Purpose-grown biomass crops in Nova Scotia: Statistical predictive modeling and real-world verification.

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A Thesis Submitted to Saint Mary's University, Halifax, Nova Scotia,
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Applied Science.

18 June 2024, Halifax, Nova Scotia

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Date:	18 June 2024

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Abstract

The bioeconomy of Nova Scotia could be stimulated by the increased production of purpose-grown biomass crops grown on marginal agricultural lands. Biomass yields of four crops of interest (switchgrass, miscanthus (*Miscanthus* × *giganteus* L.), coppiced hybrid-poplar and willow) were predicted using linear mixed-effects models created from published data in areas with similar climates to Nova Scotia. These models were validated and refined using yields from five field sites established across the province. Two locally sourced, low-cost soil amendments (pulp and paper mill effluent residue and liquid anaerobic digestate) and one plant biostimulant (*Ascophyllum nodosum* extract) were applied to the crops during the establishment year to evaluate effects on crop establishment and early yield. This research focuses on two of the five aforementioned local field sites, Bible Hill and Nappan. The grasses were harvested annually, while the trees were harvested after one 3-year growth cycle post-coppicing. Mean miscanthus biomass yield three years post-establishment (Year 4) across two sites was 7,200 kg ha^{-1} $year^{-1}$, while switchgrass yield was 1,800 kg ha^{-1} $year^{-1}$. The mean predicted yields across field sites, based on the developed models, were 6,700 kg ha^{-1} $year^{-1}$ and 4,000 kg ha^{-1} $year^{-1}$ for miscanthus and switchgrass, respectively. Mean hybrid-poplar and willow biomass yields across sites after one growth cycle were 1,200 kg ha^{-1} $year^{-1}$ and 1,700 kg ha^{-1} $year^{-1}$, respectively, while yield models predicted biomass yields of hybrid-poplar (3,300 kg ha^{-1} $year^{-1}$) and willow (4,900 kg ha^{-1} $year^{-1}$) across Bible Hill and Nappan field sites. Biomass yields reported in the field are likely lower than predicted due to the infancy of the field trials; these crops have likely not reached their maximum yield potential yet. Minimal differences were reported between amendment treatments and management factors during establishment have also been identified as important influences on early yields of these crops.

Date: 18 June 2024

Dedication

This dissertation is dedicated to my boys, Noah Alexander and Jack Douglas. Thank you for showing me how inefficient I was before you were born. I love you!

Acknowledgements

I started my journey at Saint Mary's University under the supervision of Dr. Kevin Vessey nearly 10 years ago as a Master's student, and I am so grateful for the opportunities he has given me in the past decade. Through a global pandemic and the births of my two children, Dr. Vessey's support and confidence in me has yet to waver. Thank you for continually dispelling my tendency to overthink everything and for listening to my rambling.

Dr. Yousef Papadopoulos has been one of my biggest professional supporters since my undergraduate degree. Without the opportunities that he gave me, I'm not quite sure where I would have ended up. It was through these opportunities that I came to truly love agriculture and field work. I am grateful for his guidance and support over the past decade.

Dr. Laura Weir has been such an important role model in my professional life. She has shown me what it is to be a strong-minded female in science and research. You and I had countless meetings where my personal disorganized filing system was ridiculed, but I always left those meetings feeling encouraged that I could teach myself to code, even though I would inevitably return to you with a whole new line of questions. Thank you for bringing levity to such an arduous journey.

Dr. Houman Fei has been an integral part of all of my graduate field research, from painstakingly growing thousands of *in vitro* plantlets for fieldwork to coordinating our many field workers. Thank you for your tremendous patience with me, and for all your hard work to help bring this research to fruition.

I would like to thank my fellow lab mates: Yedhu Sanil Kumar, Sanjeewa Thewage and Cameron Dalzell for their patience, friendship and manual labour in the field over the past five years.

I feel truly blessed to have so many people in my life that have always supported me, but especially through my eventful PhD journey. To my parents, for their never-ending love and patience. To my brother, Alex, for being one of the best listeners I know. To the rest of my family and friends, the appreciation and gratitude I have for all of you for believing in me and helping me however I needed it can never be exactly measured. Thank you for being a safe space for my kids when I needed to work.

Lastly, to my best friend and husband, Jeff. This endeavour would not have been possible without your support. You have helped me achieve so many of my dreams, including becoming a wife, mother, and a PhD (all within a pretty short timespan). Thank you for everything you do to help me be the person I want to be.

Without the support of the following organizations, the completion of this research would not have been possible: Acadian Seaplants Ltd., Agriculture & Agri-Food Canada (AgriScience

Program), BioFuelNet Canada, BioMass Canada, Dalhousie University Faculty of Agriculture, Nova Scotia Federation of Agriculture, Nova Scotia Innovation Hub Inc., Port Hawkesbury Paper, LP., T.E. Boyle Farm & Forestry Ltd. and Saint Mary's University.

"Taking on a challenge is a lot like riding a horse, isn't it? If you're comfortable while you're doing it, you're probably doing it wrong."

– Ted Lasso

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List of Abbreviations

AAFC	Agriculture & Agri-Food Canada
AIC	Akaike Information Criterion
ANOVA	analysis of variance
CLI	Canada Land Inventory
cm	centimetre
DG	liquid anaerobic digestate
DLUC	direct land use change
DMY	dry matter yield
GDD	growing degree days
GHG	greenhouse gas
GLM	generalized linear model
GWh	Gigawatt hours
ha	hectare
ILUC	indirect land use change
kg	kilogram
L	litre
m	metre
Mg	megagram
mg	milligram
MJ	Megajoules
mL	millilitre
MW	Megawatt
MWh	Megawatt hours
PHP	Port Hawkesbury Paper, LP
PHZ	Plant hardiness zone
PLS	pure live seed
PPER	pulp and paper mill effluent residue
ppm	parts per million
RCBD	randomized complete block design

RMSE	Root Mean Square Error
SE	seaweed extract (*Ascophyllum nodosum*)
SRWC	short rotation woody coppice

