**Michigan
Technological
University**

Michigan Technological University
Digital Commons @ Michigan Tech

Dissertations, Master's Theses and Master's Reports

2019

HYDROLOGIC IMPACTS AND TRADE-OFFS ASSOCIATED WITH FOREST-BASED BIOENERGY DEVELOPMENT ACROSS THE AMERICAS

Azad Heidari

Michigan Technological University, azadh@mtu.edu

Copyright 2019 Azad Heidari

Recommended Citation

Heidari, Azad, "HYDROLOGIC IMPACTS AND TRADE-OFFS ASSOCIATED WITH FOREST-BASED BIOENERGY DEVELOPMENT ACROSS THE AMERICAS", Open Access Dissertation, Michigan Technological University, 2019.

<https://doi.org/10.37099/mtu.dc.etr/921>

Follow this and additional works at: <https://digitalcommons.mtu.edu/etr>

Part of the [Civil and Environmental Engineering Commons](#)

HYDROLOGIC IMPACTS AND TRADE-OFFS ASSOCIATED WITH FOREST-
BASED BIOENERGY DEVELOPMENT ACROSS THE AMERICAS

By

Azad Heidari

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Civil Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2019

© 2019 Azad Heidari

This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Civil Engineering.

Department of Civil and Environmental Engineering

Dissertation Co-Advisor: *Dr. Alex Mayer*

Dissertation Co-Advisor: *Dr. David Watkins*

Committee Member: *Dr. Robert Handler*

Committee Member: *Dr. Joseph Wagenbrenner*

Department Chair: *Dr. Audra Morse*

Table of Contents

List of figures.....	vi
List of tables.....	ix
Preface.....	xi
Acknowledgements.....	xii
Abstract.....	xiii
1 Introduction.....	1
1.1 Hybrid poplar cultivation in northern Wisconsin, USA.....	2
1.2 Eucalyptus plantation in Mesopotamia region Entre Rios, Argentina	4
1.3 Oil Palm plantation in Tabasco, Mexico	5
1.4 References	6
2 Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA	12
2.1 Abstract	12
2.2 Introduction	12
2.3 Model setup, calibration and validation	14
2.3.1 Study area.....	14
2.3.2 Model input and setup.....	15
2.3.3 Model calibration and validation	17
2.3.4 Modeling scenarios	18
2.4 Results and discussion.....	19
2.4.1 Model evaluation	19
2.4.2 Impacts of planting density, rotation lengths and fertilizer application	21
2.4.3 Impacts on water use.....	23
2.4.4 Tradeoffs	25
2.5 Conclusions	28
2.6 References	29
3 Spatially variable hydrologic impact and biomass production tradeoffs associated with Eucalyptus cultivation for biofuel production in Entre Rios, Argentina	34
3.1 Abstract	34
3.2 Introduction	34

3.3	Methods	37
3.3.1	Model Setup, Calibration and Validation	37
3.3.2	Modeling Scenarios	40
3.4	Results and Discussion	41
3.4.1	Model evaluation	41
3.4.2	Analysis of watershed-scale impacts	42
3.4.3	Variability in biomass productivity due to spatial variations in soil properties and climate.....	45
3.4.4	Watershed-wide trade-offs between biomass production and water consumption as a result of targeted eucalyptus cultivation	46
3.4.5	Green water footprint.....	50
3.4.6	Discussion of Limitations	50
3.5	Conclusions	52
3.6	Data availability	53
3.7	References	53
4	Hydrologic impacts and trade-offs associated with developing oil palm for bioenergy in Tabasco, Mexico.....	61
4.1	Abstract	61
4.2	Introduction	61
4.3	Materials and methods.....	63
4.3.1	Study site, calibration and validation.....	63
4.3.2	Modeling Scenarios	66
4.4	Results	67
4.4.1	Model performance evaluation.	67
4.4.2	Optimal planting density.....	68
4.4.3	Hydrologic impacts in converted areas.....	69
4.4.4	Watershed-scale impacts from land conversion scenarios.....	74
4.4.5	Green water footprint.....	75
4.5	Discussion	76
4.6	Conclusion.....	76
4.7	References	77
5	Conclusions and Future Work	84
5.1	Hybrid poplar cultivation in northern Wisconsin, USA.....	84
5.2	Eucalyptus plantation in Mesopotamia region Entre Rios, Argentina	85
5.3	Oil Palm plantation in Tabasco, Mexico	86
5.4	Synthesis.....	87

5.5	Recommendations for future work	88
6	Supplementary Materials for Chapter 2	90
6.1	Model Setup Details	90
6.2	Calibration and Validation Details	90
6.3	References	96
7	Supplementary Materials for Chapter 3	97
8	Supplementary Materials for Chapter 4	101
A	Copyright documentation.....	106

List of figures

Figure 2-1: A) Study site location (Spirit Falls) in the state of Wisconsin; B) Land use/land cover map of the Spirit Falls watershed; C) Land cover distribution in the watershed; and D) Test watershed for calibrating plant growth parameters.	15
Figure 2-2: Intra-annual patterns of precipitation, flow and temperature in the Spirit Falls, Wisconsin watershed.	16
Figure 2-3: Measured and simulated discharge during the calibration (1980-1999) and validation (2000-2011) periods.....	20
Figure 2-4: A) Total aboveground biomass production; and B) LAI simulated for the fertilized 83-6Ir treatment compared with measured data (Hanson 1979) for USDA watershed.	20
Figure 2-5: A) Simulated total aboveground biomass production; and B) LAI simulated for the fertilized 83-6Ir treatment for the Spirit Falls watershed.	21
Figure 2-6: Cumulative biomass vs. cumulative fertilizer for irrigated treatments.	22
Figure 2-7: A) Annual ET rates for the converted area to demonstrate interannual impacts of biomass growth and cultivation; and B) Monthly average ET rates to demonstrate seasonal impacts.	23
Figure 2-8: Illustration of how ET changes relate to streamflow changes for non-irrigated and irrigated cases. Refer to text for points A, B and C.	24
Figure 2-9: Cumulative biomass vs. water use at watershed scale, excluding non-fertilization cases. Size of symbol is proportional to magnitude of cumulative fertilizer application. Refer to text for explanation of points D, E, F, and G.	26
Figure 2-10: A) Average monthly stream flow for 83-6NIR fully fertilized treatment; and B) cumulative distribution function of flow for the month of July.....	28
Figure 3-1: A) Land use/land cover map of the watershed, locations of the sub-basins, and precipitation gauges with average annual precipitation (in mm); B) Land cover distribution in the watershed; and C) Study site location within the state of Entre Rios, Argentina.....	37
Figure 3-2: Intra-annual patterns of monthly average precipitation, streamflow, temperature and actual ET (simulated).	39
Figure 3-3: Observed and simulated monthly streamflow during the calibration (1993-2005) and validation (2006-2013) periods.....	42

Figure 3-4: Average monthly baseflow, surface flow and total flow for Base case and Intensive scenario.....	43
Figure 3-5: Monthly average simulated ET rates for base case and intensive scenario.	44
Figure 3-6: Cumulative distribution functions of monthly streamflow for the full simulation period (1993-2013) under Base case and Intensive scenarios. Inset shows the low-flow tails.	44
Figure 3-7: Map of soil depth, precipitation and yield variation in the watershed.	46
Figure 3-8: Cumulative biomass and relative streamflow changes for the Base case and one sub-basin at a time scenarios. Bubbles are scaled to the area of eucalyptus plantations in each scenario.	47
Figure 3-9: Tradeoff between biomass production and hydrologic impacts at the watershed scale. The Base case and combinations of sub-basins with relatively high productivity per unit of water consumption are highlighted.....	48
Figure 4-1: (a) Land use-land cover map of the watershed, location of streamflow gauge and watershed outlet, sub-basin boundaries, and average annual precipitation (in mm) for each sub-basin; (b) overall land use-land cover fractions for the Base Case scenario; and (c) study site location in the states of Tabasco and Chiapas, Mexico.	64
Figure 4-2: Intra-annual patterns of precipitation, flow and temperature in the study area watershed.	65
Figure 4-3: Figure 3. Measured and simulated discharge during the calibration (1964-1973) and validation (1973-1984) periods.....	67
Figure 4-4: Fruit yield simulation results versus time for different planting densities, with measured values for the 150 palm/ha planting density.....	69
Figure 4-5: Annual fruit yield versus additional water use for converted areas. Symbols indicate the respective conversion scenario. Numbers next to symbols indicate the respective planting density in palm/ha.....	70
Figure 4-6: Monthly mean ET rates for the PF scenario for the converted area for the Base case and PF scenarios. Error bars indicate one standard deviation of ET from the mean ET, with the standard deviation of ET calculated across the 20-year simulation period.	71
Figure 4-7: Decrease in water yield from the converted area for the PF scenario relative to the Base case scenario. Error bars indicate one standard deviation of decrease	

in yield from the mean, with the standard deviation of decrease in yield calculated across the 20-year simulation period.	72
Figure 4-8: Cumulative distribution functions (CDFs) of monthly streamflows at the watershed scale for the Base Case, PF, PFA and PFA+ scenarios for the full simulation period (1964-1983). Inset shows the CDFs for the low flow tails of the CDFs.	75
Figure 7-1: A) Simulated annual biomass production for the intensive scenario, and B) Simulated LAI development for the intensive scenario.....	97
Figure 8-1: Simulated LAI development for the average planting density and the highest planting density during the simulation period.	101
Figure 8-2: Monthly mean ET rates for the PF, PFA and PFA+ scenario for the converted area for the Base case and PF, PFA and PFA+ scenarios. Error bars indicate one standard deviation of ET from the mean ET, with the standard deviation of ET calculated across the 20-year simulation period.	101
Figure 8-3: Decrease in water yield from the converted area for all scenarios relative to the Base case scenario. Error bars indicate one standard deviation of decrease in yield from the mean, with the standard deviation of decrease in yield calculated across the 20-year simulation period.	102

List of tables

Table 2-1: Hydrologic calibration and validation statistics.	19
Table 2-2: Observed and simulated biomass harvested and LAI at time of harvest for treatments with fertilizer application rate of 164 kgN/ha/yr and irrigation.	21
Table 2-3: Water and fertilizer requirements to produce 1 ton of biomass in 41 kg N/ha/yr fertilized treatments.	27
Table 3-1: List of eucalyptus development scenarios simulated in SWAT.	41
Table 3-2: Summary of biomass production and hydrologic impacts for each scenario. All changes are relative to the Base case.	49
Table 3-3: Water requirement for biomass, fuel and energy production estimated from this study and others.	52
Table 4-1: Oil palm densities and associated maximum LAI simulated in SWAT.	66
Table 4-2: Changes in the hydrologic components as a result of oil palm conversion scenarios, relative to the Base Case scenario.	73
Table 6-1: Modified parameters for hydrological calibration process and their final value.	92
Table 6-2: Reported values for different treatments for the Harshaw Experimental Farm (Hanson 1979).	92
Table 6-3: Plant growth parameters in SWAT database used for plant growth modification.	93
Table 6-4: Comparison of measured aboveground biomass with simulated biomass in USDA and Spirit Falls watersheds.	93
Table 6-5: Summary of SWAT simulations results for fertilizer, biomass production, and hydrology.	94
Table 7-1: Land cover/land use change during the period 2002-2013.	97
Table 7-2: Modified parameters for hydrological model calibration and their final values.	97
Table 7-3: Plant growth parameters in SWAT database used for eucalyptus growth simulation.	98

Table 7-4: Calibration and validation statistics for streamflow simulations.	98
Table 7-5: Results of the optimization model to select the combination of sub-basins in terms of maximum biomass and a limited water impact.	99
Table 8-1: Modified parameters for hydrological calibration process and their final value.	102
Table 8-2: List of plant growth parameters in SWAT database used for plant growth modification.	103
Table 8-3: landuse/landcovers in the watershed.	103
Table 8-4: Calibration and validation statistics for streamflow simulations.	104
Table 8-5: Changes in water yield of the subbasins as a result of conversion to oil palm.	104
Table 8-6: Water requirement for fruit, fuel and energy production estimated from this study and others.	105

Preface

Chapter 2 is a republication of a journal article published in the *Journal of Hydrology* (Heidari et al., 2019a).

Chapter 3 is a republication of a journal article under review in *Hydrology and Earth System Sciences* (Heidari et al., 2019b).

Chapter 4 is under preparation to be submitted to *Global Change Biology Bioenergy*.

Land cover maps produced using LANDSAT 5 and 8 in Chapter 3 were produced by Tamara Propato, Santiago Verón, and Diego de Abelleira.

Acknowledgements

This material is based upon work supported by the National Science Foundation - Partnerships for International Research and Education (PIRE) Program (OISE-PIRE #1243444) and Research Coordination Network (RCN) Program (CBET #1140152), as well as by the Inter-American Institute (IAI) for Global Change Research (CRN3105).

We thank Jeffrey Arnold and Tian Guo for consulting on plant growth simulation in SWAT, Julian Licata for consulting on field LAI measurements and geospatial data for study site in Argentina, and Cesar Jesús Vázquez Navarrete for consulting on and help collecting hydro-climate and geospatial data for the Mexican study site.

Abstract

A simulation-based framework for studying hydrologic impacts and associated tradeoffs for existing and proposed biofuel projects in the US (poplar), Argentina (eucalyptus) and Mexico (oil palm) is developed. For each case study, a representative watershed is selected and a SWAT model is set up and calibrated for an improved simulation of hydrologic processes and plant growth cycles. Potential bioenergy scenarios are developed that represent various planting densities, harvest cycles, fertilization and irrigation rates, land cover types being converted, slope, and locations across the watershed.

Simulations indicate that growth and biomass production are significantly dependent on nitrogen availability, making fertilization a necessary management practice. However, there is a threshold beyond which further fertilization has no impact on yield and only increases the potential for non-point source pollution from contaminated runoff and leaching of nutrients. In contrast to fertilization, irrigation is not an impactful parameter due to the high average annual precipitation amounts in the case study watersheds.

All the studies show significantly higher water use (evapotranspiration, ET) by the bioenergy feedstock due to fertilization, high planting density and/or morphology of the trees compared to the land cover that they replace. Simulation results indicate that average annual ET rates are 24%, 24% and 45% higher for poplar, eucalyptus and oil palm, respectively.

The higher water use leads to a decrease in streamflow, especially during the low-flow months and dry years. The timing and degree of change in the streamflow is dependent on the crop, area of the plantation, and climate. On a watershed scale, the average annual decreases in streamflow as a result of planting poplar (on 70% of the watershed), eucalyptus (63% of the watershed) and oil palm (62% of the watershed) are found to be 21%, 28% and 9%, respectively.

In all case studies, management practices are demonstrated to be significantly sensitive parameters for improving yield and mitigating negative environmental impacts. Water-energy tradeoff curves are plotted for each case to evaluate the most efficient management practices in terms of water and fertilizer use. The most productive scenarios can produce up to 6.5, 12.8 and 12.9 ton/ha/year biomass for poplar, eucalyptus and oil palm, respectively.

Farm gate-level water footprints to produce bioenergy are estimated for all the case studies, indicating a lower water requirement for biodiesel production from eucalyptus compared to other case studies and reported values in literature. The green water footprint estimates indicate 98, 57 and 87 m³ water/GJ for poplar, eucalyptus and oil palm, respectively.

1 Introduction

Increasing energy demand (Howells et al., 2013), sustained high oil prices (Guo, 2015) and limiting global warming (IPCC, 2014) are encouraging the use of alternative forms of energy. Polluting and degrading the environment while satisfying increasing energy demand is a main topic of concern (Heard, 2017). A potential way to reduce greenhouse gas (GHG) emissions and environmental impacts is using novel energy production systems (Correa, 2019). Using bioenergy as an energy alternative, such as liquid biofuels for transport, is an appealing strategy to help addressing the growing need for more efficient, cleaner and sustainable fuels (Gerbens-Leenes et al., 2012). A number GHG of emission reduction scenarios predict a considerable increase in biofuel production between 2016 and 2040, specifically an increase from $9.7 \times 10^6 \text{ GJ d}^{-1}$ to $4.6 \times 10^7 \text{ GJ d}^{-1}$, reaching 16% of total transport fuels (IEA, 2017).

Current biofuel production is primarily based on first-generation biofuels (food crops) that compete with farmlands and biodiverse landscapes (Correa, 2019). However, for a biofuel development project to be sustainable, it is widely recognized that the bio-feedstock should not compete with food crops or area preserved as native forest (Guo, 2015). First-generation biofuels have been identified as the least sustainable biofuel production method (Correa, 2019). In addition, developing biofuel production in new lands will raises concerns that increasing water use will exacerbate water stress, which is already an important global issue (Cai et al., 2010). Specifically, bioenergy feedstock production can increase evapotranspiration and interception, which can have significant implications for surface runoff and groundwater recharge (Heidari et al., 2019a; Cibirin et al., 2016).

Sustainable biofuel production projects will have minimal hydrologic and water quality impacts; thus, there is a need for scientific assessment of regional feedstock production impacts on water quantity and quality, as suggested by various researchers (Gopalakrishnan et al. 2009; Engel et al. 2010; Watkins et al. 2015). The high rate of biomass production obtained in short-rotation harvests of woody biomass is considered a major advance in bioenergy (Guerra et al., 2014). However, biomass production has been recognized as the largest water consumer around the world (e.g. Berndes, 2002; Fraiture et al., 2008; Chapagain and Hoekstra, 2008). As a result, it is crucial to minimize the potential adverse consequences on the environment by identifying the appropriate biofuel crop and management practice for any given geographic and climatic situation.

There have been studies on hydrologic impacts of first-generation biofuel production (e.g., Schilling et al. 2008; Love and Nejadhashemi 2011; Babel et al., 2011), but less so for second-generation bioenergy crops (Hillard, 2017; Guo et al., 2018; Heidari et al. 2019). Reviewing the available literature, there are several key gaps. First, most of the previous research is focused on first-generation biofuel crops, and there is a need for more research to assess potential impacts of developing various second-generation biofuel crops. Second, previous studies have tended to focus on hydrologic processes at the watershed scale and averaged over a longer period of time (such as annual). Thus,

there is a need to better understand impacts at a range of spatial and temporal scales, including spatial scales that represent management practices and impacts on other water users, and time scales that represent seasonal and interannual hydroclimatic variability. Third, there is a shortage of research and modeling available on biofuel projects in developing countries. One main reason is that developing complex hydrological models for these countries is challenging because the models require large amounts of input data which are often not available and/or require considerable pre-processing before they can be used for modeling. Finally, assessing sustainability of bioenergy feedstock requires detailed plant growth cycle simulations for an accurate water use and production estimation (Zhang et al., 2011). This can be achieved through proper parametrization of plant growth models. However, a few studies have focused on this matter so far (Guo et al., 2018; Guo et al., 2015; Ng et al., 2010).

Analyzing the complex nature of hydrologic process in the water cycle and studying potential scenarios is possible through proper use of watershed models. The Soil and Water Assessment Tool (SWAT) is a commonly used process-oriented, ecohydrological, semi-distributed simulation model (Arnold et al., 2000). SWAT has the ability to simulate at various scales ranging from hectares to a watershed level. It allows simultaneous simulation of streamflow, plant growth, and sediment and nutrient transport under a range of climatic conditions and management practices. SWAT has been used to simulate biofuel development around the world for different crops (Babel et al., 2011; Cibirin et al., 2016; Sinnathamby et al., 2017; Heidari et al., 2019).

This research's design uses a comparative framework of carefully selected existing and proposed biofuel project case studies located in three countries. The three test sites chosen for this study are characteristic of many biofuel development projects that are diverse in terms of the hydrologic, climate, biofuel crop, management, and policy settings, but representative of many biofuel development projects in the mentioned countries (Phifer, 2017). They are located in two of the largest biofuel producing countries in the world (Argentina and the US), and in one country where biofuel production is just beginning (Mexico). The case studies are described in the following.

1.1 Hybrid poplar cultivation in northern Wisconsin, USA

In this study site, the focus is on a promising second-generation bioenergy crop, hybrid poplar, in northern Wisconsin, USA. Second-generation bioenergy is based on the cellulosic fraction of woody biomass.

This case study aims to contribute to addressing the lack of knowledge on detailed hydrological impacts of second generation bioenergy crops. These impacts vary depending on the crop, the region being grown, soil and climate. Therefore, they need to be quantified on a case by case basis. Moreover, water-fertilizer-biomass production tradeoffs have not been studied before. Poplar, a second-generation biofuel feedstock,

cultivated in a short rotation and a high intensity can be very productive. Furthermore, it is a valuable raw material for reconstituted forest products, due to its genetic diversity, rapid growth, vegetative propagation ease, and coppice regeneration (Guo et al., 2015). While cellulosic feedstocks can provide environmental benefits for biodiversity and ecosystem services compared to first generation bioenergy crops, their potential impact on streamflow within a watershed should be carefully considered (USEPA 2018).

The SWAT model was chosen as the modeling platform for watershed analysis of a site (222 km²) in the Upper Mississippi River Basin (UMRB). UMRB including Wisconsin, has a key role in biofuel production in the U.S. and a considerable amount of feedstock necessary to meet the growing U.S. biofuel industry can be grown in the UMRB (Wu et al., 2012). The watershed is representative of the area that is aspen-dominated forest and snow fall/melt are the dominant hydrologic processes.

The main goal of this research is to study water-fertilizer-biomass production tradeoffs associated with poplar development in northern WI, USA. Specific objectives are to calibrate and validate the SWAT model for watershed hydrology and to improve the simulation of the plant growth cycle (LAI and biomass production) by incorporating measured data from a nearby site. This enables detailed simulation of management practices, including planting density that is not explicitly represented in SWAT. Evaluating various management practices to find the most efficient strategy in a particular geographic and climatic context is essential to sustainable biofuel development (Thomas et al., 2009).

The validated model then is used to study the hydrological impacts of poplar cultivation in different scenarios. The management practices included combinations of planting density, harvest date, fertilization rate and irrigation to produce 70 scenarios. Potential areas for poplar development are identified based on the requirement of not competing with food crops (Paine et al., 1996) or converting urban or wetland areas. Therefore, forests, rangelands and hay can be converted to poplar plantations, and hydrological impacts are investigated on an annual and monthly basis with a focus on low flow months and dry years to identify critical periods.

Based on the simulations results, the best management practices are ranked by total biomass production and water and fertilizer use efficiency per unit biomass production. Furthermore, critical periods (months and years) regarding potential streamflow drought and poplar yield loss are identified. In the end, the water footprint and the required fertilization for biomass production from poplar are reported.

This work has been published in the *Journal of Hydrology* (Heidari et al., 2019a).

1.2 Eucalyptus plantation in Mesopotamia region Entre Rios, Argentina

Several beneficial characteristics of the eucalyptus, including being highly productive (for example, $>35 \text{ m}^3$ biomass/ha/year found by Albaugh et al., (2013), having short rotation length of six to eight years, and usage as lumber and pulp (Dougherty and Wright, 2012), have made it the most widely planted hardwood genus in the world (Binkley and Stape, 2004). Several bioenergy products can be made from eucalyptus, including cellulosic biodiesel and ethanol (Gonzalez et al., 2011b) and wood pellets for direct heating or electricity generation (Pirraglia et al., 2010). Therefore, eucalyptus production is expanding around the world to meet biofuel purposes (Gonzalez et al., 2011a).

Fast-growing trees are usually more efficient water users—per unit of biomass production—compared to slower growing trees (Otto et al., 2014). This includes eucalyptus plantations that have been reported to have high water use efficiency (Stape et al. 2004a). However, eucalyptus plantations have been recognized as having high water demand compared to other species (Albaugh et al. 2013; Scott 2005). In fact, eucalyptus has one of the highest ET rates among all trees (Farley et al. 2005; Dye 2013; Hubbard et al. 2010). This is explained by their morphological and physiological characteristics, including high stomatal conductance, evergreen leaves, drought tolerance, and deep rooting (Whitehead et al., 2004).

Argentina is one of the leading biofuel production countries in the world (Statista, 2017), and planting eucalyptus is expanding rapidly in the Mesopotamia region of Argentina (Phifer, 2017). Therefore, it is vital to study water use, management and production of eucalyptus in this region to understand the potential impacts on the water resources. Another key parameter for sustainable management of resources in a watershed is proper site selection for land use conversion (Cibin and Chaubey, 2015).

For this case study, SWAT preparation includes three steps of data collection, hydrologic calibration and validation, and improvements of plant growth sub-section of the model. Land use change analysis enables studying potential areas for eucalyptus plantation. The plant growth section is enhanced by improving the LAI simulation to account for the evergreen nature of the eucalyptus tree. The biomass production is also calibrated to match the reported values for the region. These improvements contribute to more accurate simulation of water use and biomass production.

A watershed (625 km^2) was delineated based on data availability and representativeness of the Mesopotamia region in Argentina, covered by rangelands, natural forest, orchards, farmlands and rivers and wetlands draining to the Uruguay River to the east. Eucalyptus plantation scenarios are developed that include different land cover types being converted in various locations across the watershed. The eucalyptus plantations include two 7-year rotations and a 6-year rotation, fertilized at 100 kgN/ha/year rate. Irrigation treatments are also added to study the impacts of irrigation on plant growth. The scenarios provide the

opportunity to study the difference in water use and biomass production across the watershed and to identify the limiting parameters for eucalyptus growth in the region such as soil depth and precipitation. Conducting the simulations using the validated model for a 21-year period (1993-2013) allows studying hydrologic impacts of spatially varying patterns of eucalyptus plantation. The evaluation include various hydrologic components (baseflow, surface flow, and evapotranspiration) and the interannual variability of those components. Furthermore, water-biomass production tradeoffs, water use efficiency for biomass production and green water footprint of biodiesel production are studied and compared to other bioenergy studies in different parts of the world.

This is the first application of SWAT that focuses on improving eucalyptus growth parametrization and investigating the hydrologic impacts of eucalyptus plantations for biofuel development. This work is under review in Hydrology and Earth System Sciences (Heidari et al., 2019b) (<https://www.hydrology-and-earth-system-sciences.net/>).

1.3 Oil Palm plantation in Tabasco, Mexico

Oil palm (*Elaeis guineensis* Jacq.) has the highest oil productivity (4-5 ton/ha) among all the oil crops (Corley and Tinker 2003, Mukherjee 2014), and area under oil palm cultivation is rapidly increasing due to demands for food, oil, and potential for producing liquid fuels (FAOSTAT 2017). Most of the research on environmental impacts of oil palm conversion has focused on deforestation and consequent greenhouse gas impacts and loss of biodiversity (Pirker et al. 2016, Vijay et al. 2016). There is a scarcity of research on impacts of oil palm cultivation on hydrologic cycling, as well as the short- and long-term potential hydrologic impacts of oil palm plantations at a watershed scale under various management practices (Comte et al. 2012, Larsen et al. 2013, Carlson et al. 2014, Meijide et al. 2017, Manoli et al. 2018). Most of the previous research are plot scale studies of ecohydrological fluxes and/or stand level measurements from research sites generally located in Southeast Asia, while there is little published on the hydrological impacts in tropical Latin America regions experiencing oil palm expansion (Gilroy et al. 2015, Furumo and Aide 2017).

