and land resources place on the energy sector's ability to access the resources needed to meet the world's energy demands. From this it was made clear that a proactive approach to the adoption of resource conservation practices and technologies by the energy industry will help reduce conflicts between energy, water, and land going forward and in turn this will reduce commercial risks for the sector while enhancing its overall energy security.

KEYNOTE SPEAKER BIOGRAPHIES

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Bryan Hannegan is Vice President, Environment and Renewables for the Electric Power Research Institute (EPRI). In this capacity, he leads the teams responsible for EPRI's research into technologies and practices that enable cleaner and more efficient renewable power generation and reduce the environmental footprint associated with electric power generation, delivery, and use. In addition to his work leading Environment and Renewables, Hannegan also served as Vice President, Generation for EPRI during 2008–2009 with a focus on enabling technologies for reliable and sustainable fossil generation. Prior to joining EPRI in September 2006, Hannegan served as the Chief of Staff for the White House Council on Environmental Quality (CEQ), coordinating Federal agency policies and activities on a wide range of energy and environmental issues affecting air, water, land, and ecosystems. During that time, he also served as an acting Special Assistant to the President for Economic Policy, helping to formulate the Advanced Energy Initiative and to implement the Energy Policy Act of 2005. Between 1999 and 2003, Hannegan served as Staff Scientist for the US Senate Committee on Energy and Natural Resources, where he handled energy efficiency, renewable energy, alternative fuels, and environmental aspects of energy production and use. Hannegan holds a PhD in earth system science, a MS in engineering, both from the University of California, Irvine, and a BS in meteorology from the University of Oklahoma. He is a member of the California Council on Science and Technology.

Dr. Thomas Hertel
Distinguished Professor of Agricultural Economics
Purdue University

Thomas Hertel is Distinguished Professor of Agricultural Economics at Purdue University, where his research focuses on the global impacts of trade, climate, and environmental policies. In 2013, he was awarded the inaugural Purdue University Research and Scholarship Distinction Award. Hertel is a Fellow and Past-President of the Agricultural and Applied Economics Association (AAEA). He is also the founder and Executive Director of the Global Trade Analysis Project (GTAP) which now encompasses more than 10,000 researchers in 150 countries around the world (www.gtap.org). This Project maintains a global economic database and an applied general equilibrium modeling framework which are documented in the book: *Global Trade Analysis: Modeling and Applications*, edited by Hertel, and published by Cambridge University Press in 1997.

Hertel's most recent research has focused on the impacts of climate change and mitigation policies on global trade, land use, and poverty. During the 2011–2012 year he was on leave at Stanford University, where he was engaged in inter-disciplinary research on these topics. Previously, Hertel conducted research on the impacts of multilateral trade agreements, including the linkages between global trade policies and poverty in developing countries. His book: *Poverty and the WTO* (co-edited with L. Alan Winters) received the AAEA Quality of Communication award. Other AAEA awards include: Distinguished Policy Contribution and Outstanding Journal Article.

Dr. Francis O'Sullivan
Director of Research and Analysis, MIT Energy Initiative
Lecturer, MIT Sloan School of Management
Massachusetts Institute of Technology

Francis O'Sullivan is Director of Research and Analysis at the MIT Energy Initiative, and a Lecturer at the MIT Sloan School of Management. His research interests span a range of topics related to energy technologies, policy, and economics. His current research is focused on unconventional oil and gas resources, the energy-water nexus, and solar energy. He has extensive expertise regarding the production dynamics and associated economics of North America's shale plays. His work also includes the study of global gas market dynamics and the LNG trade, and he is actively studying the implications for international energy markets of emerging unconventional hydrocarbon resource plays, particularly those in China and Australia. O'Sullivan has written and spoken widely on these topics, and has made presentations to the President's Office of Science and Technology Policy; the US Environmental Protection Agency; the Brookings Institute; the Bipartisan Policy Center; the Center for Strategic and International Studies; the National Governors' Association; the National Association of Regulated Utility Commissioners at CERAWeek; the American Physical Society; and to a range of other academic, policy and industry forums. He is an author of the 2011 MIT Future of Natural Gas Study, and a member of the MIT Future of Solar Energy study group. O'Sullivan is also an elected member of the National Academies' Roundtable on Science and Technology for Sustainability. Prior to joining MIT, O'Sullivan was a consultant with McKinsey & Company, where he worked extensively in the areas of economic, investment and risk analysis; strategic planning; and operations in the private equity, oil and gas, electric utility, and renewable energy sectors. O'Sullivan received his BE degree from the National University of Ireland, and his EE, SM, and PhD degrees from MIT, all in electrical engineering.

Dr. John Reilly
Co-Director, Joint Program on the Science and Policy of Global Change
Senior Lecturer, Sloan School of Management
Center for Energy and Environmental Policy Research
Massachusetts Institute of Technology

John Reilly is co-director of the MIT Joint Program and is an energy, environmental, and agricultural economist. His research focuses on understanding the role of human activities as a contributor to global environmental change and the effects of environmental change on society and the economy. A key element of his work is the integration of economic models of the global economy as it represents human activity with models of biophysical systems including the ocean, atmosphere, and terrestrial vegetation. By understanding the complex interactions of human society with our planet, the goal is to aid in the design of policies that can effectively limit the contribution of human activity to environmental change, to facilitate adaptation to unavoidable change, and to understand the consequences of the deployment of large-scale energy systems that will be needed to meet growing energy needs. Reilly received his MS and PhD in Economics from the University of Pennsylvania and his BS in Economics and Political Science from the University of Wisconsin.

Barton H. Thompson, Jr.
Senior Fellow (by courtesy), Freeman Spogli Institute for International Studies
Stanford University

A leading expert in environmental and natural resources law and policy, Barton H. "Buzz" Thompson, Jr. has contributed a large body of scholarship on environmental issues ranging from the future of endangered species and fisheries to the use of economic techniques for regulating the environment. He is the founding director of Stanford's law school's Environmental and Natural Resources Program, Perry L. McCarty Director and senior fellow of the Woods Institute for the Environment, and a senior fellow (by courtesy) at the Freeman Spogli Institute for International Studies. In 2008, the Supreme Court appointed Professor Thompson to serve as the special master in *Montana v. Wyoming* (137 Original). Professor Thompson is chairman of the board of the Resources Legacy Fund and the Resources Legacy Fund Foundation, a California trustee for The Nature Conservancy, and a board member of both the American Farmland Trust and the Sonoran Institute. He previously served as a member of the Science Advisory Board for the US Environmental Protection Agency. Before joining the Stanford Law School faculty in 1986, he was a partner at O'Melveny & Myers in Los Angeles and a lecturer at the UCLA School of Law. He was a law clerk to Chief Justice William H. Rehnquist '52 (BA '48, MA '48) of the US Supreme Court and Judge Joseph T. Sneed of the US Court of Appeals for the Ninth Circuit. Thompson received his BA in 1972 and his JD/MBA in 1976 from Stanford University.

Dr. David G. Victor
Professor of International Relations and Director of the Laboratory on International Law and Regulation
University of California, San Diego

David G. Victor is a professor of international relations and director of the Laboratory on International Law and Regulation. His research focuses on highly regulated industries, such as electric power, and how regulation affects the operation of major energy markets. He is author of *Global Warming Gridlock*, which explains why the world hasn't made much diplomatic progress on the problem of climate change while also exploring new strategies that would be more effective. The book was recognized by *The Economist* as one of the best books of 2011. Prior to joining the faculty at UC San Diego, Victor served as director of the Program on Energy and Sustainable Development at Stanford University where he was also a Professor at Stanford Law School and taught energy and environmental law. At Stanford he built a research program that focused on the energy markets of the major emerging countries — mainly Brazil, China, India, Mexico, and South Africa. Earlier in his career, he also directed the science and technology program at the Council on Foreign Relations in New York and led the International Institute for Applied Systems Analysis in Austria — one of the first major assessments of the effectiveness of international environmental law. His PhD is from MIT and his AB from Harvard University. He has published 200 articles and books in venues that include *Nature, Science, International Organization, New York Times, Finance Times, Climatic Change*, and the *International Journal of Hydrogen Energy*. He is a member of the advisory council for Nature Climate Change, a board member of Climatic Change, and joined the EPRI board in 2013.

Dr. Ellen Williams
Senior Advisor, Office of the Secretary of Energy
Department of Energy

Ellen Williams was appointed Senior Advisor in the Office of the Secretary of Energy, DOE in April 2014. Responsibilities include serving as a key advisor to the Secretary of Energy on the Department's technology transfer policies, issues, and plans. This includes the assessment of current resources and operations and the development of long-term strategic plans for technology transfer across the Department. Williams is also the President's nominee to serve as Director of the Advanced Research Projects Agency — Energy (ARPA-E) at DOE. Her nomination is pending before the Senate at the time this report went to print. Prior to accepting this appointment, Williams was chief scientist at BP International, a post she held when this workshop was held in May 2013. Her responsibilities included assurance of technology programs, and strategic research and program development. Priority actions included developing the Advisory Oversight structure for BP's Gulf of Mexico Research Initiative, running a multi-university research program on natural resource constraints in the context of energy (the Energy Sustainability Challenge), establishing cores of scientific excellence and innovation in key disciplinary areas essential to BP's long-term technical competitiveness, and evaluating emerging technologies. Williams has been a Distinguished University Professor at the University of Maryland since September 1981, but has been on a leave of absence since January 2010.

Dr. Heather Youngs
Energy Biosciences Institute
UC Berkeley, CA

Dr. Heather Youngs is a senior fellow at the Energy Biosciences Institute at UC Berkeley and Executive Editor of the publication Bioenergy Connection. A former professor of plant and fungal biochemistry at the Michigan Technological Institute, Youngs provides expert analysis on the development of bioenergy in the context of energy access and security, climate change, and long-term economic, social, and environmental sustainability. Youngs was a post-doctoral fellow at the Carnegie Institution/Stanford University and a Graduate Research Assistant at Oregon Graduate Institute. She received a BS in Biology, from Michigan Technological University and a PhD in Biochemistry and Molecular Biology from the Oregon Graduate Institute.

APPENDICES

A. White Paper, John Reilly, Jerry Melillo, Niven Winchester, and Erwan Monier, *Climate change, water resources, and land*

B. White Paper, Thomas W. Hertel, *Global Change and the Challenges of Sustainably Feeding a Growing Planet*

C. White Paper, David G Victor, *A Political Theory of Water Governance*

D. White Paper, Barton H. Thompson, Jr., *Governance of Water in the Western United States: Learning to Live with Inefficient Institutions*

E. White Paper, Bryan J. Hannegan, *Water and Electricity: Living at the Energy-Water Nexus*

F. White Paper, Padma Gunda, Heather Youngs, *Bioenergy and Water – Understanding Impacts*

G. White Paper, Francis O'Sullivan, *The Water Intensity of Hydraulic Fracturing – Scale and Uncertainty*

Climate change, water resources, and land

John Reilly (MIT) and Jerry Melillo (MBL)
with Niven Winchester (MIT) and Erwan Monier (MIT)

MIT-CSIS Energy Sustainability Challenge Forum

I. Introduction

The goal of this paper is to briefly review how climate may change in the future and how these changes may affect water resources and land. Given that the overall theme of the Forum is energy sustainability, we will focus on climate, water, and land with an eye to how these relate to energy. Also, we focus on the needed research directions for better understanding the world in which we will live in the coming decades and for developing the tools needed to make better decisions on how to plan and invest for the future, as individuals and organizations.

The energy-water-land nexus has become a major focus of attention. Skaggs, et al. (2012) provide a comprehensive assessment of interactions for the US, but the issues extend to all parts of the world. Suffice to say it is a large tent with many separate acts rather than a scripted show with a central theme and single outcome. Issues range from the adequacy of water in western China to exploit shale gas reserves, to management of water quality in oil sands production, to disposing of or cleaning up and using water produced from oil wells. It ranges from the timing and adequacy of water for hydro-power and irrigation as snowpack, snow melt, and glacier melting changes as well as how to manage stored water to assure adequate irrigation while retaining capacity to avoid flooding. Thermal power plants that rely on withdrawals from fresh water sources are at risk in low flow periods, especially with higher temperatures. On the other hand, power plants that utilize sea-water for cooling are much less at risk from water shortage but may be affected by sea level rise. Energy is also used to pump groundwater or to power inter-basin transfers of water. Arid areas are looking to desalinization or clean up and recycling of water, both of which require significant energy. In some areas, water is readily available or in excess, while in others it is a rare commodity. Many areas suffer from both excess and insufficient water depending on the season or year. All of the above involve water and energy interactions, some of these problems overlap but many do not, and all have a strong regional character depending on water availability, geography, climate, population, economic activity, and energy resources.

The land connection to energy in most cases would appear less constraining, as for most forms of energy the land footprint is relatively small, and so land needs for siting energy facilities or extraction fields are not generally coming up against global land constraints. However, siting almost any large energy production facility or extraction field is controversial, especially if near large populations or sensitive ecosystems. Renewable energy, because of its diffuse nature, would potentially have the largest land footprint. The energy alternative where interactions of water, land, and climate at a global scale are most compelling is that of biomass. At a large scale, enough to supply liquid fuel needs of a growing and richer planet, land-based biomass production could require an amount of land equal or greater than all of the cropland used today (e.g. Melillo et al, 2009). While a cellulosic crop likely would not require irrigation and water needs for conversion would depend on the technology employed, this level of land use would require significant intensification of current crop and pasture land. One way to increase production per hectare substantially is to irrigate crops. Agriculture is also relatively energy- and GHG-intensive. It uses energy directly for field operations and for pumping water for irrigation, and indirectly in terms of energy needed for fertilizer and chemical production. Downstream food processing also requires energy for heat. There are also potential climate feedbacks of renewables at large scale. Biomass production on large scale can significantly alter biogeochemistry, hydrology, and surface albedo (e.g. Melillo, et al. 2009; Hallgren et al, 2013). In the case of wind turbines, Wang and Prinn (2009) find reductions in turbulence near the surface, warmer surface temperatures, and generally changed climate when implemented at a scale to supply a substantial fraction of the world's energy demand. Large-scale solar photovoltaics can also alter surface albedo.

While it may exacerbate or in some case ameliorate risks, climate change is layered on systems that will see pressure from growing demand due to growing populations and rising incomes. Efforts to mitigate climate change by reducing GHG emissions will almost certainly result in higher energy costs, and feedback on the cost of pumping or cleaning water and producing food and biomass crops. And some of the adaptations that may be needed, such as closed-cycle or dry cooling of thermo-electric power plants may reduce efficiency of the plants. Thus, if we are not attentive to the nature of policies and measures we undertake our mitigation or adaptation efforts may result in greater emissions of GHGs that worsen rather than abate climate change.

We begin in Section II by sketching out some alternative futures based on how we (humanity) may decide to manage the planet. In Section III, we turn to the possible climate consequences, and then in Section IV focus on the land, water and ecosystem implications. Section V addresses our need for better predictive understanding of these trends and what they imply for our future and a beginning list of what we need to advance our understanding. The final section offers concluding remarks.

II. Alternative Energy Futures

We hope the world will be a wealthier place with that wealth more evenly shared. With greater wealth we can devote more to alternative energy, alternative food production approaches, and to adaptation to climate and environmental change. However, as the scale of the economy grows, demands for food, energy, and water tend to increase in absolute terms. Thus, to decrease the pressure on resources and the environment the per unit requirements need to not only drop, but drop faster than the underlying growth trend. Water, energy (or pollution per unit of energy), and land per unit of GDP or per person need to fall faster than GDP or population is increasing. There have been a large number of scenario comparison exercises developed by governmental, academic, and industry groups. All show that absent stringent efforts to control greenhouse gas emissions, they will rise with attendant climate consequences. For example, the US Climate Change Science Program compared 3 modeling groups, finding additional radiative forcing of 6.5 to 8.5 Wm^{-2} by 2100 compared to preindustrial levels. Van Vuuren et al. (2008) compare no policy and policy scenarios from 6 different modeling groups and find that substantial policies are needed to lower the projected temperature increase. Prinn et al. (2011) compared climate outcomes of emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC), with those produced by an academic group as part of the US Climate Change Science Program (CCSP) and with those of a large private energy company. All showed substantial temperature increase. Sokolov et al. (2009) and Webster et al. (2012) conduct a formal uncertainty analysis, and estimate that absent policy the total increase in radiative forcing in 2100 compared with 1990 will range from about 6.2 to 9.8 Wm^{-2} (90% probability bounds) with an additional mean surface temperature increase ranging from about 3.5 to 7.4°C. The no policy scenarios in all of these studies include continued substantial improvement in energy efficiency, available advanced low carbon technologies, and generally rising fossil fuel prices as high grade resources deplete but these are insufficient to substantially shift the economy away from fossil fuels, which despite continuing depletion remain abundant and relatively low cost. In fact, the depletion of high quality resources often leads to the use of those with greater emissions per unit of delivered energy.

To provide a broader picture of what the world might look like under different scenarios, we choose a very recent set simulations developed as part of a US Environmental Protection Agency (EPA) Climate Impacts and Risk Analysis (CIRA) Project where a no policy, a 4.5 Wm^{-2} and 3.7 Wm^{-2} policy cases were developed. The latter is widely thought to be the target needed to have a reasonable chance of meeting the 2°C above preindustrial goal agreed in international negotiations. Here we focus on the no policy and 4.5 Wm^{-2} cases. The 4.5 Wm^{-2} is closer to a 550 ppm CO_2, with some addition forcing from other GHGs, and given the lack progress on international mitigation efforts was considered to be a somewhat more realistic target. While different assumptions about economic growth, resource availability, and technology cost will lead to somewhat differences, the basic story in these scenarios is the same as in the many reviews and comparisons discussed above:

- Absent a policy that penalizes carbon emissions, in this case via a cap and trade policy, future fuel use is likely to be dominated by coal, oil and gas, with attendant greenhouse gas emissions.

- A policy that seeks to stabilize radiative forcing in the atmosphere must very quickly turn the energy system around through some combination of reduced use/increased efficiency, non-fossil fuels, or fossil fuels with carbon capture and storage.

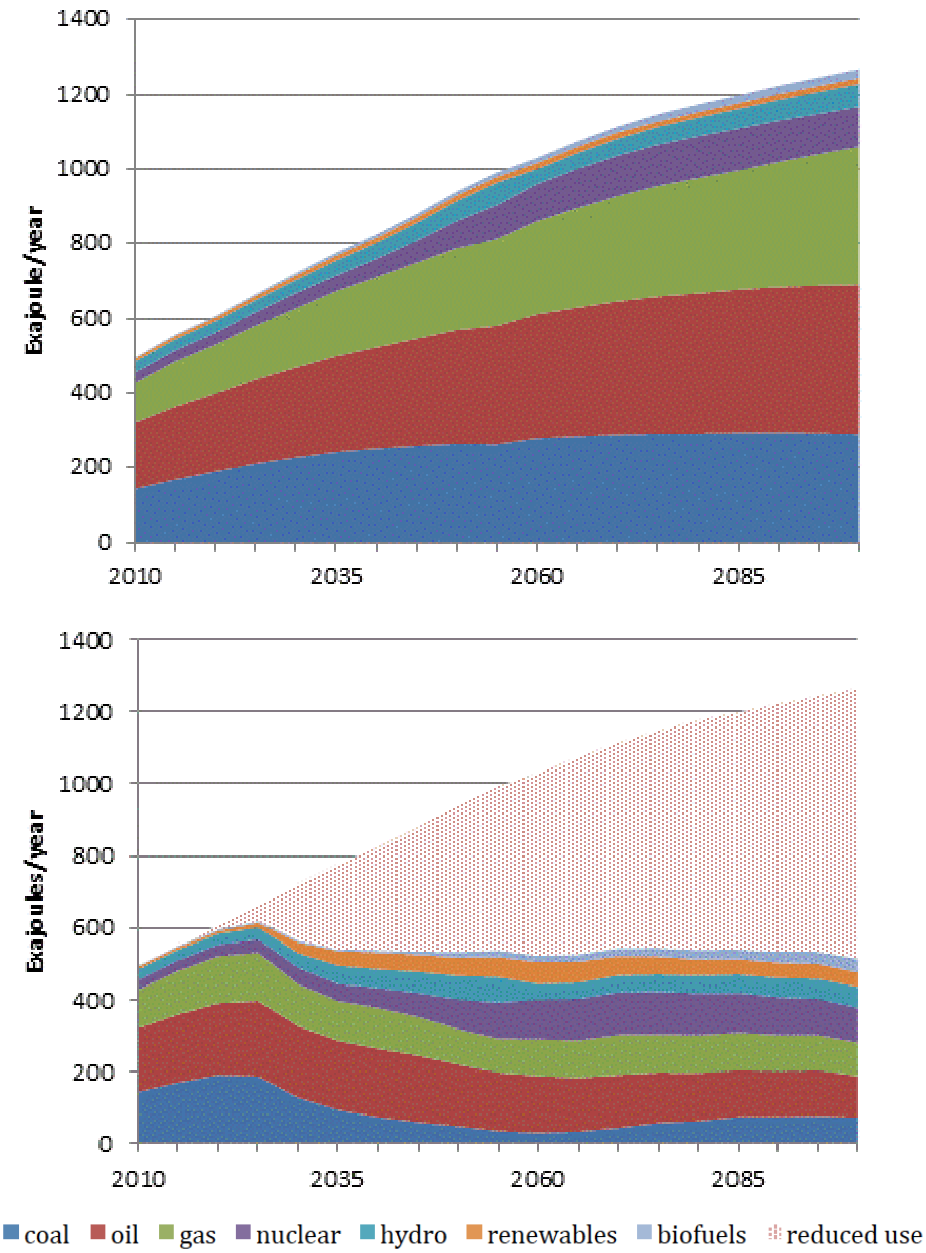

Figure 1. Energy use: a no mitigation policy scenario (top panel) and that consistent with stabilizing radiative forcing at no more than 4.5 Wm^{-2} (bottom panel).

Source: Paltsev et al. (2013).

The particular results for the CIRA project shown in Figure 1, from Paltsev et al. (2013), show energy use more than halved in the stabilization scenario relative to the no policy case in 2100, and so efficiency and reduced use play the largest role. Alternatives like nuclear, hydro, and renewables play a bigger role, but biofuels is limited by, in this scenario, incentives for reforestation to store carbon, and thus limits on land availability for conventional food and forest production and biomass energy. The continued use of coal and gas after about 2050 is only possible because of carbon capture and storage (CCS). The future energy mix is essentially an "all of the above" prescription but with much more efficient use, and delivered more cleanly. Different authors have found different ways to express this and characterize the problem, "No silver bullet" being a popular phrasing.

In the no policy scenario, world GDP (at market exchange rates) increases more than 9-fold, growing at 2.8% per year average through 2050 as rapidly growing developing countries some progress in catching up with more developed regions, and then slowing to about 2.0% per year over the latter half of the century. These estimates do not take account climate damage caused by increasing GHGs. With GDP growing 9-fold and energy use only by 2 ½ times, the energy intensity of GDP improves by 70% by the end of the century even in the no policy case.

To achieve the 4.5 Wm^{-2} stabilization scenario, GDP growth is slowed somewhat by the higher cost of energy, but still increases 7-fold. Energy use is, however, nearly the same in 2100 as today (it increases by about 4%). The arithmetic of this relationship means that energy intensity of GDP improves by almost 85%. That is every dollar of GDP in 2100 requires only about 15% of the energy used today. For more details on these scenarios see Paltsev et al. (2013). A plot of energy use for the 3.7 Wm^{-2} cases, while not shown here, is similar in character but requires a further 22% cut in energy use in 2100, and there is less time to adjust as even by 2025, energy use would be 15% below that in the 4.5 Wm^{-2} stabilization scenario.

III. Possible Climate Consequences

One of the central challenges of preparing for a future with climate change and what it means for land and water resources is to represent uncertainty, especially with regional detail. The major issue is computational demands of running full scale Atmosphere-Ocean General Circulation Models (AOGCMs) needed to capture uncertainty in climate parameters across multiple policy scenarios. Monier et al. (2013b) utilized the CIRA emissions scenarios and combined them with two relatively efficient downscaling methods (dynamical and statistical) for providing greater regional detail on climate outcomes. The study utilized the IGSM-CAM model with a 3-D atmosphere (left side of Figure 2 and Monier et al., 2013a), the 3 policy scenarios, 4 climate sensitivities and 5 different initial conditions for the climate models, creating a total of 60 separate scenarios. They also used a pattern scaling technique applied to the IGSM, with the same policy scenarios and climate sensitivities, but utilized the regional patterns of change of 3 different climate models and the multi-model mean (based on 17 climate models), creating an additional 48 scenarios. The 3 climate sensitivities (2.0, 3.0, and 4.5°C) were chosen to represent a likely probability range. The high sensitivity of 6°C was purposely chosen as an extreme range to try to capture low probability but high consequence outcomes.

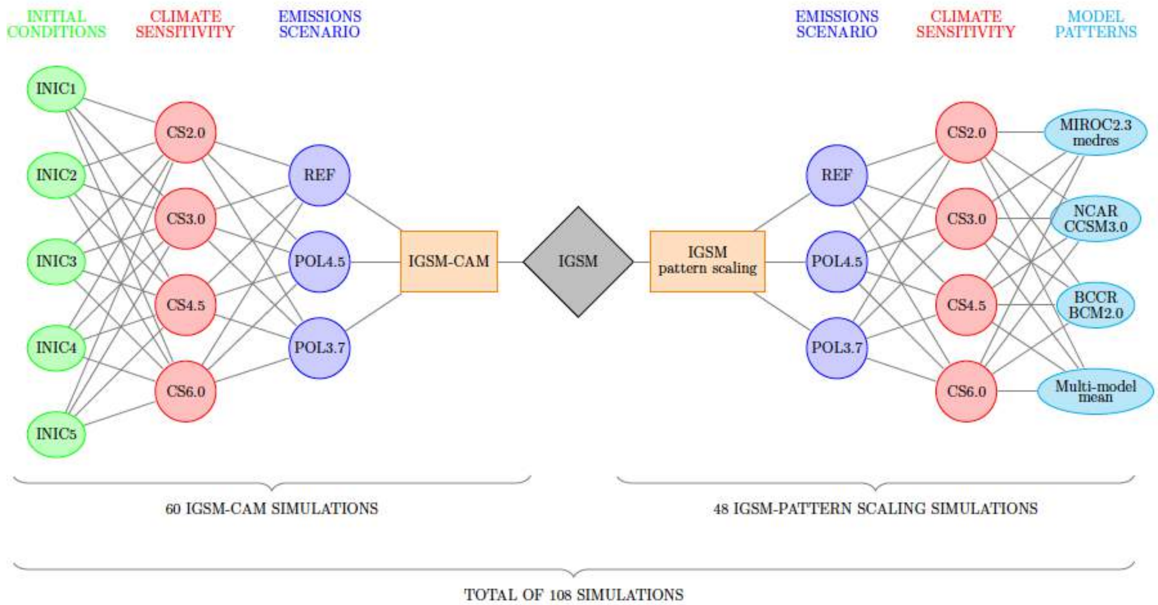

Figure 2. Scenario Development approach to represent uncertainty in regional climate.

Source: Monier et al. (2013a).

While this approach is obviously only very crudely capturing uncertainty—one would prefer a large range of climate sensitivities and other uncertain aspects of the climate system, more policy scenarios, and more initial conditions, and climate models—it is a start at more completely representing the sources of uncertainty in climate projections. And even in this streamlined fashion the number of scenarios challenges impact and adaptation analyses.[1]

Why are so many scenarios needed? Figure 3 (appearing as Figure 2 in Monier et al., 2013b) demonstrates the need. The figure shows simulated anomaly time series of US mean surface temperature and precipitation, along with observations from 1980 to 2010, individual IGSM-CAM simulations in the top panels, ensemble means (averaged over multiple initial conditions with the same policy and climate sensitivity) in the middle panels, and the pattern scaling results in the bottom panels. The IGSM-CAM simulations exhibit a strong year-to-year variability in good agreement with the observations, making long-term trends more difficult to detect. On the other hand, the pattern scaling fails to represent realistic natural variability but give clear signals of the long-term trends. Once averaged over the five initial conditions, the IGSM-CAM ensemble means show that the signal can be extracted from the noise. The IGSM-CAM and the pattern scaling provide very similar results. For precipitation, the pattern scaling approach illustrates a possible bias in relying on a single models representation of future climate. The CAM model shows, on average, more precipitation in the US with increase warming due to GHGs. With less

[1] To our knowledge none of the participating impact analyses in the CIRA project were able to use all the scenarios, and rather have the capability to use on order 10 or less.

warming the precipitation increase is less, but still an increase. In the pattern scaling, one particular model shows a weak drying over the US, and so there is a cluster of results that show decreasing precipitation currently to warming (at least until 2060).

These are important findings for future considerations of food production, water resource availabilities, and land use. Yields and water resources are subject to critical thresholds. Yields drop off quickly if temperature exceeds (or falls below critical thresholds, e.g. Rötter and Van de Geijn, 1999); soils are affected both by cumulative long term changes but also rapidly due to extremes such as erosion with excess precipitation (Rounsevell et al., 1999), and agricultural pests are often regulated by temperature and climatic extremes (Patterson et al., 1999). Thus, climate simulations that fail to include realistic variability in temperature and precipitation will underestimate crop losses due to these extreme events, and underestimate the amount of land required to produce a given amount of food or other biomass. Obviously, drought and extremely heavy precipitation also can have catastrophic effects on crops or the broader agricultural system. Similarly, water resources are subject to critical threshold. A flood stage is a critical threshold. Levee height or strength is a critical threshold. Water reservoir capacity to limit flooding or store water is also a threshold. Similarly, stream temperature for power plant cooling, especially with environmental considerations on return water temperature operates as a threshold. Rainfall and run-off up to flood stage and reservoir or levee capacity can be managed with little damage, but exceedance results in large losses. So we cannot begin to understand the consequences of climate change without realistic representation of uncertainty.

While we must understand uncertainty to understand the risk, plots like those in the top panel are often so noisy that the reaction of the public and those that must manage resources, is to throw up their hands, concluding that there is no useful information in these forecasts. If we further recognize that resource management decision makers are thinking about what they need to do today (meaning plans over the next 1, 3, 5, 10 years) where investment decisions may have a realistic economic life of at most 20 or 30 years, then the concatenation of policy uncertainty, long-term climate response uncertainty, and natural variability means that any signal will be hard to detect. Yet extremes do get more extreme and if we average out the variability through ensemble averages there indeed is a trend. But failing to recognize that the huge variability may result in mala-adaptation that fails to recognize that even with a warming trend, very cold periods are very possible, and that little average trend across models, in precipitation for example, does not preclude an ultimate trend as uncertainties are resolved.

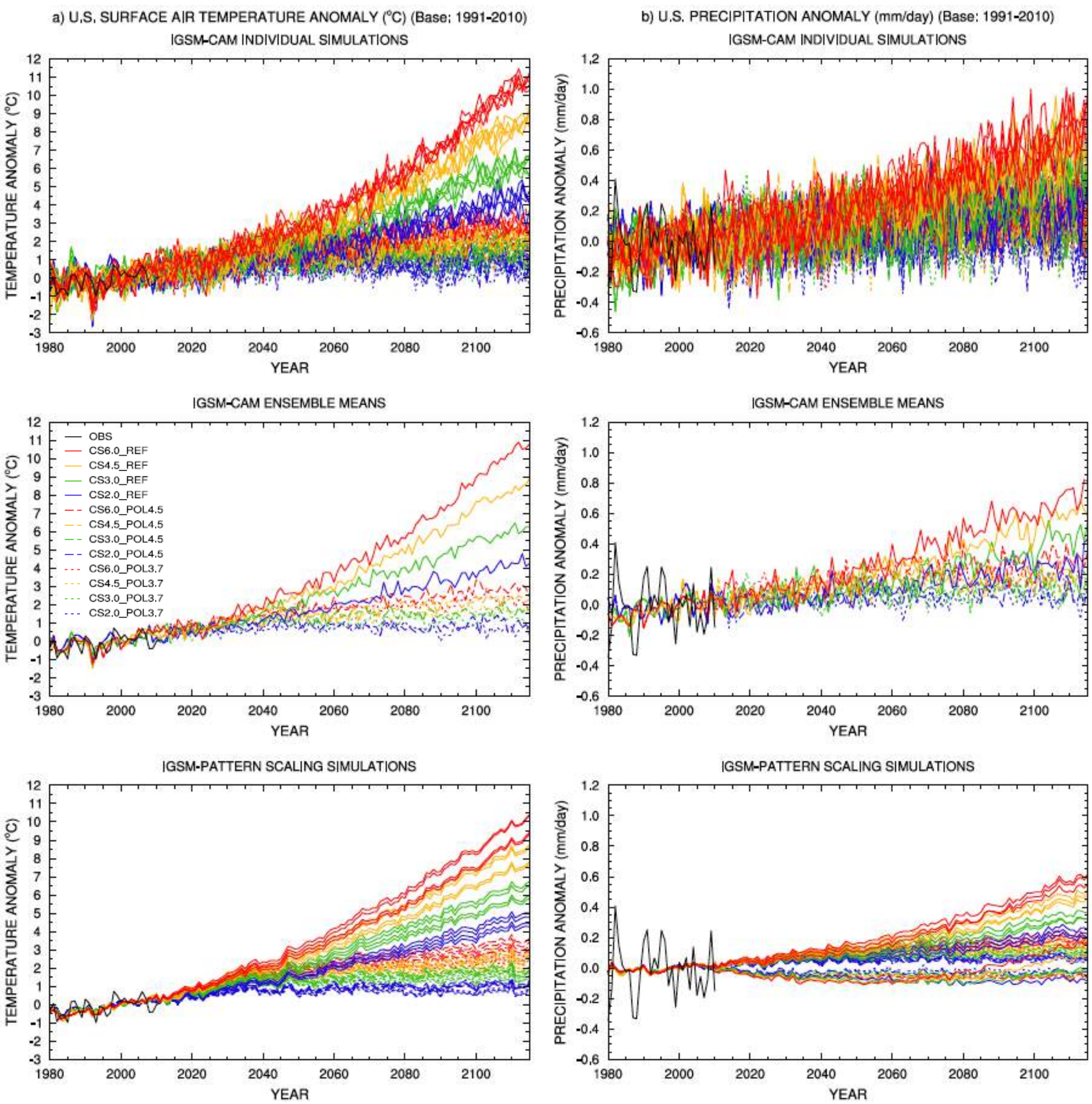

Figure 3. Time series of U.S. mean a) surface air temperature and b) precipitation anomalies from present-day (1981-2010 mean) for all the simulations with the IGSM-CAM, their ensemble mean and the IGSM-pattern scaling along with observations. The black lines represent observations, the Goddard Institute for Space Studies (GISS) surface temperature (GISTEMP, Hansen et al, 2010) and the 20th Century Reanalysis V2 precipitation (Compo et al, 2011). The blue, green, orange and red lines represent, respectively, the simulations with a climate sensitivity of 2.0, 3.0, 4.5 and 6.0°C. The solid, dashed and dotted lines represent, respectively, the simulations with the reference scenario, stabilization scenario at 4.5W/m2 and the stabilization scenario at 3.7W/m2.

Source: Monier et al. (2013b).

IV. Land, Water, Ecosystems

There are a variety of efforts to assess current stress on land, water, and ecosystems. The Food and Agriculture Organization (FAO) regularly provides a complete assessment of agricultural resources, with projections to the 2030/2050 timeframe (Alexandratos and Bruinsma, 2012). Table 1 from the recent effort provides an assessment of the potentially available rainfed cropland in the world by identifying suitable land, how much is already cropped, and subtracting out protected land to arrive at a net balance of still available cropland in the final column.

The good news is that the FAO estimates there is untapped cropland equal to or greater than all existing crop land in the world (1.4 billion hectares of untapped compared with about 1.25 billion hectares of currently cropped land). Much of this is available in Latin America, Sub-Saharan Africa and the Developed countries of the world. While the FAO subtracts out strictly protected, built-up, and forested land, such an expansion would involve intensively managing much more of the earth's surface and its annual net primary productivity. More of this land is prime, rather than good land, and bidding it from competing uses and required investment comes at a cost.

The recent Agricultural Model Intercomparison (AGMIP) project convened a comparison among 10 models that estimate future agricultural and food demand (von Lampe, et al. 2013). These types of modeling exercises are often targeted at understanding differences in model response, and demand that the models calibrate to a set of baseline conditions such as GDP growth, population, oil prices, etc., and in this case one set of impacts of climate change on crop yields. Hence the results likely narrow the range of projected outcomes. The models included a wide set of model structures from computable general equilibrium (CGE) to partial equilibrium, optimizing, and statistical estimation-based models. Often the partial equilibrium models are set up to take exogenous assumptions about GDP and oil prices, whereas CGE models solve endogenously for these variables. Despite some of these limits, AGMIP offers the most comprehensive recent comparison. We should further note that, while papers were submitted to a journal, many figures are identified as preliminary as some model groups were still reviewing and finalizing results.

Table 1. Land with rain-fed crop production potential by region (million ha).

	Total land surface	Suitable land*	Of which		Of which in use as (1999/2001)		Gross balance	Not usable**	Net balance
			Prime land	Good land	Rainfed land	Irrigated land			
World	13,295	4,495	1,315	3,180	1,063	197	3,236	1,824	1,412
Developing countries	7,487	2,893	816	2,077	565	138	2,190	1,227	963
Sub-Saharan Africa	2,281	1,073	287	787	180	3	890	438	451
Latin America	2,022	1,095	307	788	137	15	943	580	363
Near East/North Africa	11,159	95	9	86	38	12	45	9	37
South Asia	411	195	78	117	85	55	55	43	11
East Asia	1,544	410	126	283	122	53	234	140	94
Other developing countries	70	25	9	15	2	0	23	16	7
Developed countries	5,486	1,592	496	1,095	497	58	1,037	590	447
Rest of the world***	322	11	3	8	2	0	8	7	1

Note: * Crops considered: cereals, roots and tubers, sugar crops, pulses and oil-bearing crops. Includes Very Suitable, Suitable and Moderately Suitable land; ** Land under forest, built-up or strictly protected; *** Countries not included in the regions above and not covered in this study.

Source: Table 4.6 in Alexandratos and Bruinsma (2012).

Given the short space here, we focus on one illustrative result from the AGMIP exercise that is reported in Valin et al. (2013). Figure 4 shows demand by region in kilocalories (kcal) per capita per day for crops and livestock. The key results are as follows. First, the range across models is wide but that across the 1st-3rd quartile range is narrower, suggesting the wide range may be due to a few outliers (however, note our caution that range is narrowed because of standardized assumptions.). Second, the models in the project are generally higher than the FAO projection (Alexandratos and Bruinsma, 2012) which is the most widely used and regularly developed projection for agriculture. Third, there is more growth in demand in developing countries, especially more growth in demand for meat. The greater demand for meat implies greater demand for land because meat is generally more land-intensive because of the efficiency loss of feeding grains to livestock rather than producing grains for direct human consumption. This is especially true for beef. Also, one should note that the conversion of kcal per capita is a stretch for many of these models and of increasing irrelevance. For example, the CGE models solve directly in value terms, often aggregating across multiple crops. In this case, a switch to higher valued fruits and vegetables is not resolved, and so the higher food demand may be interpreted as a calorie increase when it is really an increase in higher valued crops. While the division of crops and livestock gets at some nutrient differences among food types it does not get at them all. The world's population is generally not calorie limited, but the distribution of food is unequal, and over consumption of cheap calories at the expense of nutritious food is a major problem. Thus, kcal is at best an approximate indicator of food demand.

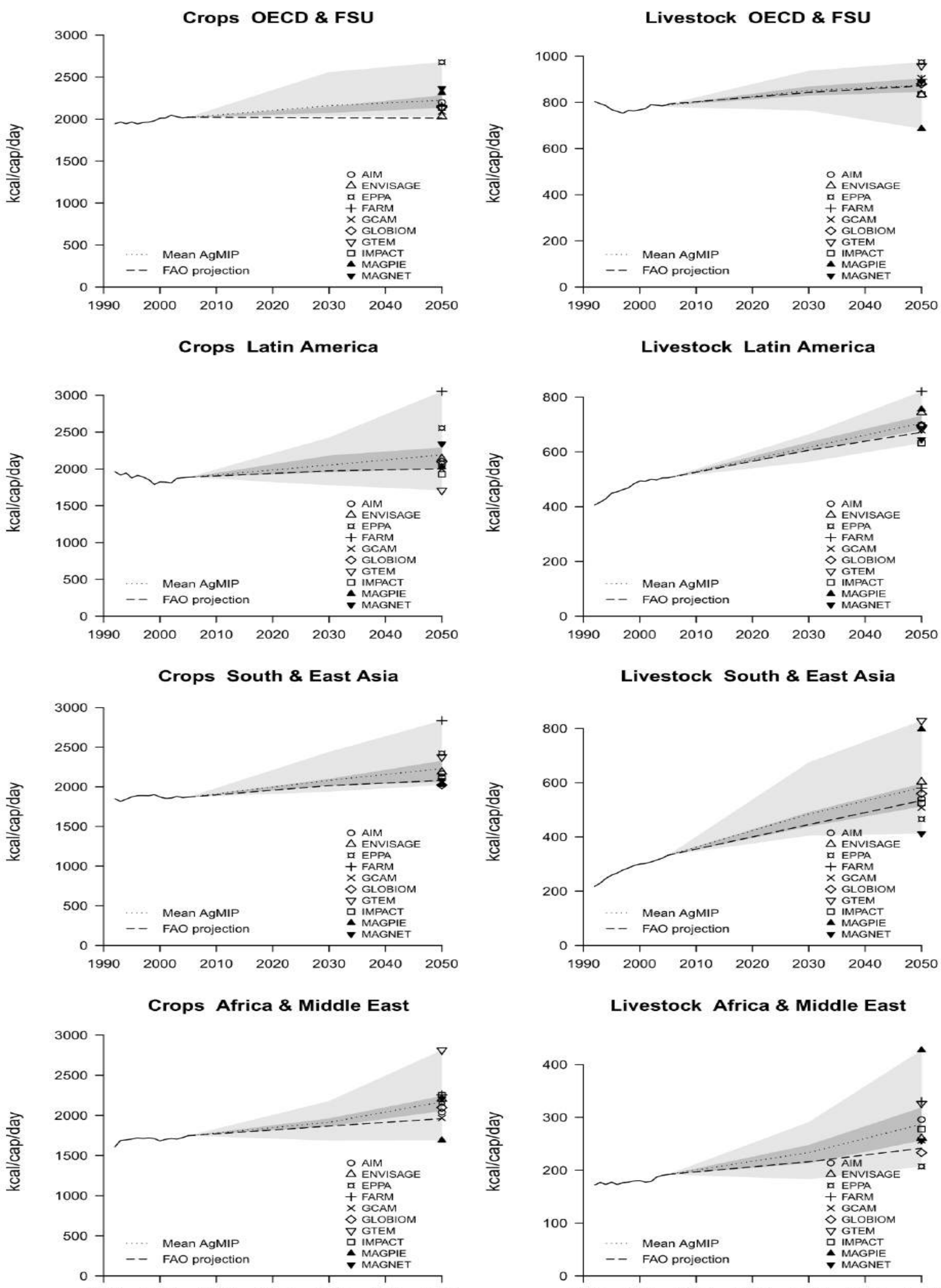

Figure 4. World food demand per capita projection for SSP2 by 2050 for AgMIP models, by region. Black plain line corresponds to historical data in FAOSTAT. Dashed line corresponds to FAO projections (Alexandratos and Bruinsma, 2012). Dotted line corresponds to mean of AgMIP model results. Light grey indicates the span of results.

Source: Valin et al. (2013).

Turning to water resources, Strzepek and Boehlert (2010) provide a recent review. Figure 5 from Strzepek and Boehlert (originally from Schmatkin, et al., 2004) illustrates the inherent regional nature of water stress and the challenge of meeting in-flow requirements for environmental services on availability for other uses.

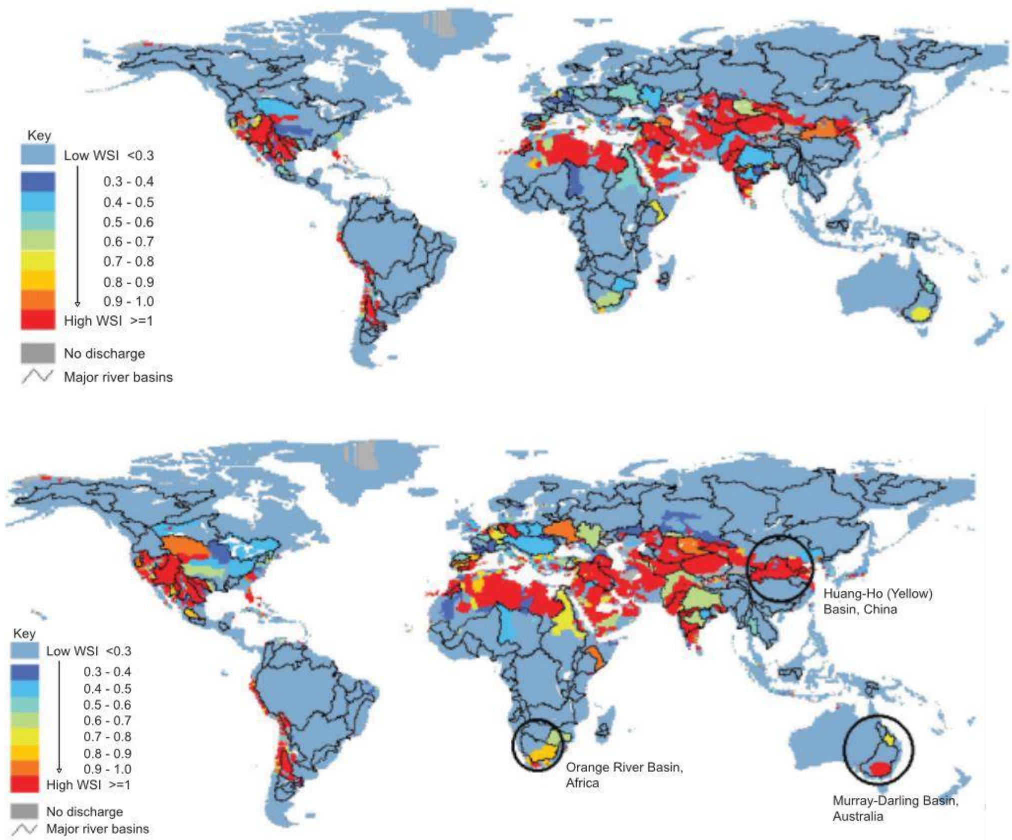

Figure 5. Traditional water stress (top panel) and water stress with environmental flows (bottom panel).

Source: Smakhtin et al. (2004b).

Strzepek and Boehlert's (2010) goal was to assess the primary threats to agricultural water availability, and model the potential effects of increases in municipal and industrial (M&I) water demands, environmental flow requirements (EFRs) and changing water supplies given climate change. They estimated that, together, these factors will cause an 18 per cent reduction in the availability of worldwide water for agriculture by 2050. The general tendency was increased stress in regions already stressed, but in considering "wet" and "dry" scenarios, they find very different levels of stress and regional signatures of climate change. Maintenance of environmental flows was the most important factor in potentially reducing water availability for irrigation. Agriculture is, and will remain, the largest user of water worldwide, especially in areas near or already under water stress conditions (Figure 6). While the often low efficiency of field irrigation systems is seen as an obvious target to reduce agricultural use while maintaining output, field efficiency is actually a poor measure in many regards. Poor field efficiency, leading to water runoff and return to the stream makes the water available again to downstream uses, and so even with poor field efficiency, the overall basin efficiency may be high.

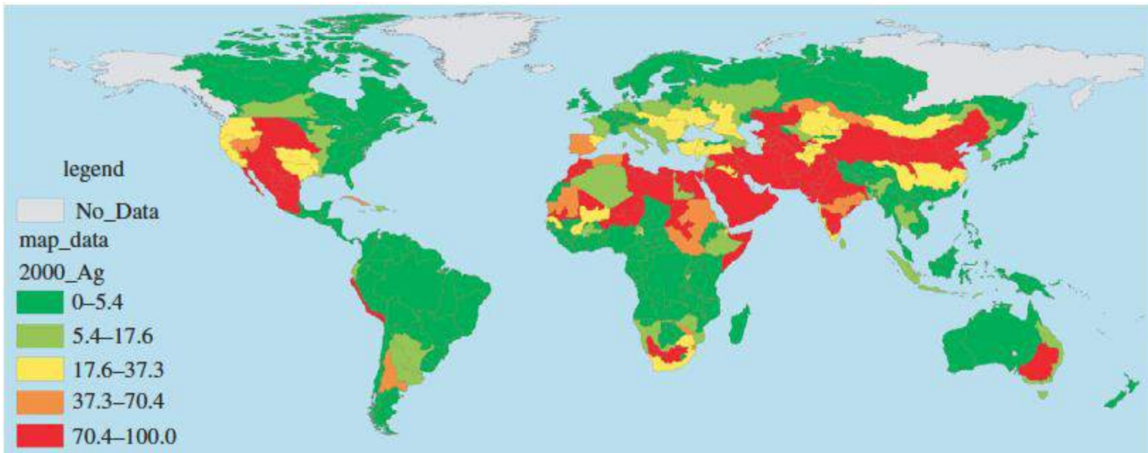

Figure 6. Agricultural water withdrawals as percentage of mean average runoff in 2000.

Source: Strzepek and Boehlert (2010).

No one, as yet, has managed to fully integrate changing demands for energy, food, biomass and water under a changing climate and broader environmental change. It is a challenging task, requiring assessment of impacts at regional and local scales, interaction of global markets, and resulting feedbacks to the global environment. A recent article (Reilly et al., 2012) combines many of these aspects—the missing component is potential additional limits on water. They assume some continued expansion of irrigated land is possible and so this may provide a somewhat overoptimistic assessment. Nevertheless, it offers some insights into the strong interactions among energy, climate, land, and food. Their goal was to consider growing demand for conventional land-based agricultural production (crops, pasture/livestock, forestry) and potential demands for biomass energy and use of forests to sequester carbon, all in the context of changes in climate, CO_2 and ozone levels. They considered 4 cases—a no climate policy scenario, a 550 ppm CO_2 stabilization scenario, and then extension of carbon pricing from the 550 ppm CO_2 scenario to land with or without the availability of biofuels.

One of the more important and interesting results is how these various factors interact to affect world food, crop, livestock and forestry prices (Figure 7.) Climate change and ozone damage threaten agricultural productivity, but interestingly the no policy and 550 ppm CO_2 stabilization scenarios show almost identical changes in agricultural prices. Avoided climate and ozone damage with stabilization also limits the benefits of expanding crop production poleward and increases the demand for biofuels. Higher energy costs also lead to increased food prices as does the need to mitigate methane and nitrous oxide from agricultural sources. So these effects essentially offset one another. The pricing-land scenario leads to the greatest increase in agricultural prices, because reforestation for carbon sequestration competes effectively for land, given the carbon prices needed. This extension does achieve somewhat more climate mitigation, saving a about .5 degrees C of warming, and bringing the total warming close to the 2 degree C target (about 2.2 degrees) widely agreed as necessary to avoid catastrophic interference with the climate system. While this is but one model and one climate scenario, it illustrates some of the very complex tradeoffs we face in managing the worlds resources to meet traditional demands, and new demands largely driven by environment concerns that themselves threaten these resources. Adding the water story to this picture would obviously add another layer of complexity.

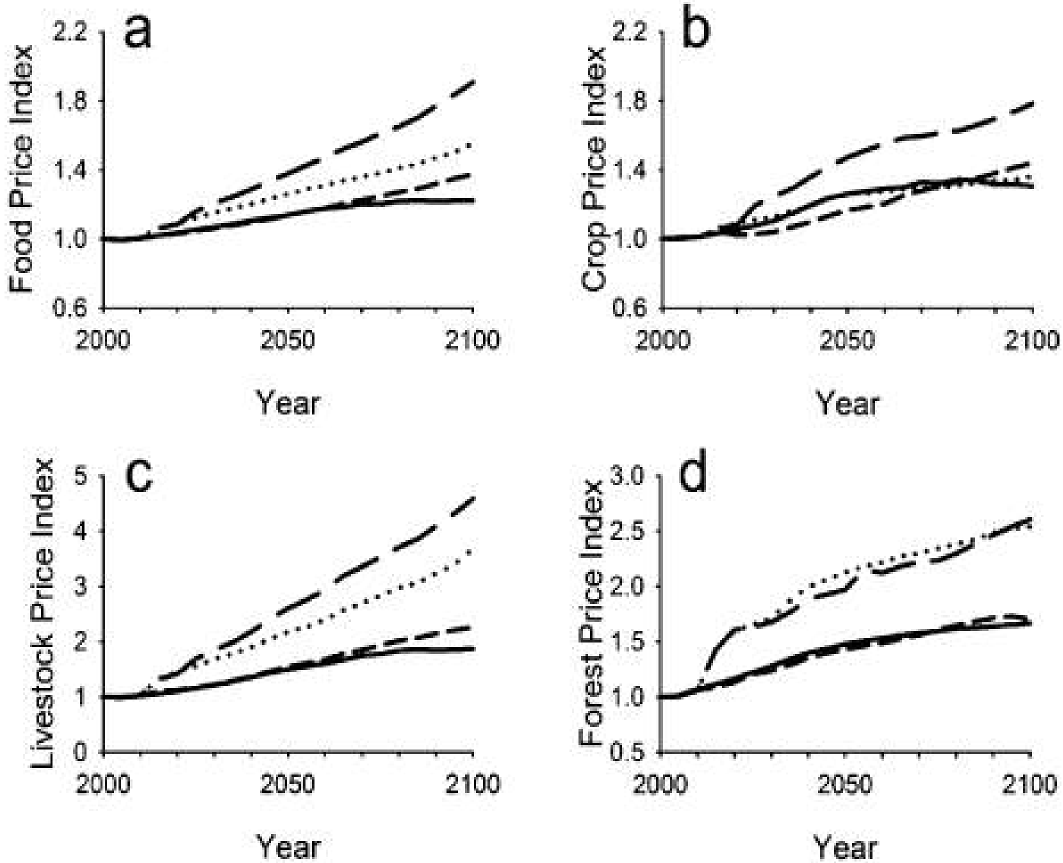

Figure 7. Changes of price indices for agricultural (a b, c) and forest (d) products for different climate/energy policies: No-Policy (solid line), Energy-Only (short dashed line), Energy+Land (long dashed line), and No-Biof uel (dotted line) using 2000 as the baseyear. Product prices are affected by changes in all input costs, including energy and land costs that are most strongly affected by the policy scenarios. Food prices (a) rise due to higher energy costs, crop prices (b), and livestock prices (c) which are intermediate inputs into food production.

Source: Reilly et al. (2012).