List of Year Descriptors

Stand Year	Gregorian Year	Description
Year 1	2019	Establishment year
Year 2	2020	1 year post-establishment
Year 3	2021	2 years post-establishment
Year 4	2022	3 years post-establishment

Chapter 1 Introduction

1.1 Anthropogenic Climate Change

The sector with the largest global greenhouse gas (GHG) emissions contribution is the energy sector, representing 34 % of total anthropogenic GHG emissions in 2019, with the largest energy subsector being electricity and heat generation (23 %) [1]. The energy sector, based principally on fossil fuels, is typically the highest priority for emissions mitigation strategies but is often the most complex for implementation [1]. Conversely, although renewable, low-carbon electricity generation has experienced substantial growth in recent years (37 % of global electricity generated in 2019 is considered low-carbon via wind or solar photovoltaics), global electricity generated by coal also grew by 7.6 % [2], leaving the most promising signs of GHG emissions reductions falling short.

One difficulty with implementing renewable energy is finding a fuel source with an energy density equivalent to the fossil fuel and the same functionality [3]. Electrification of light-duty transport has the greatest potential for decarbonizing land transport (depending on the source of electricity) and has experienced extensive deployment globally [2,4]. Unfortunately, the electrification of heavy-duty transport, such as aviation, is not as straightforward [2,3] because current battery energy density options have a lower energy density than conventional aviation fuel [5].

An additional difficulty of implementing renewable energy is the intermittent nature of solar and wind energy. While these sources of energy have become more cost-competitive with their fossil fuel counterparts in certain areas of the world [4], there are natural variations in both solar and wind that can be highly unpredictable, causing potential instability to the grid [3,6,7].

To manage these difficulties associated with electrification, bioenergy could be an appropriate alternative to fossil fuels in certain sectors [2].

1.2 Bioenergy

Biomass is an abundant global resource made up of living (or recently living) organisms [8] that can be used for energy (biomass energy = bioenergy) [9,10]. Bioenergy currently makes up approximately 10 % of global primary energy, with 70 % considered traditional bioenergy [2,11,12]. Traditional bioenergy (the thermochemical conversion of solid biomass (combustion) to produce heat and energy) has been used by humans since the beginning of time [13] and although it is typically described as having low energy density and high GHG emissions, it still makes up a great proportion of biomass used worldwide, mainly in developing countries for heating and cooking [2,11,13].

Modern bioenergy is known as the conversion of biomass to other forms prior to end-use, such as solids, liquids, and gases for biofuels [14]. Through biochemical processes (i.e. fermentation, transesterification, and anaerobic digestion), or thermochemical processes (i.e. gasification and pyrolysis), fossil fuel alternatives such as bioethanol (gasoline alternative), biodiesel (diesel alternative) and biogas (natural gas alternative) can be created from biomass [11,12,15].

A common descriptor used to classify biofuels is the feedstock type, separating biofuels into four categories. The third and fourth generations of biofuels are centred around microalgae biomass [16] and will not be discussed in this research. First-generation, or conventional biofuels, are characterized by feedstocks based on food and feed crops, such as corn, soybean, and wheat [12,14,17]. First-generation liquid biofuels are currently the most used biofuels

[2,12,13,18], as the technology for fermenting plant sugars to ethanol dates back to 4,000 B.C. and has a long history of commercial availability [13,19]. There are numerous drawbacks associated with the large-scale uptake of first-generation biofuels, including the ‘food versus fuel’ debate and small to negligible GHG emissions reductions [9,20,21]. These drawbacks have been extensively studied and ignited the development of second-generation biofuels.

Second-generation, or advanced biofuels, are characterized by non-food, lignocellulosic feedstocks, such as dedicated energy crops and agricultural and forestry residues [12,14,17]. Due to the structural composition of lignocellulosic material (i.e. cellulose, hemicellulose and lignin), there are additional steps required (pretreatment and hydrolysis) to convert these materials to liquid biofuels [19,22,23]. The technology required to accommodate these additional steps is less commonplace compared to first-generation technology [13], and is considerably more expensive [2,24].

The development of second-generation biofuels focused on addressing the drawbacks associated with first-generation biofuels, and ultimately developing a more sustainable source of biomass [14]. One drawback, the ‘food versus fuel’ debate, is only partially addressed. The exploitation of non-food feedstocks and waste materials allows food and feed crops to be grown for their original purpose rather than for biofuels. However, the plantation of dedicated energy crops, such as switchgrass (*Panicum virgatum L.*), miscanthus (e.g. *Miscanthus* × *giganteus*), hybrid-poplar (*Populus* sp.) and willow (*Salix* sp.) can divert land intended for food production into biomass production. Direct and indirect land use change (DLUC and ILUC, respectively) can continue to stimulate the ‘food versus fuel’ debate and can have severe, unintended negative consequences to the environment, including reducing biodiversity and soil carbon storage, as well as increasing GHG emissions (another drawback supposedly being addressed by second-generation biofuels), depending on the severity of LUC [7,16,20].

The sustainability of dedicated energy crops– although dependent on the entire lifecycle from land preparation and feedstock growth to final energy conversion– is considerably affected by the land being cultivated for crop production. This aspect of sustainability is known as the bioenergy land use dilemma [25,26]. There are numerous environmental implications with varying severity associated with establishing a dedicated energy plantation, however, it has been advocated that utilizing marginal land can minimize these implications and should optimize sustainability [27].

With respect to agriculture, 'marginal', is defined as "close to the limit of profitability" [28]. Marginal lands have some impediments that create a less suitable growing environment for annual crops [15], creating the ideal location for biomass for bioenergy [27]. Dedicated energy crops are known for good productivity with minimal agronomic inputs in substandard growing conditions [29–32], and as defined, these lands are not suitable for food or feed production. Throughout the literature, it has been noted that because there is no globally accepted land classification system, the words 'abandoned', 'contaminated', 'idle', 'underutilized' and 'degraded' may be used interchangeably with marginal [26,27,33]. To evaluate the most sustainable experimental conditions for dedicated energy crop production, this research will evaluate the potential of four dedicated energy crops, two perennial grass species (switchgrass and miscanthus) and two short-rotation woody coppice species (SRWC) (hybrid-poplar and willow) on marginal lands in Nova Scotia, Canada.