Mexico is experiencing a rapid expansion of area under oil palm cultivation—a 485% increase in area from 2003 to 2017 (FAOSTAT, 2017). It is vital to study how management of oil palm cultivation could mitigate tradeoffs at the plantation and watershed scales. Ultimately, optimizing water use and oil palm production could result in more efficient land use and reduce conversion from natural landscapes. The main objective of this work is to determine how oil palm cultivation practices impact hydrologic cycling at local and watershed scales in a Latin American setting.

A representative watershed (525 km²) is selected in Tabasco and Chiapas, Mexico based on data availability and proximity to oil palm areas with field measurements. A SWAT model is calibrated and validated hydrologically, and the oil palm growth simulation is

improved by adjusting the LAI development to reflect the evergreen nature of the tree. Furthermore, the yield is adjusted to match reported values of oil palm productivity. These improvements provide more accurate plant growth cycle simulation that leads to improved water use and yield estimates. Reported values from the literature are used to account for the rainfall interception process in the model.

The scenarios for this study are based on the land use classes to be converted from present use to oil palm, a range of oil palm planting densities, and the maximum land slope amenable to planting. Oil palm expansion scenarios are simulated to study hydrological impacts (streamflow, ET) of oil palm development on a watershed scale, and especially the potential severe impacts on low-flow months and dry years. Furthermore, simulation results are used to investigate how tradeoffs between oil palm fruit production and streamflow change with spatial scale and alternative management practices. Finally, the greenwater footprint per mass of biomass and per unit of energy generated is estimated. It is used as a metric to compare water-energy efficiency to literature values for oil palm fruit for biofuels production and other biofuel feedstocks.

To the author's knowledge, this is the first study using SWAT in Mexico that focuses on improving oil-palm growth parametrization, simulates yield for different planting densities, and evaluates the detailed hydrologic impacts of expanding oil-palm plantations. This work is under preparation to be submitted to *Global Change Biology Bioenergy*.

1.4 References

- Albaugh, J.M., Dye, P.J. and King, J.S., 2013. Eucalyptus and water use in South Africa. *International Journal of Forestry Research*.
- Arnold, J.G., Muttiah, R.S., Srinivasan, R., Allen, P.M., 2000. Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin. *Journal of Hydrology*, 227(1), 21-40.
- Berndes, G., 2002. Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. *Global environmental change*, 12(4), 253-271.
- Binkley, D. and Stape, J.L., 2004, October. Sustainable management of Eucalyptus plantations in a changing world. In *Proceedings of IUFRO Conference*, October (pp. 11-15).
- Carlson, K.M., Curran, L.M., Ponette-González, A.G., Ratnasari, D., Lisnawati, N., Purwanto, Y., Brauman, K.A. and Raymond, P.A., 2014. Influence of watershed-climate interactions on stream temperature, sediment yield, and metabolism along a land use

intensity gradient in Indonesian Borneo. *Journal of Geophysical Research: Biogeosciences*, 119(6), pp. 1110-1128.

Chapagain, A.K., Hoekstra, A.Y., 2008. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water international*, 33(1), 19-32.

Cibin, R. and Chaubey, I., 2015. A computationally efficient approach for watershed scale spatial optimization. *Environmental Modelling & Software*, 66, pp.1-11.

Cibin, R., Trybula, E., Chaubey, I., Brouder, S. M., & Volenec, J. J., 2016. Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model. *Gcb Bioenergy*, 8(4), 837-848.

Comte, I., Colin, F., Whalen, J.K., Grünberger, O. and Caliman, J.P., 2012. Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review. In *Advances in Agronomy* (Vol. 116, pp. 71-124). Academic Press.

Corley, R. H. V. and P. B. Tinker (2003). *The oil palm*, John Wiley & Sons.

Correa, D.F., Beyer, H.L., Fargione, J.E., Hill, J.D., Possingham, H.P., Thomas-Hall, S.R. and Schenk, P.M., 2019. Towards the implementation of sustainable biofuel production systems. *Renewable and Sustainable Energy Reviews*, 107, pp.250-263.

Dougherty, D. and Wright, J., 2012. Silviculture and economic evaluation of eucalypt plantations in the Southern US. *BioResources*, 7(2), pp.1994-2001.

Dye, P., 2013. A review of changing perspectives on Eucalyptus water-use in South Africa. *Forest Ecology and Management*, 301, pp.51-57.

Engel, B., Chaubey, I., Thomas, M., Saraswat, D., Murphy, P. and Bhaduri, B., 2010. Biofuels and water quality: challenges and opportunities for simulation modeling. *Biofuels*, 1(3), 463-477.

FAO, F.J.F., Nations, A.O.o.t.U., 2017. FAOSTAT online statistical service, <http://www.fao.org/faostat/en/#data/QC>).

Farley, K.A., Jobbágy, E.G. and Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global change biology*, 11(10), pp.1565-1576.

Fraiture, C.d., Giordano, M., Liao, Y., 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. *Water policy*, 10(S1), 67-81.

- Furumo, P.R. and Aide, T.M., 2017. Characterizing commercial oil palm expansion in Latin America: land use change and trade. *Environmental Research Letters*, 12(2), p.024008.
- Gerbens-Leenes, P., Van Lienden, A., Hoekstra, A.Y., Van der Meer, T.H., 2012. Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030. *Global Environmental Change*, 22(3), 764-775.
- Gilroy, J.J., Prescott, G.W., Cardenas, J.S., Castañeda, P.G.D.P., Sánchez, A., Rojas-Murcia, L.E., Medina Uribe, C.A., Haugaasen, T. and Edwards, D.P., 2015. Minimizing the biodiversity impact of Neotropical oil palm development. *Global Change Biology*, 21(4), pp. 1531-1540.
- Guerra, S.P., Garcia, E.A., Lanças, K.P., Rezende, M.A. and Spinelli, R., 2014. Heating value of eucalypt wood grown on SRC for energy production. *Fuel*, 137, pp.360-363.
- Guo, T., Engel, B. A., Shao, G., Arnold, J. G., Srinivasan, R., & Kiniry, J. R., 2015. Functional approach to simulating short-rotation woody crops in process-based models. *BioEnergy Research*, 8(4), 1598-1613.
- Guo, T., Engel, B. A., Shao, G., Arnold, J. G., Srinivasan, R., & Kiniry, J. R., 2018. Development and improvement of the simulation of woody bioenergy crops in the Soil and Water Assessment Tool (SWAT). *Environmental Modelling & Software*.
- Gopalakrishnan, G., Negri, M. C., Wang, M., Wu, M., Snyder, S. W., & Lafreniere, L., 2009. Biofuels, land, and water: a systems approach to sustainability. *Environmental science & technology*, 43(15), 6094-6100.
- Gonzalez, R., Treasure, T., Wright, J., Saloni, D., Phillips, R., Abt, R. and Jameel, H., 2011. Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I. Biomass and Bioenergy, 35(2), pp.755-766.
- Heard, B.P., Brook, B.W., Wigley, T.M. and Bradshaw, C.J., 2017. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews*, 76, pp.1122-1133.
- Heidari, A., Mayer, A. and Watkins, D., 2019a. Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA. *Journal of Hydrology*.
<https://doi.org/10.1016/j.jhydrol.2019.04.067>
- Heidari, A., Watkins, D. and Mayer, A., Propato, T., Veron, S., Abelleira, D., 2019b. Spatially variable hydrologic impact and biomass production tradeoffs associated with Eucalyptus cultivation for biofuel production in Entre Rios, Argentina. *Hydrology and Earth System Sciences*. Under review.

Hillard, S., 2017. Evaluation of hybrid poplar management, production potential, and estimation of impacts to water resources in the Upper Great Lakes region. PhD Dissertation. Michigan Technological University, Houghton, Michigan, USA.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., Van Velthuizen, H. and Wiberg, D., 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, 3(7), 621.

Hubbard, R.M., Stape, J., Ryan, M.G., Almeida, A.C. and Rojas, J., 2010. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. *Forest Ecology and Management*, 259(9), pp.1714-1721.

IEA, World energy outlook 2017, IEA Publications, Paris, France (2017).

IPCC, Climate change 2014: mitigation of climate change, Cambridge University Press, New York, USA (2015)

Larsen, R.K., Jiwan, N., Rompas, A., Jenito, J., Osbeck, M. and Tarigan, A., 2014. Towards 'hybrid accountability in EU biofuels policy? Community grievances and competing water claims in the Central Kalimantan oil palm sector. *Geoforum*, 54, pp. 295-305.

Love, B.J., Nejadhashemi, A.P., 2011. Water quality impact assessment of large-scale biofuel crops expansion in agricultural regions of Michigan. *Biomass and Bioenergy*, 35(5), 2200-2216.

Manoli, G., Meijide, A., Huth, N., Knohl, A., Kosugi, Y., Burlando, P., Ghazoul, J. and Fatichi, S., 2018. Ecohydrological changes after tropical forest conversion to oil palm. *Environmental Research Letters*, 13(6), p.064035.

Meijide, A., Badu, C.S., Moyano, F., Tiralla, N., Gunawan, D. and Knohl, A., 2018. Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event. *Agricultural and Forest Meteorology*, 252, pp. 208-219.

Mukherjee, I. and Sovacool, B.K., 2014. Palm oil-based biofuels and sustainability in southeast Asia: A review of Indonesia, Malaysia, and Thailand. *Renewable and Sustainable Energy Reviews*, 37, pp. 1-12.

Ng, T.L., Eheart, J.W., Cai, X. and Miguez, F., 2010. Modeling Miscanthus in the soil and water assessment tool (SWAT) to simulate its water quality effects as a bioenergy crop. *Environmental science & technology*, 44(18), 7138-7144.

Otto, M.S.G., Hubbard, R.M., Binkley, D. and Stape, J.L., 2014. Dominant clonal Eucalyptus grandis × urophylla trees use water more efficiently. *Forest ecology and management*, 328, pp.117-121.

- Paine, L.K., Peterson, T.L., Undersander, D.J., Rineer, K.C., Bartelt, G.A., Temple, S.A., Sample, D.W. and Klemme, R.M., 1996. Some ecological and socio-economic considerations for biomass energy crop production. *Biomass and Bioenergy*, 10(4), 231-242.
- Phifer, C. 2017. Impacts to biodiversity and ecosystem services from bioenergy development: a pan American experience, PhD dissertation, Michigan Technological University.
- Pirker, J., Mosnier, A., Kraxner, F., Havlík, P. and Obersteiner, M., 2016. What are the limits to oil palm expansion?. *Global Environmental Change*, 40, pp. 73-81.
- Pirraglia, A., Gonzalez, R., Saloni, D. and Wright, J., 2010. Wood pellets: An expanding market opportunity. *Biomass magazine*, 6, pp.68-75.
- Schilling, K.E., Jha, M.K., Zhang, Y.K., Gassman, P.W., Wolter, C.F., 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resources Research*, 44(7).
- Scott, D.F., 2005. On the hydrology of industrial timber plantations. *Hydrological Processes: An International Journal*, 19(20), pp.4203-4206.
- Sinnathamby, S., Douglas-Mankin, K.R. and Craige, C., 2017. Field-scale calibration of crop-yield parameters in the Soil and Water Assessment Tool (SWAT). *Agricultural water management*, 180, pp.61-69.
- Stape, J.L., Binkley, D., Ryan, M.G. and Gomes A.D.N., 2004a. Water use, water limitation, and water use efficiency in a Eucalyptus plantation. *Bosque*, 25(2).
- Stape, J.L., Binkley, D. and Ryan, M.G., 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *Forest ecology and management*, 193(1-2), pp.17-31.
- Thomas, M.A., Engel, B.A., Chaubey, I., 2009. Water quality impacts of corn production to meet biofuel demands. *Journal of Environmental Engineering*, 135(11), 1123-1135.
- Vijay, V., Pimm, S.L., Jenkins, C.N. and Smith, S.J., 2016. The impacts of oil palm on recent deforestation and biodiversity loss. *PloS one*, 11(7), p.e0159668.
- Ximing Cai, X. Z., Dingbao Wang (2010). "Land Availability for Biofuel Production." *Environ. Sci. Technol* 45: 334–339.
- Watkins, D.W., de Moraes, M.M.A., Asbjornsen, H., Mayer, A.S., Licata, J., Lopez, J.G., Pypker, T.G., Molina, V.G., Marques, G.F., Carneiro, A.C.G. and Nuñez, H.M., 2015. Bioenergy development policy and practice must recognize potential hydrologic impacts: Lessons from the Americas. *Environmental management*, 56(6), 1295-1314.

Whitehead, D. and Beadle, C.L., 2004. Physiological regulation of productivity and water use in Eucalyptus: a review. *Forest ecology and management*, 193(1-2), pp.113-140.

U.S. Environmental Protection Agency Office of Research and Development
Washington, DC. Biofuels and the Environment Second Triennial Report to Congress.
June, 2018.

Zhang, X., Izaurralde, R.C., Arnold, J.G., Sammons, N.B., Manowitz, D.H., Thomson, A.M. and Williams, J.R., 2011. Comment on “modeling Miscanthus in the soil and water assessment tool (SWAT) to simulate its water quality effects as a bioenergy crop”. *Environmental science & technology*, 45(14), 6211-6212.

2 Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA

2.1 Abstract

Growing demand for biomass-derived fuels has resulted in an increase in bioenergy projects in recent years, a trend that is expected to continue. However, broad expansion of bioenergy feedstock production may have significant environmental consequences. Accordingly, the goal of this study is to investigate how forest-based bioenergy development may affect hydrological systems at the watershed scale. Specifically, this study addresses hybrid poplar cultivation for biofuel production in a snow-dominated watershed in northern Wisconsin, USA. The Soil and Water Assessment Tool (SWAT), calibrated and validated for streamflow and biomass production cycles, is used to evaluate the effects of land use change corresponding to a range of biofuel development scenarios. The biofuel scenarios follow physically-based rules for land use conversion to poplar plantations from hay, pasture, and forested lands; along with a suite of alternative management practices, including rotation time, planting density, fertilizer application and irrigation. Trade-offs between biomass production, fertilizer use, and hydrologic alteration are evaluated for the feedstock production system. The highest density (1111 trees/ 100m²) and shortest rotation (5-year) treatments produce the highest biomass and are the most efficient treatments in terms of water and fertilizer use per ton of biomass. The high efficiency is due to optimal relationships between leaf area index, biomass production, and N uptake. At annual or greater time scales, the simulated conversion to poplar had minimal effect on ET and streamflows. However, in summer months, the ET from the poplar substantially exceeds that of the original land use, so that streamflows decrease by as much as 50%. Irrigation to meet soil water deficits increased biomass production, but only by 4% on average, which is not surprising for a temperate, humid watershed.

2.2 Introduction

Climate change mitigation and energy security are two of the primary motivations for moving toward renewable energy (Gerbens- Leenes et al., 2012). Energy demand is predicted to increase one-third by 2035 (Howells et al. 2013) and the prospect of sustained high oil prices is encouraging the use of alternative forms of energy (Guo et al., 2015). For example, using bioenergy sources, such as drop-in biofuels, can address the growing need for cleaner and sustainable fuels in the transportation sector (Gerbens-Leenes et al., 2012; Winjobi et al., 2018). The Energy Independence and Security Act (EISA) has set a target amount of 136 billion L/year of renewable fuel in the U.S transportation fuel mix, and cellulosic ethanol and biodiesel are expected to contribute 44% and 3%, respectively, to this goal (USEPA, 2010). As progress is made towards this goal, the number of bioenergy projects in the U.S. is expected to grow. Globally, it has

been estimated that by 2030 the area of land devoted to biofuel feedstock will be 42.2 million hectares (Fraiture et al., 2008).

Several researchers have argued that biomass production could eventually be the largest water consumer around the world (e.g., Berndes, 2002; Fraiture et al., 2008; Chapagain and Hoekstra, 2008). Replacing existing crops with biofuel crops can influence effective rainfall and soil moisture, apart from altering the climate due to a change in interception and evapotranspiration, which can have significant implications for surface runoff and groundwater recharge (Stephens et al., 2001). The expansion of bioenergy crop production will increase the amount of water use through evapotranspiration and reallocate water resources from available water for human consumption to the atmosphere as water vapor (Berndes, 2002). This evaporative loss could reduce already impacted groundwater recharge rates and exacerbate the water table declines that are occurring in many parts of the world (King et al., 2013). Several studies have addressed the hydrologic impacts of first-generation bioenergy feedstock development (e.g., Schilling et al. 2008; Love and Nejadhashemi 2011; Babel et al., 2011). Yield and biomass production for some second-generation biofuel crops have also been investigated (Truax et al., 2012; Jiang et al., 2017), and several studies have addressed the hydrologic impacts of second-generation biofuel feedstock production (Cibin et al., 2016; Fischer et al., 2013; Wu and Liu 2012; Wu et al., 2012; Ng et al., 2010). However, none of these previous studies of second-generation feedstock have directly addressed the tradeoff between biomass production and hydrologic impact.

Second-generation bioenergy is based on the cellulosic fraction of crops or other biomass, including woody biomass. Intensive planting, short-rotation cultivation of trees is one strategy to increase woody biomass productivity. In short rotations, dry matter and bark production can be three to five times higher than natural stands, producing up to 20,000 kg/ha/year (Hansen and Baker, 1979). Poplar, in particular, can be a very productive genus if planted in high density and short rotation. Moreover, it is a valuable raw material for reconstituted forest products, due to its genetic diversity, rapid growth, vegetative propagation ease, and coppice regeneration (Guo et al., 2015).

While cellulosic feedstocks can provide environmental benefits for biodiversity and ecosystem services, their potential impact on streamflow within a watershed should be carefully considered (USEPA, 2018). Moreover, studies are needed to determine the extent to which observed hydrologic changes – associated with changes in land use/and land management – can be attributed to biofuel feedstock production (USEPA, 2018). This emphasizes the need for more research on various second-generation biofuels crops because the local effects of biofuel crop production are dependent on the selected feedstock, soil, climate, and watershed management practices (Engel et al., 2010). Promotion of sustainable biofuel production projects that have minimal hydrologic and water quality impacts calls for the scientific assessment of regional feedstock production impacts on watershed scales (Gopalakrishnan et al., 2009; Engel et al., 2010; Watkins et al., 2015). In any given geographic and climatic context, it is vital to identify biofuel

crops and management strategies that have minimal adverse consequences on the environment (Thomas et al., 2009).

As in any cropping system, understanding the interactions between the time scales of crop cultivation and hydroclimatology is critical for assessing the impacts of biofuel feedstocks on the hydrologic cycle. The important time scales include those of crop planting, rate of growth, and harvesting; and seasonality of precipitation, runoff, solar radiation, and temperature. Furthermore, variations in crop cultivation practices, such as planting intensity, harvest time, irrigation, and fertilizer application, can be considerable and may have substantial impacts on water quantity and quality. However, little attention has been paid to temporal interactions and variations in cultivation practices in the literature on the hydrologic impacts of bioenergy feedstock development.

Watershed models are essential tools for investigating the complex nature of processes that affect the hydrologic cycle in response to land use changes, agricultural activities, and best management practices (Singh et al., 2005). Zhang et al (2011) argued that proper parametrization of crops to improve growth simulation cycles is a crucial step for assessing the sustainability of bioenergy feedstock production, and several studies have focused on improving plant growth parameters for more accurate production estimates (e.g., Guo et al., 2018; Guo et al., 2015; Ng et al., 2010). Accordingly, the goals of this study are to use watershed and plant growth modeling tools to determine how biofuel feedstock cultivation will impact hydrological systems and to assess the tradeoffs between hydrologic impacts and biomass production. Specific objectives are to calibrate and validate a Soil and Water Assessment Tool (SWAT) model for a case study of poplar cultivation in a watershed in northern Wisconsin, USA, including calibration of both hydrologic and poplar growth sub-models. The calibrated model is used to assess impacts of planting intensities and harvest cycles. Additional objectives are to improve understanding of relationships between leaf area indexes (LAI), biomass growth, and hydrologic impacts, as well as evaluate the interannual variability of the impacts. Model results are presented as tradeoffs between biomass yield, water use, and fertilizer application.

2.3 Model setup, calibration and validation

2.3.1 Study area

The Upper Mississippi River Basin (UMRB), which includes Wisconsin, plays a central role in the U.S. production of biofuel (Wu et al., 2012), and a significant portion of the feedstock required for the U.S. biofuel industry to meet renewable energy targets could be grown in the UMRB. Therefore, this case study focuses on cellulosic ethanol from poplar plantations in northern Wisconsin, USA. The Spirit River watershed in Lincoln County, Wisconsin (Fig. 2-1) was selected based on data availability and a proposed cellulosic ethanol plant in the western Upper Peninsula of Michigan, within an economically viable harvest radius. The watershed is representative of the area that is

heavily forested and includes wetlands and forested wetlands, with a mix of state, federal, and private forests. In the state of Wisconsin, forests make up 6.9 million hectares (Kurtz, 2017). In the northern part of the state, 70% of the forests stands are Aspen (*Populus* spp.) (DNR, 2016). Field measurements in Vilas and Oneida Counties found the aspen ages to range from 11 to 45 years. These aspen-dominated sites were originally clear-cut and left to regenerate without additional management (Phifer 2017).

Figure 2-1: A) Study site location (Spirit Falls) in the state of Wisconsin; B) Land use/land cover map of the Spirit Falls watershed; C) Land cover distribution in the watershed; and D) Test watershed for calibrating plant growth parameters.

2.3.2 Model input and setup

SWAT was chosen as the hydrologic modeling platform for this study. SWAT is a physically based, complex, continuous simulation model with spatially explicit parameterization (Arnold et al., 2000). It allows simultaneous simulation of hydrology, plant growth and nutrient balances. Furthermore, the model simulates a variety of agricultural practices (fertilizer and manure application, tillage), irrigation, wetlands, ponds, as well as buffer strips and it has been used to simulate biofuel development around the world for different crops, including poplar (Hillard, 2017; Love and Nejadhashemi, 2011; Powers et al., 2011; Cibin et al., 2016).

The Spirit River at Spirit Falls, Wisconsin, USGS hydrologic station (USGS 05393500) was selected as the watershed outlet, and long term daily flow data (1978–2010) were assembled. The contributing area to the gage was found to be 222 km², using the 10m Digital Elevation Model from the National Elevation Dataset and ArcGIS 10.4. Land use/land cover data from the National Land Cover Database (NLCD 1992, 2001, 2006 and 2011) and Soil Survey Geographic database (SSURGO) were downloaded from the US Department of Agriculture Geospatial Data Gateway (Soil Survey Staff). The four land cover maps were analyzed to determine the changes in the land cover of the area and to produce the business as usual trend based on the observed changes.

Maximum and minimum daily temperature and daily precipitation data were compiled from the NOAA National Center for Environmental Information from five nearby weather stations. The area receives an average of 810mm of precipitation annually, with the majority of rainfall occurring during the period of June through September. The average annual temperature is 4.5 °C. The area receives a significant amount of snowfall annually (170 mm water equivalent based on SWAT snowmelt simulations), with the majority of snowfall occurring from November to April. Snow accumulation and snowmelt are dominant hydrological processes in the watershed. Fig. 2-2 shows the intra-annual variation of streamflow, temperature and precipitation. The highest monthly average streamflow is in April as a result of snowmelt.

Figure 2-2: Intra-annual patterns of precipitation, flow and temperature in the Spirit Falls, Wisconsin watershed.

Runoff efficiency was calculated as the ratio of annual stream flow to annual precipitation in the watershed (Lo, 1992). The average runoff efficiency is around 0.4, with a range from 0.25 to 0.58, depending on the amount and distribution of precipitation

each year. Although the months of June to September receive a considerable amount of precipitation, the average stream flow is low because of high ET rates during that period. A rainfall-runoff analysis shows that most rain events during these months do not result in high stream flows because much of the rainfall is intercepted by the canopy or infiltrates into dry soils. However, rainfall events during October and November typically contribute significantly to the streamflow.

ArcSWAT version 2012.10_4.19 (Winchell et al., 2013) was used to set up the model. The watershed was divided into 9 sub-watersheds in order to represent spatial variability. The sub-basins are further subdivided into non-contiguous hydrologic response units (HRUs), which represent homogeneous areas within the sub-basin with unique combinations of land use, soil type and slope class. During the HRU definition, thresholds for retaining classes of land surface properties of 0, 10 and 15% were selected for land use/land cover (LULC), soils, and slope classes, respectively, resulting in 286 HRUs. Forested wetlands and open water comprise 19% of the watershed land cover, and thus wetlands were introduced into the model. Wetland functionality is described in detail in SWAT theoretical documentation (Neitsch et al., 2011) and the details on wetlands parametrization are presented in the Supplementary Materials.

2.3.3 Model calibration and validation

Calibration and validation focused on both the hydrologic and plant growth components of the model. Analysis was performed for 32 years (from 1980 to 2011) in order to include a combination of dry and wet years in both the calibration period (1980–1999) and validation period (2000–2011). The model was calibrated on a daily time step for higher accuracy. However, the poplar growth simulations were conducted on a monthly time step. The hydrologic calibration proceeded through a multiple-step process using a combination of manual adjustments and an automatic calibration method. Performance metrics included the Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970), coefficient of determination (R^2), and percent bias (Gupta et al., 1999). In order to improve model reliability, the ratio of baseflow to total flow was also required to be in a reasonable range. The first step in the calibration process was to analyze long term daily flow data to separate baseflow from surface runoff using Arnold's method (Arnold and Allen, 1999). A sensitivity analysis resulted in ratios of baseflow to total flow ranging from 0.42 to 0.59 on an annual basis. The next step was to conduct sensitivity analysis to identify critical model parameters. Based on literature (Arnold et al., 2012) and prior experience, 23 parameters were selected for sensitivity analysis, which was conducted using the p-value and t-statistic sensitivity tests in SWATCUP SUFI2 (Abbaspour, 2013). A total of 500 iterations were performed, with each parameter varying within a feasible range. Results of the sensitivity analysis are shown in Table 6-1 of the Supplementary Materials. The final calibration step involved adjusting the sensitive parameters to values available in literature, which ensures that each parameter stays in a range that is physically feasible. In this step, parameters were grouped according to hydrologic process, including runoff, snowmelt, baseflow, and routing. Detailed calibration steps and the final adjusted parameter values are presented in Table 6-1 in Supplementary Materials.