Also of interest are the climate feedbacks from land use change. As noted above the incentives to reduce deforestation/increase reforestation save about .5 degrees C of temperature rise, largely in this analysis through the carbon cycle. Figure 8 shows the regional pattern of carbon release or increased storage. An important message here is that without some sort of land policy that limits deforestation the authors see considerable threats to existing natural forests.

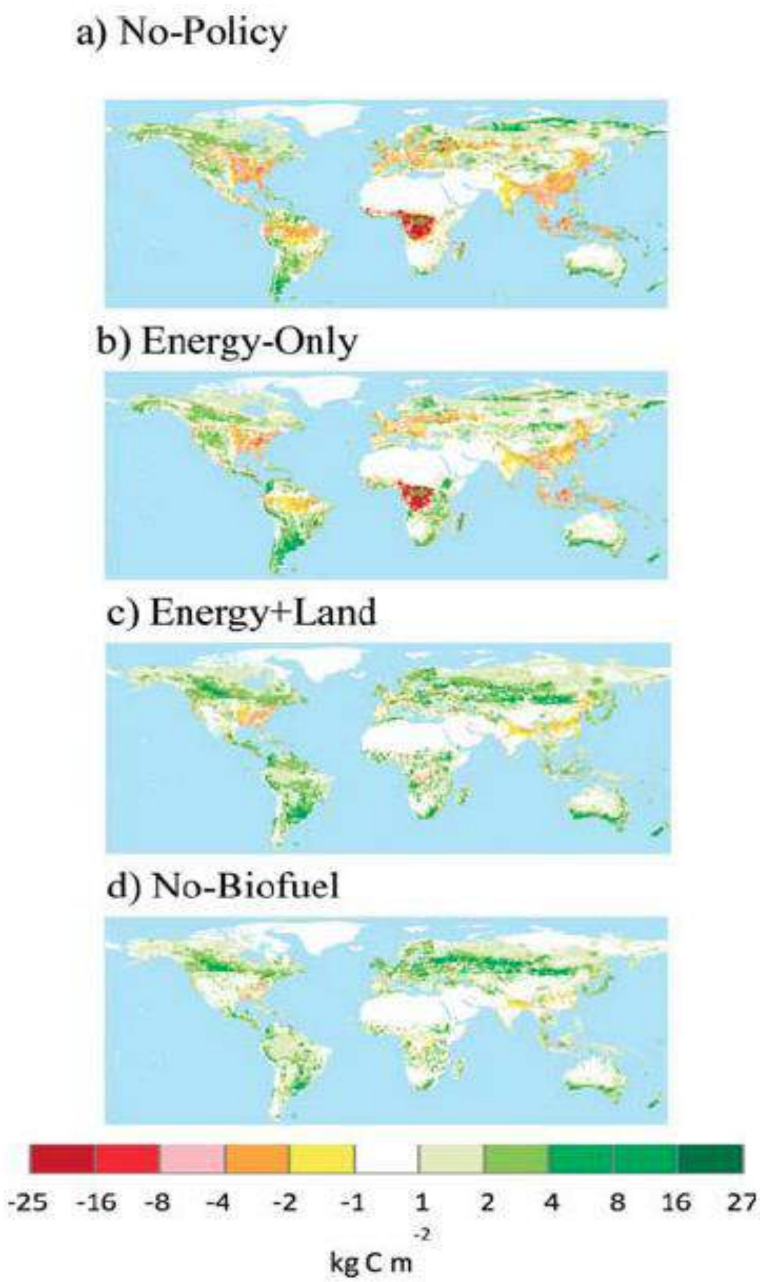

Figure 8. The redistribution of terrestrial carbon storage across the globe in year 2100 from year 2000 for different climate/energy policies: a) No-Policy, b) Energy-Only, c) Energy+Land, and d) No-Biofuel. Positive values represent net terrestrial carbon sequestration, while negative values represent net loss of terrestrial carbon

to the atmosphere.

Source: Reilly et al. (2012).

There can also be substantial feedbacks on the climate form land cover changes in these types of scenarios as shown by Hallgren et al. (2013) using earlier, but similar scenarios of land-use change from Melillo et al. (2009). In their work, they show that deforestation can have an offsetting cooling effect and would also change the hydrological cycle.

The broad message is that humanity is affecting the planet in ways that significantly affect the habitability of the earth we live on. Land, water, and energy are at the center of this problem. Even as we seek out cures for our perceived current problems, we need to be cautious not to worsen them or unbalance the planet in other ways.

V. Planning and Investing for the Future

This final section of the paper briefly describes five topics that we need to consider as we invest for the future. The first four topics challenge us to reorient our thinking about climate, climate risks, the consequences of managing resources at the global scale. The final topic calls for an investment in developing global datasets in support of management decisions.

Recognizing the Dynamic Nature of Our Climate – If investments and long-lived decisions on resource management are to be effective, they need to be resilient to the future climate changes that we will experience. Most of our planning efforts have been based on the assumption that climate is stable. We can look at hundred-year floods or statistics of heat and drought, and plan on the assumption that events will continue to occur with a similar frequency. This assumption may have been misguided in the past because looking back over the longer climate record, there is evidence of far wider ranges of natural variability. It becomes much less tenable as a strategy for the future when we admit that climate change will certainly alter these statistics. We need to build into our regular decision processes a more scientifically rigorous approach for the assessment of the risks and vulnerabilities in a dynamic climate, using new insights gained from this approach to evaluate what it means for the investments we are undertaking now.

Focusing on Low probability, High Consequence Events - Continued basic scientific research that better understands earth system linkages and responses is certainly needed. However, we need to develop a better way to direct research toward the possibility and likelihood of low probability, extreme outcome events. A clustering of effort to understand the central response of the earth system misallocates resources if the expected loss is related to potential extreme outcomes. Be well prepared for the “most likely” outcome is not a good strategy if we are ill-prepared for high-consequence low-probability events. At the same time being prepared for every wild possibility without attention to likelihood can impede progress if it involves large investment. A particular challenge is characterizing extremes of weather at the local and regional level where resource management occurs.

A related thought is that efforts need to be made to characterize existing uncertainty given what we know today, incorporating multiple lines of scientific evidence, to support the decisions we are making today. Too often the scientific challenge is cast as reducing uncertainty, promising better information in 5 or 10 years. But in those 5 or 10 years more investment commitments are made that may harden us into ill-preparedness. Undoubtedly we will learn and regret some of the things we do today, whatever information we use, but we need to take care that our method are not unrealistically narrowing potential future outcomes or throwing out insights and information that does not easily fit in existing models and methods.

Evaluating Climate and Environmental Risk With New Tools – New tools are being developed for evaluating climate and environmental risk. A good example of a start in this direction is the work of Lickley et al. (2013) on the issue of protection coastal energy infrastructure in the face of stronger tropical storms and sea level rise. Using a set of coupled modeling tools, they consider uncertainty associated with projections of the magnitude of sea level rise and coastal subsidence to produce detailed projections of risk for energy infrastructure over the century. They then apply a dynamic programming cost-benefit analysis to adaptation decisions.

The approach of Lickley et al. can be applied to other situations. At the same time, we need to realize that while complex decision making and investment evaluation criteria may be viable for large companies, many smaller companies would never be able to invest perhaps on order of $1 million or more to evaluate climate and environmental risk. As an alternative to expensive situation-specific risk analyses, engineers rely on standard "rules of thumb" and public standards such as building codes, flood plain designation, and coastal set backs. The research community will need to work with those who set these standards to revise them to reflect the new risks we face.

Considering Issues of Scale: We need to understand the implications of carrying out investments at large scale. In the aftermath of the financial crisis, we should not have to remind our selves that bad decisions by individuals, if enough participate, can spillover and punish many who were not part of what, at least in retrospect, looks like a bad decision. The shale gas story is both something of a success and also a cautionary tale. A technology that has positive economics can take off very quickly and catch everyone by surprise. It is a challenge for the regulatory system to keep up and adjust, assuring safety and environmental integrity, while not impeding progress on something that may have substantial economic and even net environmental benefits. But without looking forward to where we need to be, we may overinvest, and then add an additional anchor to making the long-term changes that are needed. The political lurch into biofuels via mandates in the US and Europe is another cautionary tale, where vested interests took advantage of a policy opportunity and succeeded in creating regulation that went beyond what the science would have likely recommended.

Improving Global Datasets for Use in Models – Slowly, the community has been gathering better global datasets on critical infrastructure, water resources, land use, and soil quality. However, these datasets remain remarkably limited. For example, a recent analysis of soils data suggests that spatial resolutions of soil maps for most parts of the world are too low to help with practical land management (Sanchez et al. 2009). In addition, many potentially useful datasets are seen as vital to a country's security interests and so there is resistance to making the information available to the research community. Satellite or remote observation can overcome some of this problem, but there is a need to establish the fundamental value to all of globally shared information resources.

While much of the useful global data is about the contemporary situation, historical data can also be important (Hurtt et al. 2011). This is particularly true for land-use data, because land use in the past can have legacy effects that influence import ecosystem service such as food production and carbon sequestration.

VI. Concluding remarks

The stationarity assumption built into our investments decisions as they relate to climate risk is no longer tenable. Methods exist to update decision rules and make better decisions in the face of climate change. Better understanding of the fundamental science is essential, but the development or risk-based approaches that can be applied to decisions that affect our daily lives are necessary. Private investors have a strong interest in applying such methods but there is also a strong role for public sector in ensuring that data are available and that public rules and regulations (such as flood plain designation, coastal set-backs, building codes, water resource allocation decisions) reflect risks as we understand them today.

Decision rules and regulations will need to be regularly updated to reflect our changing understanding of the climate risk. The broader research community has moved in the direction described above but to be adequately prepared a sharper Federal focus is needed within the US, and the US needs to also engage globally on this topic. While the Federal budgetary issues makes expansion of research effort in any area difficult, this is one area that needs attention. Investment in high return research, even if it adds to the deficit or slows our attempts to close it, leaves our children better off by improving their preparedness for climate risks. Of course, as illustrated by the potential climate outcomes in the absence of any mitigation effort, adaptation is not a substitute for mitigation. A balanced approach is needed, with concerted effort to mitigate greenhouse gas emissions while preparing the nation for what is now a considerable amount of unavoidable climate change.

Acknowledgements

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Global Change and the Challenges of Sustainably Feeding a Growing Planet[1]

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Setting the stage[3]

Since the 2007/2008 commodity crisis, there has been a resurgence of interest in the sustainability of the world's food system and its contributions to feeding the world's population as well as to ensuring the environmental sustainability of the planet. The elements of this 'grand challenge' are by now quite familiar. The number of people which the world must feed is expected to increase by another 2 billion by 2050 (Bloom 2011). When coupled with significant nutritional improvements for the 2.1 billion people currently living on less than $2/day (World Bank 2008, p.1), this translates into a very substantial rise in the demand for agricultural production. FAO estimates the increased demand at 70 percent of current production, with a figure nearer 100% in the developing countries (Bruinsma 2009, p.2).

Over the past century, global agriculture has managed to offer a growing population an improved diet, primarily by increasing productivity on existing cropland. However, a number of authors have documented signs of slowing yield growth for key staple crops (Byerlee and Deininger 2010, Box 2.1). And public opposition to genetically modified crops has slowed growth in the application of promising biotechnology developments to food production in some parts of the world. At the same time, the growing use of biomass for energy generation has introduced an important new source of industrial demand in agricultural markets (Energy Information Agency 2010). To compound matters, water, a key input into agricultural production, is rapidly diminishing in availability in many parts of the world (McKinsey & Co 2009), and many soils are degrading (Lepers et al. 2005).

In addition, agriculture and forestry are increasingly envisioned as key sectors for climate change mitigation policy. When combined, farming and land use change – much of it induced by

[3] This section draws heavily on my AAEA Presidential Address (T. Hertel 2011).

agriculture - currently account for about one-third of global greenhouse gas emissions (Baumert, Herzog, and Pershing 2009), but, if incorporated into a global climate policy, these sectors could contribute up to half of all mitigation in the near term, at modest carbon prices (A. Golub et al. 2009). Any serious attempt to curtail these emissions will involve changes in the way farming is conducted, as well as placing limits on the expansion of farming – particularly in the tropics, where most of the agricultural land conversion has come at the expense of forests, either directly (Holly K Gibbs et al. forthcoming) or indirectly via a cascading of land use requirements with crops moving into pasture and pasture into forest (Barona et al. 2010). Limiting the conversion of forests to agricultural lands is also critical to preserving the planet's biodiversity (Green et al. 2005). These factors will restrict the potential for agricultural expansion in the wake of growing global demands.

Finally, agriculture and forestry are likely to be the economic sectors whose productivity is most sharply affected by climate change (D. B. Lobell, Schlenker, and Costa-Roberts 2011; Schlenker and Roberts 2009). This will shift the pattern of global comparative advantage in agriculture (J. Reilly et al. 2007) and may well reduce the productivity of farming in precisely those regions of the world where poverty and malnutrition are most prevalent (T. Hertel, Burke, and Lobell 2010), while increasing yield variability and the vulnerability of the world's poor (Ahmed, Diffenbaugh, and Hertel 2009).

Set in this way, the world's stage offers a rather bleak picture when it comes to ensuring the long run sustainability of the planet. However, as with most such predictions, the issues are rather more complex than portrayed in 'headline' reports. The goal of this background paper is to delve into greater detail on the determinants of long run sustainability in the global system of food production and the land, water and energy resources upon which it relies, and which the food system shapes. In most of the analysis, I focus on the target year 2050. My logic (apart from joining the bandwagon of other studies with this focal point) is that I believe this to be the period during which the challenge to sustainable agricultural production will be greatest. There are reasons for this conclusion. Firstly, sometime around mid-century we expect global population growth to level off. Based on income projections, this is also the point at which we can expect most of the world's population to have upgraded their dietary requirements, thereby limiting further growth in food demand arising from increases in income. From a climate mitigation policy point of view, 2050 is also quite interesting, as the coming decades are the period over which land-based mitigation policies are likely to play the most important role – particularly those aimed at sequestering a portion of the massive increases in CO2 emissions projected over the near term. And finally, from a more practical perspective, 2050 is at the outer limit of (indeed probably beyond) the ability of economists to project patterns of long term economic growth.

With the stage thus set, let me turn to some key points which will shape global sustainability outcome between the present day and 2050.

Population and income will remain key drivers of global change, but their relative importance will change

Population and income are the twin drivers of global change which attract the most attention – and deservedly so. If the world's population does nothing to change its behavior, but demographics result in a doubling of the number of mouths to feed, clothe, house, transport and entertain, the planetary burden would effectively double. While a global population of 14-15 billion people is at the upper limit of demographic projections for the end of this century (Roberts 2011), even the projected 2050 population increase of an additional 2 billion people appears daunting in the context of a world which is already straining the environment and natural resource base. The question of population size notwithstanding, as we look forward to 2050, it is really the increase in per capita income that is of greatest concern. Just consider the following thought experiment. Which scenario is likely to generate the greatest stress on the world's resources: (a) Adding an additional 2 billion people consuming at average per capita global consumption levels, or (b) the prospect of today's 7 billion people consuming at the same rate as the current US population? Viewed from a carbon emissions point of view, the answer is very clear. Keeping per capita consumption at current levels, which boosting population by 30% would generate about a 30% rise in carbon emissions. However, raising consumption levels of current population to those of the United States has been estimated to result in a four-fold rise in global carbon emissions (Huber 2013).

Economists have sought to explain these differences in consumption behavior across countries using prices and income as well as other variables (Dowrick and Quiggin 1994), and these statistical studies can then be used to project how future consumption patterns are likely to change in the future.[4] Baldos and Hertel (Baldos and Hertel 2013b) draw on the statistical work of Muhammed et al. (2011) in order to formally compare the relative role of population and income as drivers of global food demand and land use changes over two alternative 45 year times spans: 1961-2006 and 2006-2050. From the point of view of global crop output growth, they find that population growth was roughly twice as important as growth in per capita income over the

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[4] One might reasonably ask: How can we know how consumers in Ethiopia will behave when they become as rich as consumers in South Africa? Will Chinese consumers follow the path charted by consumers in Taiwan? In order to predict the evolution of consumer spending as incomes rise, economists look at behavior across many countries, seeking to identify broad patterns across wide ranges of income. There is considerable evidence that consumers follow a common pattern with regard to broad-based consumption behavior (e.g., food, housing etc.) (Dowrick and Quiggin 1994). Muhammed et al. estimate the response of food consumption to changing prices and income. They find some relationships that are important for projections purposes – namely the diminishing marginal impact of income on consumption, as well as the fact that consumers' responsiveness to food price changes also diminishes as incomes rise. Hertel and Baldos use these relationships to "backcast" global food demand, prices and land use, and find that, at global scale, they are able to reproduce historical food consumption over a 45 year period. This gives us some hope that we can say something useful about the next 45 years.

historical period. However, in the projections period, the role of population growth in boosting crop output and prices is only about one-third as large as in the historical period, and it is now dominated by the role of growing per capita income as one looks ahead to 2050. This is a very significant change in the international landscape, with important implications for the growth in global food demand.

Much of the increased crop output demanded over the period to 2050 will be in the form of feedstuffs for livestock. This is because the demand for animal protein grows strongly as consumers move out of absolute poverty and seek to enrich their diets. Livestock can be produced via extensive production techniques (e.g., grazing in the case of ruminant livestock, or foraging in the case of poultry and pigs) or intensive techniques, epitomized by the ‘factory farms’ in which thousands of animals are fed concentrated feed rations in confined facilities (F. Taheripour, Hurt, and Tyner 2013). These two types of technologies have dramatically different implications for the food system and for environmental quality. The issue is somewhat akin to the discussion of ‘land-sparing’ vs. ‘land-caring’ technologies in crop production (Green et al. 2005), which poses the question: Is it better for society to undertake intensive production techniques which may have locally harmful environmental consequences, but which spare resources at global scale, or is it preferable to use the world’s resources more extensively, spreading the environmental impact of agricultural production more thinly across the globe?

Over the last 20 years, there has been a shift, worldwide, towards more intensive livestock production techniques, with marked implications for the composition of agricultural land use (F. Taheripour, Hurt, and Tyner 2013). Globally, area devoted to permanent meadows and pastures – typical of extensive livestock production -- fell by about 70 million hectares over the first decade of this century, with animal feed crops such as hay and fodder falling as well.

Meanwhile, the area devoted to corn and oilseeds – key inputs into concentrated livestock diets -- has risen by about 60 million hectares over the same period (F. Taheripour, Hurt, and Tyner 2013). Much of this increase has been destined for livestock – either directly through feed concentrate, or indirectly as by-products of biofuel production (dried distillers grains or oilseed meal). This increase in area has been especially notable in South America. Indeed Brazil has become a key supplier of soybeans to the Chinese livestock industry, where rising incomes have translated into strong growth in consumer demand for animal products. In short, rising incomes will continue to be an important driver of global demand for agricultural land, eclipsing population in relative importance as the growth rate in the latter continues to slow.

Energy Prices are the Wildcard Driver behind Global Land Use Change

While it is widely understood that energy prices play an important role in shaping energy-related exploration, supply, innovation and consumption, it is less-well appreciated how important energy prices can be in shaping global land use – particularly in the current era of close linkages between the energy and agricultural markets driven by growing biofuel production (Tyner 2010). Indeed, the global expansion in corn and oilseeds area over the past decade is in part due to the growth in biofuels (Farzad Taheripour and Tyner 2013). Looking forward there is great uncertainty in this linkage between energy and agricultural markets, and this uncertainty is largely fueled by the tremendous uncertainty in energy prices facing the world economy.

Steinbuks and Hertel (Steinbuks and Hertel 2013) explore the relationship between energy prices and global land use over the course of the 21st century. Their framework allows a role for energy prices to influence fertilizer prices, thereby altering the incentive to intensify agricultural production. They also allow for the substitution of first and second-generation biofuels for petroleum products in liquid fuels. In considering possible trajectories for oil prices over the 21st century, they take as their low-price case a scenario in which oil prices remain flat at current levels throughout the century. This is the ‘fracking’ scenario in which new technologies for extracting fossil fuels, as well as new fossil fuel discoveries, result in ample supplies. For the high oil price scenario, the authors extrapolate to 2100 the growth rates embedded in the baseline US Energy Information Agency scenario. As a result, real oil prices grow at an average annual rate of 3%/year, reaching a peak of $700/bbl by 2100. The authors find that, in the context of a model of optimal global land use (designed to mimic behavior of forward-looking investors), the flat energy price scenario results in much less agricultural land conversion by 2100, relative to the EIA baseline scenario. Indeed, by 2100, global land use for food and biofuels is 400 million hectares lower than under the baseline. Half of this difference is accounted for by reduced area devoted to food production – cheap energy results in cheap fertilizer and higher yields -- and half is due to the elimination of bioenergy crops in the context of this low oil prices scenario. This highlights the sensitivity of global land use to long run energy prices. Whether or not we live in a cheap energy future will have great influence over the pattern of global land conversion for food and biofuels.

Water will become more prominent in our discussion of global sustainability

It is impossible to speak about sustainability of the global food system today without considering the role of water. Agriculture accounts for 70% of freshwater withdrawals globally, and irrigated lands contribute to 42% of global crop production (Bruinsma 2009). And in some regions these withdrawals are in excess of what is sustainable over the long run. Bruinsma projects that, by 2050, 13 countries will be devoting more than 40% of their renewable water resources to irrigation – a level considered to indicate very high stress. In South Asia, he estimates that this figure will rise from 36% to 39%. Of course, as with any resource that is under-priced, or even free in many cases, there are tremendous opportunities for efficiency gains and these likely hold the key to future sustainability of water use in agriculture.

In a more comprehensive global study, undertaken at the level of individual river basins, and utilizing a suite of economic and hydrological models, Rosegrant et al. (2013) compare Irrigation Water Supply Reliability (IWSR) indices across two 2050 scenarios. The first is the Business As Usual (BAU) scenario under which agricultural productivity and water use efficiency in the agricultural, industrial and domestic uses sectors reflect current trends. In contrast, under the Bioeconomy (BIO) scenario, they allow for faster agricultural productivity growth, due to increased R&D expenditures, as well as significant improvements in water use efficiency – particularly for the non-agricultural sectors. This, too, is important for irrigation, since water available for agriculture is often a residual, based on availability other water demands have been satisfied. The authors find that, under their BAU scenario, the global IWSR – the ratio of irrigation water supplies to demand (1.0 is best) falls from 0.77 in 2000 to 0.62 in 2050. The decline is particularly sharp in the East and South Asia regions, as well as Central Asia. In contrast, under the BIO scenario, higher agricultural productivity and increased water use efficiency allow for a global IWSR of 0.73 in 2050, with far smaller declines in the Asian regions, as well as increases in some of the other regions. In short, more making more efficient use of water – both in irrigation and in non-farm uses – is critical for ensuring global sustainability of agricultural production in 2050.

Future food prices will depend critically on technological progress in agriculture

Pinning down technological progress is the key to understanding the long run trajectory of the agricultural sector, food prices and global land use. A good place to start is with a careful examination of the historical record. Given the widespread availability of data on global agriculture over the past 50 years, one would think that there might be a consensus about the historical evolution of technological progress in this sector and the prospects for future growth. However, this is not the case. Indeed, there have emerged two broad camps on this issue. For lack of better terminology, and for the sake of sharpening their differences, I will label them: the pessimists and the optimists, although many of the individuals writing in this area offer a more balanced perspective in their own writings.

To paraphrase their arguments, the pessimists suggest that science has largely ‘worked its magic’ and potential crop yields (i.e., the maximum attainable under ideal conditions) are reaching a biophysical plateau beyond which the ability of plants to convert sunlight, water and nutrients into grain cannot be easily increased. Fischer et al. (2013) discuss the biophysical components of growth in potential yields, noting that potential yields depend on the product of three key factors: the photo-synthetically active radiation intercepted by the green crop tissue, the radiation use efficiency of the plant, and the harvest index -- which measures the portion of the plant devoted to grain. They note that the first and the third elements of this formula are constrained by firm biophysical limits and therefore constrain further potential yield growth to roughly 20% beyond current levels (Fischer, Byerlee, and Edmeades 2013). They see scope for improving the radiation use efficiency of plants, but suggest this is an area of great uncertainty. In short, *increasing the potential crop yields is a challenging task*.

Of course, the likelihood of increasing potential yields depends critically on investment in basic research and development activities. This is yet another source of fuel for the pessimists. Alston, Beddow and Pardey (2009) document a slowdown in the rate of increase in US public agricultural R&D spending from nearly 4%/year in the two decades from 1950-1970 to about

1%/year over the 1990-2007 period. They argue that this slowdown, which was mirrored in Japan and Europe, has translated into slower productivity growth in these more recent decades. The potential for boosting yields with this dwindling pool of R&D funds is further challenged by the reluctance of large portions of the world to embrace GMOs, which have been shown to enable more rapid yield growth in the case of maize (Fischer, Byerlee, and Edmeades 2013).[5] In light of the very long lag time between initial research investments and the ultimate impact on production (Alston, Pardey, and Ruttan 2008), this is a sources of serious concern.

While the pessimists acknowledge that yields could be increased by closing the gap between potential yields and actual yields, which is quite large in many parts of the world, they can legitimately argue that this gap is there for a reason (Neumann et al. 2010) – poor infrastructure, limited information, lack of credit, etc. and these barriers will not be eliminated overnight. And boosting both potential and actual yields throughout much of the tropics will be made more difficult in the face of climate change and rising temperatures, coupled with more erratic rainfall (more on this below). Add to this the emerging water scarcity noted in the previous section and you have the formula to a slowdown in yield growth.[6] The bottom line for the pessimists is that the world faces a rate of yield growth which will be insufficient to meet the growing demands of the world's growing, increasingly wealthy population. This means that prices will rise, thereby affecting the food security of the poor. Since higher prices will increase

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[5] These authors compare maize yield growth in Iowa with that in France and Italy. In the 25 years prior to the introduction of GM corn (the mid-1990's), yields in the two regions grew at very similar rates. However, since 1996, GM-based maize yields in Iowa have grown at about 2%/year, whereas they have remained largely flat in France and Italy. Of course, there were other factors at work during this period, include reform of the EU Common Agricultural Policy which reduced the incentives for farmers to intensify production.

[6] Yet another, more pedestrian argument behind the slowdown in yield growth is simple arithmetic. Since trend yields tend to grow at a linear rate (e.g., 1 bushel of grain/acre/year), as the yield level grows, this annual increment represents a smaller and smaller % of the total, thereby resulting in a slowing *rate* of growth (Cassman, Grassini, and Wart 2010).

rates of cropland conversion, thereby boosting GHG emissions, the coming 50 years look rather bleak through the pessimists' lens.

The optimists take largely the same historical information and come to a rather different conclusion. They predict that productivity growth will be adequate to meet demand growth. Indeed, some would argue that agricultural prices are likely to resume their long run downward trend once the current supply-demand imbalance -- stemming from the combination of bad weather and biofuels -- is resolved. As with the pessimists, there are varied elements to the optimists' case. Firstly, they point out that, even though yield growth is slowing, so too is population growth. Therefore, in the footrace between supply and demand, yields no longer need to grow at their historical rates in order to keep pace with demand growth. Rather than the growing at 2.2%/year as was the case over the 1961-2007 period, the FAO estimates that crop production will only need to grow at half that rate – or 1.1%/year over the 2007-2050 period (Bruinsma 2009).

The optimists also appeal to the same yield gap estimates identified by the pessimists in order to suggest that, given sufficient economic incentives, as well as improved infrastructure, massive increases in output can be achieved by closing these gaps between potential yields and yields actually achieved at the farm level. For example, Licker et al. (2010) estimate that global maize production could be increased by 50% by closing the gap between current farmer yields in low income countries and those in the advanced economies producing under identical biophysical conditions (i.e. similar climate and soils). Of course, if these yield gaps were easy to close, then profit-minded farmers would surely have done so already. The point is simply that, from a biophysical point of view, there is great potential for boosting yields based on currently deployed technologies.

There is a deeper source of disagreement between some members of the two camps, and this relates to the measurement of productivity growth and the source of the recent slowdown in yields. While many attribute the yield slowdown to an approaching ‘biophysical limit’, others suggest that the slowing productivity growth has been driven by economic factors. In his global scale analysis of historical changes in agricultural output, Fuglie (2012) decomposes the sources of global output growth, by decade, for the period: 1961-2009. He isolates four distinct factors: area expansion, irrigation, intensification (more non-land inputs such as fertilizer for each hectare of land) and total factor productivity (TFP) growth. While global output growth over this period was fairly steady, ranging between 2 – 2.5%%/year, the sources of output growth have varied greatly.

In this decomposition of historical output growth, Fuglie attributes the bulk of the record output growth in the 1960’s (recall the green revolution) to the *intensification of production*. This source of growth remained high in the 1970’s, but dwindled over subsequent decades, until, in the 1990’s, intensification accounted for only about 10% of total output growth. He attributes this decline in the rate of growth in non-land input use to the steady decline in crop prices over this period. On the other hand, TFP, which is a function of historical investments in R&D, was the factor which kept global agricultural output growth above 2% throughout the 1990’s. In the most recent decade (2001-2009), Fuglie estimates that TFP growth remained at its record high growth rate, but the price sensitive contributors to output growth – intensification and land area – picked up in response to the price rises over this period. As a result, he finds that total output growth averaged 2.5%/year over this period – a rate not seen since the 1960’s. This recent TFP performance leads Fuglie to be quite optimistic about the future. He points to the long lag time in R&D, suggesting some persistence in the current rates of TFP growth. When coupled with the considerable upside potential for further intensification and area expansion in response to record high prices, this leads him to conclude that future output growth will be strong. Baldos and Hertel (2013b) incorporate Fuglie's TFP projections into the SIMPLE model of global agriculture and land use and find that the resulting 2050 crop prices are considerably below current levels – a result which bolsters the optimists' position.

I will leave the last word on this topic to Fischer, Byerlee and Edmeades (2013), who have studied in depth the issue of agricultural productivity growth and the potential ensuring food security in 2050. Their book offers a comprehensive, interdisciplinary perspective, invoking a mix of local case studies, regional scale, and global analyses. In their closing chapter, they offer the kind of balanced assessment that one might expect of a seasoned team of authors:

> In conclusion we do not foresee calamity as do some, nor are we lulled into complacency, especially by the advocates of biotechnology. But we do see multidisciplinary agricultural science as a key to success. Together with complementary investments in infrastructure and institutions, and relative peace, the world should manage. It won't be ideal, there will be environmental costs, but the perfect should not be allowed to get in the way of what is scientifically feasible, pragmatic and broadly acceptable socially in agriculture.

Climate Change will alter the path of productivity, affecting land use, nutrition and poverty

One of the largest sources of uncertainty in future productivity projections for agriculture is climate change. Assessing the impact of climate change on agriculture is a daunting task which can be broken down into four basic steps (Alexandratos (2010, pp. 14-15)): (1) develop projections of future GHG concentrations based on long run projections of the global economy, (2) use the General Circulation Models (GCMs) developed by climate scientists to translate these GHG outcomes into spatially disaggregated deviations of temperature and precipitation from baseline levels, (3) superimpose these deviations on biophysical models to determine how they will affect plant growth and the productivity of agriculture in different agro-ecological conditions, and finally (4) perturb models of the agricultural economy to determine changes in production, consumption, trade, etc. And, in the case of a fully integrated assessment model such as MIT's linked modeling system (John Reilly et al. 2012), the results from step (4) feedback to (1). Each of these steps entails considerable uncertainty, and that uncertainty is compounded as one follows the chain down from global economic projections to climate impacts. Adaptation strategies, including changing planting dates and the development and introduction of new varieties, further complicate the last two steps. In short, this activity is not for the faint of heart! In light of the fact that this white paper is being paired with a companion paper by some of the world's leading scientists working on this issue, I will focus my comments in this section on items (3) and (4): How will the changing climate affect the trajectory of global agricultural productivity discussed in the previous section? And how will this altered trajectory influence crop prices, land use, nutrition and poverty?

At the outset, there are two key points to be made. Firstly, there is already evidence that climate trends – in particular, higher temperatures -- are affecting crop yields (D. B. Lobell, Schlenker, and Costa-Roberts 2011). The global impacts of these historical changes are most pronounced for maize and wheat, and less so for soybeans and rice. Secondly, in the medium term -- in this case 2050 – effects of trend increases in temperature on crop yields are likely to be modest – translating roughly into a yield loss of 1.5%/decade – or about one year of trend productivity growth for each 10 years (David B. Lobell and Gourdji 2012). And these are expected to be roughly offset by the benefits of heightened atmospheric CO2 concentrations.

Broadly similar results are emerging from the biophysical crop modeling community. This work is being summarized in a series of forthcoming papers growing out of the AgMIP Agricultural Crop Modeling Inter-comparison Project. This work seeks to characterize the degree of uncertainty in climate impacts by simulating a wide range of globally gridded crop models in the context of a single climate change scenario (Rosenzweig et al. 2013). In order to sharpen their findings, and identify sources of differences across models, they focus on the most extreme warming scenario being considered presently, namely the Representative Concentration Pathway 8.5 scenario. In this work, they find broad agreement for maize and wheat across the crop models regarding the sign of the climate impacts, which show high-latitude yield increases, relative to baseline and low-latitude decreases. In the case of soybeans, the results are more varied, with relatively minor or positive impacts in most regions (Rosenzweig et al. 2013). An important finding of this crop model inter-comparison is that the dominant source of difference across models is their treatment of the CO2 fertilization effect, which is the main source of the gains in crop yield in the temperate regions under this extreme climate change scenario. This raises an important point about the nature of the uncertainty in climate impacts over this century. These impacts are the net result of potentially large, but uncertain, negative yield effects due to higher temperatures, and also potentially large, but highly uncertain, positive effects of non-CO2 fertilization on crops. This results in massive uncertainty about the ultimate impacts on climate change on global agriculture, food prices and land use. The net effects in 2050 could be positive (i.e., increased global output) or negative. In their overall assessment of the net effects of climate change on yields, Lobell and Gourdji (2012) suggest that the impacts could be as large at a quarter of overall yields trends. This would have a strong impact on production, prices and global land use.

While significant resources are being devoted to the further development of the crop models in order to narrow the range of uncertainty, they remain prisoners of their history which, in many cases, was focused on facilitation of crop management decisions, as opposed to the investigation of climate extremes. Indeed, developers of crop models have long cautioned against their use in climate change studies, given the lack of development and testing in extreme climate conditions (J. W. White, Hoogenboom, and Hunt 2005; Jeffrey W. White et al. 2011). For example, a recent review of 221 studies using crop models for climate change impacts, which spanned over 70 different models, found that only six studies considered the effects of elevated CO_2 on canopy temperature, and similarly few studies considered direct heat effects on seed set or leaf senescence (Jeffrey W. White et al. 2011). Overall, of the five key processes by which climate change affects crop yields, David Lobell (personal communication) estimates that most crop models capture only about two-and-a-half. He notes that most models include treatment of crop development and photosynthesis responses to temperature, but omit heat effects on grain set and damage from pests and invasive species. And, in general these omitted processes are thought to become more damaging with climate change, so models may provide estimates biased toward positive values. For example, invasive species are omitted from most analyses of the impact of climate change on crop production. Yet these species are generally better suited for adaptation to changing environmental conditions due to rapid evolution, broad tolerance to environmental shocks and strong seed dispersal (Ziska and Dukes 2011). This suggests that climate change will favor development of these plants, at the expense of commercial crops, thereby generating additional costs and/or crop losses under climate change. It is also important to note that the types of processes omitted by models tend to be more important in tropical than in temperate systems, suggesting that the existing estimates of low-latitude crop losses from climate change are likely to understate the true effects (Hertel and Lobell, 2012).

A critically important piece of the puzzle posed by climate impacts on global sustainability is the potential for farmers to adapt to the changing climate (J. M. Reilly et al. 2002). Yet many of the studies of climate impacts on agriculture limit the types of adaptation considered to biophysical variables like planting and harvesting dates and crop mix. Some studies allow for the development of new varieties which are better attuned to the new climatic conditions (T. Hertel and Lobell 2012). However, with potentially large impacts on regional yields and global prices (G. Nelson et al. 2009), the scope for adaptation is likely much greater than is captured in many of the biophysical models of climate change. Of course, much of this adaptation will depend on investments in agricultural R&D, access to credit by producers seeking to make adaptive investments (e.g., irrigation), information and access to markets which might permit producers to specialize in crops which are better suited to their new environment. Hertel and Lobell (2012) argue that, in many cases, these adaptation opportunities will be most limited in the developing countries. Add to this, the fact that tropical agriculture is likely to be harder hit by climate change (Rosenzweig et al. 2013), and is likely to have less biophysical room to adapt due to higher starting temperatures and moisture-constrained growing seasons (Deryng et al. 2011) and climate change begins to look more like a regional distributional issue, as opposed to a global food security question.

Baldos and Hertel (2013a)examine the impact in 2050 of projected changes in temperature and precipitation using the global yield estimates of Mueller et al. (2010). Their analysis focuses on the consumption channel through the resulting rise in food prices (regional per capita incomes are held constant at their baseline levels). They find that climate change (ignoring the CO2 fertilization effects) boosts malnutrition globally by about 50 million people in 2050, relative to projections without climate change. They also compute the change in malnutrition gap, which widens by about 5 kcal/capita/day in low income countries as a consequence of the combined impacts of higher temperatures and altered precipitation on global crop yields.

Hertel, Burke and Lobell (2010) have explored the impact of climate change on incomes as well as consumption, calculating the resultant changes in poverty rates across a range of developing countries in the tropics. They explore a variety of scenarios for the year 2030, ranging from a 'worst case' scenario in which yield impacts are more severe than expected to a 'best case' one which the yield impacts are generally positive. An important finding in their study is that *agricultural producers in much of the developing world could benefit from adverse climate change* due to the ensuing rise in crop prices. Upon reflection, this is hardly surprising. Consider the case of the US drought/heat wave of 2012 during which average corn yields fell by about 25%, relative to trend. It is difficult to say precisely how much corn price responded to this shock, but Abbott et al. (2011) estimate the resulting corn price rise to have been about 50%. Therefore, for any producer who experienced the average yield loss, and who was able to take advantage of the higher prices (i.e. had not already sold their crop in the futures market), their revenues would have risen as a result of the drought. Of course, for those farmers in regions unaffected by the extreme weather (e.g., parts of Minnesota), the rise in corn prices was a huge windfall. The same phenomenon is present in the climate change scenario analyzed by Hertel et al. They find that, under the worst case scenario, regions expected to be relatively lightly affected (e.g., Chile) experience significant gains as a result of the climate scenario, while those producers in those regions most severely affected (Sub-Saharan Africa) are hurt. Of course, higher prices unambiguously hurt the urban poor, who are net food buyers and who do not gain from potential increases in farm income. The authors conclude that the national poverty impact of adverse climate change depends on whether the country's yields are hit harder than average by climate change and whether the poverty is concentrated in the rural areas or in the urban ones.

Future Agricultural Land Use Faces Stiff Competition from Environmental Services

While the near-term impacts of climate change on crop production are likely to be modest – building to potentially more dramatic impacts after 2050, the same cannot be said of the impacts of policies aimed at mitigating climate change. Here, the largest consequences for land use are likely to come *before* the middle of this century. For evidence of the potential importance of these policies, one has only to look at two current examples: biofuels and REDD+ (reduced environmental degradation and deforestation) policies. While there were many factors which led to the introduction of renewable fuel standards relating to biofuels in the EU and the US, there is no doubt that the 'renewable' element was an important component. By utilizing fuels based on biological feedstocks which sequester carbon during their growth, advocates had high hopes for biofuels to become part of the climate solution. Indeed, as recently as 2007, the consensus of the scientific community was that corn ethanol, in particular, could contribute significantly to GHG abatement (Farrell et al. 2006). As the US ramped up its ethanol capacity in response to the RFS, a massive amount of corn was removed from the food system. Indeed, half of the increase in global cereals consumption during the 2005/6 – 2007/8 period was due to US ethanol production Westhoff (2010, pp. 14-15). The consequences for patterns of production and land use world-wide have been the subject of intensive research (Searchinger et al. 29; Thomas W. Hertel et al. 2010; Al-Riffai, Dimaranan, and Laborde 2010), and the global footprint of the US corn ethanol program and the EU biodiesel program can been seen in the pattern of land use change over this period (Farzad Taheripour and Tyner 2013).

Another area in which patterns of agricultural land use have been shaped by climate mitigation policies is that of REDD+. Evidence suggests that much of newly converted cropland in the tropics was in closed forest 20 years ago (H. K. Gibbs et al. 2010). REDD+ policies are designed to slow this conversion of land, which has been the source of a large share of global emissions over this period. One of the most significant efforts has been undertaken in the Philippines, with support from the Indonesian government (Busch et al. 2013). It is estimated that the resulting moratorium on conversion of forests to oil palm plantations, had it been in place from 2000-2010, would have reduced Indonesia's emissions from deforestation by 578 $MtCO_2e$, or about 8% of that which actually occurred. So putting this moratorium in place is an important environmental accomplishment. However, there has been considerable opposition from local interests groups and it has also curtailed production of a commodity for which there is rapidly growing demand in Asia – particularly by low income households. There are many other REDD+ projects currently underway, each of which will contribute to reducing GHG emissions, and each of which will potentially contribute to shifting backwards the supply of land for agriculture. The net effect is unambiguous – higher food prices – it is only the magnitude of the ensuing price increase which remains in question.

Reilly et al. (2012) explore a variety of climate policy futures and the ensuing consequences for land use and food prices. In the case where they allow for perfect pricing of carbon from land use, in addition to pricing carbon from energy combustion. (In this scenario, biofuels as a mitigation strategy expand strongly in the second half of this century.) The authors estimate that such a climate policy would result in dramatic food price increases – nearly doubling relative to their no policy baseline. Golub et al. (2012) have simulated the impact of a global forest carbon sequestration policy on land use and food prices within the current economic environment. They find that this environmental policy has a particularly strong impact on agricultural land use in the tropical, non-Annex I countries. Indeed, they find that this land use effect is strong enough to largely eliminate the leakage which results when agricultural GHG mitigation is only undertaken in the Annex I region. Overall, land values rise significantly, as do food prices. Hussein et al. (2013) delve more deeply into the distributional impacts of a global forest carbon sequestration policy. They conclude that, since most of the benefits of this policy flow to landowners, and the poor control relatively little land, the predominant impact of forest carbon sequestration on the poor would be through higher food prices – something which leads to poverty increases in the majority of their sample countries.

However, climate mitigation policies are not the only source of future competition for land. As households become wealthier, economists predict that they will demand more environmental services, including natural parks and biodiversity (Jacobsen and Hanley 2009; Kauppi et al. 2006; Antoine, Gurgel, and Reilly 2008). Steinbuks and Hertel (2012) incorporate the demand for ecosystem services into their long run model of global land use and estimate that the optimal amount of area set aside for natural uses could triple over the course of the 21st century.

In summary, there will be growing competition for scarce, productive land, over the coming century. Increased emphasis on GHG mitigation, biodiversity and other ecosystem services will only sharpen this competition, resulting in higher land prices and higher food costs than would otherwise be observed.

Globalization offers both opportunities and threats to sustainability

Globalization is playing an important role in the changing pattern of global land use. As markets become more integrated, agricultural production is shifting towards those regions that are relatively land abundant (e.g., South America) and away from those regions that are land scarce (e.g., East Asia) (A. G. Golub and Hertel 2008). This frees up agricultural land in the land scarce regions for other uses. This process of “land-sorting” is something that has been observed over the last century by geographers (Lambin and Meyfroidt 2011), and it occurs not only at the international level, but also within countries (Mather and Needle 1998). By allocating land to those uses for which it is best-suited, humanity is able to boost the overall basket of goods and services obtained from this finite resource.

However, where property rights are ill-defined, there is also a down-side to globalization which is most evident in cases where carbon-rich, bio-diverse tropical forests are subject to open-access. By offering producers the chance to sell large amounts of commercial products at nearly fixed world price, integration into the world market can provide strong incentives for producers to expand production into ecologically sensitive regions (Angelsen and Kaimowitz 2001). This is further exacerbated in cases where deforestation and farming are viewed as a means of asserting property rights over communal lands (Lambin and Meyfroidt 2011). Meyfroidt et al. (2010) identify the spillover effects which arise through international trade when countries seeking to set aside forest lands end up importing forest products and encouraging deforestation elsewhere. Of course, avoided deforestation in one region may still result in reduced land cover change globally, depending on the relative productivity of the regions in question and the price responsiveness of global demand (T. Hertel 2012). One point that surfaces clearly in this discussion is that globalization greatly complicates the analysis of land use issues as heightens the necessity for global scale assessments of policies.

Implications for future research

This overview of some of the main findings from the literature on global sustainability, as it bears on the world's food system, highlights two points in particular. First of all, research published over the past decade has significantly advanced the knowledge frontier. We now understand that large biofuel programs in one part of the world have important ripple effects throughout the global economy, thereby affecting land use and associated GHG emissions. Researchers have identified critical temperature thresholds, above which significant yield losses will occur for the world's main grains and oilseed crops and related these extreme events to market volatility. The great potential for land-based mitigation policies to contribute to slowing the rate of GHG accumulation has been identified and the broad consequences for global land use and food prices have been characterized. And we now know much more about the potential for 'leakage' of environmental damage to other regions when one country sets aside forest lands or undertakes serious GHG abatement policies. Furthermore, these findings have been effectively communicated by researchers to the media and to the broader policy community.

This significant progress notwithstanding, there remains much to be done if we hope to be able to anticipate the impacts of major policy initiatives in the area of food, energy, water and land. Certainly further refinement of the mechanisms discussed previously in this paper remains a high priority. And there are many research programs currently targeting these issues. However, the most interesting research questions at this stage seem to be arising at geographic, disciplinary and policy *intersections*. Work at the intersections between disciplines, such as the collaboration between agronomists, hydrologists, climate scientists, ecologists and economists continues to be critical to assessing climate impacts on agriculture and the environment. The human impacts of such climate change require linking these changes to nutritional outcomes (G. C. Nelson et al. 2010) as well as small-holder households and poverty (T. Hertel, Burke, and Lobell 2010; Claessens et al. 2012). This work is still at a rudimentary stage.

There are also important interactions across resources. This is illustrated by a recent study exploring the land-water-energy-food nexus shows that factoring in water availability constraints to irrigation expansion sharply changes the pattern of global land use and GHG emissions in the wake of bioenergy development (Farzad Taheripour, Hertel, and Liu 2013). Another type of interaction is that between policies aimed at adaptation to climate change and those focusing on mitigation. Lobell et al. (2013) show that investment in research and development aimed at facilitating agricultural adaptation to higher temperatures can yield significant mitigation benefits. Indeed, they find that the adaptation research could be justified entirely on the grounds of the ensuring mitigation benefits.

One of the most important types of interactions in the context of global food and environmental sustainability is the interaction between local and global scales of analysis. On the one hand, the forces driving land use, environment and food security issues are global in nature, including population, income growth, biofuels, trade, etc. On the other hand, the impacts and policy responses (or lack thereof) are often highly localized. They depend on things like land tenure, soil and forest carbon stocks, species diversity, local climate and poverty rates. To understand these local scale impacts of the forces driving global change, one needs frameworks which facilitate communication across scales. Some excellent work is already underway in this area (John Reilly et al. 2012) and will be highlighted in the companion white paper. However, this is only a start. Many more groups need to be engaged in this type of work.

Perhaps the most severe constraint faced by those seeking to undertake global-local-global scale research on land use, food and environmental security is the absence of high quality, interoperable, readily accessible, time series data bases on global land cover, land use and tenure, irrigation and poverty (Hertel et al. 2010). With the ongoing revolution in satellite imagery, geospatial data and associated software, developing such data base infrastructure is well within our reach. However, the challenge has been to facilitate collaboration to ensure interoperability of these diverse data bases, facilitate regular updates, and tie these developments into the needs of decision makers. One successful example of such collaboration on global data bases (albeit focusing just at the global-national scales) is offered by the Global Trade Analysis Project (www.gtap.org). Recently we have proposed a similar activity in the geospatial arena: www.geoshareproject.org (T. W. Hertel and Villoria 2012). There is great potential for such global public goods to elevate the level of research and policy debate in this arena.

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A Political Theory of Water Governance

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The energy industry is a major user of water and also central to the energy-intensive processes of purifying and transporting water. However, the industry is not the only sector that uses water, and looking worldwide there are huge variations in how policy makers treat different sectors even when they draw upon the same water resources. Moreover, hardly any country adopts "rational" management of water resources; instead, water problems are routinely ignored until they reach crisis proportions. Officials responsible for governing water uses and quality often embrace policy instruments, such as under-pricing of water and command and control regulation, that are highly inferior to best practices. This paper outlines a theory that can explain these broad dysfunctions and illustrates the theory with vignettes from the Middle East, China and the Southwestern U.S. It also explores some implications for widely discussed water reforms and for scholars who build models designed to simulate water-using behavior.

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In nearly all countries, fresh water resources are under increasing stress. While the sources of stress are many, the energy industry plays a particularly important role. The energy industry is the world's second largest net user of fresh water (agriculture is first). And the industry is the largest source of water withdrawals—mostly in the form of cooling water that is returned (a bit warmer) after use. In both use and withdrawal, policy makers are scrutinizing more closely the many impacts of the energy industry on water. This essay explores how that pressure is likely to arise and be translated into practical "governance."[2] In addition to its intrinsic importance to water matters, a focus on the energy industry also helps to reveal fundamental forces at work in the governance of scarce water resources.

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[2] We use governance in the broadest sense, consistent (for example) with the Global Water Partnership and UNDP which has defined "water governance" as "the range of political, social, economic and administrative systems that are in place to develop and manage water resources and the delivery of water services at different levels of society." (Rogers and Hall, 2003)

Throughout, this essay will make 4 major points. First, while there is tremendous technical potential for reducing energy and other industrial impacts on water resources, actually realizing those potentials will hinge on governance. In one vision of governance, societies identify water stresses in advance and respond with policy incentives that give firms and other users of water resources the flexibility to adjust and find the least cost means of controlling their impacts. That model—what I will call “Model 1”—is a lovely vision that rarely exists in the real world. Instead, an alternative “Model 2” is what usually prevails. In this alternative vision, water resource stresses are ignored until they become acute. Policy instruments are prescriptive and not flexible. Industries are regulated independently as “silos” rather than allowing for more efficient trading across industries and space. Model 1 is not a straw man—in fact, most of the economic-engineering models that are used to examine water scarcity adopt Model 1 views of the world. One goal of this paper is to articulate the key elements of Model 2 so that we can improve the analytical tools that are used to examine real world water stresses and governance responses.

Second, I will suggest that the biggest inefficiencies in Model 2—the tendency for societies to ignore water stresses until they become acute and the strong bias in favor of “command and control” regulation over more flexible markets—are deeply rooted in human cognition and political economy. They will be very hard to fix. Success in clearing these barriers is likely to arise only in special niches, which helps to explain why the real world experience using flexible modes of regulation in water resources are limited in scope. Most use of flexible water markets, for example, arises in a “hybrid” form in which water markets are created only for relatively few water users while the rest are subjected to traditional regulation. There has been enormous political attention to the political difficulties in getting water prices to better reflect real world scarcity. A more politically sophisticated vision of how governance systems actually operate could help explain why mis-pricing and mis-management of water is so pervasive.

Third, I will suggest that there is tremendous promise in popular new ideas for water governance—notably integrated water resources management (IWRM). However, the optimism about IWRM must be tempered by realities about how integration across many different industries and political systems might actually be achieved. IWRM—and other basin-wide management schemes—is likely to be layered on top of existing governance systems rather than replace them. Without politically difficult efforts to remove existing systems of governance while implementing new IWRM schemes, the result, I suggest, is likely to be more fragmented governance.

Fourth, I will argue that while these political challenges for efficient governance are significant where governors focus on water quantities, the problems are likely to be even greater as more jurisdictions focus on water quality such as temperature, pollution loads, seasonal flows and complex interactions between the uses of fresh water for human and natural purposes. These new missions are difficult to manage because they necessarily work across multiple government agencies, each with their own objective.

Together, these four arguments suggest that "governance" factors are likely to explain why real world outcomes in fresh water management could be radically different from the economically optimal potential. These insights may also be applicable to other natural resources that societies manage, such as forests, wilderness and open access fisheries.

I proceed in three steps.

First, I examine how societies identify problems and mobilize the resources needed to govern them. Many studies suggest that society should be more forward-looking in this process and less prone to wait until a crisis appears. I suggest that crisis-mode decision-making actually helps political systems address some of their greatest challenges, such as processing information that is laced with uncertainty and mobilizing scarce resources like financial capital and ephemeral attention of voters and politicians.

Not only is society prone to sub-optimal behavior in responding to natural resource crises, but the choice of policy instruments is also prone to be far from optimal. I examine the policy instruments that societies deploy when addressing such problems—in particular, the choice between "command and control" and market-based instruments such as prices and tradable quotas. I argue that command-and-control systems have large political benefits that help explain why they are so persistent, despite all the evidence that favors market approaches. Command and control systems allow politicians to channel the benefits of regulation toward powerful and well-organized groups while diffusing the costs across less suspecting entities. And for many firms that view water management as a problem of compliance rather than strategy, command-and-control systems make compliance easier to assure.

Second, I use this simple model of political economy—which informs the timing of policy responses and the choice of policy instrument—to illustrate real world evolution of water policy in three macro regions of the world: China, the arid Middle East, and the southwestern U.S. It is impractical in a single paper to do justice to the complexity of each of these case studies, but in my analysis I will focus on a few key elements of each. Those include the question of which forces actually drive reforms; the role of markets; and the ways that fragmentation of property rights and administrative bodies are managed.

Third, I look to the future and the possible use of new governance systems such as IWRM across whole basins and industries. I examine the incentives for politically powerful actors to adopt these kinds of mechanisms and, in particular, focus on the persistent difficulties that have arisen as governance systems for water have tried to encourage trading and flexibility across industries.

1: The Puzzle: Why Do Societies Consistently Choose Inefficient Forms of Governance?

Other papers presented at this conference will show that there already exists a wide array of technical solutions to problems of water scarcity and quality. In energy, those solutions include dramatic improvements in the efficiency with which water resources are withdrawn and used.[3] Outside the energy sector, notably in agriculture, opportunities abound as well.[4] At the same time, there is mounting evidence that many regions in the world are facing severe and growing challenges in water supply.[5] Those challenges are particularly notably in the portions of the world economy—such as China and India—that are growing most rapidly. Climate change, it is likely, will make these problems even more severe. A warmer world is likely to be a wetter world overall, but the distribution of fresh water supplies is likely to change radically. River basins that depend on high altitude snowpack—including the basins in China, India and the southwestern US already under stress—are likely to fare worse as the climate warms.

Thus we face a puzzle. Water scarcity and degradation of quality is a looming problem that, in most settings, is prone to get worse. The solutions are at hand and yet the actual adoption of better governance systems—such as the use of market-based forces and the re-allocation of water resources to more productive uses in the economy—is rare. When societies do shift their systems of governance it is often under duress even though earlier and more orderly shifts would be economically much more efficient. This section aims to explain that puzzle. It offers a simple model of how political, cognitive and economic forces interact to yield governance failures.

