WATER AND FOOD IN THE BIOECONOMY—CHALLENGES AND OPPORTUNITIES FOR DEVELOPMENT

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1. INTRODUCTION

The concept of the bioeconomy encompasses a number of characteristics, and definitions vary in the literature. The definition utilized in this paper, focusing on the interaction between the bioeconomy and water resources and agriculture, includes economic growth driven by the development of renewable biological resources and biotechnologies to produce sustainable products, employment and income (OECD 2002; Sheppard et al. 2011). There are a number of key drivers for the development of the bioeconomy, including:

- the demand for sustainable renewable biological resources and bioprocesses to replace non-renewable resources;
- the need to improve the management of renewable resources;
- the need to respond to global challenges such as energy and food security, in the face of increasing constraints on agricultural water, productive land and carbon emissions (Sheppard et al. 2011);
- the rapid uptake of biotechnologies in agricultural production; and
- the opportunity to 'decouple' agricultural growth from environmental degradation through more sustainable production methods using biotechnology.

The development of the bioeconomy will be a primary determinant of sustainable agricultural productivity growth to meet food security goals, and also to generate employment and income. Water resources in turn can be a fundamental constraint to the bioeconomy or can facilitate bioeconomic growth with appropriate policies. This paper explores how water and the bioeconomy are interlinked, including how the constraints from growing water scarcity--- in part caused by development of the bioeconomy--may influence bioeconomic growth; and how water policy, and other resource-conserving policies and institutions can facilitate sustainable development of the bioeconomy. The paper describes the impact of biofuel production on water quantity and quality, assesses the role of hydropower in responding to energy challenges, and examines the potential for improved water use through the development of biotechnology for agriculture. Then alternative scenarios for water in the bioeconomy are assessed, and policy conclusions are presented.

2. IMPACT OF BIOFUEL PRODUCTION ON WATER QUANTITY AND QUALITY

A major concern for global resource availability is the impact of expanding biofuel production on water and land resources. In the last decade, global biofuel production and cropping area devoted to producing feedstock have expanded sharply. As a result, a growing amount of the world's water resources is being consumed to produce crops and process them into fuel for motor vehicles. This has been a significant development for water resources, because the water requirement for energy derived from biomass is quite large—about 70 to 400 times greater than other energy carriers such as fossil fuels, wind and solar (Gerben-Leenes et al. 2008 as quoted in DeFraiture and Berndes 2009). Moreover, agriculture already consumes about 70 percent of freshwater withdrawals worldwide (Rosegrant, Cline and Cai 2002).

Biofuel production affects both water quantity and quality. Expanding production of biofuels—through either crop-based production systems (e.g., maize or sugarcane) or direct biomass (cellulosic) production—can significantly increase demand for water as more acreage is planted or the crop mix begins to favor thirstier crops. Water is in short supply in many parts of the world, raising the question if water should be used to produce food rather than energy crops. Water quality can also be adversely affected by increased acreage for fertilizer-intensive crops, such as maize or sugarcane, which can result in increased nitrate run-off and soil erosion. Concerns also have been raised about water requirements for biorefineries.

While the impact of first-generation biofuel crops on natural resources is arguably significant, it has been overshadowed by concerns about global commodity prices and high food prices adversely affecting poor consumers (Rosegrant 2008; Rosegrant et al. 2008).[1] Such concerns have stimulated interest in next-generation cellulosic biofuels made from crop residues and perennial grasses. These feedstocks have the potential to reduce competition between food and fuel uses for land, water and energy resources while potentially achieving larger reductions in greenhouse gas emissions than maize-based ethanol. However, as with crop-based systems, the use of cellulosic feedstocks will also affect water quantity and quality. Moreover, the large-scale adoption of cellulosic energy crops is unlikely to fully remove adverse environmental impacts. Removal of crop residues for production of biofuels can reduce soil fertility and soil water holding capacity. Dedicated energy crops can divert existing fallow or marginal lands, increasing GHG emissions.

Water Quantity

For global agriculture, approximately 80 percent of the water requirements for crop production is met by rainfall; the remainder from irrigation. Parts of the world that rely heavily on irrigation include North Africa, South Asia, the North China Plains, and the U.S. Great Plains. Increased demand for water-intensive crops raises concerns for crop production where water tables are declining in these regions and elsewhere, such as Pakistan, Mexico, and some Mediterranean countries. Agricultural water usage is also a concern in many river systems around the world, including the Yellow River (China), the Krishna River (India), and the Syr Darya River (Central Asia).

Water requirements for producing feedstocks for biofuel production depend on the type of feedstock and a host of agro-climatic factors, including crop type, variety, soil, day length, and other factors. The most water-intensive feedstock production is row-crop agriculture. According to Dominguez-Faus et al. (2009), to produce 1 liter of ethanol, the evapotranspiration water requirement is about 800 liters for potatoes and sugar beets and up to 4,200 liters for soybeans. The requirement for maize is between 1,000 and 1,500 liters of water. Estimates by Gerbens-Leenes et al. (2009) are similar for most crops, except for potatoes at 1,321 liters. The study estimates values for other crops at 2,073 liters for wheat 2,506 liters for cassava, and 5,558 liters for sorghum. For sugarcane in Brazil, the conversion rate ranges between 927 and 1391 gallons of water per gallon of ethanol (Varghese 2007).

Rosegrant et al. (2008) indicate that biofuel expansion is not likely to alter the regional- and national-aggregate patterns of irrigation water use significantly, with water use under a rapid biofuel expansion increasing by one percent or less in most countries and regions by 2020 compared to a baseline scenaio. According to De Fraiture and Berndes (2009), the global annual

[1] Along with pressure on food supplies and prices, another concern for using agricultural crops for energy production is the limited contribution of biofuels to greenhouse gas mitigation (Crutzen et al. (2008) as cited in Gopalakrishnan et al. (2009)). However, research indicates that advances in crop management and yields, biorefinery operation, and coproduct utilization have made maize ethanol much more efficient, with GHG emissions estimated to be equivalent to a 48% to 59% reduction compared to gasoline (Liska et al. 2011).

water requirement for biofuel crop production (sugarcane, maize, and rapeseed) is estimated by at 100 km^3 or about 1.4 percent of the total required for food crop production. However, while the total global impact of biofuel cropping on water use is likely to be small, biofuel production can have significant local or regional impacts on water use. For example, the U.S. Department of Agriculture estimates that 5 billion bushels of maize, or 34 percent of total production, will be used to produce ethanol in the United States in 2012 (USDA 2012), up from 2.3 billion bushels a decade earlier, with significant impacts on existing water resources. Groundwater withdrawal rates for maize in the Mississippi Delta during 2002-09 averaged 27,000 m^3 per ha and year, but only 15,000 m^3 for cotton (Welch et al. 2010). These figures imply a near doubling of ground water withdrawals when converting land from cotton to maize (see Figure 1 for U.S. acreage trends for maize and cotton). With increased demand for maize relative to other crops, a change in acreage mix in the region during this period resulted in higher groundwater withdrawals and exacerbated already declining groundwater levels, which led to a loss in baseflow in most Mississippi Delta streams. Welch et al. (2010) also point to similar concerns that stretch across parts of the U.S. Great Plains. For example, irrigated maize is produced for cattle feed and ethanol in Kansas and Nebraska, where significant acreage of irrigated maize draws water from the Ogallala Aquifer.

Elsewhere, irrigation is not needed for biofuel production because rainfall is plentiful. Examples include most of the U.S. Midwest grain belt where maize and soybeans dominate sugarcane production in Brazil (except for irrigation in the Center-West and Northeast regions during critical periods as well as fertirrigation to return residues to the field), rapeseed for biodiesel in Europe, and palm oil and cassava in most parts of the world. For areas where water supply is not a significant constraint, concerns about water use are not directly tied to crops dedicated to biofuel production. Instead, the issue is one of crop displacement, i.e., food crops must be grown in other parts of the country or world where water might be less available. A report by the National Research Council (2007) concluded that shifts in production might have significant regional and/or local impacts where water resources are already scarce (see also Gheewala et al. 2011).

Prairie-grown switchgrass as a cellulosic source should not require irrigation (Dominguez-Faus et al. 2009). Therefore, converting cropland from water-intensive crops to switchgrass in low rainfall areas implies an increase in water availability for other crops or natural vegetation. Production of grass and wood waste require fewer water inputs than current feedstocks, but Varghese (2007) points out that pursing cellulosic-based biofuel production needs to be done with attention to sustainable energy production with benefits accruing to the farming community. The author cites an example of potentially misguided development of cellulosic ethanol production using eucalyptus trees, a fast growing tree that can deplete groundwater supplies. Similarly, production of second-generation biofuels that are based on crop residues (e.g., cereal straw or maize stover) may cause long-term degradation of soil quality because at least some crop residue is necessary for long-term soil health (Rosegrant et al. 2009).

Given significant food security concerns (and implied water and land use) from production of biofuel feedstock, some governments have taken steps to slow or stop additional development. For example, China has prohibited ethanol production using maize and wheat as feedstock, except for four existing plants (Qui et al. 2010).

Biorefineries
Water usage for processing feedstocks into biofuels is also a concern, even though processing requirements are estimated at only 2 to 10 liters per liter of ethanol, compared with thousands of liters for feedstock production (Dominguez-Faus et al. 2009). For a single plant that produces 100 million gallons of liquid ethanol per year, water consumption is roughly the same as the amount needed for a town of 5,000 people (National Research Council 2007). Consequently, the major concern for water usage for biofuel manufacturing is not necessarily the absolute amount of water or that energy production might displace other uses for water on a national or global level. Instead, as identified by a number of researchers, water for biofuel processing is often drawn from single geographic (point) sources, which can put pressure on local water supplies for area residents or compete with demands for other uses in localized areas (Varghese 2007). Also, importantly, a major resource concern is potential chemical and thermal pollution from refinery effluents (see section below) (De Fraiture and Berndes 2009).

Water Quality
The leading biofuel crop, maize, uses large amounts of fertilizers, including more nitrogen than other crops it replaces, at least in the United States. The shift toward increased use of maize and its impact on water resource can be significant because of the discharge of water and chemicals from agricultural fields to ground and surface water.

For example, Welch et al. (2010) find that additional maize production in the US Mississippi Delta region, due in part to ethanol demand, increases nitrate-N contamination of groundwater. Under a scenario with constant fertilizer applications for the crop mix and application rates at the 2006 level (i.e., pre-biofuel acreage expansion), the eventual depth on contamination is estimated at 7 meters below the water table. Under a second scenario based on increased maize production, the depth of contamination is 18 meters below the water table.

Nitrogen runoff has been linked to the growing size of hypoxic (low dissolved oxygen) conditions in the Gulf of Mexico off the coast of Louisiana. Additional nitrogen applications in the region stemming from increased maize production exacerbate this problem. The conversion of cotton to maize acreage between 2002 and 2007 is estimated to have resulted in a 7 percent increase in the nitrogen load for the Yazoo River, which is part of the watershed for the Gulf of Mexico (Welch et al. 2010). In this region, impacts on changes in the crop mix and subsequent increase in inputs have been magnified by historical alterations of the landscape. Specifically, forested wetlands have been cleared or drained and reduced ecosystem health. Thus, continued expansion of maize acreage that affects water uptake (thus reducing groundwater inflow to streams) and water quality can have significant environmental consequences on ecosystems that many would argue has already been compromised, particularly during low periods of flow in summer.

Water quality is also an issue in the eastern portions of the US maize belt. Considerable rainfall in the eastern maize belt contributes to highly productive conditions, but can also result in substantial nutrient discharge, especially in fields with tile drainage systems designed to remove excess moisture (Dominguez-Faus et al. 2009). Donner and Kucharik (2008), as cited in Dominguez-Faus et al. (2009), conclude that the anticipated increase in maize production to the ethanol mandate level would increase the dissolved inorganic nitrogen load by 10-18 percent. Similarly, Simpson et al. (2009) conclude that increased maize acreage and increased fertilizer application rates, motivated by higher maize prices, increases nitrogen and phosphorous losses to streams, rivers, lakes, and coastal waters, particularly the Gulf of Mexico and Atlantic coastal waters, with both nutrient and hypoxia monitoring showing effects of this increase. Similar effects have been found coastal areas of developing countries.

