# The Importance of Water, Climate Change, and Water Policy for Bioethanol Derived from Hybrid Poplar *(Populus spp.)* in Washington State

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A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington
2015

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Program Authorized to Offer Degree:
School of Environmental and Forest Sciences

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## Abstract

# The Importance of Water, Climate Change, and Water Policy for Bioethanol Derived from Hybrid Poplar *(Populus spp.)* in Washington State

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Biofuels outperform fossil fuels on many environmental indicators, except for water consumption. With climate change, shifting water resource availability may affect the feasibility of growing feedstock for biofuel refineries in certain locations.

In this research, water consumption was analyzed for bioethanol production from cradle to gate, using hybrid poplar (*Populus spp.)* feedstock and an acetogen pathway conversion process. Volumetric water consumption was quantified using the water footprint methodology by Hoekstra et al. (2011). The water footprint for two hypothetical biorefineries near Mount Vernon, WA and Spokane, were analyzed for rainfed and irrigated feedstock in three crop yield scenarios under current climate conditions and under two climate change scenarios.

Results show that water use for bioenergy from hybrid poplar in Washington State ranges from 10-70 $m^3$/GJ, which is lower than the United States average and on the small end of the range for bioenergy (10-250 $m^3$/GJ). Results vary by climate and crop production, with the rainfed crop using 30% less water than the irrigated crop. The proportion of green, blue and grey water footprints varied for each site as well, with the Mount Vernon site's footprint dominated by green water (precipitation) and the Spokane site's footprint dominated by blue

water (irrigation). Climate scenarios show larger water footprints and increased water stress for the hot/dry scenario.

In Washington State, there are limited opportunities to obtain uninterruptible senior water rights inexpensively, so Washington water code constrains water availability for both irrigation and biorefinery conversion process water. Rain-fed crops or crops irrigated with reclaimed water avoid some of these policy constraints. The water policy landscape is highly complex, and water policy objectives are often different from the objectives of renewable fuel, land use, or air quality policies. These policies are highly site specific, and need to be evaluated for each potential production site.

# Acknowledgements

I would like to acknowledge my gratitude and appreciation for my advisor, the chair of my thesis committee, Dr. Susan Bolton. Throughout my masters experience Dr. Bolton has provided constructive feedback, endless support, mentorship, and laughter - for which I am eternally grateful. I consider myself extremely fortunate to have had the opportunity to work with and learn from Dr. Bolton, and I could not have done this without her. I would also like to acknowledge Dr. Renata Bura, who in addition to making this research possible has motivated me with her enthusiasm, energy and thoughtful questions, as well as provided an additional interdisciplinary perspective to my research. I am especially grateful for my advisor Dr. Clare Ryan, who has helped me navigate my concurrent masters program and has helped keep me on track. Dr. Ryan provided suggestions and guidance that have greatly improved the quality of my research. I would like to thank Dr. Ann Bostrom, who has provided additional perspective and helpful feedback. I am grateful for the others involved in this project, including Dr. Rick Gustafson, Dr. Luke Rogers, Erik Budsberg, and Jordan Crawford. Luke, Erik and Jordan were especially helpful by providing me with data, maps, and information that were critical to the success of this project.

In addition to their limitless support, I would like to thank Hillary Mihle and Megan Curtis-Murphy for their noble attempts at reading the entire document, and Carrie Sessions for weekly brainstorming and data visualization consultations.  And finally, I would like to thank the rest of my family and loved ones who were so patient and supportive throughout this entire project, specifically Cheryl Dickinson, Charles Mihle, Gorkem Gezici, Katie Escudero, Adrianne Leeks, Jesusita Santillan, and Alison Osburn.

This project is supported by Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30407 from the USDA National Institute of Food and Agriculture. This material is based upon work supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture under Project No. WNZ-01312013 / Accession No. 232795.

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# Introduction

Fossil fuels, or fuels from coal, oil or natural gas, are currently the world's main energy source. Fossil fuels have two problems. First, they non-renewable and will eventually be exhausted. Fossil fuels must be extracted from the earth, since they are hydrocarbon deposits formed in the geological past from the remains of ancient plants and animals. Second, they are considered one of the principal causes of global warming, because they emit carbon dioxide, a greenhouse gas, when they are burned. Global warming causes climate change, which includes increased temperatures, shifting climate patterns, melting of artic ice caps, and rising sea levels. The United States Energy Information Administration (EIA) projects that global energy consumption will increase by 35% by 2035 (The World Bank, 2015). As populations and energy consumption increases, more fuel will be required to power the global economy. If fossil fuels continue to dominate energy portfolios, then greenhouse gas emissions will continue to increase, further contributing to climate change. Biofuels, or fuels derived from living plant matter, have been proposed as an alternative fuel source, and they have two benefits over fossil fuels. First, they are renewable, since the plants can be harvested and replanted. Second, they are generally carbon neutral, because the carbon dioxide emitted from burning the fuel can be offset by the carbon dioxide sequestered during plant growth. Therefore, biofuels seem to be a viable alternative to help fuel increasing energy needs without contributing further to climate change. There are many different types of biofuels, made from many different crops, and from many different fuel conversion processes. A review of some of the main types of biofuels can be seen in ***Appendix A - Figure 1***.

## Water Energy Nexus

Energy and water are interdependent. Water is used in all phases of energy production, while energy is required to extract, clean, transport, deliver freshwater, and to treat wastewater (UNEP, 2011). If global energy demand increases according to EIA projections by 35%, then global water demand is projected to increase by 85% (The World Bank, 2015). Historically, interactions between these two sectors has been addressed only on a regional basis, if at all. Nationally, energy and water have been developed, managed and regulated independently (DOE, 2014). However, water scarcity and variability and the vulnerabilities this creates for the U.S. energy system are gaining prominence on the national agenda. Climate change has begun to affect temperature and precipitation patterns in the U.S., while U.S. population growth and regional migration trends increase stress on water scarce areas such as the Southwest (DOE, 201). In addition, the introduction of new technologies in energy and water could change energy and water demands (DOE, 2014). Lastly, policy developments that focus on water impacts of energy production introduce additional complexities into water policy and energy policy decision making (DOE, 2014). Such an interconnected problem requires an integrated approach that analyzes both water and energy together, from a technical standpoint as well as a policy standpoint.

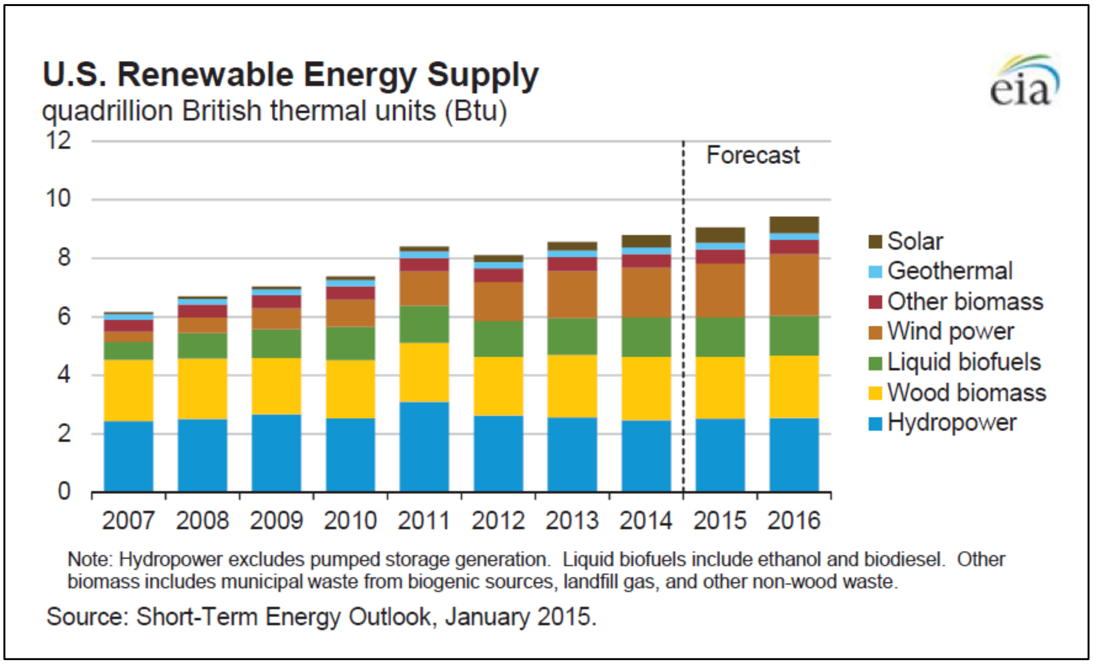
Bioenergy and water are interdependent, just as fossil fuel energy and water are interdependent. Fuels made from agricultural crops or trees, which require water to grow, requires large amounts of water. Biofuels use significantly more water than fossil fuels, but water is an often ignored environmental factor which needs to be evaluated alongside other indicators, such as global warming potential to thoroughly assess the trade-offs involved in switching from fossil fuels to biofuels.

It is important to note that **water use** is term that is often undefined or misused, especially when compared to water consumption or when comparing one study to another. In many case the term water use refers to *any* water that is withdrawn, regardless of whether this water is consumed or not. **Water consumption** generally refers to water that is withdrawn, used and no longer available for any other users or uses in the watershed in which it originates. **Water withdrawal** refers to water that is withdrawn, used, and then still available for other users and uses in that watershed.

## United States Renewable Fuel Mandate

The 2022 United States (U.S.) Renewable Fuel Standard (RFS2) and the Energy Independence and Security Act of 2007 (EISA) mandates requirements for renewable fuels to shift dependence away from fossil fuels and to reduce greenhouse gas emissions (GHG) (EPA, 2014). Greenhouse gas emissions cause increased concentrations of greenhouse gases in the atmosphere, which cause global warming. The effects of global warming are numerous, from melting ice caps and rising sea levels, to ocean acidification, shifting climate patterns, and increased risk of drought and flooding.

The expansion of biofuel production, or fuels derived from biomass, could help mitigate global warming because when lifecycle greenhouse gas emissions are assessed, many biofuels achieve significant reductions of emissions relative to fossil fuels (EPA, 2013b). The RFS2 requires 36 billion gallons of biofuel to be blended into gasoline by 2022 of which 44% should be contributed by the cellulosic ethanol and at least 3% from biodiesel (EPA, 2014). Most of the RFS2 biofuel mandate has been fulfilled with ethanol, which is now typically blended into gasoline at a 10% mixture by volume (U.S. House of Representatives Energy and Power Subcommittee hearing, 2013). These mandates seems unlikely to be met based on the amount of biofuel crops in production to date. However, biofuel production is likely to continue to increase as technological improvements are made and commercial production expands. U.S. renewable energy projections are displayed in **Figure 1.** US renewable energy supply***Figure 1***.


U.S. Renewable Energy Supply

quadrillion British thermal units (Btu)

Note: Hydropower excludes pumped storage generation. Liquid biofuels include ethanol and biodiesel. Other biomass includes municipal waste from biogenic sources, landfill gas, and other non-wood waste.

Source: Short-Term Energy Outlook, January 2015.

**Figure 1.** US renewable energy supply
(U.S. Energy Information Administration (EIA), 2015)

## What are Biofuels?

**Biofuels** are a collective term for liquid fuels derived from renewable sources. The term includes fuels such as ethanol, biodiesel or jet fuel, which are made various types of biomass. **Biomass** sources (or feedstock) include conventional food/feed crops, perennial grasses, short rotation woody crops, trees, agricultural and forestry residues, manure, process by-flows in the food and forest sector, and organic post-consumption waste such as paper, wood waste, and organic residential waste. Biofuels from algae are currently being researched, but are not yet considered economically or technically viable at a commercial scale (Hannon et al., 2010; Leite et al., 2013; Singh et al. 2011).

**Advanced or second generation biofuels** are biofuels from non-food or feed crops. Advanced biofuels are attractive compared to first generation biofuels because they are not a food crop and can be grown on marginal lands, so they can reduce competition for arable land used for food and feed production (Cheng & Timilsina, 2011).

Advanced biofuels include **lignocellulosic biofuels**, which are made up of three components: cellulose, hemicellulose, and lignin. Cellulose and hemicellulose contain sugars that can be used to make biofuel. However, unlike sugar or starch crops such as sugarcane and corn, lignocellulosic crops contain lignin, which must be removed in order to extract the sugars. In order to break down lignocellulosic biomass, four steps occur: pretreatment, enzymatic hydrolysis, fermentation, and distillation. The more sugars that can be extracted from the biomass, the higher the conversion efficiency, and the more fuel produced.

## Bioethanol from Hybrid Poplar in Washington State

Hybrid poplar trees (*Populus spp.)* are a short rotation woody crop (SRWC) that can be grown in plantations for biofuel production. They are a lignocellulosic feedstock that can be used to make ethanol. These trees are fast growing hardwoods harvested by coppicing every few years, which allows the trees to be harvested at any time and to re-sprout quickly from the established stump and roots. They can be grown on marginal lands, require less water and chemical inputs compared to other biofuel crops such as corn, yet produce high yields, making them an ideal feedstock for bioethanol production in Washington State (Budsberg et al., 2012; González-García et al., 2010; GWR, 2014; Keoleian & Volk, 2005; Stephenson et al., 2010).

Hybrid poplar biomass can be converted into ethanol using a variety of pathways, all of which have variable costs and conversion efficiencies. Based on existing research of different pathways, the research in this thesis uses an acetogen pathway. The acetogen pathway is technically feasible since it has high ethanol yields and uses less water than the ethanologen pathway (Budsberg et al., 2015). This pathway will be explained in detail in the literature review section.

## Environmental Effects of Lignocellulosic Biofuels and Water Use in Washington State

Research has demonstrated that lignocellulosic biofuels can reduce greenhouse gas emissions relative to fossil fuels. During photosynthesis, plants take in carbon dioxide through their stomata, and water and nutrients through their roots. They break apart carbon dioxide molecules and fix the carbon into their plant matter, releasing oxygen and water. When water is released, the process is called transpiration. The sum of water evaporated from land and plant surfaces and water transpired through the plant is called **evapotranspiration**. Evapotranspiration is how a plant's water use is measured. ***Figure 2*** is a simplistic diagram of what happens when water is applied to a land surface, either through precipitation or from a human application such as irrigation. Water applied to an area can take a number of pathways with some leaving the site as surface run-off or contributing to groundwater recharge, with the rest returning to the atmosphere as transpiration from plants and evaporation from surfaces, which make up evapotranspiration.

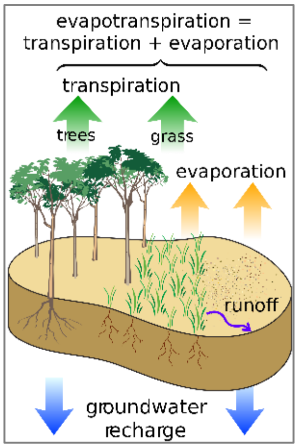
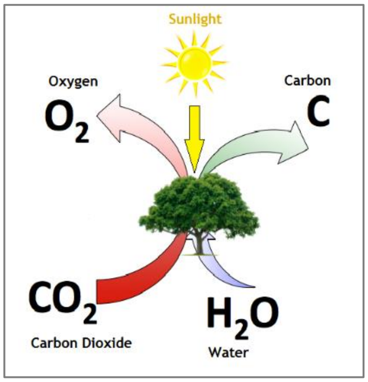


***Figure 2**. Simplified water cycle*

(Retrieved on January 15, 2015 from http://en.wikipedia.org/wiki/Evapotranspiration)



Through photosynthesis, the plant's carbon sequestration offsets the carbon dioxide released from the burning of the biofuel, making biofuels mostly carbon neutral. After harvesting, the plants can either be replanted or they can be harvested repeatedly, which makes biofuels renewable. ***Figure 3*** is a simplistic diagram which explains how plants take carbon dioxide out of the atmosphere. Reducing atmospheric carbon dioxide concentrations also reduces global warming potential (GWP), which is a measure of how much heat a greenhouse gas traps in the atmosphere.

***Figure 3****. Carbon fixation during photosynthesis*

(Retrieved on January 15th, 2015, adapted from http://clearscience.tumblr.com/post/56239435480/carbon-fixation-starts-with-carbon-dioxide-which)

When the life-cycle GWP of ethanol is evaluated, the vast majority of studies find that carbon sequestration as the plant grows can consistently offset the GHG emissions from all parts of the life cycle chain at high ethanol percentages (≥85%) (Borrion et al., 2012; Budsberg et al., 2012; Budsberg et al., 2015; Lippke et. al. 2012; Wiloso et al, 2012). All studies reviewed indicate ethanol results in a reduction of fossil fuel consumption (Borrion et al., 2012). Due to the low or negative GWP of many lignocellulosic biofuels, the development of this industry is being encouraged by many policymakers and scientists as way to deal with climate change.

However, results for other environmental impacts from biofuel production vary widely. A review of current research has produced variable results regarding the impact of acidification and eutrophication potential for ethanol compared to fossil fuels (Borrion et al., 2012). A wide range of findings on the effects of emissions on ecotoxicity and human health have also been reported (Borrion et al., 2012).

Many factors account for the variable results seen in the literature. Some variance can be attributed to differences in data quality, and difference in assessment methods, from system boundaries to allocation methods (Borrion et al., 2012). In addition, results and their respective impacts vary by region and regional characteristics, from climate to soil types, to water resources and to pollution levels.

Most analyses of biofuels focus on carbon reduction and ignore the water needs for production of feedstocks and processing of biofuel. Information on biofuels water consumption varies significantly in the literature. Regional climate and site suitability, biomass type, irrigation requirements, regional irrigation practices, and ethanol conversion pathways all affect water requirements (Gerber-Leenes et al., 2009). In general, research has shown that biofuels consume large quantities of water in both feedstock production and in the conversion process at the biorefinery, and that this critical resource management issue is often not addressed in life cycle analyses nor in other environmental impact assessments (Sevigne et al. 2011; UNEP, 2011). Studies which compared water consumption in bioenergy to water consumption in fossil fuels generally found that bioenergy uses more water (Gerber-Leenes et al., 2009).

In this research, for feedstock production, water use refers to *consumptive water use*, where water is evapotranspired by the crop and released into the atmosphere. For the conversion stage at the bioreferinery, water use is more general term. A zero water discharge system is assumed, but within this system, some water may be recycled, so the exact proportion of water consumed vs. withdrawn is unkown. This research focuses on a hypothetical biorefinery, and so water consumption vs. withdrawal would need to be modeled. So far, only the amount of input process water required has been modeled. Since water consumption during the conversion process is unknown, *all water withdrawn for conversion will be considered consumptive* until further research is conducted that demonstrates otherwise. The specifics of how this research evaluates water use will be explained in the research questions, literature review and methodology sections.

Water use for hybrid poplar plantations and conversion in Washington State has only been analyzed for the conversion process stage at the biorefinery (Budsberg et al., 2015). Research on water consumption for hybrid poplar biofuels in other regions and in general is extremely limited (Borrion et al., 2012, González-García et al., 2010; Mu et al., 2010; Sevigne et al. 2010).

Due to the lack of existing research, water consumption and water availability in Washington State and for biofuel production with hybrid poplar needs to be quantified. Water consumption also needs to be quantified based on the type of water used, such as water from precipitation, irrigation, or wastewater. These types of water have different availability, costs, and regulation. In addition, while some characteristics of the wastewater are known based on the conversion process inputs, wastewater varies by feedstock and production process, and not enough research has been done regarding the specific effluent created by this research project's biofuel conversion process.

## Climate Change and the Future Biofuel Production

Climate change introduces uncertainty into water availability for biofuel production. Climate scientists project increased temperatures, changing precipitation patterns, and a higher frequency and magnitude of extreme events (IPCC, 2014). The same predictions hold true for Washington State (Mote et al., 2010; Elsner et al., 2010).

Washington State, and the Pacific Northwest in general, rely on winter snowpack to feed the region's rivers and streams during spring and summer. A changing climate alters the balance of precipitation falling as snow and therefore the timing of streamflow over the course of the year. Snow water equivalent is projected to decrease by approximately 38-46% by the 2040s, compared to the historical mean, and temporal streamflow in snowmelt dominant and rain-snow mixed watersheds will change dramatically (Elsner et al., 2010). The decrease in winter snowpack and its water storage capacity, especially if insufficient reservoirs are available to capture precipitation falling as rain instead of snow, could reduce seasonable water availability for crop growth, as well as put stress on Washington's water resources, both in terms of surface water and in terms of groundwater recharge.

Evapotranspiration demand will increase with temperature, which suggests that traditionally rain-fed crops may need a more consistent and reliable water source, especially if drought frequency or magnitude increases. In addition, climate change modeling shows that site suitability without irrigation, based on a variety of environmental variables such as temperature, precipitation, season length, soil characteristics, and water table depth, will decrease significantly in Washington State by 2100 (Comnick et al., 2014). ***Figure 4*** illustrates the change in poplar site suitability by 2100 for Washington State.

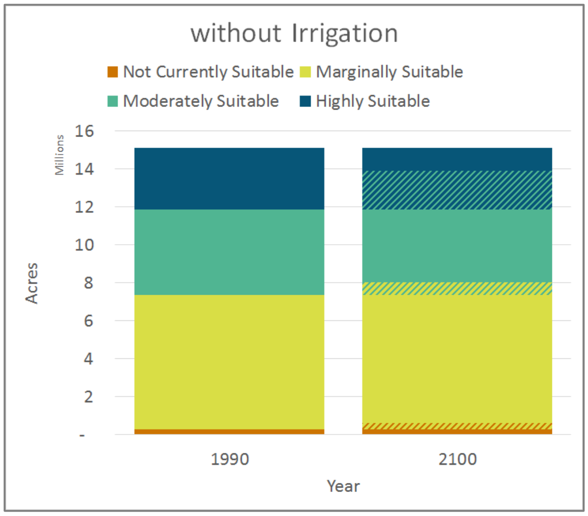


**Figure 4.** Effect of climate change on site suitability (without irrigation) in Washington State. (Comnick et al., 2014)

Crop yields could decrease if the crop becomes more water stressed, or if the crop becomes heat stressed as temperatures exceed crop photosynthesis thresholds. A recent article by Anderegg et al. (2015) modeled drought induced damage in poplar (*Populus tremuloides*, or quaking aspen) under climate change scenarios in the Southwest United States. In the high emissions scenario, they found that by 2050 drought stress will exceed the observed mortality threshold for poplar (Angeregg et al., 2015). This means that the increased water demands caused by higher temperatures, combined with a change in drought frequency under climate change, could potentially cause widespread mortality for this species, in this particular area (Angeregg et al., 2015). Their results are specific to one poplar species and to one ecosystem in one geographic area, but their results show an increase in both heat and water stress under climate change scenarios (Angeregg et al., 2015). To summarize, climate change is predicted to decrease site suitability, increase crop water requirements, and affect crop yields.

Climate change is important to potential biorefineries because climate change impacts plant productivity. Since this production process deals with economies of scale due to the high capital investment required, a production facility and its associated feedstock acreage will only be profitable after a certain period of time. If climate change could alter the water resource availability of a specific site in a way that negatively affects the ability to grow feedstock (either due to unfavorable temperatures or an increased need for irrigation (blue) water), or negatively impacts the ability acquire a constant supply of conversion process water, then this should be analyzed before siting feedstock or a biorefinery.

## Water Policy and Biofuel Production

Even in regions where water is not scarce, water rights and policy constraints can limit water availability for biofuel production. Existing uses of water resources, which have potentially limited availability, may pose a significant constraint on the expansion of the biofuels industry in Washington State. In Washington State, the water source could be limited either from hydrological constraints such as surface or ground water availability or precipitation (which could be altered by climate change), or political constraints due to water rights and other relevant regulations and policies. Washington State uses a prior appropriation water rights system, and as a result, water is largely over-allocated. Washington also has requirements for instream flows for ecological and recreational purposes. In addition, many statutes and associated permits will regulate the prospective biofuels industry, and could pose obstacles to feedstock or biorefinery siting and production. Such constraints will vary regionally, even within Washington State. This means that even if water is physically available, it may not be available for biofuel production use because of legal or ecological constraints.

# Research Goals

## Thesis Objectives

To meet the region's Renewable Fuel Standard (RSF2) target, the Northwest needs to produce around 400 million gallons of biofuel annually.

Overall, the goal is to prepare the Pacific Northwest for a 100% infrastructure compatible biofuels industry, which produces around 425 million gallons per year (Rogers, AHB presentation). The long term plan is for four 100 million gallon facilities, using 400,000 acres of hybrid poplar plantations.

Very little research exists with regards to water consumption for lignocelluslosic biofuels. Besides research conducted by Budsberg et al. (2015) for this specific project, no research exists for hybrid poplar biofuels in the Pacific Northwest or Washington State. Water consumption varies significantly by climate, so region specific results are necessary to evaluate the viability of an industry in a given region.

To investigate if Washington infrastructure is compatible for biofuels expansion, the most suitable areas for growing and refining this bioenergy crop must be evaluated, with an additional consideration of regional water consumption and potential climate change impacts, and a discussion of how this may impact policy decisions. For biofuels, understanding which regions and sites are better suited for biofuel production based on a comprehensive analysis of water consumption can help manage water resources more effectively. When this information is combined with existing research on GWP, economics, and other assessments of technical feasibility, then a more comprehensive analysis can be conducted to weigh trade-offs between locations, feedstocks, and conversion processes. This comprehensive view can better inform preparation for a biofuels industry from both a technical and a policy standpoint. Successful implementation of an environmental policy is dependent on clearly defined policy objectives that have realistic and pragmatic targets (Knights et al. 2014). Using simple, easy to understand tools such as the water footprint in conjunction with other branches of research, can potentially increase the precision of objectives and targets set by policy makers.

## Research Questions

Research was conducted for two potential biorefinery sites in Washington State to compare an irrigated feedstock with a rain-fed feedstock. Detailed site descriptions are provided in the Methodology section.

This research had three parts, summarized here, and explained in detail below:

1. *How much water is required to produce biofuel from hybrid poplar?*
2. *What happens to water requirements with climate change?*
3. *How does the water policy landscape constrain or encourage this potential industry?*

A detailed explanation of the research questions is as follows:

1. *a. How much water is consumed for each biorefinery site for biofuel feedstock production and conversion using hybrid poplar feedstock and an acetogen pathway?*

How much water consumed for each stage of the production process was quantified, based on the proposed biorefinery size, for two hypothetical sites (100 million gallon (378.5 million liters) facilities, in Eastern and Western Washington). This was analyzed by calculating a **water footprint**. For an agricultural product, it is the volume of water used during the crop growing period. For biofuels, it will be the volume of water used during the crop growing period combined with the volume of water required in the conversion process. It has three components, green, blue and grey water. These three components represent functional losses of water.

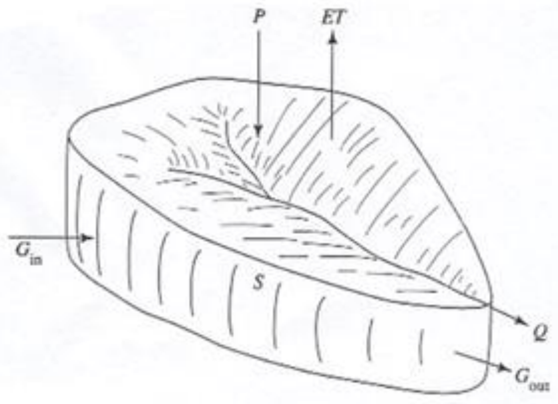
**Green water** is a naturally occurring water resource, such as precipitation.

**Blue water** is water that has been withdrawn from its source, either surface or groundwater, and applied to a use.

**Grey water** is the volume of water required to dilute pollutants in wastewater to restore it water quality standards.

A detailed explanation of the water footprint concept is explained in the literature review, and detailed explanation of methods is provided in the methodology section.

1. *b. Is there water available, in terms of watershed hydrology, for biofuel production at these two hypothetical sites? Does one site place less stress on water resources than another?*



Schematic diagram of a watershed, showing the components of the regional water balance: $P$ = precipitation, $ET$ = evapotranspiration, $Q$ = stream outflow, $G_{in}$ = ground-water inflow, $G_{out}$ = ground-water outflow.