1.3 Canada and Nova Scotia

1.3.1 Current Landscape and Opportunities

As Canada is warming at twice the rate of the entirety of the Earth [34], it is imperative that the country does its part to reduce GHG emissions and limit future warming. In 2021, Canada increased its Nationally Determined Contribution (NDC) as part of the Paris Agreement to 40-45 % GHG emissions reduction below 2005 levels by 2030 [35–37]. The energy sector in Canada contributed 81 % of total national GHG emissions in 2021, while the same sector contributed to 91 % of total provincial GHG emissions in Nova Scotia [35,38].

The abatement of GHG emissions in certain subsectors of energy is more complex than others, stalling progress towards emissions reductions. The transport subsector contributes 34 % and 37 % of total energy related GHG emissions in Canada and Nova Scotia, respectively [38]. While the electrification of road transport is a top priority within Canada's 2030 Emissions Reduction Plan, there are still modes of transport that are critical for the success of the national economy, but less amenable to electrification [37]. Low carbon intensity fuels (biofuels) could further support low carbon transport but currently they only occupy a mere 6 % of Canada's total energy supply [37]. According to the 2030 Emissions Reduction Plan, the government is exploring biofuels with respect to waste biomass (agricultural, forestry and municipal) [37]. Recent studies have shown that the quantity of agricultural and forestry residues that are available to be sustainably harvested in Canada (with considerations for ecological and technical restrictions) is the same as the quantity currently used to produce bioproducts (approximately 30 million dry Mg) [9,39–41]. Therefore, to increase the quantity of biofuels in the national energy supply without sacrificing ecological functions of residues, dedicated energy crops should be investigated as a source of biomass.

Although providing a low carbon alternative to the transport sector is more sought after [42], the commercial readiness of lignocellulosic liquid biofuels has been a major barrier to scaling up production [43]. In the interim, dedicated energy crop biomass could be a short-term fossil fuel alternative for electricity generation. In Canada, the reduction of coal and oil for electricity generation have led to a considerable 52 % decrease in GHG emissions from electricity and heat generation from 2005 to 2021 [35], owing to vast hydroelectricity and wind resources [37]. Conversely, in Nova Scotia, over half of electricity is still coal-fired [44]. While Nova Scotia has a diverse portfolio of electricity generation from renewable sources (hydroelectric, wind and biomass, totalling 25 % in 2019), the coal-generated electricity in the province is a considerable contributor to total GHG emissions (43 %) [1,38,44].

As evidenced in Nova Scotia, lignocellulosic biomass can be combusted to produce heat and electricity. The 60 MW Port Hawkesbury Paper Biomass Plant supplies roughly 3 % of the province's electricity [44,45], and the smaller Dalhousie University Biomass Energy Plant (1 MW) supplies the equivalent of 75 % of the Faculty of Agriculture's campus' electricity usage (7,750 MWh annually) to the provincial grid [46]. These facilities both generate electricity using forestry products and waste, which has stirred quite the local controversy. In addition to these facilities, biomass can be co-fired with coal in existing infrastructure as a more cost-effective strategy to phase out coal [47,48]. Electricity generated from dedicated energy crop biomass is better aligned with coal generated electricity for its dispatchable nature, a clear advantage over solar and wind power [42].

1.3.2 Limitations

With several opportunities for the utilization of dedicated energy crop biomass in Canada and Nova Scotia, it would be remiss not to address limitations. Repeatedly described throughout the literature, there are many barriers to scaling up the lignocellulosic biofuels industry at every step of the supply chain [49–51]. For agricultural producers, investing resources, time, and money into producing dedicated energy crops is very risky with no guaranteed reward. Considering a sizable initial investment with a years-long delay in recovery, in addition to minimal access to insurance and potentially high opportunity costs, there is no question why the adoption of dedicated energy crops has been stalled [37,49–51]. The technology required to convert lignocellulosic biomass to liquid fuels is extremely costly, and differs between conversion pathways and end-uses, lending minimal flexibility to biorefineries once they've been established [2,24,49–51]. Finally, the extra cost of second-generation biofuels compared with first-generation biofuels and fossil fuel equivalents calls to question the economic feasibility of the industry [49–51].

Although the refining processes are much less intensive, scaling up the production of dedicated energy crop biomass for electricity and heat generation also faces many barriers. All the same concerns from an agricultural producer's standpoint remain regardless of the end-use of the biomass. There are many unknowns within bioenergy supply chains, and the unknown market conditions incite understandable hesitation from producers.

From a local, provincial perspective, the supply chain issues can take a back seat, so the priority becomes evaluating the biomass production limitations by asking the following questions: what is the annual supply of dedicated energy crop biomass that can be produced in

Nova Scotia without sacrificing food production or environmental protection? What is the productivity of these crops on marginal lands in a Nova Scotian climate? What are the quality characteristics of the biomass grown, as this can be a determinant of end-use? Without assurances on biomass availability in Nova Scotia, there is no need to explore the supply chain further.

1.3.3 Addressing Limitations

For any biomass end-use, a proven supply of sustainably sourced biomass is required to necessitate further exploration and development of a bioenergy industry in Nova Scotia. This research will begin to evaluate the productivity potential of four dedicated energy crops, two perennial grass species (switchgrass and miscanthus) and two short-rotation woody coppice species (hybrid-poplar and willow) on marginal lands across Nova Scotia. By evaluating the growth potential on differing marginal lands across the province, real-world data can be collected locally to make more informed decisions about moving forward with dedicated energy crops for biomass in a bioenergy industry.

If these crops show good productivity potential under these experimental conditions, these data can be used in conjunction with real-world data from similar climates to develop predictive yield models to extrapolate the potential provincial biomass supply from dedicated energy crops in Nova Scotia from switchgrass, miscanthus, coppiced hybrid-poplar and coppiced willow.