Resolving this puzzle requires looking at how political action within societies is typically organized. I work on three fronts: rigidity, crisis and the choice of policy instruments.

Rigidity: The Incumbent's Advantage

Most political systems are organized to create tremendous advantages for incumbents. In general, incumbents know who they are and are well-organized; by contrast new interests and the broad public interest is more highly diffuse and less capable of mobilizing political pressure.[6] Over time, new technologies that allow for more widespread diffusion of information may have shifted the balance of influence

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[3] cite eventually to BP Handbook when published
[4] cites to conference papers.
[5] Saeijs and Van Berkel, 1995
[6] Olson, 1965; Stigler, 1971

away from incumbents and toward the purveyors of new ideas and the broader public. But that theory of democratization is still a work in progress and there is ample evidence that incumbents still carry a huge advantage.

Political systems that reward incumbency—that is, pretty much every political system on the planet--creates rigidity because politically powerful groups organize to defend the status quo. Rigidity, however, is not merely the result of fundamental political forces at work. It is also hard wired into the human brain. Cognitive psychologists and behavioral economists have studied, for example, the "endowment effect" by which humans prize items that are within their grasp and familiarity and avoid actions that would alter the status quo.[7] The endowment effect is tightly bound with high levels of risk aversion. In an ideal world in which political choices involving risk and reform are made with full rationality, people would assess risks symmetrically. In the real world where humans focus on their existing endowments, the evaluation of risk and opportunity are done highly asymmetrically. Put differently, people are highly averse to choices that might lead to losses. There is some evidence that elite experts—those who tend to control many features of the policy making process—are less susceptible to asymmetrical reasoning.[8] But experts must respond, in most societies, to public pressures; and reasoning in the broader public is heavily influenced by endowment effects and loss aversion. Uncertainty about the benefits of a change in the status quo amplifies these tendencies.

Crisis

The strong bias in favor of the status quo helps to explain, as well, why change tends to arrive during crisis. For policy makers interested in shifting to new, improved forms of governance, crisis offers at least three huge advantages over politics in normal times.

One advantage is psychological. In times of crisis—when existing modes of decision making are demonstrably failing—risk aversion and the power of endowment effects can diminish. In the extreme, when decision makers see that their status quo has failed, their approach to risk actually reverses—they imagine that new approaches will work better than is likely. Compared with the status quo, any change is seen as a gain. And in the realm of gains, there are strong cognitive biases to ignore the risks of change.

A second advantage of crisis is political defeat for incumbents. This is often evident in whole political systems wrenched by crisis—for example, a massive financial crisis in 1991 led to turmoil in the Indian political system and the rise to power of a technocratic market-oriented government. That government adopted

[7] Kahneman and Tversky, 1979
[8] For a review of the cognitive biases and how they affect expert versus non-expert reasoning see Hafner-Burton et al., 2013.

reforms that were inconceivable under the earlier ossified system of government. Newly empowered reformers didn't fix all of India's ills, of course—they started by focusing on more immediate problems and on problems that were within their grasp—but over time a new approach to policy making gained credibility. Disruptive political change does not always favor markets, of course—the Chavez-led revolution in Venezuela, for example, took power in a democratic election in 1998 by promising populist and anti-market reforms.

A third advantage of crisis is the opportunity for mass mobilization. Much politics in normal times revolves around organized interest groups devising ways to shift power and resources to themselves and away from interest groups—especially the broader public—that may be less well organized. Visible failure of the status quo can inspire broad-based political movements, especially as it is often easier to rally masses around conspicuous failure of incumbents than around complex new ideas for governing. Some of the most massive reforms in Brazil's electric power system arose in the wake of the 2001 blackouts that were the result of incumbent operators who protected vested interests within the hydro industry by under-charging for the use of water that flowed through hydro dams. The reforms created auctions for new electric power supplies, new pricing schemes that cut consumption of electricity, and more independent regulators. Prior to the blackout the public had not much focused on the electric power system; during and after the blackout it was a national obsession.[9]

Together these advantages of crisis help explain why political changes tend to arise in punctuated form. In the noise of normal policy making, evidence accumulates that the existing system isn't working. Those anomalies can lead to intellectual revolutions and, at times, even physical ones.[10] Societies need focal points to embrace complex changes in policy, especially when those changes harm the interests of powerful incumbents.

The Choice of Policy Instruments

The scarcity and degradation of water resources is hardly a unique problem in the management of natural resources. A substantial body of theory and real world experience with the design of optimal policy instruments has emerged. That scholarship points to the value of using market-based policy instruments rather than "command and control" because markets allow for more flexibility to innovate and to reallocate resources to the most productive sectors of the economy.[11] The exact choice of market-based instrument—whether taxes on consumption and pollution of tradable quotas—does not much matter in a world where information is relatively inexpensive and transaction costs are low.[12] But where information

[9] De Oliveira, 2007
[10] Hall, 1993
[11] Stavins, 1988
[12] Weitzman, 1974

about costs and impacts is imperfect—such as in the real world—priced-based policies (e.g., pollution taxes) are often preferable because they created predictability in costs. [13] Tradable quotas work well when trading systems are highly efficient and barriers to entry are low.

Thus there is a ordering of preferences—on the basis of economic theory—for the choice of policy instrument. Markets are preferred over command; within the realm of markets, prices are preferred over quotas. But what actually occurs in the real world offers a puzzle. Almost exactly the opposite outcome is usually evident. Command and control regulation is the norm. Where markets are used—for example, tradable water quotas—those markets are designed to impede full trading rather than allow the market to yield whatever outcome is most efficient. And full cost pricing—the best option in most water-related resource management situations—is rarely used.

The explanation for these odd choices lies with political organization. While command and control regulation is costly, it offers huge advantages to the players who are well organized—the incumbent users of a water resource and the regulators. For incumbents, regulatory pressure can be a source of advantage by creating barriers to entry. Operationally, command and control regulation also offers tremendous advantages to regulated enterprises because it allows them to treat regulatory pressure as a problem of compliance that can be delegated to a subdivision of the company and ignored so long as that subdivision performs well. Regulators, too, see many advantages in command and control regulation, for they are the agents of a political system that is buffeted by many different interest groups. They must deliver benefits to those groups, and regulation offers a clear path with visible outcomes—pollution standards set, technologies required, and fines levied. For both sides, the sclerosis of command and control regulation is its most prized asset.

Tradable quotas can produce many of the same predictable benefits to regulators and to enterprises if the market trading system is restrained. Incumbents don't benefit from trading if all the tradable assets are re-auctioned every few years. Regulators who are attuned to the interests of their principals won't benefit from a market system if fresh auctions continuously create a new array of principals. Thus we witness trading systems that are designed to reinforce incumbents—systems without fresh auctions of quotas (often with legal bans on such trading) and with large impediments for existing quota-holders to re-sell their assets.

[13] The full story is more complicated. For pollution or depletion problems for which there are known thresholds, a quota-based market system can be preferred because quotas can be set to avoid the dangerous threshold. Most water-based depletion and degradation problems are not of that type.

By far, the least attractive option politically is the one that economic theory tells us will be best: prices. For incumbents and regulators, alike, a price mechanism is highly undesirable. Incumbents pay the highest costs under such systems, and even if government promises to recycle the revenue back into the industry, the incumbent can't be sure that promise is credible. (A long string of broken promises is good evidence that government can't keep its word on fiscal matters without some external enforcement.) New entrants are highly advantaged by pricing mechanisms because their costs scale only when their enterprise scales, and if new entrants arrive with a superior production method they see a visible competitive advantage right at the outset. Regulators, too, will not prefer pricing mechanisms since the very transparency of a price schedule makes it hard to channel benefits to principals. (The lack of much to do but monitoring and enforcing a levy must also be a deterrent to the regulatory entrepreneur who seeks budget, personnel and stature.)

Thus we have a very simple political economy model that can begin to explain some of the major fears of real-world regulation on complex, costly matters. While I will illustrate this model in the case of water depletion and degradation, the same model is useful in many other settings as well. The model explains why policy reforms arise in crisis rather than more efficiently sequenced over time. And it explains why policy instruments that are preferred are almost exactly the opposite of what economic theory suggests will be best.

This model also helps explain the sequencing of policy instruments over time. Command and control instruments may be preferred, but they have large known inefficiencies. When incumbent groups weight those inefficiencies heavily they seek reform, and the result is more flexible regulatory systems that preserve the advantages of incumbency but allow for some application of market forces at the margin. Elsewhere I have called these "hybrid markets" or "potemkin markets"—they are governance systems in which incumbents have secure advantages because the core of governance is managed by command with flexible market-oriented incentives layered on top. In many settings, they are designed to look like markets to the outside when, in fact, the central function of a market (allocation of resources) is quite different. An interesting example, today, is the European Union's efforts to control emissions of greenhouse gases. The most visible elements of that system is the Emission Trading Scheme (ETS), but in fact the ETS has almost no practical impact on emission patterns—a wide array of other policy instruments, such as regulations on plant efficiency, feed-in tariffs for renewable power sources, soft budget constraints for nuclear plants and the like have a larger practical impact on actual emissions patterns.

2: Some Illustrations and Case Studies

The real world is a complicated place. What follows are some illustrations drawn from three regions—the Middle East, China and the Southwestern U.S.—that all face severe water shortages (and problems of water quality) and thus are good testbeds for illustrating how water governance evolves in the real world. Each of these cases is complex; each has a large role for many local factors. But looking across the cases suggests that real world policy evolution is much more aligned with the political economy model I have offered—policy evolution through crisis and persistent suboptimal choice of policy instruments—than the ideal "Model 1" vision of the world.

The cases offered here are vignettes, not full blown case studies. When looking at the Middle East I focus on the factors that explain variation in how different countries from that region have managed water resources since that variation, I will suggest, reveals a lot about the central role of public institutions in explaining why some countries manage water problems relatively well and others fail. I focus, in particular, on how the Middle Eastern countries have addressed what is always one of the greatest challenges in water management: paying for and managing water infrastructures. When looking at China I examine the challenge that is often paramount in large countries: dealing with the problem of fragmentation. And in the United States I look at how different schemes for allocating property rights across different jurisdictions affect the design and operation of water markets.

Middle East

To some observers, water is the centerpiece of Middle Eastern politics while others hold that water is structurally insignificant to most of the political forces at work in the region.[14] There is little doubt that across the region pressures on water resources are mounting and likely to get worse with climate change.[15]

As in most of the world, governments in the region have focused on large supply-side projects such as desalination and dam construction and less on an adaptive approach that emphasize important "soft" factors such as managing water demand and improving the efficiency of water use. The UN's Middle East and North Africa (MENA) region is the driest in the world with only 1% of the world's available freshwater. Eight of the 11 countries in this region are considered water scarce and 2 are water stressed.[16] Regionally, 12% of the population lacked access to safe water and 25% did not have access to sanitation.[17] With a rapidly growing urban population, housing shortages, and inadequate infrastructure, informal settlements have sprouted in urban areas, further straining already water scarce cities throughout this region. Few of these informal communities receive water and

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[14] Selby, 2005

[15] Sowers, Vengosh, and Weinthal, 2011

[16] Pérard, 2008

[17] SWI, Tropp, and Jägerskog, 2006

wastewater services.[18] The failure of public services in many countries of MENA has led to a phenomena now evident in much of the world where government does not perform—the rise of private markets. In poorly served MENA settlements, residents often buy water sold by private vendors and pay 10-20 times more per litre of water than residents who receive piped service.[19] These hybrid markets—where utility piped service is widespread but performs poorly and layered on top are private markets with much more reliable but costly service that can't take advantage of the scale economies of a well functioning utility network—are commonplace in the region.

There is a large mismatch between pricing and scarcity, especially in the sector that uses most fresh water: agriculture. More than 65% of water withdrawal in the region goes to agriculture, in line with other developing countries but significantly more than the 33% and 38% for agriculture in Europe and North America, respectively, where about half of water withdrawal is for industrial use.[20] Studies that have tried to track value-added of different sectors of the economy and the efficiency with which they use water conclude that agriculture is generally highly wasteful and industry in general is much more efficient in how it uses water—a pattern that relates directly to huge differentials in pricing for water resources. [21]

Recently the OECD led a region-wide assessment of water policies in the MENA region and identified an array of common challenges across the region as well as massive variation in the extent to which different national governing systems have addressed those challenges adequately.[22] Whether the countries began reforming their water sector decades ago, like Morocco and Tunisia, or they are just beginning, they all face important institutional challenges. All face the challenge that is evident essentially everywhere in the world: the need to mobilize massive infrastructure investment in water supply and treatment systems that, at present, charge low fixed prices. The OECD analysis tabulated a large number of water governance challenges, in particular:

- Limited enforcement of water policies
- Overlapping responsibilities between different institutions with unclear roles
- Unclear legislative and regulatory frameworks at the national level, which creates coordination problems at the local and regional levels
- Lack of an effective strategy to manage water demand growth

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[18] Faruqui, 2003
[19] Faruqui, 2003
[20] Pérard, 2008
[21] Pérard, 2008
[22] OECD, 2010

- Inadequate human resources capacity in government agencies and insufficient awareness of water issues among the general population
- Insufficient mechanisms to ensure stakeholders' participation

Countries that have done well in managing these problems have not been the richest in the region, such as the large oil exporters. These countries have been able to manage water scarcity and quality problems by showering them with costly infrastructures. Instead, the most innovative countries have generally been those that are the smallest and most vulnerable and those that tend to score well on other measures of water governance. In general, better performing countries have also been those that are exposed (and prone to brace) external ideas. For example, Morocco has adopted a model for basin-wide watershed management similar to the centralized watershed agencies developed in France, Spain, and other OECD countries.[23]

In addition to OECD's work, other studies have also examined the region carefully and come to similar conclusions. One particularly interesting set of insights concerns the effects of religion on water management. Morill and Simas (2009)[24] compare the water laws in Egypt, Jordan, Lebanon, Morocco, Oman, Tunisia, and Yemen in the context of religious and customary law.

In the predominantly Muslim countries in the MENA region, Islamic principles that address water resources present an additional challenge to solving the water-scarcity issue. The challenge is "in aligning Islamic and customary law with the realities of modern day water resources management (WRM) law and policy."[25] Islamic religious law, or Shari'a, as spelled out in the text of the Qu'ran, regulates all human actions, including the use of water resources. The Qu'ran says that "water is a gift of God and in principle belongs to the community" and all individuals and domesticated livestock have a right of *shafa* ("drink").[26] Some Muslims believe that Islam prohibits the selling of water.[27] Morill and Simas point out that, for the reason of the right of *shafa*, water pricing is one of the most difficult parts of water law to implement.

Full privatization of water, where a private company owns the water rights, is unlikely to be permissible in Islam.[28] (Of course, full privatization of water infrastructure is rare everywhere in the world because of the severe risks to private investors from owning an asset that is highly politicized.) While ownership may prove problematic, a wide array of legal forms, such as service and lease contracts

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[23] OECD, 2010
[24] Morill and Simas, 2009
[25] Morill and Simas, 2009
[26] Morill and Simas, 2009
[27] Faruqui, 2003
[28] Faruqui, 2003

or build operate transfer (BOT) schemes, are viable.[29] Comparing across the region, Morocco, Jordan, and Algeria are the most "active" users of such schemes: Jordan is the largest user of private suppliers with about 40% of its population relying on private providers for drinking water (as of 2006); Morocco, through awarding concession contracts, is the most active in outsourcing water supply; and Algeria signed a BOT contract for a desalination plant in 2001 and outsourced the water supply of Algiers through a management contract in 2005.[30] Private operators have operated in these countries since the late 1990s. In Egypt, Lebanon, Turkey, and Palestine, private sector involvement in water supply is low but increasing, while private sector presence is non-existent in Tunisia, Syria, Cyprus, and Malta.[31] As with private ownership in many other network industries, delegation to private actors does not necessarily improve efficiency unless appropriate incentives are in place as well as institutions such as independent regulatory agencies.[32] Looking across the region, the actual performance of water systems correlates less with ownership and the presence of markets and more with the quality of governing institutions.

In countries that have relied on public ownership and management of public agencies, Tunisia is a model. In the Mediterranean region, Tunisia is one of the countries with the greatest water scarcity. The country sees irregular annual precipitation and "renewable freshwater available per inhabitant is 50% below the water scarcity standard."[33] The country faces additional challenges in the remoteness of its water resources to where the water is consumed and low quality of water. The two public agencies that manage the water and sanitation sectors and the two national agencies that oversee large infrastructure projects and water resource management are highly centralized and very politicized but their performance has also been impressive. Tunisia has one of the lowest rates (18.2%) of unaccounted for water in the region; 100% of urban residents have access to safe drinking water with a household connection rate of 98%; in contrast to other cities in the region, Tunisian cities usually have continuous water supply; and their bill collection rate is over 99%.[34]

The Water Code of 1975 (updated most recently in 2001) regulates resources, planning and development, tariff rates, and the reuse and conservation of water. Since 2000 Tunisia has followed an integrated water resources management (IWRM) approach alongside the further development of the country's water

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[29] Pérard, 2008
[30] OECD, 2010
[31] Pérard, 2008
[32] OECD, 2010
[33] Pérard, 2008
[34] Pérard, 2008

resources.[35] As part of the IWRM, the government has engaged citizens and local stakeholders in decision-making processes and in designing water policies. In the water sector, private companies are limited to subcontracting roles to extend water networks and install connections; in the sanitation sector, the private sector accounts for only 13% of infrastructure maintenance and operation, although participation is expected to significantly increase in the coming years.[36] The agency that manages the water sector is working on expanding private participation.

Tunisia's scarce natural water supply has long motivated it to experiment with nonconventional and innovative forms of generating water. For instance, the country has been desalinating brackish and saline water since 1983. In the form of a build-operate-transfer contract in 2008, the government subsidized private investment in a desalination facility, viewing the technology as critical to the country's long-term management strategy.[37] The country also uses artificial groundwater recharge, which is a way to store surplus water from one season for use during dry periods. Also, it has been reusing treated wastewater in agriculture since the 1970s and has one of the highest reuse rates in the world.[38]

While Tunisia's public administration of the water and sewage system are exemplary, the country faces a problem familiar worldwide—under-charging for water services. Water and sanitation tariff structures are applied uniformly across the country instead of reflecting the real economic cost of water across differing regions and the fixed and variable tariff structure—with an emphasis on the variable component—means that 10% of customers pay for more than 80% of the population and 90% of users pay below the real marginal cost.[39]

Jordan has among the lowest amount of water resources per capita in the world. Its resources come primarily from surface and ground water and renewable ground water resources are withdrawn at an unsustainable rate (in 2009, withdrawal rates were up to 20% above the estimated sustainable capacity).[40] Water is also used inefficiently: agriculture uses more than 60% of water resources while contributing only 2.8% to GDP and unaccounted for water reaches 47% in the Amman region (2006 data).[41] "The availability of water varies throughout the country and even residents of Amman receive piped water only once a week."[42] The sector is managed by three authorities (Ministry of Water and Irrigation, Water

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[35] The goal of the IWRM is to: 1) achieve more efficient use of water; 2) promote demand management; 3) reform tariffs; 4) encourage public private partnerships; 5) reinforce regulatory frameworks for environmental protection.
[36] OECD, 2010
[37] Louati and Bucknall, 2009
[38] Louati and Bucknall, 2009
[39] This assessment based on 2006 data reported in Pérard, 2008.
[40] Zeitoun, 2009
[41] GTZ, 2006
[42] Zeitoun, 2009

Authority of Jordan, and Jordan Valley Authority) and is very much centralized and politicized. The Minister oversees the “autonomous” agencies so they are not actually independent and regulatory functions are limited to monitoring of the water sector. Additionally, the Ministry of Health is responsible for managing potable water and protecting water quality. The Ministry of Environment is responsible for developing all standards and specifications governing environmental protection, including water resources. The Ministry of Water and Irrigation adopted a national water strategy in 1997 that focused on managing demand and emphasized the role of the private sector in water supply with the goal to improve management efficiency and attract private investment.[43] In 1999 it contracted out the operation and management of water and wastewater services, resulting in significant improvements in supply.

An inefficient pricing policy is one of the main problems with the water sector. The Ministry of Water and Irrigation set a tariff structure that subsidizes the poorest communities, such as small-scale farmers in the Jordan Valley who receive preferential rates. Prices vary based on qualities and uses, where profitable markets such as tourism and industry pay the full cost of water, and higher (and presumably wealthier) consumers pay higher prices to recover the cost of subsidies. In practice, the result of this structure has been prices that are set too low to be sustainable and disparities in price that have average 2001 urban users paying 90 times more than rural users and in some desert areas water is free of charge.[44] Despite its inefficiencies, social and political considerations prevent implementation of reforms to the water pricing structure.[45]

Algeria, the country with the lowest renewable water resources of North Africa, suffers from poor public management and weak incentives to invest in infrastructure. In Algiers, up to 40% of the water carried by the network is lost: 32% due to technical losses and 8% due to illegal consumption.[46] Mediocre agency management has made matters worse. Irregular payments and illegal connections have created a huge backlog of unpaid bills.[47] The National Sanitation Office in 2005 noted that tariffs covered only 10% of operating costs and, as a result, water rationing and shortages are common.[48]

A series of recent reforms may address some of these problems. Water treatment, water supply, and sanitation were managed by four public agencies but in the early 2000’s management of the sector was reformed. In 2006, the four agencies were combined under a single agency. A new water law in 2005 emphasized private sector participation to increase efficiency and promote

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[43] Wardam, 2004
[44] Pérard, 2008
[45] Wardam, 2004
[46] Pérard, 2008
[47] Global Water Intelligence, 2005a and 2005b
[48] Pérard, 2008

competition, and encouraged the use of concession contracts in public water and sewerage services. The new law installed an independent regulatory agency to oversee the monitoring of water provision and tariff setting.

The 2005 law eliminated the fixed-fee for water system and proposed a new system where people can choose between a high fixed fee or a variable fee based on consumption, as measured by a water meter. The fixed fee is set at such a high level that most consumers would benefit from choosing the variable fee. The aim of this policy is to reduce demand.[49] Tariffs also vary by geography and, in theory, will cover the costs of renovating and expanding potable water infrastructures. The law empowers the government to regulate and enforce water quality and protect areas with vulnerable ecosystems, allowing for penalties for breaking environmental regulations. A greater role for private contractors is also envisioned. Starting in 2005 a contract to manage water and wastewater services for the city of Algiers was awarded, with incentives to upgrade and modernize the water and wastewater utilities to increase reliability and improve service quality to provide water on a 24-hour basis. By 2008, the percent of the population with 24-hour access to quality water increased to 71% from 16% in 2006. Significant progress had also been made in sanitation.[50]

Contrasting the experiences of Tunisia, Algeria, and Jordan points to a maxim that has been understood in the regulation of electric power markets: there is no single best model for reform. In countries where public institutions are well-governed public ownership and management may work adequately—as illustrated in Tunisia. In countries where the public model fails, shifting to private ownership with performance incentives may be necessary, as Algeria and Jordan reveal.[51] All three of these countries have faced severe challenges in getting prices right.

Other countries in the region reveal similar patterns. Egypt has achieved 100% coverage of drinking water supply in urban and rural areas but has been much less successful with wastewater treatment, which covers only 55%, with only 15% coverage in rural areas.[52] Public administration of the water system is highly fragmented, leading to a reorganization that has in theory streamlined the process.[53] But the country still relies heavily on public funds for financing.[54] The government expects that the cost for water services will more than triple over the next 15 years if tariffs are to fully cover financing needs. Yet as of 2006, revenues cover only 40% of costs.[55] Some limited tendering to private companies has begun, such as in New

[49] Pérard, 2008
[50] OECD, 2010
[51] Besant-Jones, 2006
[52] OECD, 2010
[53] Attia, 2004
[54] Pérard, 2008
[55] Pérard, 2008

Cairo where a Spanish company now operates a wastewater treatment plant.[56] Morocco has had similar experiences with tremendous success in providing access to water supply but much less progress in developing wastewater and sewerage systems.[57] Policy reforms in that country have been driven both by the need to develop sustainable financing for new infrastructure but also reducing the financial burden on the poor while expanding service to poor urban and periurban settlements—an extremely difficult task.

China

China's water supply is dominated by two central facts. First is rising demand from rapid growth in industry, urban populations, and agriculture. Second is a highly uneven spatial distribution of water resources—the northern parts of the country are generally arid and the south is much wetter.[58]

As in most countries, total water use in China is dominated by agriculture, which consumes 67% of the country's water while contributing only13.2% to GDP. Water in the North China Plain, where most of the country's important agricultural provinces are located, is supplied by the Haihe, Luanhe, and Yellow Rivers—all now under severe stress leading to over-exploitation of groundwater aquifer resources. Industrial demand accounts for 22% of total demand for water. And as China's economy grows, industrial output is increasingly more profitable than agricultural output, so water resources will increasingly be transferred to industrial purposes.[59]

Several ministries and commissions oversee water management in China. The fragmented nature of water governance, both regionally and nationally, has led to problems such as inefficient and ineffective pricing of urban water, conflicting competencies between government bodies, poor delineation of duties, and a lack of horizontal and vertical coordination.[60] Historically in China, water is viewed as a fundamental public good that should be available to all. Until the last twenty years the price of water within the country was essentially zero.[61] The direct result has been massive inefficiency with few incentives to conserve.

Chinese water management primarily focuses on two major rivers: the northern Yellow River and the southern Yangtze River. Both rivers suffer flood or drought on a regular basis. So water resources management has primarily been supply driven, with an emphasis on large-scale dam building projects and

[56] OECD, 2010
[57] Chauvot de Beauchêne and Mantovani, 2009
[58] Jiang, 2009
[59] Brooks, 2005; World Bank, 1993; Huang et al., 2009
[60] Carmody, 2010
[61] Rong, 2011

agriculture water supply.[62] In the 1990s, as industrial demand rose rapidly, the Yellow River began to regularly run dry leading to increased periods of drought and concerningly low levels of water supply in the north. One direct result of excess water withdrawal and consumption in the basin were the river's increasing cutoff periods from 1972–98. As a worst case, in 1997 there was no discharge at all from the basin to the sea for up to 226 days.[63] These striking facts—a river run dry and polluted—have led to massive reform efforts as well as an outpouring of ideas for improvement management.[64] Those reforms, which have been implemented in highly uneven ways around the country, have led to changes in law as well as pricing and administration.

There are two basic national frameworks for managing water issues. One is the national water law, which was originally introduced in 1988 and updated in 2002. In tandem with that law focused on water pricing and allocation, there are several laws for environmental protection, including several directly relevant to water resource management, for example, *the Law of the People's Republic of China on Prevention and Control of Water Pollution* in 2008.[65] The other main framework is the country's system of national planning, which has been the keystone to most major Chinese efforts to manage depletion and degradation of resources. In the most recent 12th Five-Year Plan (FYP) (end 2010-end 2015), the reduction of water intensity remains the same as the last one at 30 per cent. (The 11th FYP (end 2005-end 2010)'s target was easily surpassed at 37 percent.) The new plan projects that the annual water use will rise to 620 billion cubic meters by 2015. Early last year, the State Council issued *the Opinions of the State Council on Implementing the Strictest Water Resources Management System*,[66] which requires that the national total water usage must be controlled below 700 billion cubic meters in 2030. In 2011, the number was 608 billion cubic meters,[67] which means an approximate annual growth rate of 0.75%. (By contrast, in recent years the annual growth rate of national total water use has been over 1 percent.) So far, climate change has not figured prominently in Chinese water management strategies and there is considerable uncertainty about how altered climates will affect flood, drought and the availability of freshwater resources around the country.[68]

Despite these reforms, much remains to be done. Few of the new laws and formal regulations have been effectively implemented.[69] Leaders have tried to

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[62] Carmody, 2010
[63] Ringler et al., 2010
[64] Jiang, 2009; Cheng and Hu, 2012
[65] For more detailed information, refer to http://chinawaterrisk.org/regulations/water-regulation/ which provides a nice overview on water regulation in China.
[66] Please see at www.china.org.cn/china/2012-02/17/content_24664350.htm
[67] China's National Bureau of Statistics, 2012
[68] Huang et al., 2010; Piao et al. 2010
[69] Huang et al., 2009

encourage water saving technologies since the early 1990s, such as sprinkler systems, drought resistant varieties, and drip irrigation, but adoption rates in northern Chinese villages average less than 20%.[70] Xie (2009) in a World Bank report finds the legal framework still "unsatisfactory." He finds that enforcement is lacking and "the legal framework leaves much room for improvement."[71]

Pricing and Market Reforms

Here we focus on two types of reforms that have been particularly interesting and important.

First have been pricing and market reforms. Water was provided almost free of charge until 1985; since the early 1990s, China has charged for water and has increasingly raised tariffs in both urban and rural areas.[72] Various national policy papers were written in the 1990s that emphasized increasing the water fee. As a result, the total water tariff had an annual growth rate of 16.5% in the 1990s.[73] Based on the National Development and Reform Commission (NDRC) data in 123 cities, water prices and sewage rates are increasing at an annual average rate of 5.49% and 10.63% respectively. In 2006, the NDRC issued regulation suggesting that "the price of water should be based on the cost of supply, including the costs of groundwater or aquifers, constructing pipes and treating sewage."[74] Some provinces and cities in China have taken these ideas to heart and adopted wide-ranging reforms in tariffs, the introduction of limited trading, and new forms of public administration in the water sector.[75]

In addition to pricing reforms there have been three types of market transfers in China. The first type is the transfer of regional water rights. The notable example is the agreement reached in 2000 between Dongyang and Yiwu Counties in Zhejiang Province, which is widely regarded as China's first example of a regional water transfer.[76] In November 2000, Yiwu County paid a lump sum of RMB200 million to Dongyang County for an exchange of 50 million m^3 of water per year from the Hengjin Reservoir in Dongyang County.

The second type is water saving and transferring within a river basin. The Yellow River, for example, as the dominant water source for the populous but water-scarce north, has been at the forefront of innovations in China's water allocation, water regulation and

[70] Huang et al., 2009
[71] Xie, 2009, 43
[72] Xie, 2009
[73] Zhong and Mol, 2010
[74] Carmody, 2010
[75] Zhong and Mol, 2010
[76] Gao, 2006

water transfer/trading. The government—at both the central and local level—has facilitated a series of water-savings transfer projects within large irrigation districts, which transfer water from agriculture users to industrial users with the industries in turn paying the cost of the channel lining and ongoing maintenance. In theory, any enterprise in need of water could submit proposals to the government identifying their water requirements. The successful applicants would be chosen based on the government's development priorities. To date, all such water transfer projects have involved state enterprises, the majority of them from the power industry. Government agencies have been central to the process.

The last type is water transfer within irrigation districts at the farmer level. But the grant of water rights at the farmer level has only occurred to a limited extent to date, principally as part of pilot water efficiency programs in some of the most water-scarce regions. In the pilot districts, water tickets are issued to individual households and may be traded freely among farmers. In practice, however, there have been few instances of trading of water tickets. China's Ministry of Water Resources (MWR) has been working for years towards a rights-based water management system. China's 11th Five-Year Plan (2006–10) specifically requires the establishment of "an initial water right distribution system and a water right transfer system."[77] However, water rights and the rules governing them are not clearly defined yet in China[78]. Earlier drafts of the 2002 Water Law included further provisions regarding the transfer of water rights. However, because the proposal that included these provisions generated much significant controversy, the final version of Water Law does not include the provisions[79].

River Basin Management Reforms

In addition to a shift in pricing, China has also attempted a shift to basin-wide management of water resources. The triggers for these reforms include not just rising demand for water but also the need for upstream–downstream coordination. The shift to decentralized management of water resources and environmental regulation has also created the need for greater coordination at the basin level. Chinese planners have studied lessons from other parts of the world, such as the various river basin management schemes in Mexico[80] and Narmada River Valley in India[81]. Emblematic of the need for reforms is the situation of the drying Yellow river. The basin produced about 14% of Chinese grain harvest and 14% of the country's GDP using only 2% of national water resources.

The 2002 Water Law defined, for the first time, river basin management institutions and functions and strengthens the administrative rights of river basin

[77] State Council of China, 2006
[78] Speed, 2009
[79] Wouters et al., 2004
[80] Mestre R, 2009
[81] Gupta, 2001

management organizations although basin commissions formally predate that law[82]. As of today, China has established river basin management commissions (RBMCs) for its seven large river/lake basins (six river basin management commissions and the Tai Lake Basin Management Agency) as subordinate organizations of the MWR[83]. The RBMCs essentially act as regional offices of MWR and are responsible for cross-province water function zoning plans and undertake a wide array of functions related to withdrawal of water from basins and pollution such as sewage outfalls. In addition, a basin approach to flood management was strengthened in the *1997 Flood Control Law* and a basin approach to water pollution control plans was stated in the *2008 Water Pollution Prevention and Control Law*. Numerous studies, including by Feng (2009) and Shen (2009), have reviewed the experience with these commissions.[84]

As a practical matter, it is hard to see much effect of the RBMCs. The most visible effects are in the Yellow River Conservancy Commission which reacted swiftly to the watershed moment of zero discharge from the Yellow River in 1997. In 1999, the Yellow River Conservancy Commission implemented unified water flow regulation (UWFR) as enforcement of the 1987 cross-provincial water allocation agreement. Implementation of the UWFR contributed to a decline in total irrigation water use in the mid- and downstream areas.[85] The practical effect of this measure, however, stems more from the highly visible impacts of the Yellow River crisis in the country and the attention of central planners to solving the problem.

The impact of RBMCs on other water challenges, such as water quality, is much weaker. China has adopted a system that essentially separates and designates the management of water quantity and water quality to the MWR and MEP, respectively. The MWR is responsible for the water-related environmental management in the water body, while the MEP is responsible for those activities on land. At the river basin level, there is a water resources protection bureau in each river basin commission in China, which is under the leadership of both the MWR and the MEP. Thus, as a matter of theory, water quality issues should be managed in an integrated way. But at the operational level, since each bureau is dependent on different "bosses" for funding, there is little scope for independent action that would allow them to fully integrate their management of water quality in the river basin. In fact, water quality of rivers in eastern China, a populous area subject to the most severe water pollution, is hardly improved in the past decade despite of years of pollution prevention. In China, water quality is broken into five categories that can be described as ‘‘good’’ (Classes I, II, and III) or ‘‘poor’’ (Classes IV, V, and V beyond which cannot support drinking and swimming). In 2001, only 27% and 39% of Huai River and Hai River's water meet the standard of "good"

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82 Shen, 2003
83 Rong, 2011
84 Feng, 2009; Shen, 2009
85 Ringler et al., 2010

quality[86]; 10 years later, the status quo does not improve much or even slightly worsen with ratios of 38% and 36%[87], respectively.

The United States Southwest

Most of the American West relies heavily on water storage facilities that collect the snow runoffs from the mountains each spring, so not surprisingly the 10 largest dams in the US are all in the West.[88] The US Bureau of Reclamation built most of the water infrastructure in the West to irrigate agriculture and to generate electricity. Groundwater is also an important source in some areas, accounting for 25% of all withdrawals in the 11 western states (as much as 51% in Arizona to as low as 2% in Montana).[89] But in many regions, the withdrawal of groundwater exceeds the natural renewal rate. Irrigation accounts for about 75%-80% of withdrawals in the West, compared to just 34% nationally. [90] Improvements in industrial efficiency over the past two decades have helped to stabilize water usage, but, still, total per capita withdrawal is higher in this region than compared to other regions in the country.[91] During the 1990s, the population in the West grew by almost 20%, with the biggest growth in the most arid states.

Another paper for this conference will look at the Southwestern experience—in particular, the experiences in California—in much more detail.[92] Thus here I will focus briefly on just two aspects of water management in this region. One is the fragmentation of authority, especially as revealed in the management of the Colorado River. The other is the practical impact of market incentives in a system where property rights are not fungible.

States are the primary governing bodies regarding the management of water resources, with each state having different provisions and administrative rules. Federal laws are layered on top. Allocation of water from rivers that run through several states are governed by compacts that states have entered into. For example, New Mexico, Texas, and Colorado have entered a compact on the Rio Grande; Colorado, Nevada, California, Arizona, New Mexico, Utah, and Wyoming have a compact on the Colorado River; and Colorado and Kansas have a compact on the Arkansas River. The US Congress ratifies these compacts and the US Supreme Court has immediate jurisdiction to settle disputes.[93] Additionally, a treaty between the US and Mexico governs the three rivers that those countries share—the Rio Grande, the Colorado and the Tijuana River. As demand for water has risen along with awareness of the various interconnections between surface and

86 Ministry of Water Resources of People's Republic of China, 2002
87 Ministry of Water Resources of People's Republic of China, 2012
88 Tarlock et al., 1998
89 Kennedy, 2005
90 Kennedy, 2005; Donohew, 2009
91 Kennedy, 2005
92 Barton Thompson, MIT-CSIS Conference paper May 5 2013
93 Valdes and Maddock, 2010

groundwater systems there has also been rising pressure to manage surface and groundwater uses "conjunctively"—an idea that makes eminent sense yet is extremely difficult to manage in practice. Historically, water rights on the surface and under ground have been assigned in different ways. And some western states, like California and Arizona however, are reluctant to change their groundwater and surface water laws to align with the growing scientific understanding of the physical connection between the two sources.[94] Instead the water law in those two states treats surface water and ground water as separate, where surface water is appropriable but groundwater is not.[95] In addition to the diversity in the assignment of property rights, public administration is also highly fragmented. Often at the state level one department is responsible for surface water, another for groundwater, and still another for hydrology.

The surface water supply system in this region was built mainly from federal funding with the Reclamation Act of 1902 that led to the construction of dams throughout the Southwest. This water supply was intended primarily for agriculture although, over the century, the hydroelectric benefits of large dam projects rose in prominence. The US Bureau of Reclamation (USBR), the principal federal agency responsible for designing and building these dams, entered into contracts with farmers in the region where the dams were being built. The farmers paid the USBR in exchange for guaranteed water at a price level that also covered the cost of the facilities, so in essence, the farmers were paying back the cost of the dam and, when paid off, the farmers would have ownership. In tandem, especially when faced with rising costs, farmers also created irrigation districts to raise money. Today, the USBR controls releases from the reservoirs to the river or stream, the irrigation districts or the state controls diversion from the streams or rivers, and states manage intra-state stream activities.[96] For the American west, the epoch of dam-building and institutional forms that flowed from the need to pay for and manage these infrastructures is now over since building new dams is impractical. (Indeed, a growing number of dams are now slated for removal, although not yet any of the giant western dams.) Today's water management challenges arise in a context where institutions were created to serve earlier functions and must now be adapted to new ones.

One of the most interesting adaptations is the rise of water markets. The western United States began using water markets to reallocate water in the 1980s and its institutional reforms remain ongoing but the development of water markets have been slow to mature.[97] In the US, water for irrigation is still heavily subsidized by the government. For instance, farmers in California's Imperial Irrigation District pay $20 per acre-foot of water while the city of San Diego pays $225 per acre-foot for the same water.[98] These large discrepancies arise, in part, because of the complexity in defining water rights and the huge advantage that incumbents have in shaping the market.[99] The

[94] Valdes and Maddock, 2010
[95] Valdes and Maddock, 2010
[96] Valdes and Maddock, 2010
[97] Donohew, 2009
[98] Murphy, 2003
[99] Donohew, 2009

incumbent's advantage is particularly evident in the doctrine of appropriation, which is the basis for most allocation of surface water in the west. Once water is diverted and right is established, the right to the water remains available to the original and would be off-limits to potential future users.[100] The concept arose in the era of mining—an intense user of water—to prevent new settlers from diverting water upstream of already established settlements further downstream. The effect is to protect senior rights and to create strong incentives for holders of those rights to use water even when other uses might be more efficient. During times of drought, in particular, seniority is important since cutbacks in water favor more senior holders. Other parts of the U.S. use riparian methods for allocating water in which water rights cannot be separated from the land. Under Riparian systems, in times of drought, all users share the same reduced water availability. Large-scale water use that is managed by well-organized interest groups help explain why western states fully or partially embrace the doctrine of prior appropriation. Colorado dropped the riparian system for the prior appropriation system, but California has adopted a hybrid of the two systems.[101]

Thus the basic allocation of water in the southwestern U.S. comes from a series of overlapping institutions. One is the fundamental allocation of private, surface water rights mainly through the doctrine of prior appropriation. Another is the sharing of water resources of the major inter-state river (the Colorado) through a federally managed river compact adopted in 1922. A third is the allocation of those river sources between the U.S. and Mexico. As the demands for water have changed—in particular with the huge surge in demand for water in California—new hybrid markets have emerged on top of these basic institutional arrangements. I illustrate, here, with two examples.

First, along the Colorado River the rising demand for water has forced California to curtail its use and comply with the allocation it received in 1922: 4.4 million acre-feet per year. To do that, a transfer market has emerged that has allowed wealthy cities (e.g., San Diego) to buy water from other regions in California where water is used much less efficiently. A 75 year agreement, currently in its 11th year of operation, allows San Diego to purchase from the Imperial Irrigation District (IID)—a parched agricultural zone located in the desert east of San Diego near the Arizona border—at a cost of $540/acre-foot. The water transfer agreement dictates the kinds of activities that the Imperial Irrigation District must undertake, which include the fallowing of existing cropland and then eventually active conservation measures in the region. In parallel with these programs designed to pare back agricultural uses there is also a program to line two canals to reduce leakage.[102] If a full blown market for water in the Colorado states were created from scratch it is highly unlikely that prices would clear at such high values, but in the hybrid market—where transaction costs for developing trades are high and most existing users face no incentive to trade away their established rights—prices form in quite

[100] Kennedy, 2005
[101] Donohew, 2009
[102] San Diego County Water Authority (2013)

different ways. Ironically, this approach results, most likely, in excessive amounts of technological innovation—San Diego, for example, is building a pioneer desalination plant that probably would be uneconomic if pure market rates for water were prevalent.

Second, very thin hybrid markets are also emerging between the U.S. and Mexico. In the wake of a large 2010 earthquake along the California-Baja border, nearly 400 miles of Mexican canals that normally carry Colorado river water were damaged, leaving Mexico unable to fully use its quota of water. A bilateral agreement between the two countries allows Mexico to store that extra water for three years in Lake Mead while the Mexican authorities repair the canals. Building on that progress, new agreements that might include water quality trading are also taking shape.[103] (And in a sign that policies often have unintended effects, Mexico is also disputing the actions that San Diego is financing to line the U.S. canals to reduce leakage. Before the lining, leaking water in the U.S. flowed into Mexican groundwater and was a major source of water for agricultural operations just over the border in Mexico.)

3: Some Implications for the Future: Integrating Water Management and Improving Water Modeling

To close, we look at two sets of questions. First is what our simple theory of policy change and the illustrative case studies suggests about major reforms to water governance. The ideas for reforms, especially in light of growing concerns about scarcity of water resources, are many. Which of these ideas might actually get adopted? Second we will look at what all this implies for the modeling of water resources and human responses to scarcity.

The Prospects for Institutional Reforms

There are at least four major kinds of pressure for reforms in the allocation and protection of water resources. All have major implications for how water management institutions are organized.

First is Localization. Ivey, Loe, Kreutzwiser, and Ferreyra (2006) examine the influence of existing institutional factors on enhancing or constraining the capacity of local governments to protect source waters, looking specifically at the Oldman River Basin in Alberta.[104] "Source water protection refers to the development and implementation of policies, plans and activities to prevent or minimize direct or indirect release of pollutants into surface or groundwater resources currently used or intended to

[103] Quinlan, 2010
[104] Ivey, Loe, Kreutzwiser, and Ferreyra, 2006

be used in the future as sources of drinking water (O'Connor, 2002; Krewski et al., 2004)."[105] They find that as the trend in governance moves towards devolution, local governments will have to rely on exiting institutional arrangements for land use and water management. In the case of Alberta, the study found that local governments were constrained by the disconnection of land use planning and water management. There was a lack of formal mechanisms in place to allow or encourage local officials to transform knowledge at the municipal level into locally relevant knowledge. Also when the responsibility for regulating intensive livestock operations was assigned to the provincial government where there was an absence of a commitment to source water protection, local actors did not see a role for themselves and therefore their ability to protect source water was constrained. The authors state that in the absence of a commitment to environmental protection by senior levels of government, "strong institutional support to facilitate meaningful and broad public involvement and land and water integration is necessary."

Second is adaptive management. In an adaptive approach, actions are adjusted based on progress toward management objectives.[106] "Implementation of adaptive management approaches has occurred across a spectrum of styles[107], from formal experimental approaches[108] to work that focuses on the role of participation and social learning processes[109]. Although adaptive management is a well-established concept that has received significant theoretical attention, there is limited evidence of its practical effectiveness[110]. Schreiber et al. (2004) listed the vulnerabilities of adaptive management to both scientific limitations and social and institutional constraints.[111] Little information is available to managers on how to undertake adaptive management.[112] In Eberhard et al (2009), the authors focus on providing a "practical approach to guide structured learning in response to uncertainty in knowledge at the catchment scale."[113]

Third is ecosystem services. The central idea here is that natural resources exist not just to serve human needs but also to nourish ecosystems, and in theory it is possible to create markets and other incentives that would encourage those services.[114] A handful of highly successful cases—such as the water protection agreements for the watershed that supplies New York City—suggest that markets for ecosystem services could be very powerful.

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105 O'Connor, 2002; Krewski et al., 2004
106 Eberhard et al., 2009
107 Broderick, 2008
108 Walters, 1986; Gunderson, 1999
109 Berkes and Folke, 1998; Pahl-Wostl, 2006
110 Walters and Holling, 1990; Lee, 1999; Rogers et al., 2000
111 Schreiber et al., 2004
112 Allan and Curtis, 2003
113 Eberhard et al., 2009
114 Daily, 1997

Fourth is integrated water resources management (IWRM). IWRM has been defined as "*a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*".[115] The central idea behind IWRM is similar to the idea that motivated China to adopt river basin commissions and many other countries to seek similar kinds of reforms. IWRM is intended to bring together different stakeholders, to allow for flexible basin-wide management of water resources, and to incorporate a wide array of ecosystem services as well as human needs in the allocation of water resources.

Evaluating the prospects for these four requires looking at how these ideas might map onto political interests and administrative capabilities that would be needed to put these interesting ideas into practice. Localization maps well, for many political systems are shifting authority to local levels and despite the risk of fragmentation local rule makes it relatively easy for well-organized interests to control outcomes. The other three, however, are much harder to fathom. Adaptive management and ecosystem services have risen in popularity among academics, but they have not been widely enshrined in practice. IWRM is even harder to see implemented because the broad benefits of more coherent management are diffused across stakeholders. There are few interest groups that seek these systems; incumbents, in particular, rarely want the large scale changes that would be entailed in these systems.

Implications for Modeling

Finally, and briefly, I mention some implications for models that might be used to simulate the behavior of water basins and the behavior of the people and firms that utilize those water resources. There is a strong tendency in such modeling to rely on decision-theoretic frameworks that assume optimality. Yet the tenor of the work presented here is that real world outcomes will be structurally biased away from optimal allocation of resources. A new line of research might be opened to explore just how "second best" the real world is likely to be and which kinds of second-best outcomes will be most consequential for certain industries, such as the energy industry.

To get started on such research, here is a short list of standard assumptions that might be varied when building models that allow for more real world portrayal of water-related decision making:

- Differential pricing across sectors of the economy, with early incumbents (e.g., agriculture) enjoying the lowest prices and later entrants (e.g., most of industry, especially new firms) facing higher prices.

[115] Global Water Partnership, 2010

- Persistent use of command and control regulation rather than markets (or social planner perspectives), reflecting the reality that well organized interests often prefer command arrangements that are more readily controlled
- Hybrid markets rather than pure markets in which all trades are fungible. Hybrid markets and thin and marked by high transaction costs.
- A system that self-adjusts not in response to all evidence of scarcity and poor performance—as the advocates of adaptive management argue would be best—but in punctuated form in response to crisis.

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Governance of Water in the Western United States: Learning to Live with Inefficient Institutions

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The western United States is facing a wide array of changes and issues that will challenge the effectiveness of the traditional institutions that govern water-quantity management in the West. Western populations continue to grow at a much faster pace than the national population as a whole, because of both intra-national migration from East to West and external immigration. Energy companies will need additional water for both traditional and renewable energy production. Groundwater overdrafting is increasing in some portions of the West and, in a few areas, is getting close to being economically unsustainable. Climate change threatens snow-pack levels (which are a critical form of natural storage) and precipitation levels in much of the West, portends an increased rate of (more extreme) droughts and floods, and will increase evapo-transpiration levels and, as a result, water demand.

This paper evaluates the ability of the West to respond and adapt to this combination of increasing demand and less reliable water supply. As explained below, traditional water institutions in the western United States are not well suited to deal with this combined challenge. Western water institutions are afflicted by problems of fragmentation, inefficient adherence to relatively strict temporary prioritization, heterogeneity, inflexibility, and an inherently ineffective and incomplete regulatory framework. Western water institutions may have done relatively well in encouraging rapid allocation and use of water in the early history of the West (although that is challengeable), but they do not do well in addressing issues of reallocation, changing supply conditions, and unsustainable withdrawals.

After setting out the deficiencies of western water institutions, the paper looks at five different approaches by which water users, managers, and stakeholders in the West have tried to meet similar challenges in the past – and it evaluates the likely effectiveness of these approaches in meeting current and future challenges. First, users and managers can lobby state legislatures to reform water institutions to provide for greater flexibility, sustainability, integration, and foresight – e.g., by adopting institutions that better promote the marketability of water rights, or

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by prohibiting long-term groundwater overdrafting. While legislative change has and continues to take place, change is slow and is likely to remain slow for political reasons. Second, water users and stakeholders can use lawsuits either to change the institutions through judicial mandate or to encourage more rapid legislative or administrative change. While examples again exist of judicially imposed or motivated change, there are limited opportunities for bringing successful lawsuits, and lawsuits are both long and costly.

When unable to force legislative or judicial change, water users and managers can turn to one of three approaches that attempt to work around state institutional limitations. In some cases, water users and managers can try to exploit interstitial pockets of flexibility in existing legal institutions. In other cases, water users can engage in localized "reordering" of water institutions through private contract, judicial settlements, or control over local water organizations. Finally, water managers can construct new institutional overlays designed to solve institutional problems without changing the underlying institutions themselves.

While each of these approaches for overcoming traditional institutional weaknesses has been and can be successful in particular settings, all have limited applicability and can sometimes be even counterproductive. Indeed, there is a risk that, by lowering the overall inefficiencies of existing water institutions, these work-around strategies may reduce the incentive for fundamental legislative or judicial change – leaving the underlying institutional weaknesses, and accompanying administrative costs, in place. In theory, the work-around strategies could thereby lead to greater rather than less inefficiency.

FIVE MAJOR CHARACTERISTICS OF WESTERN WATER RIGHTS AND MANAGEMENT

Five major features historically have both characterized and plagued most governmental water management in the western United States: (1) fragmentation, (2) inefficient adherence to temporal prioritization, (3) heterogeneity, (4) inflexibility, and (5) an incomplete and ineffective regulatory structure. As described below, multiple geographic units typically govern a single water system, and different governmental agencies in the same geographic space may have responsibility over different aspects of water management, making coordinated governance difficult. Prior appropriation still dominates allocation of water in the West, leading to unnecessary inefficiencies in times of drought. State and federal water rights are exceptionally heterogeneous, creating unnecessary administrative costs in the management, use, and, where allowed, marketing of water. California, for example, recognizes over a dozen forms of legal water rights, with scores of additional legal overlays. Traditional western water institutions closely restricted changes in the use of water rights, including the marketing of water rights separately from the land on which the water had been used. While heterogeneity partly caused this inflexibility, separate social and political concerns also led to legal restrictions on marketability. While all state now permit water marketing, significant restrictions remain – dramatically restricting flexibility. Finally, the regulatory structure designed to promote efficiency and sustainability in the absence of market incentives is ineffective, leading to unnecessary waste, environmental damage, and groundwater depletion.

Fragmentation

In the late 19th century, John Wesley Powell suggested in his *Report on the Lands of the Arid Regions of the United States* that the borders of western states should be drawn where possible along natural watershed lines. Powell believed that irrigation in the West, which he believed essential to the West's long-term viability, required management of water by watershed. Yet in a first step toward fragmentation of western water management, Congress instead drew largely artificial (and typically straight) lines in the creation of state borders, unnecessarily dividing up major rivers among multiple states. For example, the Colorado River, which is the largest river by both water volume in the Southwest (and the second longest, after the Rio Grande), flows through seven different states before crossing the border into Mexico.

Such interstate divisions create two major problems. First, because states have principal authority over water policy and allocations in the United States (and each state claims ultimate ownership of its waters), the waters of interstate rivers and streams must be divided among the states riparian to the waterway before the waters can be effectively managed. Yet division of interstate waters is complex, costly, and often politically fraught. The United States Supreme Court and Congress both have authority to divide the waters of interstate rivers. The Supreme Court, however, has no clear formula for such division, and allocation cases can take years to resolve; Congress, by contrast, has been reticent to wade into politically-charged water disputes among states. As a result, most states divide water by negotiated "compacts" (the interstate equivalent to international treaties), which are often vague and, as described later, inflexible. Second, managerial actions in one state can impact water availability and options in downstream states. For example, increased withdrawals, improved water efficiency (which can reduce return flows), and discharges of pollution all can affect water use in downstream states. But mechanisms for resolving such disputes again are often expensive and ineffective.

Further geographic fragmentation occurs at the state level. While states typically create, monitor, and enforce water rights, those water rights are often held, managed, and distributed to the ultimate users by a wide variety of local entities. For example, in California, thousands of water districts, water utilities, and cities manage and distribute water. A farmer may hold a contractual water right from a local irrigation district, which holds a contractual right from a county-wide governmental water wholesaler, which in turn holds a state-based water right. As described below, if the farmer wishes to market or change that water right, she will likely need approval from the irrigation district, the county wholesaler, and the state, adding to the expense of water transfers and making it less likely they will be successful. This fragmentation also undermines John Wesley Powell's original vision of managing water by watershed. Management of water in a single watershed, even if wholly intrastate, is often divided among scores of local agencies.

Water is fragmented not only geographically but also substantively. Groundwater and surface water, for example, are often hydrologically coupled; in these cases, groundwater and surface water are part of one overall water system. Yet western states historically managed most groundwater as a separate resource from surface water, each with its own separate system of water rights, even where there was really only one water system. This legal failure to recognize hydrologic realities often led to unnecessary externalities; a groundwater user, for example, could increase his pumping without considering the impact on reduced surface streams. While about two-thirds of the 18 western states have taken steps to integrate groundwater and surface-water rights in some watersheds, the other states, including both California and Texas, still treat groundwater and surface water as legally distinct at the state level. No state has comprehensively integrated its surface water and groundwater systems across all basins and watersheds.