Calibration of the plant growth model in SWAT was based on measured poplar growth data in Wisconsin, including LAI, total biomass, and leaves biomass (Zavitkovski, 1983) (Table 6-2). The poplar plantations were short-rotation intensive plantations at the United States Department of Agriculture (USDA) Forest Service Harshaw Experimental Farm near Rhinelander, with measurements occurring over the period of 1970 to 1976 (Hansen and Baker, 1979; Ek and Dawson, 1976). Since SWAT does not have a parameter for planting density, three parameters were adjusted to represent that management variable—maximum potential leaf area index (BLAI), years to maximum LAI, and light extinction coefficient. The leaf area index (LAI) is typically higher for higher planting intensities, while the years to maximum LAI can be expected to be shorter for higher planting densities because they reach a high LAI in only a few years. Matching the LAI is important because it is a key driver of the actual transpiration. Therefore, LAI was first calibrated by changing BLAI and years to maximum LAI, and then the biomass production parameters were adjusted to match observed biomass. The light extinction coefficient is related to the intercepted photosynthetically active radiation and is expected to be higher for short rotation high intensities (Jiang et al., 2017). Several of the plant parameters suggested by Guo et al. (2015) were also used to improve the simulation of hybrid poplar growth. Table 6-3 in the Supplementary Materials lists the adjusted plant parameters. Full descriptions of each parameter are presented in the SWAT theoretical documentation (Neitsch et al., 2011). To calibrate the poplar the poplar growth parameters, a second SWAT model (hereafter referred to as USDA watershed) was set up to represent the experimental plots at the USDA facility. A small watershed (13.5 km²) encompassing the facility was delineated (see Fig. 2-1). Maximum and minimum daily temperature and daily precipitation data were compiled from the NOAA National Center for Environmental Information for the Rhinelander, WI station (GHCND:USC00477113) for the period of 1968 to 1980, representing climatic conditions similar to those of the nearby Spirit Falls watershed. All planting density and rotation treatments were simulated assuming optimal irrigation and fertilization, and results were compared to the measured biomass at the USDA facility and the simulated biomass in the Spirit Falls watershed.

2.3.4 Modeling scenarios

The calibrated and validated model was used to simulate 70 biofuel development scenarios to investigate the impacts of planting density, harvest timing, fertilizer application, and irrigation on biomass generation, nutrient accumulation in the soil, and water demand, as summarized in Table 6-4. In these scenarios, the base case refers to the 2011 land cover conditions (Fig. 2-1c) before any biofuel development scenario is imposed. For the biofuel development scenarios, five planting density- harvesting rotations reported by Hansen and Baker (1979) and Zavitkovski (1983) were used in this study (Table 6-2), including a density of 1111 trees/100m² and a 5-year rotation; 278 trees/100m² and 5-year rotation; 83 trees/100m² and 6-year rotation; 25 trees/ 100m² and 6-year rotation; and 17 trees/100m² and 10-year rotation. The fertilization rate of 164 kg N/ha/year reported by Guo et al. (2015) was used for the highest fertilization treatment scenario, along with five lower fertilizer application rates (5.1, 10.2, 20.5, 41, 82 kg

N/ha/year) and a no-fertilization scenario, in order to study fertilizer impacts on biomass production. Lastly, no-irrigation and supplemental irrigation scenarios were simulated. The supplemental irrigation rates were based on plant-water demand simulated by SWAT, and it was assumed that the water comes from a source outside of the watershed. Treatments are identified according to the number of trees per 100m² and the harvest cycle length, followed by “Ir” if they were irrigated (e.g., 83-6Ir means a fully fertilized treatment with 83 trees/100m² in a 6-year rotation with irrigation).

Land cover analysis showed little change in the land cover from 1992 to 2011, with the dominant land cover (66.5%) being forest (Fig. 2-1). Assumptions for determining areas for biofuel development were that plantations would not compete with food crops (Paine et al., 1996) and no urban or wetland areas would be converted, leaving forest, hay and rangelands as available area. Following a spin-up period to obtain initial conditions, each simulation occurs over the 30-year period, 1981 to 2010, using the corresponding hydroclimate time series. This period allows for a range of climate conditions to be represented, as well as several rotations for each harvesting interval.

2.4 Results and discussion

2.4.1 Model evaluation

As shown in Fig. 2-3, the simulated versus the measured discharges at the outlet of the watershed demonstrate that the calibration and verification performance of the hydrologic model was good. The Nash Sutcliffe Efficiency of 0.8, R² of 0.8 and Pbias of 1% also indicate good hydrologic model performance (Moriassi et al., 2007) (Table 2-1). Results of the LAI and biomass calibration for the USDA watershed are shown in Fig. 2-4. The simulated LAI also matches the observed LAI reasonably well, as shown in Fig. 2-4b, except for two years before harvest. Although the biomass growth model overpredicts the biomass in the years leading up to harvest (Fig. 2-4a), it is the biomass at the time of harvest that accounts for total biomass production, and the final biomass is matched closely by the biomass growth model. Accurately simulating the entire growth cycle and variation of LAI and biomass has been reported as beyond the abilities of SWAT and even plant growth models such as ALMANAC (Guo et al. 2015). The agreement between the simulated and observed LAI is important because the LAI controls ET fluxes and canopy interception in the SWAT model.

Table 2-1: Hydrologic calibration and validation statistics.

Timestep	Calibration Period (1980-1999)			Validation period (2000-2011)		
	NS	Pbias	RSq	NS	Pbias	RSq
Monthly	0.78	-1.1%	0.82	0.81	-0.5%	0.81
Daily	0.55	-1.1%	0.61	0.58	-0.5%	0.60

The results of the LAI and biomass growth simulations in the Spirit Falls watershed are very similar to the simulated values in the nearby USDA watershed, although LAI and growth are modeled over several rotations. These results are shown in Table 2-2 and Fig. 2-5, with Fig. 2-5 clearly showing the cyclic nature of the rotations. Table 6-4 in the Supplementary Materials provides a comparison of the simulated aboveground biomass in the Spirit Falls Watershed with the measured biomass in the nearby USDA watershed.

Figure 2-3: Measured and simulated discharge during the calibration (1980-1999) and validation (2000-2011) periods.

Figure 2-4: A) Total aboveground biomass production; and B) LAI simulated for the fertilized 83-6Ir treatment compared with measured data (Hanson 1979) for USDA watershed.

Figure 2-5: A) Simulated total aboveground biomass production; and B) LAI simulated for the fertilized 83-6Ir treatment for the Spirit Falls watershed.

Table 2-2: Observed and simulated biomass harvested and LAI at time of harvest for treatments with fertilizer application rate of 164 kgN/ha/yr and irrigation.

Variable	Treatment				
	1111-5	278-5	83-6	25-6	17-10
Observed Biomass (tons/ha)	29.6	23.6	27	19.5	46.6
Simulated Biomass ^a (tons/ha)	29.7	23.9	27.2	18.7	45.4
Observed LAI at time of harvest	8.6	8.7	7.8	8.2	8.4 ^b
Simulated LAI at time of harvest	8.7	8.7	7.9	8.2	8.4

^a averaged over study period

^b maximum LAI reported for the 6th year, after which LAI declines.

2.4.2 Impacts of planting density, rotation lengths and fertilizer application

The results from 50 of the 70 simulations are summarized in Table 6-5, including planting intensity, harvest cycle, biomass production, nitrogen applied and remaining nitrogen in the soil, irrigation water applied, ET at the watershed scale and over the converted area, and streamflow the watershed outlet. Treatments with more than 41 kg N/ha/yr are omitted as more fertilizer did not produce additional biomass.

Fig. 2-6 shows the relationship between fertilizer application rate and biomass production for all the irrigated treatments. These results indicate that the biomass production is heavily dependent on nitrogen availability, and, for most treatments, there is a maximum fertilizer application rate at which minimal improvement in biomass growth is achieved. The strong dependency of the poplar growth on nitrogen availability and the occurrence of maximum fertilizer application rates has been reported in many hybrid poplar growth studies (Truax et al., 2012; Brown and Driessche, 2002; Stanruff et al., 2001; Coleman et al., 2006). Chemical input during the feedstock production stage has the highest water

quality impact across biofuel production processes (USEPA, 2011). Accordingly, avoiding over-fertilization is crucial to mitigate this impact.

For all applied fertilizer amounts, the 1111-5 treatment produces the highest biomass, followed by the 278-5 treatment. The higher biomass from more intensive planting is a result of higher light interception. The 25-6 treatment has significantly poorer performance in terms of biomass production, mainly as a result of lower light interception and lower LAI early in the harvest cycle. A longer rotation might improve production under the 25-6 treatment scenario. Considering interannual variability, the 1987-1992 rotation produces less biomass than other rotations (2.5 ton/ha/harvest cycle lower than average). The limiting factor preventing optimal growth was temperature stress, resulting from cold weather during the 1992 season. A similar trend for the 1111-5 and 278-5 treatments during the 1991-1995 rotation was observed, resulting in approximately 3 ton/ha/harvest cycle lower production. It should be noted that during calibration, the base temperature and optimum temperature parameters were reduced to simulate this particular hybrid poplar species.

Figure 2-6: Cumulative biomass vs. cumulative fertilizer for irrigated treatments.

2.4.3 Impacts on water use

For hydrologic impact analysis, additional water use associated with the conversion from existing land cover to poplar cultivation is defined as the water used for irrigation and the difference in ET between the existing land uses and the land converted to poplar. Fig. 2-7 shows the average inter- and intra-annual ET rates in the converted portion of the watershed for the 83–6 irrigated treatment, demonstrating a substantial increase in ET due to poplar cultivation. Averaged across all simulated treatments, the ET rates for the converted area are 555 mm/year and 534 mm/year for irrigated and non-irrigated conditions, respectively, which are 29% and 24% higher than for the existing land covers. These ET rates for poplar are in the middle of ranges reported values from Europe, Asia, US and Canada (Fischer et al., 2013). The ET cycles in Fig. 2-7a are a result of annual climate variations for the base case (existing land uses). The cycles for the 83–6 irrigated treatment, on the other hand, are influenced by both climate variations and the timing of the poplar harvest; the ET rate is continuously increasing as the tree biomass and LAI increase each year until the trees are harvested. Fig. 2-7b shows that the ET rates for the converted portion of the watershed are significantly higher during the growing season, with the peak difference during the month of June.

Figure 2-7: A) Annual ET rates for the converted area to demonstrate interannual impacts of biomass growth and cultivation; and B) Monthly average ET rates to demonstrate seasonal impacts.

The effect of irrigation on watershed-wide streamflow is demonstrated in Fig. 2-8, where the reduction in streamflow due to a given treatment is plotted against the increase in watershed-wide ET for the treatment. As expected, for the no-irrigation treatments, the decrease in streamflow roughly correlates with the increase in ET. For the no-irrigation treatments, increases in watershed-wide ET range between 8 and 23%, and decreases in watershed-wide streamflow range from 10 to 25%. The irrigated treatments have higher ET because there is more available water, greater biomass production and LAI, but the impact of higher ET on streamflow is offset directly by return flows from irrigation and indirectly due to higher soil moisture that reduces the soil infiltration capacity and increases runoff from subsequent rainfall events. On average, across the treatments, the

annual irrigation of 38 mm/year results in an increase of ET by 20 mm/year, and the remainder contributes to the streamflow as return flow.

Scenario A in Fig. 2-8, corresponding to the 1111-5IR fertilized treatment (5.1 kg N/ha/year), has a high biomass production as well as high nitrogen and water use efficiency. The 1111-5 treatments, in general, have the highest biomass production and highest nutrient and water use efficiency. In contrast, Scenario B, which represents the 17- 10IR-fertilized treatment (20.5 kg N/ha/year), has significantly higher ET due to irrigation. This can be explained by the fact that in longer rotations, the trees maintain high LAI over longer periods (several years) leading to higher ET and water demand, while in shorter rotations the trees are harvested as they reach a high LAI. In SWAT, ET is directly influenced by the LAI, and the effect of LAI on ET rate is reported in other studies (e.g., Fischer et al., 2013). In comparing Point B with Point C, which represents the 25-6IR fertilized (20.5 kg N/ha/ year) treatment, the reason for the smaller decrease in streamflow for the 17–10 IR (Point B) treatment is that this treatment receives much more irrigation water which contributes to the streamflow.

Figure 2-8: Illustration of how ET changes relate to streamflow changes for non-irrigated and irrigated cases. Refer to text for points A, B and C.

2.4.4 Tradeoffs

Fig. 2-9 summarizes the tradeoffs between annual biomass production, water use, and fertilizer application for irrigated and non-irrigated cases. The x- and y-axes show biomass production vs. water use, respectively, and the size of the symbol relates to the magnitude of fertilizer use. The no-irrigation and irrigation treatments with the largest cumulative biomass production and lowest increased water use are labelled as Points D, E, F, and G. All of these are 1111–5 treatments, suggesting that high planting densities and short rotations offer the best tradeoff between biomass production and water use. Fertilizer application rates for Points D and F are 41 kg N/ha/year, and the rates for Points E and G are 20.5 kg N/ha/year, indicating that the higher fertilization rate produces only 1–2% more biomass. The remaining points in Fig. 2-9 have substantially lower biomass production, lower fertilizer application rates, and either lower planting densities or longer rotations, resulting in substantially lower biomass production.

Comparison of points D and E with points F and G indicates that biomass is increased by 3% and 6% with irrigation, but at the cost of increases in water use of 13%. Although the simulations show that irrigation does not produce substantially more biomass, on average, irrigation can be critical for mitigating the impacts of dry years, especially when a dry year coincides with later years in the rotation cycle, when the trees have higher water demand. The average irrigation rates over the rotation cycles range from as low as 13.8 mm/year in the 1981–86 cycle, when wet years (average 1037 mm/year) occur in the last two years of rotation. The highest average irrigation requirement over a rotation, 64.2 mm/year, occurred in the 2001–05 cycle as a result of two dry years (average 681 mm/year precipitation) at the end of the rotation.

Figure 2-9: Cumulative biomass vs. water use at watershed scale, excluding non-fertilization cases. Size of symbol is proportional to magnitude of cumulative fertilizer application. Refer to text for explanation of points D, E, F, and G.

Fig. 2-10 shows that intra- and interannual variations in climate can produce severe decreases in streamflow due to conversion to poplar. Fig. 2-10a shows that July is the most critical month, with an average decrease of 48% in average monthly flows. In Fig. 2-10b, the cumulative probability density of July streamflows over the simulation period indicates a significant shift downward in high flows (Q_{90} , Q_{95} , and Q_{99} , decreases by 45%). High flows are reduced due to lower soil moisture and higher canopy interception for the poplar-converted land, compared to the existing forest cover, especially in the last years of each rotation when LAI and water demand are high. Low flows, indicated by Q_1 , Q_5 , and Q_{10} , decreased on average by 32%.

On average for all the planting intensities, to produce 1 ton of poplar biomass on 1 ha of land, there is a need for around 128mm of water and 9.4 kg N to be applied (with 5.1 kg N uptake by the trees). Table 2-3 shows that the 1111–5 treatment requires the least amount of total and extra water, followed by the 278–5 treatment. However, it should be

noted that hybrid poplar plantations with lower planting densities have longer rotations and more flexible harvest scheduling as well as lower costs (Strong and Hansen, 1993), which are not considered in this analysis. It remains to be seen whether high-density, short-rotation treatments will be adopted by poplar plantation managers.

Table 2-3: Water and fertilizer requirements to produce 1 ton of biomass in 41 kg N/ha/yr fertilized treatments.

		Treatment					
	Parameter	1111-5	278-5	83-6	25-6	17-10	Average
Irrigated	N Uptake (kg N/ ton biomass/ ha)	3.8	4.1	4.6	4.6	7.3	4.9
	Total water use (mm/ ton biomass/ha)	93.5	113	125	185	127	129
	Extra water use (mm/ton biomass/ha)	23.7	29.9	33.3	51.4	36.9	35
No Irrigation	N Uptake (kg N/ ton biomass/ ha)	4.0	4.2	4.8	4.8	8.2	5.2
	Total water use (mm/ ton biomass/ha)	93.4	114	129	191	125	130
	Extra water use (mm/ton biomass/ha)	17.6	23.1	26.6	42.1	24.1	26.7

To evaluate the potential for large-scale biofuel feedstock development in the region, the four surrounding counties (Oneida, Lincoln, Price and Taylor) were analyzed and found to have 50% forested land. Similar to the case study watershed, hay, rangelands and herbaceous cover accounted for 4% of the area. Therefore, the scenario implemented in the model can be considered representative for the four county region, where up to 6200 km² could be available for biofuel development.

Water quality measurements were not available for this study, and thus simulated N transport and water quality were not reported. However, the N uptake in SWAT is based on measured N content of the tree in three life stages. Based on these results, the quantities of N added, N uptake, and N available for potential pollution impacts are provided (see Table 6-5 for detailed results). A study of water quality impacts of poplar development in this region remain as important future work.

Figure 2-10: A) Average monthly stream flow for 83-6NIR fully fertilized treatment; and B) cumulative distribution function of flow for the month of July.

2.5 Conclusions

A SWAT model was calibrated and validated to simulate the daily streamflow of a relatively humid watershed in northern Wisconsin. The plant growth component of the model was also calibrated to match the LAI growth and biomass production of poplar trees using measured data from a nearby research plot. The plant growth improvements enabled the model to simulate different planting densities as there is no direct parameter in SWAT to account for different planting densities. Seventy different scenarios of poplar plantation with different management treatments (densities, harvest period, irrigation, and fertilization) over a 30-year period were simulated.

Results show that poplar development increases the total ET of the watershed substantially during the growing season (June to December). This causes lower streamflow during the growing season and makes the already low-flow months of July and August more critical. Furthermore, the decline in streamflow becomes more severe in the final years of each rotation, when trees have higher LAI and more water demand. Analysis of the stream flow shows that the poplar trees take up the moisture from the soil and cause the baseflow to be more affected than the surface flow. Inspection of the interannual impacts led to two important discoveries. First, temperature stress can reduce biomass production even if the trees are fertilized and irrigated. Second, in a relatively humid watershed, the average impact of irrigation on biomass production may be minimal, but there may be a significant benefit from irrigation if the last year in a harvest cycle is a dry year. In contrast to the effects of irrigation, tree growth and biomass production are significantly dependent on N availability, making fertilization a necessary management treatment. Model results indicate that adding fertilizer leads to remarkably higher biomass production up to a level of about 41 kgN/ha/year, but additional fertilizer beyond this level does not enhance biomass production but only increases the amount of N remaining in the soil, with the potential to contribute to non-point source pollution.

The highest density (1111 trees/100m²) and shortest rotation (5- year) treatments produce the highest biomass and are the most efficient treatments in terms of water and fertilizer use per ton of biomass. The next highest density (278 trees/100m²) treatments follow closely in terms of production and efficiency. High-density plantings and short rotations are found to be efficient in terms of water and fertilizer inputs because the trees are harvested as soon as they reach maximum LAI values, while in longer rotations the trees are kept at higher LAI for longer periods leading to higher water use. Moreover, the higher planting densities capture more solar radiation, represented by a higher light extinction coefficient, which results in higher biomass production.

2.6 References

- Abbaspour, K.C., 2013. SWAT-CUP 2012. SWAT Calibration and Uncertainty Program—A User Manual.
- Arnold, J.G., Allen, P.M., 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records 1. JAWRA Journal of the American Water Resources Association, 35(2), 411-424.
- Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W. and Kannan, N., 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE, 55(4), 1491-1508.
- Arnold, J.G., Muttiah, R.S., Srinivasan, R., Allen, P.M., 2000. Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin. Journal of Hydrology, 227(1), 21-40.
- Babel, M.S., Shrestha, B., Perret, S., 2011. Hydrological impact of biofuel production: A case study of the Khlong Phlo Watershed in Thailand. Agricultural water management, 101(1), 8-26.
- Berndes, G., 2002. Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. Global environmental change, 12(4), 253-271.
- Brown, K., Driessche, R.v.d., 2002. Growth and nutrition of hybrid poplars over 3 years after fertilization at planting. Canadian Journal of Forest Research, 32(2), 226-232.
- Chapagain, A.K., Hoekstra, A.Y., 2008. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. Water international, 33(1), 19-32.
- Cibin, R., Trybula, E., Chaubey, I., Brouder, S. M., & Volenec, J. J., 2016. Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model. Gcb Bioenergy, 8(4), 837-848.

Coleman, M., Tolsted, D., Nichols, T., Johnson, W.D., Wene, E.G. and Houghtaling, T., 2006. Post-establishment fertilization of Minnesota hybrid poplar plantations. *Biomass and Bioenergy*, 30(8-9), 740-749..

Department of Natural Resources, Wisconsin. 2016. Aspen report 2016. Available online at: <http://dnr.wi.gov/topic/ForestBusinesses/documents/AspenReport.pdf>.

Ek, A.R., Dawson, D.H., 1976. Actual and projected growth and yields of *Populus* 'Tristis# 1' under intensive culture. *Canadian Journal of Forest Research*, 6(2), 132-144.

EPA 2011. *Biofuels and the Environment: First Triennial Report to Congress*. U.S. Environmental Protection Agency, EPA/600/R-10/183F: 220 pp. Washington, DC, December.

Engel, B., Chaubey, I., Thomas, M., Saraswat, D., Murphy, P. and Bhaduri, B., 2010. Biofuels and water quality: challenges and opportunities for simulation modeling. *Biofuels*, 1(3), 463-477.

Fischer, M., Trnka, M., Kučera, J., Deckmyn, G., Orság, M., Sedlák, P., Žalud, Z. and Ceulemans, R., 2013. Evapotranspiration of a high-density poplar stand in comparison with a reference grass cover in the Czech–Moravian Highlands. *Agricultural and forest meteorology*, 181, 43-60.

Fortier, J., Gagnon, D., Truax, B., Lambert, F., 2010. Biomass and volume yield after 6 years in multiclinal hybrid poplar riparian buffer strips. *Biomass and bioenergy*, 34(7), 1028-1040.

Fraiture, C.d., Giordano, M., Liao, Y., 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. *Water policy*, 10(S1), 67-81.

Gerbens-Leenes, P., Van Lienden, A., Hoekstra, A.Y., Van der Meer, T.H., 2012. Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030. *Global Environmental Change*, 22(3), 764-775.

Gopalakrishnan, G., Negri, M. C., Wang, M., Wu, M., Snyder, S. W., & Lafreniere, L., 2009. Biofuels, land, and water: a systems approach to sustainability. *Environmental science & technology*, 43(15), 6094-6100.

Guo, T., Engel, B. A., Shao, G., Arnold, J. G., Srinivasan, R., & Kiniry, J. R., 2015. Functional approach to simulating short-rotation woody crops in process-based models. *BioEnergy Research*, 8(4), 1598-1613.

Guo, T., Engel, B. A., Shao, G., Arnold, J. G., Srinivasan, R., & Kiniry, J. R., 2018. Development and improvement of the simulation of woody bioenergy crops in the Soil and Water Assessment Tool (SWAT). *Environmental Modelling & Software*.

Gupta, H.V., Sorooshian, S., Yapo, P.O., 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering*, 4(2), 135-143.

Hansen E, B.J., 1979. Biomass and nutrient removal in short rotation intensively cultured plantations. In *Proceedings: Impact of intensive harvesting on forest nutrient cycling*, at 1979. State University of New York, College of Environmental Science and Forestry, 130-151.

Hillard, S., 2017. Evaluation of hybrid poplar management, production potential, and estimation of impacts to water resources in the upper great lakes region.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., Van Velthuizen, H. and Wiberg, D., 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, 3(7), 621.

Jiang, R., WANG, T.T., Jin, S.H.A.O., Sheng, G.U.O., Wei, Z., YU, Y.J., CHEN, S.L. and Hatano, R., 2017. Modeling the biomass of energy crops: Descriptions, strengths and prospective. *Journal of integrative agriculture*, 16(6), 1197-1210.

King, J.S., Ceulemans, R., Albaugh, J.M., Dillen, S.Y., Domec, J.C., Fichot, R., Fischer, M., Leggett, Z., Sucre, E., Trnka, M. and Zenone, T., 2013. The challenge of lignocellulosic bioenergy in a water-limited world. *BioScience*, 63(2), 102-117. Lo, S.S., 1992. *Glossary of hydrology*. Water Resources Publications.

Kurtz, C. M. 2017. *Forests of Wisconsin, 2016*. :1–4 Available online at: <https://doi.org/10.2737/FS-RU-108>.

Love, B.J., Nejadhashemi, A.P., 2011. Water quality impact assessment of large-scale biofuel crops expansion in agricultural regions of Michigan. *Biomass and Bioenergy*, 35(5), 2200-2216.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3), 885-900.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, 10(3), 282-290.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. *Soil and water assessment tool theoretical documentation version 2009*, Texas Water Resources Institute.

Ng, T.L., Eheart, J.W., Cai, X. and Miguez, F., 2010. Modeling *Miscanthus* in the soil and water assessment tool (SWAT) to simulate its water quality effects as a bioenergy crop. *Environmental science & technology*, 44(18), 7138-7144.

Paine, L.K., Peterson, T.L., Undersander, D.J., Rineer, K.C., Bartelt, G.A., Temple, S.A., Sample, D.W. and Klemme, R.M., 1996. Some ecological and socio-economic considerations for biomass energy crop production. *Biomass and Bioenergy*, 10(4), 231-242.

Phifer, C. "Impacts to biodiversity and ecosystem services from bioenergy development: a pan American experience." PhD dissertation. Michigan Technological University. 2017

Powers, S., Ascough II, J., Nelson, R., Larocque, G., 2011. Modeling water and soil quality environmental impacts associated with bioenergy crop production and biomass removal in the Midwest USA. *Ecological Modelling*, 222(14), 2430-2447.

Schilling, K.E., Jha, M.K., Zhang, Y.K., Gassman, P.W., Wolter, C.F., 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resources Research*, 44(7).

Singh, J., Knapp, H.V., Arnold, J., Demissie, M., 2005. Hydrological modeling of the Iroquois River watershed using HSPF and SWAT. *JAWRA Journal of the American Water Resources Association*, 41(2), 343-360.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. Available online at <https://sdmdataaccess.sc.egov.usda.gov>. Accessed [09/18/2017].

Stanturf, J.A., Van Oosten, C., Netzer, D.A., Coleman, M.D., Portwood, C.J., 2001. Ecology and silviculture of poplar plantations. *Poplar Culture in North America(Part A)*: 153-206.

Stephens, W., Hess, T., Knox, J., 2001. Review of the effects of energy crops on hydrology. Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

Strong, T., Hansen, E., 1993. Hybrid poplar spacing/productivity relations in short rotation intensive culture plantations. *Biomass and Bioenergy*, 4(4), 255-261.

Thomas, M.A., Engel, B.A., Chaubey, I., 2009. Water quality impacts of corn production to meet biofuel demands. *Journal of Environmental Engineering*, 135(11), 1123-1135.

Truax, B., Gagnon, D., Fortier, J., Lambert, F., 2012. Yield in 8 year-old hybrid poplar plantations on abandoned farmland along climatic and soil fertility gradients. *Forest ecology and management*, 267, 228-239.

United States Environmental Protection Agency (EPA), Assessment and Standards Division, Office of Transportation and Air Quality. 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis, no. EPA-420-R-10-006 (2010). Chapter 5, Economic Impacts and Benefits.

U.S. Environmental Protection Agency Office of Research and Development
Washington, DC. Biofuels and the Environment Second Triennial Report to Congress.
June, 2018.