Brazil is the world's second largest producer of ethanol after the United States, and sugarcane is the primary feedstock. Varghese (2007) describes several studies that identify sugarcane production as a source of water pollution, including increased turbidity, nitrate leaching, and acidification. Additional water contamination stems from "ferti-gation" or delivering fertilizer or vinasse through irrigation water. Vinasse is a byproduct of sugarcane-based ethanol production, roughly produced at 10 or 13 units of vinasse per unit of ethanol. The effluent can be recycled as fertilizer because it is rich in organic matter and contains potassium and phosphorous. However, it reduces dissolved oxygen levels in water as it decomposes, damaging aquatic life, and increases acidity of soil and water. If policies such as a pollution tax were put in place to address water quality issues, De Moraes et al. (2009) conclude that some effluent would be shifted away from the sugarcane area benefiting environmental outcomes.

Importantly, expansion of biofuel production and requisite expansion of acreage for feed stocks also imply a potential shift in acreage of other crops, quite possibly to less fertile areas that need higher fertilizer rates. These marginal lands are often more susceptible to erosion and pollutant runoff, adversely affecting water quality (National Research Council 2007) or, alternatively, resulting in a decline of water usability due to water contamination (Gheewala et al. 2011). Consequently, the potential impact of expanding crop production extends well beyond the primary growing regions for biofuel feedstocks. Encouraging farming practices such as minimum tillage can help minimize soil erosion. Also, production of perennial crops such as switchgrass can hold soil and nutrients better in place than annual crops which are tilled. However, the commercial viability of producing cellulosic ethanol is still unknown.

Strains on Current Environmental Policies and Potential Options

Government policies are in place to mitigate potential adverse impacts of crop production on land and water resources. Some of these programs are straining to maintain conservation given the increased profitability of crop production as a result of biofuel mandates. An example is the Conservation Reserve Program in the United States. Landowners are paid under long-term contracts to remove marginal land (highly erodible or environmentally sensitive) from production and maintain conservation practices on it, thereby reducing erosion, runoff, and leaching of nutrients. The program is voluntary and total acreage is capped by legislation. In recent years, re-enrollment has declined, however, and some producers and agricultural commodity groups have asked for contract holders to be released early in order to plant crops and take advantage of strong market prices. Current legislative proposals would reduce the cap, which has implications for both land and water resources. Removing land from the CRP, given that is it is marginal and potentially erosive, is expected to lead to a nonlinear increase in erosion and nutrient loading to surface waters (Dominguez-Faus et al. 2009).

As a result of pressure on land availability, policymakers are looking at expanding "working lands" policies that allow crop production while incorporating either farming methods or partial land retirement in key areas along water boundaries or other areas that help minimize runoff. These types of policies would help address the conflicting objectives of meeting greater demand for agricultural commodities (for food or energy production) and maintaining or improving water quality and supplies along with other environmental benefits.

A number of other policy options have been suggested. A report by the National Research Council recommends performance incentives to encourage increased water recycling in ethanol plants and farmer adoption of improved irrigation technology (National Research Council 2007).

Others, including Moraes et al. (2011) and De Fraiture and Berndes (2009), recommend pursuing more explicit policies for biofuel crop production, given the interconnectedness between biofuel production, energy policy, and the current fragile state of global water resources. Under this approach, the focus would be on ensuring efficient water use, both in terms of feedstock selection, water management practices, and optimal conversion technologies for better water efficiency for the entire production process. The potential for biotechnology to improve biofuel efficiency is explored below.

Society would also likely benefit if researchers incorporate food and agricultural policy implications as they connect to biofuel production and water resources issues. In developed countries, where incomes are generally high enough for every person to have access to sufficient and adequate nutrition, the urgency for such analysis and policy consideration stems more from the perspective of economic efficiency. In poorer countries, stakes are higher. The convergence of many issues in the bioeconomy context—biofuel expansion, security of both energy and water, sustainability of resources for agricultural production, reasonable food costs, and meeting basic nutritional requirements—has created significant opportunity for researchers to help policymakers consider how biofuel policies and alternative energy policies can affect use of water and other resources needed for agricultural and energy production.

3. POTENTIAL FOR HYDROPOWER

Hydropower emerged as a major source of energy during the 20th century. More than 45,000 large dams have been constructed around the world to generate electricity, irrigate crops to produce food, supply water to industry, and control floods. Many smaller dams have been built to meet similar objectives.

While hydropower has been an important energy source for decades, growing environmental and social concerns in the 1990s, along with financial constraints, led to stagnant investment in hydropower (World Bank 2009). This was followed in the early 2000s by a general consensus for going slow on dams, stemming in part from a major report on the topic (World Commission on Dams 2000). The report concluded that decision-making on water and energy development should reflect a comprehensive approach to integrating a project’s social, environmental, and economic dimensions, not just strict economic and financial considerations. While it was not considered anti-development, some found the report as too cautious in its recommended approach, providing too many barriers to constructing dams for hydropower, slowing their development at a critical time.

Given today’s rising demand and prices for energy and food, along with environmental concerns associated with burning fossil fuels, a case can be made for significantly more rapid expansion of hydropower, not only for clean energy, but as a source of development and income growth in developing countries. Higher energy prices make investment in hydropower more profitable, and together with higher food prices, make multipurpose hydropower and irrigation dams more profitable. Such an approach can be controversial, as it directly and indirectly affects the lives of many people as well as aquatic ecosystems. As a result, it is necessary to recognize and address social and environmental elements while weighing global energy needs and environmental costs, which together can help policymakers work toward solutions that account for many competing interests.

The World Bank and others have pointed to potential expansion of various forms of hydropower, including large and small dams, small-scale hydropower, and unconventional power such as tidal and wave energy. As global demand for energy rises, and pressure intensifies on available energy supplies and the environmental consequences of burning fossil fuels, hydropower is once again becoming a worthy consideration for countries and investors deciding where to invest money for addressing their energy and food needs, which is reflected by the secular increase in the number of large dams after 2000 (ICOLD database).

Energy Demand and Hydropower as an Energy Source

Given continued population and rapid economic growth, particularly in the group of developing countries, combined with the environmental impacts of burning fossil fuels attention on renewable energy, such as hydropower, has increased.

Hydropower accounts for about one fifth of the global electricity supply (World Bank 2009). Leading hydropower-producing countries include China, Canada, Brazil, United States, Russia, and Norway (International Energy Agency 2010). Hydropower accounts for more than 50 percent of national electricity in 65 countries and more than 80 percent in 32 countries. It supplies almost all electricity in 13 countries. In 2000, hydropower represented more than 90 percent of total renewable energy generated (International Hydropower Association 2000).

Most of the rest of the world's energy is supplied from thermal sources such as coal, gas, and oil. The sustainability of thermal energy sources and their adverse impact on the environment have led many to question whether a truly renewable energy source, such as hydropower, should take a more prominent role in global energy policy.

Hydropower has a number of attractive characteristics. Its supply is unrelated to energy market, and hence does not fluctuate with short-term market conditions. Significant other benefits include a secure water supply, irrigation potential, and flood control, which is increasing in importance under climate change. Moreover, the technology is considered proven and well advanced, and efficiency levels are high. Importantly, because potential energy is stored as water in a reservoir, hydropower provides an option for energy storage (i.e., prior to generation), which optimizes electricity generation. A secondary benefit is flexible timing for energy generation. Moreover, power generation can be adjusted to meet demand instantaneously, with turbines spinning with zero load while synchronized with the electrical system before additional power is added. A fast response to peak demand enables hydropower to supplement less flexible (i.e., intermittent or less predictable) electrical power sources such as wind and solar energy.[2] However, in some cases, hydropower can be variable on a seasonal basis or annually due to drought or wet spells (International Hydropower Association 2000). The initial investment for hydropower depends on the plant capacity. As summarized in Table 3.1, estimates from various sources indicate that the initial cost for large plants (10 MW or larger) averages about $2-3 million per MW. Costs for small plants (1-10 MW) are approximately $4-5 million per MW, although several estimates are above and below this range. Plants considered "mini" (0.1 – 1.0 MW) and "micro" (<0.1 MW) have substantially higher unit costs, ranging from an estimated $5-500 million per MW. Micro and mini projects are typically used for communities and/or businesses. For example, a 5 kW micro hydropower station was built in south central China in

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2 An additional engineering feature of hydropower includes the "black start" or ability to start generation without an outside source of power. This capability allows multi-sourced systems with hydropower to restore service more rapidly than those dependently only on thermal sources.

1992, originally to serve a village of 24 families (Dou 2011). These investment costs compare with approximately $2 million per MW for a fossil fuel plant.

From an operational standpoint, compared with other large scale power plants, hydropower has the lowest operating costs and longest plant life. Moreover, plant life can be extended at a relatively low cost through routine maintenance and periodic replacement of turbine parts and rewinding of generators, unless sedimentation is a major issue; but some solutions have been developed here as well. With proper maintenance, the life of a typical plant in service for 40 to 50 years can be effectively doubled.

Once developed, energy supplied by hydropower can greatly benefit urban populations and others connected to the power distribution network. The report of the World Commission on Dams (2000) indicates that small increases in energy availability generate significant welfare improvements for countries with low levels of energy services.

Greenhouse Gas Emissions

Proponents of hydropower also point to significantly lower greenhouse gas (GHG) emissions compared with other energy sources.[3] According to research summarized in a report by the International Hydropower Association (2000), the GHG emissions factor is 30 to 60 times less for hydropower plants compared with fossil fuel generation. Also, development of half the world's economically feasible hydropower could reportedly reduce GHG emissions by about 13 percent, with an even more beneficial reduction in sulphur dioxide and nitrous oxide emissions (particulate emission for hydropower is essentially zero). In cases of tropical reservoirs, the emissions factor is higher—a result of decomposition of flooded biomass—but still five times below the value for coal.

Hydro energy by itself does not emit greenhouse gasses, and it has been a commonly-held belief that dam reservoirs do not emit any greenhouse gases (Ministerial Conference on Water for Ag and Energy in Africa 2008). Although GHG emissions are emitted, mostly from the initially filling of reservoirs, total emissions relative to energy produced is quite small relative to conventional fuel sources (see Table 3.2). Given the known GHG emissions of burning fossil fuels, a greater emphasis on accounting for relative emissions may in fact lead to more positive recommendations for hydropower investments.

Challenges for Hydropower

Barriers to developing hydropower in developing countries include the technical and financial capacity to design, build, and manage hydropower projects and facilities. Without assistance, most communities or even larger government entities cannot undertake such projects, especially large scale ones.

More broadly from a social standpoint, criticism of dams for hydropower and other purposes is well established. As WWF International (2007) points out, dam installations can force large-scale resettlement of human communities (sometimes millions of persons) while flooding biodiversity hotspots and fertile lands. Dams can also seriously disrupt river systems and permanently alter or destroy their ecology by changing the volume, quality, and timing of water flows downstream, and by blocking the movement of wildlife, nutrients, and sediments. From a construction and financial perspective, hydropower plants take more time to design, obtain approval, build, and recover investment, as compared to thermal plants, for example.

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3 GHG includes carbon dioxide from combustion and methane from processing coal and natural gas.

Hydropower development can seriously impact fish and fisheries. During construction and filling, river habitat is lost, which is important for maintenance of fish resources. For hydropower facilities that use large reservoir storage, altering the natural river cycle adversely affects habitat availability and stability during periods of spawning and incubation. Also, the operation of long term storage influences the river downstream from the reservoir and can adversely affect river productivity; and permanently inhibit fish migrations, which are important in most larger river systems, such as the Amazon or Mekong. Importantly, the report by the World Commission on Dams (2000) found that large dams have more negative than positive impacts on rivers, watersheds, and ecosystems, and in many cases their installation leads to irreversible loss of species and ecosystems.

Sedimentation is another problem with dams. Organic and chemical materials can be transported by a river and trapped in a reservoir rather than flushed out by the river system, potentially building up to undesirable levels. To reduce these effects, besides addressing the underlying problem of excess chemical application or runoff, conservation and agricultural practices in the catchment area can be altered to help reduce erosion prior to water entering the reservoir. Other water quality issues from dam installation include changes in water temperature of released water as well as changes in levels of dissolved gases, minerals, and chemical content.

Furthermore, the World Commission on Dams report found that benefits of dams seldom benefit the poor. Even proponents of hydropower recognize that "Difficult ethical issues, such as … ensuring rights of people and communities affected by a project are respected are also likely to arise" (International Hydropower Association 2000, p. 7). Relocating people and involuntary resettlement affect entire communities, local culture, and has significant implications for religious and burial sites.