Other forms of substantive fragmentation also afflict the West. Management of water quantity and water quality, for example, often devolves to different agencies, even though a decision to allow pollution is effectively a decision to allocate water for the dilution of waste. As described later, however, while states still maintain principal authority over water allocation decisions, Congress has federalized many issues of water quality through environmental statutes such as the Clean Water Act. Within states, moreover, "state engineers" or "water boards" typically decide how to allocate water quantities, while state environmental protection agencies enjoy authority over water quality. This quantity-quality managerial split often leads to tensions and even lawsuits. To see the problems that arise, imagine that a water supplier imports water from a distant watershed and, for transportation purposes, discharges the water into a local stream. Is this a purely water-quantity decision controlled by the state or, because the imported water might be of a different quality than water in the local stream, a water-quality decision to be managed by the federal Environmental Protection Agency? If it is both a water-quantity and water-quality decision, who decides on the appropriateness of the action?

Adherence to Temporal Priority

The American West is perhaps best known in the water field for its adoption and strong adherence to the prior appropriation doctrine. Prior appropriation governs both surface-water and groundwater in much of the West. Under the prior-appropriation system, water is allocated on a first-in-time, first-in-right basis. The first person to withdraw *X* units of flow from a river or stream enjoys a priority right to *X* units per year in the future. If someone later comes along and wishes to withdraw water from the same waterway, they must leave enough water to meet the needs of all earlier users. During a period of drought, water users are cut back in reverse order of priority. Junior users may lose all of their water during a drought, while seniors continue to draw their full entitlements. Western water thus privileges priority over all other potential considerations in water allocation.

Temporal priority also plays a major role in the allocation of water among states. The United States Supreme Court announced in one of its earliest interstate water disputes that, where a river runs through two or more prior-appropriation states, priority should be the "guiding principle" in deciding how to allocate the water among the states.[1] Although the Court has subsequently emphasized that priority is not the "sole criterion" and that allocations also should

[1] Nebraska v. Wyoming, 325 U.S. 589, 618 (1945).

reflect "additional factors relevant to a just apportionment, such as the conservation measures available to both states and the balance of harm and benefit that might result" from varying allocations,[2] priority remains the primary consideration. Because states negotiate compacts in the shadow of the Supreme Court's decisions, compacts also tend to reflect priority of use among states, although priority again is not the exclusive factor determining compact terms.

A few prominent and important exceptions exist to the West's general focus on priority. For example, federal Indian reservations and other forms of federal "reservations" such as national parks and forests enjoy "federal reserved water rights" that take precedence over any state water right that postdates the creation of the federal reservation, even if no one has ever used the right. As discussed below, California, Kansas, and Oklahoma all recognize riparian water rights that can take precedence over pre-existing prior-appropriative water uses. Such paper rights can displace prior appropriative rights at any time and thus undermine the security that prior appropriation is designed to provide to more senior water users. As a result, legislatures and courts often have tried, sometimes but not always successfully, to limit or restrict such rights.

Allocating water by temporal priority encouraged early development of water in the West, which was a goal of early institutions. Temporal allocation also provides strong security to senior water users, but only by imposing high risk on junior water users. During periods of drought, there is no reason to believe that temporal priority will lead to efficiency (senior users may or not place water to the most valuable use). Indeed, it is likely to be an inefficient rule. Assuming that the marginal value of water declines with volume, giving senior users all of their entitlement during droughts, while totally cutting off junior water users, will reduce the overall utility of water use. Although this would not be a problem if water rights could be marketed (because efficiency could be improved through trading), water marketing is difficult in the western United States, as described further below.

Heterogeneity

As earlier discussion has illustrated, heterogeneity is a significant characteristic of western water rights, raising administrative costs and undermining efficient water use.

[2] Colorado v. New Mexico, 459 U.S. 176 (1982).

Geography, of course, introduces heterogeneity from the outset. The value of a water right is site-specific, just as land rights and rights to oil and gas resources are. Precipitation is more variable in some regions than in others, and water rights in an area with relatively predictable precipitation are more valuable (all else equal).

The definitional characteristics of appropriative rights, however, make water rights even more heterogeneous. Prior-appropriative rights are defined by priority, amount of water, point of water diversion, place of use, type of use, and time of use. Under a typical appropriative right, a water user might hold the right to take (1) *X* units of flow, (2) from March 1 through September 15 of each year, (3) from a particular diversion point on the *Y* River, (4) for agricultural purposes, (5) on *Z* acres of specified land. In an effort to provide water users with relatively secure water rights (subject only to the vagaries of weather), moreover, no one can change the specifics of their water rights if the change might harm downstream water users, whether or not the downstream user is senior. If a water user wishes to change her point of diversion, use her water on different land or for different purposes, or switch her use to a different time of the year, the government will permit her to do so only if the change will not injure downstream water users. Each appropriative right, in short, is highly unique, making it more difficult for water users to change their uses – or market their water – in response to shifting conditions.

Adding to the heterogeneity of water rights, the western United States is home to a wide variety of different types of water rights, each with its own detailed rules. As already mentioned, federal reservations enjoy judicially-created federal reserved water rights. California, Kansas, and Oklahoma recognize riparian rights. Many California cities also enjoy "pueblo rights" (as did New Mexico cities until the New Mexico Supreme Court concluded earlier this century that pueblo rights are a legal fiction). And these are just the recognized forms of surface-water rights. Groundwater rights include appropriative rights (the most dominant part), "American reasonable-use rights," "absolute-ownership rights," and "overlying ownership rights." These different forms of water rights are often incompatible with each other, generating unnecessary confusion and lawsuits. Moreover, even where some forms of water rights (e.g., prior appropriative surface rights) are marketable, trading of water between categories is often difficult if not illegal.

Inflexibility

Water rights also are inflexible, although they are more flexible today than they were a century ago. Part of the reason is the heterogeneity just discussed. As explained, water rights are tightly defined by amount, diversion, and use, and a water user cannot generally change the way she is using her water right if that change would negatively impact any downstream water user. Proposals to change water rights often require lengthy and expensive factual proceedings to determine if there will be a downstream injury, and scientific uncertainty regarding the impact of any particular change can make it difficult to predict whether the state ultimately will approve the proposed change. As a result, the no-injury rule can deter water users from trying to change their water rights even if the change would be efficient. The deterrent effect is particularly strong for short-term water transfers or transfers of small volumes of water, where time delays or administrative costs can significantly undermine the value of the transaction or even make it impossible. Heterogeneity also can undermine water markets because of the difficulty of water-right changes (which are intrinsic to sales of rights separate from the land on which the water has been used) and because heterogeneity leads to more complex markets where assessing the value of any particular right can be difficult. As just mentioned, moreover, different types of water rights may not be legally or technically interchangeable.

Inflexibility in water rights, however, goes beyond the problem of heterogeneity. In the late 19th century, states throughout the West debated the wisdom of treating water as a commodity. Ultimately, a majority of the states decided that water should not be marketable. Elwood Mead, an engineer who had significant influence over the development of appropriative law in the 19th and early 20th centuries, provided a fairly typical perspective of the time:

> The doctrine that air, water, and sunshine are gifts from God should not be lightly set aside even in arid lands. …. The growth and danger of monopolies in oil, copper, coal, and iron afford a warning of the greater danger of permitting monopolies in water. ….
>
> In monarchies, streams belong to the crown, and in the early history of irrigation in Italy and other parts of Europe, favorites of the rules were rewarded with grants of streams. But in a republic they belong to the people, and ought forever to be kept as public property for the benefit of all who use them, and for them alone, such use to be under public supervision and control.[3]

[3] Elwood Mead, irrigation Institutions 365-66 (1903)

At one or another time, nine of the western states prohibited or severely restricted the ability of an appropriator to sever his water rights from his land and sell or transfer them to someone else.

Today, all western states permit water markets to one degree or another. Yet various rules and restrictions still undercut water transfers, and many water officials remain skeptical of water markets for the same reasons that led to the original market prohibition. As noted above, an appropriator cannot market her water in a way that would materially impact downstream water users. In most states, appropriators also cannot transfer water if it would unreasonably injure the environment. As just noted, state procedures for evaluating such externalities are often unduly complex, length, and costly, deterring even efficient transfers. In theory, however, such non-injury rules protect against economically inefficient water transfers by ensuring that transfers take into account “technological” or “real” externalities to other users or the environment. In short, there is a legitimate economic rationale for evaluating such externalities, even if the process of doing so is suboptimal.

Unfortunately, other restrictions do not address technological externalities and have no basis in economic efficiency. For example, various western states prohibit water transfers that would export water out of a local region or have a deleterious impact on the local community’s economy; other states prohibit transfers unless the seller can no longer make an economic use of the water. Such restrictions address pecuniary concerns rather than technological externalities and threaten efficient transfers. Other western states prohibit water transfers if the transfer would lead to an increase in consumptive use, even if the increase in consumption would not injured downstream juniors. Finally, a growing number of states prohibit market transfers that a state agency or court finds to be against the public interest, providing courts with a roving license to strike down transfers that they do not like. Using such a standard, for example, a New Mexico judge prohibited a transfer of water from agriculture to a resort complex because, according to the court, the transfer would destroy the “local culture” and create only a few, menial jobs for local residents.[4] The consequence of such restrictions is a far more inflexible water system.

Other forms of state water rights are not transferable at all. For example, riparian rights attach to riparian lands and cannot generally be transferred to other water users. Similarly, pueblo rights belong to those cities that qualify as former pueblos and again cannot be

[4] In the Matter of Howard Sleeper, No. RA 84-53 (c) (Dist. Ct. of N.M., 1st Jud. Dist., 1985).

transferred to other water users. Some forms of groundwater rights, such as rights under the American Rule of Reasonable Use, also cannot be transferred.

Interstate water allocations are perhaps even less flexible today than state water rights. Most interstate water compacts provide for relatively fixed water allocations among the signatory states and generally do not provide an opportunity for reallocations in the light of changing conditions, such as climate, economic, or demographic shifts. Indeed, the political debate that generally attends the adoption of interstate compacts often deters states from entering into compacts under which their rights may change over time. No compact, moreover, provides for interstate water markets.

The Supreme Court also has suggested that states may enjoy some authority to restrict their residents from selling or otherwise transferring water to out-of-state users. Under the commerce provisions of the United States Constitution, states normally cannot impede interstate commerce. In *Sporhase v. Nebraska ex rel. Douglas,*[5] however, the Supreme Court indicated that water transfers do not fall squarely within this doctrine. Water, according to the Court, is an article of commerce. But state claims of ownership over water resources and the Court's practice of dividing water among states are not "irrelevant" to the legitimacy of state efforts to limit interstate water markets. Where such limitations address a "legitimate local public interest" and do not impose an unnecessary burden on interstate commerce, the Supreme Court suggested that the limits might be constitutional. Several more recent decisions have upheld state prohibitions or restrictions on particular types of interstate water transfers.

Ineffective & Incomplete Regulation

Because western states historically could not depend on market incentives to encourage efficient uses and discourage waste, the prior appropriative system adopted regulatory policies against waste. Under the prior appropriation system, for example, water must be put to a "reasonable and beneficial" use. No one technically has a right to "waste" water, and if a court finds that someone is wasting water, the court can strip the appropriator of the wasted water; the water then becomes available for someone else to appropriate. Similarly, no one can gain a right to appropriate water unless they can show that they have a clear use for the water; purely

[5] 458 U.S. 941 (1982).

speculative appropriations of water are illegal. Finally, anyone who ceases to use water also loses her right to that water, which again becomes available for someone else to appropriate. In theory, none of these rules would be necessary with robust water markets because markets would help ensure that water, even if initially acquired for speculative purposes, would be used efficiently or sold to a more efficient use. The lack of effective markets, in short, creates a need for effective regulation.

Such regulation, however, has never been particularly effective. Part of the problem is practical. It is difficult for regulators, whether courts or administrative agencies, to evaluate and police the water practice of thousands of individual irrigators and other water users. Part of the problem is also political. Courts and administrative agencies have not proven eager to limit water uses because of potential waste. In many cases, practices are not initially "wasteful" because there are few other demands for the water; as local demand increases, the same practices may look increasingly wasteful. If a water user has been engaged in a particular water practice for decades, however, courts and administrators are particularly loathe to tell them that they must now expend money to reduce their waste or instead lose their water right.

Regulatory rules, moreover, can conflict with and undermine water markets, making it difficult to move toward a market system once regulation is in place. For example, if a senior appropriator proposes to conserve 20 percent of his water and sell it to a distant city, junior appropriators who are not be receiving their full entitlement to water may complain that the senior appropriator's ability to conserve and sell water is proof that the senior appropriator is wasting water, in which case the senior appropriator should lose his right to the wasted water and the wasted water should become available to the junior appropriators free of charge. Such potential conflicts have discouraged many water users from trying to market their water, fearful that the proposed water transfers may result in loss of part or all of the original appropriative rights. Thus rules designed to avoid waste instead end up undermining efficient water use by undermining markets.

The regulatory portion of western water institutions also historically ignored environmental externalities and common-pool problems. The emphasis of water institutions through the first half of the 20th century was to promote water withdrawals and use and thereby increase economic development. Because water in many areas was still under-exploited, this was not necessarily a social misjudgment. Most native species of fish and wildlife still appeared to be relatively healthy, and groundwater withdrawals were not yet exceeding recharge in most regions. As a result, environmental protection was either weak or non-existent in many regions, and groundwater law in most states did not flatly bar groundwater overdrafting.

OVERCOMING INSTITUTIONAL WEAKNESSES

The institutional weaknesses described above make it difficult for western water users and managers to adapt to new demands and challenges. Rather than acquiring needed water from willing sellers, new and expanding water users must stand in the back of the priority queue. Groundwater overdrafting goes on unabated. Climate change imposes disproportionate risk on the relatively arbitrary class of junior water users.

The remainder of this paper describes the various approaches that water managers, users, and stakeholders use to overcome the weaknesses in existing water institutions. As noted earlier, two approaches involve efforts to change the institutions themselves – either by lobbying legislatures to enact the changes, or by suing to force change. Successful examples exist of both, yet legislative and judicial change in the West has been surprisingly slow, spotty, and expensive. As a result, many water managers and users have taken the quite different approach of finding ways of dealing with the weaknesses without changing the underlying institutions themselves. Some users and managers, for example, have found interstitial pockets of flexibility that are sufficient to meet their basic needs within the framework of existing institutions. Other water users have turned to private and local mechanisms for reordering water rights and rules, including contractual agreements, negotiated judicial settlement agreements, and the powers of local water districts. Finally, some water managers have created new institutional overlays that address particular weaknesses without eliminating the underlying weaknesses.

Direct Legislative Change

Western legislatures are constantly changing western water institutions, and many of the changes in the last several decades have significantly reduced weaknesses identified earlier. Most western states, for example, have taken steps to remove unnecessary barriers to water markets and to reduce the length and complexity of change review processes. While market-proponents have argued that even greater reform is necessary, the legislative changes have increased the number of market transactions in areas with rapidly changing water demands. Most legislatures similarly have opened up opportunities for environmental market transactions, in which water users sell, lease, or donate their water rights to governmental agencies or private "water trusts" for dedication to instream purposes. A growing number of legislatures also have directly restricted groundwater overdrafting, at least in critically overdrafted basins within their states.

Not surprisingly, this change generally has been slow. Political reform is costly, so reform efforts are unlikely to begin until the value of the reform is greater than the costs that a water user or stakeholder must incur in order to achieve the reform. Because political action is uncertain, most water users or stakeholders will look for a significant premium on the costs of reform efforts before launching into political battle. Where the benefits of reform are widely spread among water users, collective action problems can also undermine the likelihood that water users as a group will form an effective coalition to seek change. Once effective reform efforts begin, moreover, reform is not instantaneous. Most reform efforts take years to succeed even when backed by adequate resources.

Not surprisingly, many legislative reforms have taken place in response to large and highly concentrated opportunities for economic gain. For example, the most significant reform in California water marketing law occurred in the early 1990s when the differential between the annual cost of water in the Imperial Irrigation District of California and San Diego grew to over $300 per acre foot. After agreeing to a long-term transfer of 200,000 acre-feet, the two entities began to lobby for necessary legislative authority and protection. The consequent changes to California water law not only enable the transfer to move forward but also helped reduce barriers to water transfers more generally. In short, once the arbitrage opportunity great large enough, long-lasting reform occurred.

Groundwater reform also illustrates the relationship between the likelihood of water reform and the value of that reform. As William Blomquist has shown, states almost inevitably regulate groundwater overdrafting once the cost of that overdrafting has grown to be sufficiently prominent.[6] Before that point, however, legislative groundwater reform can be exceptionally

[6] See William Blomquist, Exploring State Differences in Groundwater Policy Analysis, 1980-1989, Publius, Spring 1991, at 101.

difficult. Parts of California, particularly its San Joaquin Valley, suffer from tremendous overdrafting, but the cost of that overdrafting is not visible and, except for increased energy costs, not very high relevant to other farm inputs. As a result, efforts five years ago merely to monitor groundwater extraction lost in the California legislature. The most that proponents of groundwater management were able to achieve was a new law requiring local jurisdictions to monitor overall groundwater levels.

Reform efforts, in short, are likely to significantly lag the date when institutions are no longer economically efficient. This delay in effective reform efforts, in turn, can further increase the opposition to and thus cost of reform. Consider again the example of groundwater. Legal prohibitions on groundwater overdrafting can often lag the beginning of overdrafting by decades. During that period of time, local groundwater users become reliant on the groundwater and make investments based on its availability. By the time that real reform efforts begin, groundwater users are likely to put fight reform efforts far more vigorously than they would have at the time groundwater overdrafting began. The delay thus increases the cost of reform and, consequently, the level of gain that reform proponents must enjoy before they will mount an effective reform effort. Delay, in short, is likely to beget further delay.

Psychological factors can further undermine the opportunity for effective water reform. As I have explored in an earlier article,[7] for example, groundwater users are unlikely to recognize the need for reform until the condition of their groundwater aquifer is in close to crisis stage. Arguments for groundwater reform are generally expressed in a “loss framework”: groundwater users should reduce their water use today (at a cost to their operations) in order to avoid a greater catastrophe in the future. Loss frameworks, however, tend to generate risky behavior. Groundwater users are willing to risk a future catastrophe rather than reduce their groundwater extractions today. They also are likely to deep discount the future and assume (not without some evidence) that the government ultimately will bail them out. Even if they recognize the importance of reform, groundwater users also are likely to suffer from “self-enhancing attributional biases” and assume that the cause of any groundwater problem is the pumping of other groundwater users. Where a state has not previously created clear groundwater entitlements, moreover, groundwater users are likely to view any proposal to create and allocate entitlements today, which is a necessary prerequisite to groundwater regulation, as

[7] Barton H. Thompson, Jr., Tragically Difficult: The Obstacles to Governing the Commons, 30 Envtl. L. 241 (2000).

distributionally unfair.[8] While the particular psychology pathologies will differ from situation to situation, pathologies of various kinds frequently undercut rational reform.

Reform efforts also do not necessarily lead to an institutional change that is societally rather than individually beneficial. When large water users conclude that it is worth investing in reform, they may seek changes that directly benefit them alone (or that benefit a subgroup of users of which they belong) rather than more general reforms. Consider an industrial water user who is finding it difficult to obtain additional needed water. Although new water marketing legislation might allow the industrial water user to acquire the water, new legislation creating a preference for industrial water use might both better meet the user's needs and be easier to pass. An industrial water preference might provide additional water at no cost to the company. And fewer vested users may oppose a narrowly written preference. Alternatively, the industrial water user might seek legislation authorizing only its own transfer or a limited subset of similar transfers, rather than reforming water marketing institutions throughout the state. Narrow, tailored changes, in short, may be more likely to result from reform efforts than are broad, fundamental reforms.

Judicial Reform

Where legislative reform appears difficult, proponents of change may seek judicial help. The judiciary can play at least three different roles. First, courts sometimes can directly modify water institutions. For example, courts can reinterpret legislation or other legal documents in a fashion that overcomes an institutional weakness. In the last two decades, the United States Supreme Court has interpreted a handful of interstate compacts to integrate groundwater and surface water, even though the language of the compacts references only surface water.[9] Rather than getting legislatures to renegotiate the compacts, proponents of greater integration were able to achieve the same result through the courts. In a different approach, the California Supreme

[8] Thus, in Texas, landowners overlying an aquifer who did receive any rights when groundwater entitlements were created and distributed successfully challenged the effort in the Texas Supreme Court on the ground that they should have been entitled to some share of the groundwater despite never having used it in the past. See Edwards Aquifer Authority v. Day, 2012 WL 592729 (Tex. 2012).
[9] See, e.g., Kansas v. Colorado, 514 U.S. 673 (1995).

Court imposed greater environmental oversight on surface water withdrawals by concluding in 1983 that the common-law “public trust” doctrine requires such oversight.[10]

Second, courts can force the legislature to reform a water institution by holding the institution invalid without reform. In the 1990s, for example, a federal district court in Texas held that Texas’ failure to control groundwater withdrawals from the Edwards Aquifer threatened a number of species who were reliant on spring flow from the aquifer and therefore violated the federal Endangered Species Act.[11] As a consequence, the Texas legislature adopted the Edward Aquifer Act, which provided for a multi-step reduction in groundwater withdrawals, in conjunction with a market in the groundwater rights. Although the court did not directly impose the reform, it catalyzed change by invalidating the existing institution.

Finally and similarly, judicial challenges can sometimes create an atmosphere of uncertainty or crisis that provides a window for effective legislative reform. A major controversy in the late 1970s was the pricing of water under the Federal Reclamation program, which was heavily subsidized and thus undermined agricultural incentives to conserve. Legislative reform initially seemed unlikely. Several lawsuits, however, brought into legal question the Reclamation Bureau’s practice of supplying subsidized water to farmers with more than 160 acres of land. Under threat of losing water entirely, large farmers became open to legislative compromises that would trade higher reclamation prices for a higher acreage limitation.

Despite the role that courts can play, judicially-inspired reform again presents only a limited opportunity for addressing the weaknesses of traditional water institutions in the West. Effective judicial action requires an effective judicial hook – an ambiguous compact or statute, an underutilized common-law doctrine, or a substantive federal restriction on state action like the Endangered Species Act. In most situations, however, no such hook exists. Courts, moreover, are often reticent to act. Water law is generally an arcane field, and courts often do not have the confidence to wade too deeply into the water field and take too bold of an action. Judicial action also is neither quick nor cheap. In many cases, judicial action will provide no advantage in either time or cost over direct legislative reform efforts.

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[10] National Audubon Society v. Superior Court, 658 P.2d 709 (Cal. 1983).

[11] For a detailed summary of the litigation, see Todd H. Votteler, Raiders of the Lost Aquifer? Or, the Beginning of the End to Fifty years of Conflict Over the Texas Edwards Aquifer, 15 Tulane Envtl. L.J. 257 (2002); Todd H. Votteler, The Little Fish that Roared: The Endangered Species Act, Groundwater Law, and Private Property Rights Collide, 28 Envtl. L. 845 (1998).

Courts, moreover, often do not have the institutional authority, capacity, or resources to achieve effective reform of water institutions. Consider the earlier examples of judicial intervention. Two of the examples were clearly successful. The Supreme Court's integration of groundwater and surface water in interstate compacts has been successful, largely because the Supreme Court has directly overseen and enforced its decrees. And the courts' creation of a crisis under the Federal Reclamation Act was largely successful because all parties sought Congressional reform. The other two examples are far more mixed. Although the California Supreme Court extended the public-trust to water withdrawals three decades ago, California courts have resisted becoming deeply involved in the implementation of the public trust doctrine, deferring instead to expert state agencies. As a result, the doctrine has not assumed the importance that many predicted. Once the Texas legislature passed the Edwards Aquifer Act, federal courts pulled back from the controversy, again preferring to let other branches take the lead; almost two decades after its passage, the Act remains mired in controversy and is still not fully implemented.

Exploiting Pockets of Flexibility

Because of the costs and limitations of both direct legislative and judicial reform, most water users and managers are forced to learn to live with traditional water institutions. However, this does not mean that they are without any recourse, particularly in the search for greater flexibility. First, given the breadth and complexity of water institutions, there often are pockets of flexibility that water users can exploit. These pockets allow water users to meet expanding demands or changing conditions without seeking fundamental changes to the water institutions themselves.

Efforts by energy companies to obtain additional water for fracking, oil share, and other purposes provide a good example of this strategy. Energy companies have turned to several approaches to obtain needed water. First, as noted earlier, an increasing number of states have adopted rudimentary water markets, allowing energy companies to purchase or lease some of the needed water through wholesale markets (including markets for effluent from cities). Such markets, however, often suffer from the weaknesses described earlier.

Second, western cities often have available water that they can sell far more easily and without the process restrictions of traditional water markets. On the ground that cities often need to obtain reliable sources of water before they can grow, most western states adopted a “growing cities” doctrine at an early stage that allows cities to obtain water rights before they actually need them. Cities, in short, can engage in speculation that other water users cannot. This speculation, however, often means that cities have unneeded “surplus” water that they are willing to sell, at least on a temporary basis, until they need the water later. Cities, in other words, fulfill the role that private speculators might otherwise play by acquiring water before it is needed and then selling it at a profit to entities that have new needs. Because cities have not been using the water, moreover, the no-injury rule discussed earlier does not come into play.

Finally, energy companies often have taken advantage of a seemingly minor exception to the West’s general adherence to temporary minority. Because it can take time to complete an irrigation canal and put water to use, an appropriator’s priority date is when the appropriator first filed for an appropriation permit if the appropriator has diligently acted to start using the water after filing for an appropriation. The appropriator enjoys a “conditional water right” from the time that she first files, and the ultimate appropriation right “relates back” to the original filing if the water has been put to use with due diligence. Using this doctrine, many energy companies have established conditional water rights dating back to the 1950s and the 1960s. The energy companies argue that they are not violating the due-diligence requirement, even if they have never used the water, if economic conditions have not made energy production economically feasible. Energy companies thus avoid the “use it or lose it” rule otherwise central to the prior appropriation doctrine.

Local Reordering

In a display of institutional innovation, water users often have turned to private or local mechanisms to “reorder” water rights and reduce the inefficiencies of state or federal water institutions. Some surface water users, for example, have turned to private contracts to overcome inefficiencies associated with strict temporal priority and heterogeneity. Where disputes over local water priorities have arisen, the parties have agreed by contract to treat all the water rights as equal priorities, sharing proportionately in any drought-related reductions in overall water supplies. Because proportional reductions are likely to have less economic impact than reductions that require some users to give up all of their water rights while others enjoy their full rights, such contracts increase overall efficiency. They also increase the homogeneity of the water rights and the ability of local users to transfer water entitlements among themselves.

Judicial decrees sometimes can serve the same function as contracts, but with the added benefit of direct judicial enforcement. Beginning in the early 1950s in Southern California, increasing overdrafts and resulting salt-water intrusion threatened the viability of many coastal aquifers. In response, the groundwater users negotiated agreements limiting overall withdrawals to a sustainable mount, allocating that supply among the existing users, and providing for market transfers of the entitlements among users. The groundwater users then embodied the agreements in judicial decrees and asked local courts to enter and enforce them. Faced by state water institutions that were not capable of managing groundwater, the groundwater users in effect "reordered" their local groundwater rights and embodied them for enforcement purposes in judicial decrees.

Farmers also sometimes use local water districts to reorder their water rights. Farmers frequently control the policies of local water districts, allowing them to use the districts to establish managerial systems that are more efficient than those provided by state law. For example, most local water districts provide for proportionate sharing of water during droughts – thereby increasing the overall utility of the water rights during periods of water shortages for the reasons discussed earlier. Many local water districts, moreover, have developed effective and robust internal water markets under which farmers can buy and sell water rights among themselves as their needs change and with minimal if any oversight. Some districts in California have established websites or marketing programs to link willing sellers and buyers and experience thousands of transfers each year.[12]

Local reordering of water institutions through private mechanisms or local quasi-governmental organizations is not a panacea. Options for local reordering are not always available and can be more expensive than the prospective increase in efficiency. Even when local reordering can improve local efficiency, it can lower efficiency at a larger societal scale. Consider again efforts to develop local water markets through local water districts. Although

[12] For a more detailed exploration of the use of local water districts as a mechanism for local reordering, see Barton H. Thompson, Jr., Institutional Perspectives on Water Policy and Markets, 81 Calif. L. Rev. 671 (1993).

local districts often permit and actively promote internal water marketing, they often prohibit or restrict marketing of water to users outside the district. While internal markets benefit the local users who control a district, external sales can hurt them by increasing demand for internal supplies and thus raising the price for the water held within the district. Local users therefore frequently oppose external water transfers, placing an additional and frequently insurmountable hurdle in the way of efficient water transactions involving outside purchasers. Local reordering, in short, can increase efficiency for the water users responsible for the reordering, but at a cost to broader efficiency when not in the interest of the controlling water users.

Institutional Overlays

Finally, water managers can sometimes try to overcome one or more weaknesses in traditional water institutions by creating an institutional overlay that addresses the weaknesses. Three examples illustrate the concept. First is the California emergency drought water bank of 1991. The State of California was hit by a major drought in the early 1990s that created concern that major industries, such as chip manufacturers, would not be able to obtain adequate water. While water markets existed, they suffered from the problems of fragmentation, heterogeneity, and inflexibility discussed earlier. In response, the State in 1991 created a drought water bank that purchased water from willing buyers for a fixed statewide price and then sold water to interested purchasers for a slightly higher price. The 1991 emergency drought water bank was highly successful because (1) it treated all transactions the same, (2) it was able to eliminate many of the state processes and restrictions, and (3) it was run by the state and thus increased buyers' and sellers' confidence that transactions would not run into legal difficulties. In short, it homogenized water rights, created one market system with clear rules, and avoided unnecessary red tape. Ultimately, over 800,000 acre feet were traded through the bank during the course of 1991. Because of the success of this first water bank, the state created similar water banks in later water-short years (although none of the banks was as successful, in part because the state fell victim to the temptation to add more and more rules to the banks' operation).

A second example is watershed planning. Because of the problems of geographic fragmentation, many states and local water groups have formed watershed planning groups to bring together the water organizations and stakeholders in a watershed for watershed-wide planning and actions. California has gone a step further and authorized Integrated Regional Water Management (IRWM) (its own homegrown variant of Integrated Water Resource Management or IWRM). One of the most successful examples of IRWM is the Santa Ana Watershed Project Authority and its development of a "One Water One Watershed Plan." The Project Authority and Plan effectively integrated over 100 agencies in three different counties. In the eyes of the Project Authority, the plan is a "living" document that permits ongoing coordination among the myriad of local, regional, and statewide organizations working in the Sana Ana watershed.[13]

A final example is privatization of public water utilities. Privatization is a response at least in part to geographic fragmentation of water supply systems in the West (and elsewhere in the United States). One way of reducing the inefficiencies of geographic fragmentation without merging different public water suppliers together is to have a private company run a number of the local, preferably neighboring supply systems. Once common private management is in place, the private company can look for opportunities to increase efficiency by providing for coordinated and joint operations.[14]

Like the other approaches that water managers, users, and stakeholders can take to overcoming the weaknesses of traditional water institutions without directly reforming the institutions themselves, overlays are limited in applicability and effectiveness. So long as underlying institutions remain the same, they are likely to push back against and erode the overlays. Watershed groups and IRWM are illustrative. Studies have shown that watershed groups have had only limited impact in reducing fragmentation and encouraging greater coordination. Similarly, initial studies suggest that most efforts at IRWM in California have not increased long-term coordination, and many suspect that water agencies participate in IRWM only because of the promise of potential funding for projects approved as part of IRWM processes.

[13] For more on IRWM and watershed planning efforts generally in the western United States, see Barton H. Thompson, Jr., Beyond Connections: Pursuing Multidimensional Conjunctive Management, 47 Idaho L. Rev. 273 (2011).

[14] See Barton H. Thompson, Jr., Privatization of Municipal Water Supplies, Looking Ahead, May/June 1999, at 1.

FINAL THOUGHTS

As explained, the most common approaches to addressing the weaknesses of western water institutions are "work-arounds" – finding interstitial pockets of flexibility, engaging in localized reordering, and adding institutional overlays. All have limited scope, and all suffer from problems of their own. An additional concern is the possibility that work-arounds, by reducing the cost of existing institutional weaknesses, actually postpone and undermine opportunities for more fundamental reform. Water users who are able to get their water through local water-district markets or through temporary state water banks are less likely to fight for more comprehensive changes in state water institutions that will open up broad water markets. As a result, there is no comprehensive reform, and more people have to resort to work-arounds in order to meet changing needs or conditions. In theory, the result could well be a greater long-term level of inefficiency than if work-arounds were not available.

In the end, the only answer to existing weaknesses is fundamental legislative or judicial reform. As explained earlier, such reform is likely to occur once the cost of the weaknesses outweighs the cost of reform (taking into account the risk of political failure). We are not likely to go over the edge (although it is not out of the question); we're just likely to wait until the very edge to correct our direction. As a result, reform is likely to continue to take place late, leading to significant inefficiencies in the meantime and frequently costing more politically to achieve than if we could foresee and address needed reforms more quickly. At least, that is what the history of western water institutions and reform efforts suggests.

Water and Electricity: Living at the Energy-Water Nexus

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May 5, 2013

1. Introduction

Over a decade ago, the Electric Power Research Institute (EPRI) identified water availability constraints as a major issue facing current operations and future development of the electric power sector in the United States and internationally and initiated research to assess and reduce both current and future vulnerabilities to water shortages. Since then, the U.S. Congress; government agencies at national, regional, state, and local levels; environmental nongovernmental organizations; professional technical societies; universities; research organizations; and water users across all economic and social sectors have initiated discussions and studies of the energy/water nexus.

This white paper is taken directly from a recent EPRI publication[1] providing an updated scoping assessment of current and future water withdrawal requirements, compared with water availability, resolved at the level of counties across the contiguous United States. The white paper also includes a previously-published[2] detailed discussion of the potential options for water use reduction by the power sector, specifically focusing on reducing the water needs associated with thermal cooling of electricity generation units.

2. Status of Water Use in 2005

In this section we present graphs and maps providing a summary status of the nature of water withdrawals by different sectors of the U.S. economy in 2005. The water use data that are the foundation of this study are collected every 5 years by the US Geological Survey (USGS) as part of the National Water Use Information Program. These surveys were first conducted in 1950, and the most recent survey that is available is for 2005 (Kenny et al., 2009). This data gathering effort obtains information on surface water and groundwater withdrawals, and identifies use by six major categories: public and domestic water supply, industrial, mining, agricultural, and thermoelectric cooling (including fossil-fuel and nuclear power generation). In the terminology of the USGS, these are termed "offstream" uses, as opposed to "instream" uses for hydroelectric

[1] Specifically, Sections 2 and 3 of this white paper are selected text from Chapters 2 and 3 of *Water Use for Electricity Generation and Other Sectors: Recent Changes (1985-2005) and Future Projections (2005-2030). EPRI, Palo Alto, CA: 2011. 1023676.*

[2] Specifically, Sections 4 and 5 of this white paper are selected text from the EPRI article *Water Conservation Options for Power Generation Facilities, Power Generation Magazine, September 2012 (K. Zammit, author).*

power generation. Instream uses for non-human, environmental purposes, such as minimum flow requirements for aquatic organisms are not cataloged by the USGS as part of the water use survey. Saline water withdrawals, primarily seawater withdrawals for coastal electric plants, are reported by the water use survey, but are not a focus of this work. Water use data from the USGS were supplemented by other data on climate from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) (methods in Huang et al.,1996), on population from the US Census Bureau, on electricity generation from the Energy Information Administration, and on agricultural activity and land use from the US Department of Agriculture. All national scale maps in this report are presented with data resolved to the county level. This was the highest resolution of all the publicly available national-scale data sets.

On a national aggregate basis, Figure 2-1 shows the distribution of offstream withdrawal of freshwater for each of the six major categories described above (total 349 billion gallons per day or bgd across 50 states, or 346.8 bgd in the contiguous 48 states). Agricultural and thermoelectric cooling water withdrawals are the dominant components of the total freshwater withdrawal nationwide (36% and 40%, respectively).

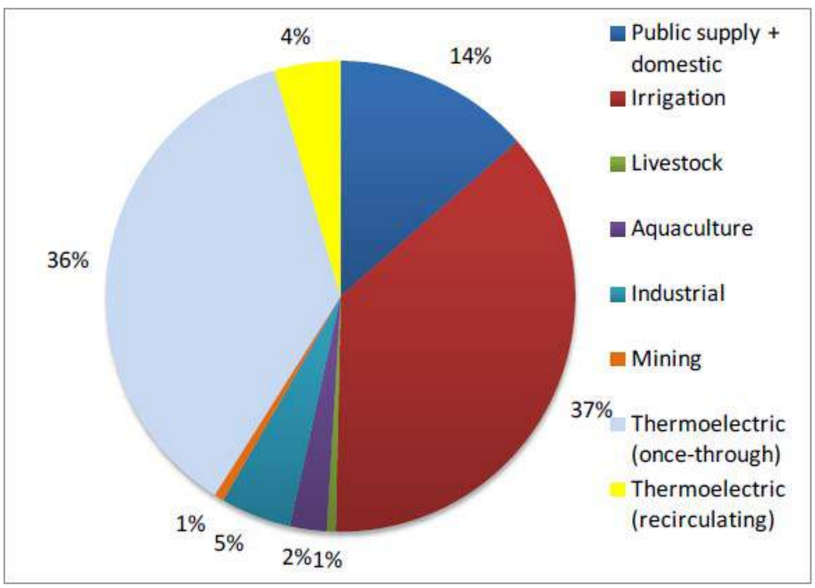

Figure 2-1
Offstream freshwater withdrawal (from surface water and groundwater) by major sectors of the economy. The total freshwater withdrawal is 349 billion gallons per day across all 50 states in the US. The numbers underlying this chart exclude saline water withdrawals, primarily by coastal thermoelectric power plants.

Although thermoelectric cooling use is a major fraction of the withdrawal, most of this use is not consumptive, i.e., a large fraction of the withdrawn water is returned to the water body after use.

Of the 40% withdrawn for thermoelectric cooling, 36% is for once-through cooling systems, and 4% is for recirculating cooling systems.[3] In a previous survey for 1995 (USGS, 1998) irrigation was the most significant consumptive user of water (82%), with thermoelectric cooling was a relatively modest fraction of total consumptive use (3%). The 2005 survey did not separate out consumptive versus non-consumptive uses of water. This analysis is focused on withdrawals, given the understanding that this quantity of water needs to be available for current uses to be met. It is important to note that withdrawals may be constrained by water quality-related as well as water-quantity issues as supplies become smaller in proportion to withdrawals. Thus, if a power plant withdraws a large amount of water from a stream and returns most of this after heat exchange, the withdrawal may be limited by thermal impacts, even though the absolute quantity of the water needed to meet withdrawal demand is present.

National aggregate trends in freshwater use from 1950–2005 (Figure 2-2) show that even as total population has grown steadily, total freshwater withdrawals have remained essentially unchanged since the mid-1980s. This figure is a concise summary of the sweeping changes in the water sector that have occurred in the last two to three decades, with a shift away from new withdrawals, to increasing efficiency of water use, reallocation of water use among sectors, and use of alternate, non-potable water sources to meet some needs. Basically, the U.S. economy has done more with the same amount of water.

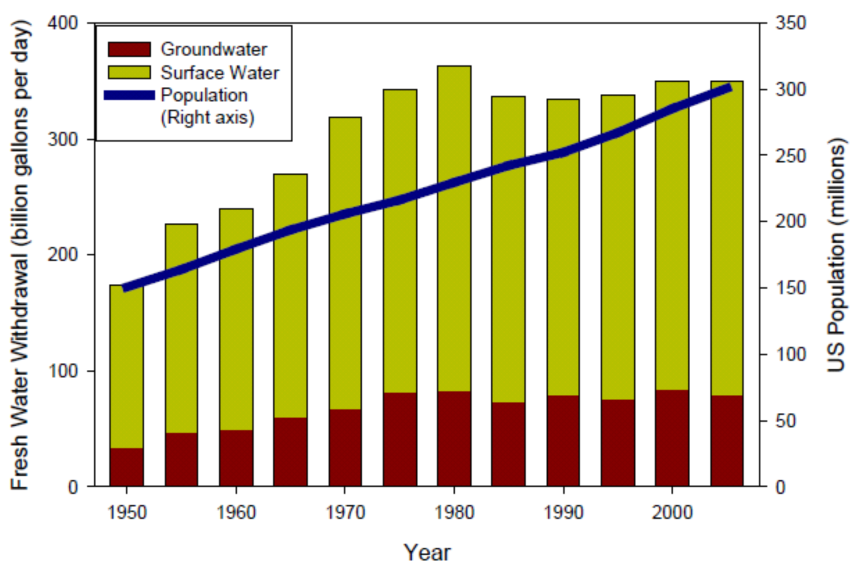

Figure 2-2
Trends in freshwater (surface and ground) withdrawals from 1950–2005 (left axis), compared to total US population (right axis).

[3] In once through cooling systems, water is withdrawn from a stream, reservoir, or lake, and returned to the source water body after a single cycle of heat exchange. In recirculating cooling systems, water is used over multiple cycles of heat exchange, with a large fraction of the withdrawn water lost to evaporation in cooling towers.

At a regional level, precipitation as rain or snow is the main source of renewable water. Some of the precipitation is lost to the atmosphere by evaporation or through transpiration by plants (these two processes are usually lumped together and termed evapotranspiration, ET). The remainder percolates into the ground and is stored as groundwater or moves as runoff into surface water bodies. For the purpose of this discussion we consider that precipitation that is not lost as ET (henceforth termed available precipitation) can be used for other purposes, and is an approximate measure of available renewable water supply in a region. Note that other somewhat more complex representations of renewable water supply may be envisioned (Weiskel et al., 2007), but the particular choice in this analysis was driven by data availability and by simplicity.

Precipitation and ET data averaged from 1934 to 2005 for the 344 climate divisions covering the contiguous United States were used to calculate the available precipitation, in inches per year (shown in Figure 2-3), based on data developed using the methods of Huang et al. (1996). This map shows data at the county level that was estimated from the climate divisions. The location of the centroid of the counties was used to assign counties to a climate division. Data are presented at the county level in Figure 2-3 to be consistent with other maps that follow. Much of the Western US, except for some coastal areas, has far lower water availability than the Eastern US. In the Eastern US, the water availability is lower in regions with higher ET, such as South Florida.

Figure 2-4 shows the total withdrawal of freshwater for all uses from surface water and groundwater sources in 2005. The withdrawals are expressed in units of inches per year to allow for comparison across counties of differing sizes, and also provide a basis for comparison with available precipitation. Areas with significant total freshwater withdrawal are scattered throughout the country with regions of elevated values in California, Florida, Arkansas, Missouri, in the Great Lakes region, eastern Washington, Idaho, and eastern Texas and Louisiana.

The three largest components of water withdrawal are for agriculture, thermoelectric cooling, and municipal demand. Withdrawal data for these uses are shown in Figure 2-5. In general, areas of high agricultural withdrawal are in the western US, whereas areas with high thermoelectric cooling withdrawal are in the Eastern US, especially near the Great Lakes and the major rivers in the Mississippi-Missouri River Basin. The distribution of agricultural withdrawal is more widely distributed than for thermoelectric withdrawal.

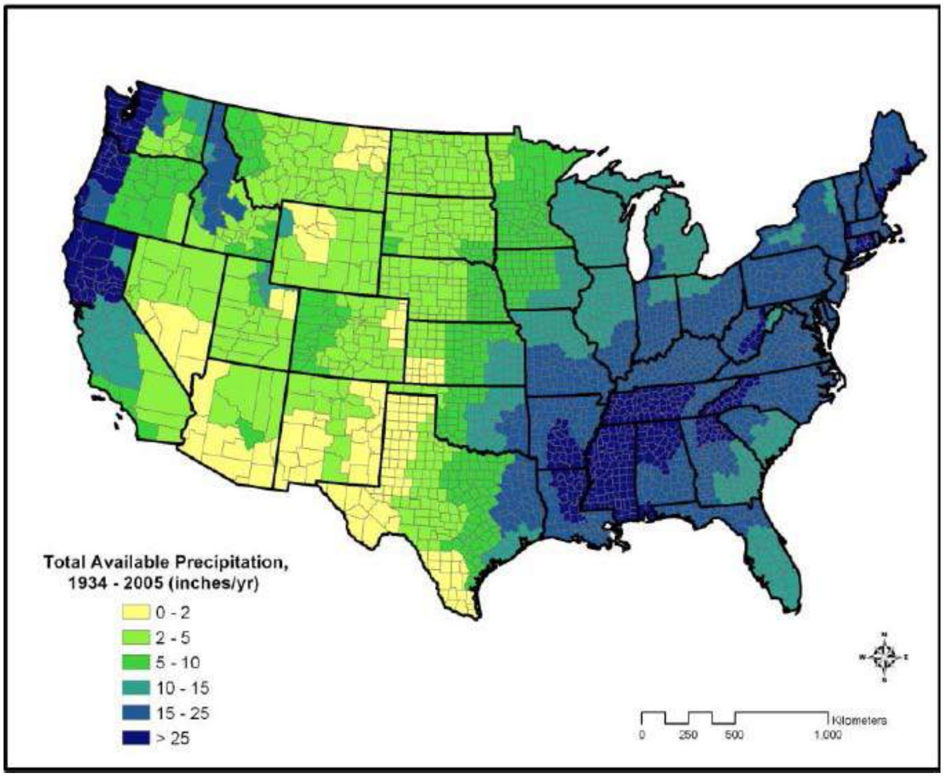

Figure 2-3
Available precipitation in the US estimated as monthly precipitation minus evapotranspiration (ET) for months where precipitation exceeds ET. Based on data averaged for 1934–2005.

As expected from the irrigation withdrawal map (Figure 2-5 top), the intensity of application is far greater in the Western states. Irrigation water is also applied in the Eastern states, although over smaller areas, and at a much lower intensity. Although agricultural production in the West is almost entirely dependent upon irrigation, it is important to note a major fraction of US agricultural production (slightly over 50% in dollar terms based on the 2007 US Agricultural Census) occurs in non-Western states, and is primarily rain fed. Figure 2-6 shows the relative percent of irrigation methodology employed across different states through pie-charts (whether flood, micro-irrigation, or sprinkler).

In general, micro-irrigation, which involves direct supply of water to plants, is the most water efficient, and flood irrigation, where entire fields are flooded, is the least efficient. Sprinkler irrigation falls somewhere in between flood and micro-irrigation. Although the magnitude of irrigation withdrawals in the Eastern US are small because of sufficient rainfall, the most common form of irrigation is sprinkler irrigation followed by micro-irrigation. In the western US, especially in the Southwest, where water is generally less abundant, flood irrigation nonetheless remains commonplace, and is used as widely as sprinkler irrigation.

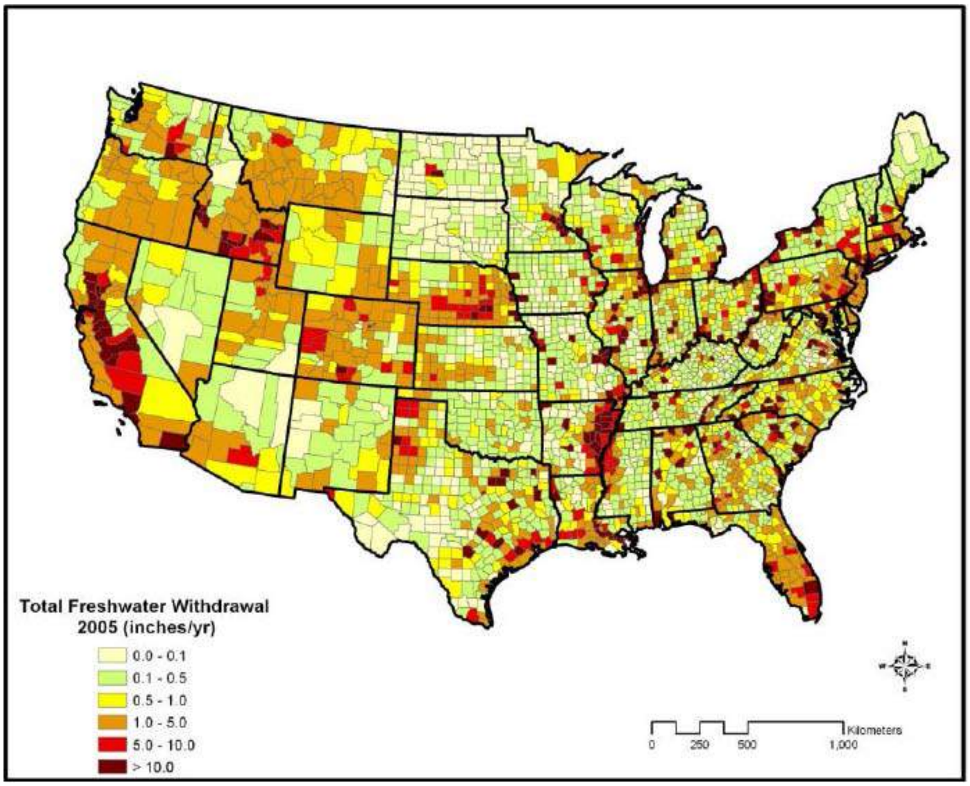

Figure 2-4
Total freshwater withdrawal from surface water and groundwater sources, normalized to inches per year to account for counties of different areas, in 2005 for the US. The specific sectors considered in the USGS water use survey include thermoelectric cooling, irrigation, public supply, industrial, livestock, aquaculture, and mining.

Thermoelectric freshwater withdrawal per unit energy generated depends largely on thermal cooling technology used. Currently there are two main types of cooling technologies used in power plants: once-through cooling and recirculating cooling (EPRI, 2008). Once-through cooling systems withdraw water from a natural water body, use it for heat exchange, and return it to the water body after one cycle of use. Recirculating technologies include wet cooling towers and cooling ponds. Wet recirculating systems use water over multiple cooling cycles and have much lower withdrawals than once-through cooling systems. Most new plants, especially those built after 1970, use some form of recirculating cooling (Argonne, 2010). Thermoelectric cooling technologies that use zero or smaller amounts of water than recirculating cooling (specifically dry cooling and hybrid wet/dry cooling systems) are also possible, but their use in the US is minimal at present.

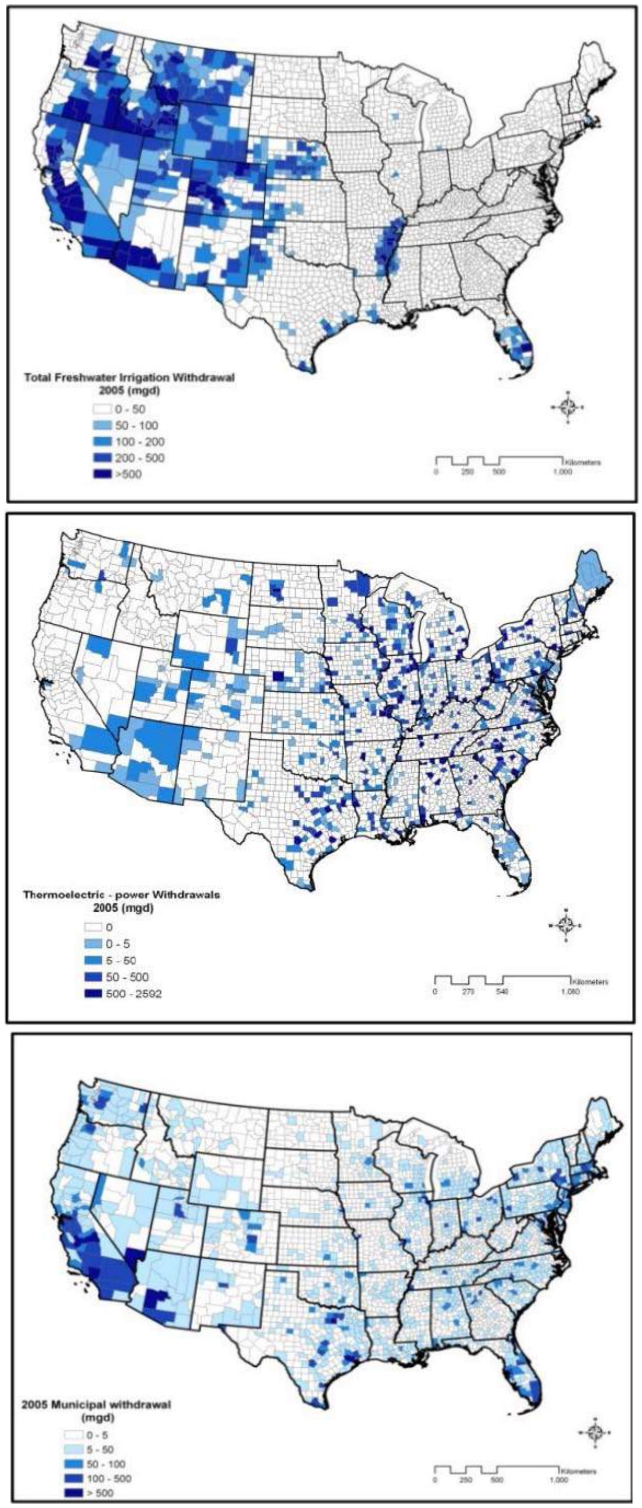

Figure 2-5
Withdrawals associated with (top) irrigation, (middle) thermoelectric cooling, and (bottom) municipal and domestic use, reported in units of mgd by Kenny et al. (2009).

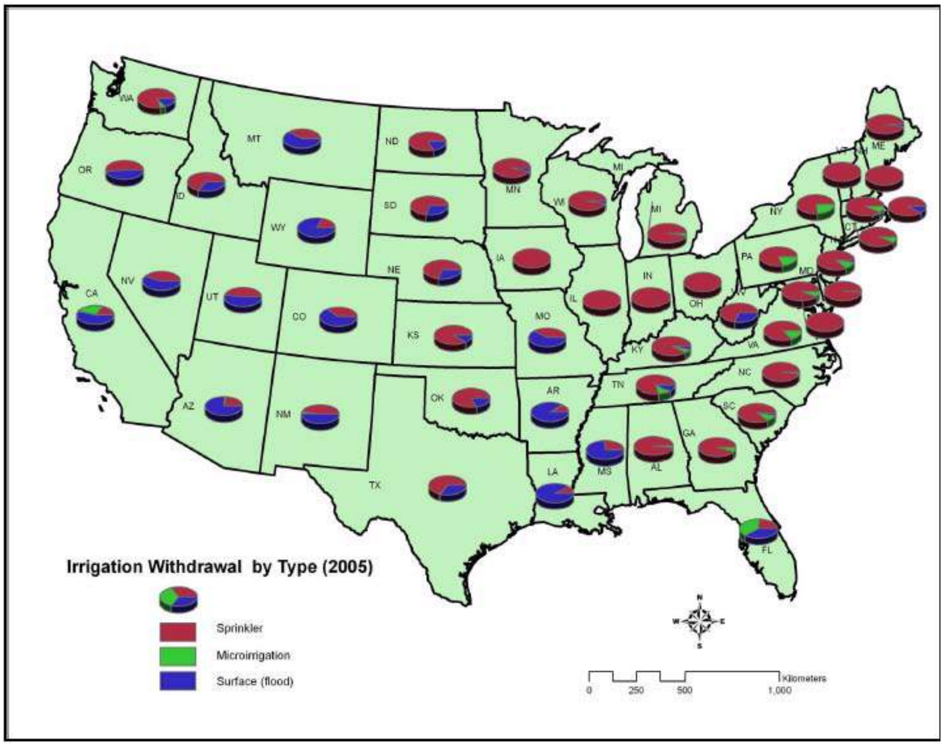

Figure 2-6
Proportion of irrigated area by type (sprinkler, micro-irrigation, and surface or flood irrigation), aggregated at the state level.