(Dingman, 2002)

***Figure 5**. Major terms of a water budget*

Existing watershed assessments and hydrology reports for the sites' Water Resource Inventory Area (WRIA) were used. Watershed assessments are required under the Watershed Planning Act (RCW 90.82) and determine water availability (or water budgets) and other watershed constraints that could impact both feedstock acreage and the biorefinery site(s). The Washington Department of Ecology (Ecology) is in charge of implementing the Watershed Planning Act. Question 1b is answered by a qualitative discussion based on availability of data and completeness of available reports, which varied widely. Such information is critical in order to assess biofuel water use in the context of relative local water availability, but to truly assess this question, a full hydrological modeling analysis should be completed, which is outside the scope of this research.

The major terms of a water budget are outlined in ***Figure 5.*** Washington's WRIA areas are displayed in ***Appendix B - Figure 1.***

2. *How might climate change impact the future viability of the biofuels industry, with regards to water use for hybrid poplar plantations?*

My research builds upon a site suitability analysis previously conducted by Comnick et al., 2014, which analyzed current and future site suitability for hybrid poplar based on a range of variables such as temperature, precipitation, and soil characteristics. Specifically, my research ran two climate change scenarios for each research site. The climate scenarios were for increased temperature and either increased or decreased precipitation, and they demonstrate how water consumption may change under climate change predictions for North America, and specifically the Pacific Northwest and Washington State.

3. *How might the water policy landscape in Washington State encourage or constrain a potential biofuels industry?*

A review of the relevant environmental policy landscape for siting biorefineries was previously conducted by Jacob Lipson (2013). This research builds upon his analysis by conducting a review of water policy specifically. The existing structure of state water rights may impact the technical feasibility of biofuel production. Water rights markets and other opportunities and policy tools may be able to relieve some of this constraint, but other federal or local policy such as wastewater permits or growth management regulations could emerge as constraints. As a result, the water policy landscape will be reviewed, summarized, and updated as needed to present a broad view of how water policy may encourage or constrain this industry.

# Literature Review

The research questions in this research include questions about water consumption in biofuel production. The feedstock is hybrid poplar, and the conversion process is an acetogen pathway, so both these topics are covered below. In order to calculate water consumption for a plant, detailed knowledge of plant evapotranspiration is required, so this topic is also reviewed. Lastly, the methodology used to answer the research questions is the water footprint methodology. An overview of this methodology and its various applications is reviewed below.

## Water and Hybrid Poplar Feedstock

Information is available for hybrid poplar yields (often for biofuel production) in different regions and for different clones, using both measured data and crop modeling (Stanton et al., 2002; Guidi et al., 2008, O'Neill et al., 2010; Verlinden et al., 2013;Tallis et al., 2013). Some research has been conducted that measures or estimates water consumption for hybrid poplar, though all used different methodologies, in different regions, and reported different metrics (González-García et al., 2012; Gochis et al., 2000; Fisher et al., 2011; Fisher et al., 2013; Aranda et al., 2012; Sevigne et al. 2011; Tallis et al., 2013; Toillon et al., 2013). In addition, no research has been published on water consumption for the study areas and/or hybrid poplar clones and production processes used in this research project, which is important because different feedstocks and production processes will produce different conditions and different environmental impacts (Borrion et al. 2012). For example, specific to water resources, stand structure and composition influences interception, runoff, and soil water balance (Aranda et al., 2012).

In terms of measuring or estimating evapotranspiration for hybrid poplars, a few studies mentioned above have been published, though none of them use similar methods, similar areas, similar coppice cycles, or report the same metrics. These studies are summarized below and in ***Table 1***.

***Table 1****. A comparison of Poplar ET from the literature*

| Author | ET Time period | ET Method | Poplar ET | Climate |
|---|---|---|---|---|
| Gochis et al. (2010) | Seasonal | Kimberly Penman | 466 mm (1 year coppice)- 839 mm (3 year coppice) /growing season | Semi-arid (Boardman, OR) |
| Fischer et al., (2013) | Two years | Bowen ratio/energy balance | 344 - 549 mm/year | Continental (Czech highlands) |

|  |  |  |  |  |
|---|---|---|---|---|
| Guidi et al. (2007) | Seasonal | Volumetric lysimeters | 590 (non-fertilized) – 725 (fertilized) (mm) /growing season | Mediterranean (Italy) |
| Sevigne et al. (2011) | Two years | LCA | 12,101 $m^3$/ha/2 years or 605 mm/year | Mediterranean (Spain) |
| Tallis et al. (2013) | Harvest year in July and August | Penman-Monteith and modeling | 2.3 mm/day | Various (United Kingdom) |

Gochis et al. (2010) was the primary literature used for water consumption for hybrid poplar feedstock. This was the only study found in a nearby region (Boardman, Oregon) that used hybrid poplar plantations. It was also the only study that used the same coppice cycle, and that used a comprehensive data set to analyze water consumption. In addition, this study measured soil water data to determine average daily, monthly, and seasonal drip-irrigated hybrid poplar water consumption (Gochis et al., 2010). The researchers used irrigation data, weekly rainfall, and changes in soil water content to construct a soil water balance and calculate weekly hybrid poplar water consumption (Gochis et al., 2010). In addition, crop coefficients were calculated using reference evapotranspiration from a nearby AGRIMET weather station, which uses the Kimberly-Penman equation to estimate reference evapotranspiration for alfalfa (Gochis et al., 2010). They presented water consumption and crop curves for one, two and three year old hybrid poplars, which is the same coppice cycle (3 years) proposed by AHB. Their table of weekly crop coefficients was used to calculate crop evapotranspiration in my research project. Gochis et al. (2010) found that seasonal evapotranspiration was 466 mm for 1-year old poplars, 676 mm for 2- year old poplars, and 839 mm for 3 year old poplars. Seasonal evapotranspiration (ET) for the alfalfa reference crop was 1,251 mm (Gochis et al., 2010). In Gochis et al. (2010), a season is from April to mid-November. Monthly crop coefficients were used for April to October.

Fischer et al. (2013) measured ET using the Bowen ratio/energy balance method for two short rotation coppice (SRC) poplar plantations and for two reference grass covers: clipped grass and a permanent grassland in the Czech highlands. Their research found that conversion of arable land into poplar plantations did not result in significant differences in ET (Fischer et al., 2013). However, their values were in the middle of the ranges they found in the research, which can be attributed to site specific differences (e.g. precipitation, temperature, soil type, groundwater level).

Guidi et al. (2007) used volumetric lysimeters to measure ten day evapotranspiration during the growing season for fertilized and unfertilized poplar SRCs in Italy. They found total growing season crop evapotranspiration to be 590 (non-fertilized) – 725 (fertilized) mm, for a region with a Mediterranean climate.

Sevigne et al. (2011) used a LCA to assess water consumption in terms of energy production and climate change for hybrid poplar in Spain, with a Mediterranean climate. They found that the consumption of water required to avoid a kg of carbon dioxide is 4.6m$^3$ and per unit of energy obtained is 45 m$^3$/GJ. They used an irrigated crop, and found that evapotranspiration over two years was 12,101 m$^3$/ha/2 yr (Sevigne et al., 2011). They concluded that in order to plant energy crops for climate change mitigation, water consumption must be taken into account.

González-García et al. (2010), used a LCA to estimate environmental impacts for poplar in the Po Valley, Italy, though they looked mainly at ecotoxicity, acidification, and eutrophication and not water consumption. They found that SRCs harvested more often had more environmental impact than SRCs harvest at longer intervals (González-García et al., 2010). They also found that higher rates of pollutant applications lead to higher rates of environmental impact (González-García et al., 2010).

Tallis et al. (2013) used a modeling approach to compare modeled poplar and willow yields and to measured yield data in different climate conditions across the United Kingdom. Their model used the Penman-Monteith equation to predict the crop evapotranspiration. Their model suggested that at similar yield, poplar had higher water use efficiency than willow (Tallis et al., 2013). They found that the average harvest year transpiration for their seven sites in July and August was 2.3mm/day for poplar.

In addition to literature on freshwater consumption, literature exists on poplars and wastewater consumption. Due to their deep root system and high growth rates, research has shown that poplar are suitable vegetation to grow at landfills and waste disposal sites for phytoremediation (EPA, 1999). Since poplars are bioenergy crops and not food crops, their remediation abilities also make them ideal candidates for applications of wastewater, sewage sludge, ash, and landfill leachate (Guidi et al., 2008). Due to poplars' high nutrient uptake, researchers found low nitrogen concentrations in drainage water relative to traditional agriculture crops, even after intensive fertilization or wastewater application (Dimitriou et al., 2009).

## Biomass Conversion using the AP Pathway

The most prominent bioconversion process was developed by the National Renewable Energy Laboratory (NREL), and uses an ethanologen fermentation process (Aden et al., 2002, Humbird et al., 2011). First, the process uses a pretreatment step which separates the cellulose, hemicellulose, and lignin, using either a chemical or physical process. The cellulose is then hydrolyzed to glucose using acid or enzymes. Then an ethanologen (bacteria or yeast) ferments the sugars to ethanol. The lignin and unfermented carbohydrates are burned to produce steam and electricity. Using this process results in ethanol yields of 310-429 L/BDT (liters per bone dry ton)(Budsberg et al., 2010; Gnansounou, 2010; González-García et al., 2010; Huang et al., 2009).

However, another, more efficient conversion pathway exists. This pathway also uses pretreatment, but uses a different fermentation pathway, using acetogen instead of ethanologen. The acetogen ferments the sugars into acetic acid, which can then be converted into ethanol using catalytic hydrogenation. The results produces a much higher yield, of 536 L/BDT (Budsberg et al., 2015).

Budsberg et al. (2015), compares the ethanologen and acetogen pathways (EP and AP, respectively) using a LCA. Budsberg et al. (2015) find the GWP of both pathways to be almost identical when compared on a per hectare basis. The AP pathway reduces fossil fuel use by 50%, while the EP pathway reduces fossil fuel use by 97% (Budsberg et al., 2015). At the biorefinery, the EP requires 6.4 L of water per L of ethanol, while the AP requires 3.7 L of water per L of ethanol (Budsberg et al., 2015).

The chemical composition of hybrid poplar chips entering the biorefinery is outlined in detail in Sannigrahi et al. (2010), which reviews published research on biomass yields, elemental composition, as well as carbohydrate and lignin content and composition.

## Evapotranspiration

The sum of water evaporated from land and plant surfaces and water transpired through the plant is called evapotranspiration (ET). There are two concepts that help desribe ET: potential (PET) and actual (AET). **Potential evapotranspiration** is the amount of ET that would occur if there were unlimited water availability. All equations that estimate ET from climate data assume ideal conditions, i.e. unlimited water availability. **Actual evapotranspiration** is the amount of ET that actually occurs when water is limited, and includes components such as soil water balance and crop canopy status.

There are a variety of methods to measure ET, but a few common methods are outlined here.

1. Pan evaporation involves placing a pan outside and measuring how much water evaporates during a specific time. Pan evaporation data can be used to estimate AET of a reference crop by multiplying the pan evaporation by a reference crop or pan coefficient.
2. Lysimeters are devices that measure water balance, and can be weighing or nonweighing. If the water input and ouputs are known from the water balance, then AET can be calculated. AET of a reference crop can be found by placing a lysimeter in the field with the crop.
3. Empirical methods estimate evapotranspiration from a variety of climate data, including some of or all of the following: air temperature, relative humidity or dewpoint, actual vapor pressure of the air, solar radiation, and wind speed. Some of these equation estimate AET and some estimate PET. Many of the equations that estimate PET are useful because climate data are often more widely available than field data required for AET calculations. In addition, PET methods can be calculated on smaller timesteps, and result in an output of a reference crop ET such as grass or alfalfa, which can then be quickly multiplied by a crop coefficient to get a specific crop’s ET. A review of some commonly used methods is displayed in ***Figure 6***.

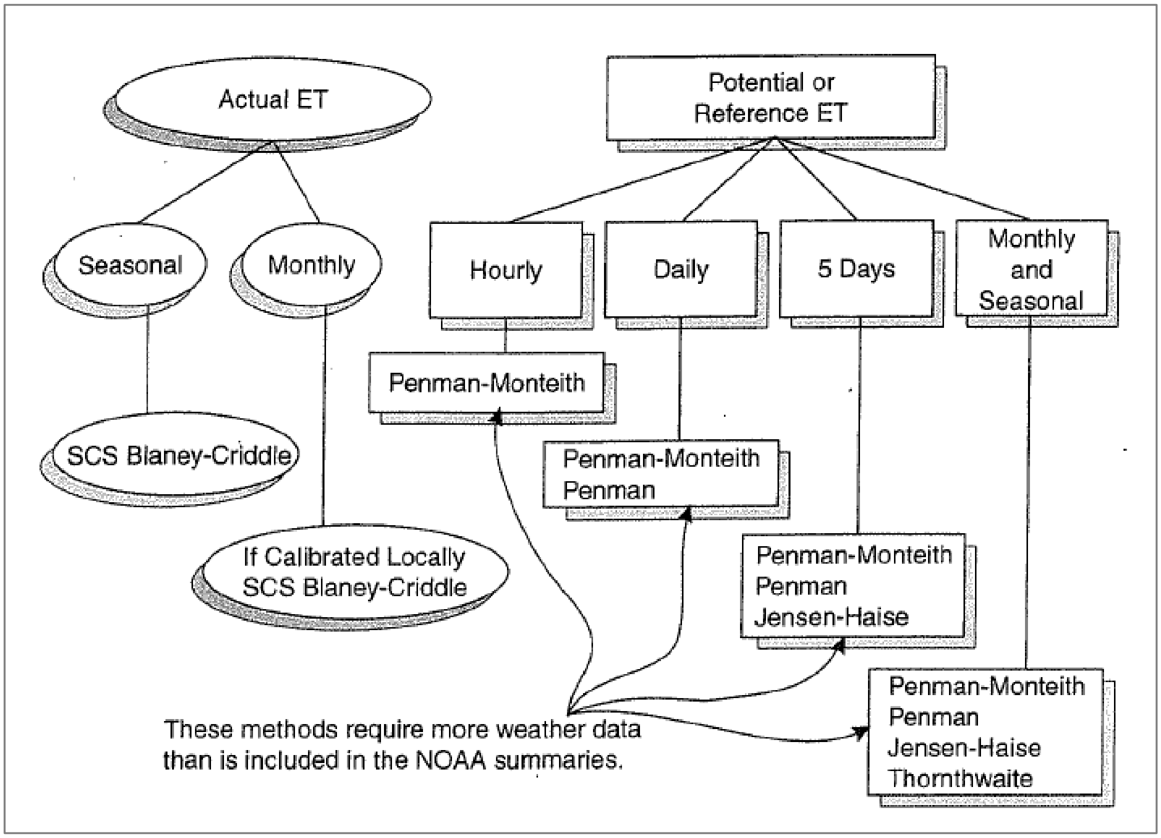


***Figure 6**. Summary of methods available to estimate ET using climate data.*

Figure adapted from Ward & Trimble, 2004.

Different empirical methods for PET use different assumptions and different data. Some methods over-estimate AET, while some methods underestimate AET, and this often varies depending on which method is used in which climate (e.g., arid or humid). In general, the methods that require more data produce more accurate estimations. The Food and Agricultural Organization of the United Nations (FAO) recommends using the Penman-Monteith equation, due to its relatively accurate and consistent performance in both arid and humid climates (Allen, 1998). FAO's chapter on the Penmen-Monteith method indicates that this method has a "strong likelihood of correctly predicting reference ET in a wide range of locations and climates" (Allen, 1998, Chapter 2).

## Estimation of Green, Blue and Grey Water Footprints

Over the past two decades, many water footprint-style indicators have been introduced to the scientific and policy community. These indicators are often promoted as tools to:

- Quantify water use for different products, services, and regions;
- Raise public awareness of how humanity exerts pressures on the environment;
- Better inform management or impact mitigation strategies; and
- Inform policy and design policy instruments for environmental issues.

There are a variety of methods used to quantify water use and/or consumption, including the creation of water scarcity indexes (Berger, & Finkbeiner, 2010). The two main approaches used in the literature will be reviewed here. Within each of these approaches, specific methods vary. There is a strong need to standardize water accounting methodology and to differentiate between water use, water withdrawal and water consumption.

- Volumetric approaches: water footprints. This approach aggregates green, blue and grey water. The main methodology for this approach is outlined by Hoekstra et al., 2011.
- Impact-oriented approaches which take volumetric approaches and then further characterize water consumption to mid or end point impacts. The main methodology for this approach is outlined by Pfister et al., 2009, and this approach is commonly used in LCA.

### ***Water Footprints***

The basics of the water footprint concept are outlined below.

A **water footprint** is:

The quantity of water used to produce a good or service. For an agricultural product, it is the volume of water consumed during the crop growing period. For biofuels, it will be the volume of water consumed during the crop growing period combined with the volume of water required in the conversion process. It has three components, green, blue and grey water (Gerbens-Leenes et al., 2009a; Hoekstra et al., 2011; Yang et al., 2009). These three components represent functional losses of water.

In order to better understand the water footprint concept, a diagram depicting the water cycle is displayed below in ***Figure 7***. Following the diagram, green, blue and grey water footprints will be explained in more detail, followed by a review of the literature on this topic.

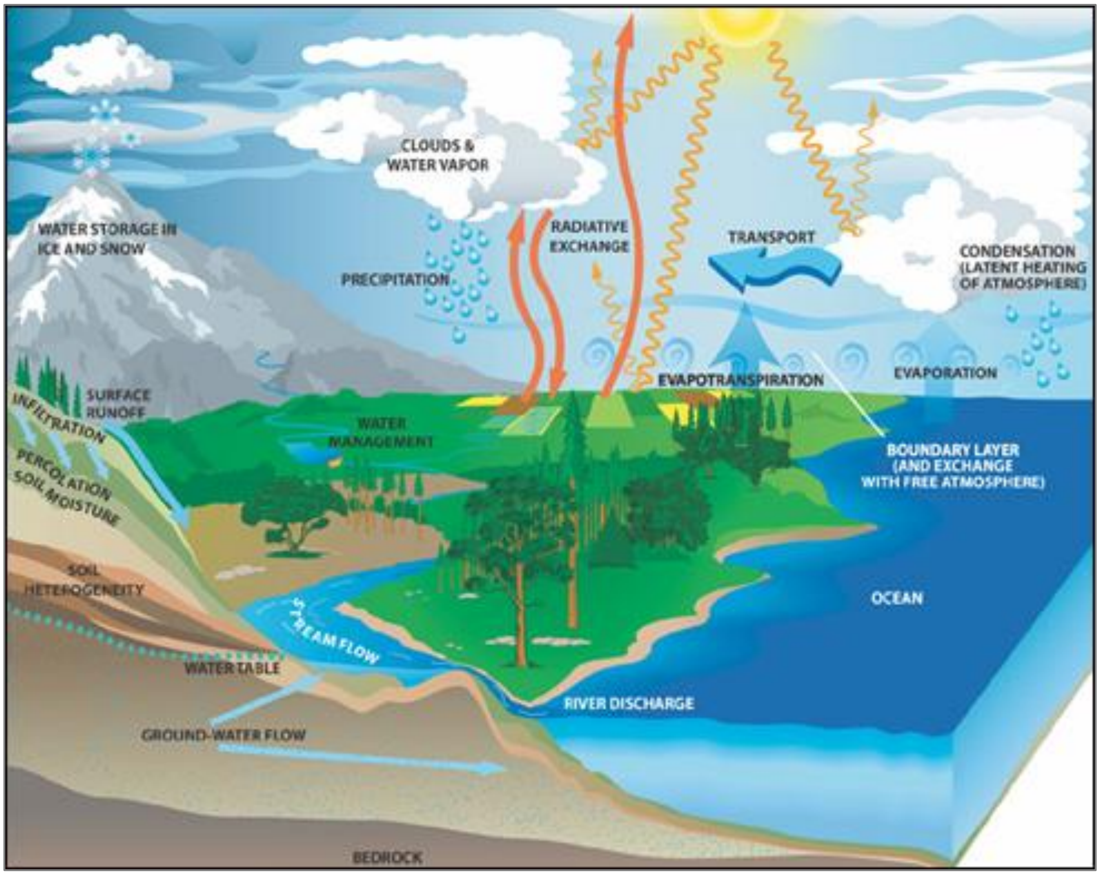


***Figure 7**. Major components of the hydrological (water) cycle.*

Figure adapted from NASA, n.d.

**Green water ($WF_G$)**, for agricultural production, is estimated as the amount of effective precipitation ($P_{eff}$) that is lost due to ET. $P_{eff}$ is defined in the USDA Soil Conservation Service's (SCS) National Engineering Handbook as the part of rainfall that be used to meet the needs of growing crops, and does not include surface runoff or percolation below the crop root zone (SCS, 1992). Any effective precipitation in excess of the crop's ET ($ET_c$) stays in the soil, or leaves the field as runoff or deep percolation. $WF_G$ is the minimum of either the $P_{eff}$ or $ET_c$. In other words, if $P_{eff}$ is greater than $ET_c$, then $WF_G$ is equal to $ET_c$. If $ET_c$ is greater than $P_{eff}$, then the crop is water stressed (full ET requirements not being met) and $WF_G$ is equal to $P_{eff}$. This addresses PET's assumptions of ideal conditions by limiting the measure of crop water consumption by the available water supply.

**Blue water ($WF_B$)** is the amount evaporated (consumed) through irrigation (effective irrigation) and water consumed from groundwater/surface water/municipal water withdrawals as process water for biofuel production. For agriculture, it is assumed that irrigation is needed in response low soil moisture content resulting in climates with low precipitation. The difference between $WF_G$ and $ET_c$ is known as the crop water deficit. If $WF_G$ is less than ET, there is a deficit, and $WF_B$ is the amount of water applied to meet this deficit.

**Grey water ($WF_{Gy}$)** is the volume of water required to dilute pollutants in wastewater in order to restore it to water quality standards. The purpose of this metric is not to measure physical consumption of water, but instead to illustrate the loss of freshwater function due to a reduction in water quality. For agricultural products, this generally concerns fertilizers and pesticides and their respective leaching rates, and the amount of water required to bring this water to drinking water standards, since the discharge point of this water is variable. Total maximum daily loads (TMDLs) could also be used. For industrial production, this requires characterization of the waste water effluent, and would most likely involve the amount of water required to meet wastewater discharge permit requirements, rather than drinking water standards.

Water footprints are calculated by the ratio of the total volume of water consumption ($m^3$/ha) to the quantity of the production (ton/year), based on the methodologies of Hoekstra et al., 2011. For biofuels and bioenergy, water intensity is defined as the amount of water consumed per unit of fuel produced ($L_{H2O}/L_{ethanol}$) and/or the amount of water consumed per unit of bioenergy produced ($m^3$/GJ). The inverse is water productivity/efficiency, or the amount of bioenergy produced for unit of water consumption (GJ/$m^3$). This metric is not indexed, and therefore provides a spatial and temporally explicit measure of water consumption, in real volume. For yields, some of the literature uses wet tons, while some use bone dry tons (BDT), and some do not specify. This makes comparison difficult since the yield is the denominator of this calculation, and using wet ton instead of dry ton would cause the water footprint to be significantly smaller.

The concept of dividing and measuring water consumption by green, blue or grey water was introduced in the concept of the virtual water footprint by Hoekstra and Hung in 2002. Virtual water refers to all the water consumed during the production of a product or service. This concept was used and refined by Hoekstra and other researchers (Chapagain & Hoekstra, 2004; Chagagain & Orr, 2009; Hoekstra et al., 2009a, Hoekstra et al., 2009b), which lead to the publication of the Water Footprint Assessment Manual in 2009, and a revised version in 2011 (Hoekstra et al.). Most of the literature uses CROPWAT or similar models to calculate ET, which is recommended by the Water Footprint Assessment Manual and by FAO (FAO, n.d). However, CROPWAT is to be used only when local data are not available. In the case of this research, more accurate regional climate and crop data were available.

The concept of water footprints has been in use only recently by researchers for biofuel production (Gerbens-Leenes et al., 2009a; Yang et al., 2009; Mekonnen and Hoekstra, 2011). The water footprint of biofuel energy depends upon the yield of the crop, climatic conditions at its production location, climate data and modeling programs uses, and agricultural practices (Gerbens-Leenes et al., 2009a; Yang et al., 2009).

Outside of comparisons between footprint and LCA methods, which will be discussed below, the main criticism of water footprints is that this indicator is too simplistic and too aggregated, and does not account for all of the hydrological complexities, such as soil water balance, land use change, varying slope and run-off rates, infiltration and porosity, ground water tables, crop root structure, and other similar factors (Perry, 2014).These critiques argue that more complex hydrological modeling, remote sensing, and field data collection should be used to measure water consumption, rather than simplistic indicators (Perry, 2014). Such a critique is valid, as water footprints do not account for all the possible factors that influence a watershed's water balance and a crop's water consumption. However, water footprints provide a metric that can be calculated for multiple crops, products, and regions. Hydrological assessments are expensive, require large data sets, and require a high level of technical expertise. A full hydrological assessment is not always required if the question can be answered with reasonable accuracy using a more simplistic approach.

### ***Water Impact Approaches in LCA***

Another approach is the one commonly used in LCA. The LCA approach also uses the water footprint, but it takes the volumetric water footprint and then focuses on impact factors, weighing different water footprint components based on their relative impact. Specifically, this approach addresses the shortcomings of the water footprint by putting this metric in terms of impacts such as relative water scarcity, human health, and ecosystem quality. To do so, LCAs use characterization factors for water use (Pfister et al., 2009). Such an analysis often removes the spatial and temporal measure from the water footprint, but provides a metric that can be more easily compared to other studies, which is a significant benefit (Pfister et al. 2009; Ridoutt et al., 2009). Some methods classify water use as consumptive or degradative or instream or off-stream or evaporative or non-evaporative, so like water footprint accounting also for LCA in general, methods vary significantly and consumptive use is not always specified (Bayart et al., 2010). Most studies are performed at national or global scales. However, these studies are most meaningful when performed at the watershed level due to large regional differences in water availability, specifically if water demand is high and resources are limited (Pfister et al., 2009).

### ***Water Footprints Compared to Impact Assessments in LCAs***

Water footprints provide a volumetric output that is spatially and temporally explicit, rather than a relative impact measure as in LCAs. The advantage of this approach is that it is regionally specific and gives a volumetric output that represents the real volume of water used (Riddout et al., 2010). The disadvantage is that this makes the metric hard to compare to other footprints, unless they were calculated for the same region and time period, using the same assumptions (Riddout et al., 2010). This metric also does not account for the relative water scarcity, opportunity costs, or impacts associated with each type of water consumption in the way that a LCA does (Riddout et al., 2010). For example, a large water footprint may be in issue in a water stressed watershed, but not in a watershed with relative water abundance, or a small amount of competition for water resources. More importantly, a large water footprint that represents water withdrawn, but not consumed, could have a lesser impact than a large water footprint that is 100% consumptive use, so this distinction must be specified. Since the footprint for crops relies on calculations of evapotranspiration, all water use is consumptive for all footprints. However, process footprints do not always make this distinction. For this research, a volumetric number was required for a specific crop, in a specific location, over a specific timescale, consumptive use is clearly defined, and so the water footprint is the most effective method.

### ***Water Footprints for Poplar***

Some water footprint assessments, either using an LCA or just calculating a footprint, include poplar as a feedstock. Location and climate data, conversion processes, coproduct allocation, and overall footprint calculation methods vary widely, so comparisons are difficult to make. However, the available data will be reviewed here despite the inability to draw comparisons.

Gerbens-Leenes et al. (2009b) calculated the water footprint for bioenergy from poplar and 14 other crops for four countries, including the United States. It is unclear what conversion process yields were used, or what kind of fuel is produced. They found that in the United States, poplar has a water footprint of 42 $m^3$/GJ, wheat had a water footprint of 84 $m^3$/GJ, and corn had a water footprint of 18 $m^3$/GJ, using the fresh weight of the crop (not bone dry tons) (Gerbens-Leenes et al., 2009b).