Watkins, D.W., de Moraes, M.M.A., Asbjornsen, H., Mayer, A.S., Licata, J., Lopez, J.G., Pypker, T.G., Molina, V.G., Marques, G.F., Carneiro, A.C.G. and Nuñez, H.M., 2015. Bioenergy development policy and practice must recognize potential hydrologic impacts: Lessons from the Americas. *Environmental management*, 56(6), 1295-1314.

Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2013. ArcSWAT interface forSWAT2012: user's guide. Blackland Research and Extension Center, Texas Agrilife Research. Grassland. Soil and Water Research Laboratory, USDA Agricultural Research Service, Texas, 3.

Winjobi, O., Tavakoli, H., Klemetsrud, B., Handler, R., Marker, T., Roberts, M. and Shonnard, D., 2018. Carbon Footprint Analysis of Gasoline and Diesel from Forest Residues and Algae using Integrated Hydropyrolysis and Hydroconversion Plus Fischer–Tropsch (IH2 Plus cool GTL). *ACS Sustainable Chemistry & Engineering*, 6(8), 10766-10777.

Wu, M., Demissie, Y., Yan, E., 2012. Simulated impact of future biofuel production on water quality and water cycle dynamics in the Upper Mississippi river basin. *biomass and bioenergy*, 41, 44-56.

Wu, Y., & Liu, S., 2012. Impacts of biofuels production alternatives on water quantity and quality in the Iowa River Basin. *biomass and bioenergy*, 36, 182-191.

Zavitkovski, J., 1983. Projected and actual biomass production of 2-to 10-year-old intensively cultured *Populus' tristis*# 1'. In: Hansen, Edward A., ed. Intensive plantation culture: 12 years research. Gen. Tech. Rep. NC-91. St. Paul, MN: US Department of Agriculture, Forest Service, North Central Forest Experiment Station: 72-76., 91.

Zhang, X., Izaurrealde, R.C., Arnold, J.G., Sammons, N.B., Manowitz, D.H., Thomson, A.M. and Williams, J.R., 2011. Comment on “modeling *Miscanthus* in the soil and water assessment tool (SWAT) to simulate its water quality effects as a bioenergy crop”. *Environmental science & technology*, 45(14), 6211-6212.

3 Spatially variable hydrologic impact and biomass production tradeoffs associated with Eucalyptus cultivation for biofuel production in Entre Rios, Argentina

3.1 Abstract

Climate change and energy security promotes using renewable sources of energy such as biofuels. High woody biomass production achieved from short rotation intensive plantations is an appealing strategy that is growing in many parts of the world. However, broad expansion of bioenergy feedstock production may have significant environmental consequences. This study investigates the watershed-scale hydrological impacts of eucalyptus plantations for energy production in a humid subtropical watershed in Entre Rios province, Argentina. A Soil and Water Assessment Tool (SWAT) model was calibrated and validated for streamflow, leaf area index (LAI), and biomass production cycles. The model was used to simulate various eucalyptus plantation scenarios that followed physically-based rules for land use conversion (in various sizes and locations in the watershed) to study hydrological effects, biomass production and the green water footprint of energy production. SWAT simulations indicated that the most limiting factor for plant growth was shallow soils causing seasonal water stress. This resulted in a wide range of biomass productivity throughout the watershed. An optimization algorithm was developed to find the best location for eucalyptus development regarding highest productivity with least water impact. Eucalyptus plantations had higher evapotranspiration rates among terrestrial land cover classes; therefore, intensive land use conversion to eucalyptus caused a decline in streamflow, with February, January and March being the most affected months. October was the least-affected month hydrologically, since high rainfall rates overcame the canopy interception and higher ET rates of eucalyptus in this month. Results indicate that, on average, producing 1 kg of biomass in this region uses 0.8 m³ of water, and the green water footprint of producing 1m³ fuel is approximately 2150 m³ water, or 57 m³ water per GJ of energy, which is lower than reported values for wood-based ethanol, sugar cane ethanol and soybean biodiesel.

3.2 Introduction

Using sources of renewable energy, such as biofuels, may result in cleaner, cost-competitive alternatives to fossil fuels (Winjobi et al., 2018; Sekoai et al., 2019). Cellulosic crops, crop residues and woody biomass are promising bioenergy sources because they have shown to produce similar fuel yields per feedstock mass as first-generation biofuels such as corn-based ethanol (Lynd et al., 1991; Tilman et al., 2009). Short-rotation harvest of woody biomass is considered a major advance in bioenergy because of high rates of biomass production (Guerra et al., 2014). Eucalyptus is the most widely planted hardwood genus in the world, covering more than 19 million hectares

(Binkley and Stape, 2004). Eucalyptus is highly productive (for example, $>35 \text{ m}^3$ biomass/ha/year found by Albaugh et al., 2013), has a short rotation length of six to eight years, and has use as lumber and pulp (Dougherty and Wright, 2012). Many parts of the world are experiencing a rapid increase in eucalyptus plantations for biofuel (Gonzalez et al., 2011a). There are several bioenergy products from eucalyptus, including cellulosic biodiesel and ethanol (Gonzalez et al., 2011b) and wood pellets for direct heating or electricity generation (Pirraglia et al., 2010).

According to Stape et al. (2004a), eucalyptus plantations have high water use efficiency (WUE). Furthermore, fast-growing eucalyptus are more efficient water users compared to slower growing trees (Otto et al., 2014). However, eucalyptus plantations have been reported to have high water use compared to other species (Albaugh et al. 2013; Scott 2005) and compared to the native plants that they replace (Farley et al., 2005; Ferraz et al., 2013). In fact, eucalyptus has one of the highest ET rates among trees (Farley et al. 2005; Dye 2013; Hubbard et al. 2010), due to morphological and physiological characteristics including high stomatal conductance, evergreen leaves, drought tolerance, and deep rooting (Whitehead et al., 2004). Farley et al. (2005) observed a higher water use rate for eucalyptus by converting grassland to eucalyptus and pine plantations on a catchment scale. They concluded that converting to eucalyptus would decrease the streamflow 25%, compared to conversion to pine. Maier et al. (2017) studied short-rotation eucalyptus planting in South Carolina, USA at the plot scale and concluded that eucalyptus had a 40% higher transpiration rate compared to pine. However, little is known about eucalyptus cultivation impacts on specific hydrologic components, i.e. baseflow vs. surface runoff, and seasonality.

Proper site selection for biofuel-related land use conversion can be crucial for sustainably managing resources in a watershed (Cibin and Chaubey, 2015). An appropriately selected biofuel crop planted at a suitable location can reduce water quality impacts of biofuel development projects (Robertson et al., 2008; Parish et al., 2012). Spatial allocation of biofuel crops has been studied on different scales, from a national level in China using geographic information systems (Zhang et al., 2017) and at a watershed scale using optimization methods (Parish et al., 2012; Cibin and Chaubey, 2015; Herman et al., 2016; Femeena et al., 2018). However, the spatial variations in biomass production across the watershed are typically neglected. Biomass yield can vary significantly in cases where soil depth, soil quality, precipitation or temperature change across the watershed.

Sustainable biofuel production with minimal hydrologic and water pollution consequences can be achieved through scientific assessments of regional feedstock development impacts at the watershed scale (Gopalakrishnan et al., 2009; Engel et al., 2010; Watkins et al., 2015; Heidari et al., 2019a). Developing proper management practices to achieve high water use efficiency, while minimizing negative environmental impacts, requires quantification of eucalyptus water demand. To fully understand impacts of eucalyptus development on water resources, their growth cycle and water use should be studied in more detail at sub-watershed scales.

Hydrological models have been used globally to study hydrological impacts of biofuels, especially for first-generation bioenergy crops (e.g., Schilling et al., 2008; Love and Nejadhashemi, 2011; Lin et al., 2015), but less so for second-generation bioenergy crops (Hillard, 2017; Guo et al., 2018; Heidari et al. 2019a). SWAT is a commonly used ecohydrological, physically-based, spatially semi-distributed simulation model (Arnold et al., 2000). SWAT provides the opportunity for detailed simulations at scales ranging from tens of hectares up to watershed or river basin scales, including both hydrologic and plant growth sub-models. SWAT has been used to simulate biofuel development around the world for different crops (Babel et al., 2011; Cibir et al., 2016; Sinnathamby et al., 2017; Heidari et al., 2019a).

The goal of this study is to determine how eucalyptus-based biofuel feedstock cultivation will impact hydrological systems. Specific objectives are to assess the impacts of spatially varying patterns of eucalyptus plantation, biomass productivity, and water use for biomass production on baseflow, surface flow, and evapotranspiration. The interannual variability of hydrologic impacts is also to be evaluated, along with the explicit tradeoff between biomass production and water use. These objectives are accomplished by calibrating and validating a SWAT model, using both hydrologic and plant growth data, for eucalyptus plantations in a watershed located in Entre Rios, Argentina. Argentina is one of the largest biofuel producing countries in the world (Statista, 2017), and the Mesopotamia region of Argentina is an appealing candidate for continuing development with eucalyptus plantations. Planting of *E. grandis*, which is considered to be one the most important eucalyptus species globally (Dougherty and Wright, 2012), is expanding rapidly in the region (Phifer et al., 2017).

While SWAT has been used to study hydrologic processes in various watersheds in Argentina (Troin et al., 2012; Schwank et al., 2014; Cisneros et al., 2011; Havrylenko et al., 2016; Romagnoli et al., 2017), to the authors' knowledge, this is the first application of SWAT that focuses on improving eucalyptus growth parametrization and investigating the hydrologic impacts of eucalyptus plantations for biofuel development. Considering the rapid expansion of the eucalyptus in this region of Argentina, there is a need for more study of the water use, management and productivity of the plantations. In this work, the SWAT hydrologic and biomass growth models are calibrated and used to assess the impacts of spatially varying patterns of eucalyptus plantation, biomass productivity and water use for biomass production. The SWAT model is used to determine the feedstock stage water demand for biomass, fuel and energy production, as well as impacts on specific hydrologic components (baseflow, surface flow, and evapotranspiration) and the interannual variability of those impacts.

3.3 Methods

3.3.1 Model Setup, Calibration and Validation

The selected watershed (see Figure 3-1) is representative of the Argentinian Mesopotamia region. Land cover in the region typically consists of rangelands, crops such as soybeans (Modernel et al. 2016), natural forests (Espinal), orange orchards, and rivers and wetlands draining into the Uruguay River to the east. The Yuqueri Grande-Concordia hydrologic station (Base de Datos Hidrológica Integrada, 2015) was selected as the watershed outlet, and daily flow data for the period 1991-2013 was used for calibration and simulations. The contributing area to the gage was found to be 625 km², using the 30-meter resolution digital elevation model from USGS (USGS Earth Explorer, 2015) and ArcGIS 10.3. A customized streamline shapefile from the Argentina National Institute of Geography (Instituto Geografico Nacional, 2015) was used to improve the streamline delineation process.

Figure 3-1: A) Land use/land cover map of the watershed, locations of the sub-basins, and precipitation gauges with average annual precipitation (in mm); B) Land cover distribution in the watershed; and C) Study site location within the state of Entre Rios, Argentina.

Land use-land cover (LULC) maps from 2002-2003, 2005-2006, and 2013-2014 and soil maps were obtained from INTA. Land use land cover classifications were made with high resolution images including LANDSAT 5 and 8 with a spatial resolution of 30m from USGS (USGS Landsat Missions, 2015). For each growing season, a majority voting approach was applied considering five supervised classification methods: Maximum Likelihood, Support Vector Machines, Random Forest, LOGIT regression and Neural Networks (Waldner et al, 2016). Classes included orange orchards, agriculture, forests, eucalyptus and rangelands. Ground truth data for training and validation was compiled from different sources, including georeferenced photos, visual identification (in situ observation), georeferenced voice recordings, land owner's information, and visual interpretation of Very High Resolution (VHR) images. The overall accuracy for each LULC maps were 0.89 for 2002-2003, 0.91 in 2005-2006, and 0.95 in 2013-2014. The series of LULC maps indicated a significant decline in natural forest land (-60%) and orchards (-76%), while the area planted with eucalyptus expanded by slightly more than 100% over the 12-year period (see Table 7-1 for a summary of land cover change analysis). Preliminary assumptions for determining areas for biofuel development were that plantations would not compete with food crops (Paine et al., 1996) and no wetland areas would be converted. However, the land cover analysis indicated a large decrease in orange orchards and a slight variation in agriculture and rangelands over the time period evaluated.

Maximum and minimum daily temperature and daily precipitation, relative humidity and wind speed data were compiled from INTA for the Aero Concordia weather station (see Figure 3-1). In addition, Climate Forecast System Reanalysis (CFSR) global weather data from four more nearby stations was added to the SWAT weather database. Spatial interpolation of the climate data indicates that the area receives an average of 1220 mm of precipitation annually, with the majority of rainfall occurring during October, November and April (see Figure 3-2). Precipitation is higher in the eastern portion of the watershed (see Figure 3-1). The average annual temperature in the watershed is 19.4 °C with slight variation across the watershed. Figure 3-2 shows the intra-annual variation of streamflow, temperature, precipitation, and SWAT-simulated estimates of evapotranspiration (ET). The highest monthly average streamflow is in October, as a result of heavy rain events and average ET. Runoff efficiency, the ratio of annual stream flow to annual precipitation in the watershed, was 0.22 over the study period. Even though the months of January and February receive around 100 mm precipitation on average, they are among the lowest streamflow months due to higher temperature and ET.

ArcSWAT version 2012.10_4.19 (Winchell et al., 2013) was used for setting up the model. The watershed was divided into 8 sub-watersheds in order to assess the potential spatial variability of hydrologic impacts associated with eucalyptus cultivation. SWAT further divides the sub-basins into non-contiguous hydrologic response units (HRUs), which represent homogeneous areas within each sub-basin with unique combinations of land use, soil type and slope class. During the HRU definition, thresholds of 0, 5 and 15% were selected for LULC, soils, and slope classes, respectively, resulting in 185 HRUs.

Rivers and wetlands comprise 18% of the watershed land cover, and thus wetlands were considered in the model. Wetland functionality is described in detail in SWAT theoretical documentation (Neitsch et al., 2011) and Heidari et al. (2019).

Figure 3-2: Intra-annual patterns of monthly average precipitation, streamflow, temperature and actual ET (simulated).

Calibration and validation focused on both the hydrological and plant growth components of the model. The analysis was performed for 21 years (from 1993 to 2013) to include a combination of dry and wet years in both the calibration period (1993-2005) and validation period (2005-2013). Periods with missing or unreliable data, attributed to a bridge construction project that impacted the stream gage measurements in some periods, were omitted from the goodness-of-fit calculations. The hydrologic calibration method was similar to Heidari et al. (2019a), which included separating baseflow and surface flow (Arnold and Allen, 1999). This analysis resulted in the ratio of baseflow to total flow ranging from 0.35 to 0.51 on an annual basis. The next step was to conduct a sensitivity analysis using the p-value and t-statistic sensitivity tests in SWATCUP SUFI2 (Abbaspour, 2013). Finally, the sensitive parameters were adjusted in groups. Final adjusted parameter values are presented in Table 7-2 in Supplementary Materials. Performance metrics included the Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970), coefficient of determination (R^2), and percent bias (Pbias) (Gupta et al., 1999). The ratio of baseflow to total flow was also required to be within the historical range.

Calibration of the plant growth model in SWAT was based on improving predictions of LAI growth and biomass production. Improving the LAI simulation is important because it is a key driver of transpiration. The calibration process included calculating the heat units for the eucalyptus in the region and changing the LAI-related parameters. Parameters related to LAI development stages along with potential heat units were fixed to reflect the evergreen nature of the tree. Specifically, the maximum LAI was adjusted based on field measurements, and the biomass growth was calibrated to match the reported biomass yield in the area (INTA, 2016) by changing the radiation use efficiency

and light extinction coefficient. Reported values for these parameters from several studies (De Costa and Jayaweera, 1996; Stape et al., 2004b) informed the calibration process. Table 7-3 in the Supplementary Material lists the adjusted plant parameters. Full descriptions of each parameter are presented in the SWAT theoretical documentation (Neitsch et al., 2011).

3.3.2 Modeling Scenarios

Biofuel development scenarios were formulated considering a number of variables, including the land cover types being replaced, locations of feedstock cultivation (e.g., in headwaters or downstream sub-basins), spatially variable soil fertility, and whether or not irrigation is applied. SWAT model simulations were performed for the period 1991 to 2013, using the corresponding hydroclimatic time series. This period included a two-year warm-up period (1991-1993) to establish initial conditions, followed by a 21-year period (1993-2013) for scenario evaluation. This period allows for a range of climate conditions to be represented, as well as several harvesting rotations--specifically, the eucalyptus trees were planted at the end of August and were harvested at the end of May, with two 7-year rotations and a 6-year rotation represented in the 21-year simulation (i.e., initial planting is towards the end of the first year of the SWAT simulations). Simulated plantations were fertilized (100 kg N/ha/year) to prevent nutrient stress. The scenarios for various land areas converted to eucalyptus consider watershed, sub-basin and HRU scales, as described in Table 3-1.

A bi-criteria optimization model was developed to determine Pareto-optimal combinations of sub-basins, i.e.,

$$\max_{s \in S} B \text{ and } \max_{s \in S} Q \quad (1)$$

Where B is cumulative biomass production over the simulation period, Q is total streamflow, s is the sub-basin index, and S is the total set of sub-basins. The optimization procedure was based on results from the one sub-basin-at-a-time scenarios, formulated as a knapsack problem to maximize total biomass production subject to a single constraint on the allowable change in total streamflow. The tradeoff curve was generated by starting with a low level of allowable change in streamflow and then incrementally relaxing the constraint to allow more conversion.

Table 3-1: List of eucalyptus development scenarios simulated in SWAT.

Treatment (code)	Scale of conversion	Description	Area converted (km²)
Base case	Watershed	LULC is based on 2002 conditions, with 69 km ² (11% of total area of 625 km ²) already planted with eucalyptus.	--
Intensive (Int)	Watershed	All LULC classes except crops and wetlands are converted to eucalyptus.	391
Extreme (EX)	Watershed	All LULC classes except wetlands are converted.	517
Intensive irrigated (IntIr)	Watershed	All LULC classes except crops and wetlands are converted to plantations with irrigation.	391
A, B, C, D, E, F, G, H, AB, AC, etc.	Sub-basin	All LULC classes, except crops and wetlands, are converted in one sub-basin at a time and in combinations of sub-basins.	Varies (28-119)
HY1	HRU	The top one-third of high-yield HRUs, defined as those with productivity >79 ton/ha/rotation, are converted.	126
HY2	HRU	The top two-thirds of high-yield HRUs are converted.	172
HY3	HRU	All high-yield HRUs are converted.	219

3.4 Results and Discussion

3.4.1 Model evaluation

Comparison of simulated and observed monthly discharges, shown in Figure 3-3, demonstrates good performance of the hydrologic model. The Nash-Sutcliffe efficiency (NSE) of 0.55, R² of 0.55, and Pbias of -2.9% for the entire simulation period indicate satisfactory hydrologic model performance (Moriassi et al., 2007). Table 7-4 shows the goodness-of-fit statistics for the calibration and verification periods. Calibration of the biomass growth model in SWAT resulted in the most productive HRUs matching the highest reported yields for the area, approximately 100 tons/ha/rotation. The average simulated biomass yield was 75 tons/ha/rotation, also matching the average reported values for the region (INTA, 2016) (see Figure 7-1 for detailed annual biomass

production and LAI development simulated with SWAT). The simulated N uptake rate of 65 kg/ha/year is within the medium-high range reported by Stape et al. (2004b).

Figure 3-3: Observed and simulated monthly streamflow during the calibration (1993-2005) and validation (2006-2013) periods.

3.4.2 Analysis of watershed-scale impacts

Simulation results from all scenarios are summarized in Table 3-2. The intensive scenario had an average yield of 77.1 ton/ha/rotation (cumulative biomass = 9×10^6 ton). Under the intensive production scenario, streamflow was reduced at the watershed outlet on average by 28%. The surface flow was reduced by an average of 24%, with the greatest relative change in December through March (34% average decline). The average overall reduction in baseflow was 31%, with the months of January to April being the most impacted months, with an average baseflow decline of 39%. Figure 3-4 shows changes in monthly average total, baseflow and surface flow for the intensive scenario and the base case.

The eucalyptus plantations had the highest annual average ET rate (842 mm/year) among the terrestrial LULC classes in the basin, which was 24% higher than the average of 638 mm/year for all terrestrial LULC classes (the average over the watershed, including water bodies, was 812 mm/year). This eucalyptus ET rate is similar to what Stape et al. (2004b) reported for high-class productivity eucalyptus in Brazil for a similar climate. In the intensive scenario, the conversion increased the average annual ET over the newly converted land (319 km²) by 32% (204 mm), corresponding to a 14% increase over the watershed (625 km²). The large increase in ET in the converted area was due to large areas of rangelands being replaced. Conversely, converting orange orchards did not result in a large ET difference per unit area, as orange trees have similarly high ET rates and

canopy interception. Figure 3-5 shows the monthly average ET for the intensive scenario versus the base case during the simulation period. The substantially higher ET rate in January to April and September to December correlated to the greatest reductions in monthly streamflow shown in Figure 3-4.

Interannual variation in climate produced some severe decreases in streamflow due to conversion to eucalyptus. During the driest years (1999, 1995 and 2008), the average precipitation was 855 mm precipitation (compared to the mean annual precipitation of 1223 mm), and there was a 53% decline in the annual streamflow under the intensive production scenario. In wet years (25th percentile high annual precipitation), streamflow decreased only by 20%, on average. An annual precipitation of about 1200 mm was usually sufficient to saturate soils and fill the wetlands to capacity. The exceptions were 1997 (1182 mm) and 2009 (1332 mm), which had an average 38% decline in annual streamflow. These years both followed dry years, which caused large declines in soil moisture and wetland volume. Figure 3-6 shows the cumulative distribution of streamflow for the base case and intensive scenario over the simulation period. A significant shift downward in stream flows is observed as a result of replacing existing land cover with eucalyptus plantations, especially for the lower flows. The shift was smaller for higher flows as they are associated with heavier rainfall.

The extreme scenario had an average biomass yield similar to the intensive scenario, with 77.2 ton/ha/rotation, but produced a higher cumulative biomass (12×10^6 ton) as a result of converting 83% of the watershed to eucalyptus. This conversion increased the average annual ET by 18%, causing a 37% decline in the average annual streamflow. When 434 mm/year of irrigation of eucalyptus was added to the intensive scenario, the number of water stress days decreased by 85% and the cumulative biomass production of the watershed increased to 12.3×10^6 ton, an increase of 36% over the non-irrigated intensive scenario.

Figure 3-4: Average monthly baseflow, surface flow and total flow for Base case and Intensive scenario.

Figure 3-5: Monthly average simulated ET rates for base case and intensive scenario.

Figure 3-6: Cumulative distribution functions of monthly streamflow for the full simulation period (1993-2013) under Base case and Intensive scenarios. Inset shows the low-flow tails.

3.4.3 Variability in biomass productivity due to spatial variations in soil properties and climate

The simulation results indicate a wide range in biomass production at the HRU scale (average area = 3 km²), from 37 to 97 ton/ha/rotation for the intensive scenario. Figure 3-7 shows the variation in soil depth, precipitation, and yield across the sub-basins. The most critical spatially variable parameters for determining biomass productivity were precipitation and soil depth. The lowest productivities were associated with shallow soils (<500 mm deep soils), which reduce growth because the reservoir of available soil water is small, leading to water stress during low-rainfall or high-ET periods. Comparing HRUs with similar soil depths across sub-basins, different yields were mainly due to precipitation differences in these sub-basins. In wetter sub-basins, the relatively high precipitation maintained the water content of the soil, leading to a reduction in water stress. The results in Figure 3-7 allow comparison between the lowest biomass yield (sub-basin B) and highest biomass yield (sub-basin H) sub-basins. Sub-basin H is typical of the downstream portions of the watershed, comprising the highest soil depths and precipitation. Sub-basin B is typical of the upstream portions, where soil depths are shallower and annual precipitation is about 200 mm lower than the downstream sub-basins. In the intensive irrigated case, the additional water increased biomass yield by 50% in the upstream sub-basins.

Using results from the intensive scenario, the HRUs were sorted from the highest biomass productivity to the lowest, and high-yield HRUs were defined as those having a productivity of more than 75 ton/ha/rotation (in the upper half of the reported range of 50-100 ton/ha/rotation). The high-yield HRUs were then grouped so as to cover approximately one-third, two-thirds, and the total area of high-yield HRUs (a total area of 213 km²). The simulation results in Table 3-2 show that converting two-thirds of the highest yield HRUs (HY2) resulted in the highest productivity (83.7 ton/ha/rotation) among all the non-irrigated scenarios simulated in this study. Table 3-2 also shows, however, the high water cost per biomass for the HY scenarios. This is due to most of the high-yield HRUs being located in basins H and G, which have deep soils and high precipitation, leading to diminishing returns with respect to water use efficiency.

Figure 3-7: Map of soil depth, precipitation and yield variation in the watershed.

3.4.4 Watershed-wide trade-offs between biomass production and water consumption as a result of targeted eucalyptus cultivation

Figure 3-8 summarizes the tradeoffs between biomass production and streamflow impacts at the main outlet for the scenarios involving conversion of each sub-basin, one at a time. In the base case, the cumulative biomass yield was 1.6×10^6 ton, or an average yield of 75 ton/ha/rotation. Sub-basins F, G, and H were inferior to the other sub-basins because they had higher precipitation rates and a greater impact on streamflow at the outlet compared to the other sub-basins. In contrast, planting in sub-basins A and B produced a considerable amount of biomass with a relatively small decrease in the streamflow. This was surprising as these sub-basins had high local impacts at a sub-basin level (Table 3-2). However, sub-basins A and B had small watershed-wide impacts because they received lower precipitation amounts and their contribution to the total streamflow at the outlet

was relatively small (see Table 3-2). Further investigation of sub-basins A and B helped to understand how the hydrological impacts were dependent on which land cover was replaced, as well as the presence of water bodies. Sub-basin A experienced a high local impact (at the sub-basin level) since it was dominated by rangelands and it had a small area covered by rivers and wetlands. In sub-basin B, even though the total amount of converted area was greater, local hydrologic impacts were mitigated due to a larger area in this sub-basin being covered by water (Figure 3-1).

Figure 3-8: Cumulative biomass and relative streamflow changes for the Base case and one sub-basin at a time scenarios. Bubbles are scaled to the area of eucalyptus plantations in each scenario.