1.3.3.1 Yield Modelling

Crop growth/ yield modelling has a long history, dating back to the very early 20th century [52]. With concurrent advances in scientific knowledge and computing technology over the past century, there have been many crop growth models developed with varying degrees of complexity and real-world applications [52–54]. Crop growth models were first applied to dedicated energy crops in the late 20th century, with miscanthus and switchgrass at the forefront [53]. Since then, numerous models have been adapted or developed specifically for energy crops [53]. Jones et al. discussed at length three characteristics for consideration with the development of crop growth models which nicely contextualize the energy crop modelling in this research: "the intended use of the models, the approaches taken to develop the models and their target scales" [54].

The causality dilemma is an ever-present theme in this research which can be directly related to the intended use of these yield models. As described by [54], the motivation behind developing crop growth/ yield models is either to further scientific understanding or to support policy/ decision making. This description in itself outlines the causality dilemma and the purpose behind this research: there is a dearth of local Nova Scotia data to sufficiently prove the success of dedicated energy crops for biomass in this province. Agricultural producers need evidence (scientific understanding) to support the success of these crops locally to invest resources into this immature industry. Further, producers also need to see a proven market demand for their biomass. At the same time, biorefineries and industry officials need evidence of a stable supply of biomass and a subsequent supply chain in the province to invest in establishing biorefining technology, creating the market demand for the biomass. The intended use of the crop yield models in this research could address both scientific understanding and policy support. The models could inform all stakeholders of the potential supply of biomass from the crops of interest in Nova Scotia and using these data, policy or decisions could be influenced.

The statistical approach to model development, using historical climatic observations, were the first models used for predicting large-scale crop yield estimates [54,55] and was the approach taken in this research. As previously alluded to, the scarcity of local, historical Nova Scotia dedicated energy crop data forced the creation of a training dataset (on which the models are developed) extrapolated beyond Nova Scotia. To develop models with the greatest comparability to the Nova Scotia climate, the literature search was expanded to include any publication in which the study location could be categorized by a plant hardiness zone (PHZ) equal to or colder than those found in Nova Scotia.

The user range of these crop yield models would be individuals from the field level up to the regional (provincial) level in Nova Scotia [53,54], as the development of these models is to inform stakeholders of the potential biomass supply from dedicated energy crops in Nova Scotia.

There are general limitations to address with the modelling framework that has been outlined in this research. There are numerous assumptions that have been made in this model development process that, if not communicated clearly, can increase user uncertainty, and jeopardize the credibility of the model outputs [27].

The training dataset is used to train and develop a statistical model, while a testing dataset is typically experimental data used to test the model. The training dataset sets the tone for the predictive ability of the model in reference to the testing dataset. If the training dataset is small, and within-parameter patterns are similar (i.e. a narrow range of historical growing season precipitation data), the model will not perform 'well' with testing data that is dissimilar to the training dataset. The broader the training dataset, both in size and within-parameter patterns, the greater predictive ability of the model across varying conditions [55]. Utilizing non-Nova Scotian data in the training datasets for all predictive yield models in this study was a necessity based on lacking Nova Scotian data. By including the ‘Location’ of each reported biomass yield as a model parameter, the models were trained to identify some form of spatial variation [55], where typically statistical models are not trained to be extrapolated across spatial scales [54]. Further to this, because statistical models are trained on historic climatic data, it is not feasible to predict yields in future scenarios with unprecedented climate scenarios (i.e. climate warming projections) because the models cannot respond appropriately to unobserved data [54].

1.4 Dissertation Objectives and Organization

Nova Scotia is well-suited to explore a local bioeconomy. It is imperative that a dispatchable, non-fossil source of energy, such as biomass, is evaluated as an alternative to coal-generated electricity which could eventually lead to the refinement of biomass to liquid biofuel, both in attempts to reduce provincial GHG emissions. The development of a local bioeconomy in Nova Scotia is caught in a causality dilemma, centralized by risk. The overarching objective of this research is to de-risk the local bioeconomy through statistical predictive yield modelling and real-world verification.

The specific objectives are:

1. Evaluate the establishment, early growth, and biomass yield of four dedicated energy crops (switchgrass, miscanthus, coppiced hybrid-poplar and coppiced willow) on marginal lands in Nova Scotia.

2. Evaluate the effect of locally sourced soil amendments and a plant biostimulant on the establishment, early growth, and biomass yield of the dedicated energy crops.
3. Develop statistical predictive crop yield models for each dedicated energy crop for Nova Scotia.

The results of locally conducted field trials of the four dedicated energy crops of interest are outlined in Chapter 2 (switchgrass and miscanthus) and Chapter 3 (coppiced hybrid-poplar and coppiced willow). In these chapters, the effects of locally sourced soil amendments and a plant biostimulant on establishment, early growth and biomass yield of these crops are evaluated. Chapter 4 (switchgrass and miscanthus) and Chapter 5 (coppiced hybrid-poplar and coppiced willow) outline the process of statistical predictive yield modelling of these dedicated energy crops based on climatic conditions in Nova Scotia. The final chapter (Chapter 6) summarizes the results of the thesis research and provides an outline of future research and a knowledge transfer plan.

Chapter 2 Real-world verification of the yield potential of miscanthus and switchgrass on marginal lands in Nova Scotia.

2.1 Introduction

Switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* × *giganteus*) are two of the most promising lignocellulosic species for bioenergy, as they provide several co-benefits alongside their production for biomass. These perennial, warm-season grasses require minimal agronomic inputs to obtain high biomass productivity and have exhibited considerable biomass productivity in sub-optimal conditions, such as marginal agricultural lands and shorter growing seasons [56–62]. Further, these grasses are highly efficient in both nutrient and water usage and provide ecosystem services including improving soil fertility, sequestering carbon, and reducing erosion [59–61,63]. Switchgrass is native to North America and its utilization as a bioenergy crop in Canada has been studied since 1991 [64,65], whereas miscanthus is native to east Asia and has only recently (within the last two decades) been studied as a bioenergy crop in Canada [65,66].