Sevigne et al. (2011) performed a LCA and found crop evapotranspiration of poplar in Southern Europe to be 12,101 m3/ha/2 year coppice cycle, for dry mass yields and excluding indirect water use such as ancillary chemicals and equipment.

# Methodology

## Description of Study Areas

This research analyzed water consumption for hypothetical biofuel production in Washington State. Washington State has a variety of climates, and climate strongly affects water consumption for plant growth. Since biofuels used biomass, it was important to compare different climates that are representative of Washington State in order to see how water consumption varies across Washington's landscape. Washington State can be split into two general climate, a temperate marine climate in Western Washington and a semi-arid climate in Eastern Washington. Eastern and Western Washington have different water scarcity concerns based on their annual precipitation, hydrology, and local policies, so they provided a good comparison for Washington State.

An industry partner for the research project, Greenwood Resources, has four demonstration plots of hybrid poplar clones in the Pacific Northwest to analyze biomass yield and production economics. Multiple hybrid poplar varieties are planted at each location at a density of approximately 1,450 stems per acre with rows aligned on 10-foot centers and trees spaced at three-foot intervals within each row (GWR, n.d.).

Potential hybrid poplar plantation sites should be within a close radius to the biorefinery site in order to maximize transportation efficiencies, so sites were selected on a WRIA watershed scale, which would fit within this proposed radius. Sites were also selected due to the availability of rain-fed and irrigated hybrid poplar crop data from GWR's demonstration plots at Pilchuck and Hayden, and their proximity to local Washington weather stations with long periods of record. The crop water use was modeled using the nearby weather station. The Pilchuck site is in Western Washington, near Mount Vernon. The Hayden site is actually in Hayden, Idaho, which is right across the border from Spokane in Eastern Washington, and in the same watershed as parts of Spokane ***(Figure 8)***

Site descriptions are below and detailed maps of each site are provide in ***Appendix B - Figure 2 and 3***. WRIA maps are provided in ***Appendix B - Figure 1***. Site information was sourced from GWR and from the weather stations for Mount Vernon and Spokane (GWR, n.d.).

**Pichuck – Mount Vernon, WA**

This area has a temperate marine climate with warm, dry summers and cool, wet winters. The regional topography varies by location, with a flat alluvial valley near the Skagit River that is bounded to the south and east by upland mountainous terrain.

Demonstration site: Located at 1440 316th St NW, Stanwood, WA 98292, near the border of Skagit and Snohomish Counties, this 95-acre plantation near Stanwood and Mount Vernon, WA, receives 33 inches of precipitation per year, which is slightly more than the nearby weather station that was used for this research. Due to sufficient precipitation, the Pilchuck planation is rain-fed only. This site was planted in the spring of 2013. An initial, non-coppice harvest was performed in 2014. The site receives various pesticide and herbicide applications, but is not fertilized.

Weather Station: Located in Skagit County, in WRIA 3, this weather station is operated by Washington State University. The coordinates of the station are latitude 48.44°, longitude -122.39°. The elevation is 23 feet. Historical data are available from November 1993 to the present. Average climate information for this station for the period of record used in this research (water years 1994-2014) is presented in ***Table 2***.

***Table 2***. *Climate at WSU Mt Vernon weather station*

| | |
|---|---|
| Average annual temperature | 50.8 °F |
| Maximum monthly average temperature | 73.2 °F (August) |
| Minimum monthly average temperature | 35.1 °F (December) |
| Average wind speed | 3.7 mph |
| Average annual precipitation | 31.8 inches |

### Hayden, ID – Spokane, WA

This area has a dry but temperate climate with hot, dry summers and cold winters, with approximately 25-40% of precipitation falling as snow. Annual precipitation ranges from 10 inches per year to 40 inches per year at higher elevations. The area transitions from shrub-steppe areas of the Columbia Basin to forested mountains in Northern Idaho.

Demonstration site: 13300 N Huetter RD, Rathdrum, ID 83858, this site receives 26 inches of precipitation per year, which is not enough for sufficient poplar growth, so the site is irrigated. This 65-acre planation was planted in the spring of 2012. An initial, non-coppice harvest was performed in the fall of 2013. The site receives various pesticide and herbicide applications, but is not fertilized.

Weather station: Located in Spokane County, in WRIA 56 (the Spokane area includes WRIAs 54,55,56,57), this climate station is operated by Spokane International Airport. The coordinates of the station are latitude 47.62°, longitude -117.53°. The elevation is 2353 ft. Historical data are available from 1932. Average climate from the period of record used in this research (water years 1982-2014) is presented in ***Table 3***. It is worth noting that the Spokane area weather station receives less precipitation than the demonstration site, and that the crop water use calculated for this research uses the available climate data from the Spokane station, so this location which would require a bit more irrigation than the more upland demonstration site in Idaho.

***Table 3***. *Climate at Spokane International Airport weather station*

| | |
|---|---|
| Average annual temperature | 48.0 °F |

| | |
|---|---|
| Maximum monthly average temperature | 85.0 ˚F (July) |
| Minimum monthly average temperature | 21.2 ˚F (December) |
| Average wind speed | 9.2 mph |
| Average annual precipitation | 16.9 inches |

*Figure 8*. *Map of study areas*

## System boundaries

The system boundaries for this analysis are cradle to gate, meaning from the beginning of crop production to when the fuel leaves the biorefinery for distribution. There are two product stages analyzed: feedstock production and the conversion process at the biorefinery. Details of assumptions made in the preparation of climate data files and evapotranspiration calculations are explained in ***Appendix E - Table 1***. ***Figure 9*** depicts the system boundaries.

1. For feedstock production, the water footprint assessment includes two years of nursery production, two years of site preparation and establishment planting, and six three-year coppice cycles. It is assumed that 100,000-125,000 acres of poplar would be required to produce approximately 700,000 bone dry tons (BDT) per year. Bone dry tons are a unit used to measure crop yield. A BDT is the volume of wood chips that would weigh one ton assuming 50% water content by weight.
2. At the biorefinery, only process water is included. Water used (either consumptive or non-consumptive) in the production of equipment, ancillary chemicals, and transportation between the field and the refinery was not included, since the water required for these products and processes would be embedded in them and not necessarily sourced from the geographic area used in this analysis. Any water used after the product leaves the biorefinery was also not included, for the same reasons. It is assumed that the biorefinery would produce 100 million gallons per year of biofuel. Water was not allocated between excess electricity generated and co-products.
3. Land use change and eutrophication from agricultural run-off also have environmental effects, especially for water resources. Land use change can increase or decrease run-off and infiltration, for example, while eutrophication can pollute water bodies many miles downstream. However, these two variables were outside of the scope of this research and would require extensive hydrological modeling.

In this research, water use refers to consumptive water use. During the feedstock production stage, water is evapotranspired by the crop and released into the atmosphere, making it unavailable for other users. For the production stage at the bioreferinery, water use is more general term. A zero water discharge system is assumed, but within this system, some water may be recycled, so the exact proportion of water consumed vs. used is unkown. Therefore, all process water is considered to be consumptive use.

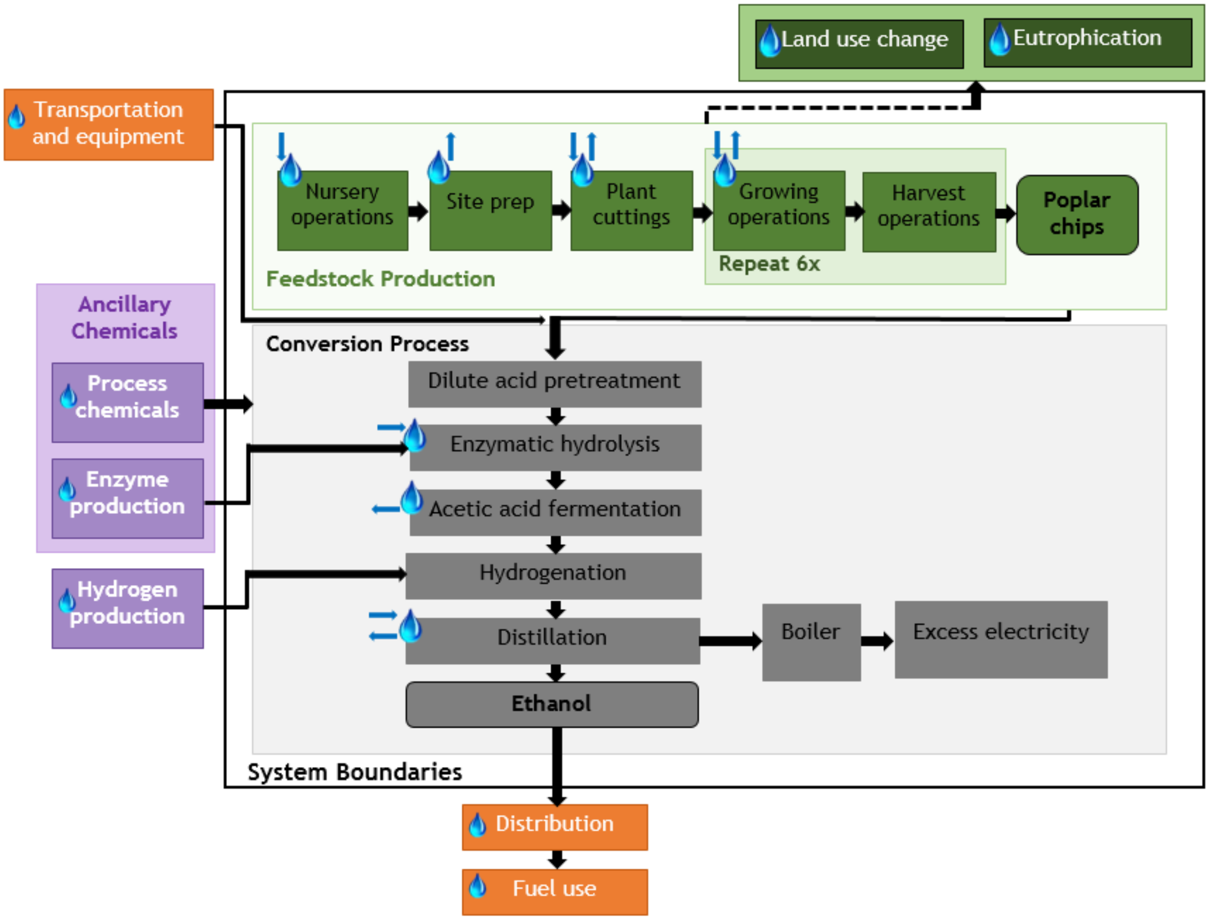


***Figure 9****. System boundaries*

***Figure 9*** shows the process flow of feedstock and conversion and at which points water is an input or output. Other process inputs and outputs with embedded water flows that were not considered in this analysis are depicted outside of the system boundaries.

## Question 1a: Water Footprints for Feedstock Production and Biofuel Conversion

For this research, the methodology designed by Hoekstra et al. (2011) in the Water Footprint Assessment Manual was used. This methodology involves a series of calculations to quantify water consumption using climate data, crop yield, process water volume, and other variables. The calculation was performed using metric units. A full list of equations are provided in ***Appendix C - Tables 1-4 and Figure 1***. Inputs are provided in ***Appendix D - Tables 1-5***. Assumptions is given in ***Appendix E - Table 1***.

***Feedstock production:*** The water footprint of the crop (m3/BDT) is the proportion of the amount of water consumed to produce the crop (m3/ha), to the crop yield (BDT/ha). It is the sum of the green, blue and grey water footprints, where the green water footprint is the amount of rainwater the crop consumes, the blue water footprint is the irrigation demand, and the grey water footprint is the amount of water required to dilute the polluted agricultural run-off to meet water quality standards. This calculation was performed for 3 yield scenarios for each site, for hybrid poplar (*Populus spp.*) Hybrids of four key species were used for industry partner's yield estimations, *P. deltoides, P. maximowiczii, P. nigra, and P. trichocarpa* (GWR, n.d.).

Green water footprint ($WF_G$) – This metric was calculated using precipitation and crop evapotranspiration ($ET_c$).

- First reference ET ($ET_r$) was calculated on a daily time step using the Standardized ASCE Penman-Monteith Equation, with a tall reference crop of alfalfa (0.50m). Daily reference ET values were then summed to monthly values.
- To obtain the crop water consumption, or ET of the hybrid poplar crop ($ET_{c)}$, $ET_r$ was multiplied by a monthly hybrid poplar crop coefficient based on crop growth during the establishment and coppicing phases.
- Then, effective precipitation was calculated, by assuming that 80% of precipitation is available for crop consumption, which is a standard assumption used by the United States Geological Survey (USGS) and the Food and Agriculture Organization of the United Nations (FOA), and for ET modeling programs such as CROPWAT.
- The green water footprint is $ET_c$ divided by the crop yield, unless $ET_c$ exceeds effective precipitation, in which case the crop is constrained by available water (water stressed) and the green water footprint is the effective precipitation divided by the crop yield.

Blue water footprint ($WF_B$) is the difference between $ET_c$ and effective precipitation. If $ET_c$ is greater than effective precipitation (the crop water requirement is greater than available water), then this number is the irrigation demand. The blue water footprint is this amount, divided by the crop yield. The nursery stage consumes only blue water as it is an enclosed greenhouse.

Grey Water footprint ($WF_{Gy}$) is the leaching run off fraction (assumed to be 10%) multiplied by the application rate of the pollutant, which is divided by the legal maximum acceptable concentration of the pollutant minus the natural background concentration, divided by the crop yield. The grey water footprint was calculated for the establishment and coppicing phases, but not for the nursery stage due to its small insubstantial contribution to the total numbers, and enclosed nature of the greenhouse.

Data sources:

- Climate data: For the WSU Mt Vernon weather station, 20 years of climate data were used from water years 1994-2014. For Spokane International Airport weather station, a longer period of record was available so 30 years of data were used from water years 1982-2014. The data were six climate variables, which included minimum and maximum daily temperature, dewpoint, average daily windspeed, daily precipitation, and daily solar radiation. Daily data were cleaned, then averaged for each day, for the entire period of record. $ET_r$ was calculated for these daily data, then summed into monthly $ET_r$ values.

- Hybrid poplar crop coefficients were sourced from the literature, and are the same crop coefficients used by other researchers for this project (Gochis & Cuenca, 2000). The crop coefficient was calculated from ET measurements in a western climate, in Boardman, OR.
- Crop yields: Crop yield data with high, medium and low yields were provided by GWR. These yields represent average coppice yields over the entire 18 year period, since each three-year coppice yield would vary based on position in the yield cycle and local conditions.
- Pollutant application rates and treatment areas were provided by GWR.
- Leaching run off fraction was not measured at these sites for the pollutants applied, so it was obtained from the literature, and according to the methodology outlined in Hoekstra, 2011.
- Maximum acceptable pollutant concentrations and water quality standards were obtained from EPA and other relevant regulatory agencies.

***Conversion Process:*** In order to calculate the water footprint of the **biofuel** and of **biofuel energy**, the process water consumed in the conversion process (blue water) is added to the total water footprint. Then, the total water footprint is multiplied by the biofuel conversion rate to obtain the water footprint of the biofuel. To obtain the water footprint of bioenergy, the footprint is divided by the biofuel energy content. A separate grey water footprint was not conducted for the conversion process, due to a lack of available data required for this wastewater calculation.

Data sources:

- Conversion process water requirements were provided by Budsberg (2015) Conversion process rate was provided by Budsberg (2015).
- The energy content of ethanol is composed of the higher heating value and density of the fuel, and is widely available.

## Question 1b: Review of Watershed Assessments

Originally, the objective was to put water footprints in terms of water availability, using the methodology outlined by Hoekstra et al., which uses existing water balance data (e.g., from WRIA Assessments) to perform a sustainability assessment. Hoekstra's method uses environmental, economic, and social criteria, but the intent was to use only environmental sustainability criteria, as the economic and social impact analysis is beyond the scope of this research. However, the availability of water budget data from WRIA assessments and other similar hydrological assessments in Washington was inconsistent or extremely outdated. Where data were available, inconsistent methods or models were used, with different assumptions. Therefore, without performing a full hydrological modeling exercise for each watershed, which was beyond the scope of this research, it is difficult to quantitatively assess this question. Instead, a brief qualitative discussion of relative water availability in each watershed will be presented, based on a review of the availability of hydrology data and reporting for the study area watersheds.

Data sources:

WRIA technical assessments and other reports, USGS reports, and other archived reports sourced with assistance from Ecology.

## Question 2: Climate Change Scenarios

Based on a review of the IPCC report and regional climate predictions, two climate scenarios were selected: hot/dry and hot/wet. Based on the this literature, these scenarios assumed that temperatures in Washington State will increase, and precipitation will become more variable and unpredictable, with certain areas receiving more precipitation, and certain areas receiving less. (Elsner et al., 2010; IPCC, 2014; Mote et al., 2010). In general, site suitability will decrease, as seen in the maps in ***Appendix F – Figure 1.***

A review of the scenarios used at each site is detailed below in ***Figure 10***.

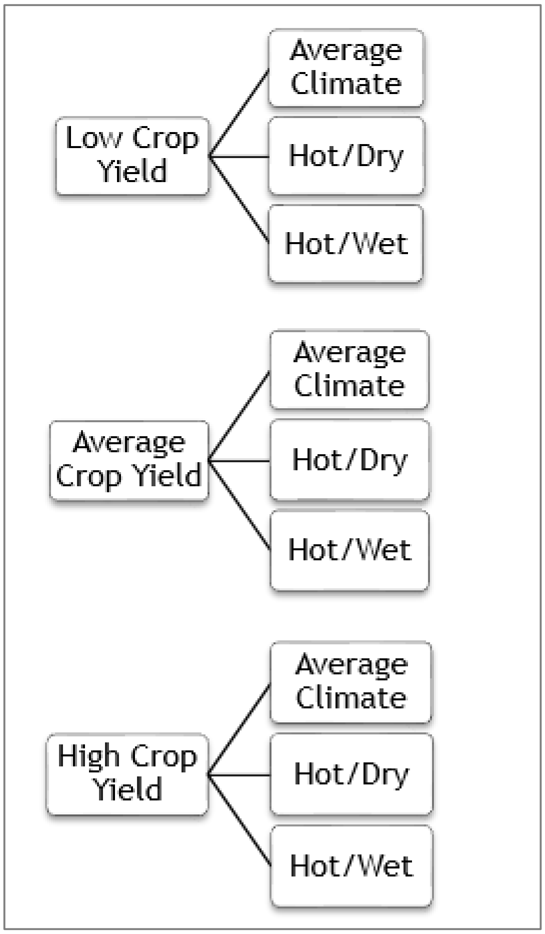


***Figure 10***. *Water consumption scenarios for crop yield and climate*

Data sources:

Data used for each scenario at each site were one water year of historical climate data that corresponded to hot/dry or hot/wet from the existing climate data set. Crop water consumption in these extreme years could then be compared to the crop water consumption for historical averages for each site. Historical data were used for the climate scenarios, instead of climate modeling. Climate models were not used due to two factors:

- Well known issues in accuracy that occur when downscaling climate models to the very small spatial scale and regional level of analysis required for this research.
- The need to have a complete set of data with all six climate variables, such as wind speed and solar radiation, rather than just a data set with temperature and precipitation.

Scenario selection:

The scenarios were selected by comparing historical monthly averages for the data sets (20 years and 30 years for Mt Vernon and Spokane, respectively) to “extreme” years based on a combination of temperature and precipitation. These variables were selected because they are the two most critical climate variables to photosynthesis and net primary productivity of the plant. These variables were analyzed during the growing period of April through October, since hybrid poplar are deciduous. In order to select the years for each climate scenario, the following steps were taken:

- Annual precipitation data from April to October were summed, for each year of available data.
- A count was performed for the number of days over 85°F (29°C) for the same period, from April to October, for each year of climate data. Eighty-five degrees Fahrenheit was selected because the ideal temperatures for poplar are between 60-85°F, as displayed in ***Figure 11***. Above this temperature, the crop becomes heat stressed and productivity decreases, leading to lower crop yields.
- Next, the April to October data were put into quartiles and ranked one through four for temperature, with a number one corresponding to the coldest quartile and a number four

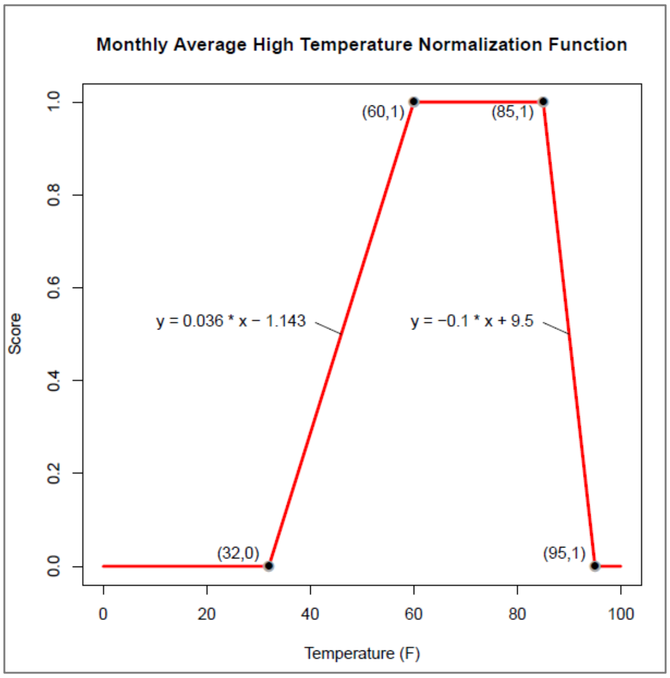


***Figure 11**. Ideal temperature for hybrid poplar*

(Rogers, 2014).

> corresponding to the hottest quartile. For the Hot/Dry year, precipitation was assigned a number one for the wettest quartile, and a number four for the driest quartile. For the Hot/Wet year, the quartiles were reversed. Lastly, these ranks were multiplied, and the years with the largest products were selected for further analysis. The potential hot/wet and hot/dry years were then graphed and analyzed relative to boxplots of the historical figures for each month. Graphs depicting this analysis are shown in ***Appendix F – Figures 2 and 3***. To the extent possible, years that emphasized extreme conditions during the critical mid-section of the growing season were selected over years that had high temperatures in only, for example, April, but not in July or for the entire summer. None of the years exhibited conditions that deviated from the historical average for every month and for every variable, though these variable conditions (abnormally wet one month, abnormally dry the next month etc.) are likely more representative of climate change predictions.

For Mt Vernon, water year 2003 was selected as the Hot/Dry year and water year 2010 was selected as the Hot/Wet year. For Spokane, water year 2003 was selected as the Hot/Dry year and water year 2004 was selected as the Hot/Wet year. These years relative to the historical averages, are depicted in ***Figure 12 and 13***.

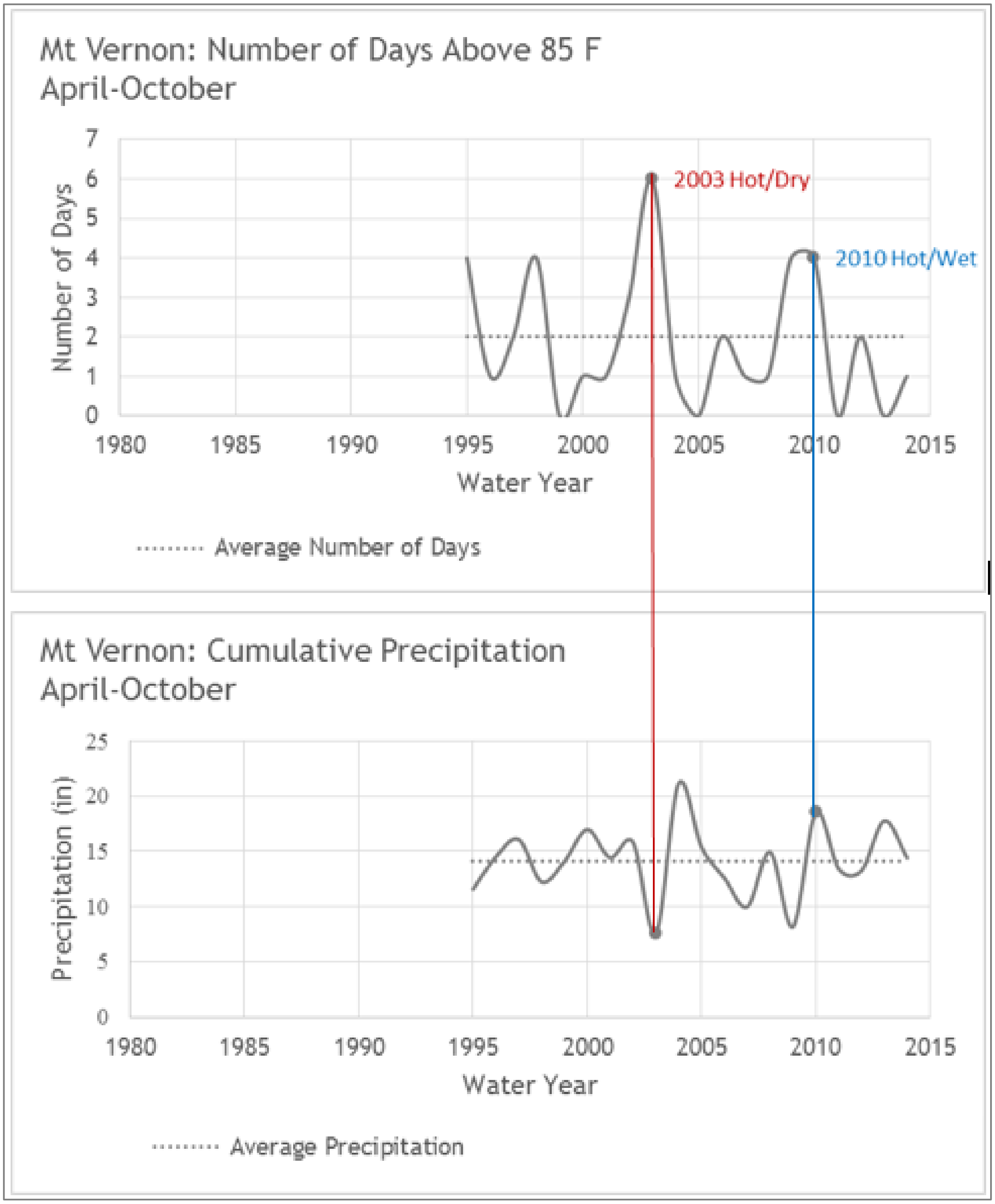


***Figure 12***. *Mt Vernon temperature and precipitation analysis for climate scenario selection*

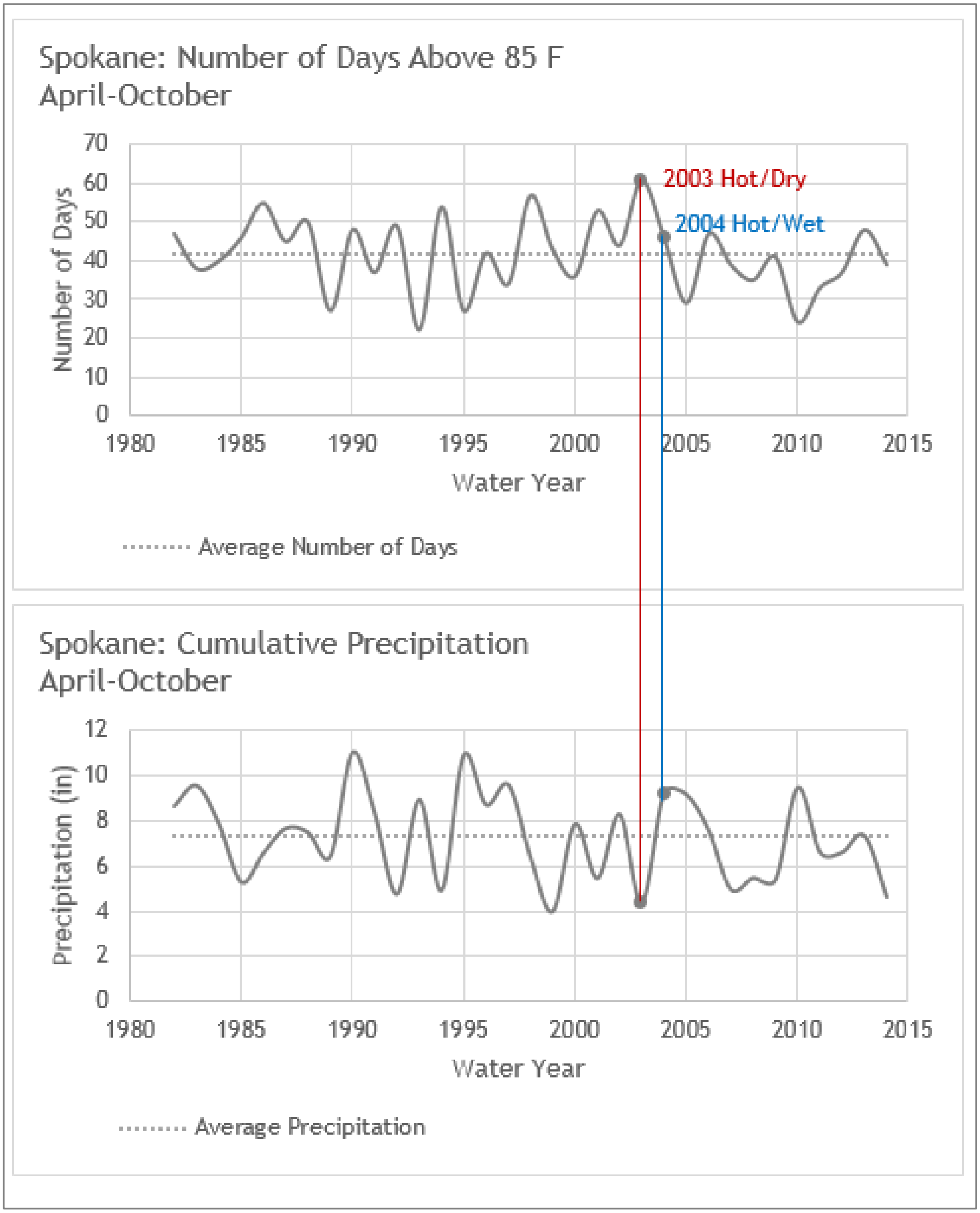


***Figure 13****. Spokane temperature and precipitation analysis for climate scenario selection.*

## Question 3: Assessment of Water Policy Landscape

Three sources of information were used to identify water regulations and policies relevant to bioethanol production:

1. Websites of federal and state agencies were searched for relevant program information. Examples of these agencies include the U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, the U.S Fish and Wildlife Service, U.S. Department of Agriculture, the Washington Department of Ecology, the Washington Department of Natural Resources, and the Washington Department of Commerce.
2. Academic literature which examines bioethanol or biofuels with regards to water and water policy was surveyed.
3. A search of recent Washington State legislation which included the word "water" was conducted.