The distribution of cooling technologies across the US is mapped in Figure 2-7, and shows a distinct east/west pattern: a larger percent of the states in the east still heavily rely on once-through cooling. For a few western states (e.g., California, Oregon, Nevada, Utah, and New Mexico), the freshwater withdrawal is mostly from recirculating cooling. States in the Southeast show a mix of cooling technologies, with both once-through and recirculating systems in use.

Per capita municipal water use varies through the country, and at the state level, varies from 54 gallons per capita per day to 187 gallons per capita per day (Kenny et al., 2009), with consistently higher values in the more arid parts of the country. Individual counties in arid areas have a per capita demand in excess of 300 gallons per capita per day (Figure 2-8). Indoor water use typically does not change much from region to region. Outdoor water use, for activities such as watering landscapes, accounts for much of the difference in municipal use across the US.

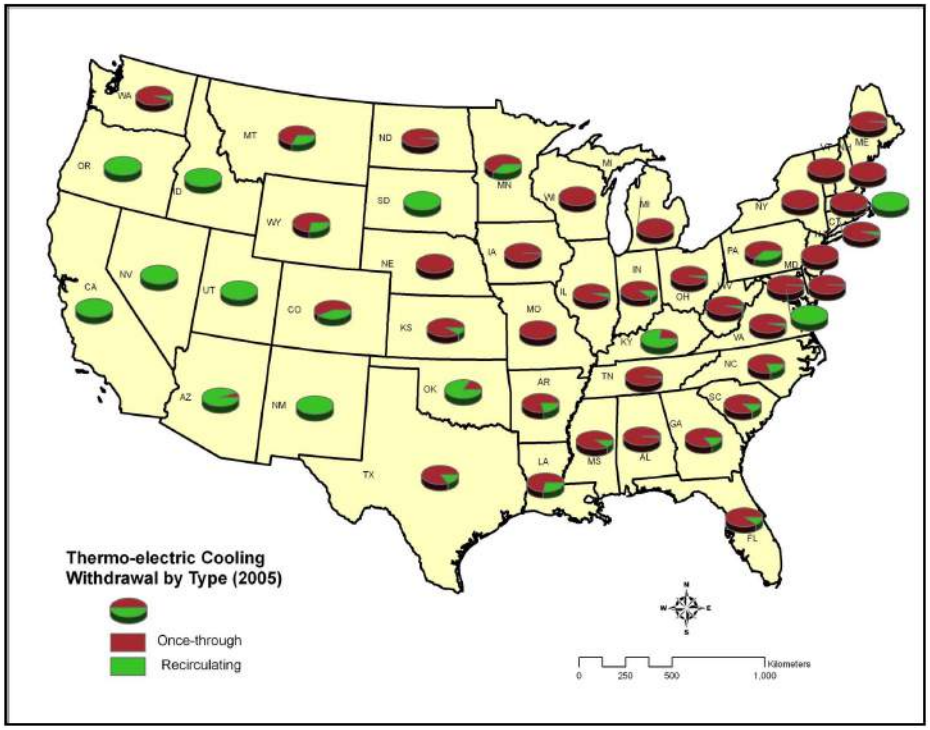

Figure 2-7
Thermoelectric cooling technology, proportion of freshwater once- through versus recirculating cooling in 2005 based on withdrawal, aggregated at the state level.

Overall, the USGS water use and supporting data from the Census Bureau and the Departments of Energy and Agriculture permit us to paint a fairly well resolved picture of water use across the US in 2005. These maps illustrate the intensity of water withdrawals by different sectors as well as the efficiency with which it is used (i.e., one can compare the relative abundance of once-through cooling systems using freshwater, or per capita use of municipal water). These data, especially when compared over a two-decade period (1985 to 2005) for which county-level information is readily available, provide an understanding of how water use is changing in the short term and are evaluated in the next chapter. The use of the water use survey data in this manner underscores the importance of the USGS data-collection effort to the larger goals of improved water management in the US.

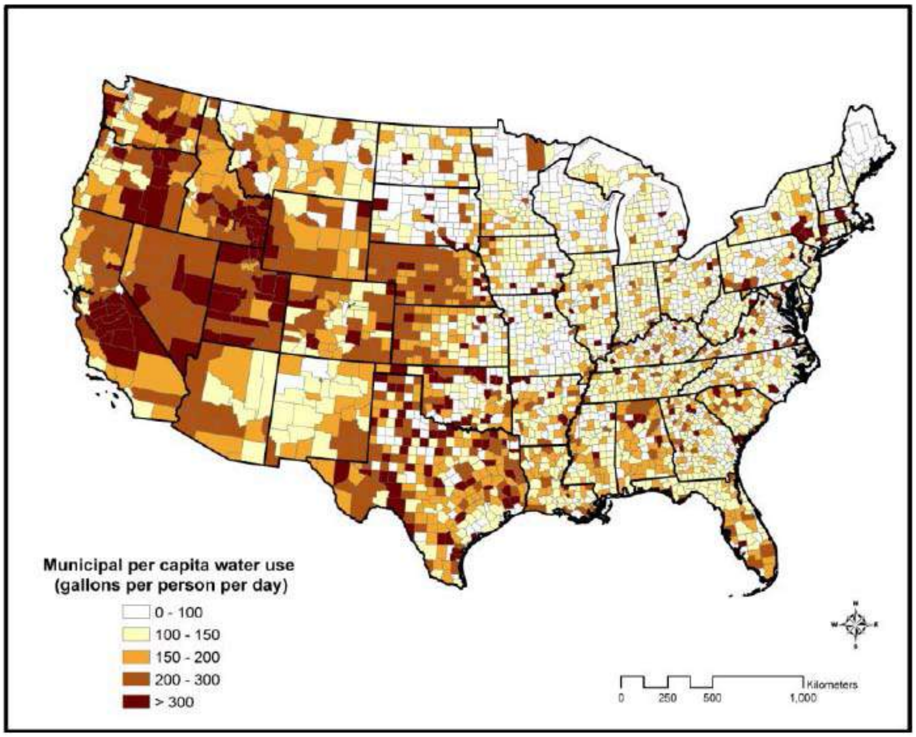

Figure 2-8
Domestic water use (includes public and self supplied uses) in gallons per capita per day.

3. Long-Term Trends in Water Use

On a national aggregate basis, there have been two distinct phases in water withdrawals in the US in the last six decades for which we have data: there was a phase of steady increase in water withdrawals from the 1950s to the 1970s, a continuation of trends from earlier in the twentieth century; and a second phase, beginning in the 1980s, with relatively uniform withdrawals (Figure 2-2). The second phase is especially interesting, and relevant to future projections, because the relatively constant withdrawals were associated with continuing population and economic growth and their associated water demands.

Irrigation water use from 1950-2005 is shown in Figure 3-1. Water use for this sector does show change over each 5-year period for which data are reported; although, the trends are not dramatic because most major irrigation projects in the US were implemented prior to the period shown. Irrigation water use shows a peak in about 1980 (150 bgd), with a gradual decline in most years since then. The most recent reported withdrawals for 2005 are 128 bgd, or slightly lower than the thermoelectric freshwater withdrawals. Irrigated areas have increased by 4 million acres over this period, reflecting a 7% net increase (comprising decreases in the west and increases in the east). However, this is not related to an increase in withdrawals over the same period, in large part because the new irrigated areas in the east have lower irrigation water application than in the west.

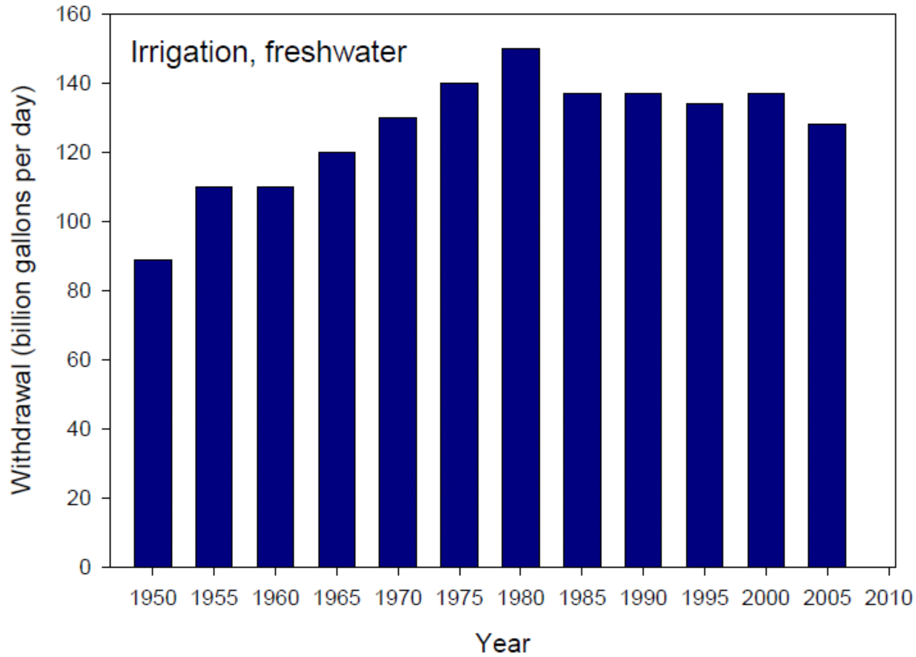

Figure 3-1
Trends in irrigation freshwater withdrawals in the U.S. for the period of 1950-2005.

The relative constancy of the irrigation withdrawal from 1985-2005 can be contrasted with agricultural production of the three most important crops in the US: maize, wheat, and soybeans. Two of the three crops (maize and soybeans) show significant increases in production over the same period, even as the area under cultivation for the two crops has shown only modest increases. Wheat production and area under cultivation both declined over this period. Yields (production per unit area) have increased significantly for all three crops over the 1985-2005 period. That this change occurred without any noticeable increase in irrigation water application highlights the increasing water efficiency in the agricultural sector.

Over the period from 1950 to 2005, thermoelectric freshwater water use has increased from 30 bgd to 143 bgd (these numbers exclude all saline surface water withdrawals, largely associated with coastal thermoelectric plants) (Figure 3-2). The total thermoelectric withdrawals have shown minimal change from the mid 1970s, and have been in the range of 126-143 bgd between 1975 and 2005. Over this period electricity generation more than doubled from 1,911 billion Gwh to 4,055 billion Gwh. The relatively constant water withdrawal despite this large increase in generation reflects a move from once-through cooling systems to recirculating wet cooling systems, with much lower water withdrawals per unit of electricity generated. As noted in the previous section, the vast majority of once-through cooling systems in use today were constructed prior to 1970, and most new plants use some form of wet recirculating cooling system.

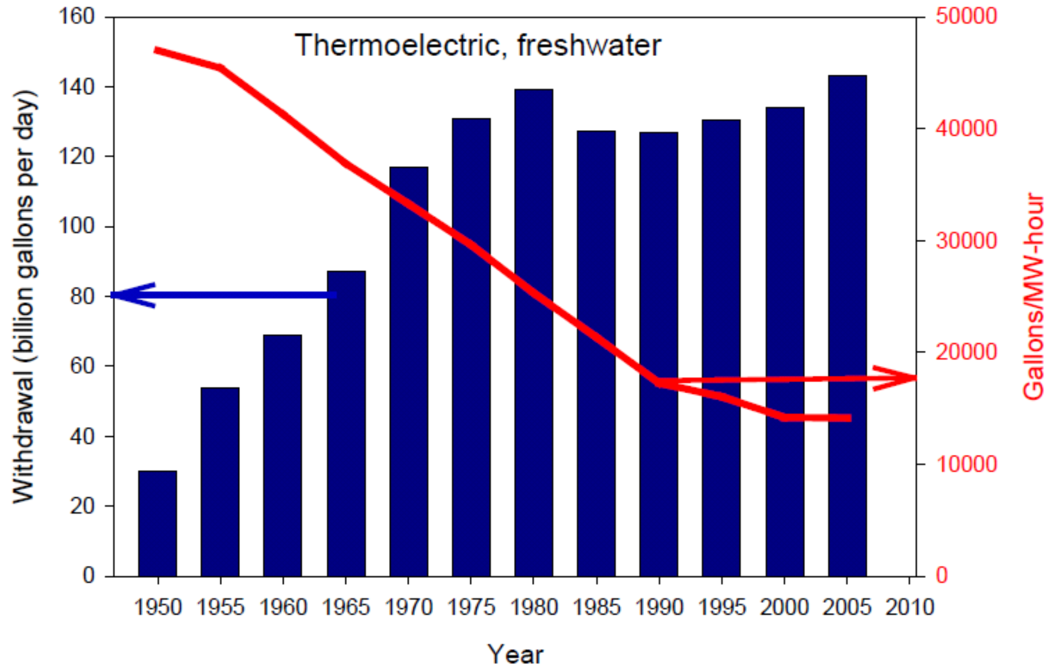

Figure 3-2
Trends in total thermoelectric freshwater withdrawals in the U.S. for the period of 1950-2005 (left axis). Saline surface water withdrawals are not part of these values. The right axis shows the average water withdrawal associated with each unit of electricity generation in gallons/MW-hr. (Data sources: USGS)

During the period of 1950-2005, domestic water withdrawals have increased significantly, from 14 to 45 bgd, largely due to the population increases (Figure 3-3). This figure also shows the per capita withdrawal over this period. It is noted that per capita domestic water withdrawal steadily increased during 1960 to 1990 and started to decrease from 1990 onwards. The increase in the first phase corresponds to increasing population growth in the Western US, where per capita withdrawals have been higher. The decrease in the last two decades, although small on the national scale, represents a concerted effort at municipal water conservation in many regions of the US. States in the West and Southeast have shown substantial per capita decreases in municipal withdrawal.

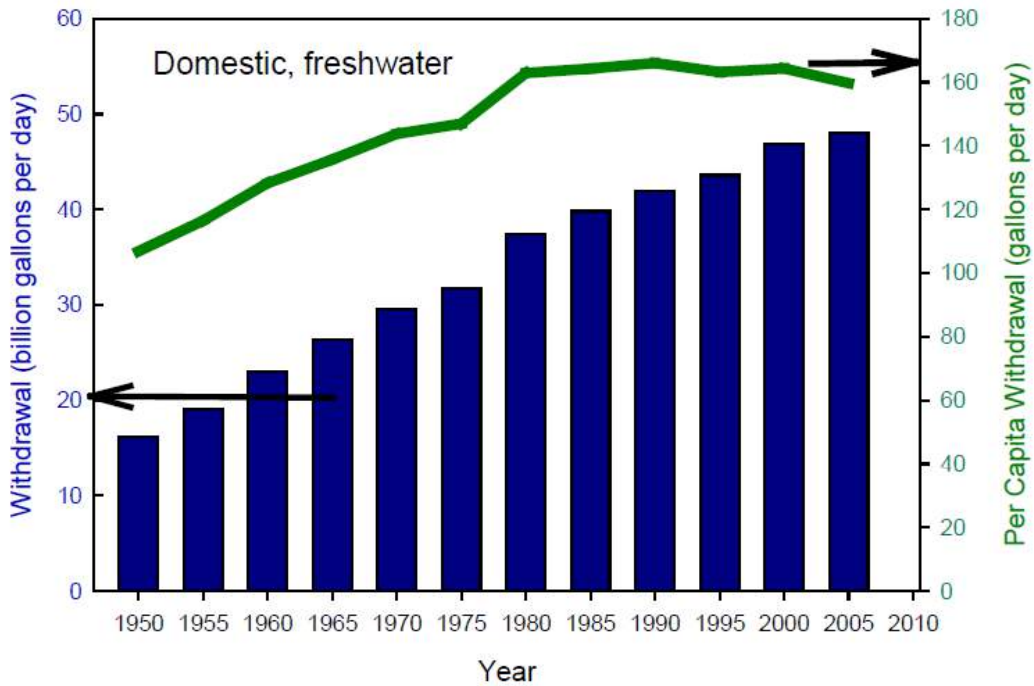

Figure 3-3
Trends in domestic freshwater withdrawals (public supply and self-supplied) in the U.S. for the period of 1950-2005. Also shown in the per capita withdrawal in gallons per day.

The data related to the use of water in individual sectors demonstrates a pattern of increasing efficiency of use, i.e., there is greater food and electricity production using the same amount of water in the individual sectors over the last 2 to 3 decades. Municipal withdrawal trends are different from thermoelectric and agricultural withdrawal trends, and have shown an increase over this period. Per capita withdrawals for municipal use, however, have demonstrated substantial declines in many states, especially in the Western US. Other regions of the US, especially states in the Southeast and the Great Plains states, have exhibited increases in total withdrawal.

Going forward, the lack of an annual increase in aggregate withdrawals over recent decades should not be a reason for complacency. Water supplies remain a topic of importance for planners and for the general public because of five reasons. First, the ability to continue existing withdrawals may be limited by environmental constraints, particularly the protection of aquatic life, thus an existing supply cannot be assumed to be present indefinitely. Second, climate variability, including drought, may limit the ability of all users to meet the full extent of their withdrawals. There continues to better understanding of long-term patterns in climate, and questioning of the assertion that climate is stationary (Milly et al., 2008). Third, there is a concern with the ability of water withdrawals to adapt in the short term because of the great inertia in institutional infrastructure. In particular, water supplies may be available in an absolute sense, but are often committed to prior users, limiting new uses or changes in use. Fourth, there are pressures for increasing water use over the long term, even in sectors that have been relatively stable, such as for irrigation. These pressures include greater demand for agricultural commodities as a result of global population and economic growth and for biofuel production. Finally, in some geographical regions, current demand for water is being met by a diminishing supply of groundwater; hence, even if demand in these areas stays constant, the reservoir of groundwater will continue to be depleted.

4. Implications for New Thermoelectric Generation

There are four major strategies for reducing fresh water use in new thermoelectric generation (fossil, nuclear, and some renewables, e.g. concentrated solar, biomass, geothermal):

1. Degraded water sources
2. Dry or hybrid cooling
3. Increased thermal conversion efficiency
4. Water recycling within the plant

Each of these options has been used to varying degrees, depending on local water resources and costs (capital and operating) for the project.

Degraded Water Sources – Many power plants have been operating for years on nontraditional or degraded water sources, particularly treated sewage effluent. Treated sewage effluent has been the most attractive source because of its year round availability, inexpensive price (although prices are increasing), relatively low cost of treatment, and minimal impacts to power plant operation. Even this water source is being protected in some areas of the country for use in irrigation and groundwater recharge, limiting its use for power plant cooling.

Additional degraded water sources that are being considered include:

- Seawater and brackish water from coastal areas
- High salinity groundwater
- Mine water and produced water from oil and gas wells
- Agricultural runoff
- Stormwater

Each of these sources will cost more than traditional surface or groundwater sources, with the highest costs usually a result of treating the water and transporting it to the power plant. Additional costs can come from the need to use different materials to minimize or avoid corrosion; chemicals to prevent scaling, fouling and corrosion; storage or backup water system; and wastewater treatment and disposal.

Dry Cooling – While dry cooling with air-cooled condensers (ACCs) can virtually eliminate the water required to cool power plants, it does have drawbacks. The capital cost for power plants with dry cooling is typically more than 10% higher than wet cooling, because they require large finned-tube heat exchangers, fans and drive motors, and steel structures to provide ground clearance for proper air circulation. The capital cost of the dry cooling system itself is three to five times higher than for wet cooling. There are also higher operating costs associated with dry cooling. The fans needed for air circulation are much more powerful and more numerous than those required for a wet cooling tower. This increases the parasitic load on the unit, and reduces the net power available from the plant. Dry cooling will provide a steam condensing temperature typically 40°F+ higher than the dry-bulb temperature. This has the effect of reducing unit efficiency up to 10% or more, and a reduction in generating capacity on the hottest days (Figure 4-1).

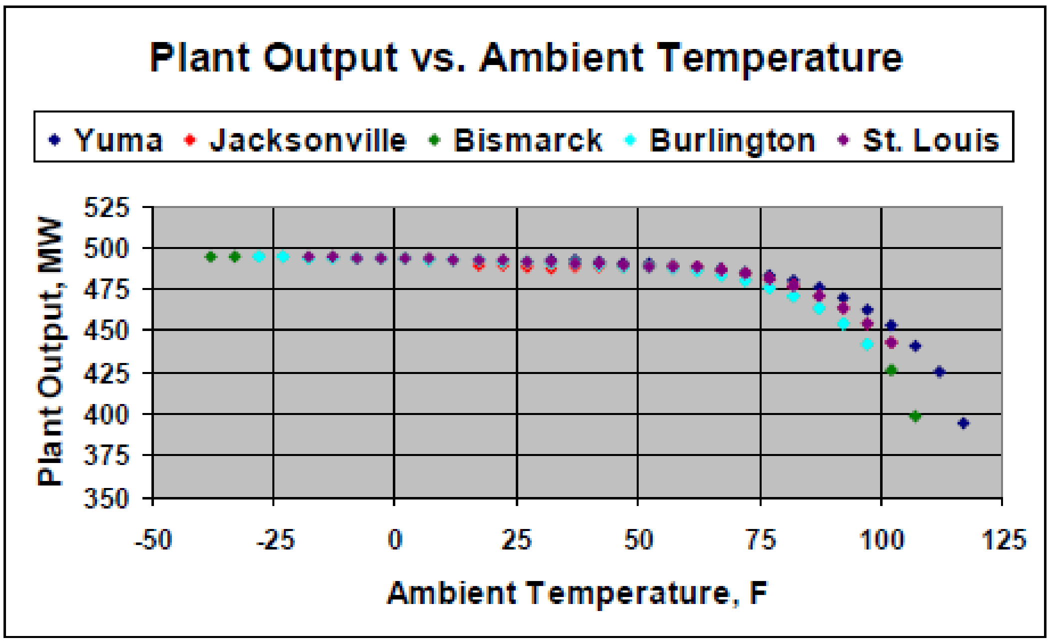

Figure 4-1
Dry Cooled Coal Plant Output vs. Ambient Temperature at Multiple U.S. Sites (EPRI, 2012)

Due to the efficiency penalty of dry cooling, more fuel is required to produce the same amount of electrical energy; therefore, the emissions of pollutants and CO_2 per unit of electrical energy delivered (e.g., lb pollutant/MWh) increase. Dry cooling systems are also significantly larger than traditional wet cooling towers, and they require additional land space to build. The large number of cooling fans can create issues with noise. This can be alleviated with the purchase of low-speed, low-noise fans, but this adds to the cost.

High winds can cause stalling of the air flow in leading edge fans, which causes a sudden drop in ACC performance, which translates into higher back pressures on the turbines. The control systems will generally reduce steam flow to the turbine as the back pressure alarm point is approached, which reduces unit generation capacity. With gusty winds, there have been cases where the controls and system components did not respond fast enough to limit backpressure and the units have tripped off line to protect the turbines from damage.

Hybrid Cooling – Hybrid cooling systems (Figure 4-2) provide a combination of a wet cooling tower and a dry air-cooled condenser. This arrangement allows most of the heat to be rejected to the atmosphere on cooler days, avoiding the use of cooling water, and still maintain the power plant's thermal efficiency during hot days, with the wet tower taking part of the cooling load.

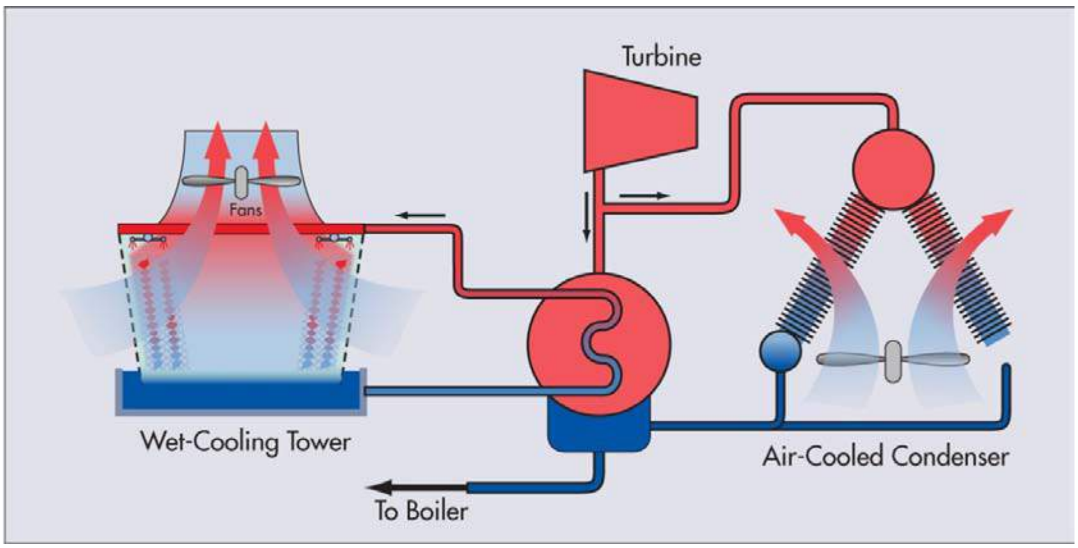

Figure 4-2
Schematic of a Hybrid Cooling System (EPRI, 2008)

Hybrid cooling is becoming more popular because the tower sizes can be minimized to reduce additional costs, and performance is better than air-cooling only. There are many ways to optimize such a system, depending on the goals of the plant design and the available water sources. EPRI guidelines are available to assist plant designers with this optimization process.

Increased Thermal Conversion Efficiency – Compared to conventional coal-based power generation, high efficiency natural gas combined cycle power plants have a large benefit from a water conservation standpoint (Figure 4-3). Since roughly 2/3 of the power is produced by the combustion turbines, cooling water consumption is reduced by an equivalent amount. In addition, the steam turbine can be cooled by ACCs, further reducing water use. The ACC will be smaller, since it is only cooling 1/3 of the total plant, and this also minimizes hot day efficiency penalties.

Combustion turbines will also sustain a hot day capacity penalty. This penalty, however, can be mitigated with inlet sprays or evaporators, or with inlet chillers that draw power.

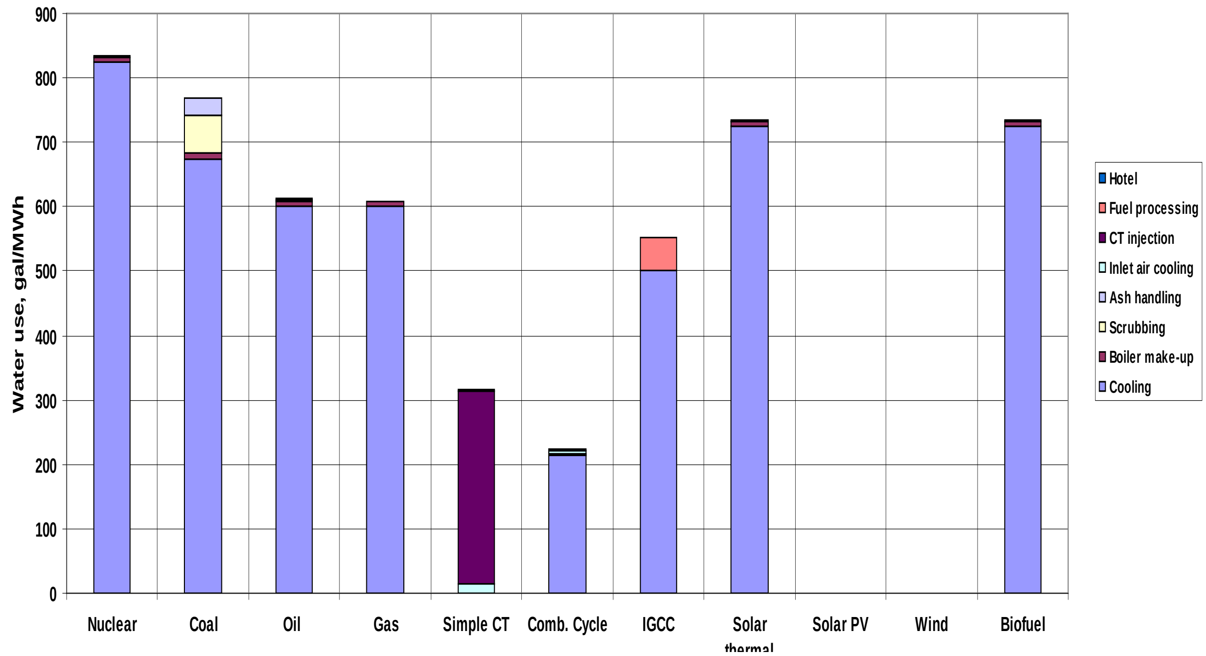

Figure 4-2
Average Water Use (in gallons per MWh) by Power Plant Type (assuming wet cooling towers)

Water Recapture – A significant amount of water is lost through power plant stacks (flue gas from fossil fuels contains 8-13% moisture as a by-product of the combustion process) and cooling tower plumes. Several research groups, including EPRI, are funding work to develop technologies to economically recapture water from plumes, but these technologies are not yet commercially available.

Water Reuse – Power plants in operation today already employ many practices to reuse water within the plant. Water is typically "cascaded" from one use to another, depending on the quality of water that is needed for each process.

Renewable Resources – Renewable energy from wind, solar photovoltaic, geothermal (when using brine for cooling water), hydroelectric, marine and hydrokinetic sources all require little to no water consumption. To the extent that these technologies can economically penetrate the generation mix, water use can be reduced.

5. Implications for Existing Thermoelectric Generation

The options for existing plants are more limited than those for new generation, as the available conservation methods usually require major modifications to the boiler and steam turbine and may have other environmental and permitting constraints. These cost increases may limit the economic viability of the plant. Some of the options that have been suggested or considered for water conservation at existing power plants are listed below, followed by discussion of the positive and negative attributes of each.

Retrofit Closed Cycle Cooling (Wet Cooling Towers) – While water withdrawals would be reduced by over 95% with wet cooling towers, the evaporative losses would approximately double. EPRI has a significant body of research in cost estimates and other impacts of retrofitting cooling towers to all once-through cooled plants in the United States.

The retrofit cost correlations for fossil plants for the four degrees of difficulty were:

- Easy: $181/gpm
- Average: $275/gpm
- Difficult: $405/gpm
- More difficult: $570/gpm

The coefficients for nuclear plant retrofits were:

- "Less difficult": $274/gpm
- "More difficult": $644/gpm

Retrofit of wet cooling towers will result in negative consequences, such as lower thermal efficiency and correspondingly higher air pollutant and carbon (CO_2) emissions per unit of electrical energy (MWh) generated, cooling tower drift and blowdown issues. In addition to the cost of purchasing and constructing cooling towers for the plant, the designer would need to consider whether to reoptimize the remainder of the power plant to reduce the efficiency penalty.

Retrofitting to cooling towers may also require pretreatment of the water (softening or clarification), scale and corrosion inhibition additions, and blowdown treatment for discharge regulations, including possible zero liquid discharge. All of these treatment processes will add millions of dollars of infrastructure as well as significant operational and maintenance expenses.

Retrofit Dry Cooling – The retrofit of dry cooling is very difficult for existing plants and the plant may no longer be economical to operate. The balance of the plant would have to be redesigned to work with the dry cooling tower, since it operates at such different conditions than wet cooling towers. The reasons for this follow:

- As noted earlier, dry cooling will cool to the dry bulb temperature whereas a wet cooling tower cools the water to the wet bulb temperature. Turbines designed for new plants to be equipped with dry cooling are normally modified to accommodate the expected higher backpressure. Figure 5-1 displays a relative comparison of the curves for the "high backpressure" and "modified-conventional" designs with a "conventional" steam turbine curve.

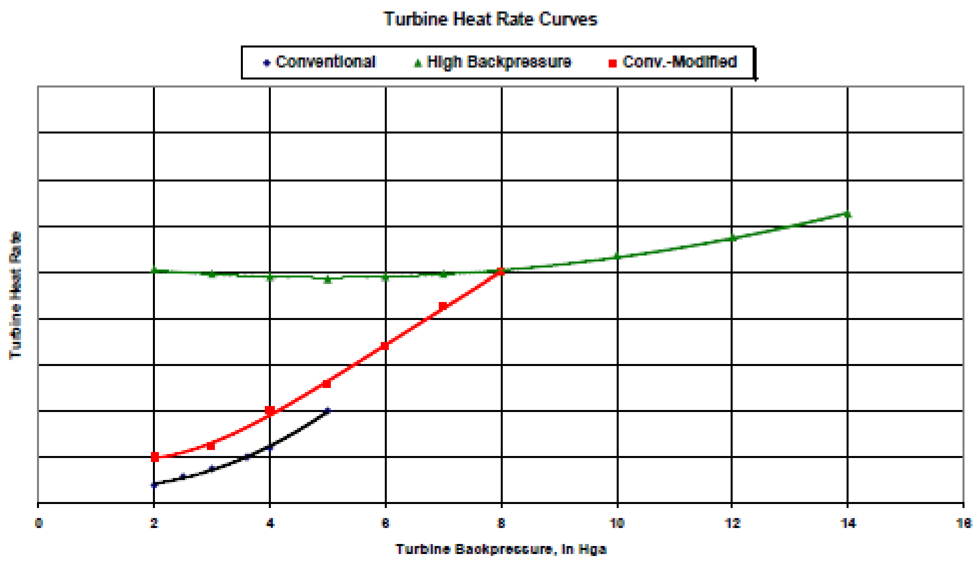

Figure 5-1
Comparison of Turbine Curves on Dry Cooled Plants with "Conventional" Plants (EPRI, 2012)

- Air cooled systems work most effectively when the steam is ducted straight out to ACC. To convert a water cooled plant to air cooling, the owner has two options: (1) use indirect dry cooling where the steam is condensed by recirculating water and the heated water is routed to an air cooled heat exchanger; or (2) remove the condenser and route the steam directly to an ACC. Since the ACC has a lower efficiency impact (by eliminating the temperature drop across the condenser), it would be preferable to using indirect dry cooling. Removing the condenser and circulating water lines and routing large-bore steam piping past the turbine pedestal and out to the ACC would be difficult and expensive, especially below grade level.

- Air cooled systems are typically used on combined cycle plants for the reasons presented earlier. This is why, in recent years, the predominant build for power plants in the western US (where dry cooling is needed) has been NGCC plants.

- In addition to the efficiency penalties discussed above, hot day operation with ACCs can also result in capacity loss, which usually coincides with peak system load (air conditioning) and highest power prices. This occurs because as turbine back pressure rises to near trip points, the operators must reduce steam flow to prevent a unit trip. Figure 5-2 shows the typical percentage loss in turbine output due to higher temperatures.

- Retrofitting ACCs to an existing unit would change and affect plant operation and internal assets. For example, iron corrosion and transport is typically an issue with units on ACCs. It would be even worse with the mixed metallurgy found in conventional boilers and steam cycles.

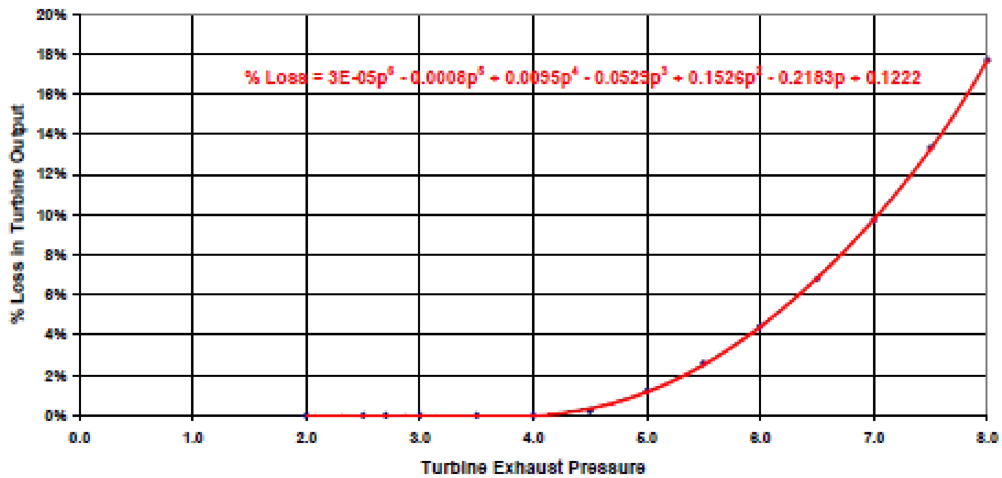

Figure 5-2
Loss of Turbine Output as a Function of Turbine Exhaust Pressure (EPRI, 2012)

Convert to Partial or Full Degraded Water Use – This method is probably the easiest water conservation technique to adopt for existing plants. The advantages are that the thermodynamics of the plant and the power block equipment remain largely unchanged. Depending on the distance of the source water from the power plant, the transportation cost (building pipelines and pump stations) can be one of the largest costs, but there may also be costs associated with water and wastewater treatment systems and chemical additives. The plant would also need to be evaluated to assure that the materials of construction are compatible with expected water quality.

Water Sharing Agreements – EPRI is currently implementing a variety of tools to assist electric power companies with water issues. For example, EPRI's Water PRISM is a modeling tool that allows stakeholders in a given watershed to evaluate water reduction and sharing options. This can even include special reductions during drought periods—such as providing revenue streams to support shifting agricultural land to non-irrigated crops or non-use for the drought periods.

6. Summary

Water is a shared, finite resource subject to the competing demands of multiple stakeholders. Despite being one of the largest users of water on a withdrawal basis, electric power is frequently assigned the lowest priority for water allocation after residential, commercial, industrial and agricultural uses. Therefore, as those other uses grow, it is increasingly likely that water availability will become a major issue for the electric power industry over the next decade and beyond. For example, siting of new plants is already constrained by access to cooling water, especially fresh water.

However, the "energy/water nexus" is much more complex than a simple discussion of how electric power plants can reduce their water intake. Strategic challenges and opportunities for the electric sector lie in each of the following important areas:

- Using less water for power production
- Using less energy for water production, treatment and use
- Ensuring that *any* use of water minimizes environmental impacts so as to make that scarce water resource available for other compatible use or reuse

Each of these challenges is urgently coming into focus as our populations and our economy grow amid a fixed, finite, and increasingly scarce water resource. Meeting the challenges and realizing the opportunities in each will require a more systematic dialogue on *sustainable water resource management* driven by collaborative decision-making across multiple societal and economic sectors. As yet, the tools for this dialogue are only now being assembled, and there is much more to be done in the years and decades ahead.

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Bioenergy and Water

Understanding Impacts

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White Paper Presented at the MIT Energy Initiative and Center for Strategic International Studies Energy-Water-Land Nexus Workshop, May 6-7, 2013, Washington, D.C.

ENERGY BIOSCIENCES INSTITUTE

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I. Introduction

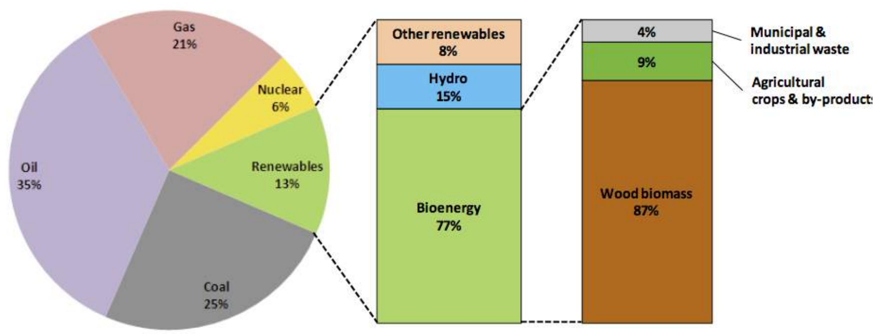
I.a. Bioenergy in context

Bioenergy is the single largest renewable energy source in use today, accounting for nearly 10% of global energy production and over 75% of renewable energy (Figure 1, top). The majority of biomass used globally is directly combusted for heat and cooking in developing countries. Biomass is also used to produce liquid transportation fuel (ethanol or biodiesel), or as a source of heat and electricity in some countries. In 2009, biomass provided 5% of total energy and 59% of renewable energy in the U.S. (Figure 1, bottom). The share of bioenergy is expected to increase with expansion of low-carbon energy demand.

Biomass production occurs in the context of ongoing agricultural and forest product production. All biomass production, regardless of end use requires water as an input and releases water of varying quality back to the environment.

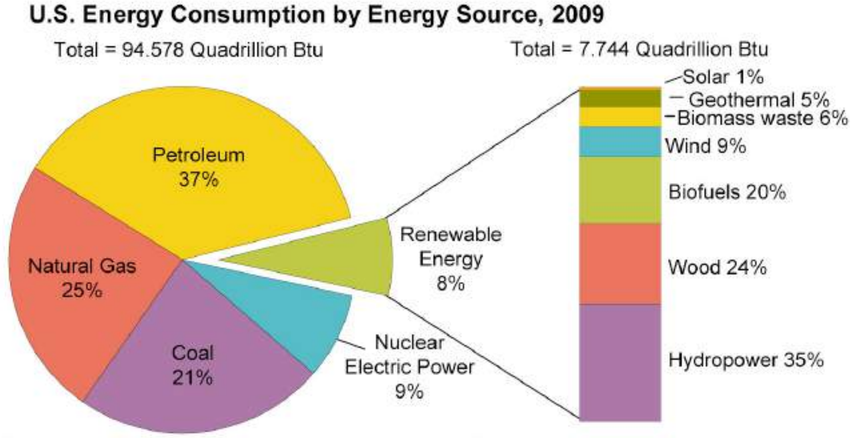
The reported water intensity of bioenergy spans a large range from several liters per GJ to tens of thousands of liters per GJ, prompting concerns as to how expansion of bioenergy will impact both water quantity and quality for food, feed, fiber and fodder production and other human and ecosystem uses. This whitepaper will discuss several of these issues with a focus on impact assessment metrics.

Figure 1 *Share of Bioenergy in the World Primary Energy Mix*



Source: Bioenergy – a Sustainable and Reliable Energy Source. IEA Bioenergy ExCo:2009:05

U.S. Energy Consumption by Energy Source, 2009



Note: Sum of components may not equal 100% due to independent rounding.
Source: U.S. Energy Information Administration, *Annual Energy Review 2009*, Table 1.3, Primary Energy Consumption by Energy Source, 1949-2009 (August 2010).

I.b. Water and bioenergy – Potential issues

Possible concerns about the impacts of bioenergy have been stated as follows:

1) The water footprint of bioenergy feedstocks may be greater than fossil energy feedstocks or renewable energy sources.

2) Expansion of bioenergy may increase unsustainable water use through irrigation.

3) Expansion of bioenergy feedstocks may decrease water quality.

4) Expansion of bioenergy feedstocks may compete with food and forests for water.

5) Expansion of bioenergy may exacerbate water scarcity associated with climate change.

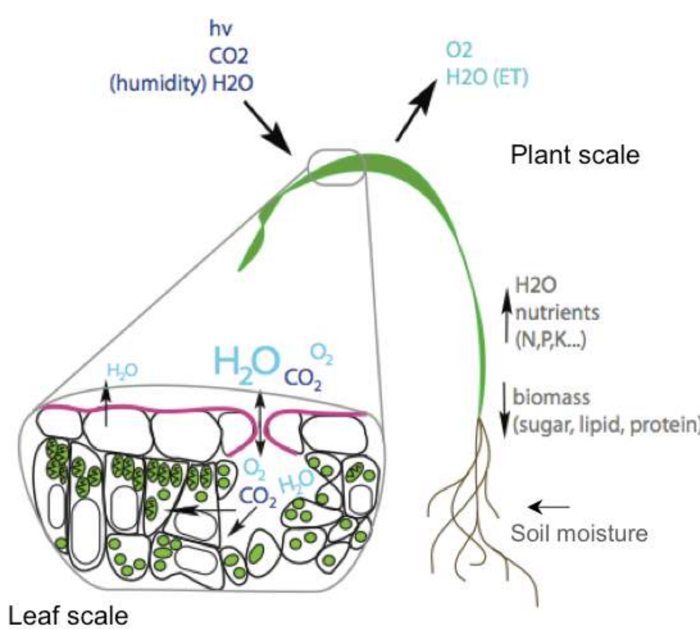
The public discourse surrounding biofuels has been a roller coaster of unbridled enthusiasm, demonization, doubt, and uncertainty, resulting in a highly polarized and sometimes confusing landscape. Understanding the risks and benefits of bioenergy expansion, especially in terms of land and water, is necessary to wisely shape our future energy systems and manage our natural resources.

I.c. Water fluxes in bioenergy production

Water is required at all stages of bioenergy production. Release of water also occurs at various stages. Thus, bioenergy affects both water quantity and water quality. It is helpful to envision these effects as water fluxes, which are part of a grander natural water cycle.

Water fluxes in natural ecosystems include many complex processes on an array of different physical and temporal scales, ranging from the microscopic to the ecosystem and from seconds to seasons. All of these fluxes contribute to the proper functioning of ecosystems. Water fluxes influence water availability, water quality, energy cycles, biotic interactions, and habitats.[1]

Figure 2. Transpiration at the leaf and plant scale



At the microscopic scale, water is a critical element in plant metabolism

[1]Naiman RJ, Bunn SE, Nillsson C, Petts G, Pinay G & Thompson LC (2002) Legitimizing Fluvial Ecosystems as Users of Water: An Overview. *Environmental Management* **30**(4) 455–467. doi:10.1007/s00267-002-2734-3.

and growth. Water is required for carbohydrate synthesis, nutrient transport, and many other metabolic processes central to biomass yield. High internal cell pressure (15 to 30 psi), driven by water potentials, is required to force cell elongation during plant growth.

Water is transported through plant tissues by a combination of physical forces that begin with gas exchange at the leaf surface (Figure 2). This exchange, called transpiration, is required to bring carbon dioxide into the plant for photosynthesis. The water use efficiency at this scale is often expressed in terms of the number of carbon molecules fixed into sugar per water molecule transpired. Many plants have evolved higher water use efficiency. The best example is CAM photosynthesis (Table 1). This special metabolism allows cacti and succulents to perform gas exchange at night, when ambient temperatures are low and relatively humidity high, reducing water loss. These plants store the carbon as an acid then perform photosynthesis during the day.

Table 1. Leaf scale water use efficiency in plants with different photosynthetic strategies. Representative plants for bioenergy include CAM plants such as Opuntia and Agave, C3 plants including poplar, willow, and soybean, and C4 plants such as maize, sugarcane, and Miscanthus.

Agronomic traits	Photosynthetic pathway		
	CAM	C_3	C_4
Average above-ground productivity [Mg (tonnes) ha^{-1} $year^{-1}$]	43	35	49
Water use efficiency (mmol CO_2 per mol H_2O)	4–10	0.5–1.5	1–2
Crop water demand (Mg H_2O ha^{-1} $year^{-1}$)	2580–6450	14 000–42 000	14 000–28 000

Most water is drawn out of tissues surrounding stomata (small pores on the plant surface, Figure 2). Additional water can be lost directly through the plant epidermis - especially in plants that lack surface waxes or cutin. At the plant scale, the water potential that is created in the leaf acts as driving force to move water and nutrients up through the vascular tissues in the stem and roots via capillary action. This flux creates a gradient that draws moisture from the soil into the root. Thus, plants serve as natural humidifiers, moving much more water from soil to the atmosphere than evaporation from bare soil. Many environmental and genetic factors contribute to the efficiency of the exchange of water for carbon at the leaf and plant scale.

Figure 3. Water fluxes at the field scale

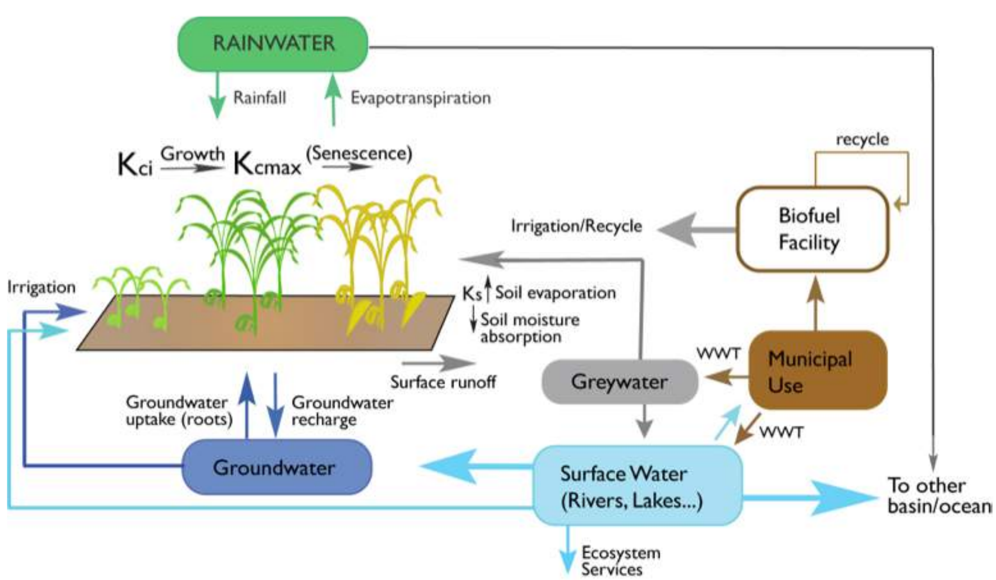


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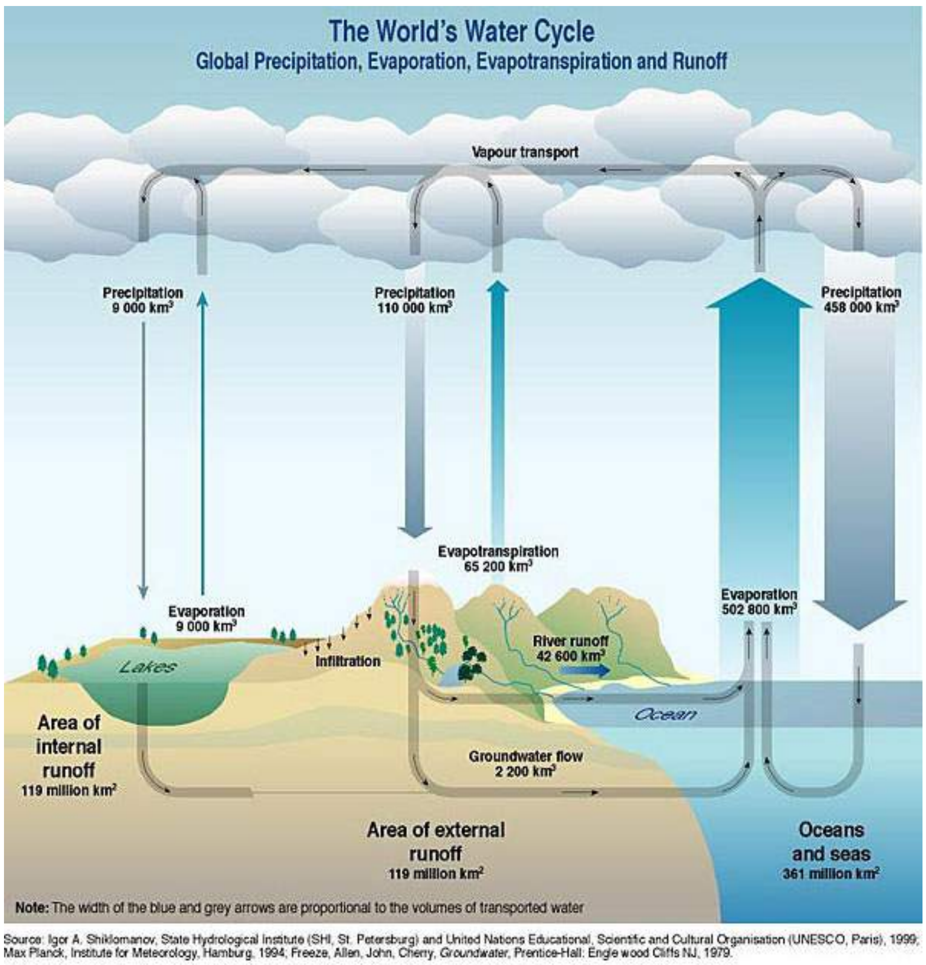
Figure 4. Global water cycle[2].



At the field scale (Figure 3), the plant water flux is accompanied by other physical water flows including precipitation, evaporation, and surface/sub-surface hydrology, which both provide water to and remove water from the plant root zone. Water fluxes at the field scale are affected by plant growth habit (canopy and root structures), environmental factors, and plant community structure (e.g. species diversity and spacing). Management decisions, including plant selection, row spacing, drainage, and irrigation have large effects on water fluxes in agriculture. Because the plant community structure and canopy architecture strongly influence evaporation from soil, it is common to combine the evaporation and transpiration flows into a single term called evapotranspiration. The interaction of environment and management on water fluxes will change throughout the growing season.

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[2]Philippe Rekacewicz, UNEP/GRID-Arendal http://www.unep.org/dewa/assessments/ecosystems/water/vitalwater/05.htm

Decisions regarding land cover and management at the field scale are integrated spatially and temporally at the watershed scale and then again at the basin scale (Figure 4). The grander water cycle takes shape at this scale with pronounced feedbacks between the soil, vegetation, and atmosphere. Water, which is not immediately accessible by plant roots, is considered lost to the system. These losses included all evapotranspiration, rainwater that is intercepted and evaporated by the canopy before reaching the soil, water that percolates below the root zone, and some portion of surface run-off. In most bioenergy systems evapotranspiration is the dominant term and is often the only parameter considered in water intensity calculations. It is important to note, however, that is some systems substantial recycling of precipitation within the watershed or basin occurs[3].

Water movements consist of precipitation, interception, evaporation, transpiration, stemflow, throughfall, infiltration, surface runoff, interflow, baseflow, and stormflow (Figure 3). Water flows can most simply be quantified in terms of magnitude (volumetric flow rate or level), timing in a year or season, duration, frequency, and rate of change (i.e. the rate at which flows or levels increase or decrease in magnitude over time). Low flows (base flows) maintain adequate habitat, temperature, dissolved oxygen, and other chemical components for aquatic organisms, as well as drinking water for terrestrial animals, and soil moisture for plants in forests and fields[4]. Higher flow pulses after precipitation have important ecological functions including: preventing vegetation from overtaking river channels, moving sediments and organic matter downstream and decreasing water temperature and increasing dissolved oxygen, which can be important for riparian invertebrates and fish. Alterations of surface flows can affect reproduction cycles, connectivity of water bodies, and seasonal species migration[3,5]. Looking broadly at the components of hydrologic cycle can more fully show relationships between the atmosphere, geosphere, biosphere, and hydrosphere, all of which affect how much water is available for human and/or ecosystem use[6].