Aside from the social issues, the report by the World Commission on Dams (2000) concluded that, in general, large dams tend to fall short of physical and economic targets. In contrast, it noted that large hydropower dams generally meet their financial targets, although performance varies considerably across projects.

Potential for Hydropower Growth

The World Bank (2009) estimated an absolute level of feasible hydropower capacity in developing countries at more than 1,900 gigawatts, with 70% of the total yet to be tapped.[4] The untapped amount is not quite double the currently installed hydropower worldwide. Regionally, the unexploited potential is greatest in Africa (93% of potential), East Asia and the Pacific (82%), Middle East and North Africa (79%), South Asia (75%), and Latin American and the Caribbean (62%). Additional energy could be created by rehabilitating existing infrastructure. The World Bank report (2009) points out that developing Africa's hydropower to the same extent as Canada would result in an 8-fold increase in electricity supply. In the United States, the Department of Energy has identified nearly 6,000 sites with undeveloped hydropower potential representing about 40% of existing hydropower capacity (U.S. Department of Interior 2005).

The World Bank reports that its lending for hydropower has increased in recent years due in part to hydropower's important role for a range of issues, including energy security, poverty alleviation, and sustainable development. The need for better water resource management—from the perspectives of energy, irrigation needs, human and industry consumption, and flood

[4] One gigawatt (GW) equals 1,000 megawatts (MW). According to Hadjerioua et al. (2012), on an annual basis, 1 MW of hydropower produces enough electricity to power nearly 400 U.S. homes. Each gigawatt could power up to 400,000 homes.

management—has elevated the importance of hydro infrastructure and contributed to a growing awareness that hydrology and economic growth are closely linked. In 2009, the World Bank reported that 67 hydropower projects had been approved since FY 2003, with $3.7 billion in contributions to support a total of $8.5 billion and nearly 9,700 MW of capacity. New lending on an annual basis increased from $250 million during 2002-04, to $500 million during 2005-07, to more than $1 billion in 2008. Major projects were approved in Africa (Senegal, Democratic Republic of Congo, Sierra Leone, and Uganda) and Asia (People's Democratic Republic of Laos and India).

While funding by the World Bank remains significant, new capital from a number of countries, including China, Brazil, Thailand, and India, is also funding dam construction (Imhof and Lanza 2010, Eberhard et al. 2010). Chinese banks and companies are reportedly involved in constructing more than 200 large dams[5] in nearly 50 countries. Within China, hydropower capacity is scheduled to increase by 50% by 2015 in order to meet energy demands as well as reduce carbon dioxide emissions (Chinadaily.com 2010). Currently, coal accounts for more than 80 percent of China's electrical output.

Eberhard et al. (2010) point out that scaling up generation capacity through large private sector–led projects is gaining momentum. One example is a privately owned 250-MW hydropower plant in Uganda, supported by World Bank guarantees and funded by a private consortium.

Multi-Purpose Dams and Adding Hydropower to Existing Dams

The development of multi-purpose dams has potential for expansion of both hydropower and irrigation water supply. In Africa, water resources for hydropower and agricultural purposes remain comparatively underdeveloped, despite economically viable potential for both power generation and irrigated area. According to Rosegrant (2010), only 3.5 percent of Africa's agricultural land is equipped for irrigation, some 7 million hectares concentrated in a handful of countries. At least 1.4 million hectares could be economically developed using existing or planned dams associated with hydropower. An additional 5.4 million hectares would be viable for small-scale irrigation. Countries with the greatest potential for dam-associated large-scale investments include Ethiopia, Nigeria, Sudan, and Zimbabwe.

Similarly, adding hydropower to existing dams has the potential to increase electrical generation without incurring cost of building new dams. For example, a potential project in Coimbra, Portugal would integrate a small hydropower plant into an existing multi-purpose dam-bridge to generate electricity for city buses and trolleys. Currently, the dam-bridge stretches across the Mondego River, creating a 1 meter drop in a "run-of-river" project (designed to not affect the natural river flow more than for daily storage). Storage is primarily for industrial and municipality supply, and flow is adjusted through spillway gates for ecological purposes and irrigation. A technical study has shown that installing "low head" turbines would provide more than enough energy for the city's transport system while addressing concerns for fish passing through the river (de Almeida et al. 2011).

Potential for adding power to existing dam exists elsewhere. The United States, for example, has more than 80,000 non-powered dams—dams that do not produce electricity—built originally for water supply, inland navigation, and other purposes. This compares with roughly 2,500 dams with hydropower capacity. A recent assessment prepared for the U.S. Department of Energy concludes that adding power to non-powered dams has the potential to increase the size

5 At least 15 meters high, or between 5 and 15 meters with reservoir capacity of at least 3 million cubic meters.

of the existing hydropower fleet by 15 percent, with a majority of the potential concentrated in just 100 non-powered dams (Hadjerioua et al. 2012).

Water resources are also under-developed in Indonesia, although the country has many irrigation weirs and dams. In many of these areas, many farmers and communities have little or no access to electricity needed for economic development. Efforts are underway to apply hydropower to existing structures where it is technically and economically feasible (Andritz Hydro 2010).

Potential for Small-scale Hydropower

Given the challenges associated with large hydropower investments, including proper accounting of environmental and social costs, a number of researchers have identified a growing potential for small-scale hydropower. Kosnik (2010) points out that, while average investment costs for small-scale hydropower exceeds the competitive cost for fossil fuels ($5 million per MW compared with $2 million per MW – see Table 3.1), hundreds of small-scale hydropower sites could be developed for $2 million or less. The implication is that while average costs remain high, considerable economic potential exists immediately where sites are favorable in the United States and elsewhere in the world.

Moreover, according to Paish (2002), small-scale hydro offers a number of advantages, including a more concentrated energy resource than wind or solar power, predictable energy availability (usually continuous and available on demand), limited maintenance, long-lasting technology, and minimal environmental impact. Similarly, a hydropower resource assessment for Africa sees substantial potential for small hydropower in Africa, due to low investment requirements, low environmental impacts, and viable technologies (Ministerial Conference on Water for Ag and Energy in Africa 2008). Importantly, small-scale hydropower is typically designed to run “in-river” rather than creating storage. This is considered more environmentally friendly because it does not interfere significantly with the flow of the river (Energy Technology Systems Analysis Programme 2010).

According to Kosnik, while the technical capacity is already available in the United States, several issues affect the path toward realizing the potential. These include the permitting process, which can involve numerous regulatory agencies at the federal, state, and local level, resulting in a costly and time-consuming process. Also, parts for building small-scale hydropower plants need to be standardized to facilitate a more streamlined and lower cost process for design and construction.

In Europe, small-scale hydropower is appealing because large-scale opportunities have already been exploited or are not considered because they are environmentally unacceptable (Paish 2002). The author also indicates that small-scale hydropower appears to have similar potential in less developed countries, concluding that micro-hydro is one of the most cost-effective energy technologies to be considered for rural electrification. In China, small hydro is seen as an environmentally sound solution to improving economic growth in the country. This may be particularly true given social and environmental impacts of large-scale dams in China over the years.

In parts of world where technology is not as readily available, individual villages have taken upon themselves to develop small-scale hydropower (Dou 2011). Some of the challenges with these projects include lack of technical expertise needed for maximum cost effectiveness and energy output (e.g., system configuration is not optimized, so generator efficiency is low). Also, a lack of knowledge in system operation and maintenance can also be a constraint.

The technical capacity for small-scale hydropower has improved over time (Paish 2002). Developments in turbines have made them more tolerant of sand and other particles in water and easier to maintain. Turbines have also been designed for use in a variety of heads (distance between top of water level and turbine) and for ease of fabrications, an important feature for developing countries. Despite improvements, the researcher concludes that many "low head" sites in Europe remain only marginally attractive from an economic standpoint compared with fossil fuel power generation, which implies additional technical advances would allow more development of these sites. Similarly, a report by Energy Technology Systems Analysis Programme (2010) states that adding hydropower capacity does not require any technological breakthroughs, additional research and development is needed to improve the technology and public acceptance. Some potential improvements for small hydropower include equipment design, materials, and control systems, particularly low-cost technology for small-capacity and low-head applications to match with the available (and smaller) resource sites.

Paish also identifies several other environmental issues that need to be addressed when installing and operating small-scale hydro plants, including reduced oxygenation of the water, erosion immediately downstream of the turbine draft tubes, and machinery noise.[6] More broadly, shortcomings for small-scale hydro (which are not unlike those for large scale projects) include finding suitable sites near demand centers for power, dealing with intermittent river flows (seasonal or drought), resolving conflicts with the interests of fisheries and irrigation needs, and increasing familiarity with the technology so it will be adopted. Paish concludes that to reach a greater potential for small-scale hydropower adoption, resources should be allocated toward: (1) technology transfer of appropriate turbines to local manufacturers, (2) loans for developing sites, (3) technical support for developers, and (4) training in operation, maintenance, repair, and business management.

Others have pointed out that despite the fact that small-scale hydropower technology is well-developed and enormous potential exists in Africa, a relatively small number of units are in operation on the continent, suggesting that barriers other than technology persist (Klunne undated; Ministerial Conference on Water for Ag and Energy in Africa 2008). These barriers include lack of access to appropriate technologies; lack of infrastructure for manufacturing, installation, and operation; lack of local capacity to design and develop small hydropower schemes, including feasibility studies; and regulatory burden for small-scale operators. More generally, Klunne concludes that small scale hydro projects need to be embedded in a national program for capacity building to foster a new industry. The Ministerial Conference paper recommends that regulations for approving projects need to be changed to accommodate small players.

Conclusion

A major conclusion on hydropower development from researchers and participants alike is that the decision-making process for large-scale projects should be broadened sufficiently to include all relevant environmental and social aspects. A more inclusive approach, and continuous communications between developers and people affected, would help increase confidence in the legitimacy of the processes for decision-making and development. The reasonable approach

[6] Within Europe, other institutional and environmental barriers must be overcome for new small-scale hydro plants, including gaining permission for land and water use. A unique challenge for the hydro operator is disposing of debris and rubbish that is collected on the intake screens. While an expense, such activity provides environmental benefits for those downstream.

outlined in the paper by the Ministerial Conference on Water is to exploit the resources while using an integrated approach to management of water resources in order to determine the optimal allocation of scarce water for competing sectors (hydropower, agriculture, industry, urban, etc.).

Historically, the World Bank has been instrumental in developing hydropower. Its strategy is to support a range of hydropower investments, including small run-of-river projects, rehabilitations, and multipurpose projects. Another component of the lending strategy, which reflects the trend in government and private funding, focuses on energy and water planning at the county and regional level, forming partnerships with private financiers and others to leverage World Bank financing.

Reducing financial risk to investing in hydropower would speed its development. One way to do so is to promote smaller-scale projects that carry relatively less risk. For small-scale hydropower, there appears to be significant technical potential as well as economic potential, although a number of challenges outlined above must be addressed before the economic potential can be realized.

As demand for energy continues to rise and environmental costs associated with burning fossil fuels mount, faster expansion of all sizes of hydropower and scaling up existing hydropower facilities appear to be a viable option. Issues and concerns with conventional forms of energy will likely only heighten the need for hydropower development. Unlike a major competing form of renewable energy—biofuels—hydropower does not consume energy nor reduce food availability. In contrast, development of hydropower can complement food production by developing structures and power that also provide irrigation water and support it distribution for growing food crops.

Tidal and Wave Power

Tidal energy is another form of hydropower that results from the gravitational effects of both the moon and sun on oceans. Contrary to popular misconception, tidal waves are not generated only by the moon's gravitational effects on the oceans; roughly one third of the energy comes from the sun's gravitational influence (Energy Consumers Edge 2012). As water is being pulled in the direction of either of the two bodies, currents form that turn generator turbines which then create electricity. Installations can consist of a barrage or dam, tidal fence (like a turnstill), or a tidal turbine (an underwater windmill).

As with other hydropower installations, tidal energy can be captured only in site-specific locations, typically with mean tidal difference greater than 5 meters and favorable topographical conditions in bays or estuaries to bring down installation costs. According to the U.S. Department of Energy, there are only 40 locations worldwide that can support a tidal energy plant given the necessary difference between high and low tides (U.S. Department of Energy, "Ocean Tidal Power").