Once potentially-relevant water policies were identified, the potential relevance to the prospective bioethanol production industry was assessed. Only policies that affected the two stages of production within the system boundaries (feedstock and biorefinery siting/ production) were included. These included policies that impacted procurement of water for feedstock or production, policies that govern the discharge of wastewater or stormwater, and more general environmental or growth management policies that include an aspect of water resource management. Since neither of the study sites were on a lake or coastline, marine and shoreline policies were excluded from this assessment, and since there are no plans to inject wastewater underground or produce drinking water, the Safe Drinking Water Act was also excluded.

It was then possible to review whether the policy what roadblocks might arise through a general discussion of each policy and its place in the overall policy landscape. Lastly, a set of policy tools that can be used to navigate this landscape was summarized.

# Results

## Water Consumption in Biofuel Production

The water footprint is an indicator of the amount of water required to produce a crop and/or product given a certain production amount, or yield. It is important to note that as production efficiency increases (i.e. yields increase), the water footprint becomes smaller. In addition, if a crop is not irrigated (blue water), and not enough precipitation (green water) is available to meet crop water requirements, then the water footprint is constrained by water availability. Even though the Pilchuck site is rain-fed only, precipitation in this area is not enough to fully meet crop water requirements 100% of the time. Therefore, the water footprint for the Pilchuck site is lower than it would be if the crop were irrigated and crop water requirements were fully met.

For the water footprint of biofuel production, the majority of the water required to produce the fuel comes from the agricultural production stage, because large amounts of water are required to grow a crop. The water required for feedstock production is seasonal, generally from April to October. The conversion process requires very little water in comparison, but requires a continuous water supply year-round. The conversion process water (100% blue water) must be sourced from surface water, groundwater, or a local utility, which has different legal and policy procurement issues compared to the precipitation (green water) that makes up a large portion feedstock production. A detailed review of the results for the feedstock and conversion production stages will be outlined in the next section.

The water footprint is presented in three units, $m^3$/BDT, $L_{H20}/L_{ethanol}$, and $m^3$/GJ of energy. The first, $m^3$/BDT, is the amount of water consumed per crop yield in BDT (bone dry ton). It is important to know how much water the crop itself consumes, since this makes up the largest portion of the total water footprint, and this can also be compared to other crops. The second, $L_{H20}/L_{ethanol,}$ is the amount of water consumed per liter of ethanol produced. This metric includes both the feedstock and conversion processes. It allows comparison across other processes that also produce ethanol. And lastly, $m^3$/GJ, is the amount of water consumed per the amount of energy produced. This metric is important because different types of fuel contain different amounts of energy. For example, ethanol is less energy dense than gasoline, so comparing a liter of ethanol to a liter of gasoline would not produce the same amount of energy.

Overall, the water footprints of hybrid poplar, ethanol, and bioenergy for this production process are much lower for the Pilchuck rainfed site than for the Hayden irrigated site (***Table 4***). For a typical climate and average yield, the water footprint of hybrid poplar at Pilchuck is 242 $m^3$/BDT, and 741 $m^3$/BDT at Hayden. For the same average scenario, the water footprint of ethanol at Pilchuck is 455 $L_{H2O}/L_{ethano}$l and 1385 $L_{H2O}/L_{ethano}$l at Hayden. The water footprint of bioenergy is 19 $m^3$/GJ at Pilchuck and 59 $m^3$/GJ at Hayden. Results for three yield scenarios in a typical climate for each site are shown in ***Table 4***. Water footprint of bioethanol production with hybrid poplar In addition, the water footprint of bioenergy for three crop yield conditions and average climate is presented in ***Figure 14***. Information for each water footprint for each climate scenario and each site is presented in ***Appendix G - Table 1***.

***Table 4***. *Water footprint of bioethanol production with hybrid poplar*

| Site | Climate Scenario | Crop Yield Scenario | WF of Hybrid Poplar ($m^3$/BDT) | WF of Ethanol ($L_{H2O}/L_{ethanol}$) | WF of Bioenergy ($m^3$/GJ) |
|---|---|---|---|---|---|
| Pilchuck (Biorefinery 1) | Average Climate | Low Crop Yield | 285 | 535 | 23 |
| | | Average Crop Yield | 242 | 350 | 19 |
| | | High Crop Yield | 210 | 396 | 17 |
| Hayden (Biorefinery 2) | Average Climate | Low Crop Yield | 871 | 1629 | 69 |
| | | Average Crop Yield | 741 | 1385 | 59 |
| | | High Crop Yield | 644 | 1205 | 51 |

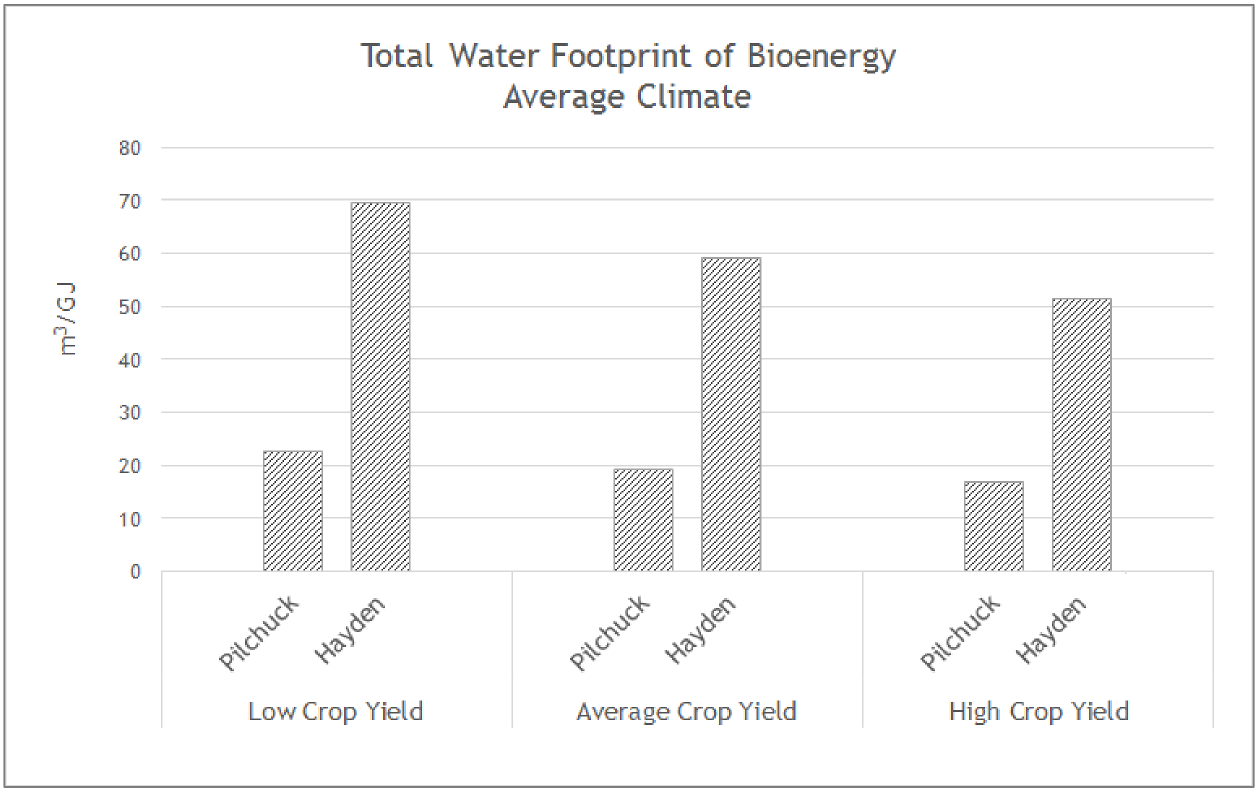


***Figure 14***. *The water footprint of bioenergy from ethanol using hybrid poplar for Pilchuck and Hayden under three crop yield scenarios and average climate*

## ***Feedstock Production***

The majority of water consumption occurs in the feedstock production stage, as water (either green or blue) used to grow the crop. The high yield scenarios were more efficient in terms of water consumption with water footprints of 210 $m^3$/BDT for Pilchuck and 644 $m^3$/BDT for Hayden. A comparison of the total water footprints including green, blue and grey water footprints for hybrid poplar under three crop yield scenarios and average climate is presented in ***Figure 15***.

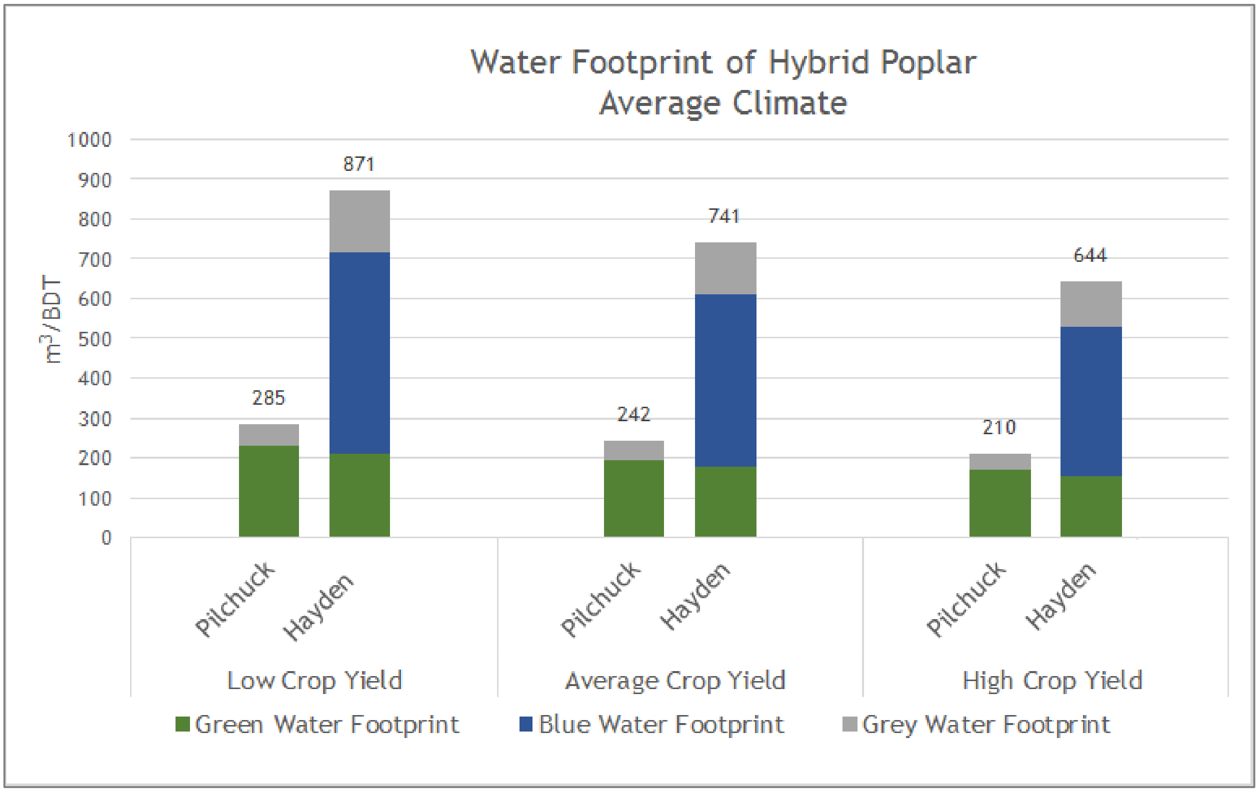


***Figure 15***. *Water footprint of hybrid poplar for average climate under three crop yield scenarios*

As an irrigated crop, the Hayden site consumes a large amount of blue water compared to the Pilchuck site. ***Figure 15*** displayed the total volume of each footprint, but ***Figure*** **16** ***16*** shows the proportion of the water footprint that is allocated to green, blue and grey water. For Hayden, the feedstock footprint is 58% blue water, while for Pilchuck the feedstock footprint is only 0.2% blue water, with 81% coming from precipitation (green water).

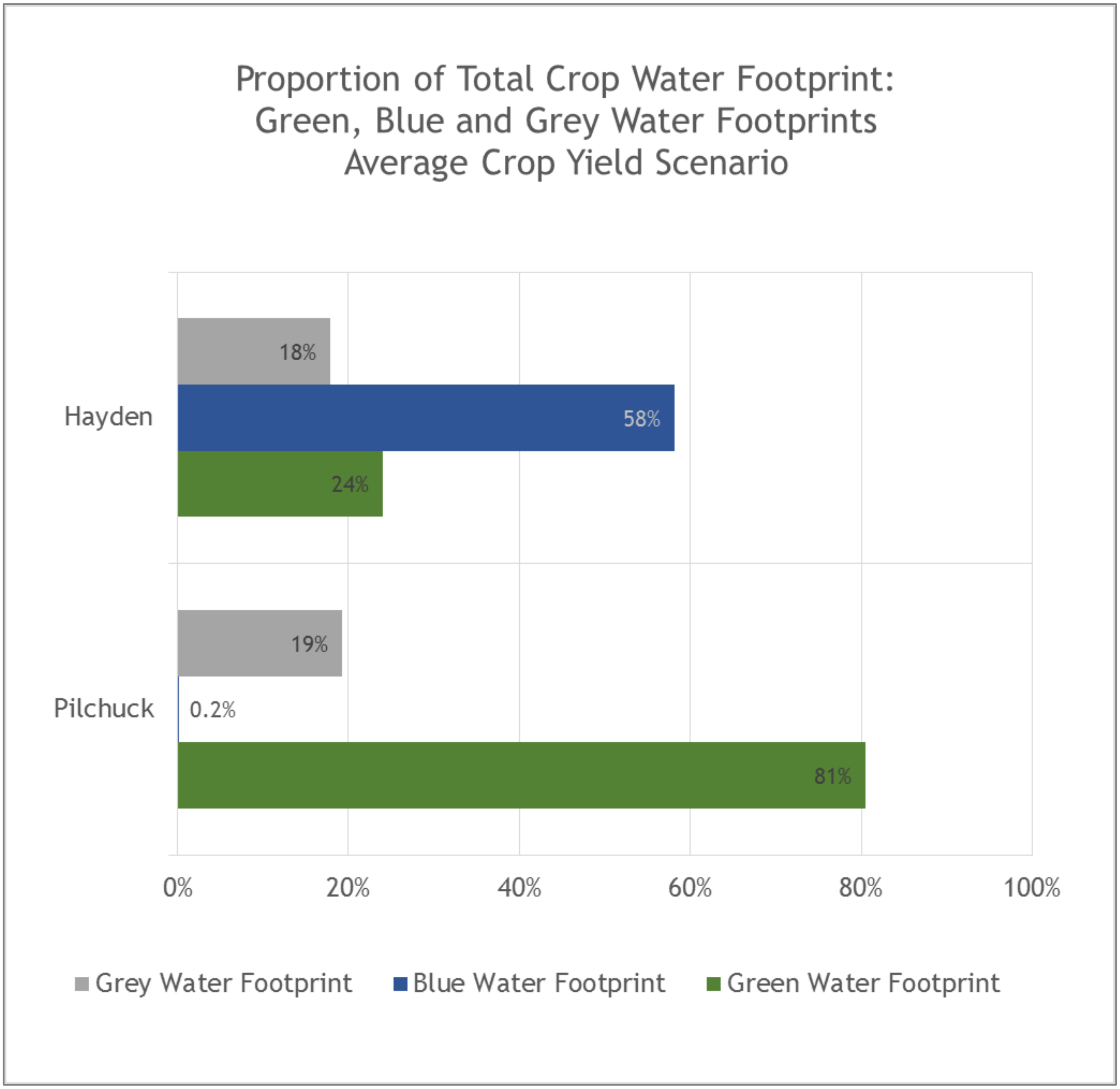


***Figure 16***. *Proportion of green, blue and grey water footprints for average crop yields in an average climate*

## ***Conversion Process***

The conversion process consumes a small amount of process water (3.7 $L_{H2O}/L_{ethanol}$) in comparison to feedstock production, and 100% of this water is blue water. The water footprint of ethanol includes both the process water in the conversion process and the embedded water used to produce the feedstock, therefore, the water footprint of ethanol looks very similar to the water footprint of the feedstock. For the average climate scenario with average crop yields, Pilchuck consumes 455 $L_{H2O}/L_{ethanol}$ while

Hayden consumes 1385 $L_{H2O}/L_{ethanol}$. The footprints for ethanol are displayed in ***Figure 17***.

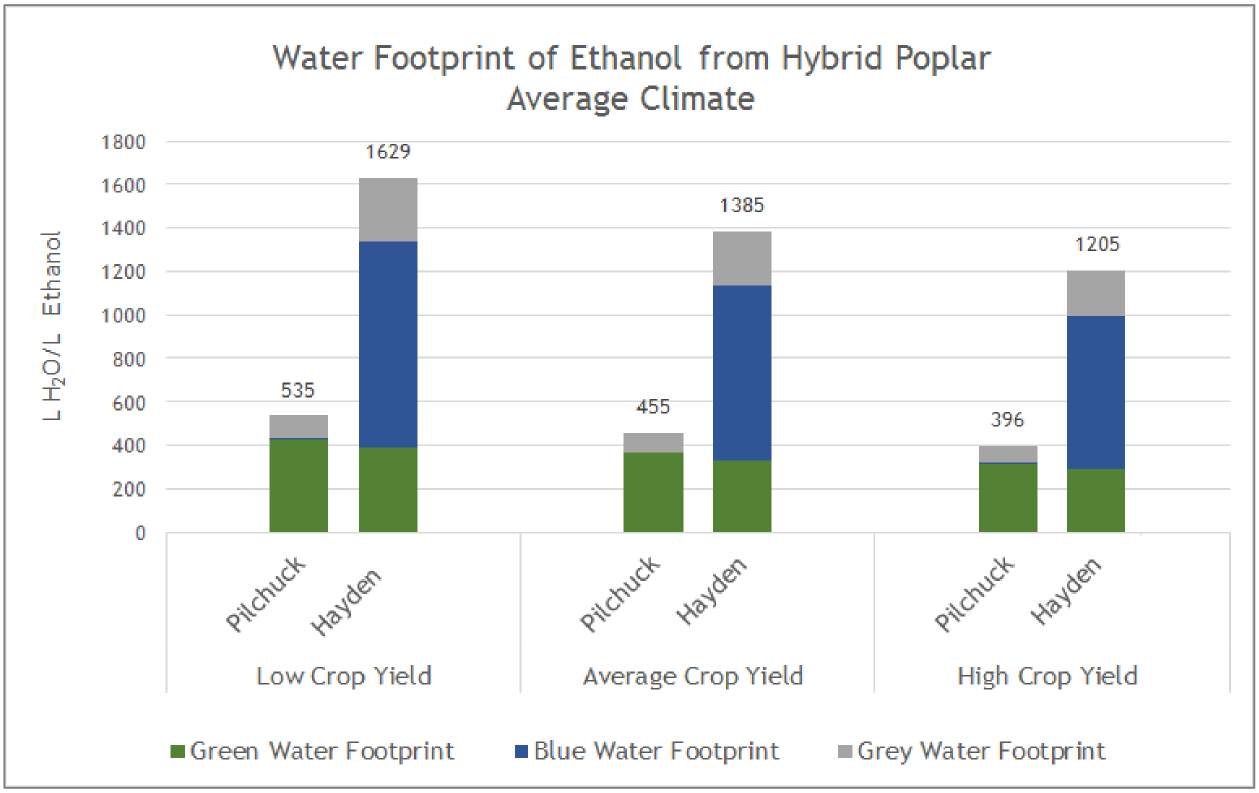


***Figure 17****. The water footprint of bioethanol from hybrid poplar for an average climate and three crop yield scenarios*

## Potential Effect of Climate Change

Because drought resistance varies among hybrid poplar clones, climate change will have varying effects on water consumption for biofuel production, depending on climate, clone and habitat. (Monclus et al., 2006). In general, higher temperatures result in higher rates of evaporation, and therefore higher rates of ET, until the crop reaches a maximum temperature threshold for photosynthesis. After this threshold, the crop stops producing, either temporarily, or for the entire season if the period of heat stress is too prolonged. Hybrid poplar trees are most productive between 60-85 degrees Fahrenheit. Above 95-100 degrees, the crop cannot photosynthesize. In addition, higher temperatures lead to higher rates of ET, which requires more water. If more water is available and the temperature is below 85 degrees, then the crop may become more productive. However, if water is unavailable, then the crop will become water stressed.

The results show that the water footprint of hybrid poplar for three climate scenarios (average climate, hot/dry and hot/wet) generally increases for the hot and dry climate at Hayden. At Pilchuck, the crop experiences a larger amount of unmet water demand, which is exemplified by the hollow bars on top of Pilchuck's water footprints in ***Figure 18***, and reviewed in detail later in Figure 20. For the hot/wet scenario, the water footprint decreases, due to more available precipitation.

Climate change could create conditions in which the crop becomes water or heat stressed, either through higher temperatures or through drought or variable precipitation, or a combination of both variables. If these conditions occur, the crop cannot photosynthesize at maximum efficiency, and crop yields will go down. This phenomenon has been well documented for most agricultural crops (Bocchiola et al., 2013; Jalota et al., 2013). Yield scenarios based on climate inputs were not modeled in this research. However, it is likely that an unfavorable climate scenario such as a hot/dry year would result in lower yields compared to the cooler and wetter average climate scenario.

Based on this knowledge of plant photosynthesis, rather than comparing the average climate to a climate change scenario across the same crop yields, a more logical comparison would be to compare the average climate, average yield scenario to for hot/dry, low yield scenario, or the hot/wet, high yield scenario. Such an analysis shows that the water footprint goes up for the hot/dry year and down for the hot/wet year, and is more representative of the potential effect of climate on crop yields.

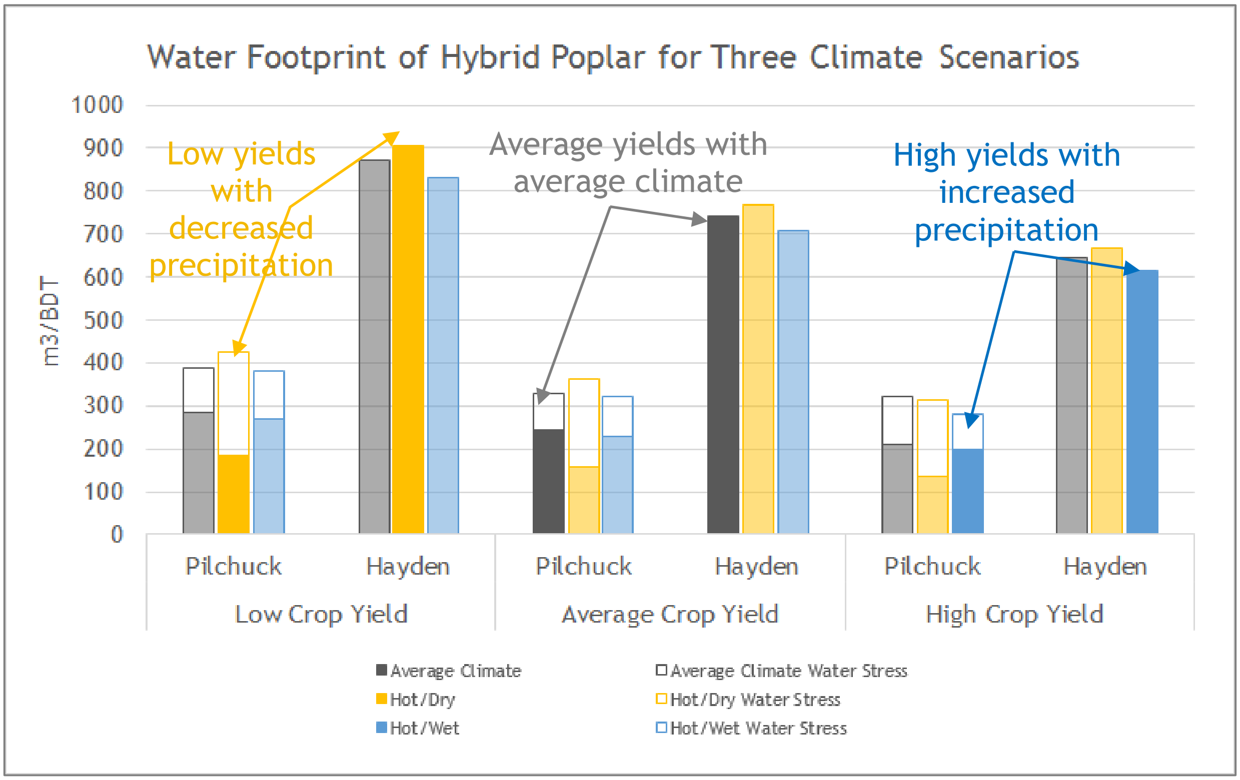


***Figure 18****. The water footprint of hybrid poplar for three climate scenarios*. Shaded bars represent the water footprint, while hollow bars represent the amount of unmet crop water demand (irrigation demand) for the rain-fed Pilchuck crop.