Unfortunately, the great potential of these dedicated energy crops does not come without risks. The establishment, and associated establishment costs of these species are substantial [67,68]. Firstly, switchgrass is typically seeded into the field [69]. There are challenges in establishing switchgrass as it cannot compete well with weeds, prolonging the time to establish a complete canopy to at least two years post-planting [70]. Miscanthus (*M.* × *giganteus*) rhizomes are usually directly planted into the field. Establishment rate is greatly impacted by rhizome quality [71], but is also impacted by growing conditions. In addition, cold winter conditions following planting can augment unsuccessful establishment of rhizomes (down to 40 %) [72], forcing a replant to compensate for the losses. This replanting inevitably leads to prolonging the peak miscanthus yield of the plantation [73]. The establishment costs of a miscanthus plantation are 2-3 times greater than that of a switchgrass plantation, based on the cost of rhizomes and differences in planting between switchgrass seeds and miscanthus rhizomes [69,74].

Over time, alternatives to rhizome planting have been developed for the sterile miscanthus clone (*M.* × *giganteus*), including rhizome-derived plants and micropropagated plants [71,72]. The inherent advantage of these planting protocols over rhizomes is two-fold: the quality of the plants can be evaluated prior to planting (unlike rhizomes) and subsequently, any establishment issues due to rhizome quality are bypassed in the field with plants [71], creating the opportunity for greater establishment and overwintering of more mature plants. The production systems of either rhizome-derived plants or micropropagated plants are intensive, and do not provide any immediate reductions to establishment costs [72]. However, if miscanthus establishment rate is significantly improved via rhizome-derived or micropropagated plants, could the resulting biomass productivity (and co-benefits) offset for the cost of improved establishment?

Evaluating the productivity of switchgrass and miscanthus in Nova Scotia on marginal agricultural lands is a crucial first step in developing a sustainable supply of biomass for energy. Over half of electricity generation in Nova Scotia is from burning coal, generating 43 % of greenhouse gas emissions [44]. While renewable alternatives have been implemented to reduce coal consumption, the intermittent nature of wind and solar power continue to pose challenges to larger-scale dispatchable implementation [75,76]. A more sustainable renewable alternative to coal-powered electricity is by co-firing biomass with coal. Co-firing can be a cost-effective strategy to reduce reliance on and emissions from fossil fuels for electricity [47,48]. An equally important next step is to evaluate the quality of the biomass produced. By determining the composition of the biomass produced (cellulose, hemicellulose, lignin, ash) [56,77], not only can the end use of the biomass be better assessed, but adjustments in harvesting protocols can be made accordingly.

Perennial grasses for bioenergy are harvested annually, but the timing of the harvest within the year is subject for discussion. There are three timings that are discussed in the literature, each with their own merits. Firstly, a summer harvest in August or September, during the anthesis growth stage could maximize biomass yield [32,78–80]. A fall harvest in October, marked by the first killing frost and the beginning of plant senescence allows for nutrient translocation from aboveground biomass to belowground rhizomes, increasing biomass quality in exchange for a slight decrease in biomass yield [79,81,82]. A late winter/ early spring harvest during plant dormancy typically results in the highest quality biomass (lower ash and moisture content, higher energy content compared to fall harvests) but the lowest biomass yield of all three timings [62,70,81,83].

One of the numerous advantages of warm-season grasses as dedicated bioenergy crops is the minimal agronomic inputs required for growth, even on marginal soils [31,32]. Although there is evidence to support that synthetic fertilizer plays an important role in increasing biomass productivity [81], the application of conventional fertilizers to attain higher establishment and/ or biomass productivity of miscanthus and switchgrass on marginal land is counterproductive to the sustainability and emissions reductions goals of bioenergy.

Biological soil amendments, such as waste products (pulp and paper mill sludge and anaerobic digestate) and a plant biostimulant, seaweed extract, can be locally sourced in Nova Scotia, thereby significantly reducing both the energy consumption and GHG emissions associated with their use [84,85]. Pulp and paper mill effluent residue is a substantial waste by-product from pulp and paper production. Beneficial characteristics for its use as a soil amendment include low heavy metal components, high water-holding capacity, and potential to stimulate soil microbial activity [85–87]. Liquid anaerobic digestate is one by-product of the digestion of organic materials in the absence of oxygen. Digestate typically contains high levels of nutrients and like pulp and paper mill residue, digestate also has the potential to stimulate soil microbial activity [88,89]. Seaweed extract (*Ascophyllum nodosum*) is native to the northern Atlantic Ocean and has been extensively researched for its biostimulant properties in agriculture, including improved crop productivity and stress tolerance [90,91].

2.1.1 Objectives

The overarching objective of this research is to de-risk biomass feedstock supplies in Nova Scotia to aid in the development of a renewable, dependable source of electricity. This electricity could be implemented immediately with the eventuality of encouraging the start-up of a dedicated biomass refinery (biorefinery). The objectives of this paper are:

1. To evaluate the establishment, early growth and biomass yield of switchgrass and miscanthus on marginal agricultural lands in Nova Scotia;
2. To evaluate the effect of locally sourced soil amendments and a plant biostimulant on the establishment, early growth and biomass yield of switchgrass and miscanthus;
3. To investigate the quality of miscanthus biomass.

2.2 Materials and Methods

2.2.1 Field Site Characterization

Field trials were conducted at two field sites in Nova Scotia, Canada. The Bible Hill field site (latitude 45°38’N, longitude 63°24’W) is owned by Dalhousie University’s Faculty of Agriculture and has a mean annual daily temperature of 6.0 °C and a mean annual precipitation of 979.5 mm [92]. Soils are classified as sandy loam and silty clay with imperfect drainage (Class 2, moderate limitations) [93,94] (Table A-1). The Nappan field site (latitude 45°46’N, longitude 64°14’W) is within Agriculture & Agri-Food Canada’s Food and Horticulture Research Station and has a mean annual daily temperature of 6.0 °C and a mean annual precipitation of 1,154.8 mm [95]. Soils are classified as sandy clay loam with imperfect drainage (Class 3, moderately severe limitations) [93,96] (Table A-1).