Tidal power plants require no fuel and are relatively easy to maintain. As a renewable source of energy, tidal power does not emit carbon or other pollutants as thermal, gas or oil power plants do. Also, with tidal waves driven by timing of orbits, energy generation is easy to predict, making such plants a reliable source of energy (Biofuels Congress 2012). Aesthetically, natural current generators can be built into existing bridges and be hidden from view, thus not disrupting any surrounding scenery.

Tidal energy projects can initially be more expensive than conventional power generators, such as fossil fuels and natural gas, due to high capital investment. The majority of the cost goes towards the start-up costs, which can be influenced by the current's velocity and its distribution, the number of installed units, insurance, and device reliability (Altprofits 2012). The costs include the turbine and generator, deployment, maintenance, and connecting it to the grid. Seabed composition also will affect capital costs and the foundation design of the tidal stream device. Due to economies of scale, a larger number of units will result in lower electricity costs. However, the operation cost of a tidal energy plant is less than conventional plants because fuel is free.

Drawbacks of tidal energy include a requirement for a considerable amount of space to construct barrages or dams. Also intermittent tidal flow results in start/stop power generation that is inefficient for power generation (similar to wind generators). The effect on marine life can be disruptive, as the moving turbines may increase the amounts of silt in the water as well as kill fish passing through it. Structures that block estuaries can impede sea life migration, and silt build-up affects local ecosystems.

In contrast to capturing tidal energy, ocean ***wave*** power is energy extracted directly from surface waves or from pressure fluctuations below the surface. (U.S. Department of Energy, "Ocean Wave Power"). Some analysts think energy in ocean waves is twice the electric generating capacity currently available throughout the world. Areas of the world with the greatest wave-power potential include the western coasts of Scotland, northern Canada, southern Africa, Australia, and the northeastern and northwestern coasts of the United States.

Offshore wave power systems are typically set in water greater than 40 meters and use the bobbing motion of the waves to power a pump that creates electricity. Special floating platforms can also harness wave energy. Onshore systems collect energy in breaking waves using an oscillating water column or other device. Site selection is important for minimizing environmental impacts, including altering the flow patterns of sediment on the ocean floor. Reportedly, wave power systems are generally not economically competitive with traditional power sources, but costs are declining. As with other hydropower options, because fuel is free, wave power units have low operating costs.

A study conducted by the United Kingdom government and international energy-centered organizations determined that tidal and wave energy sources have the potential to be major suppliers of energy worldwide. The potential market value for wave energy is about $1 trillion, according to the World Energy Council, and the U.S. could provide 6.5% of its energy solely on tidal and wave energy (Altprofits 2012).

4. BIOTECHNOLOGY AND WATER

The need to expand crop production in a world with finite resources, particularly water, quickly leads to a focus on increasing productivity. One potential area for improved water use is through the development of biotechnology for agriculture. Crop biotechnology can be an important substitute (and/or complement) for direct water management and provide solutions to reducing water scarcity in agriculture.

Given the increasing demands on global agriculture, it is likely that biotechnology, in addition to conventional breeding, will be needed to increase genetic diversity to achieve some of the necessary breakthroughs. Ultimately, a combination of yield improvement output per unit of water—plus improved farming systems to better use water or help retain moisture (e.g., minimum tillage)—needs to contribute greatly to increased global crop output.

The use of biotechnology has the potential to address crop production and water scarcity in several ways. These include: (1) making biofuels crops more productive in the field and processing, thereby reducing their water footprint, (2) improving the productivity and water use efficiency of rainfed crops, thereby reducing pressure on irrigation water use for crops, (3) developing drought tolerance in crops.

Biotech Advancements for Biofuels Crops[7]

Biotechnology has been used to make biofuels crops more productive in the field and for processing into fuels. Increasing output relative to inputs, including water, helps relieve pressure on those resource and makes them available for producing other crops or for other uses. Currently, production of ethanol from starch crops and biodiesel from oil crops is based on established technologies. Improvements in crop productivity, crop suitability and biofuels processing are all within the realm of proven biotechnological approaches. Biotechnology can be used to improve the crop to make it more productive or more suitable to biofuels use. Molecular marker technologies can separate quantitative traits into individual components, enabling market assisted selection of desired traits in a much shorter time than conventional breeding (Pathan et al. 2007).

The measure of a crop's usefulness for biofuel production is closely related to its yield, whether it is starch, oil, or biomass yield. Historically, plant breeding has been the primary approach for improving yield across growing environments. Initial application of biotechnology has been aimed at single gene traits; and while insect resistance has improved yields in some situations, approaches to improve yield directly with the tools of biotechnology are still being developed. A crop's ability to produce yield across many different growing environments is complex and can be affected by many different genes. The genes involved in determining yield potential, their importance and expression patterns vary widely depending on the crop and growing environment. Even so, genes affecting yield directly have been identified and are being evaluated in the field.

In most growing environments, environmental stresses such as drought, heat, cold or salinity result in yields that are below the crop's potential. Improving abiotic stress tolerance improves the yield a farmer realizes. Research in *Arabidopsis* and rice has resulted in identification of many genes associated with various types of stress tolerance. These genes must now be associated with changes in crop tolerance to abiotic stresses in the field.

For cellulosic feedstocks, biomass production can be increased if a plant continues to grow vegetatively and does not flower. The switch from vegetative growth to flowering is under genetic control. Modifying these genes so that additional vegetative growth occurs before flowering could result in increased biomass for biofuel use. Demand for biofuel and high crop prices has led to research focused on using cellulose and other plant biomass components for biofuels, spawning a generation of dedicated energy crops (Cavalieri and Rosegrant 2008).

The application of biotechnology and plant breeding for crop improvement has been concentrated on widely grown, commercial crops primarily maize, soybean, cotton, and canola. Breeding and research in these crops is supported by the private investment of the seed industry. Crop cultivars with transgenic traits have been broadly commercialized in the last 15 years, with most of the activity in the United States, Argentina, Brazil, Canada, India, and China. Expansion of biotech technologies beyond large commodity crops in industrialized countries is occurring more slowly.

As Cavalieri and Rosegrant (2008) point out, many of the challenges of using crops for biofuels production can be addressed through biotechnology. Crops must be adapted for growth

7 This section is summarized primarily from Cavalieri and Rosegrant 2008 (and references therein).

in a wide variety of environments making biotechnological approaches for crop adaptation of value in biofuels crops as well as food and fiber crops, and biotechnology may be required in some case to convert plants to biofuels feedstocks. Introduction of specific traits related to crop use for biofuels can increase the economic feasibility of a crop's use by raising productivity or increasing the efficiency of processing. While plant breeding over many years has resulted in high, consistent yields of maize, soybeans and canola in the developed world, yields remain low in much of Africa, Asia and Latin America because of unimproved germplasm, poor soil nutrition, abiotic stresses and pests, and weak policies and institutions.

Genes for agronomically important traits such as disease resistance, drought tolerance, salinity tolerance, heat tolerance and yield have been identified and are in various levels of field testing. Cultivars containing these traits are projected to be commercialized by seed companies in the markets where genetically modified (GM) products are currently accepted (Cavalieri and Rosegrant 2008). Commercial breeding programs routinely incorporate the use of molecular marker based approaches to incorporate transgenes and improve the efficiency of selection for multiple gene traits in these crops.

Most of the major research-driven seed companies are also marketing conventional maize hybrids identified for use in ethanol production. Yield of starch is the most important trait in maize hybrids used for ethanol production while oil content is the most important trait for biodiesel production from oil crops. Transgenic approaches for increasing starch in maize or oil in soybean and canola, as well as, modifying oil profile for biofuel use are also in the company pipelines. Syngenta has developed a transgenic maize containing amylase that converts starch to sugar for the production of ethanol. In February 2011, after a government review process, the US Department of Agriculture approved maize amylase Event 3272, making it the first genetically modified output trait in maize for the ethanol industry (Syngenta 2012).

Sugarcane, cassava, oil palm are tropical food crops with high suitability for biofuel use. Relative to maize, soybean and canola, they have not been the target of significant research spending for breeding or biotechnology, but progress is being made. For example, biotech advancements have been made in sugar beets to help growers manage weeds and improve productivity, while sugar cane varieties with biotech traits are currently being evaluated in various parts of the world (Sugar Industry Biotech Council 2012). At the Shanghai Center for Cassava Biotechnology (SCCB)[8], biotechnological tools are being developed for genetic improvement of cassava yield, quality and other factors (Shanghai Center for Cassava Biotechnology 2012). For oil palm, research and development activities have been undertaken by the Malaysian Palm Oil Board (MPOB), resulting in a number of biotechnological product developments including a "low pour point" palm oil biodiesel (USDA 2010).

Sugarcane is the most energy efficient crop based ethanol source. It is the most successful and widely used biofuel crop, with Brazil developing extensive experience in substituting sugarcane ethanol for petroleum for motor fuel beginning in the 1970's. The crop is characterized by a narrow gene pool, complex genome, poor fertility (seed set) and long breeding times, making it an ideal candidate for biotech development. As a result, molecular marker based approaches for improving sugarcane are being used to study crop diversity within sugarcane varieties. However, the large size of the sugarcane genome has limited efforts at DNA sequencing to expressed sequence tags (EST's) or genes that code for proteins. Brazilian researchers have generated more than 250,000 EST's that mark 33,000 unique genes. Microarray

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8 SCCB is a joint "virtual laboratory" supported by Shanghai Institutes for Biological Sciences, Chinese Academy of Sciences, and Swiss Federal Institute of Technology.

technologies that identify gene expression for large numbers of genes are also being applied to identify genes involved in disease resistance and carbohydrate metabolism.

Similar to sugar cane, cassava improvement is technically challenging because it does not reproduce true to type from seed, there is strong inbreeding depression, and the breeding cycle is long. Given the difficulties with conventional breeding, molecular markers and marker assisted selection have become important for cassava, including sourcing genes from wild relatives (Setter and Fregene 2007). Transformation systems have been developed to introduce genes into plants, and it is possible to insert genes into cassava and regenerate plants. Interest has been focused on insect (whitefly and stem borer) resistance, African Cassava mosaic virus disease resistance, nutritional quality, and starch composition (Cavalieri and Rosegrant 2008 and references therein). Development of transgenic cassava plants with bacterial enzymes involved in starch accumulation increased the biomass of above ground portions and starch in roots suggesting that biofuels yields could be increased by increasing the starch yield (Cavalieri and Rosegrant 2008 and references therein).

Oil palm is the most productive oil crop in the world, and while oil palm has been an important source of edible oils, demand for biodiesel in Europe has resulted in extensive planting of oil palm plantations in the tropics, particularly Malaysia and other parts of Southeast Asia. Palm oil has been a relatively low value commodity which has limited incentives to improve yield through conventional methods. However, yield potential is quite high and improved management and improved varieties through breeding can double existing yields. Since oil palms do not produce seed for 6-7 years, molecular marker breeding approaches are quite valuable for making early selections. Tissue culture has also been used for mass clonal propagation. This technique allows a breeder to select a tree with desirable traits and propagate it immediately without waiting for seed production. Clonal propagation has been applied at the commercial plantation scale and is now an important tool. In spite of limited resources for the application of biotechnology to oil palm, a workable transformation system exists.

While most of the recent biotechnological advances in crop genetics have focused on grain production, biotechnology is beginning to determine how plant cell walls are synthesized. This information can be used to alter genes in plants that make them more productive in cellulose production and make the cellulose more easily converted to biofuels (Mosier 2006).

Several species with commercial cellulosic potential are likely to be of widespread importance and to be impacted by biotechnology (Cavalieri and Rosegrant 2008 and references therein). These include switchgrass (*Panicum virgatum*), *Miscanthus* (Miscanthus giganteus), sorghum (*Sorghum bicolor*) and *Jatropha curcas*.

For switchgrass, there are a number of approaches that use biotechnology to improve. Significant sequencing of the expressed genes of switchgrass has resulted in 12,000 sequenced genes which are being evaluated for their effects on biomass composition and biofuel conversion traits. Transformation systems have been developed for switchgrass and transgenics for drought tolerance, salinity tolerance, and herbicide resistance are in the early stages of product development. While programs using biotechnology to improve switchgrass are promising, several hurdles exist. Switchgrass is not widely grown and agronomic systems are currently in the development stage. Widespread demand for biomass for biofuels is also not imminent. Conventional cultivars of switchgrass with reasonable levels of environmental adaptation and adequate yields are still in the development stage. GM cultivars will be developed concurrently with conventional improvements in the species; however, transgenic traits in switchgrass are not expected to impact production for a number of years.