Details of the green, blue and grey water footprints for each site under each climate scenario are further outlined in ***Figure 19 and 20***. In addition, green, blue and grey water under the average climate scenario is presented again for comparison in ***Figure 15***. ***Figure 19***, the hot/dry scenario, shows that blue water increases at Hayden, meaning that a larger amount of the crop water requirements are unmet by precipitation alone and water consumption is therefore dominated by irrigation.

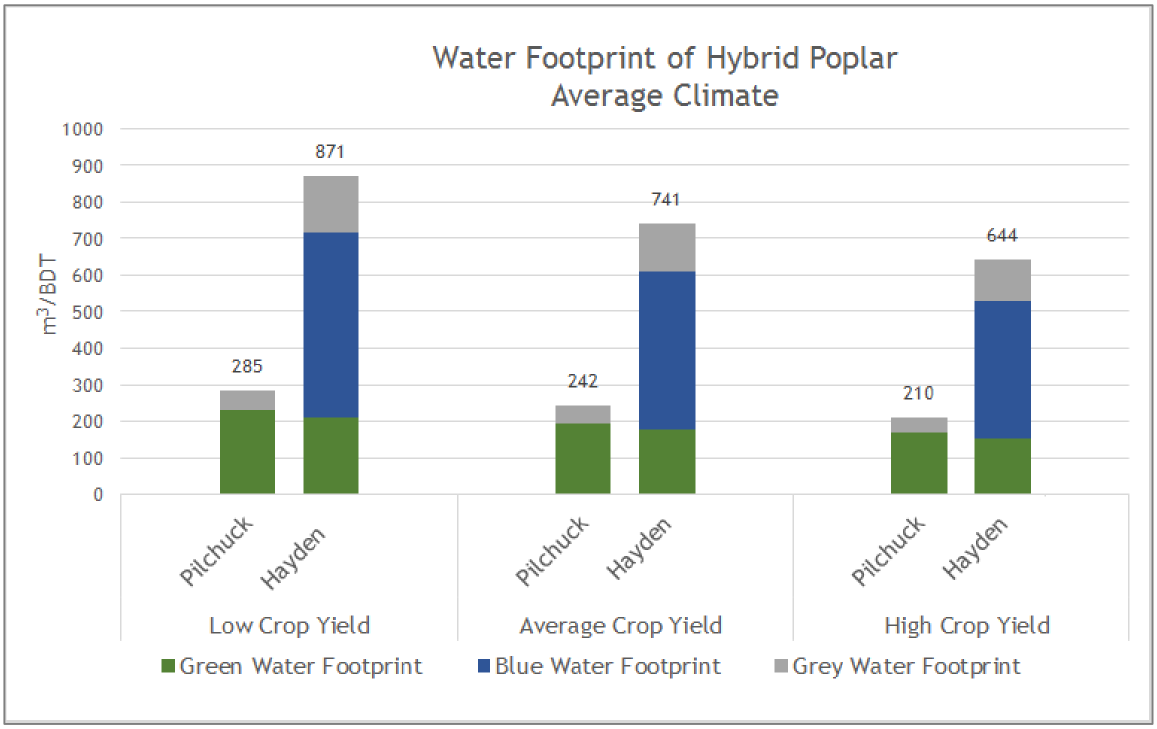


**Figure 15.** Water footprint of hybrid poplar for average climate under three crop yield scenarios

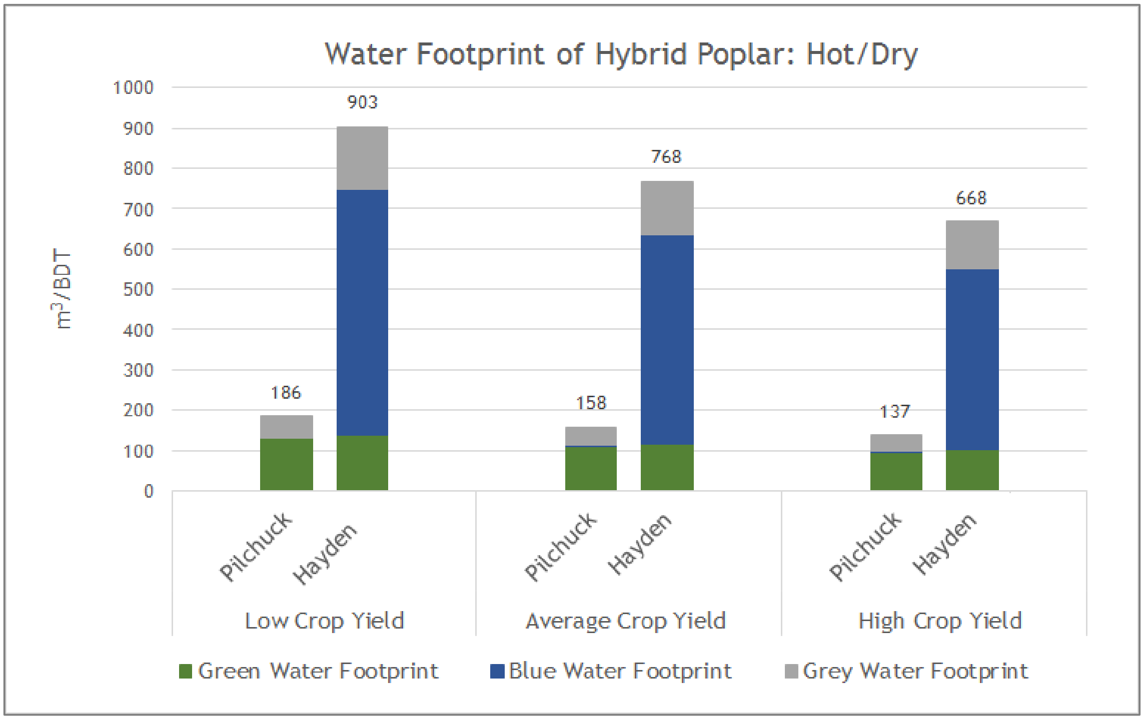


***Figure 19***. *Water footprint of hybrid poplar for hot/dry climate under three crop yield scenarios*

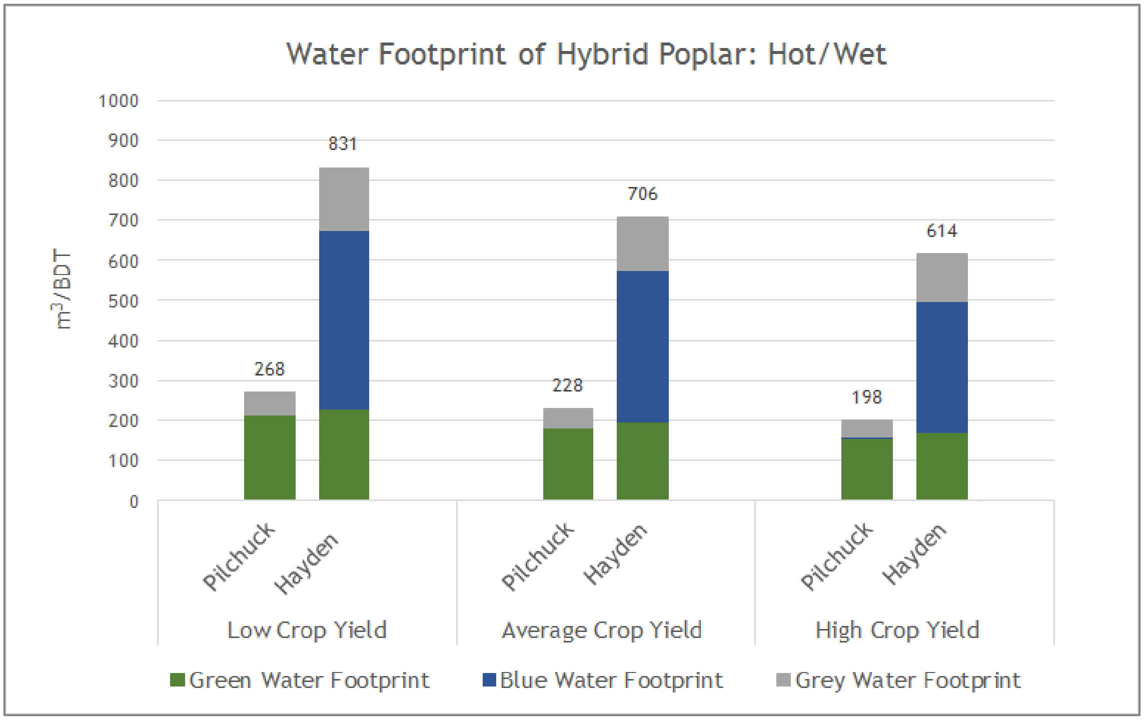
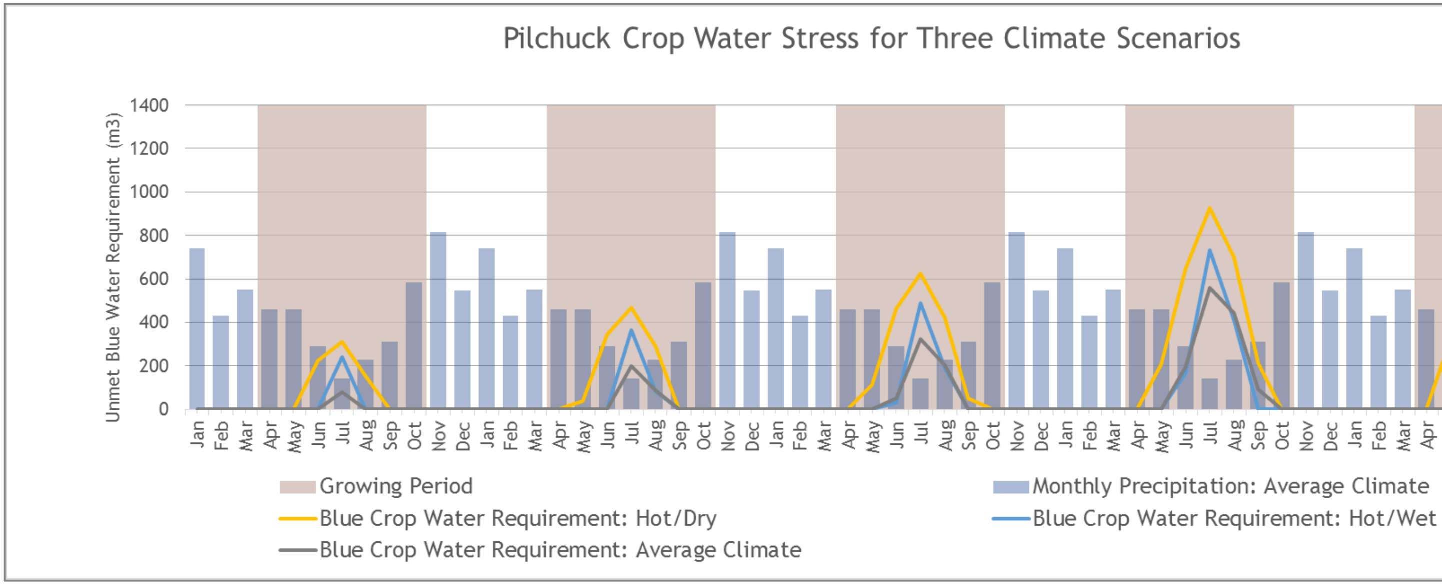


***Figure 20***. *Water footprint of hybrid poplar for hot/wet climate under three crop yield scenarios*

***Figure 21*** shows how crop water stress increases under the hot/dry scenario and decreases in the hot/wet scenario for the Pilchuck site. Despite the Pilchuck site receiving high annual precipitation, most of this rain falls during the wet winter months. Hybrid poplar is a deciduous tree, so unlike a conifer that can photosynthesis year-round, especially during winter months when water is available, poplar only photosynthesizes from April to October, with peak productivity in July and August - the two driest months in Washington State. Due to this seasonality of precipitation and the rain-fed nature of this crop, the crop will experience water stress during the summer months. ***Figure 22*** demonstrates the seasonality of water stress over the establishment period and one average coppice cycle.



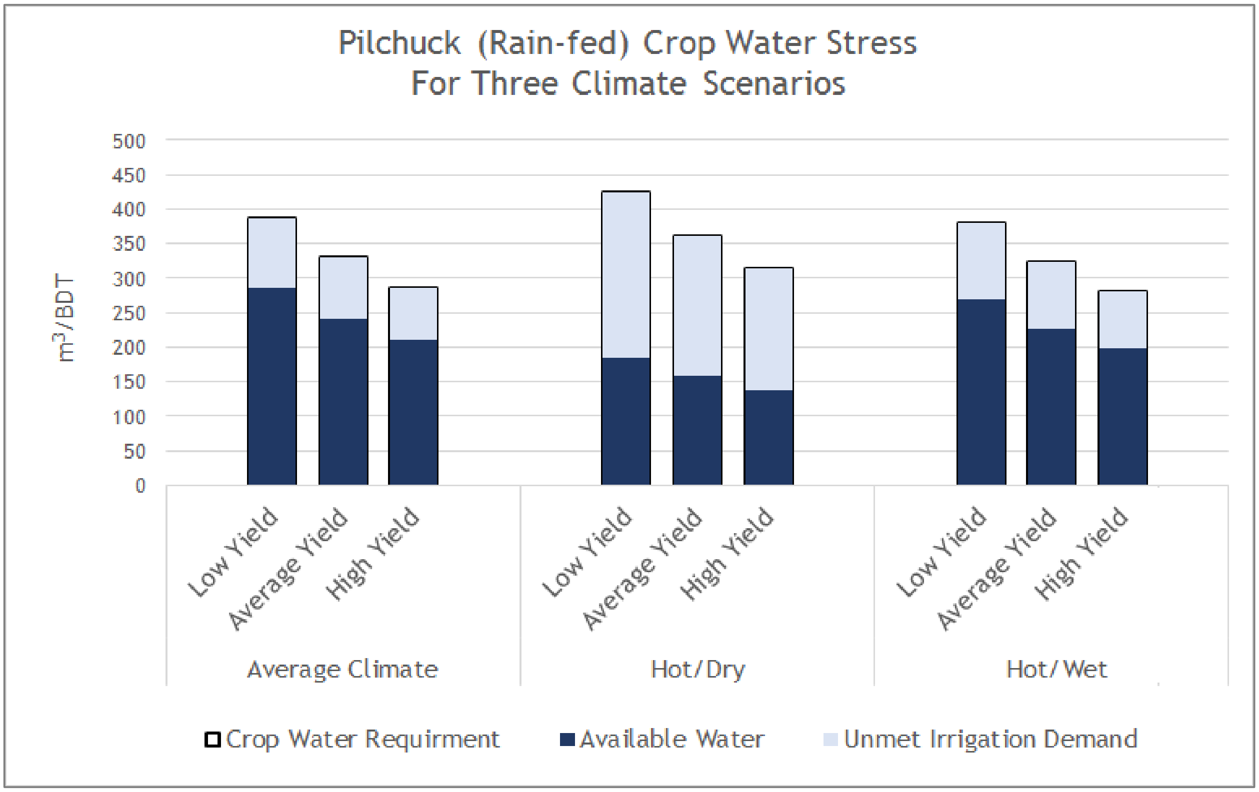


***Figure 21.*** *Crop water stress for Pilchuck under three climate scenarios and three yield scenarios*

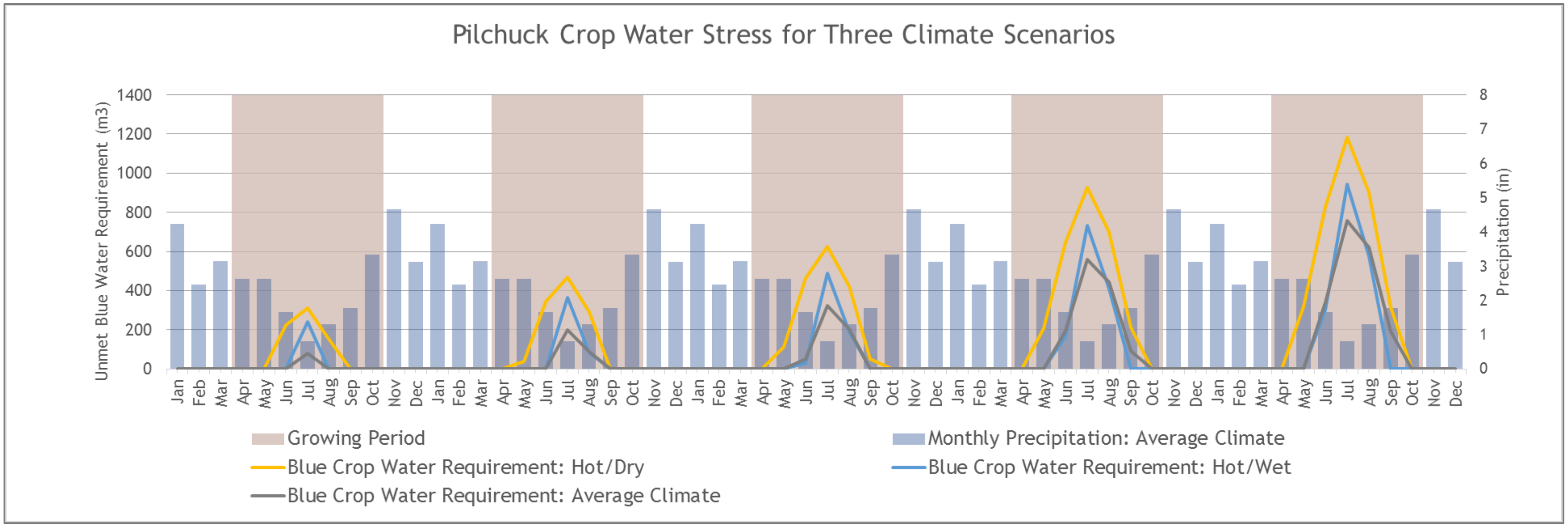


***Figure 22**. Seasonal crop water stress at Pilchuck for three climate scenario*

## Water Availability by Watershed

The availability of data for watershed water budgets varied, and was not sufficient to answer this research question. Some water budget data were available, but periods of record, methodologies, and reported metrics were too varied to accurately assess this research question for multiple sites and have the results be comparable. In addition, some WRIAs had performed assessments of existing water users, while others had not. An analysis of water rights in each watershed is detailed in the next section. To accurately assess this question, a full hydrological modeling exercise would need to be conducted for each site and its surrounding watersheds. A brief summary of the findings and status of the data is outlined below.

Two WRIA watersheds are near the Mt Vernon/Pilchuck site. These are WRIA 3 and WRIA 5, the Lower Skagit and the Stillaguamish. Water budget data were not readily available for these WRIAs. A 2009 USGS report for the Lower Skagit (WRIA 3) calculated a water budget of 284,000 acre feet of precipitation, of which 35% is surface runoff, 32% (90,880 acre feet) is evapotranspiration, and 33% is groundwater recharge (Savoca, 2009).

Four WRIAs are near the Spokane/Hayden site. These are WRIA 54-57 (Lower Spokane, Little Spokane, Hangman, and Middle Spokane). Water budget data were only available for WRIA 54, Lower Spokane. This water budget reported an annual precipitation inflow of 333,972 acre feet, and annual evapotranspiration of 923,212 acre feet (Tetra Tech/KCM, 2007). WRIA 54's evapotranspiration is 165% higher than WRIA 3, mainly due to higher temperatures in this region during the summer months. The technical assessment for WRIA 54 has a comprehensive assessment of surface and ground water inflows and outflows, as well as existing water uses. However, none of the other WRIAs in this area had this information available. Detailed information for WRIA 54 can be referenced in Chapter 4 of the technical assessment (Tetra Tech/KCM, 2007). WRIA 56 has a management plan that includes some technical assessment and a survey of existing water rights claims, uses, and USGS withdrawls (WRIA 56, 2005). WRIA 56 reports 738,670 acre feet of annual precipitation, 545,815 acre feet of evapotranspiration, and 33,592 acre feet of infiltration (WRIA 56, 2005). However, the methodologies and metrics differ widely from those reported in WRIA 54, and no watershed modeling was conducted. WRIA 55 and 57 have a joint management plan (WRIA 55 & 57, 2006). This plan mainly assessed groundwater availability using a model, assessed minimum flow requirements for aquatic biota, and reviewed the status of existing water rights (WRIA 55 & 57, 2006). Average flows and precipitation are reported but a full water budget is not available in this plan ((WRIA 55 & 57, 2006).

Approximately 100,000 acres of poplar trees would be required for each biorefinery site. Without a comprehensive, comparable assessment of the water budgets and existing water uses in the watersheds of these sites, it is not possible to compare poplar water use to relative water availability.

## Water Policy Landscape

Previously, a review of the general policy landscape was conducted for five potential biorefinery sites in Washington State by Jacob Lipson (2013). These sites were specific property addresses in Tacoma, Everett, Spokane, Aberdeen, and Centralia. He split policies in four broad categories of *Harvesting*, *Transportation*, *Manufacturing* and *Customer Markets*, then further categorized policies based on the aspect of the supply chain stage each policy affected (Lipson, 2013). For example, within policies affecting the *Manufacturing* of bioethanol, he categorized policies as primarily affecting (a) industrial facility siting, zoning or land-uses (b) hazardous substance and waste disposal (c) water use and quality or (d) air quality (Lipson, 2013). Laws which contained multiple provisions relevant to bioethanol production were identified separately for each provision relevant to the supply chain (Lipson, 2013). His review found 67 policy components that were relevant to the prospective development of bioethanol in Washington State (Lipson, 2013). These policies included a wide range of policies such as the Renewable Fuels Standard (federal and state), Washington State Forest Practices Act, Biomass Crop Assistance Program, Washington State Noise Control Act, the Clean Air Act, Growth Management Act, Washington Water Code, and various tax programs, to name a few.

This review of the water policy landscape is intended to build upon the previous review by Lipson (2013) and to be a broad overview of the most important water policies for a potential biofuels industry, rather than an exhaustive review of all provisions of all statutes which might apply. Since neither site is located in a marine area, marine policies were not included in this assessment.

Agricultural, energy, and industrial policies which would apply to feedstock and conversion, such as renewable fuel subsidies and credits, the Resource Conservation and Recovery Act (RCRA), which governs the disposal of solid waste and hazardous waste, farm bills such as the Agricultural Act of 2014, or land use policies, were not included in this assessment, but could also be limiting factors or affect this industry.

A summary of a few of the key water policies is provided below, split into state and federal policies. The policies are listed in ***Table 5***. This is not an exhaustive list, rather it is meant to highlight some of the key policies that may affect a potential biofuels industry. Only water policies that impact the feedstock and biorefinery stages were included. It is worth noting that local policies, not included here in the absence of actual sites (actual properties and parcel numbers), could also have a large effect on the potential biofuels industry.

***Table 5**. Key state and federal policies potentially relevant to the Washington State biofuels industry*

| Level | Policy | Code |
|---|---|---|
| State | Washington Water Code: Water Rights | *Chapter 90.03 RCW* |
| | Washington Water Code: In-stream Flow Rules | *Chapter 90.54 RCW* |
| | Growth Management Act (GMA) | *Chapter 36.70A RCW* |
| | State Environmental Policy Act (SEPA) | *Chapter 43.21C RCW* |
| Federal | Clean Water Act (CWA) | *33 U.S.C. §1251 et seq. (1972)* |
| | Endangered Species Act (ESA) | *16 U.S.C. §1531 et seq. (1973)* |

## State policies:

### *Washington Water Code: Acquiring water rights*

The Washington Water code may be the most significant roadblock to the potential biofuels industry. The waters of Washington State collectively belong to the public. A **water right** is a legal authorization to use a predefined quantify of public water for a beneficial use (Ecology, Water Rights, n.d.). **Beneficial use** requires reasonable water quantities applied to a non-wasteful use such as domestic water supply, irrigation or industrial production (Ecology, Water Rights, n.d.). Water “use” is the legal term used in most water rights regulations. Often a water right specifies an amount for withdrawal, but the nature of the right’s use could impact the consumptive or non-consumptive nature of that water right, so the legality surrounding consumptive use is a complicated legal process as well. In general, any use of surface or groundwater requires a water permit. Washington State uses a prior appropriation system, commonly called “first in time, first in right,” which establishes a system of senior and junior water rights (Gregoire et al., 2000). Junior water rights cannot impede senior rights, and when water is scarce, senior water rights are served first (Gregoire et al., 2000). Many basins in Washington State are over-allocated, essentially meaning no new water rights are available (Ecology, Water Rights, n.d.).

Water rights regulate blue water, and if the crop is irrigated, and would likely apply to both stages of biofuel production. Acquiring a new water right would be difficult (or impossible) for the watersheds studied in this research, since this water right would likely be a junior right subject to interruption, which is not ideal for biofuel production (Ecology, WRIA 3, 54,55,56,57, 2014). The biorefinery would require a continuous water supply, so cannot have an interruptible water right. Interruptions would likely occur during the summer months in times of scarcity, so this would be a major constraint to an irrigated feedstock as well. Therefore, existing water rights must be purchased and transferred. Water rights are typically associated with *a point of diversion, a place of use, a period of use, and/or nature of use* (Gregoire, et al., 2000). To change or transfer these conditions requires a legal process that evaluates whether the water right is valid, and in what quantity (Washington State has a “use it or lose it” clause), and whether the transfer can injure other (junior) water rights holders (Gregoire, et al., 2000). Therefore, purchasing water rights is often an expensive and difficult legal process. Senior water rights are more much more expensive than junior water rights, as they are much more valuable.

A review of water rights for each site’s WRIAs revealed the following:

- Pilchuck: In WRIA 3, the only new rights available are non-consumptive and interruptible rights. Current flows in the Skagit are not sufficient to meet all existing water rights 100% of the time (Ecology – WRIA 3, 2014).
- Hayden: In WRIA 54-57, Surface Water Source Limitations (SWSL) limit most water sources, and no new rights can be processed until a release is granted from the Bureau of Reclamation (BOR). WRIA 54, 56, and 57 are over-appropriated for both surface and groundwater, which means that any new rights would be interruptible or the impact would need to be fully offset through mitigation, or subject to a variety of other stringent restrictions. WRIA 55 is closed to all new water rights (Ecology – WRIA 54,55,56,57, 2014).

*Washington Water Code: In-stream Flow Rules*

These rules are set by the Washington Department of Ecology and establish minimum flow requirements, and because of their connection to water rights, have a large impact on the potential biofuels industry. An instream flow rule is essentially a water right for the river (Ecology, Instream Flows, n.d.). Once the rule is established, all water uses established after the rule are potentially interruptible (meaning all water rights junior to the instream rule are subject to interruption if the instream flow is not met) (Ecology, Instream Flows, n.d.). In-stream flow rules are typically set to provide adequate aquatic habitat, especially for listed species, such as salmon, under the Endangered Species Act (ESA). In addition, in-stream flow rules help maintain river channel morphology and provide other hydrological and aquatic benefits.

In-stream flow rules regulate blue water, and apply to both stages of biofuel production, because they impact junior water rights. Unless senior water rights are obtained (which are expensive and difficult to obtain), these rules mean that water rights are subject to interruption, which could negatively impact biofuel production, resulting in lost profits.

A review of in-stream flow rules for each site revealed the following:

- Pilchuck: In WRIA 3, the Skagit River has an in-stream flow rule (Ecology – WRIA 3, 2014).
- Hayden: WRIA 55 has an in-stream flow rule, and WRIA 55 and 57 are developing joint plans. There is a proposed rule for the Spokane River (Ecology – WRIA 54,55,56,57, 2014).