Figure 3-9 shows the biomass production-water impact tradeoff analysis generated by the optimization model (see detailed results in Supplemental Material, Table 7-5). At low levels of allowable change in streamflow (less than 3%), only one sub-basin was converted at a time (i.e., E, F, C, A). As the streamflow constraint was relaxed, the model continued with the best combination of two or more sub-basins until all sub-basins were converted. During the optimization, sub-basins A and C were picked the most frequently (22 and 19 times, respectively, out of 29 solutions), even though sub-basins H and G had the highest productivity (selected 5 and 6 times each). This result is explained by the fact that the high biomass yield in those two basins came with the cost of high water consumption. In other words, the biomass production per unit of water consumption was

highest for sub-basins A and C. A notable water-efficient solution, corresponding to ABC, produced 3.0×10^6 additional tons of biomass with only a 9.9% decrease in total streamflow relative to the base case. For comparison, the intensive scenario produced an additional 7.0×10^6 tons of biomass but resulted in a 28.8% decrease in total streamflow. Point ABCDE was also a critical point, as the slope of the trade-off curve steepened beyond this point due to the optimization model being forced to select sub-basins F, G and H in the rest of the solutions. Sub-basins G and H were the selected the least because of their low productivity per unit of water consumption.

Figure 3-9: Tradeoff between biomass production and hydrologic impacts at the watershed scale. The Base case and combinations of sub-basins with relatively high productivity per unit of water consumption are highlighted.

Table 3-2: Summary of biomass production and hydrologic impacts for each scenario. All changes are relative to Base case.

Treatment	Code	Fraction water-shed with eucalyptus	Cumulative biomass produced (10 ⁶ ton)	Yield of biomass (ton/ha /rotation)	Annual ET watershed (mm) (% change)	Annual streamflow at outlet (mm) (% change)	Additional water ^a per additional biomass (mm/10 ⁶ ton)	Contribution to flow at outlet in Base case	Change in water yield at sub-basin
Base case		11.0%	1.6	75.1	812 (-)	248 (-)	-	-	-
Basin A	A	17.6%	2.5	76.5	826 (1.7%)	240 (-3.0%)	8.9	6.7%	-41.1%
Basin B	B	21.2%	2.8	71.0	832 (2.4%)	238 (-4.2%)	8.3	12.1%	-34.1%
Basin C	C	17.2%	2.4	74.3	824 (1.5%)	241 (-2.7%)	8.8	7.3%	-32.0%
Basin D	D	23.9%	3.4	75.8	840 (3.4%)	233 (-6.1%)	8.3	12.7%	-42.7%
Basin E	E	12.8%	1.9	77.6	817 (0.7%)	245 (-1.1%)	10.0	5.4%	-19.9%
Basin F	F	15.1%	2.1	74.6	823 (1.3%)	242 (-2.5%)	12.0	17.5%	-14.1%
Basin G	G	15.4%	2.3	79.6	825 (1.6%)	238 (-3.9%)	14.3	15.2%	-24.2%
Basin H	H	16.5%	2.5	80.4	828 (2.0%)	235 (-5.2%)	14.4	23.0%	-22.3%
Intensive	Int	62.6%	9.0	77.1	927 (14.2%)	179 (-27.8%)	9.3	-	-
Extreme	Ex	82.8%	12.0	77.2	961 (18.3%)	157 (-36.7%)	8.8	-	-
Intensive, Irrigated	IntIrr	62.6%	12.3	104.9	1171(44.2%)	193 (-22.1%)	5.1	-	-
High yield 1	Hy1	19.4%	3.0	83.2	839 (3.3%)	228 (-8.0%)	14.3	-	-
High yield 2	Hy2	25.8%	4.0	83.7	853 (5.0%)	219 (-11.7%)	12.1	-	-
High yield 3	Hy3	34.1%	5.2	82.6	872 (7.3%)	208 (-15.9%)	11.1	-	-

3.4.5 Green water footprint

Water footprints represent the total water consumption associated with a production system, with green water defined as precipitation that is stored in the soil and available for evapotranspiration, and blue water defined as water extracted from rivers, lakes and aquifers (Hoekstra and Chapagain, 2006; Chiu and Wu 2013). Table 3-3 summarizes the range of water requirements for different biofuel production scenarios estimated in this study and several others. The calculations for Table 3-3 were based on an assumption of using the total aboveground biomass with no losses. Furthermore, this study only reports the water use at the farm gate, considering that total water use in the life cycle of biofuels is dominated by the feedstock production stage (Gerbens-Leenes et al., 2009). Water use values in Table 3-3 mostly account for rainfall and soil moisture and can be considered green water, except for a few cases that include irrigation, which is categorized as blue water. On average, simulations conducted herein indicate a water requirement of 0.79 m³ to produce 1 kg of dry biomass, or 1.26 kg of dry biomass would be produced from 1 m³ of water. This value is similar to that found by Maier et al. (2017), 0.69 m³ water/kg dry biomass for short rotation eucalyptus in South Carolina, USA. Moreover, Stape et al. (2004b) reported a similar but slightly lower range (0.31-0.62 m³/kg wet biomass) for eucalyptus production in Brazil.

Assuming each kilogram of biomass can produce 0.32 kg of fuel (GREET, 2016), and neglecting the water used at the refinery, an average of 2150 m³ of water would be used to produce 1 m³ of biodiesel. Further assuming this liquid fuel would have an energy content that is similar to conventional diesel fuels, 43 MJ/kg (BP, n.d.), results in a water footprint of 57.1 m³ water/GJ, or 205,588 l/MWh. A similar result from Maier et al. (2017) shows 50.1 m³/GJ for biodiesel derived from eucalyptus feedstock. The “additional water” shown in Table 3-3 is defined as the difference in water use (ET) between the intensive case and the base case. This represents the direct hydrologic impact of converting land to eucalyptus, which is just 0.17 m³/kg of biomass, or 14.6 m³/GJ of energy. Notably, these water use estimates for eucalyptus are orders of magnitude lower than what Dominguez-Faus et al. (2009) reported for irrigated corn and soybean. Moreover, the 57.1 m³/GJ found in this study is significantly lower than the reported values for wood-based ethanol (Schyns et al., 2017) and ethanol from sugarcane and soybean (Rodriguez et al. 2018). This indicates that planting eucalyptus in the case study basin can be a water-efficient method for biofuel feedstock production, especially if plantations are located on deep fertile soils which, considering the region’s high average annual precipitation, will eliminate the need for irrigation.

3.4.6 Discussion of Limitations

Leaf area index is a key parameter for plant growth models. It is related to photosynthesis, water and nutrient use, rate of growth, and accumulation of dry matter (Smethurst et al., 2003; Ishak and Awal, 2007). Similarly for SWAT, LAI is a key

parameter for simulating actual ET and biomass production (Neitsch et al., 2011). LAI measurements (Maire et al., 2011; Smethurst et al., 2003) indicate the non-linear nature of LAI development over time in eucalyptus trees. However, in SWAT, LAI increases at a constant rate until it reaches a specified maximum allowable LAI, and the annual growth rate is limited by a single parameter (number of years to maturity). This simplified model of LAI development can lead to inaccurate estimates of water use and annual incremental biomass production. LAI development in SWAT can be calibrated by changing the number of years to maturity, but this parameter also impacts the ratio of aboveground biomass to total biomass. Thus, there may be a tradeoff between accurate modeling of aboveground biomass and total biomass production. Another limitation in the growth model is the dormancy period. In SWAT, trees, perennials, and cool-season annuals go dormant as the day length nears the minimum for the year. Furthermore, the LAI starts to decrease to a specified minimum leaf area index during the dormant period. Both of these model assumptions are inaccurate for an evergreen tree such as eucalyptus. Despite the improvements to modeling LAI in this study (see LAI-related parameters in Table 7-3), a dormant period was simulated for two weeks in winter (mid-July), when the minimum day length occurs. However, this short dormancy period had a small impact on biomass production at an annual time scale.

Table 3-3: Water requirement for biomass, fuel and energy production estimated from this study and others.

Scenario	Water per biomass (m ³ / kg)	Water per fuel (m ³ / m ³)	Water per energy (m ³ / GJ)
Average	0.79	2148	57.1
Lowest yield	0.81	2207	58.7
Highest yield	0.75	2073	55.1
Irrigated ^a	0.85	2328	61.9
Additional water ^b	0.20	551	14.6
<u>Other studies:</u>			
Maier et al. (2017) – Eucalyptus biodiesel	0.69 0.35 (Wet)		50.1 ^c
Schyns et al. (2017) - Wood-based ethanol		2260	97.0
Dominguez-Faus et al. (2009) - Corn ethanol, irrigated			630-2408
Dominguez-Faus et al. (2009) - Soybean ethanol, irrigated			3861-77490
Wu et al. (2012) Corn stover ethanol		760-1000	
Rodriguez et al. (2018) - Sugarcane ethanol	0.2		76.0
Rodriguez et al. (2018) - Soybean biodiesel	1.5		242
Rodriguez et al. (2018) – Soybean, 2 nd harvest biodiesel	2.5		411
Chiu and Wu (2013) – Wood residue ethanol		212-1705	
	0.31-0.62 (Wet)		
Stape et al. (2004b) – Eucalyptus biomass			
Babel et al. (2011) - Oil palm biodiesel			110
Gerbens-Leenes et al. (2009) - Sugarcane ethanol			108
Gerbens-Leenes et al. (2009) - Soybean biodiesel			394

a) Includes green and blue water.

b) Computed as increased ET relative to the base case land use/land cover; refer text for details.

c) Not directly given by the author. Calculated with this study's assumptions.

3.5 Conclusions

The main objectives of this work were to study the hydrological impacts and water-biomass tradeoffs associated with the development of eucalyptus plantations for bioenergy production. A SWAT model was set up to study the hydrological impacts of biofuel development projects in a humid subtropical region of Argentina (northeastern Mesopotamia region, Entre Rios province). The model was calibrated and validated using long-term weather data and streamflow measurements, and plant growth parameters were

adjusted to improve the LAI growth and biomass production predictions. The model was used to simulate 21 years of eucalyptus growth in two 7-year rotations and one 6-year rotation. A range of eucalyptus plantation scenarios were defined to evaluate hydrological effects, biomass production potential, and the green water footprint of energy production under different assumptions about land use conversion.

Hydrologic model results indicated that the ET rates of eucalyptus were the highest among the local terrestrial LULC classes in the watershed, which resulted in a decline in the streamflow the amount of which depended on the area and location of the plantations. For an intensive scenario of converting rangelands, orange orchards, and forest (62.5 % of the watershed), an average annual decline of 28% in the total streamflow (including both surface and baseflow) was simulated. The greatest decline occurred during months of February, January and March, with an average decrease of 37%.

Planting eucalyptus in different parts of the watershed resulted in a wide range of biomass productivity (37-100 tons/ha/rotation), due to variability in soil depth and precipitation across the watershed. The lowest biomass production occurred on shallow soils, where limited soil moisture storage led to more frequent water stress. The water stress was more severe if the shallow soil was located in a sub-basin with lower average annual precipitation.

Water-biomass tradeoffs resulted from the more productive plantations having higher ET rates and consequently greater impacts on water yield at the watershed outlet. To some extent, the tradeoffs could be mitigated by accounting for the land cover being replaced and the amount of water bodies in the area. The ET rate was higher for open water than all terrestrial LULC classes, making it a controlling hydrologic process for the sub-basins. Further, conversion of orange orchards had less hydrologic impact per unit area than converting rangeland, although the total area of orange orchards was small.

Based on model results, the average green water footprint of biodiesel produced from eucalyptus was 2150 m³ per m³ fuel, or 57 m³ per GJ energy. These amounts are lower than or similar to reported values from other studies and crops in different parts of the world.

3.6 Data availability

The input data and modeling results of the SWAT model are available at <http://www.hydroshare.org/resource/ff7fbbcb8a0a451da606f855ec391639> (Heidari et al., 2019b).dictum

3.7 References

Abbaspour, K.C.: SWAT-CUP 2012: SWAT Calibration and Uncertainty Program: A User Manual, 2013.

Albaugh, J.M., Dye, P.J., and King, J.S.: Eucalyptus and water use in South Africa, *Int J For Res.*, 2013.

Arnold, J.G., and Allen, P.M.: Automated methods for estimating baseflow and ground water recharge from streamflow records, *J Am Water Resour Assoc.*, 35(2), 411-424, 1999.

Arnold, J.G., Muttiah, R.S., Srinivasan, R. and Allen, P.M.: Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin, *J Hydrol.*, 227(1-4), 21-40, 2000.

Babel, M.S., Shrestha, B. and Perret, S.R.: Hydrological impact of biofuel production: A case study of the Khlong Phlo Watershed in Thailand, *Agr Water Manage.*, 101(1), 8-26, 2011.

Base de Datos Hidrológica Integrada, <http://bdhi.hidricosargentina.gob.ar/>, accessed January 2015.

Binkley, D. and Stape, J.L.: Sustainable management of Eucalyptus plantations in a changing world, In *Proceedings of IUFRO Conference.*, 11-15, 2004.

BP. n.d.: Leading countries based on biofuel production in 2017 (in 1,000 metric tons of oil equivalent), Statista. Accessed March 12, 2019, Available from <https://www.statista.com/statistics/274168/biofuel-production-in-leading-countries-in-oil-equivalent/>.

Chiu, Y.W. and Wu, M.: Assessing county-level water footprints of different cellulosic-biofuel feedstock pathways, *Environ Sci Technol.*, 46(16), 9155-9162, 2012.

Chiu, Y.W. and Wu, M.: The water footprint of biofuel produced from forest wood residue via a mixed alcohol gasification process, *Environ Res Lett.*, 8(3), 035015, 2013.

Cibin, R. and Chaubey, I.: A computationally efficient approach for watershed scale spatial optimization, *Environ Modell Softw.*, 66, 1-11, 2015.

Cibin, R., Trybula, E., Chaubey, I., Brouder, S.M. and Volenec, J.J.: Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model, *Gcb Bioenergy.*, 8(4), 837-848, 2016.

Cisneros, J.M., Grau, J.B., Antón, J.M., De Prada, J.D., Cantero, A. and Degioanni, A.J.: Assessing multi-criteria approaches with environmental, economic and social attributes, weights and procedures: A case study in the Pampas, Argentina, *Agr Water Manage.*, 98(10), 1545-1556, 201.

De Costa, W.A. and Jayaweera, K.G.: Radiation use efficiency and above-ground biomass production of selected forest tree species, In Proceedings of International Forestry and Environment Symposium, 1996.

Dominguez-Faus, R., Powers, S.E., Burken, J.G. and Alvarez, P.J.: The water footprint of biofuels: A drink or drive issue?, *Environ. Sci. Technol.*, 43, 3005-3010, 2009.

Dougherty, Derek, and Jeff Wright.: Silviculture and economic evaluation of eucalypt plantations in the Southern US, *Bioresources.*, 7(2), 1994-2001, 2012.

Dye, P.: A review of changing perspectives on Eucalyptus water-use in South Africa, *Forest Ecol Manag.*, 301, 51-57, 2013.

Engel, B., Chaubey, I., Thomas, M., Saraswat, D., Murphy, P. and Bhaduri, B.: Biofuels and water quality: challenges and opportunities for simulation modeling., *Biofuels*, 1(3), 463-477, 2010.

Farley, K.A., Jobbágy, E.G. and Jackson, R.B.: Effects of afforestation on water yield: a global synthesis with implications for policy, *Glob Change Biol.*, 11(10), 1565-1576, 2005.

Femeena, P.V., Sudheer, K.P., Cibilin, R. and Chaubey, I.: Spatial optimization of cropping pattern for sustainable food and biofuel production with minimal downstream pollution, *J Environ Manage.*, 212, 198-209, 2018.

Ferraz, S.F., de Paula Lima, W. and Rodrigues, C.B.: Managing forest plantation landscapes for water conservation, *Forest Ecol Manag.*, 301, 58-66, 2013.

Gerbens-Leenes, W., Hoekstra, A.Y. and van der Meer, T.H.: The water footprint of bioenergy, *Proceedings of the National Academy of Sciences*, 106(25), 10219-10223, 2009.

Gonzalez, R., Treasure, T., Wright, J., Saloni, D., Phillips, R., Abt, R. and Jameel, H.: Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I, *Biomass Bioenerg.*, 35(2), 755-766, 2011.

Gopalakrishnan, G., Negri, M.C., Wang, M., Wu, M., Snyder, S.W. and Lafreniere, L.: Biofuels, land, and water: a systems approach to sustainability, *Environ Sci Technol.*, 43(15), 6094-6100, 2009.

GREET Life-Cycle Model User Guide, Argonne National Laboratory, 2016.

Guerra, S.P., Garcia, E.A., Lanças, K.P., Rezende, M.A. and Spinelli, R.: Heating value of eucalypt wood grown on SRC for energy production, *Fuel.*, 137, 360-363, 2014.

Guo, T., Cibin, R., Chaubey, I., Gitau, M., Arnold, J.G., Srinivasan, R., Kiniry, J.R. and Engel, B.A.: Evaluation of bioenergy crop growth and the impacts of bioenergy crops on streamflow, tile drain flow and nutrient losses in an extensively tile-drained watershed using SWAT, *Sci Total Environ.*, 613, 724-735, 2018.

Gupta, H.V., Sorooshian, S. and Yapo, P.O.: Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration, *J Hydrol Eng.*, 4(2), 135-143, 1999.

Havrylenko, S.B., Bodoque, J.M., Srinivasan, R., Zucarelli, G.V. and Mercuri, P.: Assessment of the soil water content in the Pampas region using SWAT, *Catena.*, 137, 298-309, 2016.

Heidari, A., Mayer, A. and Watkins, D.: Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA, *J Hydrol.*, 20 Apr 2019a.

Heidari, A., Mayer, A., Watkins, D., Propato, T., Verón, S., and Abelleira, D.: Data for a SWAT modeling paper: Spatially variable hydrologic impact and biomass production tradeoffs associated with Eucalyptus cultivation for biofuel production in Entre Rios, Argentina, *HydroShare*, <http://www.hydroshare.org/resource/ff7fbbcb8a0a451da606f855ec391639>, last access: 13 May 2019b.

Herman, M.R., Nejadhashemi, A.P., Daneshvar, F., Abouali, M., Ross, D.M., Woznicki, S.A. and Zhang, Z.: Optimization of bioenergy crop selection and placement based on a stream health indicator using an evolutionary algorithm, *J Environ Manage.*, 181, 413-424, 2016.

Hillard, S.: Evaluation of hybrid poplar management, production potential, and estimation of impacts to water resources in the upper great lakes region, PhD dissertation, Michigan Technological University, 2017.

Hoekstra, A.Y. and Chapagain, A.K.: Water footprints of nations: water use by people as a function of their consumption pattern, *Integrated assessment of water resources and global change*, Springer, Dordrecht, 35-48, 2006.

Hubbard, R.M., Stape, J., Ryan, M.G., Almeida, A.C. and Rojas, J.: Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations, *Forest Ecol Manag.*, 259(9), 1714-1721, 2010.

Instituto Geografico Nacional, <http://www.ign.gob.ar>, Accessed September 2015.

Ishak, W. and Awal, M.A.: Leaf area index model for oil palm FFB yield prediction, *Pertanika Journal of Tropical Agricultural Science.*, 30, 51-56, 2007.

- Le Maire, G., Marsden, C., Verhoef, W., Ponzoni, F.J., Seen, D.L., Bégué, A., Stape, J.L. and Nouvellon, Y.: Leaf area index estimation with MODIS reflectance time series and model inversion during full rotations of Eucalyptus plantations, *Remote Sens Environ.*, 115(2), 586-599, 2011.
- Lin, Z., Anar, M.J. and Zheng, H.: Hydrologic and water-quality impacts of agricultural land use changes incurred from bioenergy policies, *J Hydrol.*, 525, 429-440, 2015.
- Lo, S.S.: Glossary of hydrology, Water Resources Publications, 1992.
- Love, B.J. and Nejadhashemi, A.P.: Water quality impact assessment of large-scale biofuel crops expansion in agricultural regions of Michigan, *Biomass Bioenerg.*, 35(5), 2200-2216, 2011.
- Lynd, L.R., Cushman, J.H., Nichols, R.J. and Wyman, C.E.: Fuel ethanol from cellulosic biomass, *Science.*, 251(4999), 1318-1323, 1991.
- Maier, C.A., Albaugh, T.J., Cook, R.I., Hall, K., McInnis, D., Johnsen, K.H., Johnson, J., Rubilar, R.A. and Vose, J.M.: Comparative water use in short-rotation Eucalyptus benthamii and Pinus taeda trees in the Southern United States, *Forest Ecol Manag.*, 397, 126-138, 2017.
- Modernel, P., Rossing, W.A., Corbeels, M., Dogliotti, S., Picasso, V. and Titttonell, P.: Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America, *Environ Res Lett.*, 11(11), 113002, 2016.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, *Transactions of the ASABE.*, 50(3), 885-900, 2007.
- Nash, J.E. and Sutcliffe, J.V.: River flow forecasting through conceptual models part I—A discussion of principles, *J Hydrol.*, 10(3), 282-290, 1970.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R.: Soil and water assessment tool theoretical documentation version 2009, Texas Water Resources Institute, 2011.
- NIST Chemistry WebBook, OECD/IEA Electricity Information (various editions), International Gas Union, Natural Gas Conversion Guide (<http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx>), accessed on 03/09/2019.
- Otto, M.S.G., Hubbard, R.M., Binkley, D. and Stape, J.L.: Dominant clonal Eucalyptus grandis × urophylla trees use water more efficiently, *Forest Ecol Manag.*, 328, 117-121, 2014.

Paine, L.K., Peterson, T.L., Undersander, D.J., Rineer, K.C., Bartelt, G.A., Temple, S.A., Sample, D.W. and Klemme, R.M.: Some ecological and socio-economic considerations for biomass energy crop production, *Biomass Bioenerg.*, 10(4), 231-42, 1996.

Parish, E.S., Hilliard, M.R., Baskaran, L.M., Dale, V.H., Griffiths, N.A., Mulholland, P.J., Sorokine, A., Thomas, N.A., Downing, M.E. and Middleton, R.S.: Multimetric spatial optimization of switchgrass plantings across a watershed, *Biofuel Bioprod Bior.*, 6(1), 58-72, 2012.

Phifer, C.: Impacts to biodiversity and ecosystem services from bioenergy development: a pan American experience, PhD dissertation, Michigan Technological University, 2017.

Pirraglia, A., Gonzalez, R., Saloni, D. and Wright, J.: Wood pellets: An expanding market opportunity, *Biomass magazine*, 6, 68-75, 2010.

Potencial de desarrollo de plantaciones dendroenergéticas en Argentina. Instituto Nacional de Tecnología Agropecuaria, 2016.

Robertson, G.P., Dale, V.H., Doering, O.C., Hamburg, S.P., Melillo, J.M., Wander, M.M., Parton, W.J., Adler, P.R., Barney, J.N., Cruse, R.M. and Duke, C.S.: Sustainable biofuels redux. *Science.*, 322(5898), 49-50, 2008.

Rodriguez, R.D.G., Scanlon, B.R., King, C.W., Scarpore, F.V., Xavier, A.C. and Pruski, F.F.: Biofuel-water-land nexus in the last agricultural frontier region of the Brazilian Cerrado, *Appl Energ.*, 231, 1330-1345, 2018.

Romagnoli, M., Portapila, M., Rigalli, A., Maydana, G., Burgués, M. and García, C.M.

: Assessment of the SWAT model to simulate a watershed with limited available data in the Pampas region, Argentina, *Sci Total Environ.*, 596, 437-450, 2017.

Schwank, J., Escobar, R., Girón, G.H. and Morán-Tejeda, E.: Modeling of the Mendoza river watershed as a tool to study climate change impacts on water availability, *Environ Sci Policy.*, 43, 91-97, 2014.

Schyns, J.F., Booij, M.J. and Hoekstra, A.Y.: The water footprint of wood for lumber, pulp, paper, fuel and firewood. *Adv Water Resour.*, 107, 490-501, 2017.

Scott, D.F.: On the hydrology of industrial timber plantations. *Hydrol Process.*, 19(20), 4203-4206, 2005.

Sekoai, P.T., Ouma, C.N.M., Du Preez, S.P., Modisha, P., Engelbrecht, N., Bessarabov, D.G. and Ghimire, A.: Application of nanoparticles in biofuels: An overview. *Fuel.*, 237, 380-397, 2019.

- Sinnathamby, S., Douglas-Mankin, K.R. and Craige, C.: Field-scale calibration of crop-yield parameters in the Soil and Water Assessment Tool (SWAT), *Agr Water Manage.*, 180, 61-69, 2017.
- Smethurst, P., Baillie, C., Cherry, M. and Holz, G.: Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations, *Forest Ecol Manag.*, 176(1-3), 531-542, 2003.
- Stape, J.L., Binkley, D., Ryan, M.G. and Gomes A.D.N.: Water use, water limitation, and water use efficiency in a *Eucalyptus* plantation, *Bosque.*, 25(2), 2004a.
- Stape, J.L., Binkley, D. and Ryan, M.G.: *Eucalyptus* production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil, *Forest Ecol Manag.*, 193(1-2), 17-31, 2004b.
- Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C. and Williams, R.: Beneficial biofuels—the food, energy, and environment trilemma, *Science.*, 325(5938), 270-271, 2009.
- Troin, M., Vallet-Coulomb, C., Piovano, E. and Sylvestre, F.: Rainfall–runoff modeling of recent hydroclimatic change in a subtropical lake catchment: Laguna Mar Chiquita, Argentina, *J Hydrol.*, 475, 379-391, 2012.
- USGS Earth Explorer, <https://earthexplorer.usgs.gov/>, Accessed January 2015.
- USGS Landsat Mission, [https://landsat.usgs.gov /](https://landsat.usgs.gov/), Accessed January 2015.
- Watkins, D.W., de Moraes, M.M.A., Asbjornsen, H., Mayer, A.S., Licata, J., Lopez, J.G., Pypker, T.G., Molina, V.G., Marques, G.F., Carneiro, A.C.G. and Nuñez, H.M.: Bioenergy development policy and practice must recognize potential hydrologic impacts: Lessons from the Americas, *Environ Manage.*, 56(6), 1295-1314, 2015.
- Whitehead, D. and Beadle, C.L.: Physiological regulation of productivity and water use in *Eucalyptus*: a review, *Forest Ecol Manag.*, 193(1-2), 113-140, 2004.
- Winchell, M., Srinivasan, R., Di Luzio, M. and Arnold, J.: ArcSWAT interface for SWAT2012: user's guide, Blackland Research and Extension Center, Texas Agrilife Research. Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, Texas, 3, 2013.
- Winjobi, O., Tavakoli, H., Klemetsrud, B., Handler, R., Marker, T., Roberts, M. and Shonnard, D.: Carbon Footprint Analysis of Gasoline and Diesel from Forest Residues and Algae using Integrated Hydropyrolysis and Hydroconversion Plus Fischer–Tropsch (IH2 Plus cool GTL), *Acs Sustain Chem Eng*, 6(8), 10766-10777, 2018.

Wu, M., Chiu, Y. and Demissie, Y.: Quantifying the regional water footprint of biofuel production by incorporating hydrologic modeling, *Water Resour Res.*, 48(10), <https://doi:10.1029/2011WR011809>, 2012.

Zhang, J., Chen, Y., Rao, Y., Fu, M. and Prishchepov, A.V.: Alternative spatial allocation of suitable land for biofuel production in China, *Energ Policy.*, 110, 631-643, 2017.