Beyond crop production, processing efficiency for biomass is a critical factor determining the eventual commercial feasibility of cellulosic biofuels. Several companies are working to engineer plants to contain genes for enzymes that will digest the cellulose and other cell wall compounds. Precise expression of these genes will be required so that the enzymes are produced in a controlled way following harvest. Also, biotechnology can also be applied to the microbes involved in processing biomass into biofuels (Cavalieri and Rosegrant 2008).

Improving Productivity and Water Use Efficiency of Rainfed Crops

Critical to future water use and availability for agriculture, and by extension global crop production, is productivity gains for rainfed crops. These improvements could reduce pressure on irrigation water use for crops while increasing total agricultural output for food and fuel use. Importantly, approximately 82% of global cropland is rainfed, representing a major contributor to local and regional food security (Morison et al. 2008). Besides increasing output for the vast majority of global crop acreage (i.e., rainfed areas), many have suggested that better rainfed varieties of crops need to be developed to reduce the use of irrigation in hot, dry environments because plants are the most water inefficient in these situations due to high evaporation rates. Climate changes, including prospective increase in mean temperatures, are expected to increase evapotranspiration rates in warmer regions, adding to the urgency of increasing plant water use efficiency and yields in general.

Varietal improvements over the last 40+ years have not only resulted in overall crop yield gains, but they also enabled production on many rainfed areas where production was previously limited or not feasible (Rosegrant et al. 2002). For example, in the 1980s in India, modern varieties of major cereals spread to an additional 20 million hectares, with rainfed regions accounting for three quarters of the total gain. While rainfed area has expanded in India and elsewhere, yield gains for crops in these areas remain lower than in irrigated areas because erratic rainfall, variable climate, and other factors make plant breeding a difficult task. Nevertheless, both conventional and non-conventional breeding techniques have led to rates of yield gain that are higher for varieties targeted for rainfed areas compared with those targeted for irrigated areas.

The fundamental concept for improving crop yields is captured by the Passioura formula that is cited by many researchers (Richards et al. 2002; Ortiz et al. 2007; Morison et al. 2008). It posits that when water is limiting, grain yield is a function of (i) the amount of water used (or available) through plant transpiration[9] and soil evaporation, (ii) how efficiently the crop uses this water for biomass growth (i.e., the water-use efficiency as above-ground biomass/water use), and (iii) the harvest index, (i.e. the proportion of grain yield to above-ground biomass).[10] Since these three components are likely to be largely independent of each other, then an improvement in any one of them should result in an increase in yield.

Water use (and availability) not only includes transpiration but also evaporation and what agronomists consider other water "uses" such as drainage from the root zone and run-off (Morison et al. 2008). This has generated interest in genotypes with rapid leaf growth to improve the degree of ground cover (to reduce losses from soil evaporation) and deeper rooting to recover

[9] According to Morison et al. (2008), well over 90% of water required by plants is not used in a biochemical way but lost through transpiration.

[10] Passioura et al. (2007) describes the challenge as producing cultivars that: (1) capture more of the water supply for use in transpiration, (2) exchange transpired water for CO_2 more effectively in producing biomass, and (3) convert more of the biomass into grain.

more water from the soil profile (see next section for discussion of deficit irrigation and partial root zone drying to enhance root growth). Runoff and leakage from irrigation reservoirs may be available to other users and not necessarily “lost.”

Conventional breeding has led to recent releases of cereal varieties with improved yields, with approximately half of the gains in Mediterranean cropping systems related to crop improvements and the other half related to improved agronomy and management. However, only limited progress has been made through directly selecting physiological traits apart from flowering time and plant height. The challenge stems from variability in timing of rainfall (or lack thereof) and in the amount of water the crop receives each year, and whether particular areas depend entirely on rainfall or partly on water stored in the soil profile. This creates a multitude of varied targets for plant improvement under dry conditions (Morison et al. 2008 and reference therein). Also, while conventional breeding has resulted in significant gains over the decades, especially in the harvest index, the absolute level of the index is likely limited because sufficient leaves are necessary for photosynthesis and the stem must be strong enough to support grain weight and avoid lodging (Hsiao et al. 2007). Nevertheless, the harvest index might be further increased through manipulations that increase carbohydrate supply to developing grains during drought stress, which decrease abortion and increase grain yield (Morison et al. 2008).

Morison et al. 2008 points out that advances in genetics and the molecular sciences (and technology, generally) can now help scientists exploit a new understanding of drought stress and plant response, resulting in a more targeted selection program where biotechnology is combined with conventional breeding to increase biomass water use efficiency. Variations in complex traits that increase water use efficiency are the basis for crop breeding programs, and identifying this variation can lead to the association of the trait with particular regions of the plant’s genome. The combination of particular DNA sequences or markers and the associated trait can be used for marker-assisted selection, which improves the efficiency of breeding programs where complex traits are involved. The process avoids costly physiological test on all the material, and pre-selection of progeny also saves time and expense. An example of this approach is new lines of wheat that were released in Australia in 2002 and 2003 which were selected for higher transpiration efficiency. Trials indicated a 23% yield increase compared with existing varieties in the most severe environments.

More generally, improved yields have resulted from selecting plants with several features that positively affect factors in the Passioura formula (Richards 2004 as referenced by Morison et al. 2008). These include: extended crop duration, which allow crops to be grown at different times of the year, thereby reducing soil evaporation and increase water use; increased resistance to water transport to slow down water use and ensure it is available during anthesis (flowering) and subsequent grain filling; and reduced anthesis-silking interval in maize to reduce chances of drought stress during this vital stage of development.

Some researchers claim that there is little hope to improve any of the three factors by breeding, so essentially all yield gains require increased water use. For example, Steduto et al. (2007) concludes that biomass production with respect to a unit of water is essentially fixed. This would leave only the harvest index, which is reaching its limits, to be improved. The paper provides an exception for a genetic breakthrough, which would change the intrinsic respiration capacities of the plant. Blum (2005) is somewhat less pessimistic, concluding that in water-limited environment, a single “drought adaptive” gene can be assessed only by considering multiple factors of yield potential, drought resistance, and water-use efficiency, and not any one in isolation. Still, the author concludes that high water-use efficiency is largely a function of reduced water use rather than an improvement in plant production.

However, many scientists, while acknowledging the challenges, expect that progress for yield gains without requiring commensurate increases in water use is far from over (Richards et al. 1993; Richards et al. 2002; Ortiz et al. 2007). Breeding can influence biomass/unit of water through transpiration rates and efficiency of biomass per unit of transpiration. They conclude that, because it is a difficult challenge to breed for these three factors, the use of biotechnology and marker-assisted selection is a necessity for significant progress in the longer term. Similarly, Morison et al. (2008) emphasizes that many interlinked processes and factors underlie plant water needs, and additional progress will depend on a combination of disciplines, including agronomy, hydrology, agricultural engineering, crop and plant physiology, and molecular genetics. These researchers also comment that incorporating physiological and agronomic expertise into the design of transgenic experiments is crucial in realizing improvements in water productivity. This has been lacking on occasion when molecular biologists have studied genes associated with severe dehydration stress.

Developing Drought Tolerance

Developing drought tolerance is important to minimizing catastrophic yield losses that threaten food security. The human toil can be high in terms of food availability. Moreover, uncertain of crop production can roil commodity markets worldwide, increasing the price of food that affects everyone, particularly the poor who spend a high proportion of income on food.

Plants are especially susceptible to drought during the reproductive stages as plant resources are redirected to support root growth and leaf stomata (pores for gas exchange) close to reduce water loss through transpiration. Conventional breeding is a slow process which requires the identification of genetic variability to drought among crop varieties and introducing this tolerance into varieties with suitable agronomic characteristics. It is limited by the availability of suitable genes for breeding. In contrast, developing drought-tolerant crops by genetic engineering involves identifying key genetic determinants (several hundred genes) relating to stress tolerance in plants, and introducing these genes into crops.[11] For example, in 2012, Monsanto is field testing the first U.S. government-approved biotech crop developed to tolerate drought before its commercial release. Monsanto developed it with a gene taken from a bacterium commonly found in soil and vegetation (Monsanto 2012).

Over the years, traditional breeding strategies in areas that suffer drought have seen limited progress for two reasons: (1) the domestication of crops has narrowed the genetic diversity within crops for stress tolerance, which limits options in traditional crop breeding; and (2) selection for high yield potential generally works against a plant's ability to respond to drought (Jenks et al. 2007). Because plants have developed a range of strategies to balance growth and reproduction with stress (drought) resistance, it is hard to identify selection criteria that contribute to high and stable yields under drought (Hollington and Steele 2007). As a complement to traditional breeding programs, promising biotechnology applications for improving plant tolerance to drought include discovering existing genetic variation in crop germplasm and wild relatives, and manipulating genetic variation using mutation, transgenic, and molecular market-assisted breeding approaches.

[11] International Service for the Acquisition of Agri-biotech Applications. "Biotechnology for the Development of Drought Tolerant Crops." http://isaaa.org/resources/publications/pocketk/32/default.asp

Christensen and Feldmann (2007) point out that a significant accomplishment in biotechnology has been the sequencing of several plant genomes. This has greatly increased the number of genes being evaluated for conferring stress tolerance, leading to over 50 genes reported to confer drought tolerance. They consider this identification as boding well for the prospects of developing genetically engineered drought-tolerant crops, but recommend that research focus explicitly on crop productivity in the field rather than on desiccation (drying) recovery or other efforts only in the laboratory. The challenge for crop improvement is driven by the tradeoff between drought tolerance and plant productivity. Therefore, identifying the genes that affect plant water relations is useful, but only if it results in the kind of drought tolerance that is valuable for agriculture productivity (Christensen and Feldmann 2007).

To be successful commercially, drought tolerance must be accompanied by an array of characteristics—such as resistant to disease and desirable food or feed properties—that are most effectively integrated by convention breeding (Munns and Richards 2007). The researchers conclude that challenge for breeders is to efficiently integrate trait-based and molecular methods (e.g., molecular markers for key traits) to increase yields in dry climates. The molecular biologists and physiologists, in turn, must convince the breeders that the next adopted trait will be significant, and that the trait they are selecting for is highly heritable using molecular markets, while having a clear understanding of how a particular trait will influence yield. According to Banziger and Araus (2007), the separate approaches by these two groups in maize research could be complementary and result in significant yield stability given that many transgenic approaches target different mechanism for drought tolerance than conventional breeding.

In general, for drought tolerance, a significant question is whether it is necessary to sacrifice yield potential under “normal” water conditions to gain performance at very low water levels. Given this apparent tradeoff, current technology, and the need to minimize catastrophic losses, the answer for researchers and policymakers is likely a qualified yes. Progress on reducing or eliminating the tradeoff should be the goal for researchers focused on biotechnology for the process itself as well as for enhancing crop productivity. Moreover, as concluded by a FAO conference on water scarcity, biotechnology has a valuable role in addressing the challenge of water scarcity in developing countries, and many applications of it have not yet met their full potential to deliver practical solutions (FAO 2007).

Crop Management Practices for More Efficient Water Use

Several crop management/tillage practices can serve as a complement to genetic improvement in crop water efficiency and drought tolerance. These practices can ensure that rainwater is held long enough on the land to ensure infiltration, particularly where rainfall is generally available but water infiltration rates are not adequate to reach desired moisture levels (Rosegrant et al. 2002). Examples include mulching to reduce soil evaporation, and adding organic matter, which can enhance physical characteristics of the soil.[12] Deep tillage can improve soil moisture capacity by increasing soil porosity, and runoff is reduced by increasing the roughness of soil surface. Contour farming can be used in more hilly areas to slow runoff and retain rainfall on the cropping area. Where rainfall is limited, special terraces (e.g., flat-channel) can be used to capture all rainfall and spread it across a wider area, thereby preventing water runoff.

[12] Morison et al. (2008) (and references therein) report that mulching and improved irrigation schedules in the North China Plain have increased yield and water use efficiency for wheat and maize by 50% over the last 20 years. Also, no-tillage practices in the Central U.S. Plains has increased water use efficiency by 30% and made possible more intensified cropping rotations (typically wheat-fallow).