*Growth Management Act (GMA)*

The Growth Management Act requires state and local governments to manage Washington's growth by identifying and protecting critical areas and natural resource lands, designating urban growth areas, preparing comprehensive plans and implementing them through capital investments and development regulations (Washington State Department of Commerce, 2012). This regulation impacts blue and grey water indirectly, but in an important way. First, critical areas regulations protect wetlands, aquifer recharge areas, and other natural resources (Washington State Department of Commerce, 2012). Feedstock or biorefinery sites may be limited by the proximity of these areas to potential sites. Zoning regulations under the GMA could also affect feedstock or biorefinery siting, if potential sites are within the GMA zone. This means that agricultural lands can only be sited in agricultural zones, and the biorefinery could only be sited in an industrial zone area. Finding an industrial area that is connected to municipal utility lines, which could provide consistent and cost effective water supply, would be ideal for biofuel production, but may have other limits in terms of air quality ordinances, local land use policies, or cost. Zoning may also impact the ability to procure a water right in the right location, for example a potential water right could be available in an area where feedstock or biorefining cannot occur under the GMA. For example, in Spokane, a property located within the city limits and urban growth boundary that is zones for light industrial use could still be adjacent to fish and wildlife habitat, and may require additional review (Lipson, 2013). A careful review of zoning restrictions, development permit requirements and other provisions of the GMA would need to be conducted prior to siting feedstock acreage or a biorefinery.

### *State Environmental Policy Act (SEPA)*

SEPA provides the framework for agencies to consider the environmental consequences of a proposal before taking action. It also gives agencies the ability to condition or deny a proposal due to identified likely significant adverse impacts. Environmental review is required for any proposal which involves a government "action," as defined in the SEPA Rules (WAC 197-11-704), and is not categorically exempt (WAC 197-11-800 through 890), so could potentially apply to a biorefinery depending on the specifics of the biorefinery. This act regulates blue and grey water, as it deals with adverse environmental impacts. The SEPA process sometimes requires preparation of an Environmental Impact Statement (EIS), which can be costly and time consuming. If the EIS is not approved, revisions prior to approval could delay production timelines and cause lost profits.

## *Federal Policies:*

### *Clean Water Act (CWA)*

The Clean Water Act establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters (EPA, 2015). It applies to both stages of production, with Total Maximum Daily Loads (TMDLs) for 303(d) listed water bodies impacting feedstock production and the biorefinery, and National Pollutant Discharge Elimination System (NPDES) permits potentially required for stormwater and wastewater at the biorefinery (EPA, 2015a). The CWA regulates blue and grey water. The combination of permit fees, wastewater treatment, stormwater treatment, pollution prevention plans, and implementing agricultural and industrial best management practices or installing new technology could potentially result in high costs for the biofuels industry. In addition, Washington State water quality regulations are often more stringent than the federal CWA. Overall the CWA could have a large impact on the potential biofuels industry.

### *Endangered Species Act (ESA)*

The Endangered Species Act (ESA) provides a program for the conservation of threatened and endangered plants and animals and the habitats in which they are found (EPA, 2015b). The Fish and Wildlife Service (FWS) keeps a list of endangered species, such as birds, insects, fish, reptiles, mammals, and plants (EPA, 2015b). The law requires federal agencies, in consultation with the U.S. Fish and Wildlife Service and/or the NOAA Fisheries Service, to make sure that actions they authorize, fund, or carry out are not likely to “jeopardize the continued existence of any listed species or result in the destruction or adverse modification of designated critical habitat of such species” (EPA, 2015b, webpage1). The law also prohibits any action that causes a "taking" of any listed species of endangered fish or wildlife, which includes actions such as harassing, harming, hunting, collecting etc. (EPA, 2015b). Washington State has 39 listed animal species and 11 listed plant species (FWS, 2015). Of particular relevance, due to their threatened or endangered status, cultural and tribal importance, and general popularity, are the Chinook and Chum salmon and steelhead listed for Puget Sound and the Columbia River (FWS, 2015). Agricultural run-off is one water quality pollutant that negatively impacts these fish species, so a review of the ESA would be useful when looking at specific sites. If feedstock or biorefinery production results in a “taking” of these species or jeopardizes their existence or critical habitat, then this could potentially present a large and costly obstacle to biorefinery production, especially if the courts become involved after the production process has begun.

# Discussion and Conclusion

## Research Limitations

There are a number of limitations to the water footprint methodology in general. One key critique is that in an effort to create simple, clear indicators, too much detail and scientific rigor have been discarded, especially when compared to more rigorous measures of hydrological impact (Stirzaker et al. 2010; Perry 2014). Any action that reduces water consumption may simply shift the impact to another category, such as ecological degradation, increased carbon emission, or higher energy use.

Water consumption indicators are therefore most effective when combined with other indicators and regionalized to the hydrological context. These can include land use indicators, watershed hydrology, or political and economic context. In LCAs, characterization factors and a treatment of baseline versus counterfactual scenarios in order to give a more accurate assessment of changes in water resource allocation and impacts to a specific region (Pfister et al 2009; Ridoutt and Pfister 2010b).

In addition, while these indicators are often coupled with a larger life cycle assessment or economic/cost-benefit analysis, these indicators generally offer no insight into environmental justice, distributive effects, or a host of other considerations that inform their applicability.

In addition to these general concerns regarding water footprint indicators, the following specific limitations apply to this research:

### Data limitations

Crop yield and management data were obtained from Greenwood Resources hybrid poplar demonstration plots. However, pesticide/herbicide use varies year to year based on conditions and the characteristics of the plantation. Once a plantation is scaled up to production levels, crop yield and management practices could vary from the initial results of the demonstration plantings. In addition, yield numbers were approximated from establishment growth, and actual coppice yields are not yet available.

Twenty and thirty year period of records were available for the weather stations used in this research, however, a longer period of record would be ideal. In addition, the solar radiation data were modeled, not measured.

### Methodology limitations

The water footprint considers evapotranspiration (ET) and available precipitation, but does not include important factors such as groundwater table, soil characteristics, or soil water balance, all of which can affect plant water consumption.

In addition, different equations to calculate ET lead to different results, with some equations over or under-estimating ET. The Penman-Monteith equation tends to over-estimate ET, because it assumes ideal conditions and no water scarcity. The water footprint combines this ET output with effective precipitation. The literature shows that the effective rainfall methods significantly underestimate the annual ET in all cases, as they do not adequately account for the depletion of stored soil water during the summer (Hess, 2010). Therefore, the degree to which this methodology over or under-estimates actual ET in a given location is unknown.

In addition, many important components were excluded from the system boundary, such as indirect water consumption from land use change, transportation, equipment, and ancillary chemicals.

Process wastewater (grey water) was excluded from the conversion process calculations due to a lack of data. However, this is a critical component that dictates how much additional process water is required, what type of wastewater technology is to be used, and what conditions a wastewater permit might need to comply with.

### Limitations on applicability of results

The water footprint provides a volumetric result of water consumption. Environmental effects such as eutrophication, acidification, or land use change were not included, but could be important or limiting factors.

In addition, due to variation in climate and methodologies, this metric is hard to compare to existing research.

## Application of Findings to Washington's Potential Biofuels Industry

Water consumption is often discussed in general terms. However, the kind of water consumed matters, which is why water was split into the categories of green (precipitation), blue (irrigation/process water) and grey (amount of water required to dilute wastewater to legal standards). For the potential biofuels industry, each type of water is consumed in different quantities for different stages of the production process. If the feedstock is irrigated or rain-fed, the composition of green, blue and grey footprints also changes. Some kinds of water are easier or cheaper to procure, so understanding how much water is consumed, where it is consumed, and what kind of water is consumed is an extremely important consideration for the potential biofuels industry.

Climate change has the potential to shift availability of both precipitation (green water) and surface water consumed for irrigation or conversion (blue water). In addition, while green water is often not directly regulated outside of rainwater harvesting, blue water is heavily regulated, and many legal or economic barriers exist to obtaining it for biofuel production. Climate change also affects water availability in terms of water rights, because if blue water becomes scarcer, as a result of less precipitation, variable precipitation, or a change in precipitation type, then some junior water rights will be interruptible as senior rights holders or instream flow rules receive water first. Such blue water interruption could create crop stress for an irrigated crop, or disrupt the conversion process at the biorefinery, which needs a constant supply of blue water. If the current conditions or the conditions under a climate change scenario lead to blue water acquisition issues for the conversion process, then this may create a significant barrier to the potential biofuels industry. Feedstock siting, crop management, and crop yields become irrelevant considerations if the biorefinery cannot operate. Understanding water consumption, water policy, and potential climate change impacts is therefore an important factor in assessing the feasibility of the biofuels industry in Washington State.

### *Water Resource Factors and Industry Viability*

This analysis of water footprints for two sites, one rain-fed and one irrigated, serves to demonstrate which type of water is consumed at each site, and in what quantity.

In terms of specific comparisons of water consumption footprints, for average yield and average climate scenarios, both sites have a similar green water footprints in terms of volume. However, the proportion of footprints is very different. For the Pilchuck site, for the water footprint of bioethanol in $L_{H20}/L_{ethanol}$, the ratio of the green water footprint to the blue water footprint is 85:1, so this site consumes almost entirely green water. The Hayden site, in contrast, is 1:2 green to blue water, essentially consuming half as much green water as blue water (***Figure 23)***. When each site is compared to each other, the Hayden site consumes more than 200 times more blue water than Pilchuck, which consumes barely any blue water at all (***Figure 24)***. In terms of overall footprints, both sites' footprints are comprised of about 20% grey water, though the Hayden site consumes three times as much grey water as Pilchuck because it uses approximately three time more water overall.

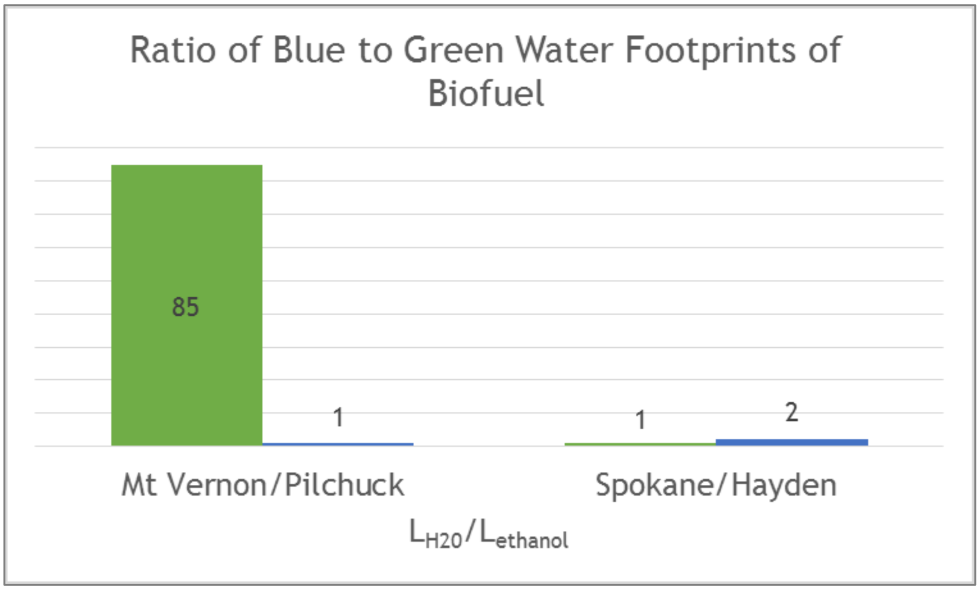


***Figure 23***. *Ratio of green and blue water footprints*

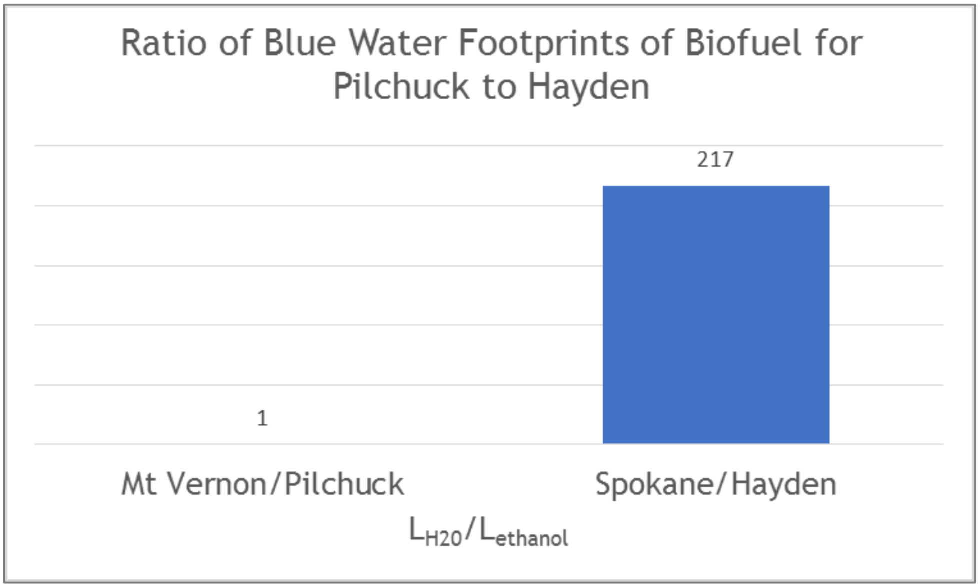


*Figure 24. Ratio of blue water footprints of biofuel between two sites*

Feedstock sites that maximize green water consumption (precipitation) and minimize blue water consumption (irrigation) are ideal in terms of water footprints. Feedstock sites that minimize pollutant effects through small grey water footprints could potentially have less effect on the environment, so sites that require fewer pesticide, herbicide, or fertilizer (if the crop required fertilization – currently it does not) applications would be more favorable.

The conversion process consumes an extremely small amount of water compared to feedstock production. However, this water is 100% blue water, and must be supplied continuously. When combined with zoning restrictions and water rights, such water may be difficult or expensive to procure. If senior water rights are not economically feasible, then a biorefinery that is connected to a public water supply system would be necessary. The biorefinery could also be co-sited with an existing facility with an existing water right, since changing the allocation of water to two beneficial uses instead of one would be an easier legal and possibly less expensive process than purchasing a new water right and changing its place of use, type of use, or other aspects of the water right. Another alternative is to site the biorefinery somewhere with a seasonal water right and obtain the necessary permits to store water on-site.

### ***Climate Change and Industry Viability***

The climate change scenarios were run because this production process deals with economies of scale. Due to the high capital investment required, a production facility and its associated feedstock acreage will only be profitable after a certain period of time. If climate change alters water resource availability in a way that negatively affects the ability to grow feedstock (either due to unfavorable temperatures or an increased need for irrigation (blue) water), or negatively impacts the ability acquire a constant supply of conversion process water, then these constraints must be taken into account before a biorefinery is constructed.

The results of the climate change scenarios indicate that if climate change creates increased temperatures and increased precipitation (hot/wet), then this may create a more beneficial climate for hybrid poplar. As long as the temperatures remain within the crop's ideal temperature range, so as not to negatively impact crop yields, then higher temperatures and more precipitation may lead to higher crop yields and a lower water footprint. However, if increased temperatures results in too many days above the crop's ideal temperature range (60-85 degrees F), then the crop will experience heat stress, which could decrease crop yields and result in a larger water footprint. Such a scenario is more likely in Hayden, where the Spokane weather station had an average of 42 days per year above 85 degrees than at Pilchuck, where the Mt Vernon weather station had an average of 2 days per year above 85 degrees. Pilchuck's hot/dry scenario had 6 days above 85 degrees, and the hot/wet scenario had 4 days above 85 degrees. In comparison, Hayden's hot/dry scenario had 61 days above 85 degrees and 46 days above 85 degrees in the hot/wet scenario. An analysis of crop yield variation under these climate change scenarios, and that includes minimum and maximum production temperatures in the analysis, would be an interesting area for future research.

In addition to climate change impacts on green water availability (precipitation) or irrigation demand (blue water) for the feedstock, climate change could affect the bigger picture. For example, if climate change shifts the hydrological cycle in a way that also decreases stream flow, then climate change can impact the availability of water. Water availability changes how water rights are served. Specifically, if not enough water is available to satisfy all existing water rights (as is already common), then senior water rights will be served first, and junior water rights could go unmet in dry years. Such a situation could create crop water stress, or disrupt the conversion process at the biorefinery if a constant supply of water is unavailable.

### *Complexity of Water Policy Landscape*

A survey of major water policies shows that almost all policies constrain the industry in some way. The major constraint for water availability is the Washington water code and its system of water rights. Senior water rights are extremely expensive, and could be cost prohibitive. Some tools exist to procure less expensive but more junior water rights, such as seasonal rights or water storage, but because the conversion process requires a constant supply of water for operations, such rights present risks to the production process. In addition, if blue water is unavailable legally for the conversion process, then it becomes less important if green or blue water is available for feedstock production.

There are no loopholes in water policy for the biofuels industry the way there are for the oil and gas industry. For example, hydraulic fracking operations are not required to comply with the Safe Drinking Water Act, despite the common process of injecting process wastewater into underground wells. While this research does not advocate for regulatory loopholes in regulations designed to prevent environmental and human harm, it is worth noting that renewable fuel and energy policies do not have corresponding water policies, and often serve as roadblocks to one another. Water policies are just one category of policy that could potentially affect the biofuels industry. The overall policy landscape is complex, and the objectives of water policies often competes with not only the objectives of renewable fuel policies, but also land use, air quality, and other policies. A simplistic representation of the various policies and a few of their general objectives is below in ***Figure 25***. All of these competing policies could affect the potential biofuels industry. These competing objectives must be balanced and navigated in order for a biofuels industry to be successful.

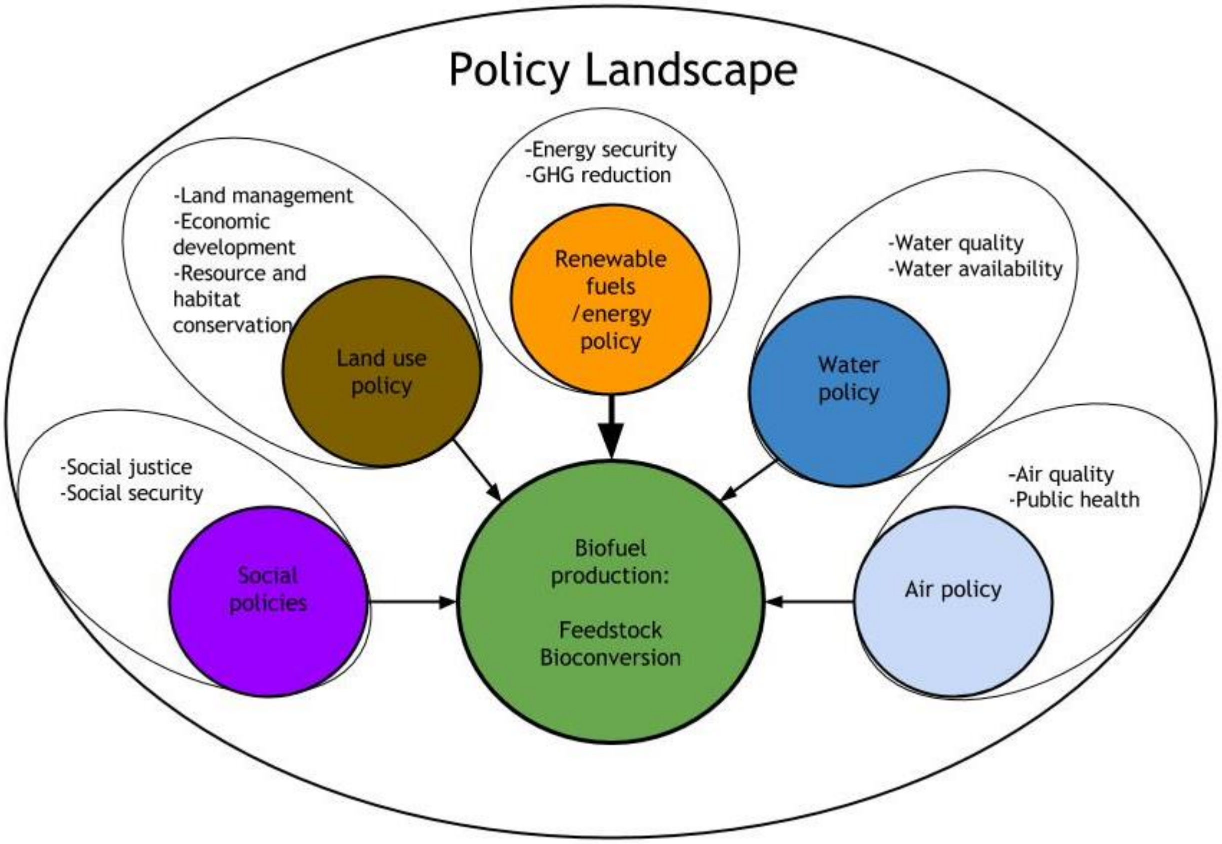


***Figure 25***. *Variety of policies and policy objectives affecting biofuel production*

## ***Approaches for overcoming water policy challenges***

There are a number of approaches which can be used to navigate the water policy arena.

The first relevant water policy tools are the permits required under the policies reviewed. These tools provide a means to comply with the regulations. These include development and construction permits, NPDES permits, TMDL best management practices, though this is not an exhaustive list.

The second set of approaches are a variety of actions can be used to navigate Washington water code. These are listed and explained below:

- Do not obtain a water right, instead connect to a local public water supply system.
- Develop a rainwater catchment system, retention pond, or obtain a trucked water supply to serve domestic or commercial needs.

- Acquire and transfer a senior water right within the same basin as the proposed project (subject to transfer review as mentioned above).
- Acquire a seasonal right (winter) combined with storage to deal with interrupted flows (storage would need to be large, and permitted).
- Use reclaimed water, which is water that has been reclaimed from municipal wastewater or sewage (DOH, 1997). Different standards of treatment exist for reclaimed water, from Class A to Class D (DOH, 1997). For the conversion process, class A water would likely be required, which may be more difficult/expensive to obtain as not all facilities treat their reclaimed water to this standard. However, for an irrigated non-food feedstock crop such as hybrid poplar, class D reclaimed water can be applied to the crop (DOH, 1997). Reclaimed water does not have a water right, and can be bought and sold similar to how water is purchased from a local public water system. There is a reclaimed water facility near Arlington, WA, near the Pilchuck site. There are two facilities near Spokane, WA, near the Hayden site. A map of these facilities is provided in ***Appendix B - Figure 4***.
- Water markets are a general term for ways to acquire and distribute water (Ecology, 2010). There are some water exchanges that are approved under new rule-making, such as the Yakima River Basin Water Exchange (Ecology, 2010). However there are no water exchanges in the basins for Pilchuck or Hayden. Ecology has three programs that fall under water markets, most of which are designed for environmental benefit rather than agriculture or industrial production:
    1. Trust Water Rights Program – used to hold the water in trust for some future use, without losing the water right. This can be used for environmental (instream) and human (out of stream) uses, either temporarily or permanently (Ecology, 2010).
    2. Water Banking – used to provide water for mitigation in order to facilitate new water rights (Ecology, 2010).
    3. Water Acquisition – a voluntary program to increase stream flows in 16 watersheds with vulnerable salmon populations (Ecology 2010).

## Areas for Future Research

Many areas for future research exist. These are outlined below.

- The University of California at Davis has a model for hybrid poplar yields (3PG model) which could model crop yields for each location. While slightly different data inputs and calculations are used, it would be interesting to select the same baseline climate scenario as well as the climate change scenario years, and see if the model predicts different yields. These yields could then be included in the footprint calculation to provide a more dynamic assessment of the impact of climate scenario on the water footprint.
- In order to provide a comparison to other potential biofuel crops, the water footprint could be calculated for other crops, such as wheat straw, to provide an accurate comparison of water consumption for the same climate, the same

temporal and spatial scale, and using the same parameters and methodology. Such a comparison would help decisions regarding which crops to use and in which locations in order to minimize environmental impact, maximize economic efficiency, or other relevant considerations.

- A characterization of the conversion process water is needed for different wastewater treatment scenarios. A grey water footprint needs to be calculated for the conversion process wastewater to provide a more comprehensive footprint for the entire production process.
- Hydrological modeling could be conducted to survey the relative water availability in a potential site's watershed.
- A full legal review of regional water rights could be conducted, including a more in depth analysis of each WRIA. Such a review would be extremely time consuming, but could identify the claimed volumes of water within a basin. However, unless a basin has been adjudicated, this would be an extremely difficult task.
- An economic review of land availability for crop production, as well as the effects of land use change for converting acreage to bioenergy crops, and the effect of land use policy on the biofuel industry would all be interesting areas for future research. Local land use policy varies greatly, and could affect the ability to site bioenergy crops in otherwise ideal locations. Land use and land use policy may be the limiting factor, rather than water consumption, so this is a topic that deserves more research.

## Conclusion

Bioenergy from hybrid poplar with an acetogen conversion pathway uses less water than most other biofuel crops and conversion processes in the literature, but due to the range of methodologies and climates evaluated, it is difficult to accurately compare water consumption between studies. Standardization of these methodologies would be a beneficial improvement to creating more accurate measures and indicators to easily compare biofuel crops and processes in order to evaluate potential trade-offs. The biofuels industry does require large volumes of water, but certain crops, conversion processes, and site selection could use water more efficiently from both a technical standpoint and a legal one. Biofuels from hybrid poplar consume less water than biofuels from corn, for example, and the acetogen pathway uses water more efficiently than other pathways such as the ethanologen pathway. In addition, siting biofuel crops in areas that are water rich, such as west of the Cascades, or east of the 100th meridian in the United States, could be a potential option to increase the feasibility of this industry.

Overall, biofuels outperform fossil fuels across a range of factors, most importantly, they are renewable and they are carbon neutral. However, these are not the only two environmental factors, or the only two factors, which are important to the potential viability of the biofuels industry. The full range of trade-offs needs to be evaluated in order to fully assess the viability of this potential industry. Besides other factors such as economics and technical feasibility, water consumption in biofuel production is an important, though often ignored, factor. Whether there is water available for biofuel consumption, from a physical or policy standpoint, is a question that is seldom asked. In addition, climate change could potentially shift water availability, in terms of seasonal availability and volume, as well as exacerbate legal water scarcity in terms of water rights. Climate change can also affect where biofuel crops such as hybrid poplar can grow, and how productive those crops can be, and whether a crop that is currently rainfed might require irrigation in the future.

Lastly, governments such as the United States and Washington State are encouraging renewable fuel development, like biofuels, through renewable fuel standards, subsidies, and other clean energy policies. However, none of these policies align with water policies, and often, they conflict. In order to make this industry possible, the biofuels industry will need to work within the existing water policy framework, which in most cases for Washington State, will constrain the industry and make it more difficult or more expensive to develop. If renewable fuels such as biofuels are a fuel choice that governments want to encourage, then the interconnected nature of water and energy needs to be considered when these policies are made. For example, the hydraulic fracking industry is exempt from the Safe Drinking Water Act, despite injecting wastewater underground. While not advocating for exemptions from regulations critical to protect human health and the environment, it is worth noting that no similar exemptions exist for the biofuels industry. In addition, in the United States, water is primarily owned by the states, meaning that water law varies from state to state. Although states other than Washington State were not evaluated in this research, certain states, especially those in the Eastern United States with riparian water law doctrines, could potentially pose less policy constraints than Western states with prior appropriation doctrines.

# List of Figures and Tables

# Glossary of Terms and Acronyms

## Terms:

**Beneficial use** requires reasonable water quantities applied to a non-wasteful use such as domestic water supply, irrigation or industrial production.

**Bioenergy** is energy derived from any fuel that comes from biomass

**Bioethanol**, or **ethanol** is a liquid fuel derived from the fermentation of biomass. It can be blended with gasoline or used in its pure form.

**Biofuel** is any liquid fuel that contains energy derived from biomass

**Biomass** is any material derived from living or recently living organisms (typically plants).

**Blue water** is water that has been withdrawn from its source, either surface or groundwater, and applied to a use. In this research, it is the amount evaporated (consumed) through irrigation (effective irrigation) and water consumed from groundwater/surface water/municipal water withdrawals as process water.

**Cellulosic biomass** is any biomass derived from cellulose, hemi-cellulose, and/or lignin.

**Evapotranspiration** is the sum of water evaporated from land and plant surfaces and water transpired through the plant.

**Feedstock** is biomass sources for biofuels.

**Green water** is a naturally occurring water resource, such as precipitation. It is not withdrawn, but is consumed during evapotranspiration. In this research, green water is the amount of precipitation available to be evapotranspired by the crop (effective rainfall).