Meteorological conditions were monitored through pre-existing Environment Canada weather monitoring equipment. The closest Environment Canada monitoring station to the Bible Hill field site is located approximately 20 km north of Truro in Debert, Nova Scotia (World Meteorological Organization ID: 71317) while there is an Environment Canada monitoring station located at the AAFC Research Station in Nappan (World Meteorological Organization ID: 71311) [97] (Table 2.2.1).

Table 2.2.1 Cumulative growing season (May – October) precipitation (mm) as measured at two Environment and Climate Change Canada – Meteorological Service of Canada (ECCC-MSC) weather stations compared to the 1981 – 2010 mean.

Year	Cumulative Growing Season (May – October) Precipitation (mm)	
	Debert, Nova Scotia[1] WMO ID[2]: 71317	Nappan, Nova Scotia WMO ID[2]: 71311
2019	706.9	771.8
2020	459.6	351.0
2021	575.6	644.2
2022	534.5	482.1
1981 – 2010 Mean[3]	600.0	551.6

[1] 20 km north of the Bible Hill field site.

[2] World Meteorological Organization Identification.

[3] Canadian Climate Average [92].

2.2.2 Plant Material

Rhizomatous miscanthus material (*Miscanthus* × *giganteus* cv. ‘Nagara’) was received from the University of Guelph (Guelph, Ontario, Canada) and grown at the Agriculture & Agri-Food Canada Nappan Research Farm (Nappan, Nova Scotia, Canada). Dormant buds of miscanthus were used to cultivate plantlets via *in vitro* tissue culture propagation and further grown in the greenhouse [98]. Miscanthus plantlets were planted approximately 10 cm deep with row spacing between plants of approximately 0.7 m (90 plants per split-plot or 22,500 plants ha^{-1}) (Figure 2.2.1).

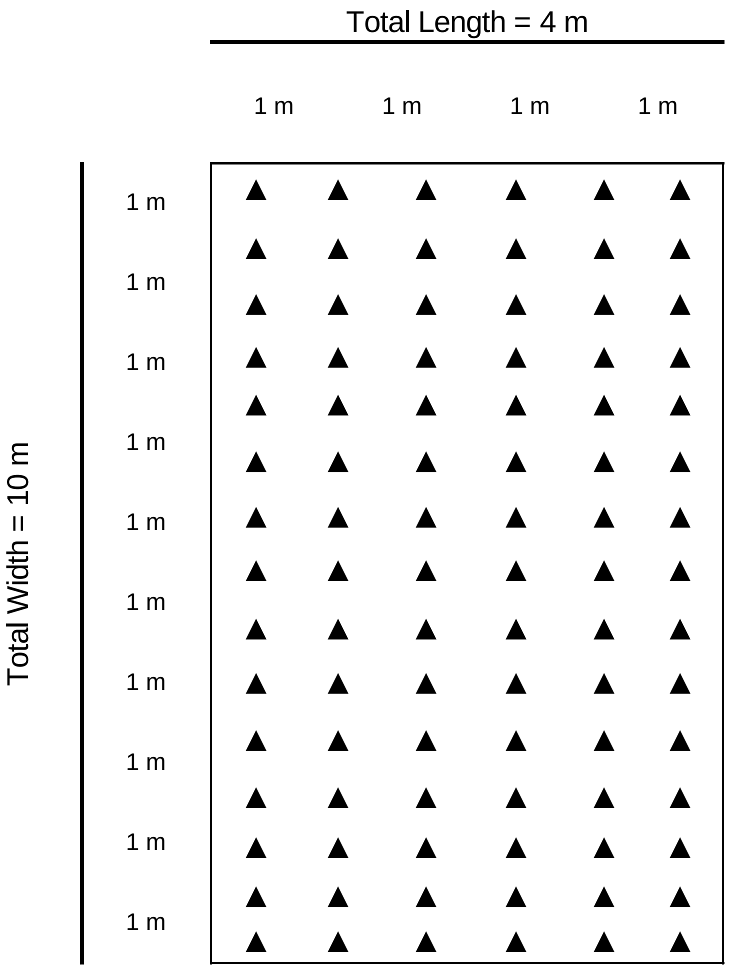

Figure 2.2.1. Diagram of the planting design of each miscanthus split-plot at the Bible Hill and Nappan, Nova Scotia field sites.

Seeds of switchgrass (*Panicum virgatum* L. cv. 'Cave-in-Rock') were received from Ferme Norac Incorporated (St-Timothée, Quebec, Canada). Switchgrass was seeded into the soil via 'seeding circles', evenly distributed within each split-plot. The 'seeding circles' were used to facilitate a similar application of the soil amendments to the crops, particularly the pulp and paper mill effluent residue. At the location of each 'seeding circle' (0.5 m row spacing), 0.2 g of seed (approximately 120 seeds) were planted, resulting in a seeding rate of approximately 8 kg ha^{-1} (160 'seeding circles' per split-plot) (Figure 2.2.2).