Other techniques include conservation tillage (e.g., no-till or minimum till), which can help conserve soil water and decrease the rate of soil water evaporation if undertaken with other suitable inputs such as equipment and weed/insect management practices. Additional plant residue on the soil surface protects it against erosion and water runoff. No-till technology has improved soil moisture conservation and reduced crop failure in dry years, particularly in arid or semi-arid areas such as Sub-Saharan Africa. Under conservation tillage, weed management is critical to maximize water available for the crop.

Deficit irrigation is a promising management option as well, as outlined in Morison et al. (2008) and Hsiao (2007). By applying only a predetermined percentage of calculated potential plant water use, mild soil drying occurs results in restricted shoot growth and leaf development, which reduces competition within the plant for reproductive development. For cereals, it can redirect plant energy from storage to developing grains, which increases the harvest index and crop yield. In a similar manner, alternate partial root-zone irrigation might improve water use efficiency without significant crop yield reduction by manipulating the plant response system so that a continuous soil-drying signal restricts plant water use in the long run (Kang and Zhang 2004).

5. BIOECONOMY SCENARIO FOR 2050

In this section, we assess whether significant improvements in key aspects of water use and the bioeconomy can make significant improvements in food and water security. The analysis is undertaken through a scenario assessment. We utilize the IMPACT model: a partial equilibrium, multi–commodity, multi-country model which generates projections of global food supply, demand, trade, and prices (Rosegrant et al 2008). IMPACT covers over 46 crops and livestock commodities and it includes 115 countries/regions where each country is linked to the rest of the world through international trade and 281 food producing units (grouped according to political boundaries and major river basins). Demand is a function of prices, income, and population growth. Crop production is determined by crop and input prices, the rate of productivity growth, and water availability. The *Business-as-Usual* scenario assumes a continuation of current trends and existing plans in agricultural and water policies and investments in agricultural productivity growth. Population projections are the "Medium" variant population growth rate projections from the Population Statistics division of the UN and Gross Domestic Product (GDP) projections are estimated by the authors, drawing upon Millennium Ecosystem Assessment (2005). These projections embodied a long and deliberate process of choosing plausible drivers of socio-economic changes to illustrate the various alternative "story lines" that were used for the assessment. Subsequently the GDP projections for various regions were adjusted in order to better reflect the rates of economic growth that have been seen in recent years.

Bioeconomy Scenario Description

The *Bioeconomy Scenario* presents a view of the world that moves in the direction of more sustainable growth in the bioeconomy. This scenario emphasizes the importance of sustainable development to achieve economic growth through a set of drivers, ranging from higher agricultural productivity and income growth to earlier adoption of second generation biofuels, and increased water use efficiency which are further discussed in this section. The *Bioeconomy Scenario* also highlights the importance of making informed choices by farmers, consumers, the private sector, governments and policy makers to combat obstacles in achieving food security and reducing malnutrition and hunger while ensuring sustainable and environmentally friendly economic growth.

The scenario assumes, in common with the *Business As Usual* scenario, medium population growth rates produced by the Population Statistics division of the United Nations (UN, 2011). The population numbers for the countries in the UN data have been aggregated to IMPACT's 115 regions. GDP growth is increased relative to *Business As Usual* to reflect the increased productivity in the agricultural and water sectors (see below). The computable general equilibrium (CGE) model GTEM (Ahammad and Mi, 2005) was used iteratively with IMPACT to generate the multiplier effects from agricultural and water sector productivity growth to GDP growth. Globally, GDP growth increases from 3.2 percent per year under *Business As Usual* to 3.6 percent per year under the *Bioeconomy Scenario*. Adhering to the criteria of sustainability, we increase the efficiency in the use of water resources for three sectors – irrigation (agricultural sector), and domestic and industrial water use. Increased water use efficiency lowers water use in these three critical sectors, underlining the importance of sustainable use of natural resources. This aspect of the scenario is discussed in more detail below.

To assess the impact of faster technological change in the biofuels sector in the *Bioeconomy Scenario,* we assume that commercial scale second generation biofuels start 5 years earlier than assumed in the *Business As Usual* scenario (2025 rather than 2030), thus lowering demand for crop-based feedstocks for first generation biofuels. We also look into the impact of higher energy prices by increasing fertilizer prices in the world market by 25 percent. In doing so, we capture the effect of lower fertilizer input (lower nitrogen per hectare).

The importance of agricultural R&D and crop productivity is examined in the *Bioeconomy Scenario* through an increase in the intrinsic productivity growth rates for crop yields. The aim is to assess the effect of improvement of crop technologies through the yield enhancement strategies including investment in agricultural research with an emphasis on biotechnology. discussed above that lead to realization of higher growth rates of yield. First, we compute in the model the necessary crop productivity growth rate increases that would be required to maintain the 2050 crop prices at the levels found in 2010. This requires a very high increase in crop productivity relative to recent performance for most crops; and would be very difficult to attain given the investments required and lags in realization of improved varieties. Therefore, in the next step, we reduce these crop productivity growth rate increases by one-half and apply them to the *Business As Usual* crop productivity growth rates. The increased productivity growth rates are applied to key crops as shown in Table 5.1. Livestock productivity growth is increased by a factor of 0.2.

Impacts on Food Supply and Demand and Food Security

In this section, we provide a discussion of the scenario results, which are presented as the percentage difference between the *Bioeconomy Scenario* and the *Business as Usual Scenario* for the year 2050. Table 5.2 presents the percent change in world commodity prices between the two scenarios. As seen here, prices for most of the commodities decrease, except for meats, fruits and vegetables. The largest decline in price is for rapeseed oil at 23 percent, followed by maize at 18 percent, rapeseed at 14 percent, and wheat at 11 percent. Prices for beef, sheep, poultry, vegetables and fruits increase reflecting the impact of higher income on these commodity markets.

Increased income growth leads to a subsequent increase in the demand for agricultural commodities and thus puts upward pressure on prices. On the other hand, earlier adoption of second generation biofuels reduces demand, which eases the pressure on prices. On the supply side, increased efficiency in water use and higher productivity growth rates of crop and livestock increase supply, resulting in lower prices. At the same time, the impact of higher fertilizer prices results in reduced crop yields and increased prices. Income plays a prominent role in the demand for specific commodities such as beef, fruits, and vegetables. As the demand for livestock products increase with growth in income, prices for these commodities also rise. Effects are less pronounced for pork and milk.

Lower demand for maize for ethanol in the *Bioeconomy Scenario* frees up supply resulting in a price decline. Similarly, demand for vegetable oils is lower, which in turn lowers its prices and crush profit margins.

Table 5.3 illustrates the percent change in production of commodities between the *Bioeconomy Scenario* and the *Business As Usual Scenario*. With the increase in crop and livestock productivity growth rates the supply of both meats and cereals increase. Meat production increases 10 to 21 percent, with the largest increase observed in the Middle East and North Africa and Sub-Saharan Africa. At the same time, the supply of cereals increases by 8 to 14 percent. The East Asia and Pacific region has the highest level of increase in production, followed by Middle East and Africa.

Table 5.4 presents scenario results for per capita food demand for meats and cereals for major regions. As expected per capita demand levels increase under the *Bioeconomy Scenario* as a result of higher income growth and lower agricultural commodity prices; moreover, there is a small shift toward increased consumption of higher-valued livestock products away from staple cereals. The impact of high income growth is found to be stronger for the consumption of meats relative to cereals. The Middle East and North Africa region has the highest percent increase in cereal food demand, followed by Latin America and the Caribbean and the Europe and Central Asia regions. On the other hand, the highest increase in per capita meat demand is seen in Sub-Saharan Africa, followed by Latin America and the Caribbean.

Table 5.5 shows net exports for the *Business As Usual* and *Bioeconomy Scenarios* for 2050 for different regions. As a result of higher productivity and higher incomes, net cereal and meat exports continue to increase from regions such as Latin America and the Caribbean, Europe and Central Asia, while South Asia and Sub-Saharan Africa remain net importers.

An important measure of food security is the number of people facing risk of hunger in the different regions of the world. Table 5.6 illustrates the projected change in the population at risk of hunger presented as the percent change between the *Business As Usual* and the *Bioeconomy Scenario* by 2050. Higher yield growth that lowers prices and induces increased food demand reduces the number of people at the risk of hunger. Thus, in the *Bioeconomy Scenario*, the share of the population at risk of hunger declines for all the regions. Sub-Saharan Africa shows the largest decline, with a 44 percent reduction in the share of population facing risk of hunger, followed by Latin America and the Caribbean, South Asia and East Asia and Pacific.

Impacts on Consumption and Reliability of Water Resources

Renewable water resources (RWR) in a nation provide the natural limit of water development potential. Figure 5.1 presents RWR by continents based on hydrological simulations of IMPACT using 1971-2000 climatology. On average, the estimated 40,000 km3 of global RWR are distributed unevenly across continents. For instance, the LAC region accounts for a third of global RWR; in contrast, MENA possesses only a tiny fraction. Significant variations also exist within each of these continental regions.

We use the Water Simulation Module of the IMPACT model to simulate water allocation and uses by sector over the period 2000-2050, for the *Business As Usual* and the *Bioeconomy Scenarios*. Two sets of factors contribute to changes in water use in the *Bioeconomy Scenario*. On the one hand, we raised water use efficiencies in the domestic, industrial and irrigation sectors to reflect direct water-saving effects in the *Bioeconomy Scenario*. On the other hand, indirect water use consequences were channeled through changes in irrigated crop areas caused by higher income growth, changed timing of new biofuels technology adoption, higher crop and livestock productivity growth and higher fertilizer prices, which are specified in the *Bioeconomy Scenario*. As a result, simulated water uses under the *Bioeconomy Scenario* reflect the combined direct and indirect effects.

The assumed water use efficiency increases in the *Bioeconomy Scenario* are summarized at the continental level for 2030 and 2050 as presented in Table 5.7. They represent percent reductions in the consumptive water demands of the sectors compared to the *Business As Usual Scenario*. For the domestic sector, efficiency increase ranges from 22.2 percent to 29.5 percent by 2030, and 37.5 percent to 49.2 percent by 2050, with a global average of 27 percent in 2030 and 45.1 percent in 2050. For the industrial sector, greater regional variations of changes are assumed and the average global efficiency increase reaches 26 percent in 2030 and 43.4 percent by 2050. Smaller efficiency gains are assumed for the irrigation sector. The average global efficiency gains are 8.8 percent in 2030 and 14.5 percent in 2050. The efficiency gains for industrial and residential water use are taken from the WaterGAP model used in GEO5's Chapter 16 (Ozkaynak et al. 2012). The underlying assumptions of water use efficiency gains as described in GEO5 report include stringent efficiency measures are taken in industry and residential water use and climate policies lead to a reduced demand for thermal cooling in power generation as fossil-fuel-powered plants are partly replaced by renewable energy sources. For agriculture, we estimate the basin water use efficiency gains based on more efficient transpiration (including drought resistant varieties and other advances in research and biotechnology as described in Section 4 above), reduced non-beneficial ET and reduced losses to water sinks (e.g. due to water-conserving irrigation and crop management technologies and reduced evaporative losses during conveyance).

Table 5.8 presents the total consumptive water use of all sectors under the *Business As Usual Scenario* and the *Bioeconomy Scenario*, and the percent changes due to efficiency gains in the latter, for 2030 and 2050. Regionally, the biggest water users in the world are East Asia and the Pacific and South Asia, owing to their high populations, vast irrigated areas, and multiple irrigated cropping seasons in Asia. For all continents, total consumptive water uses decrease in the *Bioeconomy Scenario*, though the magnitude of change differs. The largest percent reductions are found in Europe and Central Asia and Western Europe, while the smallest percent reductions are found for Middle East & North Africa and South Asia.

The small reduction of total water consumption in the Middle East & North Africa and South Asia are due to the fact that irrigation water consumption in South Asia actually increases under the *Bioeconomy Scenario*. In this region, water use efficiency growth in the domestic and industrial sectors reduces water consumption in these two sectors, and as a result, more water is available for irrigation. With higher productivity and lower prices, food demand increases, inducing increased irrigation water use.