**Grey water** is the volume of water required to dilute pollutants in wastewater to restore it water quality standards. For agricultural products, this generally concerns fertilizers and pesticides and their respective leaching rates. For industrial production, this requires characterization of the waste water effluent.

**Lignocellulosic** biomass always contains lignin. These terms generally refer to non-crop biomass, such as forest residues, trees, and grasses.

**Second generation** or **advanced biofuels** are biofuels from non-food or feed crops, and include cellulosic and lignocellulosic biofuels.

**Water consumption** generally refers to water that is withdrawn, used and no longer available for any other users or uses in the watershed in which it originates.

**Water footprint** is the quantity of water used to produce a good or service. For an agricultural product, it is the volume of water used during the crop growing period.

**Water right** is a legal authorization to use a predefined quantify of public water for a beneficial use.

**Water withdrawal** refers to water that is withdrawn, used, and then still available for other users and uses in that watershed.

**Acronyms:**

Bone dry tons (BDT)

Bureau of Land Management (BLM)

Clean Water Act (CWA)

Endangered Species Act (ESA)

Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)

Greenwood Resources (GWR)

Growth Management Act (GMA)

National Environmental Policy Act (NEPA)

Office of Pesticide Programs (OPP)

Revised Code of Washington (RCW)

U.S. Code (U.S.C)

U.S. Department of Agriculture (USDA)

U.S. Environmental Protection Agency (EPA)

U.S. Fish and Wildlife Service (FWS)

U.S. Forest Service (USFS)

U.S. National Oceanic and Atmospheric Administration (NOAA)

Shoreline Management Act (SMA)

State Environmental Policy Act (SEPA)

Washington Administrative Code (WAC)

Washing State Department of Commerce (DOC)

Washington State Department of Ecology (Ecology)

Washington State Department of Health (DOH)

Wild and Scenic Rivers Act (WSR)

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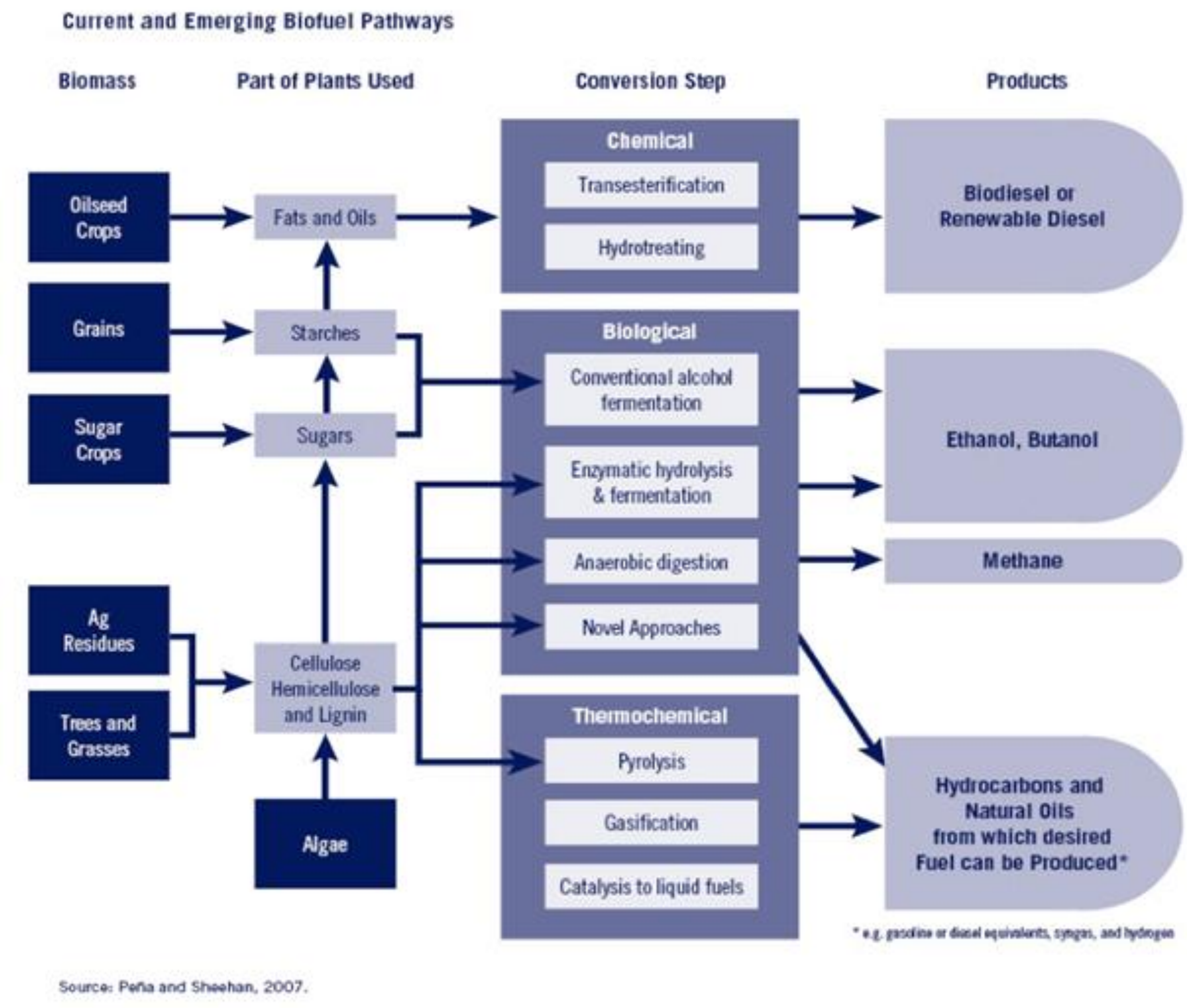
# Appendices

## A: Biofuel Pathways

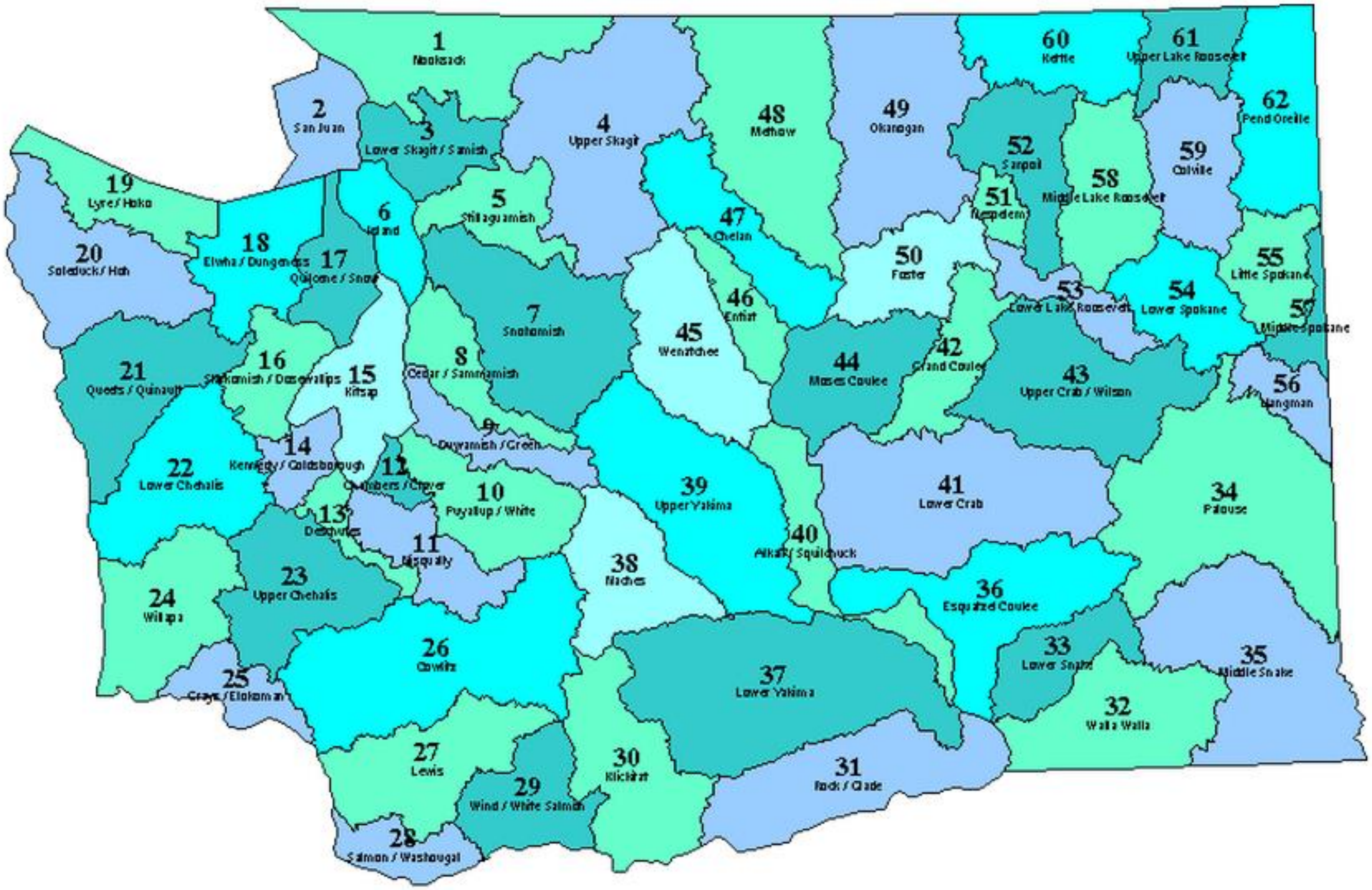

Current and Emerging Biofuel Pathways

* e.g. gasoline or diesel equivalents, syngas, and hydrogen

Source: Peña and Sheehan, 2007.

***Appendix A - Figure 1.*** *Current and emerging biofuel pathways.*

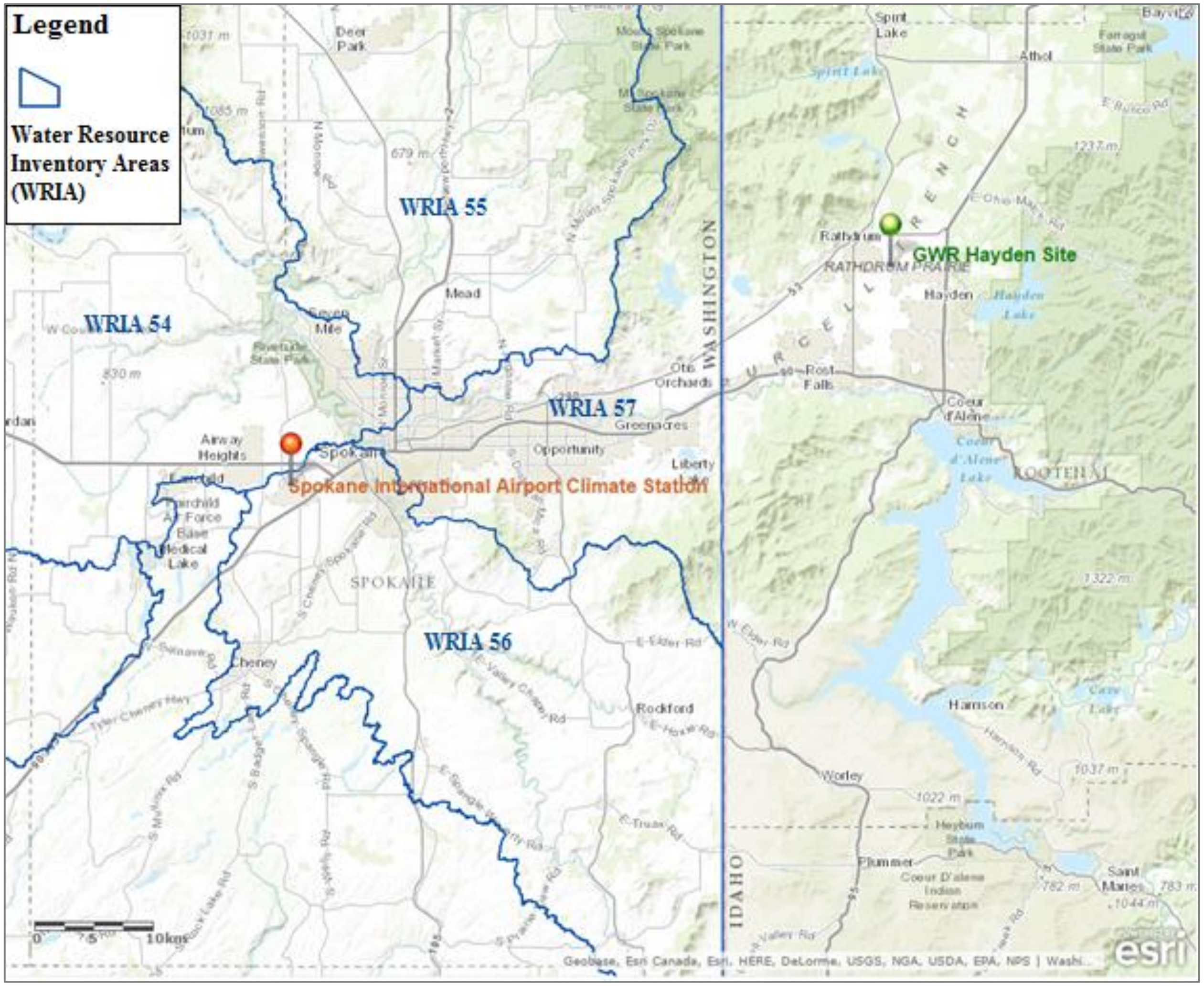
## B: Maps



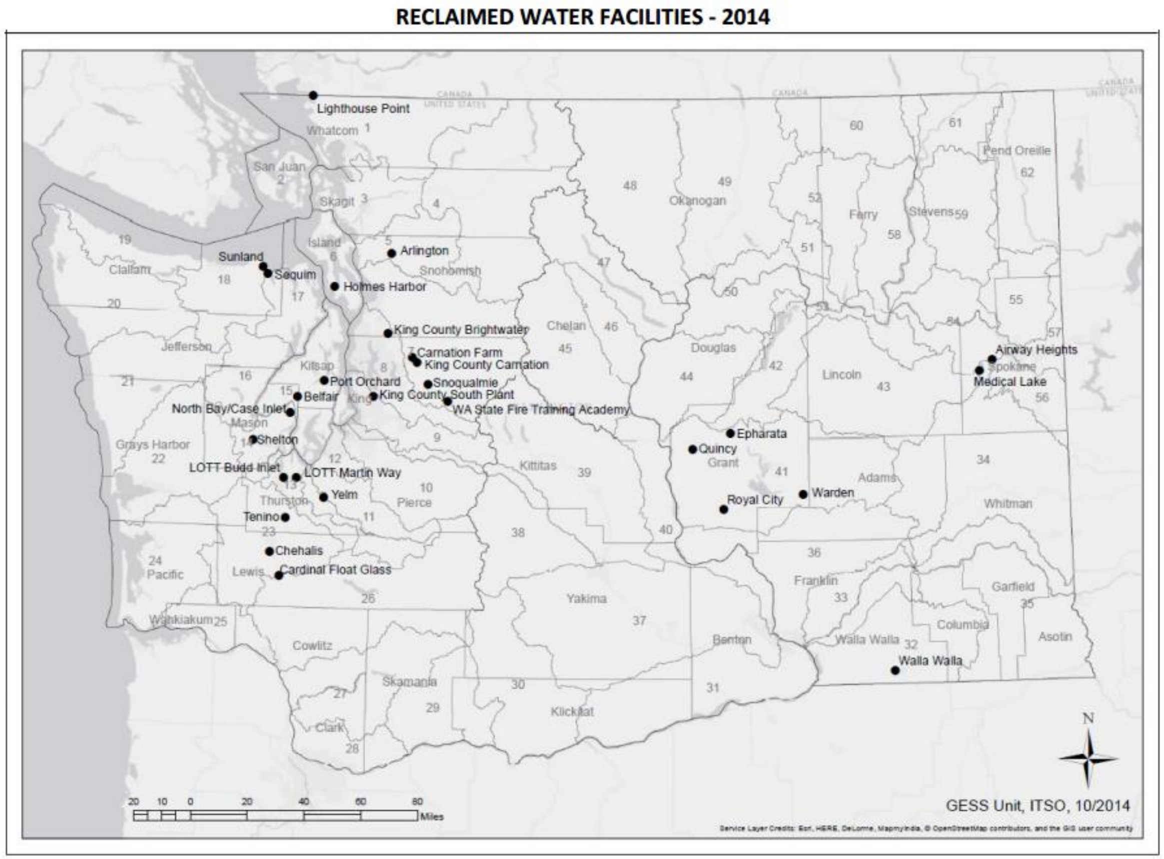
***Appendix B - Figure 1****. WRIA watershed map.*

Retrieved on January 15, 2015 from http://www.ecy.wa.gov/services/gis/maps/wria/wria.htm

***Appendix B - Figure 2.*** *Mt Vernon/Pilchuck Study Area*



*Appendix B - Figure 3.* Spokane/Hayden Study Area



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***Appendix B - Figure 4****. Reclaimed water facilities in Washington State*

# C: Equations

| Terms | |
|---|---|
| WF | Water footprint (m3/BDT) |
| CWU | Crop water use (m3/ha) for the coppice or production stage (establishment 2 yrs, coppice 3 yrs) |
| Y | Crop yield (BDT/ha) |
| CWR | Crop water requirement (mm/month) |
| IR | Irrigation requirement (mm/month) |
| Etc | Evapotranspiration of the crop (mm/month) |
| Etr | Reference evapotranspiration (mm/month) (alfalfa) using ASCE Standardized Penman-Monteith (local climate data used) |
| Kc | Crop coefficient (Gochis et. al) |
| Kc ini | Kc outside of growing season |
| Peff | Effective rainfall/precipitation (mm) |
| $\alpha$ | Leaching run off fraction (%) |
| AR | Chemical application rate to the field (kg/ha) |
| cmax | Maximum acceptable concentration for the pollutant considered (kg/m3) |
| cnat | Natural acceptable concentration for the pollutant considered (kg/m3) |
| Biofuel energy content | Higher heating value (HHV) * density of ethanol |
| ConversionY | Conversion yield |

***Appendix C - Table 1.*** *Terms*

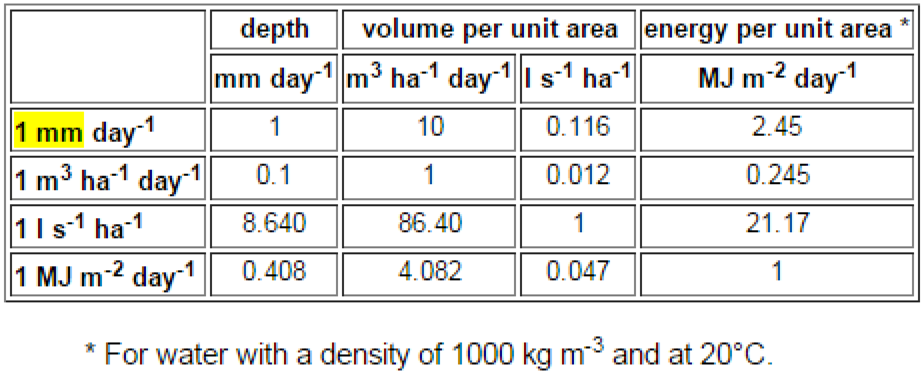
| **Water footprint equations** | | | |
|---|---|---|---|
| WF of crop (m3/BDT) | CWU/Y or [(a*AR)/(cmax-cnat)]/Y | | |
| WF of biofuel (LH20/Lethanol) | Process water (L/L) + Wfcrop/ConversionY | L H20/Lethanol +[ (m3/BDT*1000)/(L h20/L ethanol)] | ***1000 conversion factor m3 to L |
| WF of bioenergy (m3/GJ) | Wfbiofuel/biofuel energy content | (L H20/Lethanol*1000)/(energy content of fuel MJ/L*1000) | ***1000 conversion factor L to m3, MJ to GJ |

***Appendix C - Table 2****. Water footprint equations*

| **Equations** | | | | | | |
|---|---|---|---|---|---|---|
| WF | = | WFgreen | + | Wfblue | + | Wfgrey |
| Wfgren or blue | = | CWU green or blue | / | Y | | |
| Wfgrey | = | [(α*AR) | / | (cmax-cnat)] | / | Y |
| α | = | 10% | (see WF assessment manual for reference) | | | |
| CWUgreen or blue | = | 10 | x | sum of ETgreen/blue over growning period | | *factor of 10 converts ET in mm to m3/ha |
| CWR | = | Etc | under optimal conditions (disease free, optimum soil water conditions achieving full production etc) | | | |
| CWR | = | Kc | × | Etr | mm/month | |
| ETgreen | = | min | (ETc | , | Peff) | |
| ETblue | = | max | (0, | ETc | – | Peff) |
| IR | = | max(0, | CWR | – | Peff). | |
| Peff | = | Precip * .80 | CROPWAT uses a fixed % of 80% | | | |

***Appendix C - Table 3****. Equations*

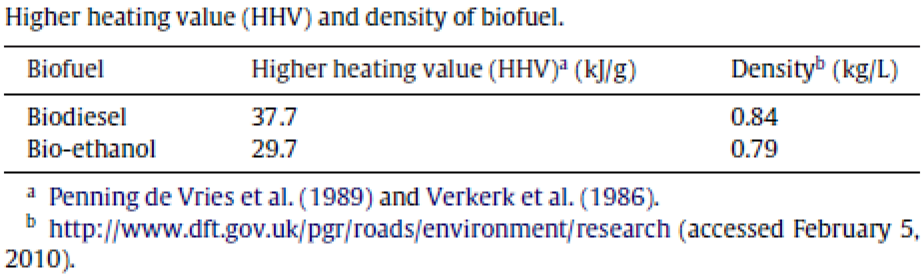
FAO Conversion factors http://www.fao.org/docrep/x0490e/x0490e04.htm (Allen, 1998)



| | depth | volume per unit area | | energy per unit area * |
|---|---|---|---|---|
| | mm day$^{-1}$ | m$^{3}$ ha$^{-1}$ day$^{-1}$ | l s$^{-1}$ ha$^{-1}$ | MJ m$^{-2}$ day$^{-1}$ |
| **1 mm day$^{-1}$** | 1 | 10 | 0.116 | 2.45 |
| **1 m$^{3}$ ha$^{-1}$ day$^{-1}$** | 0.1 | 1 | 0.012 | 0.245 |
| **1 l s$^{-1}$ ha$^{-1}$** | 8.640 | 86.40 | 1 | 21.17 |
| **1 MJ m$^{-2}$ day$^{-1}$** | 0.408 | 4.082 | 0.047 | 1 |

* For water with a density of 1000 kg m$^{-3}$ and at 20°C.

***Appendix C - Table 4****. Conversion factors for evapotranspiration*



Higher heating value (HHV) and density of biofuel.

| Biofuel | Higher heating value (HHV)[a] (kJ/g) | Density[b] (kg/L) |
|---|---|---|
| Biodiesel | 37.7 | 0.84 |
| Bio-ethanol | 29.7 | 0.79 |

[a] Penning de Vries et al. (1989) and Verkerk et al. (1986).
[b] http://www.dft.gov.uk/pgr/roads/environment/research (accessed February 5, 2010).

***Appendix C - Table 5****. Higher heating value and density of biofuel*

## The Standardized ASCE Penman-Monteith Equation(s)

In 2005, the ASCE Technical Committee on Evapotranspiration in Irrigation and Hydrology recommended that two Standardized Reference Evapotranspiration Equations be adopted for general practice along with *standardized* computational procedures. The standardized equations are derived from the ASCE Penman-Monteith (ASCE-PM) equation (Eq. 1-6 of this appendix) as described in ASCE Manual 70 (Jensen et al., 1990), in the ICID Bulletin (Allen et al., 1994), and in the ASCE Hydrology Handbook (1996). The computation of parameters for the reference equations incorporates procedures for calculating net radiation, soil heat flux, vapor pressure deficit, and air density as described in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998). A constant latent heat of vaporization, $\lambda$, equal to 2.45 MJ $kg^{-1}$ is used for simplicity. Albedo for the reference surfaces is fixed at a constant 0.23. The equations assume that measurement heights for air temperature and water vapor content are made at a height in the range of 1.5 to 2.5 m above the ground. The standardized equations require that wind speed, $u_2$, is measured at or is adjusted to a 2 m measurement height. The coefficients in the ASCE standardized reference evapotranspiration equations presume that the weather data are measured over a grassed weather station having a vegetation height of about 0.1 to 0.2 m.

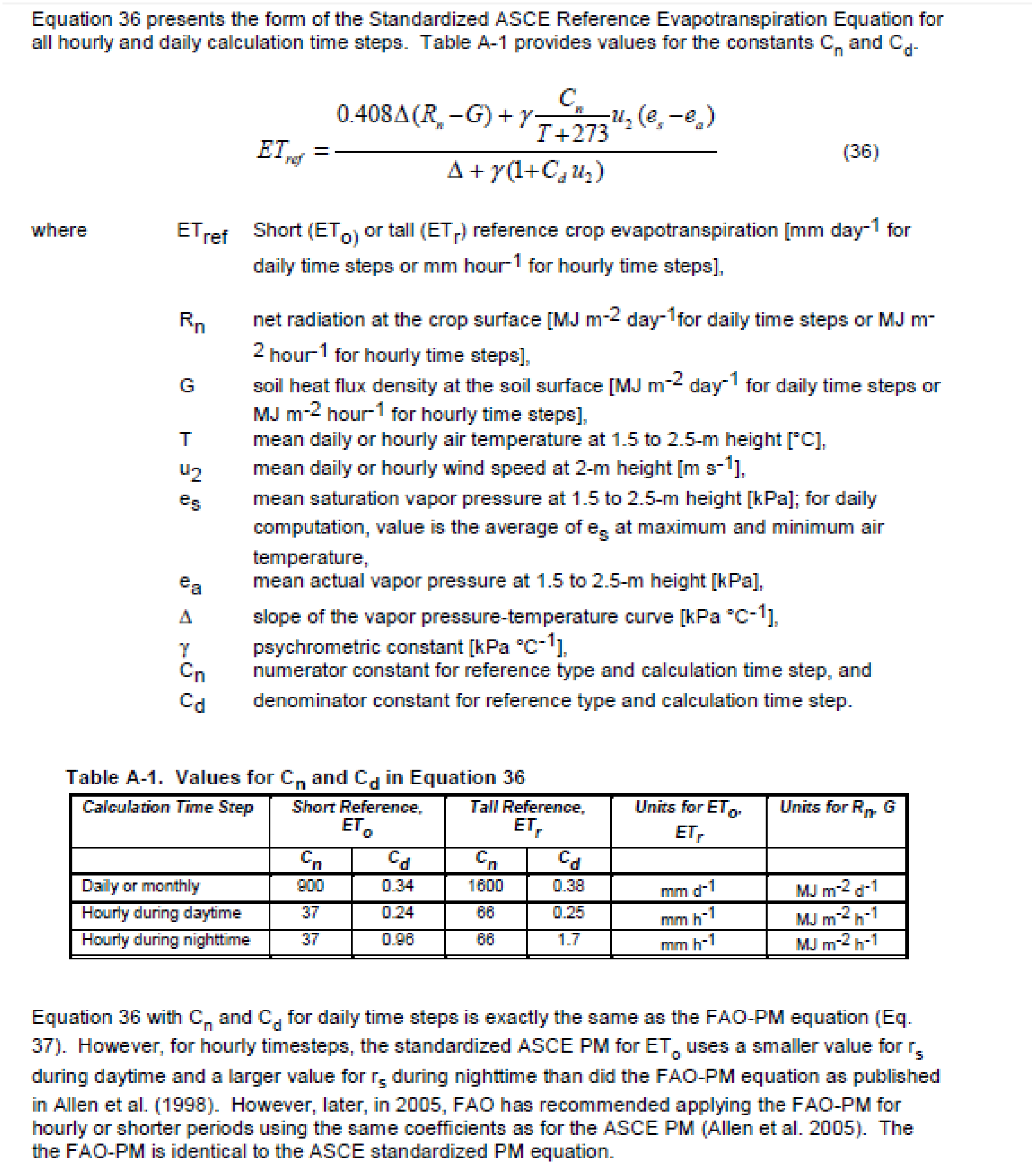
The two standardized reference evapotranspiration (ET) definitions by ASCE (2005) are:

Standardized Reference Evapotranspiration Equation, Short ($ET_o$): Reference ET for a *short* crop having an approximate height of *0.12* m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall ($ET_r$): Reference ET for a *tall* crop having an approximate height of *0.50* m (similar to alfalfa).