Zhang, X., Zhang, L., Zhao, J., Rustomji, P. and Hairsine, P.: Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions, *Water Resour Res.*, 44(7), 2008.

4 Hydrologic impacts and trade-offs associated with developing oil palm for bioenergy in Tabasco, Mexico

4.1 Abstract

Area under oil palm cultivation has rapidly expanded worldwide due to demands for food oil, the potential for conversion of oil palm to liquid fuels, and the high oil productivity of palm. However, there is a scarcity of research on the short- and long-term potential hydrologic impacts of oil palm plantations at a watershed scale under various management practices. To investigate these potential impacts, a Soil and Water Assessment Tool (SWAT) model was set up and calibrated hydrologically to simulate the long-term streamflow. The plant growth module was also calibrated for improved leaf area index (LAI) and yield simulations. Oil palm development scenarios were simulated to investigate the hydrologic impacts of planting density, and land cover types being converted. Simulations results indicated significantly higher evapotranspiration rates of the oil palm (51%) compared to other land cover classes. However, the higher water use did not significantly impact the streamflow at the watershed level (maximum 9% decline) due to high precipitation over the southern parts of the watershed. In contrast, the hydrologic impacts were severe in the converted areas of the watershed (14.5% decline), especially for the low-flow months of April, May and June, when there was an average decline of 33.5%. Investigating the water-yield tradeoffs associated with management practices, a planting density of 150 palm/ha was the most efficient in terms of water use and fruit production. At this planting density, the green water footprint for producing biodiesel from oil palm was estimated to be 87 m³/GJ energy, which is lower than or similar to the footprints estimated for oil palm produced in other parts of the world.

4.2 Introduction

The African oil palm (*Elaeis guineensis*) can produce 4-5 ton/ha of oil, which is among the highest yields for the oil crops (Corley and Tinker 2003, Mukherjee 2014). Palm oil is used for biofuels in addition to cooking oil and as an ingredient in personal care products and processed foods (Mukherjee 2014). Oil palm is the fastest expanding tree species in humid tropical low lands, especially in Southeast Asia (FAOSTAT 2017). Land area for oil palm cultivation increased from 10 to 17 million ha from 2000 to 2012 (Pirker et al. 2016), resulting in attention to the environmental impacts of conversion to palm oil. Most of the research on environmental impacts of oil palm conversion has focused on deforestation and consequent greenhouse gas impacts and loss of biodiversity (Pirker et al. 2016, Vijay et al. 2016). The impacts of oil palm on hydrologic cycling are less well publicized or understood (Comte et al. 2012, Larsen et al. 2013, Carlson et al. 2014, Meijide et al. 2017, Manoli et al. 2018). Oil palm requires humid, warm conditions, such as those found in the tropics, to produce high yields (Sheil et al. 2009). While the

tropics are renowned as water-rich, oil palm yields could be increased substantially by irrigation in regions with greater variability or lower rainfall (Ludwig et al. 2011, Dislich et al. 2017, Woittiez et al. 2017). The impacts of drainage of land for oil palm cultivation also has been shown to be of concern, including soil subsidence and associated increases in flood risk. (Sumarga et al. 2016). Furthermore, conversion of tropical forests to oil palm has been shown to decrease streamflows substantially during dry seasons or droughts (Bruijnzeel 2004, Yusop et al. 2007, Adnan and Atkinson 2011, Merten et al. 2016, Dislich et al. 2017). Research on oil palm cultivation on hydrology has focused primarily on plot-scale studies of ecohydrologic fluxes, such as the impact of tree age on canopy rainfall interception (Farmanta and Dedi 2015, Chong 2018) and transpiration rates in palms with varying ages and grown on different slopes (Röll 2015, Hardanto et al. 2017). A small number of modeling studies have been used to investigate impacts from oil palm conversion, focusing on nutrient cycling (Babel et al. 2011) at the watershed scale and carbon-water-energy budgets at the plot scale (Manoli et al. 2018).

The tradeoffs between oil palm production and hydrologic impacts have been acknowledged, but there are no studies of how management of oil palm cultivation could mitigate these tradeoffs at the plantation and watershed scales. Ultimately, optimizing water use and oil palm production could result in more efficient land use and reduce conversion from natural landscapes. Moreover, while most of the studies on impacts of oil palm cultivation on hydrology have focused on Southeast Asia, there is little published on these impacts in tropical Latin America regions experiencing oil palm expansion (Gilroy et al. 2015, Furumo and Aide 2017). While deforestation due to oil palm cultivation occurs in Latin America (Vijay et al. 2016), as in Southeast Asia, the primary mode of conversion in Latin America is the transformation of cattle pasture to oil palm (Furumo and Aide 2017, Ramankutty and Graesser 2017). Thus, there is little information on how land use change from existing land use to oil palm cultivation impacts, or will impact, hydrologic cycling in the tropical Latin America setting. Our study area is located in the Mexican states of Tabasco and Chiapas, which underwent rapid deforestation to pasture lands in the late 1900s and is now experiencing oil palm conversion at a rapid rate. In Mexico at large, oil palm-cultivated area increased 485% from 2003 to 2017 (FAOSTAT 2017).

The goal of this study is to determine how oil palm cultivation practices impact hydrologic cycling at local and watershed scales in a Latin American setting. A calibrated Soil Water Assessment Tool (SWAT) hydrologic-agronomic model is used to simulate hydrologic fluxes and oil palm fruit production. The simulation results are synthesized to assess tradeoffs between hydrologic impact, e.g. impacts on dry season streamflows, and bioenergy feedstock production, for a range of management scenarios. Management scenarios based on the land use classes to be converted from present use to oil palm, oil palm planting densities, and maximum land slopes are formulated and simulated to investigate how tradeoffs between oil palm fruit production and streamflow change with spatial scale and alternative management practices.

4.3 Materials and methods

4.3.1 Study site, calibration and validation

The study area watershed, which includes areas in Tabasco and Chiapas, Mexico (Figure 4-1), was selected based on data availability and proximity to existing oil palm plantations in the region. The watershed land use is predominantly pasture for cattle raising, crop production and forests. The majority of the remaining forest is found at higher elevations and slopes. Long-term daily flow records from the Pichucalco hydrologic station (<http://www.conagua.gob.mx>) were used for hydrologic calibration and validation purposes. The contributing area to the gage was estimated as 361 km², based on 15-meter resolution digital elevation model provided by the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía- INEGI). The simulated watershed was extended 22 km downstream of the Pichucalco hydrologic station to capture more low-slope areas typical of oil palm plantations in the study region, resulting in a watershed area of 561 km². A customized streamline shapefile from CONAGUA (<http://www.conagua.gob.mx/>) was used for stream delineation. Land use-land cover (LULC) maps for 2000 and 2014 and soil maps were obtained from INEGI.

Maximum and minimum daily temperature and daily precipitation were compiled from the National Climatological database (Base de datos climatológica nacional, <http://clicom-mex.cicese.mx>). In addition, Climate Forecast System Reanalysis (CFSR) global weather data (<https://globalweather.tamu.edu/>) was added to the SWAT weather database (Fuka et al. 2013). Spatial interpolation of the climate data indicates that the area receives an average of almost four meters (3,960 mm) of precipitation annually, with the majority of rainfall occurring during June to October (see Figure 4-2). Precipitation is higher in the southern portion of the watershed (see Figure 4-1), where elevation increases to 2100 m ASL. The average annual temperature in the watershed is 25.2°C, with slight variation across the watershed. Figure 4-2 shows the intra-annual variation of streamflow, temperature and precipitation. The highest monthly average streamflow is in October, as a result of heavy rain events, with the lowest flow months occurring in March through May.

Figure 4-1: (a) Land use-land cover map of the watershed, location of streamflow gauge and watershed outlet, sub-basin boundaries, and average annual precipitation (in mm) for each sub-basin; (b) overall land use-land cover fractions for the Base Case scenario; and (c) study site location in the states of Tabasco and Chiapas, Mexico.

ArcSWAT version 2012.10_4.19 (Winchell et al. 2013) was used to incorporate the year 2000 land use-land cover (LULC) map for the region, which most closely aligns with the historical streamflow data. The watershed was divided into 9 sub-watersheds and 142 non-contiguous hydrologic response units (HRUs), which represent homogeneous areas within each sub-basin with unique combinations of land use, soil type and slope class. Thresholds of 0%, 10% and 10% were selected for LULC, soils, and slope classes, respectively, for the HRU definition. Calibration and validation focused on both the hydrologic and vegetation components of the model. The hydrologic model analysis was performed with 22 years of hydroclimatic data (from 1962 to 1983) to include a combination of dry and wet years in both the calibration period (1962-1973) and validation period (1974-1983). The hydrologic calibration method was similar to Heidari et al. (2019a and b), which includes separating baseflow and surface flow (Arnold and

Allen, 1999, <http://www.EnvSys.co.kr/~swatbflow>). Performance metrics include the Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe 1970), coefficient of determination (R^2), and percent bias (Pbias) (Gupta et al. 1999). The ratio of baseflow to total flow also was required to be within the range observed from the streamflow time series. Final adjusted SWAT parameter values are presented in Table 8-1 in Supplementary Materials.

Figure 4-2: Intra-annual patterns of precipitation, flow and temperature in the study area watershed.

The vegetation growth model simulates the change in biomass of the oil palm trees, including changes in canopy, modeled as leaf area index (LAI), and fruit yield as dry mass. Calibration of the plant growth model in SWAT was similar to Heidari et al. (2019a and b), where the maximum LAI, light extinction coefficient, and harvest index were adjusted to reflect reported changes yield with age in the literature (Woittiez et al. 2017, Corley and Tinker 2003, Ishak 2007, Gerritsma and Wessel 1997, Goh et al. 1994). Values for fruit yield were taken from fully fertilized treatments, such that no nutrient limitations were expected. A range of planting densities are simulated by adjusting the parameters controlling LAI and fruit yield to match LAI and yield reported in the literature (Goh 1982, Lamade and Setiyo 1996, Corley and Tinker 2003). Canopy interception parameters in the SWAT model were calibrated with guidance from literature values, accounting for changes in LAI and canopy interception as a function of planting density (Chong 2018, Farmanita and Dedi 2015, Arnold 2012). Table 8-2 in the Supplementary Material lists the adjusted plant parameters. A full description of each parameter is presented in the SWAT theoretical documentation (Neitsch et al. 2011).

4.3.2 Modeling Scenarios

The calibrated and validated model is used to simulate a range of oil palm conversion scenarios. In general, conversion to oil palm and subsequent fruit production are simulated as (a) initial planting of nursery stock in the first year of conversion; (b) a yield building phase, which lasts up to three years after planting (YAP) during which the canopy is not closed and no fruit is harvested; (c) a linear increase in fruits yield phase a (4-7 YAP); (d) a mature or plateau yield phase (8-14 YAP), (e) a yield decline phase (15-25 YAP), and (f) removal of the tree at 25 YAP (Woittiez et al. 2017, Fairhurst et al. 2014). Since planting densities are an important decision in oil palm cultivation, and planting densities impact both fruit production per area and ET, five planting densities were simulated (see Table 4-1) for each land use conversion scenario.

Table 4-1: Oil palm densities and associated maximum LAI simulated in SWAT.

Density (palm/ha)	Maximum LAI
55	2.00
105	3.75
150	5.50
210	7.25
270	9.00

The most recent LULC map (2014) was used in model simulations for the Base Case scenario, and the relevant model parameters were adjusted to account for the 2014 land cover (see land cover change analysis in Table 8-3 in the Supplementary Materials). The impacts of allowing or disallowing conversion of existing crop lands are simulated to assess policies of prohibiting land use competition between food crops and crops with potential industrial uses, such as using palm oil for biofuels. While current guidelines for optimal yield and minimizing soil erosion (Woittiez et al. 2017, Paramanathan 2013) indicate that plantations occur on lands with slopes less than 12% (Corley and Tinker 2008, Furumo and Aide 2017), we also allow oil palm conversion on slopes as high as 30%, to simulate the intensification of palm oil production due to higher demand and/or prices. The resulting four scenarios then are (a) Base Case; (b) conversion of pasture and forest (PF scenario) to oil palm on lands with slopes $\leq 12\%$ (127 km² converted); (c) conversion of crop, pasture and forest (PFA scenario) on lands with slopes $\leq 12\%$ (214 km² converted); and (d) conversion of crop, pasture and forest (PFA+) on lands with slopes $\leq 30\%$ (346 km² converted). Table 4-2 shows the areas of land use classes converted for each of the scenarios. Following a warm-up period to obtain initial conditions, each scenario simulation occurred over a 20-year period, using the 1964-1983 hydroclimatic time series. This period was deemed to have the most consistent and reliable hydroclimatic record for the site.

The green water footprint is the volumetric water consumption associated with consumption by a given production process of precipitation stored in the soil and available for evapotranspiration. The green water footprint is used as a metric to

compare, for example, water to energy efficiency for biofuels and other energy sources (Hoekstra and Chapagain 2006, Chiu and Wu 2013). We report the green water use per mass of biomass and, by using literature values for the expected energy generated per unit of biomass, we convert the green water consumption per mass to green water consumption per unit of energy generated. (Gerbens-Leenes et al. 2009). We then compare the green water footprints to literature values for oil palm fruit production and other biofuel feedstocks.

4.4 Results

4.4.1 Model performance evaluation.

Comparison of simulated and observed monthly discharges, shown in Figure 4-3, demonstrates good performance of the hydrologic model. The Nash Sutcliffe efficiency of 0.72, R^2 of 0.74 and Pbias of 4.5% for the entire simulation period indicates good hydrologic model performance (Moriassi et al., 2007). Table 8-4 shows the fitting statistics for the calibration and verification periods.

Figure 4-3: Figure 3. Measured and simulated discharge during the calibration (1964-1973) and validation (1973-1984) periods.

4.4.2 Optimal planting density.

Comparison across planting densities (Figure 4-4) shows that the highest fruit production occurs with an average planting density of 150 palm/ha. At planting densities lower than 150 palm/ha, the yields are lower simply because there are fewer oil palms per cultivated area. While planting densities greater than 150 palm/ha are more productive in earlier years, competition for solar radiation causes a rapid decline in the yield starting in year 7 or 8 for the high planting densities. In the vegetation growth sub-model, fruit yield is a function of intercepted solar radiation and radiation use efficiency (RUE). RUE does not change with tree age, but light interception, LAI, and fruit yield increase with oil palm age. However, the fruit production simulations account for a decline in yield at a threshold around LAI of 6, as observed by Breure (2010), due to competition for solar radiation, resulting in the simulated declines in fruit production for higher planting densities. Figure 4-5 shows the annual fruit yield versus the annual additional water use for all planting densities and scenarios. Additional water use is defined as the difference between ET for the base case and ET for a given conversion scenario for the converted land. These results indicate that, for every scenario, the 150 palm/ha planting density is the most efficient in terms of maximizing fruit production and minimizing additional water use. The increasing trend in efficiency from lower planting densities (55 and 105 palm/ha) to the 150 palm/ha planting density reflects a greater fractional increase in fruit production, due to the greater number of palms (see Figure 4-4) than the corresponding fractional increase in water use. The smaller fractional increase in water use is due the lower sensitivity of ET sub-models to LAI, relative to the sensitivity of fruit production to LAI. The efficiency decreases when planting density increases from 150 palm/ha, indicating that fruit production decreases and water use increases. While the fruit yield declines steeply with planting density greater than 150 palm/ha (see Figure 4-4), due to the threshold LAI that indicates radiative crowding, the increase in LAI with planting density tends to slightly increase the ET rate. Since the overall pattern of efficiency of water use per biomass production is similar across the planting densities (Figure 4-5), results for only the most efficient density of 150 palm/ha are reported in the remaining text.

Figure 4-4: Fruit yield simulation results versus time for different planting densities, with measured values for the 150 palm/ha planting density.

4.4.3 Hydrologic impacts in converted areas

The results in Table 4-2 show that the overall ET rate increases by 39% to 51% in the land areas converted to oil palm, with a resulting reduction of water yield of 11% to 15%, depending on the conversion scenario. The results in Figure 4-5 show that both the volumetric water use and fruit yield increase roughly linearly with the area of converted land for each scenario (PF: 127 km² converted; PFA: 214 km² converted; PFA+: 346 km² converted). The results in Table 2 also show that the increase in ET and subsequent decrease in water yield somewhat diminish from the PF to the PFA and PFA+ scenarios. This trend can be explained by the mixture of land uses that are converted in each scenario. In the PFA scenario, the additional converted agricultural land produces a slightly smaller increase in ET compared to the other land conversions in the PF scenario, resulting in a small decrease in the change overall ET for the PFA scenario (49%) compared to the PF scenario (51%). However, for the PFA+ scenario, the converted land classes have a higher ET to begin with, because of the higher elevation in the watershed, reducing the increase overall ET rate substantially for the PFA+ scenario (39%) compared to the PFA scenario (49%).

Figure 4-5: Annual fruit yield versus additional water use for converted areas. Symbols indicate the respective conversion scenario. Numbers next to symbols indicate the respective planting density in palm/ha.

While the annual average increase in ET and decrease in water yield are substantial, the simulated average monthly flows for the Base Case and the PF scenario, shown in Figure 7, indicate that the seasonal impacts can be even greater. In March and April, ET increases by 100%, due to higher temperatures and the palms reaching the yearly maximum LAI for these months. The error bars in Figure 4-6 indicate the standard deviation of monthly flows across the 20-year simulation period. The widths of the error bars for the PF conversion scenario are substantially greater, due both to the higher mean ET values and the higher sensitivity of ET rates to annual variations in climate for the PF oil palm conversion case than for the Base Case. In particular, the month of May displays an exceptionally high variability in ET across the 20 years. During the driest years (1971 and 1977, average precipitation of 2923 mm compared to annual precipitation of 3962 mm), the increase in ET and decrease in water yield were 60% and 23%, respectively, for the PF case compared to the Base Case. On average, the month of May has the greatest changes in water yield, with a reduction as large as 60% in the driest year. Similar patterns of seasonal and inter-annual variations in ET were observed in the simulations of the PFA and PFA+ scenarios (see Figure 8-2).

Figure 4-6: Monthly mean ET rates for the PF scenario for the converted area for the Base case and PF scenarios. Error bars indicate one standard deviation of ET from the mean ET, with the standard deviation of ET calculated across the 20-year simulation period.

Annual variations in the ET rate also depend, but to a lesser extent, on the life cycle of oil palm as the LAI increases and eventually reaches the maximum value in year 10 (see Figure 8-1).

Figure 4-7 shows the average monthly decrease in water yield for the converted area for the PF scenario relative to the Base Case. The mean decreases are highest in May, due to lower rainfall and especially high temperatures (see Figure 4-2), with decreases higher than 50% in the driest years. Again, similar patterns of seasonal and inter-annual variations in water yield were observed in the PFA and PFA+ scenario simulations (see Figure 8-3).

Figure 4-7: Decrease in water yield from the converted area for the PF scenario relative to the Base case scenario. Error bars indicate one standard deviation of decrease in yield from the mean, with the standard deviation of decrease in yield calculated across the 20-year simulation period.

Table 4-2: Changes in the hydrologic components as a result of oil palm conversion scenarios, relative to the Base Case scenario.

Scenario	Land Cover Converted to Oil Palm	Area (km ²)	Annual Precipitation (mm)	Base Case Annual ET (mm)	Base Case Annual Water Yield (mm)	Change in Annual ET from Base Case	Change in Annual Water Yield from Base Case
PF	Pasture	112.4	3780	836	2910	52%	-15%
PF	Mixed Forest	7.8	4050	936	3080	37%	-11%
PF	Evergreen Forest	5.9	3360	813	2510	53%	-17%
PF	Total/Mean	126.1	3777	841	2902	51%	-15%
PFA	Pasture	112.4	3780	836	2910	52%	-15%
PFA	Mixed Forest	7.8	4050	936	3080	37%	-11%
PFA	Evergreen Forest	5.9	3360	813	2510	53%	-17%
PFA	Agriculture	88.5	3770	806	2940	50%	-14%
PFA	Total/Mean	214.6	3774	827	2918	49%	-14%
PFA+	Pasture	191.1	4048	882	3136	47%	-13%
PFA+	Mixed Forest	37.2	3930	869	3031	45%	-13%
PFA+	Evergreen Forest	7.1	4190	953	3209	36%	-11%
PFA+	Deciduous Forest	4.4	4183	984	3172	36%	-11%
PFA+	Agriculture	106	4128	932	3166	39%	-11%
PFA+	Total/Mean	345.8	4064	899	3136	39%	-11%

4.4.4 Watershed-scale impacts from land conversion scenarios

The model simulations indicate higher water use throughout the watershed as a result of oil palm conversions. Planting oil palm increases the ET rate over the whole watershed by 11%, 18% and 29% for the PF, PFA and PFA+ scenarios, respectively, compared to the Base Case scenario. Due to the high annual precipitation rates in the watershed, especially in the southern portions of the watershed where the elevation increases above 2100 m ASL, the increases in ET only slightly affect the streamflow at the outlet, with 3%, 6% and 9% declines in average annual streamflows for the PF, PFA and PFA+ scenarios, respectively. Interannual variation in climate produces a slightly larger decrease in the streamflow due to oil palm conversion in some years. During the driest years (1977 and 1971), annual streamflow at the outlet declines by 5.0%, 8.6% and 13.5% under the PF, PFA and PFA+ scenarios, respectively, relative to the Base Case scenario. In contrast, during the wet years (highest 25th percentile annual precipitation), streamflow at the outlet decreases by an average of 3%, 5% and 8% for the PF, PFA and PFA+ scenarios, respectively.

Figure 4-8 shows the cumulative distribution functions (CDFs) of monthly watershed-scale streamflow for the Base Case, PF, PFA and PFA+ scenarios over the simulation period. The CDFs for the PF, PFA and PFA+ scenarios are almost identical in terms of the deviation from the Base Case scenario, except for the magnitude of low flows. For example, the 90% exceedance flow for the PF and PFA+ scenarios differ from the Base Case scenario by 16% and 35%, respectively.

At the sub-basin level, the simulation results indicate that sub-basin 1 (Figure 4-1) will experience the greatest decline (24%) in average annual water yield as a result of oil palm expansion for all three scenarios. On a seasonal basis, during the low-flow months of April, May and June, streamflow will decrease 50% on average. The significant decline in annual and seasonal streamflows in sub-basin 1 is due to the low average annual precipitation in the sub-basin (2580 mm/year, which is 35% lower than the watershed-wide average). For sub-basin 2, which has 50% more rainfall than sub-basin 1 (3841mm/year), the decline in average annual water yield in sub-basin 2 was only 14%, although the fraction of converted land in sub-basin 2 was identical to that for sub-basin 1 for the PF scenario.

Figure 4-8: Cumulative distribution functions (CDFs) of monthly streamflows at the watershed scale for the Base Case, PF, PFA and PFA+ scenarios for the full simulation period (1964-1983). Inset shows the CDFs for the low flow tails of the CDFs.

4.4.5 Green water footprint

The simulations indicate an ET water requirement of 0.98 to 1.4 m³ to produce 1 kg of dry fruit, across the scenarios. This range is similar to the range of 1.1 to 1.4 m³ water/kg fruit reported by Pleanjai et al. (2007) for oil palm cultivation in Malaysia. Assuming each kilogram of fresh fruit (dry weight) can produce 0.30 kg of fuel (Pleanjai et al. 2007), the green water footprint is 3,300 m³ of water per 1 m³ of biodiesel (biodiesel density = 874.7 kg/m³, USDOE). Further assuming that the liquid fuel would have an energy content similar to conventional diesel fuels, 43 MJ/kg (International Gas Union 2019), the green water footprint is 87 m³ water/GJ. Babel et al. (2011) reports a slightly higher value of 110 m³/GJ for biodiesel derived from oil palm in Thailand. If the green water footprint is calculated based on the additional ET relative to the Base Case scenario (shown in Table 8-6), the green water footprint is 0.34 m³/kg of biomass or 25.2 m³/GJ of energy.

In addition to conversion of the oil palm fruit, 50-70 tons/ha of biomass residue in the form of fiber, shell, palm kernel fronds and trunks, can be collected over the life span of the oil palm (Salathong 2007). The simulations conducted here indicate a total biomass production of 57 ton/ha (including fruit, above and below ground biomass), with 34 tons of biomass left as residue at the end of the 20-year simulation period. This residual is equivalent to an extra 323 GJ/ha, or a total of 4.0, 6.9 and 11.2 million GJ of bioethanol energy for the PF, PFA and PFA+ scenarios, respectively, over the roughly 20-year lifetime of the oil palms.

4.5 Discussion

At the watershed scale, the results of this work imply that hydrologic impacts of oil palm conversion in a tropical Latin American region are minimal even for the scenario with the greatest area of conversion (PFA+). However, the impacts at the watershed scale are subdued because of the high overall precipitation rate in the watershed (~ 4,000 mm/yr) and the substantial fraction of land (~40%) in the watershed that cannot be converted due to high slopes and elevations. On the converted lands, the results indicate that oil palm conversion from existing land uses can have large impacts on local-scale ET and water yield, especially when seasonal and interannual variability are considered. These results point to the potentially severe hydrological impacts of oil palm plantations in areas with lower precipitation, such as other locations where oil palm is grown in the Americas, which have average annual precipitation between 1600-3500 mm/year (Woittiez et al. 2017).

The results across the conversion scenarios indicate that the biomass production and the local hydrologic impacts, measured as loss in volumetric water yield, change linearly with the area of palm conversion, including the PFA+ scenario. However, the PFA+ scenario involves planting on steeply sloped lands, which could offer several disadvantages, including the potential for higher erosion rates and added labor or machinery expenses (Corley and Tinker 2008). In addition, yields of oil palm have been known to decline on higher slopes because soils tend to be shallower on higher slopes (Corley and Tinker 2008). In the case of the study area, however, soil depths are relatively thick over all of the slopes in the PFA+, so shallow depths were not a factor in this case.

4.6 Conclusion

The main objective of this work was to study the hydrological impacts and water-biomass tradeoffs associated with the development of oil palm plantations for bioenergy production in a Latin American context. A SWAT model was set up to study the hydrological impacts of oil palm development projects in a humid region of Mexico (along the Tabasco - Chiapas border). The model was calibrated and validated using long-term weather data and streamflow measurements, and plant growth parameters were adjusted to improve the LAI growth and fruit production predictions. The model was

used to simulate 20 years of oil palm growth, with fruit production after 4 years. A range of oil palm plantation scenarios were defined, including five planting densities and assumptions about land cover types being converted.

Plotting the water-biomass tradeoff curve indicated a direct relationship between water use and planting density. The most efficient planting density in terms of water use and fruit production yield was 150 palm/ha. Hydrologic model simulations with this planting density indicated an 11%-29% increase in the overall ET rate of the watershed across the conversion scenarios. However, the higher water use did not result in a notable decline in the streamflow at the watershed scale due to the high average annual precipitation in this region. Plotting the cumulative distribution of streamflow did not show a significant shift downward, except for the month of May. For the most extreme scenario of converting pasture land, forest and agriculture to oil palm (61% of the watershed in PFA+ scenario), an average streamflow decline of 9% was simulated at the outlet.