I.d. Water flows in the context of population growth and climate change

Human activities and natural processes, such as succession, greatly water availability, and water flows. The world population, currently at 7 billion, is expected to increase to 9 billion by 2050[7], requiring an additional one billion tons of cereals and 200 million tons of livestock every year[8]. Additional production is required to improve nutrition for the 1 billion people currently undernourished. Thus, future demand for agricultural products is predicted to rise faster than population growth, as incomes rise and diets change in many developing countries. This will

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likely need to occur on existing agricultural lands and could mean a 70-90% increase in global water demand, assuming current production patterns and water productivity[8].

Increased productivity will require the sustainable intensification of land and water resources as scarcity for both rise. Competitive demand between municipal, industrial, and agricultural water uses may increase. Urbanization and economic development are likely to further stress water resources in regions with growing populations[9].

In addition to the demands of a growing population and urbanization, climate change is expected to alter temperatures, precipitation, river flows, and ecosystem water balances. Agricultural systems in higher latitudes may see warmer temperatures and other benefits such as increased land availability for crop cultivation but decreases in snow pack will affect seasonal water flows at lower altitudes[10]. In subtropical regions, the frequency and intensity of droughts and flooding are expected to increase. Deltas and coastal areas may face rising sea levels that overrun the land with saline water. The rate of evaporation and precipitation, and consequently the relative humidity of regions may all change to varying degrees in different regions, affecting the cultivation of crops for agriculture and bioenergy differently in each area[10].

By 2025, two-thirds of the global population is projected to be living in areas of water stress, where periodic water shortages can be expected[11]. Unfortunately, the world's poor will be disproportionately affected by many of these changes. Agricultural land per person in developing countries is less than half of that in developed nations. Unmanaged water resources, poor quality soils, land degradation, and climate uncertainty may contribute to production gaps[8]. Poor practices can further degrade resources, creating a poverty trap in many small farms and contributing to environmental deterioration of local ecosystems[8]. Increasing production of food, forest products, and bioenergy must all be evaluated with a systems view, in the context of regional practices, infrastructure, governance, and resource limitations.

II. Water quantity impacts and metrics

Water use for bioenergy production can be evaluated through a number of different metrics. Two primary measures of water use are water consumption and water withdrawal.

Water consumption is the volume of water removed from the system in question (field, watershed, basin) through incorporation into an activity's product, evaporation, or plant transpiration. In other words, water that is no longer immediately available to the plant, ecosystem or watershed from which the water was drawn is considered consumed.

Water withdrawal is the volume of water extracted from a surface water body or groundwater aquifer. Withdrawn water can be used consumptively, or it can be returned to the

[9] Satterthwaite D, Mcgranahan G & Tacoli C (2010) Urbanization and its implications for food and farming. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**(1554), 2809–2820. doi:10.1177/0956247806063971.

[10] Backlund, P., Janetos, A., & Schimel, D. (2008). The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States. *Synthesis and Assessment Product 4.3 Report by the U.S. Climate Change Science Program* and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC., USA1-202.

[11] United Nations Environmental Programme (UNEP) (2007) *Global Environment Outlook 4*. Environment for Development. Progess Press Ltd., Malta. 1-572.

environment—although it may be to a different water source or at a later time—through seepage, runoff, and discharge[12].

Neither water withdrawal nor consumption fully captures the impact of activity to a watershed. Focusing only on withdrawals ignores the fact that a large portion of water withdrawn may return to the same basin or watershed. Focusing only on consumption ignores that significant water withdrawals may exert localized and/or seasonal impacts on the ecosystem, as in the case of thermoelectric plants with once-through cooling systems. Water that is discharged may not be of the same quality as that which was withdrawn (i.e. returned water may be chemically and/or thermally polluted) and the withdrawal, even though it is eventually returned, can be detrimental to water bodies during times of water scarcity[13]. The vulnerability and resiliency of the watershed to extractions and losses are a critical component of watershed management schemes.

The use of water for irrigation in agriculture illustrates the importance of an integrated view of water use. Roughly half the irrigation water in the U.S. is withdrawn from surface flows (lakes and rivers). Due to inefficiencies in irrigation systems, a large fraction of the withdrawn water may be "lost" from the field. Through one lens these losses are considered be wasteful; however, leakage can be productive. For example, losses from unlined irrigation canals may help maintain surface water flows, recharge groundwater sources, assist removal of salts, restore soil percolation flows, and lead to other hydrological benefits[13]. Understating the sustainability of water diversion and reallocations requires a systemic detailed understanding of the water flows and hydrology.

II.a. Water Footprints

In order to compare across different uses for water and different products, it is often important to evaluate water intensity, the water use per unit of production. This metric is also called the *Productive Water Use*, the *Water Use Efficiency*[14], or the *Water Footprint*. The danger of relying solely on a productive water use measure is the loss of information regarding the *total water use* impacts (i.e. how much total water is leaving the watershed)[15]. Often water footprints are described according to water type. "Blue" and "green" water are terms used to describe artificial and natural water inputs, respectively. These designations allow separate analysis of irrigation (blue) versus precipitation (green). "Grey" water refers to water that was once used by humans (i.e. residential, industrial, or agricultural wastewater). Often grey water is used as a proxy for water quality impacts.

All water footprints include blue water, however, not all analysis treats blue water in the same manner. Blue water may indicate only groundwater irrigation sources or it may include both groundwater and surface water, and may refer to withdrawal or consumption. Some blue water analysis includes hypothetical consumption calculated as the difference between the crop

[12] Gheewala SH, Yeh S, Fingerman KR, Diaz-Chavez RA, Moraes M, Fehrenbach H, Metzler J & Otto M (2011) The bioenergy and water nexus. *United Nations Environment Programme (UNEP), Oeko-Institut, IEA Bioenergy Task 43*, 1–40.

[13] Fargione JE, Plevin RJ & Hill JD (2010) The Ecological Impact of Biofuels. *Annual Review of Ecology, Evolution, and Systematics* **41**(1), 351–377. doi:10.1146/annurev-ecolsys-102209-144720.

[14] Crop or productive water use efficiency must be differentiated from the photosynthetic or gas exchange water use efficiency mentioned previously.

[15] Röckstrom J, Falkenmark M, Karlberg L, Hoff H, Rost S & Gerten D (2009) Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research* **45**, W00A12. doi:10.1029/2007WR006767.

water requirement under non-limited conditions minus the available green water (See Section II.e.2).

Green water refers to natural water inputs such as rainwater. Green water often refers to the evapotranspiration volume that is supplied by precipitation but can include stored soil water and snow melt. "Rain-fed" crops will use only green water sources; whereas the majority of irrigated crops use blue water to augment green water inputs[16]. The inclusion of green water in water footprints is controversial. By some analysis, this water is part of the natural ecological water cycle and therefore should not be counted side-by-side with blue water, which is equivalent to industrial process water when comparing across energy products. It is our view that changes in green water use from a reference state should be considered but that they need to be placed in context with the reference state. For example, comparison of the change in water use between the bioenergy crop and an alternative crop or the natural ecosystem. This use, in conjunction with any blue water use, should also be placed in the full context of the water budget for the specific watershed and/or basin (See Section II.c)

Water intensities, as strictly defined, do not address impacts to water quality (See Section III). One attempt to address this is the broadening of the water footprint to include "grey water". Grey water footprints are defined as the "volume of freshwater needed to dilute a given pollution load to a level that enables the water to be used productively elsewhere"[17]. This metric is somewhat vague and is applied unevenly in the literature. Under this definition, dilution criteria would vary according to the robustness of the subsequent use and/or legal requirements for water purity. The literature supplies insufficient methodology for applying this metric, although many water footprint assessments continue to use it.

Water intensities are often determined by two contrasting methods: 1) estimation based on simple, very rudimentary calculations of water use, and 2) calculation based on the more rigorous full life-cycle assessment (LCA), which includes detailed processing and embedded water across the entire production chain[18,19]. In addition to direct water use, LCA may include water use avoided as a result of co-products, which can displace other processes that require water[20]. In some cases, LCA analyses have moved beyond water footprints to measure impacts related to spatial heterogeneity in water availability and ecosystem consequences[21]. Many new water life cycle bioenergy studies combine all water use and explicitly state sources of water inputs throughout the life cycle, whether green water, blue water (surface or ground), or degradative use/grey water, and some studies are also beginning to estimate application and conveyance losses[15,21,27]. Further integration of local and regional conditions into the LCA, including water quality, water availability, the opportunity cost of water and other socioeconomic considerations, the previous state of the resource and its sensitivity or tolerance

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[16] Hoff H, Falkenmark M, Gerten D, Gordon L, Karlberg L & Rockstrom J (2010) Greening the global water system. *Journal of Hydrology* **384**(3-4), 177–186. doi:10.1016/j.jhydrol.2009.06.026.

[17] Gerbens-Leenes W, Hoekstra A & Meer TVD (2009) The water footprint of bioenergy. *Proceedings of the National Academy of Sciences* **106**(25), 10219-10223.

[18] Ridoutt B & Pfister S (2010) A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global environmental change* **20**, 113–120. doi:10.1016/j.gloenvcha.2009.08.0030.

[19] Wu M, Mintz M, Wang M & Arora AS (2009) Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline. *Argoone National Laoratory Report* ANL/ESD/09-1, January, 1–90.

[20] Arora S, Wu M & Wang M (2008) Update of distillers grains displacement ratios for corn ethanol life-cycle analysis. *Argonne National Lab Report* ANL/ESD/11-1, September, 1–25.

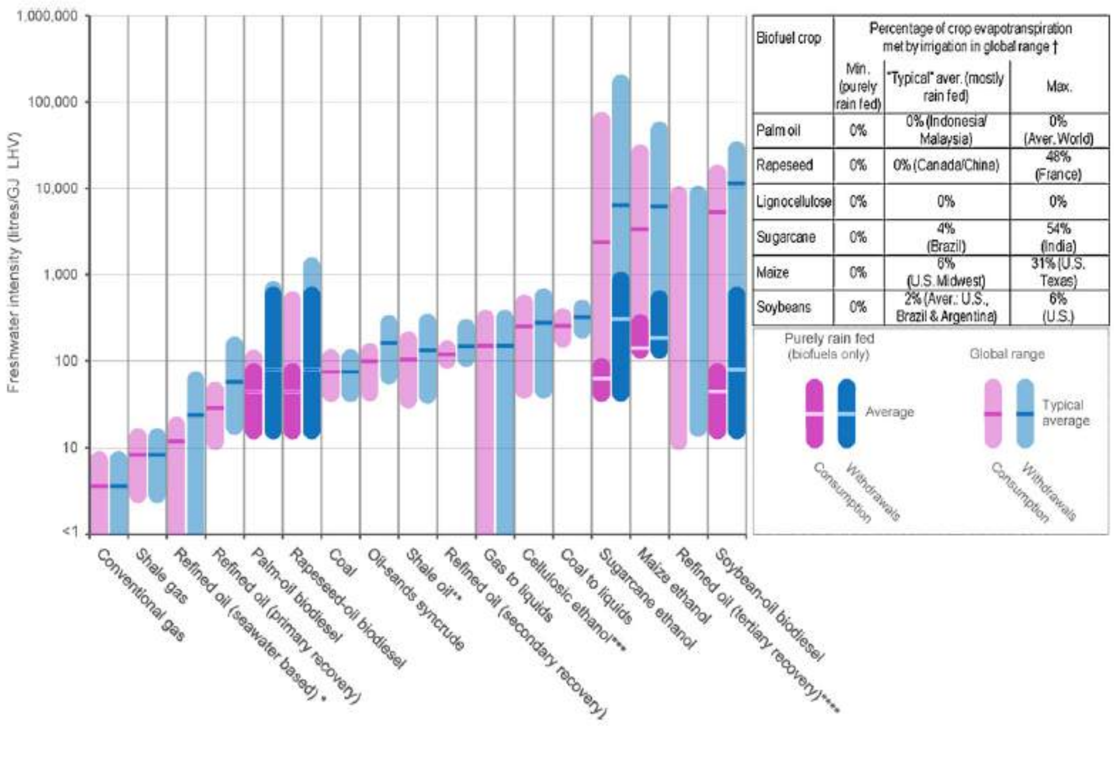
[21] Kounina A, Margni M, Bayart J-B, Boulay A-M, Berger M, Bulle C, et al. (2012). Review of methods addressing freshwater use in life cycle inventory and impact assessment. *The International Journal of Life Cycle Assessment*, **18**(3), 707–721. doi:10.1007/s11367-012-0519-3.

to withdrawal, and temporal variations is expected. These evaluations can be made at a variety of scales.

Comparisons of the lifecycle water intensity of biofuels to their fossil counterparts vary by orders of magnitude[17,19,22] (Figure 5). The intensity for biofuel has two major components, biomass production and conversion of biomass to biofuels. Typically, the water intensity of the conversion process for biofuels is similar to fossil fuels, ranging from one to ten liters of water per liter of fuel. The biomass production water intensity, however, can range from zero to several thousand liters of water per liter of fuel. This variation results primarily from two factors: 1) the many physical and biological factors that affect evapotranspiration and yield of biomass and 2) the system boundaries of the lifecycle analysis – particularly, the variable inclusion of green water input.

As currently applied, these analyses ignore the ecosystem service value of evapotranspiration and, as a result, overestimate water intensity. Unless the bioenergy is being grown on previously paved land, that land was most likely previously covered with vegetation and evapotranspiring. Understanding the difference in evapotranspiration following land cover change is important to evaluating the ecosystem impact of that change. Thus, many biofuel water footprints include water that would be consumed even if bioenergy production were not implemented, obscuring both positive and negative impacts.

Figure 5. Lifecycle Water Intensities of Various Transportation Fuels[23].



[22] Mishra GS & Yeh S (2011) Life cycle water consumption and withdrawal requirements of ethanol from corn grain and residues. *Environmental Science and Technology* 45, 4563–4569.

[23] Schornagel J, Schornagel J, Niele F, Niele F, Worrell E, Worrell E & Böggemann M (2012) Water accounting for (agro)industrial operations and its application to energy pathways. *Resources Conservation And Recycling* 61, 1–15. doi:10.1016/j.resconrec.2011.12.011.

Despite a wide range in possible impacts (orders of magnitude) (Figure 5), well-chosen and well-managed bioenergy crops can help regulate soil moisture levels, reduce run-off, and provide other sustainability benefits to the local environment, provided that the bioenergy production does not strain water flow and recharge for other uses. When considering blue water alone, some rainfed crops may consume less water than the amounts needed for unconventional fossil fuel production[22]. The water intensity of future fossil fuel sources of energy, including bituminous sands (oil sands), require substantial amounts of water and could have severe impacts on water flows and water pollution in the coming decades[24]. Careful assessments of water uses for all future energy sources will be needed to determine the impacts on water availability on local ecosystems.

LCA has been used extensively to characterize the impacts of greenhouse gas emissions. However, greenhouse gases have a relatively similar impact regardless of the point of origination, making their impact assessment easier with a single global metric. Water consumption impacts, by contrast, vary widely by location and context. Tools should account for local water stresses, environmental flows in an ecosystem, and the relative importance of water use impacts relative to other impacts. Quantitative analysis should include cumulative effects, impacts on key habitats, resilience to scarcity, social concerns, and other indirect effects[12]. Comparison of similar activities across locations should be made to assess where and how water use efficiencies can occur. For example, LCA estimates have shown that 10 – 324 liters of water can be required to produce one liter of corn ethanol, depending on the region the feedstock is grown[19]. This variability in water usage highlights the importance of choosing the right crop for the right location. The choice of functional units in LCA can also play an important role in understanding the results of impact assessment and how they are perceived. For example, comparing ethanol production by the water impact per liter of fuel produced or per hectare of land used[25].

The water footprint metric is widely known and popular. It condenses water usage into a single, intuitive measure with appears to be normalized for comparison. However, because it represents water use in a system as a single figure based on average spatial and temporal conditions, it cannot capture local water impacts such water availability, seasonal or other dynamic variations (including droughts), or different types or sources of water used[26]. For example, a volume of water used for agriculture, forestry, or bioenergy in a wet and humid area will have very different consequences than the same volume used in an arid region. Water pumped from a groundwater aquifer with a slow recharge rate is very different from water diverted from a flowing river, though both are considered consumptive water use. Furthermore, impacts can differ widely depending on the time in which the water is consumed. Seasonal or even yearly variability in water availability can change productivity of natural and managed ecosystems. It is thus desirable to estimate water use at the highest spatial and temporal resolution possible. Methods to weight water footprints for regionalized water stress indices have been propsed[18], but these altered footprints still lack enough detailed information to address the hydrology and water flows of the system.

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[24] Taylor A & Woynillowicz D (2006) *Troubled waters, troubling trends. Technology and policy options to reduce water use in oil and oil sands development in Alberta.* 1st Edition, The Pembina Institute, May, 1–171.

[25] Scown CD, Horvath A & McKone TE (2011) Water Footprint of U.S. Transportation Fuels. *Environmental Science and Technology* 45(7), 2541–2553. doi:10.1021/es102633h.

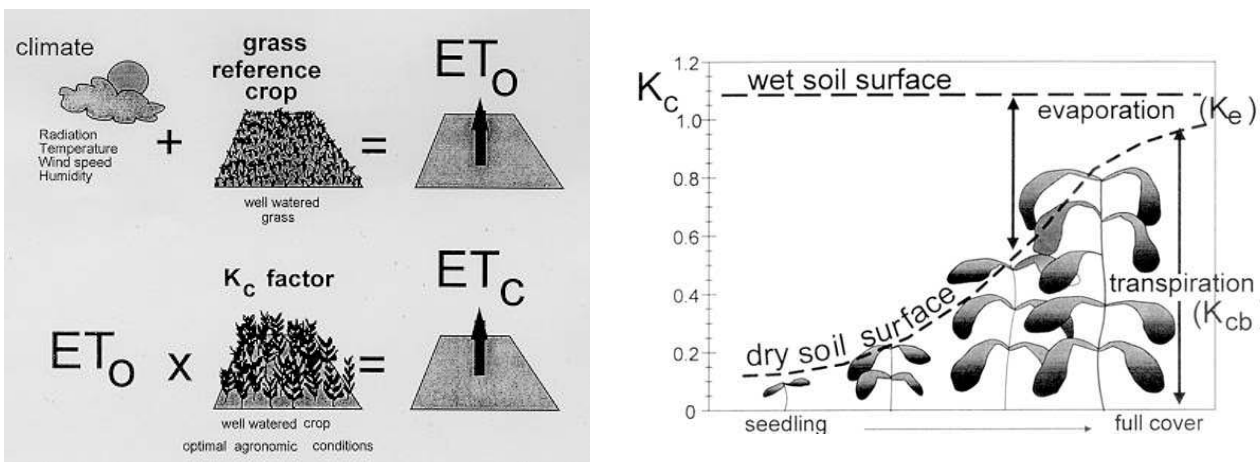
[26] Ridoutt B & Poulton P (2010) Dryland and irrigated cropping systems: comparing the impacts of consumptive water use. CSIRO Sustainable Agriculture Flagship Report, 1–12.

II.b. The special role of evapotranspiration

Evapotranspiration (ET) is the largest driver of water flux in an ecosystem. Evapotranspiration drives plant growth and is an important factor in plant yield. Simple footprints rely on only two terms - water use and yield, both of which are dependent on the evapotranspiration.

Typically, crop evapotranspiration is calculated relative to a reference evapotranspiration rate, ET_o, usually a well-watered turfgrass, using local weather data such as temperature, incidence of radiation, humidity and windspeed, which affect evaporation rates. The crop evapotranspiration, ET_c, is calculated through the crop co-efficient K_c as following: $ET_c = K_c\ ET_o$ (Figure 6). The crop co-efficient represents the growth phase of plant, where evapotranspiration is roughly linear to biomass accumulation. Usually a "typical", mid-season, Kc value is used and the ETc represents a theoretical or potential ET.

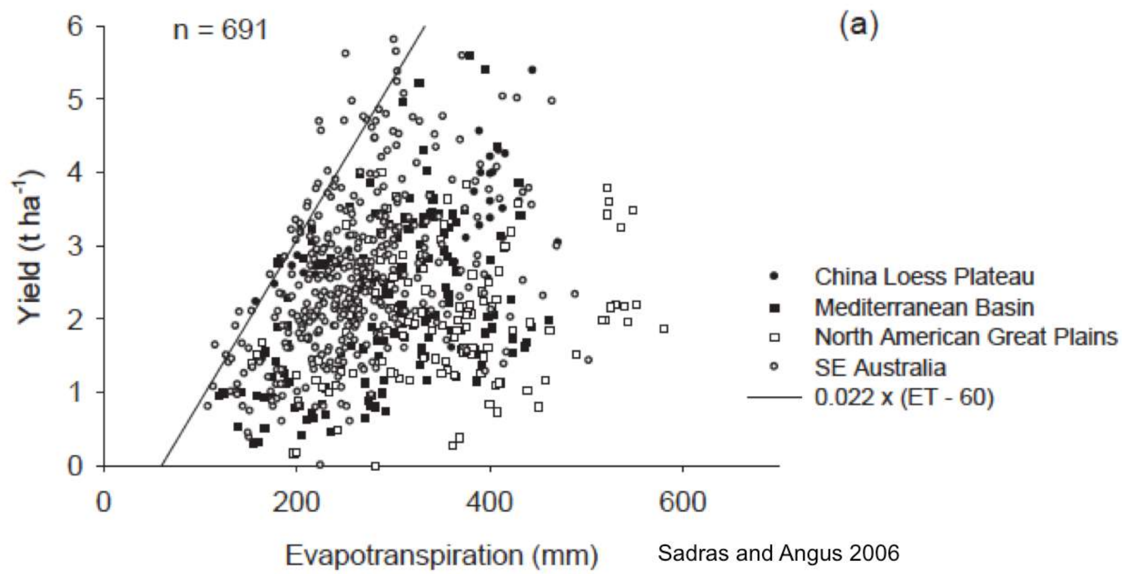
Figure 6. Calculation of crop evapotranspiration[27].

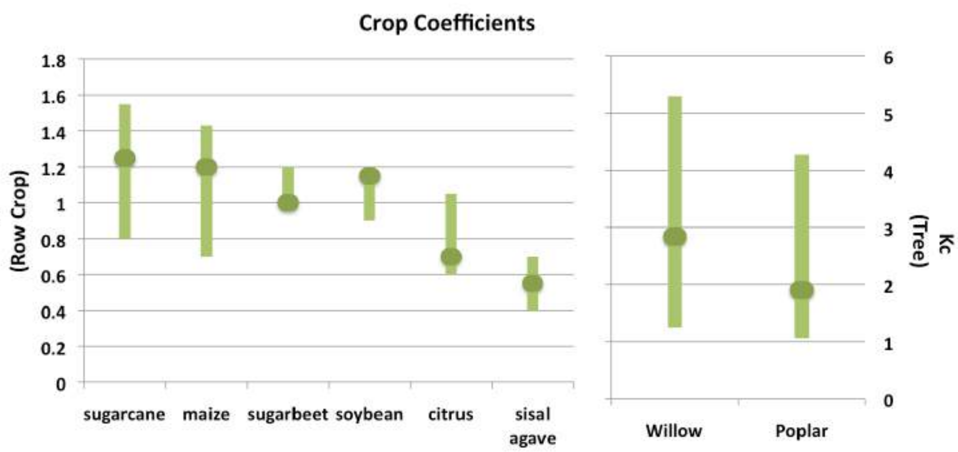


Differences in leaf anatomy, stomatal characteristics, aerodynamic properties and albedo all cause the crop evapotranspiration to differ from the reference ET under the same climatic conditions. Thus, cultivar specific information is more accurate than generalized crop coefficients. Similarly, soil salinity, land fertility, ground cover, plant density and soil water content all affect ET and yield, highlighting the importance of location specific information.

[27] Allen RG, Pereira LS, Raes D & Smith M (2000) Crop evapotranspiration(guidelines for computing crop water requirements). *FAO Irrigation and Drainage Paper* **No. 56**, 1–333.

Figure 7. Measured evapotranspiration of wheat cultivars at various locations[27,28].





Many impact estimates rely on the potential evapotranspiration (PET), rather than actual ET (AET). Of those that use AET, even fewer estimates use actual, measured data, as opposed to modeled "data". Some calculations include an adjustment factor or second crop coefficient called the stress coefficient which modulates yield based on a measured or fitted growth response. Evapotranspiration is modulated by many inter-related genetic and physiological responses, including the number of canopy structure, stomatal number, cuticular waxes, leaf

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[28] Sentelhas P, Gillespie T & Santos E (2010) Evaluation of FAO Penman-Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. *Agricultural Water Management* **97**, 635–644.

[28] Sadras VO & Angus JF (2006) Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* **57**(8), 847. doi:10.1071/AR05359; Guidi W, Piccioni E & Bonari E (2008) Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter. *Bioresource technology* **99**(11), 4832–4840. doi:10.1016/j.biortech.2007.09.055

structure, plant hormones, photosynthesis strategy, and stress responses. The variation in crop coefficients and in AET can be very large (Figure 7).

There are many methods to estimate ET (e.g. Blaney-Criddle, Priestly-Taylor/energy balance, Thornthwaite/water balance, etc.) Accoring to Rose and Sharma, "Some methods are more suitable than others in terms of convenience, accuracy or cost for the measurement of ET at a particular spatial scale or over a particular time scale. It appears no single method has clear advantages in all contexts"'[29]. Many estimates for ET consider only an ideal case - a well-watered, fertilized plant. They thus minimize the uncertainty of abiotic or environmental stress.

ET, and the associated yield, can be limited under conditions of too much or too little water. Under dry conditions, ET is limited by the amount of water in soil that is available to the plant (i.e. in the root zone) or "soil moisture limited". Continued dry periods can cause a plant to lose critical cell moisture for cell homeostasis causing wilting and plasmolysis. Beyond a critical threshold of prolonged water scarcity, the permanent wilting point, plants will be unable to reestablish water movement regardless of how much water is supplied. Yield and ET can also be limited when there is too much water. Under conditions of high humidity and full soil saturation, the physical driving forces to move water through the plant are abated and the plant is said to be "atmospheric moisture limited". Prolonged saturation depletes delivery of oxygen to root cells, a situation to which only some land plants have adapted (e.g. rice). Waterlogging can deplete yield and cause irrecoverable damage to plants.

Another challenge in making ET estimates involves the scale of the modeling calculations. Often ET data at the leaf or field scale is then used to determine effects at the watershed or basin scale. This scaling often neglects microclimate and soil heterogeneity (affecting underlying hydrology and water availability). Similarly, mid-season crop co-efficients are used to estimate total ET in a growth season or year. This scaling of averages introduces large errors, making impact analysis very difficult. Finally, calculations of the same water use in the same region can vary widely due to differences of the spatial boundary chosen for analysis. Different crop yield models have widely varying approaches to the water budget, soil modeling, ET modeling and inclusion of stress parameters – all of which can have profound effects on yield and the water footprint (Table 5, see Section IV).

The ecosystem value of evapotranspiration from both natural and managed vegetation cannot be understated. ET cools the surface layer[30] and can contribute threshold moisture that affects cloud formation and precipitation patterns. Although most ET is considered to be lost from agroecosystems in the current water intensity framework, this water is never lost in the hydrological sense[31]. It will return as rain or other precipitation, either to the watershed in question, or possibly to a neighboring watershed. For example, 15-56% of precipitation in the Amazon basin originates within the basin[3]. Given that water use and losses are effectively water transfers in the wider hydrosphere, incorporating all water flows becomes increasingly important in estimating water use. This often depends on how well the system is defined for capturing

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[29] Rose CW & Sharma ML (1984) Summary and recommendations of the workshop on "Evapotranspiration from plant communities." *Agricultural Water Management* **8**, 325–342.

[30] Mahmood R, Keeling T, Foster SA & Hubbard KG (2013) Did irrigation impact 20th century air temperature in the High Plains aquifer region? *Applied Geography* **38**, 11–21. doi:10.1016/j.apgeog.2012.11.002.

[31] Perry C, Steduto P & Allen R (2009) Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management* **96**(11), 1517–1524.

spatial and temporal differences. Land cover changes, specifically shifting from annual to perennial crops or vice-versa, can have profound watershed effects[32].

Decreasing the water footprint or increasing water productivity, i.e. the amount of crop produced per unit of water used or evapotranspired, is often proposed as a way to balance human and ecosystem needs. The mantra "more crop per drop" epitomizes the desire to value water diversions for human uses. The goal of increased productive water use and valuation of ecosystems will likely drive intensification of agricultural lands for food, feed and bioenergy[8]. There are several non-productive uses of water that can be reduced in order to improve water efficiency[33]. However, "productive" use should include ecosystem services. For example, water runoff from a farm due to irrigation inefficiencies can be recycled back to nearby rivers and used productively at a downstream site, or to support ecosystems.

The shift of non-productive water loss from ET on marginal lands to the productive evapotranspiration (ET) of bioenergy production may also be a positive benefit. To ensure this transition occurs without overstraining the local ecosystem, an understanding how the land use or land cover change will be beneficial or not relies, in part, on sound estimates of changes in the rates of evaporation/evapotranspiration resulting from these transitions requires full knowledge of the local water balance.

II.c. Water budgets

Water budgets or water balances are one of the most important tools for understanding water impacts of bioenergy production. Water budgets attempt to account for water input (e.g. precipitation in all forms, irrigation) and withdrawals (e.g. evaporation, transpiration, seepage/drainage, runoff). Such a budget can be used to assess potential water surplus or deficit, which is useful for projecting irrigation requirements. Water budgets are also important in understanding changes in surface flows for ecological function and have been used to understand the effects of land cover and land use change mainly in forests, especially in the context of afforestation.

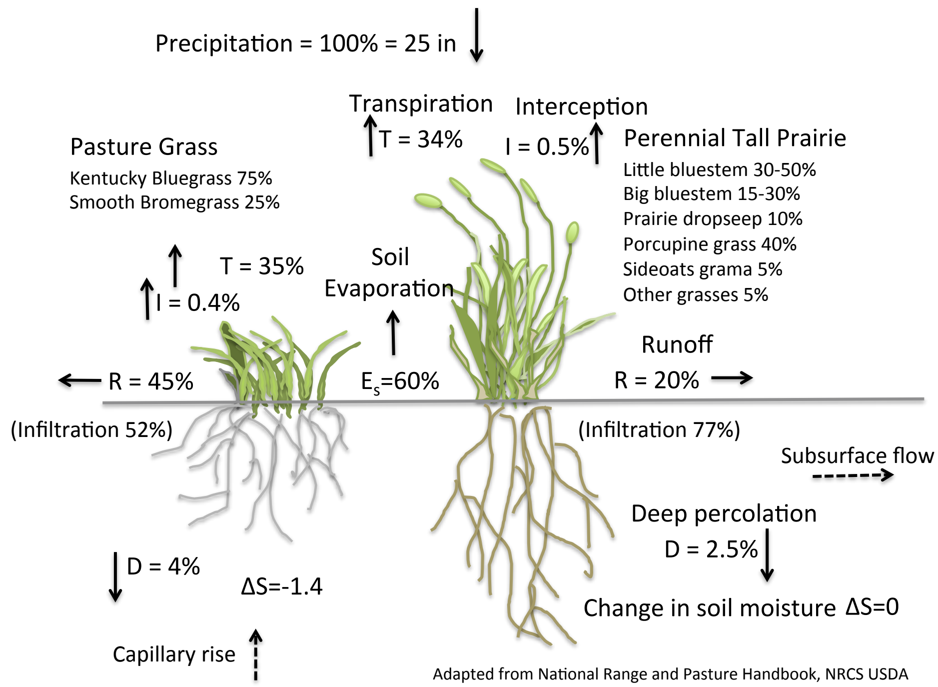
In general, moving from systems with bare soil to those with increased canopy coverage and/or above-ground biomass will shift water loss from evaporation to transpiration, increase interception of rainfall, and increase water extraction from the soil. Changes in surface and atmospheric water flow will be affected by weather conditions, soil moisture and permeability, slope, canopy architecture, plant spacing and plant physiology. Similarly, moving from annual systems with relatively low root profiles to perennial systems with extensive and persistent root systems will enhance soil water infiltration, increase soil water extraction and reduce runoff. The changes on the subsurface water flow will be affected by root architecture, water table, subsurface water flows, and soil structure and chemistry (Figure 8).

[32] Bagley JE, Desai AR, Dirmeyer PA & Foley JA (2012) Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets. *Environmental Research Letters* **7**(1), 014009. doi:10.1088/1748-9326/7/1/014009; Schilling KE, Jha MK, Zhang Y-K, Gassman PW & Wolter CF (2008) Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resources Research* **44**(7) W00A09. doi:10.1029/2007WR006644.

[33] Burt CM, Clemmens AJ & Strelkoff TS (1997) Irrigation performance measures: efficiency and uniformity. *Journal of irrigation and engineering*. **123**:423-442.

Unfortunately, the wide variation in the use and availability of measured data and the application of modeling methodology and theoretical approaches makes it very difficult to compare water budgets side by side from different analyses. These differences can be categorized based on resolution of various parameters as described in Section II.d.

Figure 8. Water Balance for two grass mixtures[34]



The effect of canopy cover is an important consideration in water budgets that is often included in forest water budgets but insufficiently parameterized in agricultural water budgets[35]. Plants with large canopies effective reduce the precipitation reaching soil by intercepting rainfall and allowing some portion to evaporate directly from leaf surfaces. During intense rainfall events or rainfall with large drop size, interception is diminished, increasing effective precipitation and runoff. For example, an oak tree might normally intercept 25% of precipitation but only 7% of heavy rainfall[36] (Figure 9). Whereas conventional row crops may not present large changes in interception, next generation energy crops such as Miscanthus are likely to have large effects on effective precipitation. Sodgrass intercepts only 10% of rainfall, whereas Tall Bunchgrass intercepts 18% and Miscanthus intercepts 25%[37].

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[34] NRCS (2003) Rangeland and Pastureland Hydrology and Erosion. In National Range and Pasture Handbook, National Resources Conservation Service, USDA 190-VI, NRPH December, 7.1–7.31.

[35] Calder IR (2002) *The blue revolution: Land use and integrated water resources management*. 2nd Edition. Earthscan, London. 374p.

[36] Blackburn WH (1985) Range improvements to maximize rainfall runoff. *Proceedings of the International Ranchers Roundup. Laredo, Tex* 375-382; Hester JW (1996) Influence of woody dominated rangelands on site hydrology and herbaceous production, Edwards Plateau, Texas. Master's thesis, Texas A&M University. Available electronically from http : / /hdl .handle .net /1969 .1 /ETD -TAMU -1996 -THESIS -H47.

[37] Finch, J. W., & Riche, A. B. (2010). Interception losses from Miscanthus at a site in south-east England-an application of the Gash model. *Hydrological Processes*, *24*(18), 2594–2600. doi:10.1002/hyp.7673

Sidebar - Water budget parameters

II.c.1 Resolution of water budget variables.

Most water budgets include precipitation, potential evapotranspiration and runoff. More nuanced budgets will also account for canopy interception, soil storage, drainage, and actual evapotranspiration. Most budgets do not discriminate evaporation from transpiration in vegetated areas but rather report a combined evapotranspiration term, which may or may not include soil evaporation in some form. Variation in resolution aboveground, in the canopy layers, or belowground, in root zone layers, impacts yield, water availability, and evapotranspiration calculations.

II.c.2 Geographic resolution.

Geographic areas range from field or stand to county or regional scale, only sometimes corresponding to watershed boundaries. Water budgets at the field scale are most appropriate to water use decisions by farmers which may include the need to invest in irrigation in water limited scenarios or drainage in water excess scenarios. However, field scale budgets may not be representative of water balance in the watershed or basin.

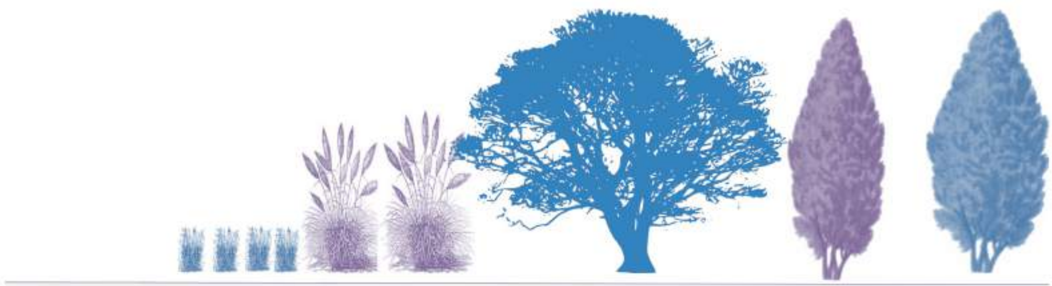
II.c.3 Temporal resolution.

Most budgets report in terms of seasonal or yearly totals. Seasonal budgets are reported only for the "growing season", starting at planting and ending with harvest. Thus, the number of growing days during which evapotranspiration is occurring will differ for different crops and different regions. In these cases, accounting for soil moisture during the non-growing season is handled by a variety of methods of variable rigor. Reporting of seasonal or yearly budgets does not adequately reveal short-term water imbalances such as water deficit in dry summer months or periods of excessive run-off following high precipitation events. While many models have moved to hourly data, this resolution is not often translated into the budget analysis.

II.c.4 Resolution of data

It is sometimes difficult to distinguish between measured and modeled or estimated parameters in water budgets. Often budgets are artificially closed through adjustment of different terms. For example, an unexplained loss of water from the system may be counted as drainage or runoff, whereas an unexplained gain of water may be counted as non-seasonal soil water storage or subsurface in-flow. This can result in over-estimated water quality impacts and mis-estimation of plant available water and thus evapotranspiration, water demand, and yield. Most often, these represent systematic errors that can be detected and corrected by model validation through actual measurements. However, measurement techniques may also introduce errors. For example, the use of eddy-covariance at the canopy level of a forest may underestimate water flux in humid environments, as well as, conflating soil evaporation and understory evapotranspiration. Problems with up-scaling of leaf-level measurements and resolution and down-scaling of remote sensing methods have also been observed. Models and data for first-generation bioenergy feedstocks such as maize, sugarcane, wheat, sugarbeet, sorghum and some woody systems are available with varying degrees of validation and resolution, however, very little data is available for novel feedstocks such as perennial grasses and agave.

Figure 9. Water budgets for different land covers[36].



	Bare ground	Shortgrass/ Sodgrass	Tall Bunchgrass	Live Oak/Oak Motte	Redberry Juniper	Ashe Juniper
Canopy Interception	0%	10.8% [0.4%]	18.1% [0.5%]	25.4% [7.0%]	25.0%	36.7%
Runoff	[75%]	[45%]	[24%]	[0%]		
Litter Interception				20.7% [12%]	40.1%	43.0%
Stemflow				3.3%	7.9%	5.1%
Infiltration	[25%]	89.2% [54.6%]	81.9% [75.5%]	53.9% [81%]	34%	2.03%

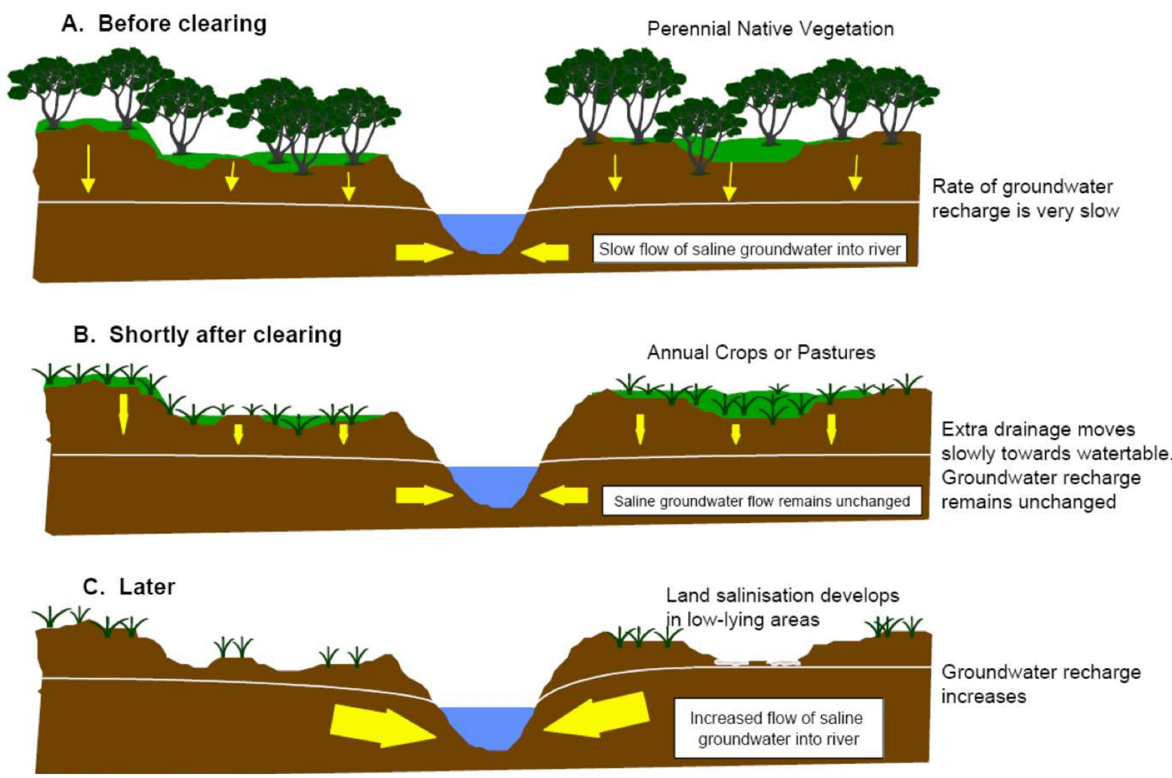
Adapted from Hester 1997 and Blackburn 1985. [Brackets denote intense rain event 10 cm in 30 minutes]

A water footprint, primarily based on an estimate of water loss through ET alone, is clearly insufficient to account for all of the impacts of land management choices. Water budgets, while much more comprehensive, also do not include effects of land cover changes on water quality nor do they take system stress, vulnerability or resiliency into account. They do offer an important starting point for an integrated framework. The water balance is required to further understand choices in land use on watershed hydrology and can be used in land-climate feedback modeling. Resolved water flow information is also critical in evaluating possible non-point source contributions of land cover and mangement to water quality. Monitoring and remediation of surface flows is part of on-going land-water management decisions worldwide. In particular, the effects of land cover choices, particularly transitions between perennial grasses or forest and annual cropping systems, on water flows is being closely examined in the US, China, South Africa and Australia (see Impact Case Study Section II.d. and Impact Case Study IV.a.). This type of anlaysis is particularly appropriate when considering wide-scale implementation of next-generation energy crops.

II.d. Impact case study I: Land cover changes in Australia

Australia represents an interesting case study where land cover changes have resulted in substantial changes to the regional water balance. Clearing of perennial vegetation for cultivation of annual row crops increased infiltration and recharge rates, which, in turn, increased flows to rivers and raised water tables. The occurrence of shallow groundwater tables allowed migration of saline water to the surface, contaminating soils (Figure 10).

Figure 10. Effect of perennial vegetation clearing in Australia[38].



In some parts of the country, transitions to plants with higher water use such as Eucalyptus, are being used at field borders to draw down water tables and reduce salination. The public reaction to "decreased water flows" represents an interesting example of the importance of reference systems. Decreased water flow in rivers following restoration of perennial vegetation is more representative of the native ecosystem state but may still be perceived as a negative change. The change in vegetation may also be responsible for as much as a 10% reduction in vapor flows across the continent, equal to 240 kM^3 of freshwater. Additionally, land cover change may be responsible for an increased volume of unmanaged freshwater runoff, up to 15 times the managed volume, representing substantial depletion in available freshwater[39].

[38]Cook PG, Kennett-Smith WGR, Budd GR, Williams RM & Anderson R (1997) The impact of dryland of agriculture on land and river salisation in south-western New South Wales. *Australian Journal of Soil and Water Conservation* **10**:29-36.

[39] Gordon L, Dunlop M & Foran B (2003) Land cover change and water vapour flows: learning from Australia. *Philosophical Transactions of the Royal Society B: Biological Sciences* **358**(1440), 1973–1984. doi:10.1098/rstb.2003.1381.

II.e. The special role of irrigation

Irrigation has contributed greatly to our ability to produce more food and feed, using less land per ton. It has also reduced risk to food supplies from climate effects. More than 40% of the increase in food production in the last 50 years has occurred on irrigated acres[8]. Crop yields on irrigated acres can be twice that on productive rainfed acres, highlighting the advantage of water availability and timing through the growing season. Because the yield advantage with irrigation is substantial, it is likely that many parts of the world will choose to use irrigation to produce food, fiber and, possibly, bioenergy. Globally, roughly 301 million hectares (~20% of cultivated land) is equipped with irrigation. 70% of irrigated acreage in 2009 was in Asia, 12% in North America, 8% in Europe, 10% in the rest of the world. The majority of irrigation infrastructure will be used to augment rainfed production[8]. Irrigated acreage is expected to increase to 318 million hectares in 2050, reflecting a slowing rate of expansion. The largest potential for expansion of irrigation is in Africa and Eastern Europe[8].

Although irrigation has many advantages, it can also cause many problems including salination of soils, land degradation from waterlogging, attenuation of river flows, contaminated drainage water, as well as increasing competition for limited water supplies with other industries[40]. These problems have diminished support for irrigation in many contexts[41,56]. Whether irrigation can be beneficial in the long-term or not depends on a variety of water flow and water quality factors, each specific to an individual watershed and water management strategy.

Worldwide roughly 323 million hectares of land are considered saline. While a large fraction of salt-affected soils are naturally occuring, the increase in salty soils due to human activity is disturbing. Most crop plants have very little tolerance for salt, thus, management that increases salt accumulation effectively removes arable land from produciton. Worldwide, roughly 11% of irrigated land has some degree of salination.

Salt accumulation in soils occurs through a number of mechanisms, in both wet and dry soils. All water contains dissolved salts to some degree. In dry conditions water is consumed by transpiring plants, leaving much of the salt behind it can collect in the root zone of soils that are irrigated[57]. Over time, these accumulated salts can change the land's ability to support vegetation, unless leached from the soil to surface water bodies and/or driven downward through seepage.

Waterlogging, or the saturation of soil water, occurs when fields are irrigated in excess of the amount of water taken up by the crop, which can mobilize ions to move from deeper soil or groundwater to the root zone. Waterlogging can be prevented with better management, precise application of irrigation water, and an understanding of the local water table. In areas of seasonal heavy rainfall, accumulated salts wash out naturally and irrigation is less problematic. For example, in many areas of Southeast Asia irrigation is used to extend crop cultivation in the dry season. In arid or semi-arid regions, however, where most irrigation occurs,

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[40] Letey J (1994) Is Irrigated Agriculture Sustainable? *Soil and Water Science: Key to Understanding Our Global Environment.* Baker RS, Gee GW, Rosenzweig C (eds.) Soil Science Society of America Special Publication No. 41 R.S. Baker, Madison, WI. 23-39.

[41] Hillel D & Vlek P (2005) The sustainability of irrigation. *Advances in Agronomy* **87,** 55–84.

excess water application is sometimes used as a method to prevent salts from accumulating in the root zone[42].

If the water table is deep and the system naturally well-drained (i.e. lateral flows are rapid), the balance of water and salts in the soil can remain productive for crop cultivation. If, on the other hand, the water table is shallow and drainage is slow, the application of irrigation water can force the water table to rise. Within years, it can reach the soil surface and saturate the root zone, in some cases with salty water, flooding crops and depriving their roots of oxygen necessary for respiration. Hence, adequate drainage from the root zone is important for land maintenance[43].

Salt accumulation can be prevented through precise control of water application to satisfy exact crop requirements as well as a fractional amount extra for leaching[44,45]. Modern irrigation technologies such as micro-sprayers, low-energy precision application sprinklers, and drip irrigation tubes placed on the ground or below the soil surface can help by applying water directly into the root zone without wetting the entire soil surface and minimizing the wetting of vegetation, and can achieve much higher water efficiencies than conventional systems[45].

High frequency irrigation can modulate the concentrations of salts at the soil surface at levels near the irrigation water itself, better distributing the salts deeper into the soil away from the root zone and keeping the matric potential of soil moisture at a level high enough to avoid stressing the crop[45,41]. Of course, this can increase water use. Further improvements are achieved by multifunctional systems permitting fertilizers and pesticides to be applied with irrigation water; computerized control systems can improve application precision while reducing labor, and remote-sensing techniques (such as infrared monitoring of canopy temperature to detect plant stress) can help tailor treatments to spatially variable field and plant conditions. Average irrigation efficiencies may be less than 50% and can be as low as 30%; however with proper management, irrigation efficiencies of 80 to 90% can be achieved[33,41]. Promoting water use efficiencies not only lowers water costs, it can also mitigate land degradation by waterlogging and soil salination.

In areas where natural drainage is slow and artificial drainage installation and persistent operation of artificial drains may be required[46]. Surface drainage involves appropriately shaping the land to remove water from the surface with laser-guided shaping and surge-flow techniques. The leaching process can also be enhanced if the applied water contains electrolytes to reduce the swelling and dispersion of clay in the soil. The most common compounds used for pulling clay colloids out of suspension and enhancing water infiltration are gypsum ($CaSO_4 \bullet 2H_2O$) and calcium chloride dihydrate ($CaCl_2 \bullet 2H_2O$)[47]. Groundwater drainage systems buffer against water table rise with ditches, pipes, and channels to drain accumulating water to a nearby stream, lake, or ocean. In some cases, drainage water may be collected and

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42 Hillel D (2000) *Salinity Management for Sustainable Irrigation. Integrating Science, Enviroment, and Economics*. World Bank. Report 20842, August. 92 p.
43 Wallender WW & Tanji KK (2011) *Agricultural Salinity Assessment and Management*, Second Edition. ASCE Manuals and Reports on Engineering Practice Vol. 71, American Society of Civil Engineers. 1094 p.
44 Rawlins SL & Raats P (1975) Prospects for High-Frequency Irrigation. *Science* **188,** 604–610.
45 Pereira LS, Oweis T & Zairi A (2002) Irrigation management under water scarcity. *Agricultural Water Management* **57**(3), 175–206.
46 Hoffman GJ (1985) Drainage required to manage salinity. *Journal of Irrigation and Drainage Engineering* **111**(3), 199–206.
47 Nelson RE (1982) Carbonate and gypsum. In *Methods of Soil Analysis Part 2 Chemical and Microbiological Properties*. Page AL (ed.) Soil Science Society of America, Madison, WI. pp 181-197.

recycled or reused. Sustainability concerns arise when irrigation redistributes groundwater to surface drainage in excess of recharge rates.

If low quality irrigation drainage percolates downward toward an aquifer rather than laterally, it can contaminate groundwater and make the larger resource unusable. Nitrates, chlorides, and pesticides can collect in groundwater, posing health hazards to those relying on wells for water[48]. In many areas, complex water quality problems must be addressed to achieve sustainable irrigation. The concentrations of naturally occurring elements (selenium, arsenic, and boron), fertilizers (nitrates, phosphates, and organic chemicals), and pesticides must be reduced in agricultural drainage water to protect the quality of groundwater and surface water[49]. Farmers can reuse saline drainage water, rather than discharging it to public waterways, so long as water salinity isn't excessive. The major salts in irrigation water contributing to high salinity include Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{-3}, and HCO_3^{-}. Thus, monitoring the quality of water for total salt concentrations and other toxins becomes an important component water management in irrigated systems to determine where and to what extent used irrigation water can be discharged or reused.

In certain circumstances, available brackish or recycled drainage water can be used for the irrigation of salt-tolerant crops. This is especially relevant with deep sandy soils, where there is rapid drainage and little risk of water table rise or soil salination. Various strategies have been proposed for the use of brackish water, including the direct (re)use for irrigation, or first blending with clean for subsequent use in irrigation. Another option is to alternate applications of brackish water with higher quality water when applicable. As with many water-related issues, the optimal strategy will depend on the local circumstances, including how saline the water is, how tolerant the crops are, how sensitive the soil is, how rapidly salt leaching can occur.

Several salt-tolerant next-generation bioenergy crops could be important in utilizing stranded agricultural land. Salt-tolerant trees, which include *Eucalyptus*, *Acacia*, *Casuarinas*, poplar, mesquite, *Elderica* pine, and tamarisk, have the ability to successfully grow with brackish water, and can also lower the water table via extraction and transpiration of water from deeper layers in the soil, reducing the volume and expense of drainage needed in an area. The harvested wood may be used for bioenergy, pulp, or construction. Salt-tolerant crops and grasses include sugar beets, sorghum, barley, cotton, and prairie cordgrass. The tolerance of a crop to salinity greatly depends on its stage of growth and its overall health, as well as on external variables like ambient temperature, atmospheric humidity, soil matric potential, nutrient availability, and soil aeration -- again making the cultivation of salt-tolerant crops a local decision.

The human health effects of water diversion and irrigation should also be considered. Mismanagement of of water resources can lead to a spread of water-born diseases. Therefore, in planning any expansion of irrigation systems, public health professionals should be involved in the irrigation scheme's design and operation. Concrete lining of the delivery and drainage channels can be useful to reduce water loss and prevent water stagnation along riverbanks. Vegetation adjacent to channels and reservoirs can be managed to prevent the clogging and stagnation waterways and the harboring of water-related diseases[65].

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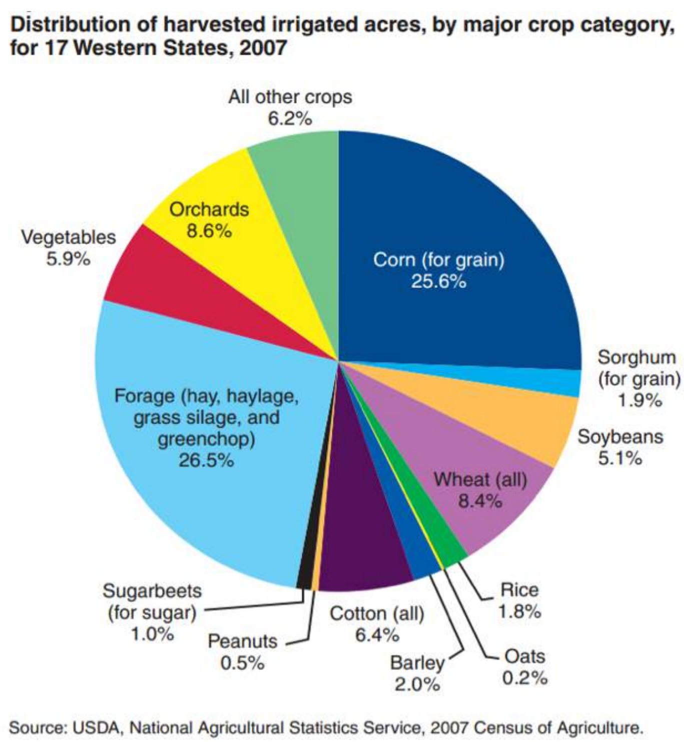
[48] Köhler K, Duynisveld WHM & Böttcher J (2006) Nitrogen fertilization and nitrate leaching into groundwater on arable sandy soils. *Journal of Plant Nutrition and Soil Science* **169**(2), 185–195. doi:10.1002/jpln.200521765.