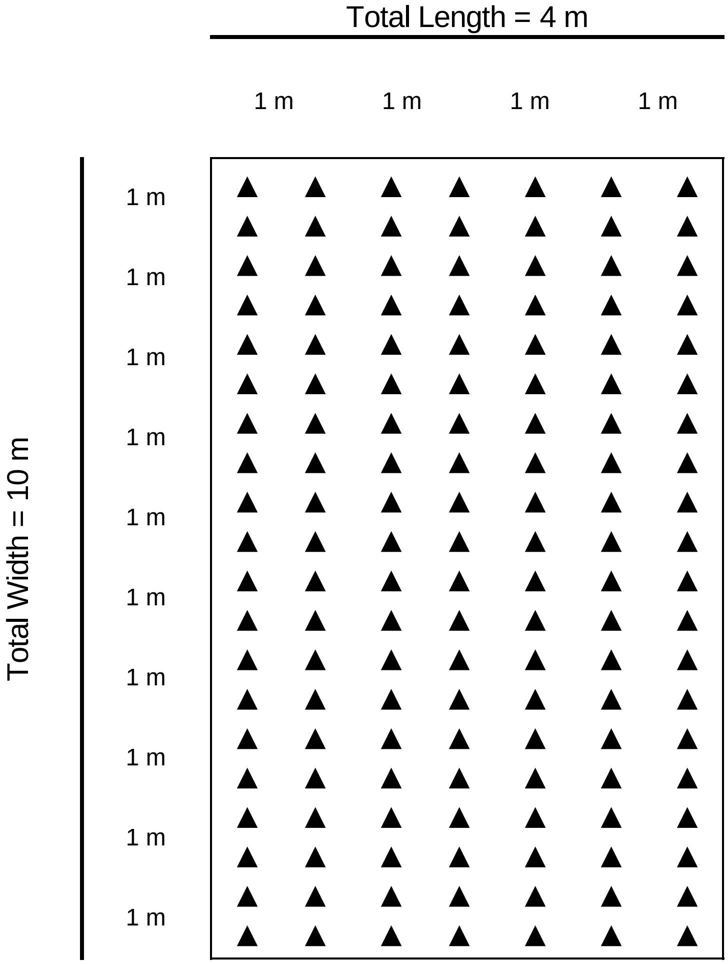

Figure 2.2.2. Diagram of the planting design of each switchgrass split-plot at the Bible Hill and Nappan, Nova Scotia field sites. Each triangle represents a 'seeding circle'.

2.2.3 Soil Amendments and a Plant Biostimulant

Two locally sourced soil amendments (Table 2.2.2) and one plant biostimulant were applied to miscanthus and switchgrass in the establishment year (2019). The nutrient composition of the pulp and paper mill effluent (PPER) and liquid anaerobic digestate (DG) are outlined in Appendix A (Table A-2, Table A-3).

Table 2.2.2. Source and experimental abbreviation of two locally sourced soil amendments and one plant biostimulant applied to miscanthus and switchgrass at the Bible Hill and Nappan, Nova Scotia field sites.

Abbreviation	Material	Commercial Name	Scientific Name	Source
PPER	Pulp and paper mill effluent residue	-	-	Port Hawkesbury Paper, LP
DG	Liquid anaerobic digestate	-	-	T.E. Boyle Farm and Forestry Limited
SE	Seaweed Extract	Stella Maris®	*Ascophyllum nodosum*	Acadian Seaplants Limited

Pulp and paper mill effluent residue was applied to miscanthus and switchgrass during planting in early June of year 1 at both field sites. Amendment application rates were as follows: PPER (~ 12,000 kg ha^{-1}), DG and SE (16,250 L ha^{-1}). For consistency between amendment applications, the application rate of PPER was calculated in litres (Table 2.2.3). Holes (approximate depth of 30 cm) were dug for each miscanthus plant or ‘seeding circle’ and filled with PPER. Miscanthus plants were planted into the holes and subsequently covered with soil. For the ‘seeding circles’, soil was distributed evenly over the PPER, and then seeds were planted and rolled with a lawn roller.

Table 2.2.3 Application rate (per plant or ‘seeding circle’) of two soil amendments and one plant biostimulant for miscanthus and switchgrass during the establishment year (2019) at the Bible Hill and Nappan, Nova Scotia field sites.

Crop	Number of Plants or ‘Seeding Circles’ per Split-plot	Application Rate (L $plant^{-1}$)		
		Pulp and paper mill effluent residue	Liquid Anaerobic Digestate [a]	Seaweed Extract (1 mL L^{-1}) [a]
Miscanthus	90	3.5	0.69	0.69
Switchgrass	160	2.0	0.39	0.39

[a] Application rates were the same in Year 1 (2019) and Year 2 (2020).

Liquid anaerobic digestate and seaweed extract were applied as a soil drench treatment post-planting. The initial application of these treatments occurred in mid-August 2019 at both field sites. A second application (following application rates from 2019) was applied in July 2020 to compensate for the late application in the establishment year. Split-plots from 2019 were divided in half lengthwise (2 m × 10 m) to create split-split-plots.

2.2.4 Experimental Setup

Each field site followed the same randomized complete block design split-split-plot structure, with miscanthus and switchgrass as two of four biomass crops planted. Four crops were planted (treatment factor A, ‘plot’) and treated with two soil amendments, one plant biostimulant and one untreated control (treatment factor B, ‘split-plot’). One amendment (liquid anaerobic digestate) and the plant biostimulant (seaweed extract) received a secondary application in 2020, creating treatment factor C, ‘split-split-plot’). Each block (four block replicates total) contains all levels of all treatment factors (Figure 2.2.3). Prior to field site establishment, plots were prepared by spraying Roundup® herbicide (according to the manufacturer’s recommendation), followed by ploughing the soil to a depth of approximately 30 cm and lastly, the plots were harrowed.