Hydrologic impacts were investigated on smaller spatial and temporal scales, including analysis of impacts over the converted area, impacts at the sub-basin scale, and seasonal impacts. Over the converted area, hydrologic model simulations indicated that the ET rates of oil palm were significantly higher (51%) compared to the base case. This led to a 14.5% decline in average annual water yield and up to a 35% decrease in monthly water yield from the converted area during the hottest month of the year (May). In the northern sub-basin, with 35% less precipitation, simulations indicated a significant decline in the annual water yield (24%) and a decrease in water yield of up to 50% in the low-flow months of April to June. Analysis also showed that impacts are dependent on the spatial location of the converted area and land cover that is converted. For example, simulation results indicated that the highest relative increase in ET (53%) and largest decrease in water yield (-17%) occurred in lower precipitation areas where evergreen forest is converted.

Based on model results, the green water footprint of biodiesel produced from oil palm was 3,300 m³ of water per m³ fuel, or 87 m³ per GJ energy. This water footprint is lower than or similar to values reported in other studies of oil palm and other bioenergy crops in different parts of the world.

Finally, we note that, in addition to hydrologic impacts, large or small, there are major social acceptability and adaptation concerns (Pischke et al. 2018a, b), as well as biodiversity and ecosystem impacts (Knowlton et al. 2017, Brito et al. 2017), associated with existing and potential expansion of oil palm conversion in the region that should to be considered.

4.7 References

Adnan, N.A. and Atkinson, P.M., 2011. Exploring the impact of climate and land use changes on streamflow trends in a monsoon catchment. *International Journal of Climatology*, 31(6), pp. 815-831.

- Arnold, J.G. and Allen, P.M., 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records 1. *Journal of the American Water Resources Association*, 35(2), pp. 411-424.
- Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B. and Neitsch, S.L., 2013. SWAT 2012 input/output documentation. Texas Water Resources Institute.
- Babel, M.S., Shrestha, B. and Perret, S.R., 2011. Hydrological impact of biofuel production: A case study of the Khlong Phlo Watershed in Thailand. *Agricultural Water Management*, 101(1), pp. 8-26.
- Oil palm NPKMg fertiliser trial (Sei Lakitan) EXPT EG00.1412A. Bah Lias Annual Report Volume 1, Bah Lias Research Station, PTPP London Sumatra Indonesia, Medan (2011), pp. 89-92
- Breure, C.J., 2010. Rate of leaf expansion: A criterion for identifying oil palm (*Elaeis guineensis* Jacq.) types suitable for planting at high densities. *Wageningen Journal of Life Sciences*, 57(2), pp. 141-147.
- Brito, T.F., Phifer, C.C., Knowlton, J.L., Fiser, C.M., Becker, N.M., Barros, F.C., Contrera, F.A., Maués, M.M., Juen, L., Montag, L.F. and Webster, C.R., 2017. Forest reserves and riparian corridors help maintain orchid bee (Hymenoptera: Euglossini) communities in oil palm plantations in Brazil. *Apidologie*, 48(5), pp. 575-587.
- Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees?. *Agriculture, Ecosystems & Environment*, 104(1), pp. 185-228.
- Carlson, K.M., Curran, L.M., Ponette-González, A.G., Ratnasari, D., Lisnawati, N., Purwanto, Y., Brauman, K.A. and Raymond, P.A., 2014. Influence of watershed-climate interactions on stream temperature, sediment yield, and metabolism along a land use intensity gradient in Indonesian Borneo. *Journal of Geophysical Research: Biogeosciences*, 119(6), pp. 1110-1128.
- Chiu, Y.W. and Wu, M., 2013. The water footprint of biofuel produced from forest wood residue via a mixed alcohol gasification process. *Environmental Research Letters*, 8(3), p.035015.
- Chong, S.Y., Teh, C.B.S., Ainuddin, A.N. and Philip, E., 2018. Simple net rainfall partitioning equations for nearly closed to fully closed canopy stands. *Pertanika Journal of Tropical Agricultural Science*, 41(1).
- Comte, I., Colin, F., Whalen, J.K., Grünberger, O. and Caliman, J.P., 2012. Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review. In *Advances in Agronomy* (Vol. 116, pp. 71-124). Academic Press.

- Corley, R. H. V. and Tinker, P.B., 2003. The oil palm, John Wiley & Sons.
- Corley, R.H.V. and Tinker, P.B., 2008. The oil palm. John Wiley & Sons.
- Dislich, C., Keyel, A.C., Salecker, J., Kisel, Y., Meyer, K.M., Auliya, M., Barnes, A.D., Corre, M.D., Darras, K., Faust, H. and Hess, B., 2017. A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological Reviews*, 92(3), pp. 1539-1569.
- Fairhurst, T., Griffiths, W., 2014. Oil Palm: Best Management Practices for Yield Intensification. International Plant Nutrition Institute (IPNI), Singapore.
- FAOSTAT online statistical service. FAOSTAT 2017, <http://www.fao.org/faostat/en/#data/QC> (accessed on March 2019).
- Farmanta, Y. and Dedi, S., 2015. Rainfall Interception by Palm Plant Canopy. International Seminar on Promoting Local Resources for Food and Health, 12-13 October, Bengkulu, Indonesia.
- Fuka, D.R., Walter, M.T., MacAlister, C., Degaetano, A.T., Steenhuis, T.S. and Easton, Z.M., 2014. Using the Climate Forecast System Reanalysis as weather input data for watershed models. *Hydrological Processes*, 28(22), pp. 5613-5623.
- Furumo, P.R. and Aide, T.M., 2017. Characterizing commercial oil palm expansion in Latin America: land use change and trade. *Environmental Research Letters*, 12(2), p.024008.
- Gerbens-Leenes, W., Hoekstra, A.Y. and van der Meer, T.H., 2009. The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, 106(25), pp. 10219-10223.
- Gerritsma, W. and Wessel, M., 1997. Oil palm: domestication achieved?. *Wageningen Journal of Life Sciences*, 45(4), pp. 463-475.
- Gilroy, J.J., Prescott, G.W., Cardenas, J.S., Castañeda, P.G.D.P., Sánchez, A., Rojas-Murcia, L.E., Medina Uribe, C.A., Haugaasen, T. and Edwards, D.P., 2015. Minimizing the biodiversity impact of Neotropical oil palm development. *Global Change Biology*, 21(4), pp. 1531-1540.
- Goh, K.H., 1982. Analyses of oil palm spacing experiments [Malaysia]. In *International Conference on Oil Palm in Agriculture in the Eighties*, Kuala Lumpur (Malaysia), 17-20 Jun 1981. PPP (ISP).
- Boo, T.C., Joo, G.K. and Soon, C.P., 1994. Maximising and maintaining oil palm yield on commercial scale in Malaysia management for enhanced profitability in plantations. In

International Planters Conference on Management for Enhanced Profitability in Plantations October 24-26, 1994Kuala Lumpur (No. L-0281).

Gupta, H.V., Sorooshian, S. and Yapo, P.O., 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering*, 4(2), pp. 135-143.

Hardanto, A., Röhl, A., Niu, F., Meijide, A. and Hölscher, D., 2017. Oil palm and rubber tree water use patterns: effects of topography and flooding. *Frontiers in Plant Science*, 8, p.452.

Heidari, A., Mayer, A. and Watkins, D., 2019a. Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA. *Journal of Hydrology*.

Heidari, A., Watkins, D. and Mayer, A., Propato, T., Veron, S., Abelleira, D., 2019b. Spatially variable hydrologic impact and biomass production tradeoffs associated with Eucalyptus cultivation for biofuel production in Entre Rios, Argentina. *Hydrology and Earth System Sciences*. Under review.

Hoekstra, A.Y. and Chapagain, A.K., 2006. Water footprints of nations: water use by people as a function of their consumption pattern. In *Integrated Assessment of Water Resources and Global Change* (pp. 35-48). Springer, Dordrecht.

Instituto Nacional de Estadística y Geografía- INEGI, <http://www.inegi.org.mx/>

Ishak, W. and Awal, M.A., 2007. Leaf area index model for oil palm FFB yield prediction. *Pertanika Journal of Tropical Agricultural Science*, 30, pp. 51-56.

Knowlton, J.L., Phifer, C.C., Cerqueira, P.V., Barro, F.D.C., Oliveira, S.L., Fiser, C.M., Becker, N.M., Cardoso, M.R., Flaspohler, D.J. and Dantas Santos, M.P., 2017. Oil palm plantations affect movement behavior of a key member of mixed-species flocks of forest birds in Amazonia, Brazil. *Tropical Conservation Science*, 10, p.1940082917692800.

Lamade, E. and Setiyo, I.E., 1996. Test of Dufrêne's production model on two contrasting families of oil palm in North Sumatra. In: *Proceedings of the 1996 PORIM International Palm Oil Congress. Competitiveness for the 21st century* (Ed. by D. Ariffin et al.), pp. 427-435, Palm Oil Research Institute of Malaysia, Kuala Lumpur.

Larsen, R.K., Jiwan, N., Rompas, A., Jenito, J., Osbeck, M. and Tarigan, A., 2014. Towards 'hybrid accountability in EU biofuels policy? Community grievances and competing water claims in the Central Kalimantan oil palm sector. *Geoforum*, 54, pp. 295-305.

- Ludwig, F., Biemans, H., Jacobs, C., Supit, I., van Diepen, C.A., Fawell, J., Capri, E. and Steduto, P., 2011. Water use of oil crops: current water use and future outlooks. ILSI Europe aisbl.
- Manoli, G., Mejjide, A., Huth, N., Knohl, A., Kosugi, Y., Burlando, P., Ghazoul, J. and Fatichi, S., 2018. Ecohydrological changes after tropical forest conversion to oil palm. *Environmental Research Letters*, 13(6), p.064035.
- Maier, C.A., Albaugh, T.J., Cook, R.I., Hall, K., McInnis, D., Johnsen, K.H., Johnson, J., Rubilar, R.A. and Vose, J.M., 2017. Comparative water use in short-rotation *Eucalyptus benthamii* and *Pinus taeda* trees in the Southern United States. *Forest Ecology and Management*, 397, pp. 126-138.
- Mejjide, A., Badu, C.S., Moyano, F., Tiralla, N., Gunawan, D. and Knohl, A., 2018. Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event. *Agricultural and Forest Meteorology*, 252, pp. 208-219.
- Merten, J., Röhl, A., Guillaume, T., Mejjide, A., Tarigan, S., Agusta, H., Dislich, C., Dittrich, C., Faust, H., Gunawan, D. and Hein, J., 2016. Water scarcity and oil palm expansion: social views and environmental processes. *Ecology and Society*, 21(2).
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3), pp. 885-900.
- Mukherjee, I. and Sovacool, B.K., 2014. Palm oil-based biofuels and sustainability in southeast Asia: A review of Indonesia, Malaysia, and Thailand. *Renewable and Sustainable Energy Reviews*, 37, pp. 1-12.
- Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology*, 10(3), pp. 282-290.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.
- NIST Chemistry WebBook, OECD/IEA Electricity Information (various editions), International Gas Union, Natural Gas Conversion Guide (<http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx> (accessed on march 2019)).
- Paramananthan, S., 2013. Managing marginal soils for sustainable growth of oil palms in the tropics. *Journal of Oil Palm, Environment and Health (JOPEH)*, 4.
- Pirker, J., Mosnier, A., Kraxner, F., Havlík, P. and Obersteiner, M., 2016. What are the limits to oil palm expansion?. *Global Environmental Change*, 40, pp. 73-81.

- Pischke, E.C., Rouleau, M.D. and Halvorsen, K.E., 2018a. Public perceptions towards oil palm cultivation in Tabasco, Mexico. *Biomass and Bioenergy*, 112, pp. 1-10.
- Pischke, E.C., Mesa-Jurado, M.A., Eastmond, A., Abrams, J. and Halvorsen, K.E., 2018b. Community perceptions of socioecological stressors and risk-reducing strategies in Tabasco, Mexico. *Journal of Environmental Studies and Sciences*, 8(4), pp. 441-451.
- Pleanjai, S., Gheewala, S.H. and Garivait, S., 2007. Environmental evaluation of biodiesel production from palm oil in a life cycle perspective. *Asian Journal of Energy and Environment*, 8(1-2), pp. 15-32.
- Ramankutty, N. and Graesser, J., 2017. Latin American oil palm follows an unfamiliar route to avoid deforestation. *Environmental Research Letters*, 12(4), p.041001.
- Rodriguez, R.D.G., Scanlon, B.R., King, C.W., Scarpore, F.V., Xavier, A.C. and Pruski, F.F., 2018. Biofuel-water-land nexus in the last agricultural frontier region of the Brazilian Cerrado. *Applied energy*, 231, pp. 1330-1345.
- Röll, A., Niu, F., Meijide, A., Hardanto, A., Knohl, A. and Hölscher, D., 2015. Transpiration in an oil palm landscape: effects of palm age. *Biogeosciences*, 12(19), pp. 5619-5633.
- Salathong, J., 2007. The sustainable use of oil palm biomass in Malaysia with Thailand's comparative perspective. See also: http://www.wiaps.waseda.ac.jp/initiative/2006/intern/group_02/PDF/Jessada%20Salathong.pdf.
- Schyns, J.F., Booij, M.J. and Hoekstra, A.Y., 2017. The water footprint of wood for lumber, pulp, paper, fuel and firewood. *Advances in Water Resources*, 107, pp. 490-501.
- Sheil, D., Casson, A., Meijaard, E., Van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K. and Kanninen, M., 2009. The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know? (Vol. 51). Bogor, Indonesia: Center for International Forestry Research.
- Sumarga, E., Hein, L., Hooijer, A. and Vernimmen, R., 2016. Hydrological and economic effects of oil palm cultivation in Indonesian peatlands. *Ecology and Society*, 21(2),
- Vijay, V., Pimm, S.L., Jenkins, C.N. and Smith, S.J., 2016. The impacts of oil palm on recent deforestation and biodiversity loss. *PloS one*, 11(7), p.e0159668.
- Winchell, M., Srinivasan, R., Di Luzio, M. and Arnold, J., 2013. ArcSWAT interface for SWAT2012: user's guide. Blackland Research and Extension Center, Texas Agrilife Research. Grassland. Soil and Water Research Laboratory, USDA Agricultural Research Service, Texas, 3.

Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk, M. and Giller, K.E., 2017. Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy*, 83, pp. 57-77.

United States Department of Energy, https://afdc.energy.gov/fuels/biodiesel_basics.html

Yusop, Z., Chan, C.H. and Katimon, A., 2007. Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment. *Water Science and Technology*, 56(8), pp. 41-48.

5 Conclusions and Future Work

This research contributes to bioenergy systems planning and water resources management by providing a simulation-based framework for studying hydrologic impacts of cultivating bio feedstock and assessing water-yield- fertilizer tradeoffs. It is comprised of evaluating potential bioenergy related land use conversion scenarios across three countries with different management practices including fertilization rate, planting density, rotation, and irrigation. The best management practice for each case is recommended to reduce the potential environmental impacts and to identify the most efficient management practice in terms of yield and water use.

Major findings and contributions are described as follows.

5.1 Hybrid poplar cultivation in northern Wisconsin, USA

For a representative watershed in northern Wisconsin, a SWAT model was set up, calibrated and validated to simulate daily streamflow at the watershed outlet. The plant growth section of the model was calibrated using measured data on poplar growth from a nearby research station, enabling the SWAT model to simulate various planting densities. The model was used to simulate seventy poplar plantation scenarios with different management practices including planting density, harvest period, supplementary irrigation, and fertilization over a 30-year period.

Investigating the water use showed a substantial increase in average ET of the watershed during growth season (Jun- Dec) due to poplar plantation. This caused a decline in streamflow especially during the low-flow months of July and August. Grown trees with higher LAI and consequently higher water demand in the final years of the rotation caused a severe decline in the streamflow. Analyzing the streamflow, it was discovered that the base flow is more affected than the surface flow due to trees removing moisture from the soil. Studying interannual plant growth behaviors showed that irrigation impact on biomass production was small, unless the last year of harvest is a dry year. In that case, supplementary irrigation could be an effective management practice to prevent biomass loss.

In contrast to irrigation, fertilization proved to be a necessary management practice since the tree growth and biomass production were significantly dependent on N availability. Model results indicated that fertilization rates up to around 41 kgN/ha/year increase the biomass production remarkably. However, additional fertilizer above this level almost did not improve the yield and increased the potential for non-point source pollution from contaminated runoff and leaching of nutrients.

Among all the treatments, the shortest rotations with the highest density (1,111/100m², 5-year) produced the highest biomass and had the highest water and fertilizer use efficiency. The next highest cumulative biomass and efficiency belonged to the second highest planting density of 278/100m². The better efficiency of the short rotation-high

intensity plantations was due to trees being harvested as soon as they reach maturity and maximum LAI, preventing them from staying at high LAI with more water use. Furthermore, more solar radiation is intercepted in higher intensity planting, which leads to increased biomass production in early stages of growth.

Finally the water and fertilizer requirement to produce 1 ton of biomass over 1 ha of land was estimated to be 128 mm and 9.4 kg N should be applied. This equals 0.93 m³/ kg biomass and 98 m³ water/ GJ from bioethanol.

This work was the first to explicitly assess trade-offs between biomass production, cultivation practices, and hydrologic alteration—including changes in evapotranspiration, surface flow, groundwater recharge—for the feedstock production system and to recommend practices for optimal tradeoffs.

5.2 Eucalyptus plantation in Mesopotamia region Entre Rios, Argentina

The study site was a watershed located in humid subtropical region of Argentina (northeastern Mesopotamia region, Entre Rios province). The study relied on land use/land cover maps that were created for the area using high-resolution images of LANDSAT5 and 8. A SWAT model was calibrated and validated for streamflow and plant growth (LAI and biomass) simulations. The calibrated model was used to simulate a range of eucalyptus plantation scenarios over a range of 21-year period. The scenarios were developed considering a number of variables including planting eucalyptus over different land cover types at various locations across the watershed, spatially variable soil fertility and precipitation, and an irrigation treatment.

Results of the model indicated higher ET rates of eucalyptus relative to other terrestrial LULC in the watershed. The greatest ET difference was simulated when a rangeland was replaced with eucalyptus. This caused a decline in the streamflow at the outlet of the watershed depending on the area and location of the plantation. Model simulations indicated that converting all the rangelands, orange orchards and forest lands in an intensive eucalyptus plantation resulted in 28% decrease in streamflow at the outlet of the watershed. The months of February, January and March experienced the highest decrease in average annual flow of 37%, with baseflow being affected slightly more than the surface flow. The degree of decline in the streamflow was variable depending on the average annual precipitation, ranging from 20% in wet years up to as much as 53% in the driest year. Furthermore, flow duration curve analysis showed that the low flows (lowest 10% of monthly flows) were affected significantly compared to higher flows.

A wide range of biomass production (37-100 ton/ha/rotation) was simulated for eucalyptus plantations in different parts of the watershed due to spatially variable soil properties and annual precipitation rates. Further investigation showed that shallow soils reduce growth because of smaller soil water reservoir that results in water stress, especially during high-ET periods. Being located in a sub-basin with higher precipitation

could slightly alleviate the water stress and produce higher yields in shallow soils. Studying the water-biomass tradeoffs revealed that higher production comes at a higher water use (ET), which will consequently have a more significant impact on the streamflow. Results of an optimization model suggested prioritizing conversion of the slightly lower productive western sub-basins as this development pattern would have less hydrologic impact at the outlet of the watershed.

The water footprint for biodiesel production from eucalyptus biomass was estimated based on the model results. The average green water footprint was estimated to be 2150 m³ per m³ fuel, or 57 m³ per GJ energy, which is significantly lower than reported values for sugar cane ethanol, wood-based ethanol and soybean biodiesel in different parts of the world.

To the author's knowledge, this paper was the first paper to simultaneously address cultivation location practices in making recommendations for minimizing hydrologic impacts.

5.3 Oil Palm plantation in Tabasco, Mexico

A SWAT model was set up in a humid region of Tabasco-Chiapas, Mexico, where land use is predominately forest, pasture, and farmland. This region is experiencing rapid expansion of oil palm plantations. The model was calibrated hydrologically using streamflow measurements, and the plant growth module was calibrated using literature and field measurements to reflect the evergreen nature of the tree and improve the yield simulations. Data collected from literature review, including precipitation interception and evapotranspiration rates, was used to further improve the hydrologic simulation. The oil palm development scenarios were formulated considering a number of variables, including the land cover type being converted, maximum land slopes for planting, and planting densities.

Comparison of the simulated and measured oil palm yields demonstrates that the calibration of the plant growth model was reliable ($R^2 = 0.81$) over all phases of fruit production. Fruit production for five different planting densities was simulated and compared to reported fruit yields. The highest fruit production occurred with an average planting density of 150 palm/ha. At planting densities lower than 150 palm/ha, the yields were lower simply because there are fewer oil palms per unit of cultivated area. Higher planting densities than 150 palm/ha were more productive in the earlier years. However, competition for solar radiation caused a rapid decline in the yield starting in year 7 or 8.

Analyzing fruit yield versus water use for all planting densities and scenarios indicated that, for every scenario, the 150 palm/ha planting density was the most efficient in terms of maximizing fruit production and minimizing additional water use.

Simulation results also indicated that the oil palm planted areas experienced a large increase in water use, i.e., 39% to 51% more ET. Some seasonal impacts were even greater, with up to a 100% increase in ET during March and April due to higher temperatures and the palms reaching the yearly maximum LAI in these months. The higher water use did not significantly impact the streamflow at the watershed level (maximum 9% decline), but the hydrologic impacts were relatively severe in the converted areas of the watershed (11% to 15% decline). Annual variations in climate caused variability in ET and streamflow, suggesting additional research may be needed to better understand potential ecosystem impacts during low-flow months. In particular, the month of May displayed an exceptionally high variability in ET, and the greatest changes in water yield, with a reduction as large as 50% in the driest year due to lower rainfall and particularly high temperatures. At the sub-basin level, the simulation results indicated that the driest sub-basin experienced the greatest decline (24%) in average annual water yield as a result of oil palm expansion for all scenarios.

Finally, the water footprints for fruit production and potential biodiesel production from oil palm in the region were estimated. In this region, 0.98 m³ and 87 m³ of water were estimated to be required to produce 1 kg of fresh fruit bunches and 1 GJ of energy from oil palm, respectively.

This research is the first of its kind, as no paper has explicitly addressed impacts on hydrologic cycling due to land use change for oil palm cultivation in a tropical Latin America setting.

5.4 Synthesis

Modeling results for eucalyptus and poplar case studies indicated that for successful biofuel projects, they should be planted at high densities. All the three crops had to be fertilized to be productive. These two parameters coincide with significantly higher ET rates than the land covers that they replace. The higher ET rates during the growth seasons eventually cause a reduction in the streamflow. The timing and degree of change in the streamflow is dependent on the area of the land being converted, the climate of the region, and the composition of the streamflow (% surface flow, baseflow) in that basin. If the baseflow is affected more than the surface flow, then streamflows during the low-precipitation, low-flow months, such as the months of July and August in WI, are more vulnerable and can cause potential harm to the ecosystem. In contrast, if the streamflow is mostly dependent on the surface flow, such as in the Argentina case, then the streamflow impacts in a normal year would be small. However, in a dry year, the streamflow could have a remarkable decline (up to 53%), since the high ET rates of the feedstock deplete the soil moisture and increase infiltration capacity. For the oil palm case, high average annual precipitation in the region prevented significant changes on a watershed scale. However, high ET rates in the planted areas, can cause local depletion of streams, especially in low-flow months and dry years.

All the plantations showed that fertilization was able to increase yields significantly. However, fertilization could increase yield only up to a certain amount, and additional fertilization increases the potential for non-point source pollution of water resources. The threshold amount is different for each crop and is dependent on the physiological characteristics of the plant and total produced biomass.

The water- energy tradeoff curves plotted for these bioenergy studies indicate that the highest yield does not necessarily correspond to the highest planting density, highest fertilization rate or the most water use. It is generally considered that a more intense plantation would have a higher water use and be more productive. However, in WI, the densest plantation poplar treatment was the most productive with the lowest water use among all treatments, while the highest density of oil palm in Mexico had the highest water use with a low productivity. It was concluded that short rotations will prevent high water use, as the trees have high LAI for a short period of time. In contrast, for the oil palm development case, the highest density resulted in competition among trees and prevented optimal yield. It is necessary to evaluate various management practices for each specific system to find the most efficient treatments in regard to water use, fertilization and yield.

In every case study, the plant growth module was calibrated to improve plant growth simulation. This resulted in improved LAI simulations, leading to a more accurate simulation of the ET rates and the ability to distinguish between different planting densities in terms of water use. For USA and Mexico case studies, it enabled simulating yield in various planting densities that led to identifying the best management practice to obtain the highest yield. This process results in improved simulations of the hydrologic impacts due to more accurate water use estimates.

Greenwater footprints for bioenergy production were estimated for all the three case studies. The farm gate level water requirement to produce 1 GJ of energy from poplar, eucalyptus and oil palm was estimated to be 98, 57 and 87 m³, respectively. The water requirement to produce liquid fuel from poplar was slightly higher than eucalyptus and notably lower than oil palm. However, lower heating values of ethanol compared to diesel results in lower energy production from poplar. Eucalyptus planted at the Argentina case study was found to have the highest efficiency in terms of water requirement per yield and fuel production. Throughout this research, the additional water was defined as the difference in water use (ET) between the planted area and the base case. The poplar production in the WI case study required the least amount of additional water, indicating lower hydrological changes in planted areas. In contrast, high water use of oil palm planted areas compared to the pasture land that they replace resulted in the having the highest additional water (nearly double) among the case studies.

5.5 Recommendations for future work

All the simulations included fertilization, raising concern over potential environment pollution that requires careful study. However, water quality measurements were not

available in this study, and analysis was limited to applying different fertilization rates and reporting the nutrient uptake by the trees. Therefore, important future research could be studying the water quality impacts of biofuel development and studying the fate and transport of nutrients in the watershed.

Impactful management practices were planting density and harvest rotation. Both the eucalyptus plantation in Argentina and poplar plantation in the US included high-density, short-rotation plantations. However, no economic analysis was conducted in this research. It is generally considered that lower densities have longer rotations and more flexible harvest scheduling, as well as lower costs. A necessary future topic for study would be evaluating the costs associated with different management practices, such as planting and harvesting trees with different densities. Further economic analysis could include fertilization, irrigation and labor costs for various scenarios.

For all the three case studies, the plant growth sub-model was calibrated for better plant growth simulation. This not only improved the plant growth cycle, but also improved simulations of the hydrologic impacts due to more accurate water use and nutrient uptake estimates. However, there were limited data available, especially for the non-US case studies. Therefore, potential future work for further improving the simulations would include collecting more field measurements on LAI, biomass production, water use, and solar radiation interception for various planting densities of biofuel crops.