[49] US National Research Council (2012) *Water implications of biofuels production in the United States*. US National Academies Press, Report 12039, 1–87.

By having full consideration of watershed dynamics, it is possible to sustainably incorporate irrigation into agriculture, forestry, and bioenergy production systems. Investing in sustainable irrigation, with careful management and a complete watershed approach, can result in long-term improved economic and social well-being. Additional costs include those for modern water delivery, control, and monitoring systems, as well as robust systems for water drainage and transport. Careful management of water resources requires knowledge of the rates of water table rise or depletion, groundwater recharge, surface runoff, and other water flows. Full valuation of water and water services is also an imperative. Where the price of irrigation water is often lower than the cost of labor or equipment needed for careful management and does not include environmental value[7]. Improving water productivity must include development of crop strains that require less water and fewer nutrients, as well as combined metrics that balance economic and environmental productivity. Careful management decisions such as the strategic selection of well-suited crops for local watersheds often requires systemetization of options beyond simple profit- or market-mediated factors.

II.f. Impact Case Study II - Irrigation in U.S. Corn Ethanol Production

Figure 11. Irrigation in the western United States.

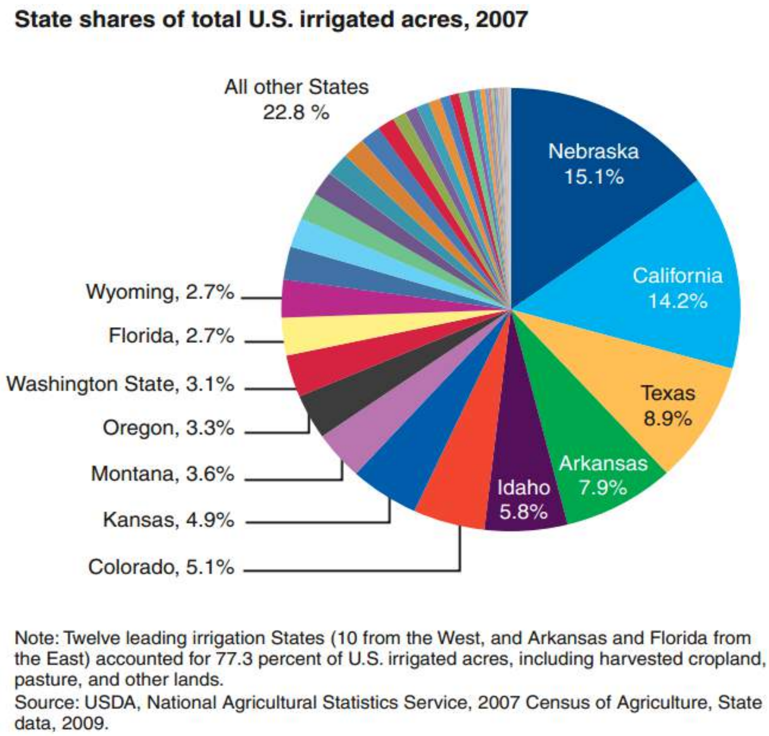


Roughly 7.5% of all cropland and pasture in the U.S. was irrigated in 2007[50]. Large-scale irrigation efforts in the American West began at the turn of the 19th century with settlement by European farmers. Extensive expansion of irrigated acres occurred from 1940 to 1970, following the Great North American Dust Bowl of the 1930s[51]. Irrigation and conservation farming were implemented to reduce erosion, mitigate crop risk, and encourage population of the western and plains states. In the U.S., irrigated acres have increased but only marginally over the last 40 years, rising from 40 million acres in 1969 to 57 million acres in 2007[52]. Over that same time period, the average amount of applied water has decreased from 25 inches to 20 inches[57], derived roughly equally from surface and groundwater sources[52]. The decreased rate of expansion and improved efficiency was due, at least in part, to improved environmental awareness and sustainability concerns.

[50] US Department of Agriculture National Agricultural Statistics Service (2010) 2007 Census of Agriculture, 2008 Farm Ranch and Irrigation Survey. Summary Report 1–4. (The most recent Census of Agricultural Data available is for 2007, the survey deadline for 2012 will be completed later this year.)

[51] Opie J (1989) 100 Years of Climate Risk Assessment on the High Plains: Which Farm Paradigm Does Irrigation Serve? *Agricultural history* **63**(2), 243–269.

Figure 12. Irrigated acreage by state.



In 2007 corn was grown on 23% of the total irrigated acreage in the U.S. (Figure 12), and 26% of the irrigated acreage in the Western states with the highest irrigation demand (Figure 11). The long-term sustainability of these water withdrawals deserves much scrutiny. The ethics of depletion of future water supplies for the nutritional needs of current populations (food, feed, fodder) must be weighed carefully. Arguably, even more care must be exercised when using shared water resources for fuel production.

There appear to be two main camps with regards to irrigation and biofuel production. One view is that with a new market for biomass and economic drivers to mitigate yield risk, irrigation water will be a substantial input for biofuel feedstock production, threatening sustainability of watersheds. The opposing view is that the economics and drivers for sustainability will limit the expansion of irrigated biofuel feedstocks (especially lignocellulosics) in favor of rain-fed feedstocks. Current estimates indicate that biofuel production represents less than 1% of irrigated acreage worldwide[8].

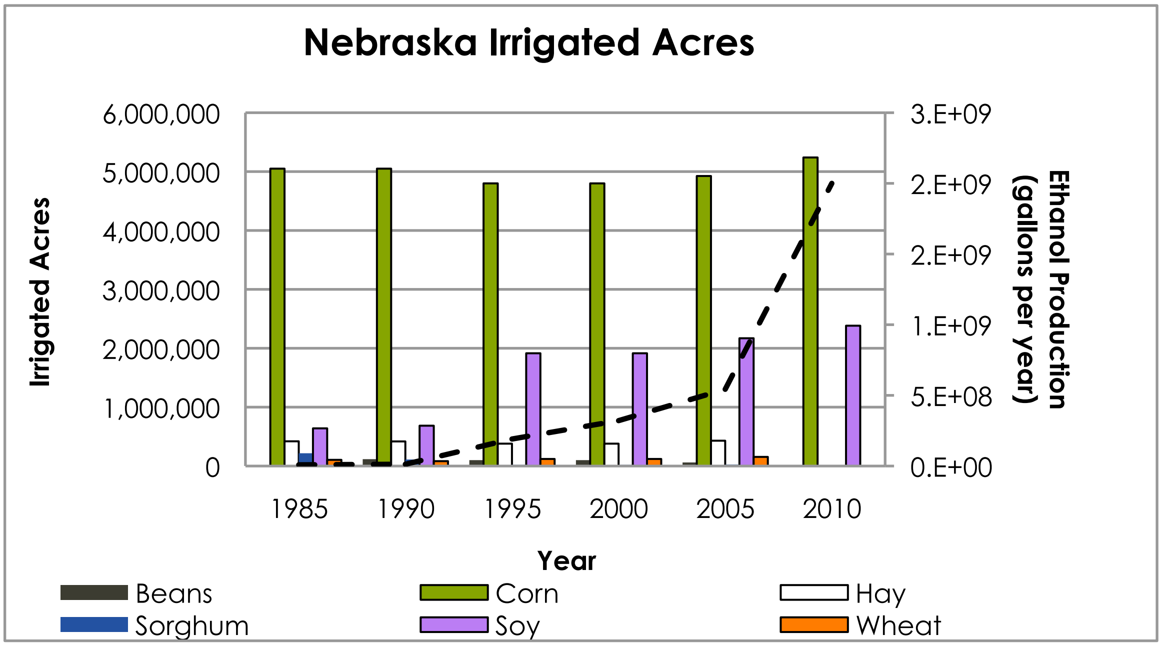
The dataset for corn production in the U.S. is easily accessible and spans a century of agricultural development, including expansion of irrigation and the corn ethanol era. Thus, it should be possible to discern the effect of the ethanol expansion on irrigated corn. Nebraska has the highest number of irrigated acres in the U.S. (Figure 12) and is one of the major corn producers. The state is home to 25 corn ethanol plants, which began production in 1987. Thus, it makes a great case study for examining the expansion of biofuel in a water limited area and the effects on irrigation.

It has been stated that expansion of ethanol production was one of many drivers that increased irrigated acres in Nebraska.

"From 2002 to 2007, agricultural water use reflected a net increase of nearly 1.3 million irrigated acres across the United States. Nebraska accounted for nearly a million of those additional acres, with lesser increases in Arkansas, Colorado, Mississippi, Missouri, and Georgia. Irrigated acreage expansion in these States was attributed to availability of water supplies, improved irrigation economics (partly due to higher crop yields and reduced water costs associated with more efficient irrigation systems (USDA/NRCS, 2006)), **increased biofuel demand for corn**, recurring regional drought conditions, and the prospect of future restrictions on new irrigation development (at least for Nebraska)"[52]

To understand this effect, we looked at statistics for irrigated corn in Nebraska, with the hypothesis that at a critical threshold of ethanol production straining demand for corn, a substantial increase in irrigated corn would be detected. The data does not appear to support this. The number of acres of irrigated corn did not substantially increase during the expansion of ethanol production. Irrigated water use during this period also did not increase, despite an increase in yield (Figure 13).

Figure 13. Irrigated crops by acreage in Nebraska since the implementation of corn ethanol



Irrigated corn area appears to be steady at 5 million acres, with a slight increase between 2005 and 2010, despite an increase in corn ethanol production from 8.5 million gallons to over 2 billion between 1985 and 2010 (Figure 13). In contrast, there an additional 1 million acres of irrigated soybean were harvested between 1990 and 2010[53]. The ratio of irrigated to non-irrigated corn acres actually declined during the period of ethanol expansion in Nebraska (Figure 14). Although there does not appear to be a large increase in water use for corn production, the variation is quite large. It is clear, however, that yield increases have been steady for both irrigated and non-irrigated corn (Figure 15).

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[52] Schaible GD & Aillery MP (2012) Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands. *Economic Research Service Report* No. 99, 1–67.

[53] Nebraska has no current biodiesel production. Northeast Nebraska Biodiesel operated from 2007 to 2009 producing 5 million gallons per year of soy biodiesel; Horizon Biofuels operated from 2006-2009 producing 400,000 gallons of biodiesel from waste oils, planned to build a 6.2 million gallon per year facility were scrapped, currently the company has reorganized to sell wood pellets; Beatrice Biodiesel had planned a 50 million gallon per year soy plant but the plant was never completed.

Figure 14. Ethanol production and irrigation in Nebraska[54].

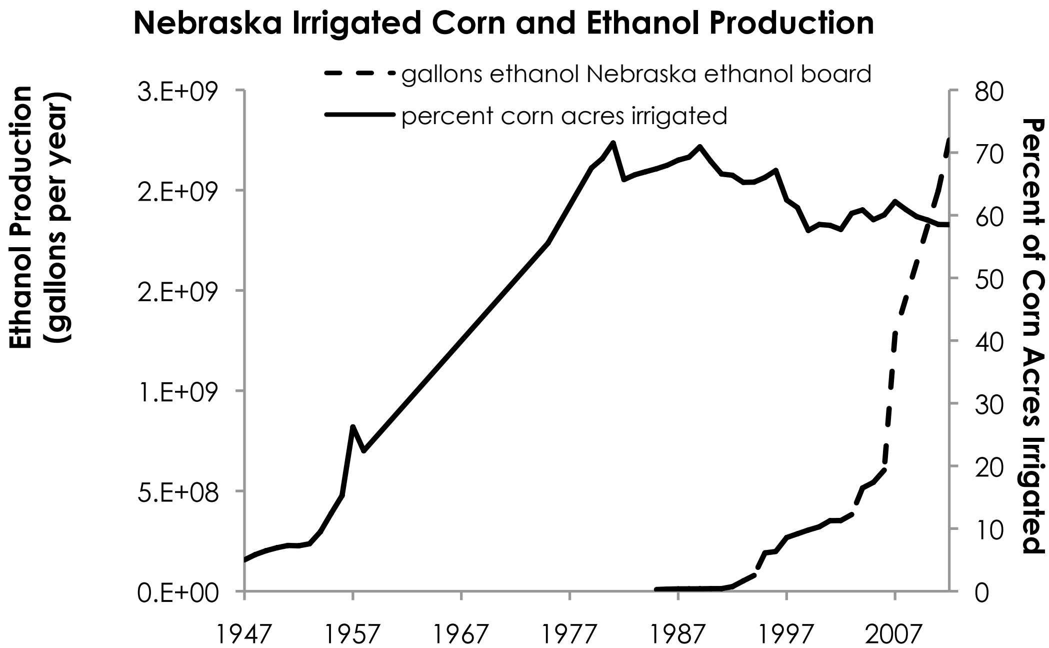
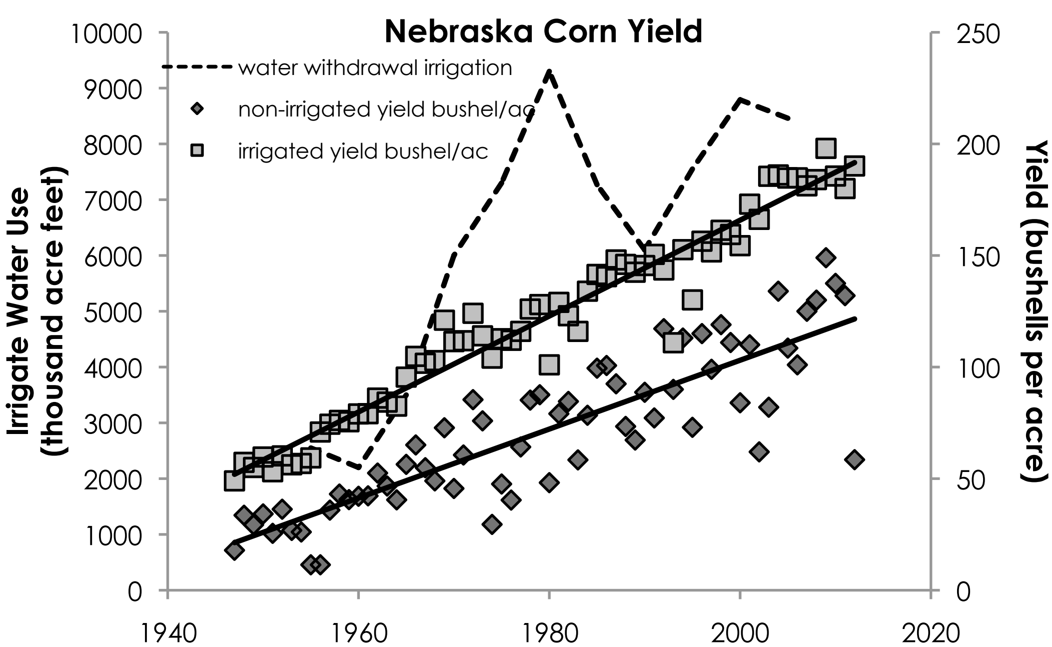


Figure 15. Corn yield and irrigated water use in Nebraska[54,50].



[54] USDA National Agricultural Statistics. QuickState 2.0 http://www.nass.usda.gov/Quick_Stats/index.php Accessed May 2013.

Counter to popular belief, preliminary examination of this data provides no evidence that implementation of corn ethanol has caused an increased demand for irrigated corn or the water to irrigate corn. This is not to say that irrigated corn is not being used for biofuel production. It only means that irrigated corn acreage and water use for irrigated corn was not substantially influenced by *in an obvious manner* by ethanol production. The additional corn supply for ethanol production can be explained by increased yield (some of which is on irrigated acres), displacement of feed corn by distiller's grains, and a slight increase in non-irrigated acres, or through movement of corn feedstock from neighboring states.

It is possible that the increase in irrigated soy in Nebraska was an indirect result of pressure on corn production. For example, if changes in the corn and soy rotation in Iowa pushed soy production from rainfed acres to irrigated acres in Nebraska, the additional blue water demand should be partially attributable to corn. However, we do not see any evidence for this either. Soy acreage increased from 8 million acres in 1985 to 10.6 million acres in 2000, falling to 9.7 million acres in 2010. During the period of soy increase in Nebraska (1990-1995), soy acreage in Iowa also increased, by 1.36 million acres. A further examination of soy demand for biodiesel production, feed demand and other market interactions is required to rule out indirect effects.

It may be argued that increases in corn yields would have caused irrigated corn acreage to decrease in the absence of corn ethanol such that the current situation represents an increase in water use over a hypothetical present with ethanol. However, others have argued that without the additional demand driver, yield improvements would not have been realized. It is important to recognize that drawing a system boundary around Nebraska may not be sufficient in understanding the total water impacts. Understanding the total market including the supply-side, demand-side, fungibility and market interconnectedness is required to fully account for impacts on land and water use

The Nebraska analysis prompted a further investigation of estimates of irrigation or blue water footprints of biofuels. The literature revealed four main types of estimates of varying detail, rigor, and bias. A detailed analysis of feedstock sourcing by ethanol plants and a total supply market analysis is required to understand several important factors including the fungibility of corn in the different markets and possible indirect effects. The role of contracts, production costs for irrigated corn, and other socioeconomic factors may affect fungibility of corn stocks.

SideBar: General Estimate Types

Type 1 – Standard "back-of-the-envelope" estimates.

Simple, straight-forward, intuitive, back-of-the-envelope estimates can be extremely valuable in scoping the general sense of an issue setting the stage for discussion. However, most require gross simplification, usually with several key assumptions that can bias the calculation.

Type II – The pessimistic estimate or "pestimate"

Analyzing a pessimistic scenario is an important technique for exercising the precautionary principle in risk management and can be extremely useful in examing the extreme boundaries of scenarios. There may be a tendency to adopt the extreme as "the value", rather than "the extreme value", which can become a self-validating metric in subsequent analyses.

Type III – The optimistic estimate or "bestimate"

Bestimates are just as important as pestimates. They provide the other boundary of an assessment – what could things look like if everything is done well and we have not blundered in our understanding of what is possible.

Type IV – The "highly resolved" estimate example

The best water analyses will always have higher resolution because water impacts have complex, very local, interactions. Geographic resolution is especially important as water impacts are a local issue. That being said, geographic resolution is not always enough. An understanding of the system dynamics is also required. It is tempting to treat "resolved" estimates as measurements because they may have (or give the appearance of having) detailed underlying data.

II.g. Corn Blue Water Footprint Estimates

II.g.1 Type I – Standard "back-of-the-envelope"

A simple estimate of irrigation for corn ethanol uses the fraction of corn irrigated (15% of harvested acres in 2007) and the fraction of corn going to ethanol production. These numbers vary depending on the accounting. For example, in 2010, 12.4 billion bushels of corn were produced, of which 5 billion were used as ethanol feedstock (~40%) but an estimated 1.2 billion bushels corn equivalent worth of DDGS were "returned" as feed[55], bringing the percentage actually producing ethanol down to (~31%). Most analysis use the higher estimate such that 40% of 15% or roughly 6% of corn would be considered irrigated for ethanol production. This type of estimate has shown up in popular press including the Wall Street Journal and various blogs. It assumes that all corn is completely fungible (complete elasticity for irrigated versus non-irrigated substitutions with no regional constraints – see below) which likely results in a slight overestimate of irrigated feedstock and/or water use for biofuel.

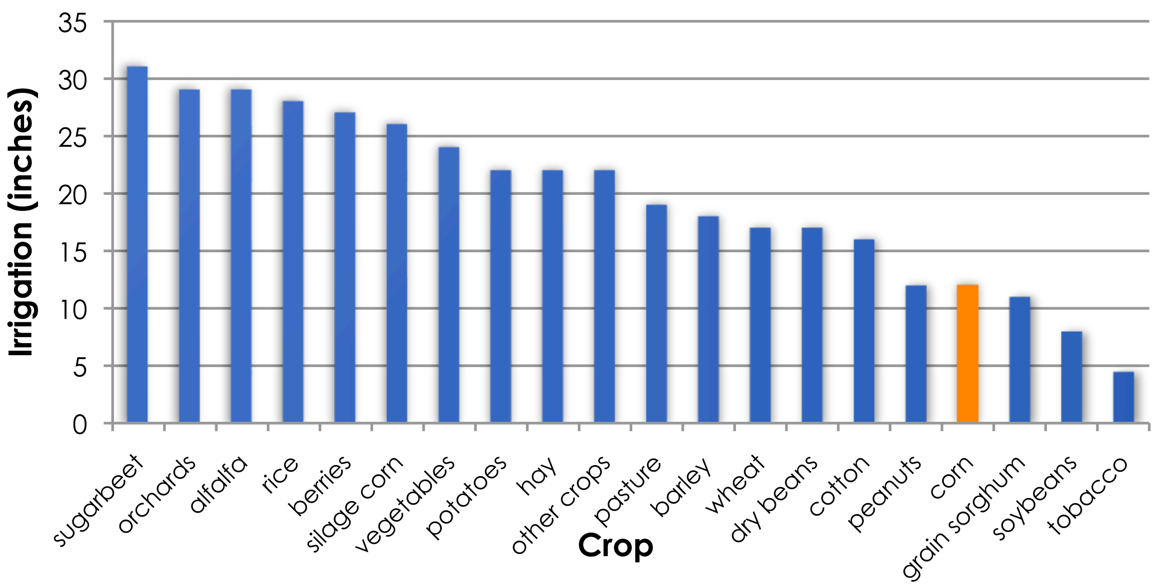
[55] Jessen H (2012) World of Corn report breaks down corn used for ethanol, DDGS. *Ethanol Producer Magazine*, March 1.

Another version is….

"From 2001 to 2006, irrigated corn-planted acreage held fairly steady between 8.6 to 8.9 million acres. Beginning in 2007, however, irrigated corn acres varied between 9.1 and 10.1 million, an increase between 6 and 18 percent from the prior average.[19,20] To put this in some context, this means that in 2007, when 20 percent of corn production went for ethanol, water consumption for irrigated corn for ethanol amounted to approximately 3 percent of total water consumption in the United States. In 2010, 40 percent of the crop went to ethanol, bumping water consumption to roughly 6 percent of the U.S. total….Irrigation uses 80.6 percent of all water consumption; in 2007, the last year for which data are available, there were 10.1 million acres of irrigated corn out of a total of 56.6 million acres of all irrigated land (17%); 20 percent of corn production went to ethanol in 2007. (0.806*(10.1/56.6)*0.20)*100 = 2.8 percent."[56]

This example further assumes that there is no difference in irrigation requirements of corn versus other crops such that a percentage of irrigated corn acreage can approximate a percentage of water use for irrigation. Figure 16 clearly shows that this is not true.

Figure 16. Applied irrigation (inches) of major US crops[57].



II.g.2 Type II – The pessimistic estimate or "pestimate"

Pestimates abound in the bioenergy literature. For example, the calculation of the water footprint for ethanol from sugar beet, sugarcane, and maize was approached as follows.

"The calculation of the crop water requirement (m3/ha) was done by applying the calculation model CROPWAT 4.3 (FAO, 2008b) which applies the FAO Penman-Monteith method (Allan et al., 1998) to estimate reference evapotranspiration. The irrigation requirement is calculated as the difference between the crop water requirement

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[56] Faeth P (2012) U.S. Energy security and water: The challengs we face. *Environment Magazine* January-February. http://www.environmentmagazine.org/Archives/Back%20Issues/2012/January-February%202012/US-Energy-Full.html

[57] Gollehon N (2011) Groundwater and agricultural bioenergy feedstock production. 2011 Groundwater Protection Council Annual Forum, Atlanta, GA September 26. (1 inch = 1 acre inch per acre = 27,160 gallons)

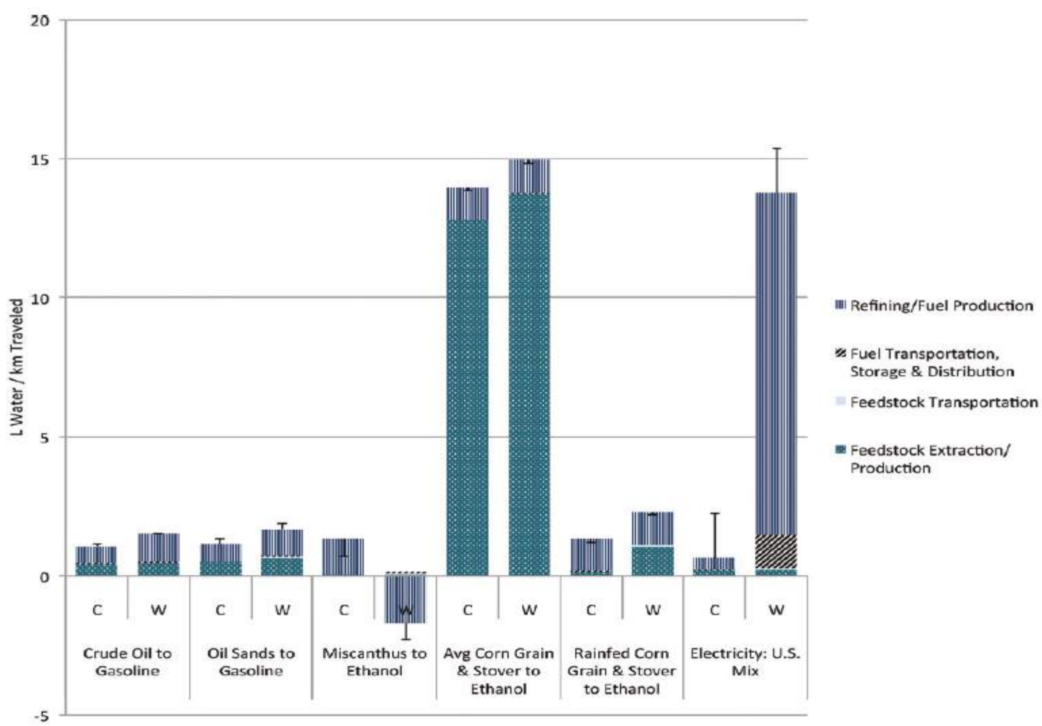
and the effective rainfall. It is assumed in this study that irrigation requirements are actually met, which may lead to some overestimation of water use in some cases. On the other hand, evaporation losses in irrigation have not been included, which may lead to some underestimation in some other cases."[58]

While this example did actual calculations of evapotranspiration that are quite involved, it then went a step further to maximize evapotranspiration through the assumed use of irrigation to meet perceived water deficit from the limits of actual precipitation. The second component of a water footprint is the yield. In the above example, FAO yields were used, which reflect the actual growing conditions where the feedstock has been produced in the past, which are limited by precipitation and other climate effects. Water availability and management practices such as use of high yielding strains and fertilizers will affect yield. In most cases, the actual yield is less than theoretical. Dividing the theoretical maximum evapotranspiration by a physically limited yield will overestimate or give a very pessimistic water footprint.

II.g.3 Type III –The optimistic estimate or "bestimate"

In terms of water and bioenergy, bestimates are most often applied to lignocellulosic feedstocks. The fundamental premise is that if next generation biofuels are "done right", new perennial feedstocks such as energy grasses will not compete with conventional agriculture for land or water. In other words, they will be grown on marginal acres without irrigation and therefore there will be no water impact. In a far-reaching example, one could even come out ahead with a negative footprint if wastewater were to be used as an input and returned as potable, or if other water intensive energy production was displaced in ethanol production (Figure 17). This would be considered an extremely optimistic footprint.

Figure 17. Life-cycle analysis of water use in biofuels[25].



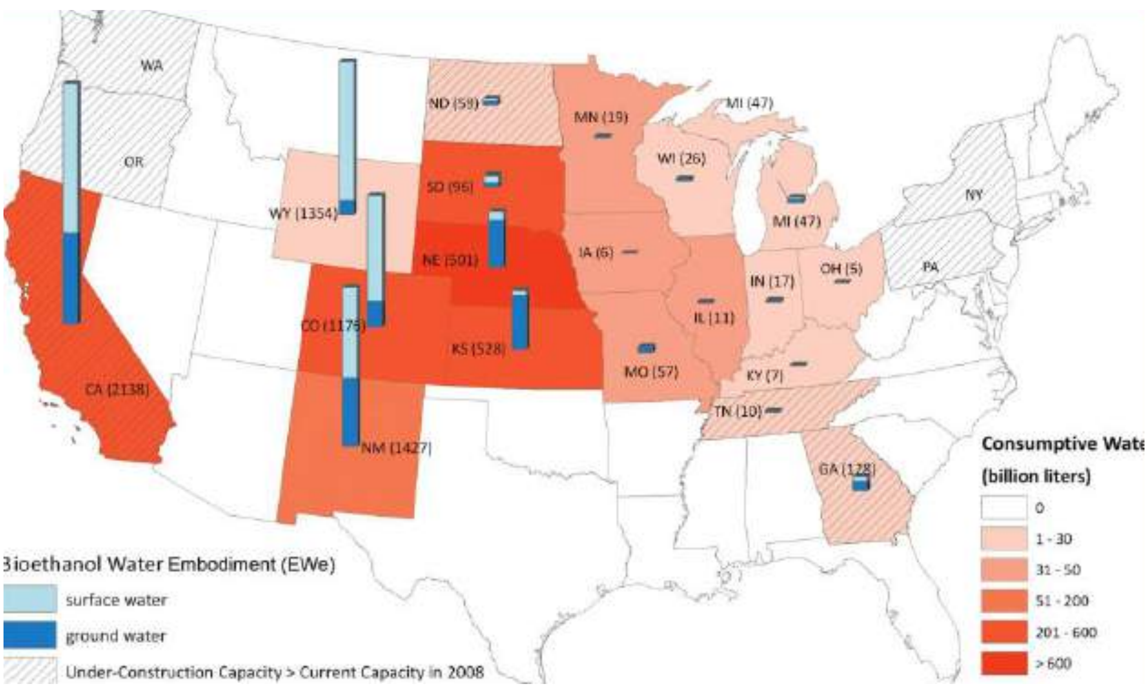
[58] Gerbens-Leenes PW & Hoekstra, AY (2009) The water footprint of sweeteners and bio-ethanol from sugar cane, sugar

As discussed elsewhere, changing land use cover will affect water resources. Whether this impact is positive or negative requires detailed analysis. It is also entirely probable that some dedicated energy crops will receive irrigation at some point in their growth cycle, typically during establishment. The precedence for irrigating low value crops has been set. Behind corn, which occupied 23% of irrigated acres in the US in 2007, irrigated hay is the next largest occupying 21% of irrigated acres. In California, the largest water use in irrigation is alfalfa at five million acre feet per year, followed by pasture at 3.3 million acre feet per year[59].

II.g.4 Type IV – The "highly resolved" estimate example

This type of estimate has the potential to be highly informative and/or very misleading, depending on the reliability of the underlying, often highly reticulated, data. In this example, spatially explicit data regarding corn production and irrigation is documented and overlaid with corn ethanol production (Figure 18)[60]. The resultant local water footprint by state and region is calculated and normalized for production and this weighted footprint is used to show that irrigation in ethanol has increased. The approach is intuitive and has a level of resolution that could be valuable in forward-looking scenarios.

Figure 18. Geographically resolved water footprint for corn ethanol



Unfortunately, the data as presented give rise to potentially misleading conclusions. For example, this work evaluates]the embodied water (water footprint) of ethanol in California and New Mexico. Both states do grow irrigated corn and both states have ethanol plants. Irrigated

beet and maize. *UNESCO-IHE Institute for Water Education Value of Water Research Report Series*, November (No. 38), 1–44.

[59] Hanson B (2010) Irrigation of agricultural crops in California. Presentation to the California Air Resources Board. December. Sacramento, CA. (1 acre foot = 325,900 gallons)

[60] Chiu Y-W, Walseth B & Suh S (2009) Water Embodied in Bioethanol in the United States. *Environmental Science and Technology* 43(8), 2688–2692. doi:10.1021/es8031067.

corn acreage in California is about 670,000 acres while Arizona has 56,000 acres. California has several ethanol plants with a combined production capacity exceeding 250 million gallons per year, while Arizona has one plant with capacity for 15 million gallons per year. The authors assume the following.

> "For corn used by biorefineries, we assumed that corn ethanol was produced using locally grown corn as the primary feedstock, because more than 80%of the corn supply was transported from within 64 km of ethanol facilities (24) because of the proximity of ethanol facility location and corn production (Figure 1). [...] "After determining each county's corn production levels, we measured what portion of each state's production was required for bioethanol production. As illustrated in Figure 1, county corn production closely relates to ethanol facility location. In an earlier study in 2003, Shapouri et al. (24) found a similarly close correlation of facility location and corn production in their energy balance study of corn ethanol in the U.S."[61,62]

In most locations, the assumption that ethanol facilities are built where corn is produced is justified. Biomass is generally expensive to transport. However, the situation in California is unusual. The corn in California is largely dedicated to satisfy feedlot and dairy feed demand not ethanol production. In fact, only two of the five large refineries even attempted to use some percentage (up to 20%) from local sources. Instead, corn was brought in by rail from the unspecified regions of the Midwest[63]. This is confirmed by the production data (Table 2).

Table 2. Corn and ethanol production in California.

Year	Grain Corn (tons)	Silage Corn (tons)	Operating Ethanol Production Capacity (million gallons)
2007	968,240	12,058,000	80
2008	928,200	13,118,000	247
2009	806,400	10,010,000	5
2010	982,800	11,263,000	57
2011	777,000	12,350,000	177

In 2007, California farmers produced close to a million tons of grain corn, which can be used for animal feed or ethanol, but they produced twelve million tons of silage corn, which is used exclusively for local animal feed. In 2009, following the economic turndown of 2008, all of the corn ethanol facilities in the state were idled. Only plants using local waste products as feedstocks remained in operation. However, corn production was not significantly altered. Nor was production significantly altered as corn ethanol production came back on line in 2010 and 2011.

It is understandable how the assumption that local corn would be used to supply the ethanol plants could be made without a thorough understanding of the system. These plants were using corn and local corn was being produced. However, the result is an extremely inflated water

[61] Chiu Y-W, Walseth B & Suh S (2009) Water Embodied in Bioethanol in the United States. *Environmental Science and Technology*, **43**(8), 2688–2692. doi:10.1021/es8031067.

[62] Note the use of the word "measured" as applied to the portion of corn production needed for in-state biofuel production. This is an unfortunate illustration of confusion of observed data with calculated, modeled or estimated values which permeates the biofuel space at almost every level of analysis. To *calculate* the portion of production needed, the authors had to assume a conversion efficiency which they fail to specify. No *measurements* were taken.

[63] McKinney J (2009) Status of Biofuel Production Facilities in California. AB118 Investment Plan Biofuels Workshop, September 14-15, Sacramento CA, 1–11.

footprint (2,138 liters water per liter ethanol compared with 6 liters per liter in Iowa). It is impossible to qunatify the actual water footprint of California corn ethanol without more detailed knowledge of the market sales and/or production contracts. The issue again becomes one of the fungibility of corn and the interconnectedness of the feed corn and corn for ethanol markets. The effect of indirect effects must also be considered. For example, did pressure from the corn for ethanol demand result in increased water impacts in total production or displacement of feed corn production.

The assessment for New Mexico is a little more baffling. The authors acknowledge that the corn production in the state is insufficient to support the plant and must be imported from other states but no specification as to the source of imported feedstock is mentioned (the plant is located near the Texas border). What is baffling is that the plant has never used corn. It uses locally grown sorghum (milo)[64]. It is not clear that the footprint for sorghum, most likely irrigated, would be any better than the estimate for corn; however, the system should at least be faithfully represented in the analysis.

III. Water Quality Impacts and Metrics

III.a.Water Quality Indicators

In any comprehensive management of water resources, the quality of water that is run off or discharged into surface water bodies, or percolated into groundwater aquifers, can have great impacts on the local ecosystem and must be addressed in addition to any water quantity concerns. Agricultural, forestry, and bioenergy systems can have profound positive and/or negative effects on water quality in the immediate vicinity, and, because water systems are highly interconnected, they can also impact supplies very far away. The biological, chemical, or physical type of water quality alteration can vary significantly from location to location. These changes can affect aquatic ecosystems and as a consequence human health and biodiversity as well[12].

The ecosystem vulnerability and resilience of watersheds to water quality impacts is highly variable. The local conditions, land cover choices and the extent of management of an agricultural, forestry, or bioenergy system determines either water quality degradation or improvement. Bioenergy production affects water quality in both the growth of biomass feedstocks and the conversion of biomass to biofuel. Feedstock production occurs over vast areas and is categorized as non-point source; while the conversion of biomass feedstocks into fuel occurs at specific biorefinery sites, and is considered a point source of pollution, as many other industrial uses of water are. Generally, regulation of water quality impacts from point sources is easier than regulating pollution from diffuse sources[65].

Water quality assessments, regardless of the exact pollutant in question, most frequently involve comparison of measurement criteria indicators against reference standards. Commonly, a maximum permissible concentration, or change in the indicator is set by policy[66]. Most often

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[64] http://ethanolproducer.com/articles/7391/abengoa-restarts-30-mmgy-portales-ethanol-plant; http://www.grainnet.com/articles/abengoa_bioenergy_corp__begins_expansion_at_portales__nm_ethanol_plant-24750.html

[65] Boyd CE (2000) *Water Quality: An Introduction*. Kluwer Academic Publisher, Norwell, MA. 330 pp.

[66] US Environmental Protection Agency (1994) *Water Quality Standards Handbook: Second Edition* http://water.epa.gov/scitech/swguidance/standards/handbook/index.cfm.

these standards address human health (the safety of human contact, drinking water), the potential of water use by other industries, and, less often, some ecosystem criteria.

There are many physical, chemical, and biological indicators to gauge aspects of water quality. The most accurate measurements of water quality are made on-site when the sample water is still in equilibrium with the environment. Common measurements made in direct contact with the water source include temperature, pH, dissolved oxygen, conductivity (measuring total salt concentration), and oxygen reduction potential (ORP). These inidicators have immediate impact on aquatic species health and survival.

Other common indicators include biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). Biochemical oxygen demand indicates the dissolved oxygen amount needed by aerobic organisms in a body of water to break down organic material present in a given water sample under set conditions. It is a measure of the amount of biologically active organic matter present in the water, indicating organic water quality. Chemical oxygen demand more generally measures all organic material, not just that which is biologically active. Total suspended solids are the dry-weight of particles (e.g. inorganic material from sugarcane washing or soil sediment) found in a sample trapped by a filter of specified pore size and is related to water turbidity[67]. The oxygen demand can indicate the liklihood of anoxic zone formation, which can devastate aquatic diversity.

To assess fertilizer and pesticide inputs of bioenergy production, the NRC has suggested calculating the amount of fertilizers and pesticides per unit of net energy gain[67]. Under this scheme, low-input, high-diversity lignocellulosic feedstocks or other native species, which require few supplemental nutrients and produce large amounts of biomass to be converted to fuel, would fare well as compared to the first-generation corn and soybean biofuels[49]. Even though these metrics exist, using them to determine acceptable standards of environmental degradation by a given process or industry can be complicated, because local conditions will determine how sensitive or tolerant an ecosystem is to the polluted water. Furthermore, regulations and standards vary widely throughout the world. In Brazil, the BOD and pH standards are very different from those of the U.S. EPA or the World Bank[68]. Some certifications also evaluate the use of the agrochemicals or pesticides for water quality assessment.

III.b.The water-nutrient-productivity nexus

A catch-22 of water use in agriculture is the inverse relationship of water and nutrients use efficiencies in most crops[69,70,71]. Often as nutrients become more available, water productivity decreases (Figure 19). This poses a dilemma of (low) water quantity use versus (high) water quality for attaining a desired productivity level that must be decided for each system[42]. Even further, these relationships imply a trade-off between yields and water & fertilizer use that need

[67] Perry J & Vanderklein EL (2009) *Water Quality: Management of a Natural Resource*. 2nd Edition e-book. Wiley-Blackwell, Cambridge, MA. 656 pp.

[68] Smeets E, Junginger M, Faaij A, Walter A, Dolzan P & Turkenburg W (2008) The sustainability of Brazilian ethanol—An assessment of the possibilities of certified production. *Biomass and Bioenergy* **32**(8), 781–813. doi:10.1016/j.biombioe.2008.01.005.

[69] Pereira LS, Oweis T & Zairi A (2002) Irrigation management under water scarcity. *Agricultural Water Management* **57**(3), 175–206.

[70] Wani SP, Rockström J & Oweis T (2009) Rainfed Agriculture: Unlocking the Potential. *CABI Comprehensive Assessment of Water Management in Agriculture Series* **7**, 1–326.

[71] Sadras VO, Grassini P & Steduto P (2011) Status of water use efficiency of main crops. *UN FAO SOLAW Background Thematic Report* - TR07, 1–41.

to be evaluated not only for local ecosystems but also for local socioeconomics. Achieving water and nutrient use efficiency may conflict with efforts for agricultural intensification and land use efficiency.

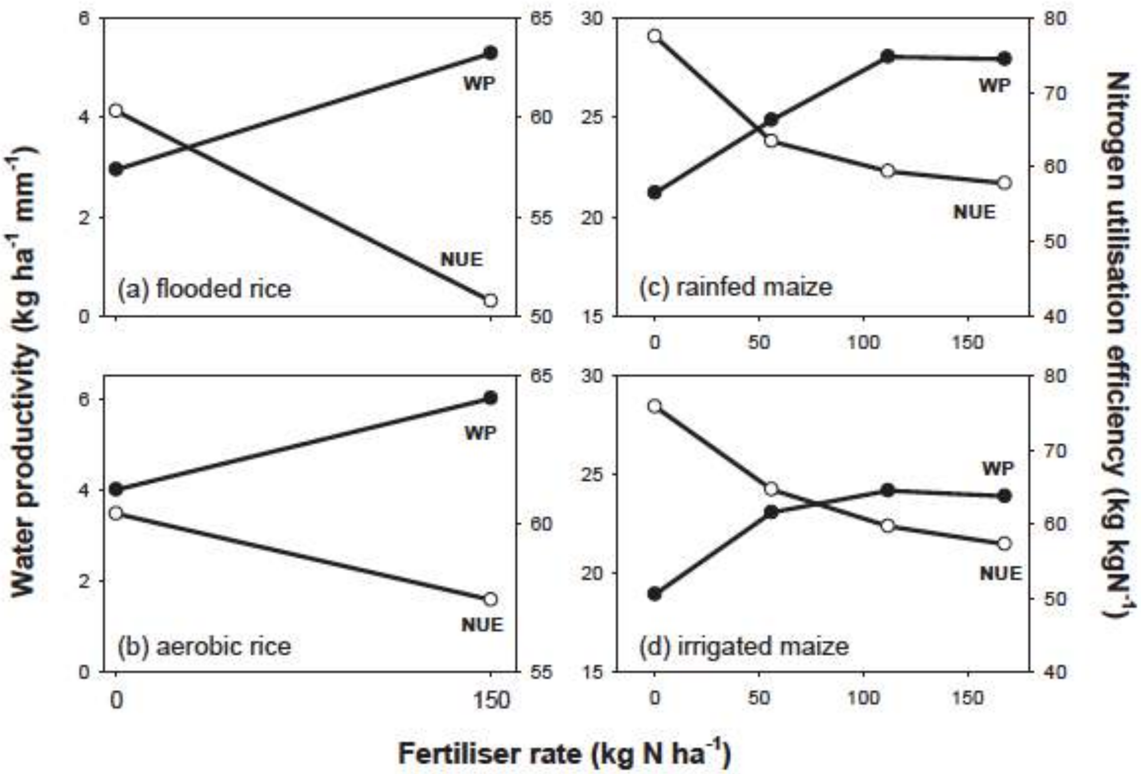

Figure 19. Water productivity and nutrient use[7].

Fertilizers, mainly nitrogen (N) and phosphorous (P), are used to increase yields but their application on the soil surface may eventually end up in water bodies. They can have significant impact on the quality of both groundwater and surface waters, and in particular may lead to the eutrophication of wetlands and other water bodies[72]. High nutrient loading stimulates algae growth, which eventually produces an excess of organic matter and depletes water of available oxygen, causing the death of other organisms including fish. An extreme example of this is the excess nitrogen from the Mississippi river that has created an anoxic 'dead zone' in the Gulf of Mexico. Thus, the application of fertilizers, while important for yields, can have severe implications for water quality and the local ecosystem. Irrigation in agriculture also has water quality effects, where the runoff of salts may contribute to salinization of surface waters. In agriculture and forestry, water quality parameters typically examined are nitrate-nitrogen (NO_3-N), ammonia nitrogen (NH_3-N), total N, total phosphorus (P) and orthophosphate (PO_4- P),

[72] Ongley ED (1996) Control Of Water Pollution From Agriculture. *FAO Irrigation and Drainage Paper* 55. http://www.fao.org/docrep/W2598E/W2598E00.htm.

cations such as sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg), micronutrients, sediment, and temperature[73].

Tillage and plowing can also have negative effects on water quality if done negligently, too intensively, or in unsuitable soils[49]. Sediment runoff to surface water bodies modifies the physical quality of the water by increasing the total suspended solids. If tillage and plowing cause soil erosion, the silt or clay transferred to water bodies may lead to the siltation of river beds. Increased sediment deposition can raise lake or river bed levels, allowing land plants to colonize the edges and eventually transform them to dry land. This process can destroy many animal habitats. In addition, sediment can also display chemical effects on water quality, when organic compounds such as phosphorus and pesticides are adsorbed. Pesticides (herbicides, insecticides, fungicides) affect biodiversity in local aquatic and terrestrial ecosystems, and can accumulate in edible fish species as well. Fires during harvesting can also release a variety of nutrients. Thus, tillage, plowing, and other harvesting practices should be carefully evaluated when removing agricultural or bioenergy residues, because the land effects (erosion) and water quality effects can be substanial[72,6].

Land erosion is additionally problematic, not only because it may lower the quality of activities (agriculture, bioenergy production) that the land supports, affecting water flows of the local ecosystem and economic productivity. Alteration of physical properties of soils changes the infiltration, surface flow, and percolation rates change, which can affect flood flows and altered groundwater recharge[6].

Despite the tradeoffs between water, nutrient, and land use efficiency, there is significant potential for intensification on land currently supporting rain-fed agriculture[70,8]. Rain-fed agriculture constitutes 80% of global agriculture, 58% of the global breadbasket, and will play a large role in food security and protecting against water scarcity in a changing world. Most rain-fed agriculture occurs in Asia and Africa, and current rainwater use efficiency is expected to only be 35-45% in these areas. Furthermore, water used for food production is three times as high on rain-fed lands as compared to those that are irrigated. Consequently, it is estimated that yields in Asia can readily be doubled in rain-fed areas, and that yields in rain-fed Africa could be quadrupled or quintupled, with improved soil, water, crop and pest management. These management decisions include crop selection (including drought-tolerant crops), water and soil conservation, efficient fertilizer applications, and other better farming practices. These can include mulching, low tillage, contour ploughing, field boundaries, terraces, rainwater harvesting, supplementary irrigation, crop rotation, reducing fallow periods, among others. Many of these considerations can also be applied to the production of bioenergy in rain-fed areas throughout the world[6].

III.c. Water quality impacts of bioenergy production – Can bioenergy improve water quality?

Whether water quality is improved or degraded for a given land activity largely depends on how land cover is changed and managed. Transitioning land from growing conventional food and feed crops, which have high demands for supplemental nutrients and intensive

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[73] Neary DG & Hornbeck JW (1994) Impacts of harvesting and associated practices on off-site environmental quality. *Impacts of Forest Harvesting on Long-Term Site Productivity* Dyck, W. J., Cole, D. W., & Comerford, N. B. (eds) Springer-Verlag, New York, NY. p. 81-118.

management practices, to low-input next-generation bioenergy crops, many of which can be grown in perennial cycles with little land disturbance, can lead to positive effects for local water quality[74].

Bioenergy feedstocks that may fall under this category include perennial grasses (e.g. *Miscanthus*, *Sorghum,* switchgrass, and many others) as well as short rotation, coppiced woody plants (e.g. willow, poplar, eucalyptus) that are grown in multiyear rotations. These plants typically require less inorganic fertilizer, less weed control and fewer pesticides, and fewer tillage events. These systems typically generate large root systems, accumulating soil carbon, improving soil tilth, decreasing erosion and providing filtration of subsurface water destined for rivers and lakes. The practice of using the natural filtration capacity of forests to provide high quality water for downstream use is widely recognized. It is possible that some next-generation bioenergy systems could a provide similar function.

Given the potential for water quality improvements with bioenergy crops, one option to manage eutrophication and other agricultural impacts includes landscape-level management. For example, bioenergy perennial grasses or woody plants could be used as riparian buffers in agricultural locations where fertilizers and sewage sludge could cause significant nitrate leaching to surface waterways[75]. These feedstocks would filter the agricultural runoff by scavenging nutrients before they reached surface water bodies, improving water quality and nutrient use efficiency. Vegetation buffers exist in numerous forms and can achieve a variety of water quality and land use goals. In addition to the use of bioenergy crops to filter agricultural runoff and wetland treatment of effluents, the planting of trees can be used in strategic locations to reduce water erosion, prevent flooding, and reduce wind erosion[75]. Certain plant varieties can also be used to scavenge heavy metals and other toxins from soils; for example, some willow trees can accrue and store cadmium and zinc[76]. In addition to vegetation buffers, other mixed systems relevant to agriculture and bioenergy include double cropping, relay cropping, agroforestry, and mixed crop/livestock systems, all of which aid intensification efforts as well as provide soil carbon accumulation and possible climate benefits[17,77]. Thus landscape management should play a large role in future land and water use management.

Replacement of annual crops with perennial bioenergy crops could also improve water quality improvement in regions with high water tables. Often past land use change, involving replacement of grassland or forests with annual row crops or grazing pastures, resulted in rising water tables and mobilization of salt otherwise stored deep in the soil. The mobilized salts can then infiltrate surface water bodies. To improve both water quality perennial bioenergy feedstocks with higher ET rates can be introduced to productively redirect the excess soil moisture and keep salts in deep soils. This strategy increases economic productivity of the land and ameliorates soil and water degradation[12].

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[74] Aronsson PG, Bergström LF & Elowson SNE (2000) Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater. *Journal of Environmental Management* **58**(2),135–145. doi:10.1006/jema.1999.0319.

[75] Aronsson P & Perttu K (2001) Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. *The Forestry Chronicle* **77**(2), 293–299.

[76] Berndes G, Fredrikson F & Borjesson P (2004) Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems and Environment* **103**(1), 207–223. doi:10.1016/j.agee.2003.09.013.

[77] Heggenstaller AH, Anex RP, Liebman M, Sundberg DN & Gibson LR (2008) Productivity and nutrient dynamics in bioenergy double. *Agronomy Journal* **100**, 1740–1748.

III.d. The special role of integrated and mixed systems

A powerful approach to addressing water quality and quantity issues involves integrating various activities that consume and release water. For example, in bioenergy systems, the conversion of biomass into liquid fuel requires water for the biomass pretreatment, deconstruction, and fermentation, as well as for cooling during distillation. In certain schemes, the water for cooling can be recirculated internally. The remaining slurry after the fermentation process (the stillage) contains a large amount of salts and nutrients and this water cannot immediately be reused easily. The stillage can be separated and evaporated into Dried Distillers Grains with Solubles (DDGS) and clean water. The DDGS contains protein and micronutrients, and is suitable for animal or fish feed in most cases. Wet and dry distillers grains are being used incresing to replace whole corn and soy, reducing the need for row crop cultivation and possibly some grazing lands for the corresponding amount of feed[67].

In many industries, including sugarcane ethanol production in Brazil and corn ethanol production in the U.S., water discharge and intensities have been reduced substantially by the use of a number of practices, including water reuse, wastewater treatment (performed either onsite or outsourced to a nearby wastewater treatment plant), and more efficient equipment and processes[68,7879]. In Brazil, the vinasse (i.e. the slurry remaining after sugarcane fermentation, similar to stillage) contains a high nutrient loading and has been treated and reused for fertirrigation on sugarcane fields.[51] This recycles both the water and the nutrients in sugarcane production, reducing energy use, water pumping, and costs, while improving yields and soil conditions.

Wastewater treatment can be used for either recycling water or for lowered environmental damage prior to discharge to a surface water body[80]. Preliminary treatments adjust the pH and temperature, and remove large and heavy solids. Primary anaerobic digestions then remove about 85% of suspended solids and BOD/COD. These anaerobic fermentations typically require little energy input and even generate methane gas, which can be used to power the wastewater treatment facility. Secondary aerobic digestions further lower organic material loads and remove nitrogen and phosphorus from the water, after which wastewater can be discharged to municipal sewage systems. Additionally, tertiary treatment of wastewater may be conducted through the use of natural systems, e.g. constructed wetlands. This involves using cattails, reeds, and rushes in wetlands to serve as vegetation filters, whose biomass can also be harvested and burned for electricity generation.

The use of process water to supplement crop water requirements can be quite attractive. A special case of such integration is the common practice of using stillage or vinasse from sugarcane ethanol produciton to both fertilize and irrigate sugarcane fieds (See Section III.e).

[78] Willington IP & Marten GG (1982) Options for handling stillage waste from sugar-based fuel ethanol production. *Resources and Conservation* **8**, 111–129.

[79] Sparovek G, Berndes G, Egeskog A, de Freitas FLM, Gustafsson S & Hansson J (2007) Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, Bioproducts and Biorefining* **1**(4), 270–282. doi:10.1002/bbb.31.

[80] Wilkie AC, Riedesel KJ & Owens JM (2000) Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. *Biomass and Bioenergy* **19**(2), 63–102.

III.e. Impact Case Study III: Brazilian Sugarcane

Several changes to sugarcane management have reduced water quality impacts in Sao Paulo. The widescale adoption of mechanical harvesting, combined with legislation to phase out of burning of cane fields, which was required for manual harvest, has significantly reduced erosion (Table 3)[81].

Table 3. Effects of straw on erosion in sugarcane fields[81].

	Burnt Straw	Tilled Straw	Surface/No-till Straw
soil erosion rate (t/ha/yr)	20.2	13.8	6.5
run-off rate (%Precipitation)	8	5.8	2.5

There are several points during processing that wastewater is accumulated. Perhaps the largest volume is the stillage or vinasse, which can range from 9.5 to 18 liters per liter of ethanol, depending on recycling[82] (Table 4).

Table 4. Effluents associated with sugarcane processing and distillation[82].

Effluent	volume (l/TC)	BOD (mg/l)	T (°C)
vacuum condenser system	10.000-30.000	10-150 (400-1000)	40-45
washing of cane	3.000-10.000	100-500 (2.000-4.000)	25-35
cooling water	1.500-5.000	-	35-45
evaporation condensates	500-650	100-800	70-80
vinasses	665-1260	6.000-25.000	85-90
washing of floor and equipment	30-100	800-1.500	25-50

Source: CTC and CETESB. Note: l/TC = litres per tonne of cane processed; figures between brackets represent closed systems and are only a very rough indication; the ranges are very significant, since modes of operation vary between different distilleries; more details on the various effluents are given in the text.