In the Middle East and North Africa region, total water consumption only declines marginally under the *Bioeconomy Scenario* because irrigation efficiency growth in this region under *Bioeconomy* is significantly smaller than in other regions, given that irrigation efficiency is already very high today.

Table 5.9 and Table 5.10 summarize the regional and global total and beneficial irrigation water consumption. By definition, beneficial irrigation consumption is the portion of applied irrigation water that is beneficially used by crops, including crop evapotranspiration plus any required water for leaching of salts from the crop root zone (Howell, 2003). In contrast, total irrigation water consumption also includes evaporative losses during water conveyance and application, and any percolation into saline aquifers not suitable for economic use, in addition to beneficial consumption.

The *Bioeconomy Scenario* lowers irrigation water consumption in most regions except for South Asia in 2030 and 2050 and Europe & Central Asia in 2050. Irrigation water consumption increases in these two regions because water saved in the domestic and industrial sectors as a result of higher efficiencies is then used for irrigation to meet increased food demand.

The regional beneficial irrigation consumption is presented in Table 5.10. The regional pattern of beneficial irrigation consumption follows that of total irrigation consumption; however the changes of beneficial irrigation consumption due to efficiency gains differ from that of total irrigation consumption. In fact, for many regions beneficial irrigation consumptions increases under the *Bioeconomy Scenario* because of increased water available for crop evapotranspiration as the non-irrigation sectors consume less water and the irrigation sector "wastes" less water. The decline of beneficial irrigation consumption in several regions is caused by irrigated area changes in those regions that are determined by the interplay of the multiple assumptions in the *Bioeconomy Scenario*.

Table 5.11 presents irrigation water supply reliability (IWSR) results for 2000, 2030 and 2050. IWSR is defined as the ratio of irrigation water supply to demand, at an annual basis (Rosegrant, Cai, and Cline, 2002). It reflects the level of water scarcity in irrigation, and the higher the value, the more secure the water supply is. In general, Europe and Central Asia, South Asia and, to some extent, East Asia and the Pacific face the most serious irrigation water shortages, as indicated by their low IWSR values. Under the *Business As Usual Scenario*, their IWSR values decrease over time and reach fairly low levels by 2050. The water use efficiency gains under the *Bioeconomy Scenario* relieve water shortage situations in these regions and other regions as well. Globally, the IWSR value is 0.619 under the *Business As Usual Scenario* represents a significant decline in reliability of water supply compared to the value of 0.766 in 2000. The improvements in water use efficiency under the *Bioeconomy Scenario* result in a much better water supply reliability of 0.726 in 2050 compared to the *Business As Usual Scenario*, supporting increases in irrigated area and crop yields.

6. CONCLUSIONS

This paper discussed important water, food and energy interactions in a world under pressure for increased, more efficient and more sustainable use of natural resources to meet complementary and competing objectives in the food, water and energy sectors. As suggested in the introduction, the bioeconomy faces both challenges—exemplified in the current use of first-generation biofuel technologies that compete for both water and land resources in ways that experts did not consider at the start of the biofuels boom—but also opportunities for enhanced natural resource use—through judicious second-generation biofuel technologies, other natural resource use for energy and food, such as hydropower production, and a stronger focus on biotechnologies that have already significantly contributed to conserving natural resources and are also important means for achieving enhanced access to food for rapidly growing developing countries.

The *Bioeconomy Scenario* as developed, combining increased resource use efficiency in agriculture and water through advanced technologies and increased use of economic incentives, more rapid adoption of second-generation biofuel technologies and higher fertilizer prices to both reflect increased energy prices and reduced fertilizer application with higher economic growth results in increased food security while removing pressure on water and land resources. However, as higher food demand increases irrigation water use, agricultural water use will increase in some countries and regions under this scenario. As was laid out in the introduction, how such a bioeconomy will be developed in practice will be a primary determinant of sustainable agricultural productivity growth to meet food security goals.

Despite growing natural resource scarcity, many policies in both the developed and developing world continue to support wasteful use of natural resources, particularly water, and subsidize practices that harm the environment, through fuel, energy or fertilizer subsidies, mandates for biofuels, and/or free access to these resources, such as irrigation water or subsidized industrial and domestic water supplies.

To move the pathway of development towards the Bioeconomy Scenario it will be crucial that institutions are developed in support of valuing the full cost of natural resource use, using a mix of approaches, such as market-based instruments, regulations and rules as well as direct interventions. In the water sector, pricing has been shown to work very well for the domestic and industrial sectors, while for irrigation, pricing will only work well if farmers have full control over water resources. In the irrigation sector, other avenues, such as formal or informal water marketing, investments in improved water infrastructure and on-farm technologies, as well as innovative measures, such as paying farmers for using less irrigation water are feasible. Importantly, policy changes in non-water sector might do more to water outcomes than many direct water policies. Examples include changes in trade policies (toward increased trade liberalization, removal of food self sufficiency policies, and removal of energy and fertilizer subsidies. One of the most important strategies to conserve agricultural water will be continued breeding for higher-yielding crop varieties.

In addition to changes in policies, investments in increased energy and water use and new development in hydropower are important avenues toward achieving the *Bioeconomy Scenario* postulated here. While investments have increased in these sectors over the last 5-10 years, efficiency and environmental impact benefits remain mixed, and most investments continue to neglect to incorporate important water, energy, land and food interlinkages in the design and implementation of these projects.

Thus, the potential for achieving the *Bioeconomy Scenario* is large and there are multi-faceted, cross-sectoral opportunities for policies and investments to move in this direction, but much needs to be done—urgently—to make a more efficient bioeconomy a reality for future generations.

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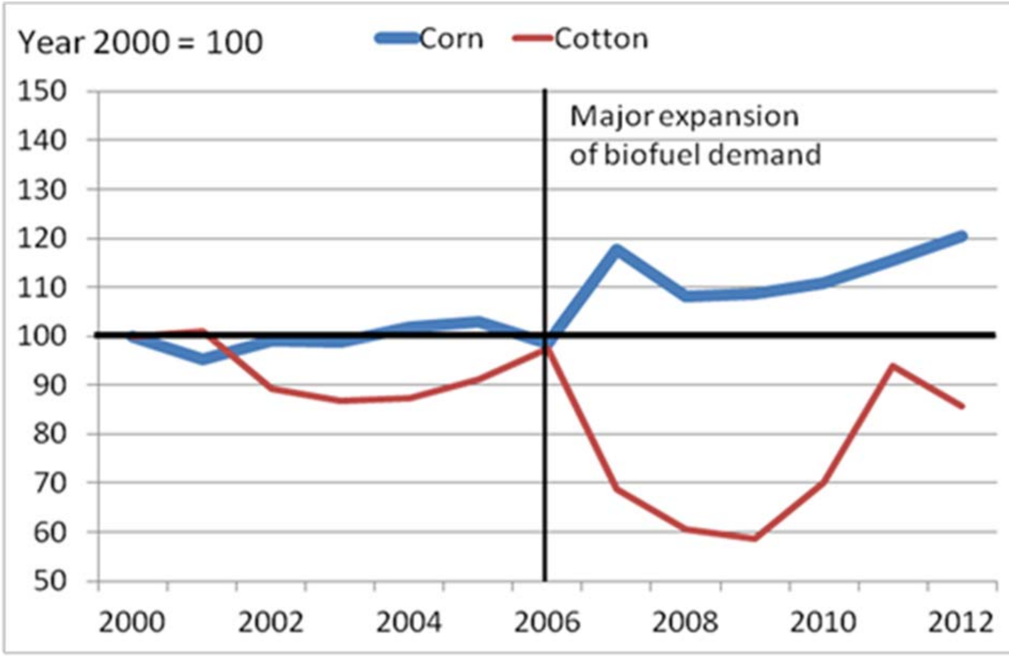
Figure 2.1—Indices of U.S. planted area of maize and cotton, 2000-2012.



Source: Indices calculated by author using acreage data published by U.S. Department of Agriculture.

Figure 5.1—Internal renewable water resources by region (in km^3/yr).

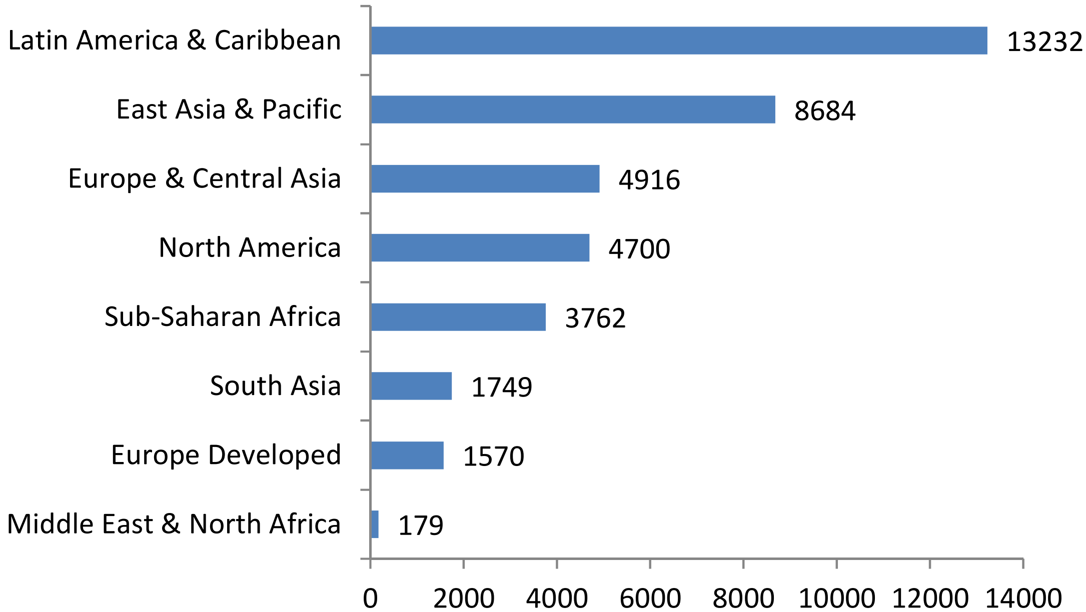


Table 3.1—Average cost of initial investment per unit of installed capacity and average cost per unit of electricity power generated

Energy source	Output (MW)	Investment cost (US$ Mil./MW)	Levelized capital cost (US$/ MWh)	Operational & maintenance cost (US$/MWh)	Reference
Fossil fuel	--	$2 mil.	--	--	Kosnik (2010)
Coal	--	--	$65.3	$28.2 -$42.3	U.S. Energy Information Administration (2010)
Natural gas	--	--	$17.5-$45.8	--	U.S. Energy Information Administration (2010)
Hydropower			$74.5	$10.1	U.S. Energy Information Administration (2010)
Micro	< 0.1 MW	$500 mil. (using median cost at 1 MW equivalent)	--	--	Kosnik (2010)
Mini	0.1-1.0 MW	$12 mil. (using median cost at 1 MW)	--	--	Kosnik (2010)
	<0.5 MW	$10 mil.	--	--	Paish (2002)
	<1 MW	$5 mil.	--	1.5% to 2% of investment	Energy Technology Systems Analysis Programme (2010)
Small	Not specified	$0.6-$6 mil.	--	--	Domingo et al. (undated)
	<2 MW	$2.5-$3.0 mil.	--	--	Paish (2002)
	1-10 MW	$4.5 mil.	--	1.5% to 2% of investment	Energy Technology Systems Analysis Programme (2010)
	<10 MW	$2-$4 mil.	--	$10-$40 / MWh	IEA (2010)
	1-30 MW	$5 mil. (using median amount)	--	--	Kosnik (2010)
Large	>10 MW	$4 mil	--	1.5% to 2% of investment	Energy Technology Systems Analysis Programme (2010)
	10-100 MW	$2-$3 mil.	--	$5-$20 / MWh	IEA (2010)
	100-300 MW	$2-$3 mil.	--	$5-$20 / MWh	IEA (2010)
	>300 MW	<$2 mil.	--	$5-$20 / MWh	IEA (2010)
Large dam in Congo	196 MW	$1.2 mil.	--	--	Ministerial Conference on Water for Ag and Energy in Africa (2008)
Aswan high dam in Egypt	2,810 MW	At least $0.4 mil.	--	--	Ministerial Conference on Water for Ag and Energy in Africa (2008)

Table 3.2—Greenhouse gas emissions per unit of electricity generated.