Greenwater footprints for bioenergy production were estimated for all three case studies at a farm-gate level. Water requirements for bioethanol and biodiesel production were estimated based on simplifying assumptions and not accounting for water use in different fuel production processes. Therefore, a future area of research could be studying the full life-cycle analysis for these bioenergy production systems.

This study conducted highly detailed hydrologic analysis for various crops with different climate conditions. However, there are many perspectives associated with expansion of biofuel projects that need further research to help ensure sustainable development. Future interdisciplinary work can expand the analysis to consider ecological impacts more broadly (e.g., more interdisciplinary collaboration), including impacts on aquatic and terrestrial biodiversity.

Finally, the three case studies were different in terms of climate and bio feedstock and found different hydrologic responses in each case. More case studies are necessary to justify generalization and improve the prediction of hydrological responses for bioenergy development projects. The studies should include investigation of potential environmental impacts in various geographic and climatic contexts for different crops, as well as evaluation of potential management practices.

6 Supplementary Materials for Chapter 2

6.1 Model Setup Details

Wetland area was calculated based on the NLCD 2011 land use and land cover. Mapped areas of woody and herbaceous wetlands were assumed to be the surface area of wetlands when filled to the normal water level, the wetland area at the maximum water level was assumed to be 1.3 times the normal area. Based on author's experience and calibration in nearby areas, the average water depth in wetlands when filled to the normal water level was estimated as 0.2 m, and the average depth for maximum water levels was estimated to be 0.4 m.

The 32 years of climate data included years with precipitation ranging from 550 mm (1998) to 1140 mm (1991), and stream flow ranging from 157 mm (1987) to 570 mm (1991).

6.2 Calibration and Validation Details

Baseflow separation was performed and used for model calibration in SWAT CUP 5.1.6.2 (Abbaspour 2013). The ratio of baseflow to total flow ratio can be important in modeling land use change scenarios as the evapotranspiration attributed to the new land use is dependent on the amount of soil moisture. A model can be also calibrated with different sets of parameters and different baseflow/total flow ratios. It might be easier to calibrate a model with high baseflow/total flow ratio as there are more adjustable parameters for the baseflow contribution; however, this could lead to unrealistic estimates of ET and water stress during plant growth periods.

The sensitivity analysis indicated that simulated stream flow was most sensitive to the Curve Number (CN) and snow-related parameters. Channel routing parameters and ground water contribution to stream flow were also important. The description of the parameters, their allowable range and final calibrated values, along with their sensitivity rank are shown in Table S1. Three parameters related to baseflow (REVAPMN, ALPHA_BF_D, ALPHA_BF) and one related to snowmelt (SFTMP) were not identified as a priority in the initial sensitivity analysis but were found to be important in later steps of calibration.

The Curve Number (CN) is typically a critical parameter for determining rainfall contribution to the streamflow and for separating baseflow from surface flow. Since CN can be determined from land use/land cover and soils data, and the model calculations of the baseflow /total flow ratio and total outflow were reasonable, the CN values were not changed. Furthermore, since the model calculations matched the total water balance reasonably well, parameters related to water losses through percolation to a deep aquifer and water uptake of the deep roots were not changed from default values. The next group

of watershed parameters were ground water contribution and routing parameters, respectively.

Leaf Area Index (LAI) may be used to account for planting density. However, different planting densities can result in similar LAIs after a few years (e.g., 25 trees have an LAI of 8.2 after 6 years, while 83 trees have an LAI of 7.8). Table S2 shows the data on poplar growth that were used in this research (Hansen, 1979 and Zavitkovski 1983). The ratio of intercepted radiation has close relationship with planting density (Jiang et al., 2017), i.e., more trees per area will capture more solar radiation and will have a higher light interception coefficient. Therefore, the light extinction coefficient in 5- and 6-year rotations was reduced slightly to account for different planting intensities. For the 10-year rotation, since the trees would not have sufficient time to fully grow and capture radiation, the higher light extinction coefficient was used.

Table S3 shows all adjusted parameters related to poplar plantation treatments and growth. The first seven parameters were held constant, while the next three were adjusted slightly to reflect the plantation density. The last two parameters (age of the trees at plantation date, and initial biomass weight) were fixed to improve the plant growth simulation after personal communication with SWAT developers.

After calibrating the LAI growth, the biomass production was calibrated. In SWAT, the biomass is divided into aboveground biomass and root biomass. The woody aboveground biomass (no leaves) was calculated as the total aboveground biomass minus the leaf weight. The measured leaf biomass was collected from Zavitkovski (1983). Table S4 provides a comparison of the measured aboveground biomass at the USDA experimental facility with the simulated biomass in the Spirit Falls and USDA watersheds.

The calibrated and validated model was used to simulate 70 biofuel development scenarios to investigate the impacts of planting density, harvest timing, fertilizer application, and irrigation on biomass generation, nutrient availability in the soil, and water demand. All results are summarized in Table S5.

Table 6-1: Modified parameters for hydrological calibration process and their final value.

Parameter	Description	Final value	Default value	Range	Sensitivity rank, group
CN2	SCS runoff curve number	62(average)	62	*0.8 – 1.2	1, Runoff
SFTMP	Snowfall temperature [°C]	-1.975	1	-5, 5	Snow
SMTMP	Snow melt base temperature [°C]	1.025	0.5	-5, 5	4, Snow
SMFMX	Melt factor for snow on June 21 [mm H ₂ O/°C-day]	4.625	4.5	1 - 10	3, Snow
SMFMN	Melt factor for snow on December 21 [mm H ₂ O/°C-day]	1.075	4.5	1 - 10	6, Snow
TIMP	Snow pack temperature lag factor	0.1675	1	0.01 - 1	7, Snow
CH_K2	Effective hydraulic conductivity [mm/hr]	28.875	0	0 - 25	2, Routing
CH_N2	Manning's n value for main channel	0.0415	0.014	0.01 – 0.1	5, Routing
ALPHA_BF	Baseflow alpha factor [days]	0.245	0.048	0.01- 0.9	Baseflow
ALPHA_BF_D	Baseflow alpha factor for deep aquifer [days]	0.034	0.01	0 – 0.1	Baseflow
GW_DELAY	Groundwater delay time (days)	1.225	31	1 - 45	8, Baseflow
REVAPMN	Threshold depth of water in the shallow aquifer for deep root to uptake water from aquifer (revap) to occur [mm]	500	750	100 - 1500	Baseflow

Table 6-2: Reported values for different treatments for the Harshaw Experimental Farm (Hanson 1979).

Duration (years)	Tree Spacing (#tree / 100m²)	Treatment Code	Aboveground woody biomass at harvest (t/ha)	Leaf weight at harvest (t/ha)	LAI in last year
5	0.3×0.3 (1111)	1111-5	29.6	3.6	8.6
5	0.6×0.6 (278)	278-5	23.6	3.4	8.7
6	1.1×1.1 (83)	83-6	27	4	7.8
6	2×2 (25)	25-6	19.5	3.6	8.2
10	2.4×2.4 (17)	17-10	46.6	4	8.4

Table 6-3: Plant growth parameters in SWAT database used for plant growth modification.

Parameter	Description	Final Value	Default value
Bio E	Radiation use efficiency	20	30
T base	Minimum temperature for plant growth	4	10
T opt	Optimal temperature for plant growth	25	30
GSI	maximum stomatal conductance	0.007	0.004
CNYLD	Normal fraction of nitrogen in yield kg N/kg Yield	0.0005	0.0015
CPYLD	Fraction of phosphorous in harvested biomass	0.0002	0.0003
ALAI_MIN	Minimum LAI for plants during dormant period	0	0.75
BLAI	Maximum leaf area index	8.9-9.9	5
EXT_COEF	Light extinction coefficient	0.13-0.5	0.45
MAT_YRS	Number of years required for trees to reach maturity	6	10
CURYR_MAT	Current age of Trees (years)	1	0
BIO_INIT	Initial dry weight biomass (kg/ha)	0.5	0

Table 6-4: Comparison of measured aboveground biomass with simulated biomass in USDA and Spirit Falls watersheds.

Treatment	Measured - USDA facility (ton/ha/rotation)	Simulated - USDA (1970-1980) (ton/ha/rotation)	Simulated - Spirit Falls (1980-2010) (ton/ha/rotation)
1111-5	29.6	29.4	29.7
278-5	23.6	23.5	23.9
83-6	27	26.2	27.2
25-6	19.5	19.0	18.7
17-10	46.6	43.2	45.4

Table 6-5: Summary of SWAT simulations results for fertilizer, biomass production, and hydrology.

Planting Density (# trees /100 m ²)	Harvest Cycle (years)	Biomass Produced (ton/ha)	Fertilizer Applied (tons N/ha)	Nitrogen Uptake (tons N/ha)	Nitrogen Remaining in Soil (tons N/ha)	Irrigation Water Applied (m)	Evapo- trans- piration (m)	ET water- shed (m)	Stream flow at Watershed Outlet (m)
Base Case	NA	NA	NA	NA	NA	NA	12.9	13.5	10.0
17	10	9	0	90	-90	0.0	15.0	14.9	8.6
17	10	71	154	396	-243	0.0	16.0	15.7	7.9
17	10	105	308	662	-355	0.0	16.0	15.7	7.9
17	10	127	615	958	-343	0.0	16.1	15.7	7.9
17	10	129	1230	1058	172	0.0	16.1	15.7	7.9
25	6	8	0	40	-40	0.0	15.3	15.2	8.4
25	6	59	154	226	-72	0.0	16.6	16.1	7.5
25	6	85	308	348	-41	0.0	16.6	16.1	7.5
25	6	87	615	414	201	0.0	16.6	16.1	7.5
25	6	87	1230	417	813	0.0	16.6	16.1	7.5
83	6	12	0	55	-55	0.0	14.9	14.9	8.7
83	6	73	154	280	-126	0.0	16.3	15.8	7.7
83	6	113	308	450	-143	0.0	16.3	15.9	7.7
83	6	126	615	571	44	0.0	16.3	15.9	7.7
83	6	127	1230	613	617	0.0	16.3	15.9	7.7
278	5	15	0	56	-56	0.0	14.8	14.8	8.8
278	5	82	154	273	-119	0.0	16.2	15.8	7.8
278	5	128	308	442	-135	0.0	16.2	15.8	7.8
278	5	142	615	574	41	0.0	16.2	15.8	7.8
278	5	142	1230	592	638	0.0	16.2	15.8	7.8
1111	5	20	0	78	-78	0	14.5	14.6	9.0
1111	5	96	154	317	-163	0.0	15.8	15.5	8.0
1111	5	148	308	444	25	0.0	15.9	15.6	8.0
1111	5	160	615	590	545	0.0	15.9	15.6	7.9
1111	5	171	1230	685	-95	0.0	16.0	15.6	7.9

Continued									
17	10	11	0	95	-242	0.3	15.3	15.1	8.6
17	10	71	154	396	-336	1.2	16.7	16.2	8.3
17	10	110	308	644	-261	1.6	17.0	16.3	8.3
17	10	133	615	876	246	1.8	17.1	16.4	8.3
17	10	136	1230	984	-39	1.8	17.1	16.5	8.3
25	6	8	0	39	-85	0.2	15.4	15.2	8.5
25	6	60	154	239	-49	1.1	17.2	16.5	8.0
25	6	90	308	356	193	1.2	17.3	16.6	7.9
25	6	93	615	422	803	1.2	17.3	16.6	7.9
25	6	94	1230	427	-55	1.2	17.3	16.6	7.9
83	6	12	0	55	-145	0.2	15.0	14.9	8.7
83	6	76	154	298	-148	1.0	16.8	16.2	8.0
83	6	120	308	456	36	1.2	16.9	16.3	8.0
83	6	134	615	579	605	1.2	17.0	16.3	8.1
83	6	135	1230	625	-56	1.2	17.0	16.3	8.1
278	5	15	0	56	-121	0.1	14.8	14.8	8.8
278	5	82	154	275	-139	1.0	16.7	16.2	8.1
278	5	133	308	446	35	1.3	16.9	16.3	8.2
278	5	148	615	580	620	1.3	16.9	16.3	8.2
278	5	149	1230	610	-78	1.3	16.9	16.3	8.2
1111	5	20	0	78	-164	0.0	14.5	14.6	9.0
1111	5	97	154	318	-141	0.9	16.3	15.9	8.3
1111	5	151	308	448	22	1.2	16.6	16.1	8.4
1111	5	165	615	593	542	1.3	16.6	16.1	8.4
1111	5	178	1230	688	-90	1.3	16.6	16.1	8.4

6.3 References

Abbaspour, K.C., 2013. SWAT-CUP 2012. SWAT Calibration and Uncertainty Program—A User Manual.

Hansen, E.A. et al., 1979. Short-rotation intensive culture practices for northern Wisconsin, Proceedings, 16th Annual Meeting, North American Poplar Council, Joint Meeting of the United States and the Canadian Chapters, pp. 47-63.

Jiang, Rui, Tong-tong Wang, S. H. A. O. Jin, G. U. O. Sheng, Z. H. U. Wei, Ya-jun YU, Shao-lin Chen, and Ryusuke Hatano, 2017. "Modeling the biomass of energy crops: Descriptions, strengths and prospective." *Journal of Integrative Agriculture* 16, no. 6 (2017): 1197-1210.

Zavitkovski, J., 1983. Projected and actual biomass production of 2- to 10-year-old intensively cultured *Populus* 'Tristis # 1'. In: Hansen, Edward A., ed. *Intensive plantation culture: 12 years research*. Gen. Tech. Rep. NC-91. St. Paul, MN: US Department of Agriculture, Forest Service, North Central Forest Experiment Station: 72-76., 91.

7 Supplementary Materials for Chapter 3

Figure 7-1: A) Simulated annual biomass production for the intensive scenario, and B) Simulated LAI development for the intensive scenario.

Table 7-1: Land cover/land use change during the period 2002-2013.

Land Cover	Land cover portion of the watershed		
	2002	2005	2013
Orchard-Orange	4.9%	3.5%	1.1%
Agriculture	20.2%	23.4%	21.7%
Mixed Forest	12.0%	6.5%	3.6%
Eucalyptus	10.9%	13.0%	22.0%
Rangelands	34.5%	36.2%	34.2%
Wetlands and rivers	17.4%	17.4%	17.4%

Table 7-2: Modified parameters for hydrological model calibration and their final values.

Parameter	Description	Default value	Final value	Range
CN2	SCS runoff curve number	80	56.9	+/- 30%
CH_K2	Effective hydraulic conductivity (mm/hr)	0	16.8	0 - 25
ALPHA_BF	Baseflow alpha factor (days)	0.048	0.75	0.01- 0.9
ALPHA_BF_D	Baseflow alpha factor for deep aquifer (days)	0.01	0	0 – 0.1
GWQmin	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H ₂ O)	1000	1060.5	200 - 2000
Rchrg_dp	Deep aquifer percolation fraction	0.05	0.62	0 - 1
CANMAX_Euca, Oran	Maximum Canopy Storage (mm H ₂ O)	0	4	0 - 10

Table 7-3: Plant growth parameters in SWAT database used for eucalyptus growth simulation.

Parameter	Description	Default value	Final Value
BLAI	Maximum potential leaf area index	2.5	4
FRGRW1	Fraction of the plant growing season corresponding to the 1 st point on the optimal leaf area development curve	0.1	0.05
LAIMX1	Fraction of the maximum leaf area index corresponding to the 1 st point on the optimal leaf area development curve	0.15	0.05
FRGWRW2	Fraction of the plant growing season corresponding to the 2 nd point on the optimal leaf area development curve	0.5	0.2
LAIMX2	Fraction of the maximum leaf area index corresponding to the 2 nd point on the optimal leaf area development curve	0.75	0.95
HVSTI	Harvest index for optimal growing condition.	0.1	1
DLAI	Fraction of growing season when leaf area begins to decline	0.99	1
Mat_yrs	Number of years required for trees to reach maturity	10	5
Bio_E	Radiation use efficiency	15	26
EXT_coef	Light extinction coefficient	0.65	0.4
Bio_Leaf	Tree biomass accumulated each year that is converted to residue	0.3	0.2
BIO_INIT	Initial dry weight biomass (kg/ha)	0	0.5
CURYR_MAT	Current age of trees (years) at time of planting	0	1

Table 7-4: Calibration and validation statistics for streamflow simulations.

Time step	Calibration Period (1993-2005)			Validation period (2005-2013)		
	Metric					
	<i>NS</i>	<i>Pbias</i>	<i>RSq</i>	<i>NS</i>	<i>Pbias</i>	<i>RSq</i>
Monthly	0.58	-7.60	0.58	0.62	6.77	0.51

Table 7-5: Results of the optimization model to select the combination of sub-basins in terms of maximum biomass and a limited water impact.

Solution Number	Additional Biomass (above Base case) (10 ⁶ ton)	Total Biomass (10 ⁶ ton)	Yield (ton/ ha/ rotation)	Area Eucalyptus (km ²)	% Change in total flow	A	B	C	D	E	F	G	H
1	0.3	1.9	77.9	79.9	-1.1%	0	0	0	0	1	0	0	0
2	0.6	2.1	74.8	93.9	-2.5%	0	0	0	0	0	1	0	0
3	0.8	2.4	74.4	107.1	-2.7%	0	0	1	0	0	0	0	0
4	1.0	2.5	76.7	109.8	-3.0%	1	0	0	0	0	0	0	0
5	1.2	2.7	76.2	118.4	-3.8%	0	0	1	0	1	0	0	0
6	1.3	2.8	78.2	121.1	-4.2%	1	0	0	0	1	0	0	0
7	1.6	3.1	72.8	144.0	-5.3%	0	1	0	0	1	0	0	0
8	1.8	3.4	75.7	148.3	-5.7%	1	0	1	0	0	0	0	0
9	1.8	3.4	75.9	149.0	-6.1%	0	0	0	1	0	0	0	0
10	2.1	3.7	76.9	159.6	-6.9%	1	0	1	0	1	0	0	0
11	2.3	3.8	72.9	173.9	-7.2%	1	1	0	0	0	0	0	0
12	2.7	4.2	75.3	187.5	-8.8%	0	0	1	1	0	0	0	0
13	3.1	4.6	72.9	212.4	-9.9%	1	1	1	0	0	0	0	0
14	3.1	4.7	77.5	201.5	-10.3%	1	0	0	1	1	0	0	0
15	3.7	5.2	75.9	228.7	-11.8%	1	0	1	1	0	0	0	0
16	4.0	5.5	76.8	240.0	-13.0%	1	0	1	1	1	0	0	0
17	4.1	5.6	74.0	254.3	-13.3%	1	1	0	1	0	0	0	0
18	4.4	6.0	74.8	265.6	-14.4%	1	1	0	1	1	0	0	0
19	4.9	6.5	73.8	292.8	-16.0%	1	1	1	1	0	0	0	0
20	5.3	6.8	74.6	304.1	-17.1%	1	1	1	1	1	0	0	0
21	5.5	7.0	73.8	318.1	-18.5%	1	1	1	1	0	1	0	0
22	5.8	7.4	74.5	329.4	-19.6%	1	1	1	1	1	1	0	0
23	6.0	7.5	75.9	331.4	-21.1%	1	1	1	1	1	0	1	0
24	6.2	7.8	75.2	345.4	-22.4%	1	1	1	1	0	1	1	0
25	6.6	8.1	75.7	356.7	-23.5%	1	1	1	1	1	1	1	0
26	6.7	8.3	76.1	363.7	-24.8%	1	1	1	1	1	1	0	1

27	6.9	8.5	77.3	365.7	-26.3%	1	1	1	1	1	1	0	1	1
28	7.2	8.7	76.6	379.7	-27.6%	1	1	1	1	0	1	1	1	1
29	7.5	9.0	77.1	391.0	-28.8%	1	1	1	1	1	1	1	1	1
Times Selected						22	16	19	18	15	8	6	6	4

8 Supplementary Materials for Chapter 4

Figure 8-1: Simulated LAI development for the average planting density and the highest planting density during the simulation period.

Figure 8-2: Monthly mean ET rates for the PF, PFA and PFA+ scenario for the converted area for the Base case and PF, PFA and PFA+ scenarios. Error bars indicate one standard deviation of ET from the mean ET, with the standard deviation of ET calculated across the 20-year simulation period.

Figure 8-3: Decrease in water yield from the converted area for all scenarios relative to the Base case scenario. Error bars indicate one standard deviation of decrease in yield from the mean, with the standard deviation of decrease in yield calculated across the 20-year simulation period.

Table 8-1: Modified parameters for hydrological calibration process and their final value.

Parameter	Description	Default value	Final value	Range
CN2	SCS runoff curve number	*variable	variable	+/- 20%
CH_K2	Effective hydraulic conductivity (mm/hr)	0	24.9	0 - 25
CH_N2	Manning's "n" value for the main channel.	0.14	0.12	0.025-0.15
GW_DELAY	Groundwater delay time (days)	31	35.9	10-50
ALPHA_BF	Baseflow alpha factor (days)	0.048	0.49	0.01-0.9
ESCO	Soil evaporation compensation factor.	0.95	0.91	0.7-1
SOL_AWC	Available water capacity of the soil.	variable	variable	+/- 20%

*Variable depending on land use and soil, changes in calibration were therefore expressed as percent change.

Table 8-2: List of plant growth parameters in SWAT database used for plant growth modification.

Parameter	Description	Default value	Final Value
BLAI	Maximum potential leaf area index	5	2 - 9
FRGRW1	Fraction of the plant growing season corresponding to the 1st point on the optimal leaf area development curve	0.1	0.05
LAIMX1	Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve	0.15	0.05
FRGWRW2	Fraction of the plant growing season corresponding to the 2nd point on the optimal leaf area development curve	0.5	0.2
LAIMX2	Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve	0.75	0.95
HVSTI	Harvest index for optimal growing condition ((kg/ha)/(kg/ha))	0.18	0.5
DLAI	Fraction of growing season when leaf area begins to decline.	0.99	1
HI_OVR	Harvest index override ((kg/ha)/ (kg/ha)).	-	0.37 - 0.45
Bio_E	Radiation use efficiency	12	13
EXT_coef	Light extinction coefficient	0.65	0.57 - 0.72
CANMX	Maximum canopy storage (mm H2O).	0	3 - 19
BIO_INIT	Initial dry weight biomass (kg/ha)	0	0.5
CURYR_MAT	Current age of trees (years) at time of planting	0	1

Table 8-3: landuse/landcovers in the watershed.

Land use/land cover	Percent watershed	
	2000	2014
Pasture	47.7	51.3
Agriculture	13.5	19.9
Forest	35.9	25.9
Urban	0.1	0.3
Wetland-non forested	2.8	2.7

Table 8-4: Calibration and validation statistics for streamflow simulations.

Timestep	Calibration Period (1964-1973)			Validation period (1973-1983)		
	Metric					
	NS	Pbias	RSq	NS	Pbias	RSq
Monthly	0.71	3.22	0.73	0.72	5.71	0.75

Table 8-5: Changes in water yield of the subbasins as a result of conversion to oil palm.

Sub basin #	Water yield (mm)		Average annual precipitation (mm)	% difference in water yield	% subbasin converted
	Base Case	150-PF			
1	1710	1291	2582	-24%	87%
2	2949	2550	3841	-14%	87%
3	2950	2789	3132	-5%	34%
4	2885	2741	3625	-5%	30%
5	2879	2776	3841	-4%	27%
6	3145	3022	4176	-4%	30%
7	3228	3124	4284	-3%	26%
8	3272	3250	4278	-1%	5%
9	3241	3241	4297	0%	0%

Table 8-6: Water requirement for fruit, fuel and energy production estimated from this study and others.

Scenario	Water per yield (m ³ / kg)	Water per fuel (m ³ / m ³)	Water per energy (m ³ / GJ)
Optimum scenario (155palm/ha)	0.98 (fruit bunches, dry)	2819	74.9
Average	1.2	3354	86.8
Worst Scenario (55palm/ha)	1.4	3909	103.9
Additional Water ^a	0.34	948	25.2
<u>Other studies:</u>			
Babel et al. (2011) - Oil palm biodiesel			110
Pleanjai (2007)	1.1 – 1.4		151 - 232
Gerbens-Leenes et al. (2009) - Soybean biodiesel			394
Schyns et al. (2017) - Wood-based ethanol		2260	97.0
Rodriguez et al. (2018) - Sugarcane ethanol	0.2		76.0
Rodriguez et al. (2018) - Soybean biodiesel	1.5		242
Rodriguez et al. (2018) – Soybean, 2 nd harvest biodiesel	2.5		411
Maier et al. (2017) – Eucalyptus biodiesel	0.69 0.35 (Wet)		50.1 ^b
Heidari et al. (2019a) Poplar Ethanol	0.93 (dry biomass)	2306	98.1 ^b
Heidari et al. (2019a) Additional water	0.18	435	18.5
Heidari et al. (2019b) Eucalyptus Biodiesel	0.79 (dry biomass)	2148	57.1
Heidari et al. (2019b) Additional water	0.20 (dry biomass)	551	14.6
Mayer et al., (2019) Algae biodiesel			8.3- 17 (blue water)

A Copyright documentation

Communication with Geoff Syme, Editor-in-Chief, *Journal of Hydrology*, regarding permission to reprint a published paper as Chapter 2 of this document.

Email from Azad Heidari:

Sent: Thursday, 4 December 2019 1:00 PM

To: geoff.syme@bigpond.com

Subject: Enquiry: Permission to place my published paper in my PhD dissertation

Dear Prof. Syme,

I am a PhD Candidate at Michigan Technological University and I am asking you to kindly grant me permission to reprint my paper in my PhD dissertation.

Paper is titled "Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA" in Volume 574, July 2019, Pages 421-429.

I thank you in advance for your help.

Best regards,
Azad Heidari

Email from Geoff Syme, geoff.syme@bigpond.com

To: azadh@mtu.edu

Date: Dec 4, 2019, 3:09 PM

Dear Azad

I am happy for this to occur. Good luck with your dissertation.

Best wishes

Geoff

RE: Enquiry: Permission to place my published paper in my PhD dissertation

3:09 PM (1 hour ago) ☆ ↶ ⋮

Geoff Syme <geoff.syme@bigpond.com>

to me

Dear Azad

I am happy for this to occur. Good luck with your dissertation.
Best wishes
Geoff

-----Original Message-----

From: azadh@mtu.edu [mailto:azadh@mtu.edu]

Sent: Thursday, 5 December 2019 4:21 AM

To: geoff.syme@bigpond.com

Subject: Enquiry: Permission to place my published paper in my PhD dissertation

The following enquiry was sent via the Elsevier Journal website:

-- Sender --

First Name: Azad

Last Name: Heidari

Email: azadh@mtu.edu

-- Message --

Dear Prof. Syme,

I am a PhD Candidate at Michigan Technological University and I am asking you to kindly grant me permission to reprint my paper in my PhD dissertation.
Paper is titled " Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA" in Volume 574, July 2019, Pages 421-429.

I thank you in advance for your help.

Best regards,
Azad Heidari