Direct discharge of vinasse into rivers has been replaced with the use of a process called "fertigation" where the vinasse is sprayed in a diluted form onto fields so that the residual nutrients can be used by as fertilizer. Regulations of fertigation such as proximity to rivers are in place but measurement and monitoring can be spotty[83].

Vinasse composition can vary depending on the fermenting sugar source (Table 5), and can have very high biological and chemical oxygen demand (BOD/COD). The use of vinasse to partially fulfill additional water and nutrient requirements is generally perceived as an environmental positive; however, the indirect water quality impacts resulting from the use of

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81 Macedo IC (2005) *Sugar Cane's Energy: Twelve studies on Brazilian sugarcane agribusiness and its sustainability.* Sao Paulo Sugar Cane Agroindustry Union (UNICA), Beriendis Editores Ltd., Sao Paulo SP, translation Walter Heinrich Rudolph Frank and Marcio Mendonça, 1–228.

82 Moreira J (2005) Water use and impacts due ethanol production in Brazil *World* ***41***(6,960) 3,414.

83 Duarte CG, Gaudreau K, Gibson RB & Malheiros TF (2013) Sustainability assessment of sugarcane-ethanol production in Brazil: A case study of a sugarcane mill in São Paulo state. *Ecological Indicators* **30**, 119–129. doi:10.1016/j.ecolind.2013.02.011.

dilute vinasse as fertilizer compared with conventional fertilizer application are not well understood.

Sugarcane requires substantial amounts of fertilizer addition. Typically, phosphorous and potassium are required. Nitrogen requirments vary widely, with some cultivating regions reporting no need for exogenous nitrogen. Some soils may also require pH adjustment, calcium or other micronutrient addition. The ability to substitute recycled nutrients from ethanol processing for these requirements alleviates energy requirments and cost for fertilizer production and transport, as well as wastewater treatment. Ironically, since water is used in most electricity generation, alleviation of energy requirements saves additional water.

Table 5. Vinasse composition from 28 mills in Sao Paulo[82].

Parameter	molasses	mixture	sugar juice
pH	4.1 - 5.0	4.4-4.6	3.7-4.6
temperature (°C)	80-100	80-100	80-100
BOD (mg O_2/l)	25000	19800	6000-16500
COD (mg O_2/l)	65000	45000	15000-33000
total solids (mg/l)	81500	52700	23700
free solids (mg/l)	60000	40000	20000
fixed solids (mg/l)	21500	12700	3700
nitrogen (mg N/l)	450-1610	480-710	150-700
phosphorous (mg P_2O_5/l)	100-290	9-200	10-210
potassium (mg (K_2O/l)	3740-7830	3340-4600	1200-2100
calcium (mg CaO/l)	450-5180	1330-4570	130-1450
magnesium (mg/MgO)	420-1520	580-700	200-490
sulphate (mg SO_4/l)	6400	3700-3730	600-760
carbon (mg C/l)	11200-22900	8700-12100	5700-13400
C/N ratio	16-16.27	16.4-16.43	19.7-21.07
organic material (mg/l)	63400	3800	19500
reducing substances (mg/l)	9500	8300	7900

Source: CETESB

IV. Integrated Assessment Tools

It is clear that single impact metrics are insufficient to represent the full spectrum of water-associated effects, not only for bioenergy production, but generally. There is a dire need for integrated assessment tools - utilizing a full spectrum of real data and regionally specified models. Analysis needs to extend beyond the field or stand to the watershed or ecosystem level. Only a handful of crop models capable of ecosystem scale evaluations are available and they are parameterized for very few bioenergy systems (Table 6).

The continued development of coupled models such as the Community Land Model, which can span subsystems such as hydrology, soil chemistry, plant physiology, and atmospheric science must be a priority. To date, such models are fairly limited in the types of vegetation and land cover changes they can accommodate. They also require more highly resolved, data.

Table 6. Crop yield models[84]. Water budge parameters: E=evaporation, T= transpiration, I=rainfall interception, R=runoff, F=Freezing, S=Snow melt; Stress level parameters W_s=water, T_s=Temperature, N_s=Nutrient, A_s=Aeration, S_s=solar radiation

Model	Feedstock Type	Water Budget Parameters	Stress	Scale	Soil Water Modeling	ET modeling
EPIC	Switchgrass, Miscanthus	E, T, I, R, F, S	W_s, T_s, N_s, A_s	Field	Multiple Bucket	modified Penman-Monteith
ALMANAC	Switchgrass, Miscanthus	E, T, I, R, F, S	W_s, T_s, N_s, A_s	Field	Multiple Bucket	Penman-Monteith
MISCANMOD	Miscanthus	E, T		Field		Penman-Monteith
MISANFOR	Miscanthus	E, T	W_s, T_s, N_s	Field		Thornwaite
WIMOVAC	Switchgrass, Miscanthus	E, T, R	W_s	Field, Ecosystem	Multiple Bucket	Penman-Monteith
Agro-IBIS	Miscanthus, Sugarcane	E, T, I, R	W_s, N_s	Ecosystem		Pollard-Thompson
Agro-BCG	Switchgrass	E, T, I, R, S	W_s, N_s	Ecosystem	Single Bucket	modified Penman-Monteith
APSIM	Sugarcane	E, T, R	W_s, N_s	Field	Multiple Bucket	Penman-Monteith
AUSCANE	Sugarcane	E, T, I, R, F, S		Field	Multiple Bucket	Penman-Monteith
LPJmL	Sugarcane	E, T, I, R, S	W_s, T_s, N_s, A_s	Ecosystem		Prentice
CANEGRO	Sugarcane	E, T, I, R	W_s, T_s	Field	Multiple Bucket	Penman-Monteith
3PG	Willow, Hybrid Poplar	E, T, I, R	W_s, T_s, N_s	Stand	Single Bucket	Penman-Monteith
SECRETS	Poplar, Miscanthus	E, T, I, R	W_s	Stand, Ecosystem	Two Bucket	Penman-Monteith
EPI	Opuntia, Agave	Index	W_s, T_s, N_s, S_s	Field	Indexing	

Models that have attempted to include economic parameters are too underdeveloped to be useful at this time. The reliance on global equilibrium economic models to understand evolution of novel feedstocks and fuels and associated land use change is a distracting and potential dangerous exercise. While economic simulations can be very useful, we feel that more attention

[84] After Surendran Nair, S, Kang S, Zhang X, Miguez FE, Izaurralde RC, Post WM, Dietz M, Lynd LR & Wullschleger SD (2012) Bioenergy crop models: descriptions, data requirements, and future challenges. *GCB Bioenergy* 4(6), 620–633. doi:10.1111/j.1757-1707.2012.01166.x.

should be given to agent-based models, which can reflect temporal adaptation of market structures.

IV.a. Impact Case Study IV: South Africa Afforestation Permitting

One example where watershed-level monitoring of land use change has been implemented is the regulation of afforestation in South Africa. Spurred by economic opportunity, expansion of forest products through afforestation in South Africa has caused substantial changes in water availability. Scott et al. estimate that the planting of 1.4 million ha of trees reduced annual runoff by 1417 million m^3 (3.2%) and reduced annual low flows by 101 million m^3 (7.8%)[85].

Several policies were enacted to address the issue. The Afforestation Permit System in 1972, followed by the Forest Act of 1984 regulated the area of afforestation and required a rough calculation of effect on flow. The early regulation ignored other water users, did not consider catchment size or low flow (seasonal effects). The National Water Act of 1998 and the implementation of the Stream Flow Reduction Allocations (SFRA) Water Licensing System in 1999 integrated catchment management and established catchment agencies to examine streamflow. The areas were categorized according three levels of activity (Table 5).

Table 5. Categorization of afforestation areas for water catchment regulation.

Category	Description	Restriction
Category I	Biggest demand; other purposes with higher priority	No more new afforestation
Category II	Sporadic water shortages occurring already; existing priority rights to be safeguarded	New afforestation limited to a level where the Mean Annual Runoff (MAR) would not be reduced by more than 5% of pre-1972 levels
Category III	Remainder of the catchments in South Africa	New afforestation limited to a level where the Mean Annual Runoff (MAR) would not be reduced by more than an arbitrarily chosen figure of 10% of pre-1972 levels

A publically available Strategic Environmental Assessment was then required that Strategic Environmental Assessment should include biophysical, economic, social components including a soil survey and a preliminary assessment of impacts on allocatable water and on the water resource, including environmental and statutory constraints. The issued water use license would then extend for 40 years, with a review every 5 years. Interestingly, the evaluations are only for the establishment of stands and do not consider water impacts of harvest or decommission of the enterprise.

[85] Scott DF (1998) Forestry and Water Resources: Correct Figures. *South African Forestry Journal*, **181**, 51-52.

V. Conclusions

The estimates for water use in bioenergy production are highly variable. Processing of biomass to biofuel typically requires one to six liters of water per liter of fuel. The water requirements for biomass production vary significantly by crop, region, and methodology of analysis. Several hundred to several thousand liters of water per liter biofuel can be consumed in natural evapotranspiration of rainfed crops is included as a water loss, rather than an ecosystem service. The evaluation of bioenergy systems with respect to reference systems is not well-developed. Often water quality effects are poorly resolved and poorly represented. The reliance on water footprints obscures complete impact analysis, discounting local effects.

Even with a plethora of data and analysis tools, we do not fully understand the water impacts of first-generation fuels. While estimates have place and can move the discussion forward, there is a danger to consider estimates as "data". Without a thorough understanding of the systems for which we have data, we risk an even greater promulgation of error when examining systems for which we lack data. This is true of scenarios for biofuels in developing nations, for novel feedstocks and fuel production routes, and for the forward-looking scenarios that are required to respond to climate change. Next-generation biofuels represent an opportunity for both positive and negatie water impacts. Rational choices of feedstocks, resource management, and production pathways requires integrated assessement tools for field, watershed and basin level.

VI. Recommendations for Analysis of Water Impacts

1) Wherever possible, full water budget analysis should be conducted for the bioenergy system and an appropriate reference state (e.g. other crop, native ecosystem).

2) Analysis should be in context of the entire watershed, rather than a field-only basis.

3) Water impacts should not be condensed into convenient, weighted parameters. The importance of an impact must be place in context to the watershed's vulnerability to the impact and resiliency to recover from the impact. Both water quantity and water quality impacts need to be assessed.

4) Water impact analysis should be transparent. Assumptions – Make underlying assumptions in analyses and estimates should be clear and any bias discussed.

5) Water impact estimates need to be called estimates. Estimates should not be treated as though they are measurements.

6) The difference between actual measured data and modeled data should be clear.

7) Water impacts need to be subjected to more rigorous standards through the peer-review process.

VII. List of Figures and Tables

The Water Intensity of Hydraulic Fracturing - Scale and Uncertainty

Francis O'Sullivan

Abstract Today's global energy supply outlook is very different to what it was ten years ago. The rise of unconventional hydrocarbon production has profoundly altered perceptions of domestic U.S. energy availability and cost. In fact, the impact has been such that it is altering the balance of energy geopolitics. Hydraulic fracturing has been a key enabler of this remarkable dynamic. The process has a long history in oil and gas production; however, it is its application on a very large-scale that enables unconventional resources to be produced economically. Its use though, is not without significant controversy and today concern abounds in many quarters regarding the environmental and community impacts of hydraulic fracturing. A substantial water requirement is one of the major environmental issues associated with the process. This paper provides an assessment of just how water intensive hydraulic fracturing is. The paper begins by outlining the scale of hydraulic fracturing-enabled growth in unconventional hydrocarbon production in the U.S. over the past decade. The paper then describes the hydraulic fracturing process, including its physical principles, and the reasons why today's fracturing is so water dependent. How estimates of the amount of energy yielded by a hydraulic fracture treatment is then discussed. Following this, a case study that assesses the life cycle water intensity of 400 unconventional gas wells in the Barnett Shale is presented. The study shows that the hydraulic fracturing-related water intensity of that play's energy production is likely higher than previously reported. The paper goes on to describe how the temporal asymmetry between water use and energy production from unconventional sources is not captured by a life cycle metrics alone. In fact the metric offers no insight at all into the very impulsive water demand that large-scale unconventional resource development can place on local resources. The final sections of the paper discuss how freshwater consumption can be reduced, what impact refracturing has on the water intensity, and what some of the research needs on the subject of hydraulic fracturing are.

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1 Growth in Unconventional Hydrocarbon Production

The United States has experienced significant growth in production from its unconventional hydrocarbon resources over the past decade. Growth in output from the range of ultra-low permeability hydrocarbon-prone mud rock formations, widely referred to as the "shale resource" has been particularly remarkable. Between 2005 and 2012, natural gas production from shale resources rose from < 1 Bcf per day to more than > 23 Bcf per day. This rapid growth means that today, shale gas accounts for 33% of total U.S. gas output, and this is projected to rise to 50% by 2035 [1]. Figure 1 illustrates how natural gas production levels have changed in the major U.S. shale plays over the past 8-9 years.

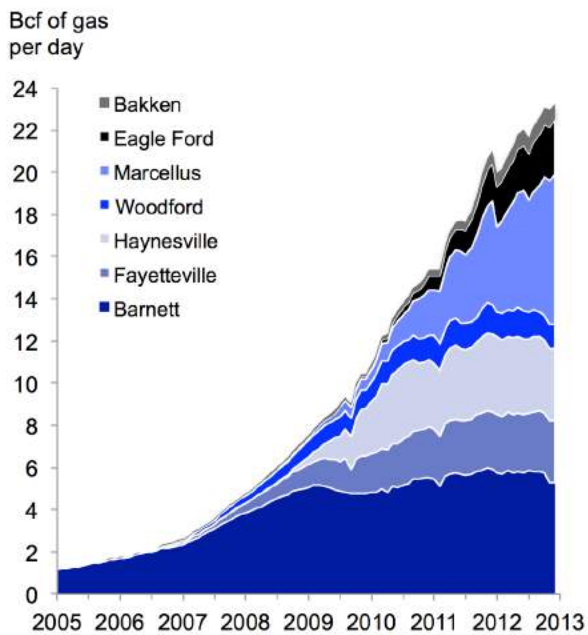


Fig. 1: Growth in natural gas production from the main U.S. shale plays since 2005

As the figure shows, shale gas production growth during the latter half of the last decade was supported by the Barnett, Fayetteville, Haynesville and Woodford plays. However, since 2010 production from these plays has plateaued, and today's production growth is driven by the Marcellus, Eagle Ford, and to a lesser extent Bakken plays. Much of the reason for this dynamic is linked to changes in the relative pricing of oil and natural gas in the U.S. over the past four years. The shale enabled increase in overall natural gas production during those years pushed U.S. natural gas prices to record low levels. As a result, gas producing operators have looked to develop more economically attractive ”wet” shale plays, where the natural gas contains higher proportions of heavier, and generally more valuable hydrocarbon products such as ethane, propane, butane etc. Portions of both the Marcellus and Eagle Ford plays are ”wet”, and so have been aggressively developed in recent years. The Bakken play falls into a different category in that it is not a gas play, rather it is an oil play with considerable associated natural gas production.

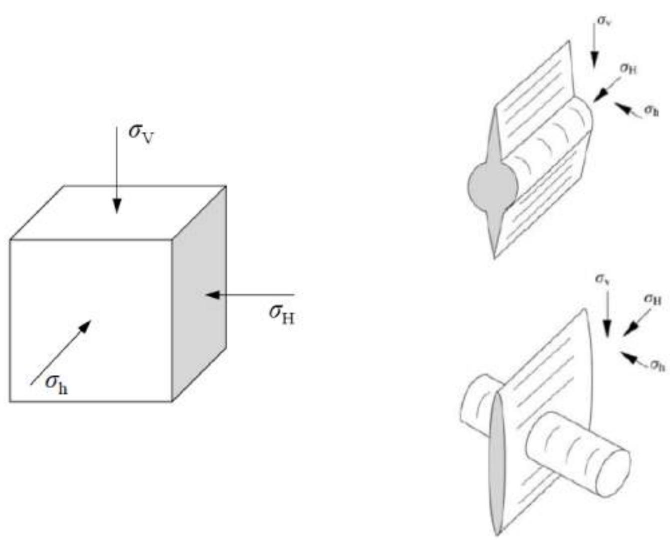
2 Hydraulic Fracturing - A Key Enabler of Unconventional Production

The shale resource is really a collection of many hydrocarbon-prone mud rock formations with a diverse set of geological, geomechanical, geochemical and petrophysical characteristics. One unifying feature of these formations is that they generally do not produce gas or indeed oil at economically feasible rates unless artificially stimulated, owing to very low rock matrix permeability [2]. Hydraulic fracturing of these formations results in a significant enhancement in well productivity, and today it is a ubiquitous reservoir stimulation technique across shale and other low and not so low permeability formations.

Although certainly synonymous with shale gas development, the process of hydraulic fracturing has much wider utility. Its use is widespread across the oil and gas sectors, and its adoption predates large-scale shale gas production by decades. Some specific non shale applications of hydraulic fracturing include production accelerate from conventional formations, and the management of skin and near-well bore damage issues. Regardless of what type of formation is being stimulated, the fundamental processes involved in hydraulic fracturing remain the same. A fluid is injected into the well bore at a sufficient rate to generate a pressure differential between the well bore and the reservoir. This causes stresses around the well bore to increase beyond the tensile stress of the rock, at which point it splits or ”fractures”. Assuming a sufficient pumping rate is maintained, it is possible to ”grow” these fracture both in terms of width and length, such that they propagate away from the well bore into the surrounding formation. Generally speaking, once pumping ceases the induced fractures would close. So in order to keep fractures open, a proppant material must be placed in the fractures. This is achieved by transporting the proppant down hole as part of a slurry comprising of the proppant and the fracturing fluid itself.

2.1 Hydraulic Fracturing Physics

The hydraulic fracturing process is based upon sources of energy gain and loss, all of which can be ultimately related to pressures. The sources of energy gain are unsurprisingly, the fluid pumps, and the hydrostatic head, i.e. the weight of the fluid on itself in the well. The sources of energy loss include well bore friction, perforation and near-well tortuosity, overcoming in-situ stress, fracture friction loss, fluid leakoff, producing fracture width, and splitting rock at the fracture tip.



(a) Illustration of in-situ principal stresses acting on a unit volume of rock, where in general $\sigma_V > \sigma_H \geq \sigma_h$

(b) Illustration of induced fracture orientation relative to the wellbore when the azimuth is parallel and perpendicular to maximum horizontal stress

Fig. 2: Illustration of how wellbore orientation relative to the in-situ principle stresses influences the orientation of hydraulically-induced fractures.

For a given pumping rate and well depth, all of the energy sinks listed will result in the fracturing fluid having a specific pressure, ρ_{fluid}. The difference between this pressure and the fracture closure pressure, ρ_{close}, is the fluid's net pressure, ρ_{net}. For a fracture to remain open, ρ_{net} must be greater 0. Assuming $\rho_{net} > 0$, then the product of ρ_{net} times the volume of the fracture represents the energy available to maintain or increase the fracture's width and extend its length. Simply having

$\rho_{net} > 0$ is not sufficient to grow a fracture, though it is enough to hold a fracture open at a given width. To grow fractures, the net pressure must exceed a higher fracture extension pressure threshold ρ_{extend}. Given the fact that ρ_{net} must remain remain greater than ρ_{extend}, it becomes clear that producing large fractures requires ever increasing pumping rates to compensate for the pressure drops caused by fluid leakoff and increasing fracture volume.

The in-situ stress regime in a target formation is central to the design and outcome of a hydraulic fracture treatment. As illustrated in Figure 2a, the in-site stress distribution in any given subsurface setting can be resolved into three orthogonal principal stresses, σ_V, the principal vertical stress, and two principal horizontal stresses, σ_H and σ_h. In the case of elastic deformation in a homogenous isotropic formation, the two principal horizontal stresses will be equal; however, in most realistic scenarios some differences do exist between the two horizontal stresses. When such a contrast exists, the larger of the two is referred to as the maximum principal horizontal stress, σ_H, and the smaller is the minimum principal horizontal stress σ_h. In many (but certainly not all) setting of relevance to hydraulic fracturing, σ_V will be the largest of the principal stresses. This fact has great significants for the orientation of hydraulic fractures, since they always (ignoring the near-well bore) form in the plane perpendicular to the the minimum in-situ principal stress. Since this stress is typically horizontal, fractures typically form in a vertical plane. These features of fracture formation have implications for the choice of horizontal well bore azimuths. If a horizontal well's azimuth is aligned parallel to σ_H, the maximum principal horizontal stress, a hydraulic fracture treatment will yield fractures aligned parallel to the well bore. This situation is show in the upper diagram of Figure 2b. There are operational situations where this may be of use; however, for the stimulation of shale formations a much more typical approach involves orientating the well azimuth parallel to σ_h, the minimum principal horizontal stress. Stimulation in this orientation yields fractures that intersect the well bore perpendicularly, as show in the lower diagram of Figure 2b. This allows the placement of multiple fractures along a horizontal well bore's length and greatly enhances the effective stimulation of the reservoir. For a more detailed discussion of reservoir geomechanics and the process of hydraulic fracturing please refer to [3, 4]

2.2 The "Slickwater" Fluid-System

As a reservoir stimulation method, hydraulic fracturing treatments have been in use for decades, and come in a variety of forms that are often characterized by the particular "fluid system" used. These include water and oil-based fluids, energized fluids, foams and emulsions [4] . Each of these general systems can be further sub-categorized based upon the particular chemistries used. This plethora of fluid systems reflects the fact that hydraulic fracturing treatments are carried out in many different reservoir types, each of which require particular fluid characteristics in order for stimulation to be successful. For many years, cross-linked polymer fluid systems dominated fracturing, owing in particular to their ability to transport very high proppant loads. However, today's shale development is dominated by "slickwater" fluid systems.

Many factors, both economic and technical have combined to make slickwater fracturing popular for shale. On the technical front, the fact that shale permeability tends to be extremely low means that the aim of hydraulic fracturing is to generate as much rock matrix-fracture contact area as possible. This is achieved by long fractures. In contrast, fracturing in higher permeability formations is often designed to generate ultra high conductivity fractures, and to achieve this, fracture width and proppant concentrations are more important [4]. The low viscosity of water, and the low rates of leakoff in shale makes water an excellent fluid for generating long fractures. Additionally, since generating very large fractures requires large volumes of fluid the low cost of water (at least in regions without water scarcity) is a major advantage of the slickwater system. Other advantages of slickwater include the fact that the fluid system's lower polymer loading causes less formation damage, enables better post treatment "clean up," and in the case of naturally fractured formations, it can generate a more complex fracture network than is possible with higher viscosity fluid-systems [5]. However, along these advantages, slickwater also has its disadvantages. One major issue is the very large volumes of water needed to execute a slickwater stimulation. As an example, in 2010, the mean per-well volume of water used for slickwater fracturing in Texas' Barnett Shale was 2.8 million gallons, while in the Haynesville Shale, the average volume used was 5.7 million gallons [6]. Another disadvantage of the slickwater fluid system is that it is not as effective a proppant transporter as other systems. A significant literature exists on these topics, much of which is dealt with in [5, 7].

Slickwater fluid systems utilize simpler chemistries than many of the other fluid systems available. This makes them more economically attractive, particularly with very large volume stimulations that are now de rigueur in shale development. Common additives to the water base of a slickwater fluid include a friction reducing agent, often polyacrylamide, a relatively low concentration gelling agent, typically guar or a guar derivative, a polymer breaking agent, and depending on the geochemistry of the formation being stimulated, a range of biocide, anti-scale, iron control, surfactant and clay stabilization agents may also be added. No standard chemistries exist and the service companies who provide the additives guard their formulations carefully. This opaqueness with respect to the exact chemical formulations used is one of several aspects of the process that is highlighted by those opposing unconventional resource development.

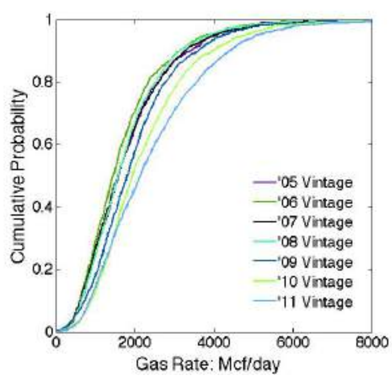
3 Shale Well Productivity - A Key Determinant of Water Intensity

Assessing the water intensity of hydraulic fracturing can be done in a number of ways depending upon what questions need to be answered. An inventory type assessment allows the water demands of hydraulic fracturing to be compared to total water demand within a particular geography over a fixed period of time. This approach is ”cross-sectional” in nature and is very helpful when for example, analysis is focused on how the demand for limited water resources in a particular region is affected by certain levels of hydraulic fracturing activity. In contrast, longitudinal ”life cycle” type assessments of water intensity are useful in quantifying relative water intensities of various energy production pathways. The output of the inventory approach is an *absolute* metric, e.g. m^3. The output from the life cycle approach is a *specific* metric, e.g. liters per gigajoule. Both types of assessment are important, however, here we will mainly focus attention on assessing the specific water intensity of hydraulic fracturing.

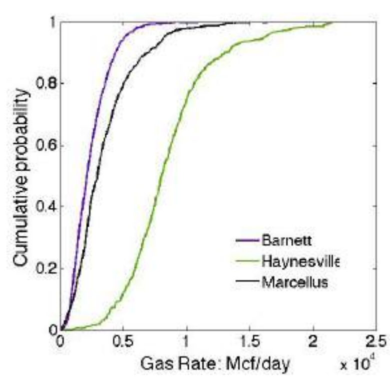
3.1 Trends in the Early-Life Productivity of the Shale Resource

Knowing the energy quantum produced as the result of a hydraulic fracture treatment is fundamental to establishing the water intensity of that energy. In the simple case of a gas well that has been fractured once, and subsequently produced to either its economic or technical ultimate recovery limit without any further water input, the calculation of life cycle hydraulic fracturing-related water intensity is trivial. It is simply the quotient of the volume of water used to fracture, and the amount of energy produced. Both figures should be known with a relatively high degrees of accuracy (assuming little if any unmetered gas venting and flaring took place). Unfortunately, the nascent nature of contemporary shale gas and oil production means most wells that have been stimulated with large-volume slickwater fracture treatments are young, and so have not been produced to their ultimate recovery. In the case of the Barnett Shale for example, of the 13,750 horizontal gas wells drilled in the play to date, 12,800 have been drilled since 2005, while in the Haynesville Shale, 1,650 of the play’s 1,750 horizontal gas wells were drilled since 2009 [8]. A similar situation exists in all of the other major unconventional plays. This lack of longer-term production and ultimate recovery data from hydraulically fractured wells means that ultimate productivity must be estimated if the life cycle water intensity of hydraulic fracturing is to be assessed.

Fortunately, an abundance of early-life shale well productivity data does exist, and this provides a useful starting point when attempting to establish estimated ultimate recovery (EUR) projections. Studying the early-life productivity data available from those wells drilled in the main U.S. shale plays over the past 6-7 years reveals a number of important points. The first is that intra-play well-to-well productivity varies significantly, and the level of this variability has remained relatively constant year-to-year. The second point is that well productivity levels vary significantly from play-to-play. Of course this is no surprising given the varying depositional histories, geochemical and petrophysical characteristics of each play. However, what it means is that conclusions drawn regarding well productivity and derivative metrics including life cycle water intensity based on data from one play may not necessarily apply in other plays. Figure 3a provides a quantitative illustration of intra-play variation in well productivity by plotting per vintage distributions of the peak production rates recorded from the Barnett Shale horizontal well ensemble drilled between 2005 and 2011[1]. This data shows that the average peak production rate has increased year-to-year; however importantly, the level of intra-vintage variability remains very consistent, with the P80-P20 ratio always falling between 2.5:1 and 3:1. Figure 3b illustrates the point that average well productivity can differ appreciably between shale plays, by plotting the peak production rates of the 2011 vintage horizontal wells drilled in the Barnett, Haynesville and Marcellus plays. Relative to the mean Barnett well, the productivity of the mean Marcellus wells is 50% higher, while that of the mean Hynesville well is 350% higher.



(a) Intra and inter-vintage well-to-well variability in peak production rates observed within the Barnett Shale's horizontal shale well ensemble [8].



(b) Inter-play variation in the peak production rates of 2011 vintage horizontal wells in the Barnett, Haynesville and Marcellus plays [8].

Fig. 3: Illustration of the level of variability in early-life well productivity observed among horizontal well ensembles in some major U.S. shale plays.

[1] Peak production rate is defined as the average daily rate during a well's highest productivity month. Typically this will be the first full calendar month on production.

3.2 Estimating Ultimate Recovery from Shale Wells

Estimating ultimate recovery from wells is something the oil and gas industry have been doing for a very long time. It is an important input into many aspects of the business including asset valuation and the calculation of proved reserves, and of course it is vital for assessing life cycle water intensity levels. A variety of techniques exist for establishing well EURs. Reservoir simulation is an obvious choice; however, in practice that approach requires detailed knowledge of a plethora of parameters often not readily available, particularly for today's unconventional reservoirs. Furthermore, as Duong points out [9], many of today's reservoir simulation tools do not yet adequately model the physics of unconventional reservoirs. Lee and Sidle [10] describe and critique a range of "production analysis" techniques used for EUR assessment, and they point out that our lack of understanding of the physics governing production from shale formations can limit their usefulness and accuracy. Of the production analysis techniques available, the "decline curve" method is one of the most commonly used (and indeed abused). Its application involves establishing a production decline trend from observed data and projecting it forward to arrive at an EUR. The original work on this method was carried out by Arps, who proposed an entirely empirical decline curve model [11], the general form of which is given by Equation 1.

$$q = q_i \frac{1}{(1 + bD_i t)^{(1/b)}} \tag{1}$$

q is the well's instantaneous production rate, t is time, q_i is the well's initial production rate, and b and D are constants. For $0 < b < 1$, Equation 1 is referred to as the hyperbolic decline equation. With $b = 0$, the equation simplifies to the exponential form:

$$q = q_i \exp(-D_i t) \tag{2}$$

while when $b = 1$ the equation simplifies to what is known as the harmonic form:

$$q = q_i \frac{1}{(1 + D_i t)} \tag{3}$$

Only the exponential form of Arps' equation can be derived analytically. The conditions necessary for this derivation are that the well is producing a low compressibility fluid, at a constant flowing bottom hole pressure, with steady state or boundary flow, within a fixed drainage area, and assuming a constant skin factor [12].

Today, many analysts use the Arps equation to establish shale well EURs. A detailed example of such an analysis is presented in [13]. Unfortunately, this widespread use of the Arps equation is often flawed in a manner that leads to erroneously high EURs [10, 14, 15]. The reason for this is best illustrated by an example. First consider Figure 4 and Table 1, which illustrate the normalized production de-

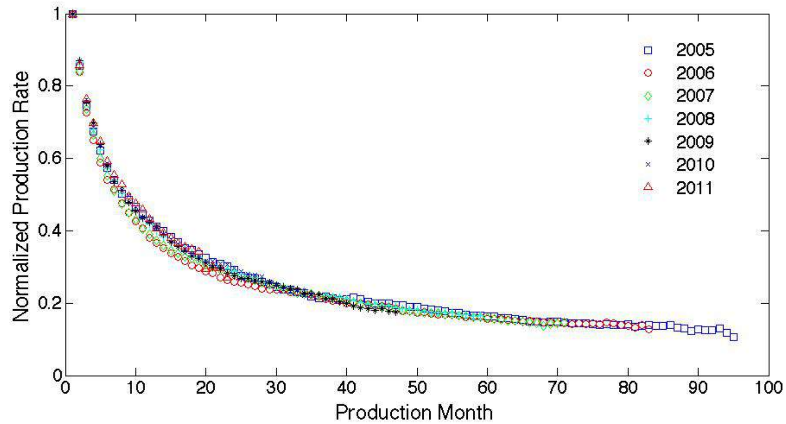


Fig. 4: Normalized production decline trends for the 2005-2011 horizontal Barnett Shale well vintages [8]

Vintage	b	D_i
2005	1.556	0.1683
2006	1.695	0.2156
2007	1.659	0.2156
2008	1.575	0.1733
2009	1.454	0.1612
2010	1.545	0.1640
2011	1.433	0.1522

Table 1: b and D_i parameters from unconstrained fitting of Equation 1 to vintage-averaged production decline data from the Barnett Shale horizontal well ensemble

cline trend for each horizontal well vintage in the Barnett Shale from 2005 to 2011, and report the associated best fit b and D_i Arps equation parameters. Now consider the Arps equation in terms of cumulative production:

$$Q = \int_0^t q_i \frac{1}{(1+bD_it)^{(1/b)}} dt \tag{4}$$

In the limit $t \to \infty$, using a b value > 1 will result in:

$$\lim_{t\to\infty} Q = \frac{{q_i}^b}{D_i(b-1)} \left[\frac{1}{q(t)^{(b-1)}} - \frac{1}{{q_i}^{(b-1)}} \right] \to \infty \tag{5}$$

In other words, applying the Arps equation with $b > 1$ will always yield a physically unreasonable EUR. To deal with this problem, those that use the Arps equation with $b > 1$ tend to define a finite well lifetime over which to integrate. [13], who uses this approach, assumed a 30 year lifetime. Unfortunately, this is not a satisfactory solution. One of the physical reasons why fitting the Arps equation to early-life shale production data very often yields b values > 1 is because these wells often remain in transient flow for extended periods, owing to low rock permeability and ill defined reservoir boundaries [16, 17, 15]. In the recent past Ilk et al. [14] and Valko [18] have proposed new decline curve methodologies, both of which account for transient flow, and provide finite and reasonable EURs under all circumstances. The rate-time form of Ilk's model is:

$$q = \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n] \tag{6}$$

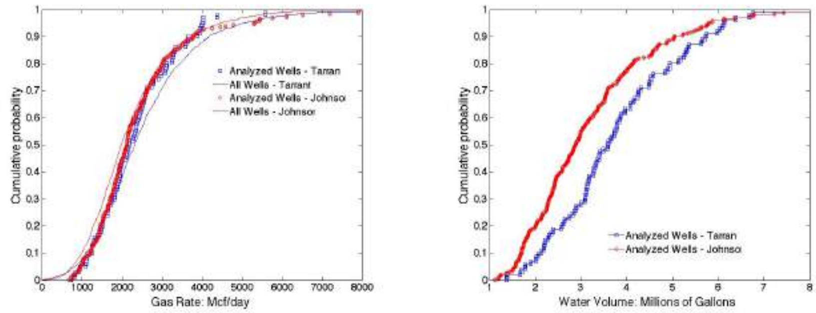
where $\hat{q}_i$ is the initial (or zero time) rate, and D_∞, $\hat{D}_i$ and n are parameters derived from empirical data. Valko's rate equation is:

$$q = q_i \exp\left[-\left(\frac{t}{\tau}\right)^n\right] \tag{7}$$

where q_i is the initial well rate, and τ and n are parameters derived from empirical data. You will note that in practical terms, the difference between Equations 6 and 7 is that Ilk assumes a terminal decline rate, D_∞ as $t \to \infty$, which Valko's form does not feature. The utility of these "power-law exponential" decline curve methodologies have been examined in detail using numerical models and real world data [19, 20, 14]. Invariably, the use of these models results in lower EURs than would result from the application of the Arps equation (even with a constrained well lifetime). In fact, if the Arps equation is used carelessly with early-life productivity data it can result in a $> 100\%$ overestimation of EUR [20, 14]. The implications of this in the assessment of water intensity are clear. EURs must be established carefully, otherwise unreasonably low estimates of life cycle water intensity will result.

4 Hydraulic Fracturing-Related Water Intensity - A Barnett Shale Case Study

To assess the hydraulic fracturing-related water intensity of natural gas produced from a contemporary shale play, a case study was carried out that included 400 horizontal hydraulically fractured wells drilled in the Barnett Shale. The majority of these wells were drilled and completed between 2008 to 2010, and all are located in two of the Barnett Shale's core counties, Johnson and Tarrant.



(a) Comparison of analyzed well ensemble peak production rates with those of Johnson and Tarrant counties' overall well populations [8].

(b) Distributions of analyzed well ensemble's per-well hydraulic fracture treatment water volumes

Fig. 5: Distributions of early-life well productivity and hydraulic fracture treatment water volumes for analyzed well ensemble

Although a subset of the overall well population in the two counties, the analyzed ensemble's early-life well productivity distribution is a reasonably proxy for the overall population. This is illustrated in Figure 5a, which plots the distributions of the analyzed wells' peak month production rates along with those of the overall well populations in Johnson and Tarrant. In Johnson, the mean peak month rate for the analyzed wells was 2,400 Mcf/day, slightly ahead of the overall Johnson rate of 2,220 Mcf/day. In Tarrant, the mean peak rate of the analyzed wells was also 2,400 Mcf/day, but in this case slightly lower than the overall county value of 2,550 Mcf/day. The level of well-to-well variability within the analyzed ensemble was consistent, with a P80:P20 performance ratio of 2.1:1. The P80:P20 ratio for both counties total populations was slightly higher at 2.3:1.

The amount of water used for hydraulically fracturing can vary quite considerably on a well-to-well basis. Many factors play into this including the specifics of the fracture design and the length or the horizontal bore. This variability is evident in the volumes of water used for the fracturing of the analyzed well ensemble. Figure 5b illustrates the distributions of these volumes. The mean volume used in Johnson was 3.2 million gallons, with the Tarrant mean being 3.8 million gallons. These values are between 0.5-1 millions gallons higher than the play-level average of 2.8 million gallons reported by Nicot and Scanlon in [6]. The lower bounds of the volumes used to fracture the analyzed wells is also significantly higher than previously reported values for horizontal wells in the play. The P05 fracture volumes in Johnson and Tarrant were 1.6 and 1.8 million gallons respectively compared to the 0.75 reported in [6]. At this point it is worth noting that in the case of the analyzed well ensemble, the correlation between early-life well productivity and the volume of water pumped during fracturing is relatively week. This is illustrated by the scatter plot shown in Figure 6.

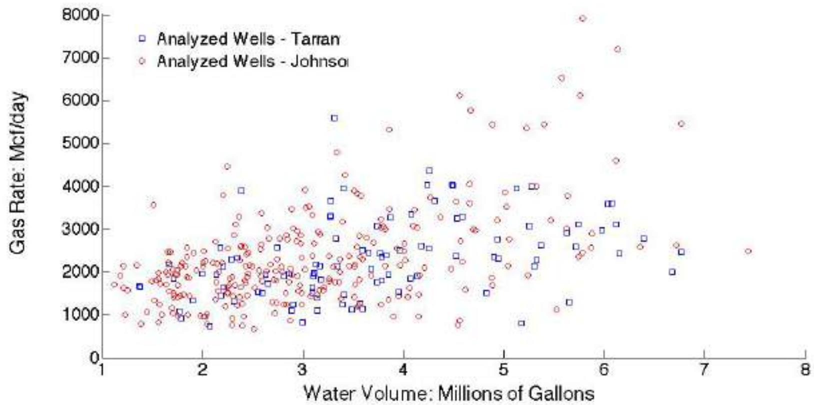


Fig. 6: Scatter plot of early-life well productivity versus hydraulic fracture treatment volume for analyzed well ensemble

4.1 Analyzed Well Ensemble EURs

EURs for the analyzed well ensemble were established using Ilk's "power-law exponential" rate-time decline model [14]. The necessary model parameters were calculated using production data from the 2008 vintage case study wells. To reflect operational realities, it was assumed that each well would only be produced for 30 years or until its daily rate drops to 50 Mcf/day, whichever comes first. This temporal constraint has a de minimis impact on the calculated EURs as most of the analyzed wells' rates fell to the 50 Mcf/day threshold before 30 years. As with the application of this power-law exponential decline model in previous work [19, 20] EURs (limited to 30 years) were also established using the Arps equation. The distribution of EURs for the analyzed well ensemble are shown in Figure 7. Unsurprisingly, the distributions for both counties are similar and display some degree of skewness. This means that the ensemble's mean EUR is higher than its median, or put simply, there are more low than high performance wells in the ensemble. This trend is universally observable within and between shale plays [21]. Table 2 shows the well-to-well variability in EUR among the analyzed wells. The table also reports the substantially higher EURs that result from the application of the Arps equation.

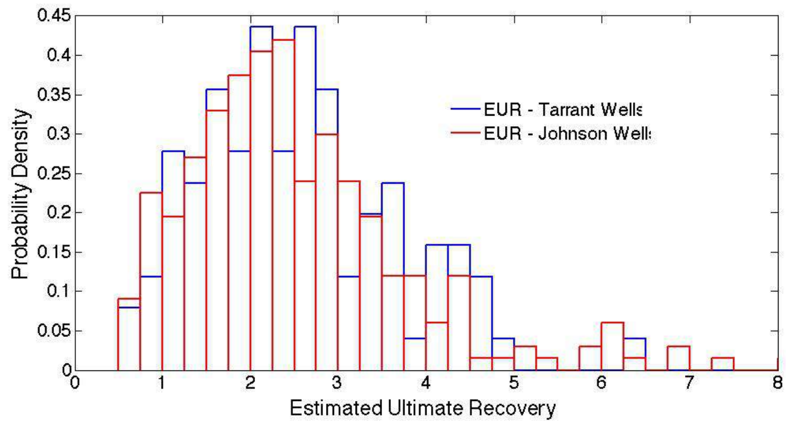


Fig. 7: Probability distribution of EURs for the analyzed well ensemble based on the application of Ilk *et al's* power law exponential decline curve model

County	Power Law Exponential Model				Arps Model
	Mean	Median	P95	P05	Mean
Johnson	2.64	2.33	5.99	0.91	3.01
Tarrant	2.65	2.39	4.52	0.99	3.03

Table 2: Statistical breakdown of the analyzed well ensemble's EUR values.

4.2 Hydraulic Fracturing-Related Water Intensity - Life cycle versus Time on Production

Well fracturing water volumes were coupled with their associated EURs to assess the life cycle water intensity[2]. The resulting distributions of are plotted in Figure 8. The mean life-cycle intensity for the Johnson wells was 5.2 L/GJ, while in Tarrant, the mean was higher at 6.1 L/GJ. The well-to-well variation was significant. In

[2] For analysis purposes, 1 scf of natural gas was assumed to have an energy content of 1.055 MJ

the case of the Johnson wells, the P05-P95 range was 2.3-10.3 L/GJ, while for the Tarrant wells it was 2.8-11.4 L/GJ.

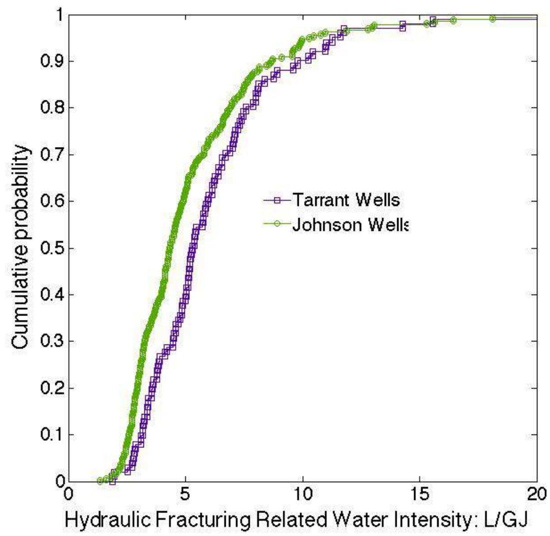


Fig. 8: Distribution of life cycle hydraulic fracturing-related water intensity values for the analyzed well ensemble

Along with the water requirements for hydraulic fracturing, water is also needed for drilling. In the case of the Barnett Shale these volumes can be significant. [22] estimates that drilling a typical Barnett horizontal well requires 0.4 million gallons of water. Today that figure is likely higher due to increasing average well lengths. When water for drilling is included, the typical life cycle water intensity of the energy produced from the assessed well ensemble appears to fall in the 6-7 L/GJ range, though the well-to-well variability around this is large. This range is appreciably higher than the previously suggested value for the play of 4.8 L/GJ [23].

The nature of water use in hydraulic fracturing-enabled energy production differs considerably from many other energy pathways including coal, and oil. This is due to the extreme temporal asymmetry between water demand and energy production. The pumping portion of a modern fracture treatment may take no more than a day, while it can take decades to fully produce the associated energy, and as a result the ”time on production” water intensity of hydraulic fracturing-enabled energy can differ dramatically from the life cycle intensity. As an illustration of this concept, consider Figure 10, which shows how the water intensity of energy from a shale well changes relative to time on production. This example is based on a well with the same mean initial productivity and decline characteristics as those in the case

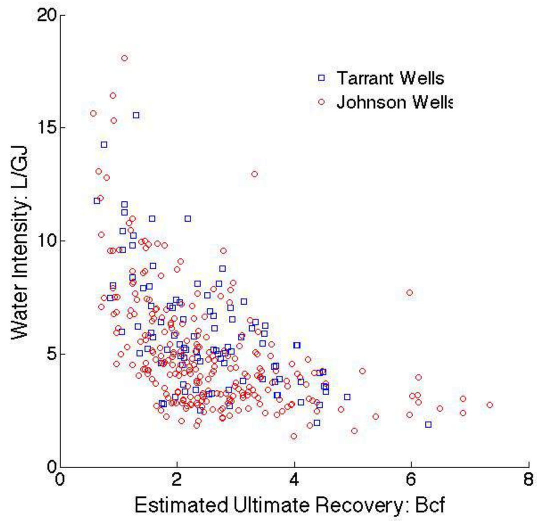


Fig. 9: Scatter plot of the analyzed well ensemble's hydraulic fracturing-related water intensity versus EUR

study's analyzed well ensemble, and assumes a combined drilling and completion water demand of 3.8 million gallons. In regions where water availability is limited the shorter-term water intensities may become an important consideration.

5 Discussion

The widespread application of large-scale hydraulic fracturing has had a profound impact on the North American energy sector and will likely be transformative elsewhere also. Nevertheless, many question remain regarding the process' technical effectiveness, and its impacts on water resources, air quality, greenhouse gas emissions and communities [24, 25, 26, 27, 28, 29, 30, 31]. This paper has focused on one small, but important aspect of the water issue, the specific water intensity, and we have attempted to describe the opaqueness and complexities involved in assessing that metric. The Barnett Shale case study presents a reasonable real world assessment of the life cycle water intensity of the drilling and hydraulic fracturing. Our results indicated that life cycle hydraulic fracturing-related water intensity levels are likely higher than perviously suggested. The main reason for this is likely that previous assessments have used unreasonably high well EURs. This paper also makes the important point that life cycle water intensity is a maetric that does not adequately communicate the temporal asymmetry of water demand and energy pro-

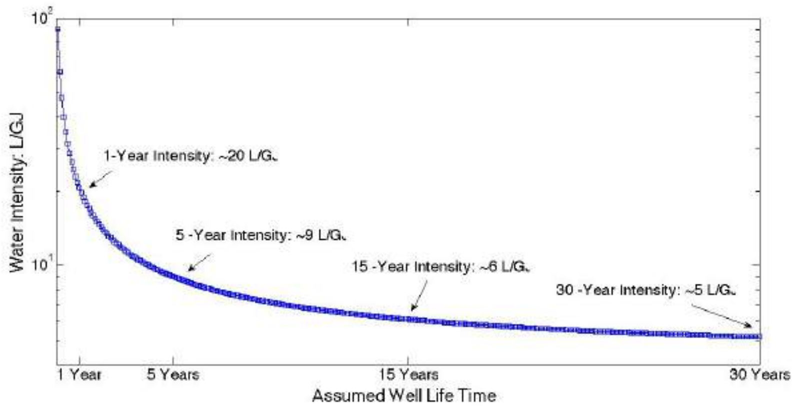


Fig. 10: Illustration of how increasing the temporal integration period reduces the time on production water intensity of shale gas until it converges with the EUR-based life cycle intensity

duction associated with hydraulic fracturing. There are several other aspects to the hydraulic fracturing-related water intensity issue that have yet been discussed that warrant consideration. These include the issue of freshwater consumption, and how it can be minimized, and the impact on water intensity of refracturing. These are important considerations that can significantly alter water intensities.

5.1 Hydraulic Fracturing's Consumptive Water Use - Can it be Reduced?

To date, most hydraulic fracturing operations have used freshwater, and this use has been entirely consumptive, i.e. the water is not subsequently available for other beneficial use in the watershed, at least not without substantial remediation. Given the scale of development in some plays, hydraulic fracturing-related water demand can place a significant strain on local freshwater resources, even in regions where water is relatively abundant. As a result, efforts are now ongoing to reduce the consumptive freshwater intensity of the process. One approach is to reuse ”flowback” water for subsequent fracturing operations. Flowback water is the term used to describe the fluid that returns to the surface in the days immediately following a hydraulic fracture stimulation. Flowback volumes vary from well-to-well and play-to-play with anywhere from 10-30% of the originally injected volume being representative [32]. Until recently, the management of flowback water either involved disposing of it via wastewater injection wells or by passing it through a treatment facility [33].

Increasingly, operators are now blending flowback water into the feed water for subsequent fracturing operations. This is not entirely straight forward as the flowback water's chemical composition can negatively impact the overall fracture fluid efficacy. However, these issues will likely be surmountable. How achievable any substantive reduction in freshwater intensity will be as the result of flowback reuse remains to be determined. Given the operational realities associated with executing hydraulic fractures, it is unlikely that complete reuse will be possible in all but the most ideal circumstances. Furthermore, the techno-economic optimization may well indicated that traditional disposal methods are economically optimal in many circumstances. Other options with the potential to yield a much more significant reduction in the freshwater consumption include moving to brackish water fluid systems and waterless systems [4]. Such systems already exist, but are not yet in widespread use in the U.S. unconventional space, likely owing to their relative economics.

5.2 Economic Aspect to Water Intensity - The Impact of Refracturing

The conclusions drawn regarding hydraulic fracturing-related water intensities in the preceding discussion are predicated on the assumption that a single well will only be hydraulically fractured once during its productive life. However, the economics of producing from unconventional resources might alter this. The reason is that although it may require 20-30 years for a hydraulically fractured well to produce its EUR, that same well yields all of its economic value within the first 3-4 years. This is due to the combination of significant early-life production decline, and the financial discount rates applied by operators. Given this, it would not be unreasonable for operators to consider refracturing a certain subset of their well populations. Such activity would alter the calculus regarding the water intensity of energy produced from unconventional resources, and certainly result in an increase in the specific water intensity above the 6-7 L/GJ mean value calculated in this report.

A clear example of how refracturing results in an increase in the specific water intensity of a shale well is presented in [34]. This paper reports on the refracturing of two horizontal Barnett Shale wells. The refracturing treatments used 2-2.5 million gallons each, and resulted in projected increases in well EUR of 20%. Given that the original early-life well productivities of these refractured wells was less than the mean productivity of the case study wells analyzed in the paper, 0.5 Bcf would represent a conservatively high estimate of the increase in EUR resulting from the refracturing treatments. This corresponds to a life cycle water intensity for the additional gas produced due to refracturing of 14.4-18 L/GJ, a much higher intensity than for the gas assumed to be produced by a single lifetime fracture treatment.

5.3 Water Intensity Comparison with other Energy Pathways

Comprehensive comparative studies of energy pathway water intensities are few and far between. The most commonly cited work in the area includes that of Peter Gleick [35] and the U.S. Department of Energy [36], although some of the numbers reported in these are not reflective of contemporary technology. A number of issues make such comparisons extremely difficult. The first is that pathway specific variability in the water intensity can be very significant. This is obvious even from the analysis in this paper that shows shale gas life cycle intensities varying by a factor of 4-5X within a single play. A second major issue is that the temporal profile of water intensities can differ significantly among pathways. Two energy sources, oil produced via water flooding, and gas produced via fracturing might have similar life cycle specific water intensities (assuming for example a 30 year well life). However, what if your temporal horizon of interest is shorter, or the wells cease production earlier due to for example an economics-driven decision to shut in the well? In such circumstances the oil and gas derived energy could end up having very different realized water intensities. A third issue with such comparative work is that it generally provides no insight at all into the critical issue of instantaneous water demand versus water availability.

6 Future Research Directions - Some Thoughts

This paper has focused on understanding and assessing the specific water intensity of the hydraulic fracturing process as it pertains to unconventional hydrocarbon production, and even within that limited remit a great deal of uncertainty is evident. Given this, it is clear that hydraulic fracturing should be subjected to a broad multidisciplinary research effort. Needless to say, a great deal of research on the subject is already ongoing; however, it is likely that additional coordinated work is warranted, particularly at research institutions that publish results such as our research universities and national laboratories.

Although many of the issues requiring further research could be characterized as high priority issues, it is this author's belief that the highest priority should be placed on understanding the environmental and ecosystem impacts, and human health risks off hydraulic fracturing. Some of the many issues in that area needing further work include: understanding how injected fluids migrate, and where they settle in the subsurface; what are the risks to potable aquifers (both from injected fluids and hydrocarbons) and how if at all these risks can be eliminated; and what are the impacts of drilling/flowback/produced waste streams on surface and ground water resources and the environment in general.

On the operational-focused side a great deal of research is also needed. The lack of knowledge regarding the fundamental production mechanisms of the unconventional resource must be addressed along with associated issues of effective stimulation design. Recent analysis has shown that the the realized well productivity across the shale resource is in fact statistically random at operationally relevant length scales [21]. This supports previous anecdotal suggestions that contemporary shale development is as much an art as a science. Clearly, such a situation is not acceptable, particularly given the relative importance to overall energy supply being envisioned for unconventional resources [1].

Regarding the water needs of unconventional resource development, there are a number of issues that could benefit from a concerted research effort. Linking in with the operation issues, it is clear that since well EUR is the denominator in the life cycle water intensity calculation, a much better understanding of the long-term productive potential of hydraulically fractured wells is needed. It is also unclear if the life cycle water intensity is the most appropriate metric for assessing the water needs of unconventional resource development. More work is needed in assessing and developing techniques and procedures to better manage stresses on local water resources that result from large-scale hydraulic fracturing programs. Similarly, work must continue on how waste streams can be reduced or eliminated in an environmentally benign manner. And finally of course, a focus should be placed on developing stimulation techniques that do not consume freshwater at all.

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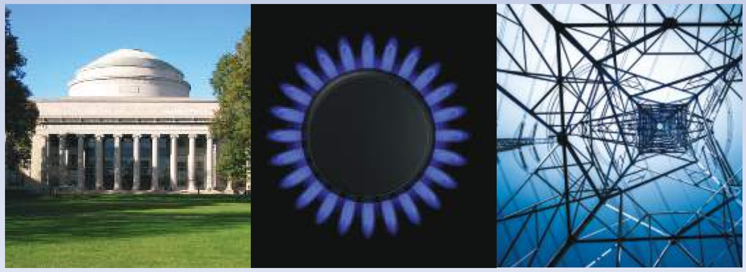

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