Energy source	Emissions Pounds (CO_2/kWh)	Emissions (kt eq. CO_2 /TWh)	Reference
Coal	--	974	Ministerial Conference on Water for Ag and Energy in Africa (2008)
	--	941– 1022	Gagnon (2003)
	2.02 – 2.12	--	U.S. Energy Information Administration (2012)
Oil	1.57-1.70	--	U.S. Energy Information Administration (2012)
	--	841 – 1177	Gagnon (2003)
Natural gas	1.12	--	U.S. Energy Information Administration (2012)
	--	551	Ministerial Conference on Water for Ag and Energy in Africa (2008)
	--	422 – 499	Gagnon (2003)
Hydropower	--	15 (with reservoir) 1 (run of river)	Ministerial Conference on Water for Ag and Energy in Africa (2008)
	--	10 – 33 (with reservoir) 3 – 4 (run of river)	Gagnon (2003)
	--	Negligible	Energy Technology Systems Analysis Programme (2010); Kosnik (2010); Energy Technology Systems Analysis Programme (2010).
	--	More than typical estimates	Middleton and Lawrence (undated) of the International Rivers Network

Table 5.1—Change in productivity growth rates (%).

Item	Bioeconomy Scenario
Crop	
Rice	0.205
Wheat	0.375
Maize	0.575
Other grains	0.07
Soybeans	0.165
Sweet potato	0.125
Cassava	0.225
Chickpeas	0.065
Sorghum	0.215
Sugarcane	0.295
Sugar beet	0.295
Rapeseed	0.395
Total other oilseeds	0.275
Palm oil	0.025
Groundnut	0.025
Livestock	
Beef	0.20
Pork	0.20
Poultry	0.20
Lamb	0.20
Eggs	0.20
Milk	0.20

Source: Authors' computations.

Table 5.2—Projected change (%) in world commodity prices between Business as usual and Bioeconomy Scenario for 2050.

Commodity	Bioeconmy Scenario
Beef	7%
Pork	-3%
Lamb	7%
Poultry	5%
Milk	-5%
Rice	-10%
Wheat	-11%
Maize	-18%
Other Grains	3%
Millet	-1%
Sorghum	-4%
Rapeseed	-14%
Rapeseed Meal	10%
Rapeseed Oil	-23%
Soybeans	-3%
Soybean Meal	9%
Soybean Oil	-11%
Vegetables	6%
Tropical and Sub-Tropical Fruits	8%
Temperate Fruits	6%
Sugar	-8%

Source: IFPRI IMPACT projections (2012).
Notes: Other grains include barley and rye.

Table 5.3—Projected change (%) in food production between the Business as usual and Bioeconomy Scenario for 2050.

Commodity/Regions	Bioeconomy Scenario
Meats	
East Asia and Pacific	11%
Europe and Central Asia	10%
Latin America and the Caribbean	11%
Middle East and North Africa	12%
South Asia	11%
Sub-Saharan Africa	12%
Developed	10%
Developing	11%
World	11%
Cereals	
East Asia and Pacific	14%
Europe and Central Asia	8%
Latin America and the Caribbean	9%
Middle East and North Africa	13%
South Asia	10%
Sub-Saharan Africa	8%
Developed	8%
Developing	10%
World	10%

Source: IFPRI IMPACT projections (2012_.
Notes: Meat includes beef, pork, poultry, and sheep & goat. Cereals include rice, wheat, maize, other grains, sorghum, and millet.

Table 5.4—Projected change (%) in per capita food consumption between the Business as usual and Bioeconomy Scenario for 2050.

Commodity/Regions	Bioeconomy Scenario
Meat	
East Asia and Pacific	13.0%
Europe and Central Asia	8.9%
Latin America and the Caribbean	14.0%
Middle East and North Africa	8.9%
South Asia	11.9%
Sub-Saharan Africa	30.8%
Developed	0.2%
Developing	14.4%
World	10.6%
Cereals	
East Asia and Pacific	7.0%
Europe and Central Asia	7.3%
Latin America and the Caribbean	7.3%
Middle East and North Africa	8.1%
South Asia	5.4%
Sub-Saharan Africa	4.5%
Developed	5.2%
Developing	10.9%
World	10.2%

Source: IFPRI IMPACT projections (2012).
Notes: Meats include beef, pork, poultry, and sheep & goat. Cereals include rice, wheat, maize, other grains, sorghum, and millet.

Table 5.5—Net exports ('000 mt) for Business as usual and Bioeconomy Scenarios for 2050

Regions	Business as usual	Bioeconomy Scenario
East Asia and Pacific		
Cereals	-85,784	-88,577
Meat	-17,007	-22,438
Europe and Central Asia		
Cereals	192,436	208,881
Meat	1,597	2,163
Latin America and the Caribbean		
Cereals	18,110	12,985
Meat	23,754	24,230
Middle East and North Africa		
Cereals	-60,889	-65,646
Meat	616	1,151
South Asia		
Cereals	-82,614	-88,654
Meat	-2,906	-3,702
Sub-Saharan Africa		
Cereals	-144,306	-202,430
Meat	-12,019	-20,451
Developed		
Cereals	166,862	227,473
Meat	7,756	20,724
Developing		
Cereals	-166,862	-227,473
Meat	-7,756	-20,724

Source: IFPRI IMPACT projections (2012).
Notes: Meats includes beef, pork, poultry, and sheep & goat. Cereals include rice, wheat, maize, other grains, sorghum, and millet.

Table 5.6—Projected change (%) in population at risk of hunger between the Business as usual and Bioeconomy Scenario for 2050.

Regions	Bioeconomy Scenario
East Asia and Pacific	-30%
Europe and Central Asia	-8%
Latin America and the Caribbean	-34%
Middle East and North Africa	-26%
South Asia	-30%
Sub-Saharan Africa	-44%
Developing	-35%

Source: IFPRI IMPACT projections (2012).

Table 5.7—Efficiency growth assumptions as percent reduction of water demand by sector in Bioeconomy Scenario compared with Business As Usual in 2030 and 2050.

Region	Domestic		Industrial		Irrigation	
	2030	2050	2030	2050	2030	2050
East Asia & Pacific	-22.2	-37.5	-16.3	-35.0	-14.7	-24.6
Europe & Central Asia	-29.2	-48.7	-43.6	-72.1	-8.2	-13.7
Latin America & Caribbean	-28.8	-48.1	-41.2	-68.9	-6.8	-11.3
Middle East & North Africa	-29.5	-49.2	-21.5	-35.9	-1.8	-2.9
South Asia	-29.5	-49.1	-17.4	-28.9	-6.6	-10.9
Sub-Saharan Africa	-26.5	-43.7	-41.8	-72.8	-9.6	-16.4
North America	-29.5	-49.2	-21.7	-35.5	-7.3	-12.2
NAFTA	-29.5	-49.2	-21.9	-36.0	-7.3	-12.1
Europe Developed	-29.5	-49.2	-28.5	-47.4	-7.9	-13.2
Developed	-29.5	-49.2	-24.1	-39.7	-7.1	-11.7
Developing	-26.4	-44.4	-26.7	-44.3	-8.9	-14.7
World	-27.0	-45.1	-26.0	-43.4	-8.8	-14.5

Source: IFPRI IMPACT projections (2012).

Table 5.8—Total consumptive water use (km3/yr) under Business As Usual and Bioeconomy Scenarios in 2000, 2030 and 2050.

Region	2000	2030			2050		
		BAU	BIO	Change (%)	BAU	BIO	Change (%)
East Asia & Pacific	428.5	493.4	476.2	-3.5	588.8	508.9	-13.6
Europe & Central Asia	100.6	158.2	118.8	-24.9	219.3	121.3	-44.7
Latin America & Caribbean	113.5	160.0	142.0	-11.3	188.4	149.3	-20.8
Middle East & North Africa	72.7	96.6	90.5	-6.3	105.1	96.1	-8.6
South Asia	502.8	608.7	592.8	-2.6	693.3	663.1	-4.3
Sub-Saharan Africa	50.5	100.5	90.2	-10.2	139.5	114.1	-18.2
North America	146.4	184.7	161.3	-12.7	218.6	159.9	-26.9
NAFTA	180.0	225.7	198.0	-12.3	262.7	196.0	-25.4
Europe Developed	48.7	57.9	44.3	-23.4	66.4	40.1	-39.6
Developed	235.3	289.0	246.9	-14.6	331.6	237.7	-28.3
Developing	1269.0	1617.4	1510.6	-6.6	1934.4	1652.8	-14.6
World	1504.3	1906.4	1757.5	-7.8	2266.0	1890.6	-16.6

Source: IFPRI IMPACT projections (2012).

Table 5.9—Total irrigation water consumption (km3/yr) under Business As Usual and Bioeconomy scenarios in 2000, 2030 and 2050.

Region	2000	2030			2050		
		BAU	BIO	Change (%)	BAU	BIO	Change (%)
East Asia & Pacific	348.0	299.3	285.4	-4.6	250.8	226.3	-9.7
Europe & Central Asia	57.9	57.1	56.2	-1.7	47.0	51.1	8.7
Latin America & Caribbean	85.3	111.9	105.4	-5.8	126.3	114.9	-9.0
Middle East & North Africa	61.5	77.4	75.5	-2.5	78.1	74.9	-4.1
South Asia	462.6	496.5	500.3	0.8	432.8	472.6	9.2
Sub-Saharan Africa	34.0	51.0	48.0	-6.0	62.1	55.9	-10.1
North America	80.8	89.3	82.2	-8.0	91.1	79.6	-12.6
NAFTA	109.4	122.6	112.9	-7.9	125.8	109.9	-12.6
Europe Developed	12.6	11.8	10.7	-9.4	11.6	9.8	-15.7
Developed	119.2	128.9	119.6	-7.2	128.5	114.6	-10.8
Developing	1049.6	1093.2	1070.8	-2.1	997.1	995.7	-0.1
World	1168.7	1222.1	1190.4	-2.6	1125.5	1110.4	-1.3

Source: IFPRI IMPACT projections (2012).

Table 5.10—Beneficial irrigation water consumption under Business As Usual and Bioeconomy Scenarios

Region	2000	2030			2050		
		BAU	BIO	Change (%)	BAU	BIO	Change (%)
East Asia & Pacific	186.9	167.5	186.4	11.3	141.8	168.6	18.9
Europe & Central Asia	34.0	35.1	37.9	7.9	29.6	37.8	27.5
Latin America & Caribbean	37.9	51.7	52.2	1.1	59.5	61.0	2.5
Middle East & North Africa	40.2	51.9	51.5	-0.7	53.0	52.4	-1.2
South Asia	254.8	290.1	310.9	7.2	257.5	312.6	21.4
Sub-Saharan Africa	15.3	23.9	25.0	4.6	29.5	32.1	8.8
North America	55.3	64.3	63.9	-0.6	67.4	67.1	-0.4
NAFTA	69.9	82.5	81.9	-0.7	87.4	86.9	-0.6
Europe Developed	6.9	6.8	6.7	-1.6	6.9	6.7	-2.9
Developed	79.8	91.1	91.0	-0.1	93.3	94.4	1.2
Developing	569.3	620.2	664.1	7.1	570.9	664.5	16.4
World	649.1	711.3	755.1	6.2	664.3	758.9	14.2

Source: IFPRI IMPACT projections (2012).

Table 5.11—Irrigation water supply reliability under Business As Usual and Bioeconomy scenarios in 2000, 2030 and 2050.

Region	2000	2030		2050	
		BAU	BIO	BAU	BIO
East Asia & Pacific	0.754	0.631	0.714	0.554	0.675
Europe & Central Asia	0.668	0.617	0.666	0.515	0.655
Latin America & Caribbean	0.911	0.933	0.954	0.936	0.973
Middle East & North Africa	0.986	0.975	0.978	0.972	0.975
South Asia	0.706	0.622	0.679	0.517	0.645
Sub-Saharan Africa	0.825	0.747	0.785	0.715	0.780
North America	0.978	0.984	0.990	0.987	1.000
NAFTA	0.983	0.988	0.993	0.991	1.000
Europe Developed	0.974	0.997	0.999	0.994	0.996
Developed	0.958	0.961	0.972	0.956	0.982
Developing	0.749	0.670	0.728	0.592	0.705
World	0.766	0.692	0.747	0.619	0.726

Source: IFPRI IMPACT projections (2012).