Both standardized reference equations were derived from the ASCE-PM equation (Eq. 1) by fixing h = 0.12 m for the short crop ($ET_o$) and h = 0.50 m for the tall crop ($ET_r$). The short crop and tall crop reference equations are traceable to the commonly used terms grass reference and alfalfa reference.

As a part of the standardization, the "full" form of the Penman-Monteith equation and associated equations for calculating aerodynamic and bulk surface resistance have been combined and reduced into a single equation having two constants in the same manner as done for the FAO-PM equation (Smith et al., 1991; Allen et al., 1998). The constants vary as a function of the reference surface ($ET_o$ or $ET_r$) and time step (hourly or daily). This was done to simplify the presentation and application of the methods. The constant in the right-hand side of the numerator ($C_n$) is a function of the time step and aerodynamic resistance (i.e., reference type). The constant in the denominator ($C_d$) is a function of the time step, bulk surface resistance, and aerodynamic resistance (the latter two terms vary with reference type, time step and daytime/nighttime). The $C_d$ constants reflect surface resistance values that are 70, 50, and 200 s $m^{-1}$ for $ET_o$ for 24-hour, hourly daytime, and hourly nighttime periods and that are 45, 30, and 200 s $m^{-1}$ for $ET_r$ for 24-hour, hourly daytime, and hourly nighttime periods.



Equation 36 presents the form of the Standardized ASCE Reference Evapotranspiration Equation for all hourly and daily calculation time steps. Table A-1 provides values for the constants $C_n$ and $C_d$.

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (36)$$

| | | |
|---|---|---|
| where | $ET_{ref}$ | Short ($ET_o$) or tall ($ET_r$) reference crop evapotranspiration [mm $day^{-1}$ for daily time steps or mm $hour^{-1}$ for hourly time steps], |
| | $R_n$ | net radiation at the crop surface [MJ $m^{-2}$ $day^{-1}$for daily time steps or MJ $m^{-2}$ $hour^{-1}$ for hourly time steps], |
| | G | soil heat flux density at the soil surface [MJ $m^{-2}$ $day^{-1}$ for daily time steps or MJ $m^{-2}$ $hour^{-1}$ for hourly time steps], |
| | T | mean daily or hourly air temperature at 1.5 to 2.5-m height [°C], |
| | $u_2$ | mean daily or hourly wind speed at 2-m height [m $s^{-1}$], |
| | $e_s$ | mean saturation vapor pressure at 1.5 to 2.5-m height [kPa]; for daily computation, value is the average of $e_s$ at maximum and minimum air temperature, |
| | $e_a$ | mean actual vapor pressure at 1.5 to 2.5-m height [kPa], |
| | $\Delta$ | slope of the vapor pressure-temperature curve [kPa °$C^{-1}$], |
| | $\gamma$ | psychrometric constant [kPa °$C^{-1}$], |
| | $C_n$ | numerator constant for reference type and calculation time step, and |
| | $C_d$ | denominator constant for reference type and calculation time step. |

**Table A-1. Values for $C_n$ and $C_d$ in Equation 36**

| *Calculation Time Step* | *Short Reference, $ET_o$* | | *Tall Reference, $ET_r$* | | *Units for $ET_o$, $ET_r$* | *Units for $R_n$, G* |
|---|---|---|---|---|---|---|
| | *$C_n$* | *$C_d$* | *$C_n$* | *$C_d$* | | |
| Daily or monthly | 900 | 0.34 | 1600 | 0.38 | mm $d^{-1}$ | MJ $m^{-2}$ $d^{-1}$ |
| Hourly during daytime | 37 | 0.24 | 66 | 0.25 | mm $h^{-1}$ | MJ $m^{-2}$ $h^{-1}$ |
| Hourly during nighttime | 37 | 0.96 | 66 | 1.7 | mm $h^{-1}$ | MJ $m^{-2}$ $h^{-1}$ |

Equation 36 with $C_n$ and $C_d$ for daily time steps is exactly the same as the FAO-PM equation (Eq. 37). However, for hourly timesteps, the standardized ASCE PM for $ET_o$ uses a smaller value for $r_s$ during daytime and a larger value for $r_s$ during nighttime than did the FAO-PM equation as published in Allen et al. (1998). However, later, in 2005, FAO has recommended applying the FAO-PM for hourly or shorter periods using the same coefficients as for the ASCE PM (Allen et al. 2005). The the FAO-PM is identical to the ASCE standardized PM equation.

***Appendix C - Figure 1.*** *The Standardized ASCE Penman-Monteith Equation*

## D: Data Inputs

| Kc | Jan (Kc Ini) | Feb (Kc Ini) | March (Kc Ini) | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EY1 | 0.15 | 0.15 | 0.15 | 0.15 | 0.2 | 0.1775 | 0.195 | 0.21625 | 0.217 | 0.1885 | 0.15 | 0.15 |
| EY2 | 0.15 | 0.15 | 0.15 | 0.225 | 0.2 | 0.26625 | 0.2925 | 0.324375 | 0.3255 | 0.28275 | 0.15 | 0.15 |
| Y1 | 0.15 | 0.15 | 0.15 | 0.3 | 0.3 | 0.355 | 0.39 | 0.4325 | 0.434 | 0.377 | 0.15 | 0.15 |
| Y2 | 0.15 | 0.15 | 0.15 | 0.332 | 0.4 | 0.49 | 0.58 | 0.6525 | 0.654 | 0.6 | 0.15 | 0.15 |
| Y3 | 0.15 | 0.15 | 0.15 | 0.416 | 0.5 | 0.6225 | 0.742 | 0.8175 | 0.798 | 0.567 | 0.15 | 0.15 |

***Appendix D - Table 1****. Monthly poplar crop coefficients for establishment years and coppice years*

Assume 2 years nursery, 2 years establishment, and 6 coppice cycles (so nursery and establishment phases is divided by 6 to get water use for that period/coppice)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1450 trees/acre | 145000 | trees total | | 3,915.00 | trees/ha | | | | | | | |
| Yield (estimated from GWR) | | | 1 acre = .404686 ha | | | | | | | | | |
| **CROP YIELD** | **Low** | **Average** | **High** | **Low** | **Average** | **High** | **Low** | **Average** | **High** | **Low** | **Average** | **High** |
| | **(BDT)/100 acres** | | | **(BDT)/acre** | | | **(BDT)/ha** | | | **(BDT)/ha/month** | | |
| Hayden (establishment) | 289 | 340 | 391 | 2.89 | 3.4 | 3.91 | 7.141339 | 8.401576 | 9.661812 | 0.198371 | 0.233377 | 0.268384 |
| Pilchuck (establishment) | 289 | 340 | 391 | 2.89 | 3.4 | 3.91 | 7.141339 | 8.401576 | 9.661812 | 0.198371 | 0.233377 | 0.268384 |
| Hayden (coppice) | 1623.5 | 1910 | 2196.5 | 16.235 | 19.1 | 21.965 | 40.11752 | 47.19709 | 54.27665 | 1.114376 | 1.31103 | 1.507685 |
| Pilchuck (coppice) | 1623.5 | 1910 | 2196.5 | 16.235 | 19.1 | 21.965 | 40.11752 | 47.19709 | 54.27665 | 1.114376 | 1.31103 | 1.507685 |

***Appendix D - Table 2****. Poplar yield estimates*

| **Grey Water inputs** | EPA | USGS | | | | GWR | | | | literature |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cmax (mg/L | Cnat (mg/L | Cmax kg/m3 | Cnat kg/m3 | Cmax-Cnat Low Cnat kg/m3 | Cmax-Cnat High Cnat kg/m3 | Rate of application (lb/100acre) | Rate of application (lb/acre) | AR: Rate of application (kg/ha) | α |
| N | 10 | 1 | 0.01 | 0.001-0.002 | 0.009 | 0.008 | | | | 0.1 |
| Glyphosate | 0.7 | 0 | 0.0007 | 0 | 0.0007 | | 200 | 2 | 2.241702 | 0.1 |
| Trifluralin | 0.02 | 0 | 0.00002 | 0 | 0.00002 | | 50 | 0.5 | 0.560426 | 0.1 |
| Imidacloprid | 0.05 | 1 | 0.00005 | 0 | 0.00005 | | 12.5 | 0.125 | 0.140106 | 0.1 |
| Coragen/Chlorantraniliprole | 0.05 | 1 | 0.00005 | 0 | 0.00005 | | 9.375 | 0.09375 | 0.10508 | 0.1 |
| Rozol - chlorophacinone | 0.05 | 1 | 0.00005 | 0 | 0.00005 | | 300 | 3 | 3.362553 | 0.1 |

***Appendix D - Table 3.*** *Grey water inputs*

| **Grey water sources** | | | | |
|---|---|---|---|---|
| http://water.epa.gov/drink/contaminants/ | | Natural background concentrations of nutrients in streams and rivers of the conterminous United States. Env Sci Tech (Smith, USGS et al) | | |
| drinking water standards (10mg/L N) | | | | |
| http://pubs.usgs.gov/circ/circ1225/index.html | | | | |
| Trifluralin | WHO drinking water recs | http://www.who.int/water_sanitation_health/dwq/chemicals/trifluralin.pdf | | |

| | | | | |
|---|---|---|---|---|
| imidacloprid and Chlorantraniliprole | NY state | http://pmep.cce.cornell.edu/profiles/insect-mite/fenitrothion-methylpara/imidacloprid/imidac_let_1003.html | http://pmep.cce.cornell.edu/profiles/insect-mite/cadusafos-cyromazine/chlorantraniliprole/chlorantraniliprole_mcl_1112.pdf | general New York State drinking water standard for an “unspecified organic contaminant” (10 NYCRR Part 5, Public Water Systems). |
| 1 milligram / l = | 0.001 kilograms / cubic meter | | | |
| 1 pound / acre = | 1.12085116 | kilograms | / | hectare |
| http://extension.usu.edu/files/publications/publication/NR_RM_05.pdf | | | | |

***Appendix D - Table 4.*** *Grey water sources*

| **Grey Water Data** | | | | | |
|---|---|---|---|---|---|
| Pilchuck | AR (kg/ha) | Portion of field treated | AR weighted (kg/ha) | # of applications/year | Year applied |
| Herbicide - dormant (glyph) | 2.24170232 | 1 | 2.241702 | 1 | EY1 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.25 | 0.560426 | 1 | EY1 |
| Herbicide - dormant (glyph) | 2.24170232 | 1 | 2.241702 | 1 | CY1 |
| Rodenticide - Rozol | 3.362553 | 0.1 | 0.336255 | 1 | CY1 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.25 | 0.560426 | 1 | CY2 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.25 | 0.560426 | 1 | CY3 |
| Rodenticide - Rozol | 3.362553 | 0.1 | 0.336255 | 1 | CY3 |
| Hayden | AR (kg/ha) | Portion of field treated | AR weighted (kg/ha) | # of applications/year | Year applied |
| Herbicide - preemergent (trifluralin) | 0.5604255 | 1 | 0.560426 | 1 | EY0 |
| Herbicide - dormant (glyph) | 2.24170232 | 0.25 | 0.560426 | 1 | EY1 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.75 | 1.681277 | 2 | EY1 |
| Insecticide (imidacloprid) | 0.14010638 | 1 | 0.140106 | 1 | EY1 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.75 | 1.681277 | 2 | EY2 |
| Insecticide (imidacloprid) | 0.14010638 | 1 | 0.140106 | 1 | EY2 |
| Herbicide - dormant (glyph) | 2.24170232 | 1 | 2.241702 | 1 | CY1 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.75 | 1.681277 | 2 | CY1 |
| Herbicide - dormant | 2.24170232 | 0.5 | 1.120851 | 1 | CY2 |
| Herbicide - post emergent (glyph) | 2.24170232 | 0.5 | 1.120851 | 1 | CY2 |
| Insecticide (coragen) | 0.10507978 | 1 | 0.10508 | 2 | CY2 |
| Herbicide - post emergent | 2.24170232 | 0.25 | 0.560426 | 2 | CY3 |
| Insecticide (coragen) | 0.10507978 | 1 | 0.10508 | 2 | CY3 |

***Appendix D - Table 5****. Greywater inputs*

Conversion rate: 536 L water / ethanol (Budsberg 2015).

## E: Data Assumptions

ET calculations:

- *Gochis uses Kimberly Penman and Etr. I am using Etr and PM. Also Kc was calculated using irrigated hybrid poplar in boardman, OR
- Nov-March Kc ini is estimated using bare soil crop coefficients
- Kc Ini estimated to be .15 based on agrimet - Kc at bud break
- Kc for EY1 estimated at 50% of Y1 (approximated because there is no data)
- Kc for EY2 estimated at 75% of Y1 (approximated because there is no data)
- No missing data in average year of the period of record used for ET calculations. For climate scenario years, missing data were averaged from surrounding days (minimal missing data in these years).

Spokane climate data:

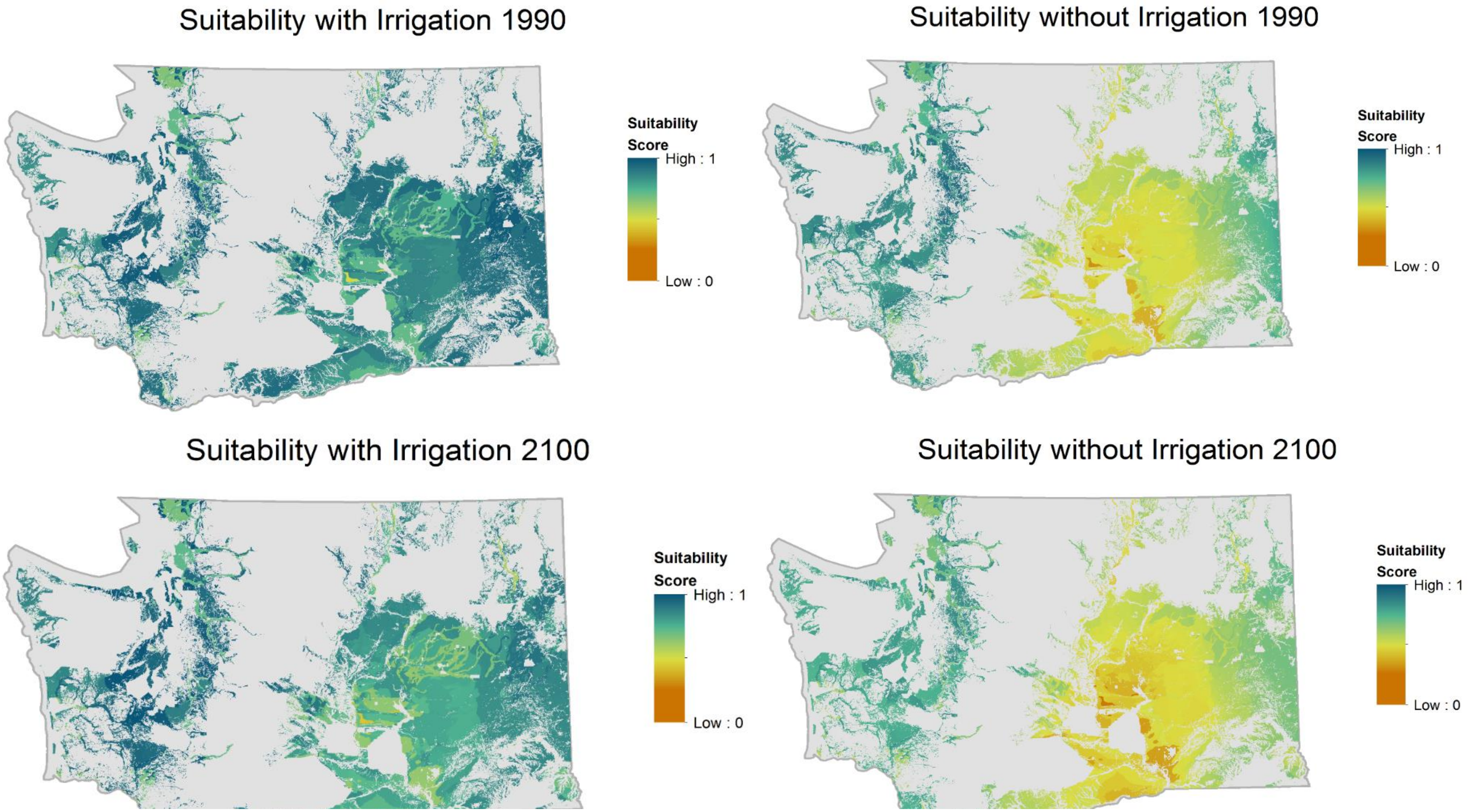
- Airport heights for windspeed (10m, so 2m value calculated and used in ET equations)
- Precipitation data recorded as trace (T) was substituted with 0, assuming that trace amounts add up to trace amounts = 0
- Summed hourly radiation data in Wh/m2 by each day - to get daily radiation in W/m2
- Missing precip data was estimated by averaging the two daily values surrounding it and then the cell highlighted in yellow
- 2010-2013 solar radiation data averaged from Fairfield, Green Bluff, and Agrimet RTHI ID stations
- NCDC data used 1981-2004, then QCLCD data used 2005-2010 for Temp, Precip, Dewp, WS
- NSRBD data used for solar (from 2 data sets 1981-1990, 1991-2010)
- when missing DEWP or WS from QCLCD data used NCDC data
- removed feb 29th - since doesn't have 30 years to average

Mt Vernon climate data:

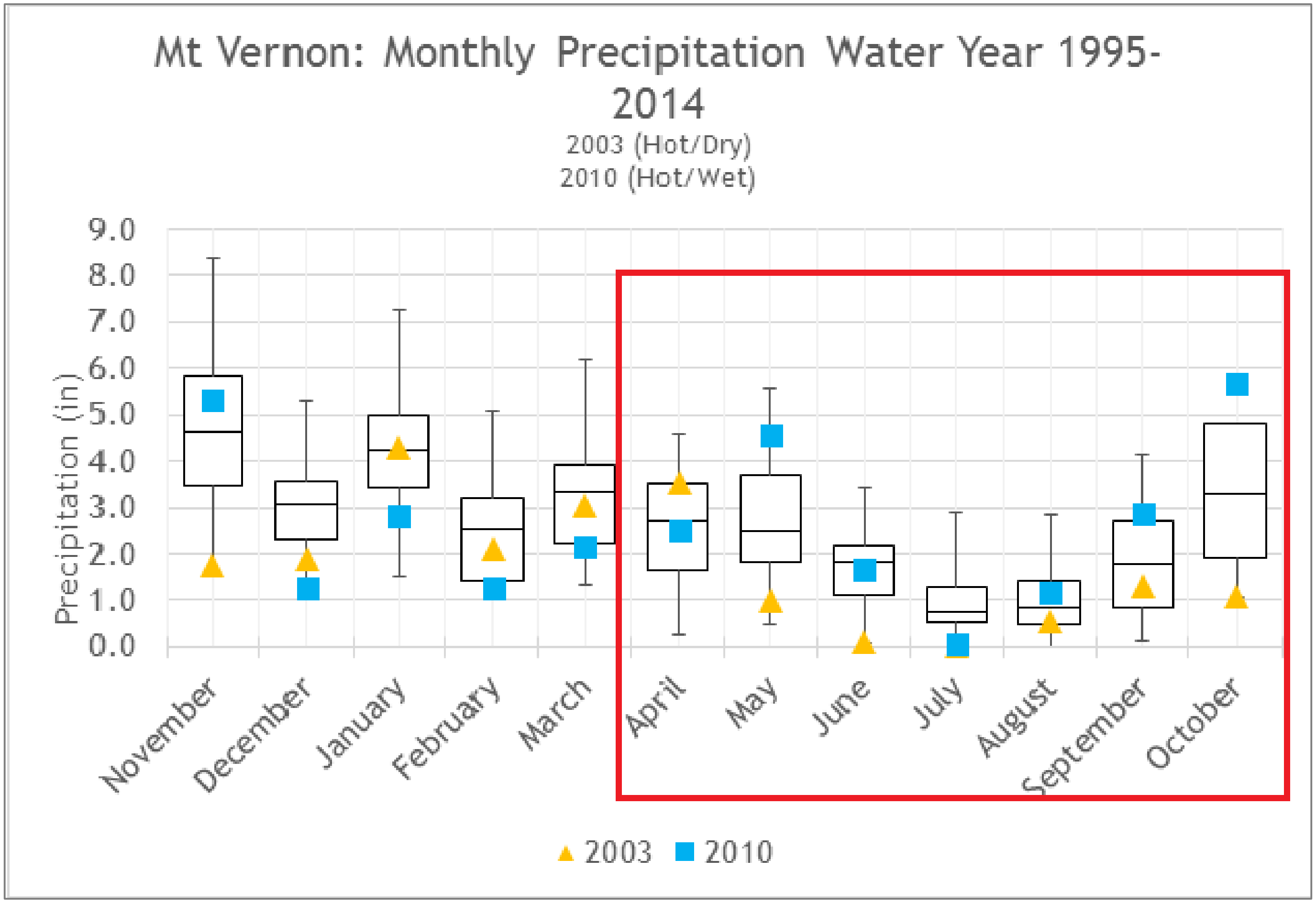
- Agricultural heights for temp and wind speed anemometer (1.8 and 2m).
- All data from WSU
- 1994-2007 data cleaned, 2007+ data already cleaned by WSU
- Daily averages - null values were excluded from averages, null values were in large chunks couldn’t approximate data from surrounding day values so left as null.
- feb 29th was removed

***Appendix E - Table 1.*** *Data Assumptions*

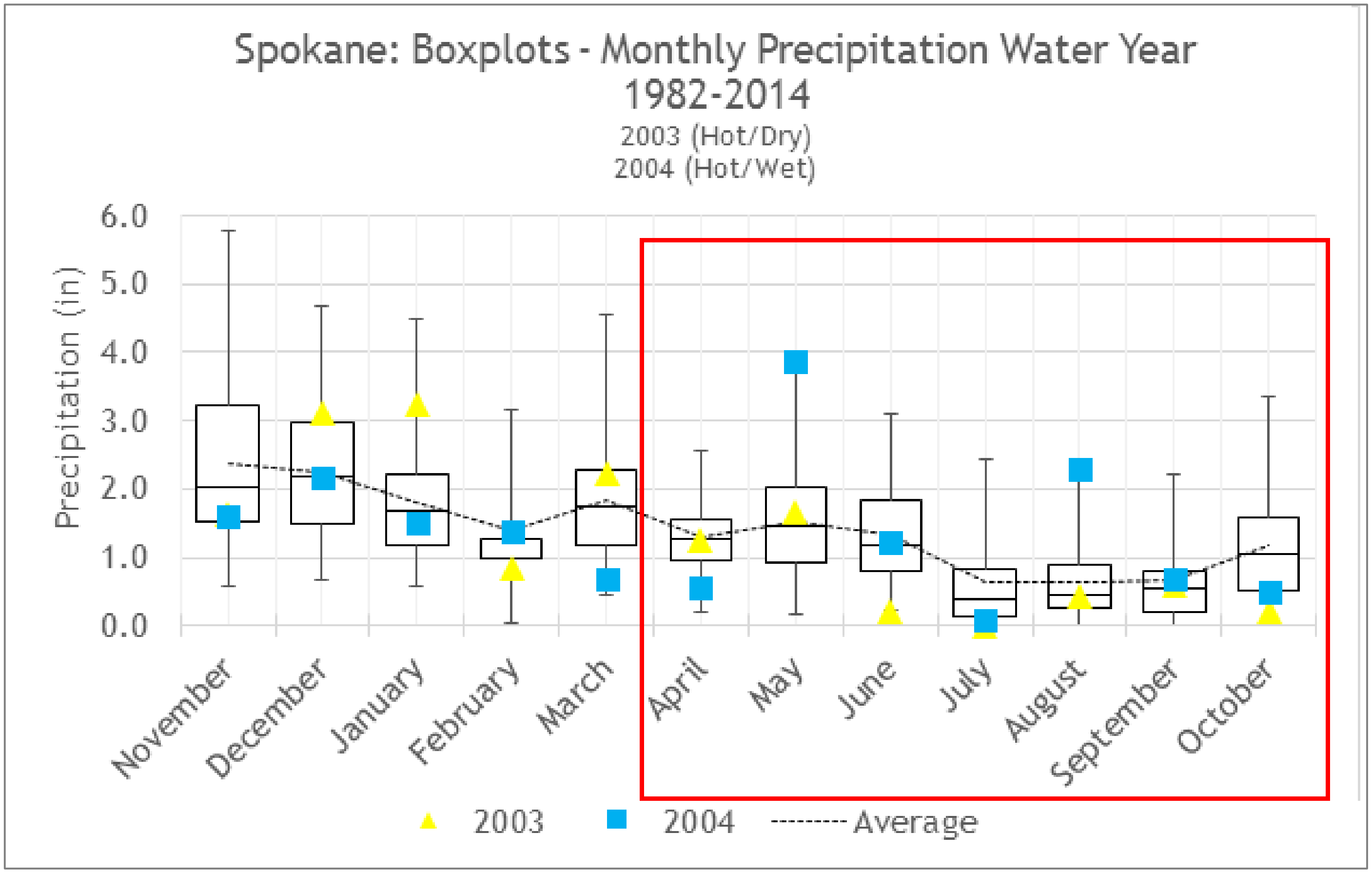
## F: Climate Change Supplemental Materials



***Appendix F - Figure 1****. Poplar Site Suitability with and without irrigation in 1990 compared to 2100 with climate change modeling (Comnick et al., 2014)*



**Appendix F - Figure 2.** *Box plots of monthly average precipitation for Mount Vernon, which were used to select which water year of data would be used for each climate scenario.*



***Appendix F - Figure 3***. *Box plots of monthly average precipitation for Spokane, which were used to select which water year of data would be used for each climate scenario.*

# G: Water Footprint Results

**Table 1.** Water Footprint of Bioethanol Production with Hybrid Poplar

| Site | Climate Scenario | Crop Yield Scenario | WF of Hybrid Poplar ($m^3$/BDT) | WF of Ethanol ($LH_2O/L_{ethanol}$) | WF of Bioenergy ($m^3$/GJ) |
|---|---|---|---|---|---|
| Pilchuck (Biorefinery 1) | Average Climate | Low Crop Yield | 285 | 535 | 23 |
| | | Average Crop Yield | 242 | 350 | 19 |
| | | High Crop Yield | 210 | 396 | 17 |
| | Hot/Dry | Low Crop Yield | 186 | 350 | 15 |
| | | Average Crop Yield | 158 | 298 | 13 |
| | | High Crop Yield | 137 | 260 | 11 |
| | Hot/Wet | Low Crop Yield | 268 | 504 | 21 |
| | | Average Crop Yield | 228 | 429 | 18 |
| | | High Crop Yield | 198 | 374 | 16 |
| Hayden (Biorefinery 2) | Average Climate | Low Crop Yield | 871 | 1629 | 69 |
| | | Average Crop Yield | 741 | 1385 | 59 |
| | | High Crop Yield | 644 | 1205 | 51 |
| | Hot/Dry | Low Crop Yield | 903 | 1689 | 72 |
| | | Average Crop Yield | 768 | 1436 | 61 |
| | | High Crop Yield | 668 | 1250 | 53 |
| | Hot/Wet | Low Crop Yield | 831 | 1554 | 66 |
| | | Average Crop Yield | 706 | 1322 | 56 |
| | | High Crop Yield | 614 | 1150 | 49 |

***Appendix G - Table 1****. Results: Water footprint of bioethanol from hybrid poplar*