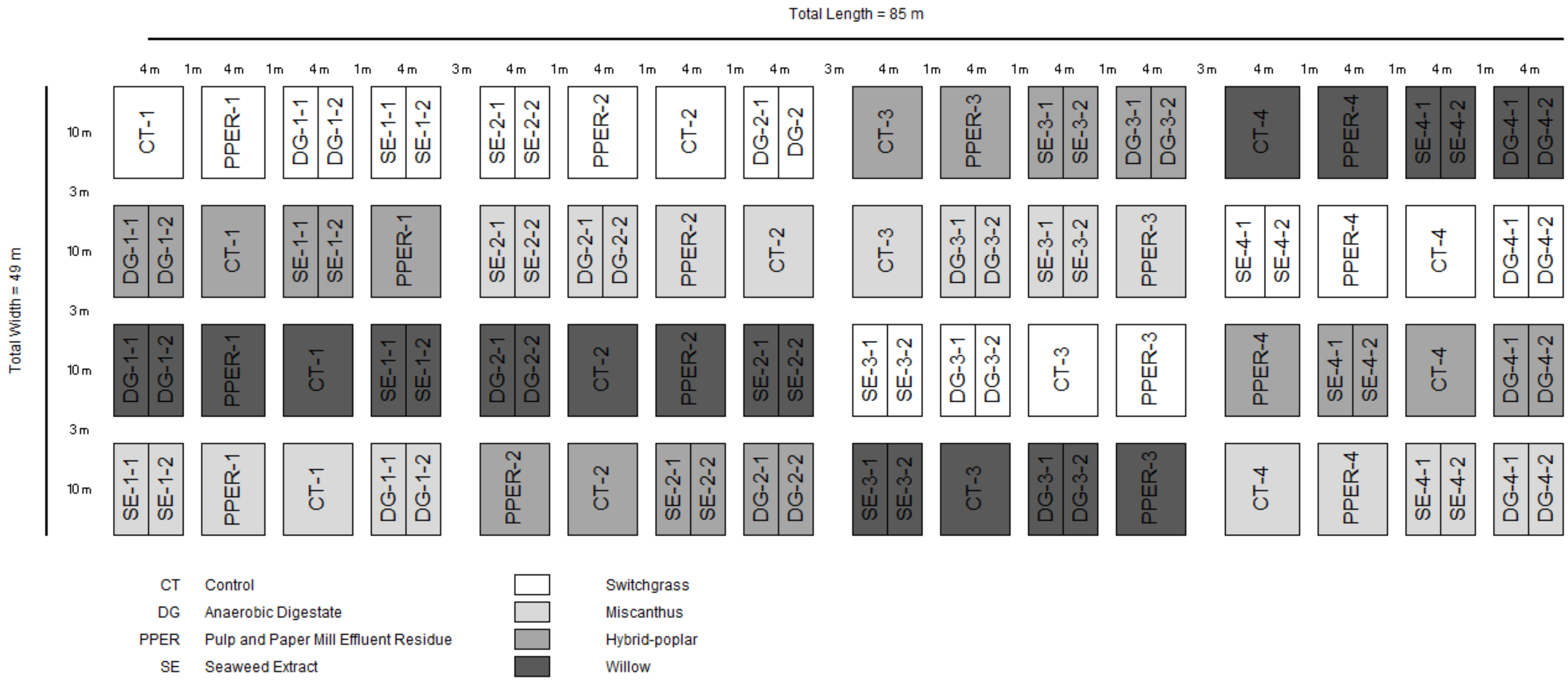

Figure 2.2.3. Diagram indicating randomized complete split-split plot design of four biomass crops, including hybrid-poplar and willow, planted at the Bible Hill and Nappan, Nova Scotia field sites.

2.2.5 Field Site Maintenance

Moderate to high weed pressure was observed at both Bible Hill and Nappan field sites approximately four weeks post-planting. To aid crop establishment, weeds were mechanically removed from miscanthus plots using a combination of mowing, trimming, hoeing, and hand-pulling. All forage within the switchgrass plots were mowed to a height of approximately 10 cm, to reduce competition for emerging switchgrass [99]. In year 2, the weed pressure in the switchgrass plots was too immense to control manually. A broadleaf herbicide (Weed B Gon® MAX, ScottsMiracle-Gro Company) was applied using a backpack sprayer across switchgrass plots in July and August, following mowing. Weed removal occurred once per growing season at the Nappan field site and twice per growing season at the Bible Hill field site (apart from only one weeding session in year 3). Early in year 2, an electrified deer fence (DeerBusters, Waynesboro, PA, USA) was installed according to the manufacturer's recommendations to reduce deer grazing pressure.

2.2.6 Data Collection

2.2.6.1 Soil Sample Collection

Soil cores (0-15 cm and 16-30 cm) were collected across each field site prior to planting to establish baseline soil characteristics (Table A-1). Soil cores (0-15 cm) were subsequently collected within each split-plot in year 2 and within each split-plot (or split-split-plot following the secondary application of DG and SE) in year 4. Soil cores were collected equidistantly between plants or 'seeding circles'.

2.2.6.2 Mid-Season Data Collection

To capture potential additional indicators of the soil amendments and the plant biostimulant on miscanthus, mid-season growth parameters were collected in August of year 2. Ten randomly selected miscanthus plants per split-plot were selected as sub-samples for all mid-season data collection. Tiller count, longest tiller, and area per leaf (sampled from the longest tiller) per plant were measured for the ten randomly selected miscanthus plants per split-plot. Leaf area was measured using a LiCor LAI03300C Plant Canopy Analyzer. Due to the morphology and abundance of miscanthus leaves per tiller, a sub-sample of leaves was removed from the tallest tiller of each sub-sampled plant and measured for leaf area. Miscanthus survival rate (the ratio of presently living plants to the total number of plants initially planted) was also recorded during mid-season data collection. There was no mid-season data collection completed for switchgrass.

2.2.6.3 End of Season Data Collection

2.2.6.3.1 Switchgrass

At the end of each growing season, a sub-sample of switchgrass was harvested per split-plot (or split-split-plot) and collected for dry matter yield analysis. Switchgrass was cut approximately 5 cm above the ground to simulate a machine harvest. There was no switchgrass harvested in year 1 at the Bible Hill site due to minimal switchgrass growth combined with substantial weed growth. In year 1 (Nappan) and year 2 (both sites), eight randomly selected 'seeding circles' per split-plot (or split-split-plot) were harvested using a 1 m^2 quadrat. All the grass within the quadrat was collected and subsequently analyzed for DMY.

In years 3 and 4, the random sampling protocol was amended as the 'seeding circles' were no longer indistinguishable. Starting from the plot marker in the bottom right corner, samples were collected using a 0.25 m^2 quadrat with movement through the plot as noted in Figure 2.2.4. For split-plots (CT and PPER), sampling followed the pattern in (Figure 2.2.4 A) while in split-split-plots (DG and SE), sampling followed the pattern in (Figure 2.2.4 B), totalling six switchgrass samples per split-plot (or split-split-plot). A sub-sample (approximately 100 g) of the pooled sample (six randomly selected spots per split-plot (or split-split-plot)) was collected to calculate DMY. All DMY samples were dried at 70 ºC for at least seven days.

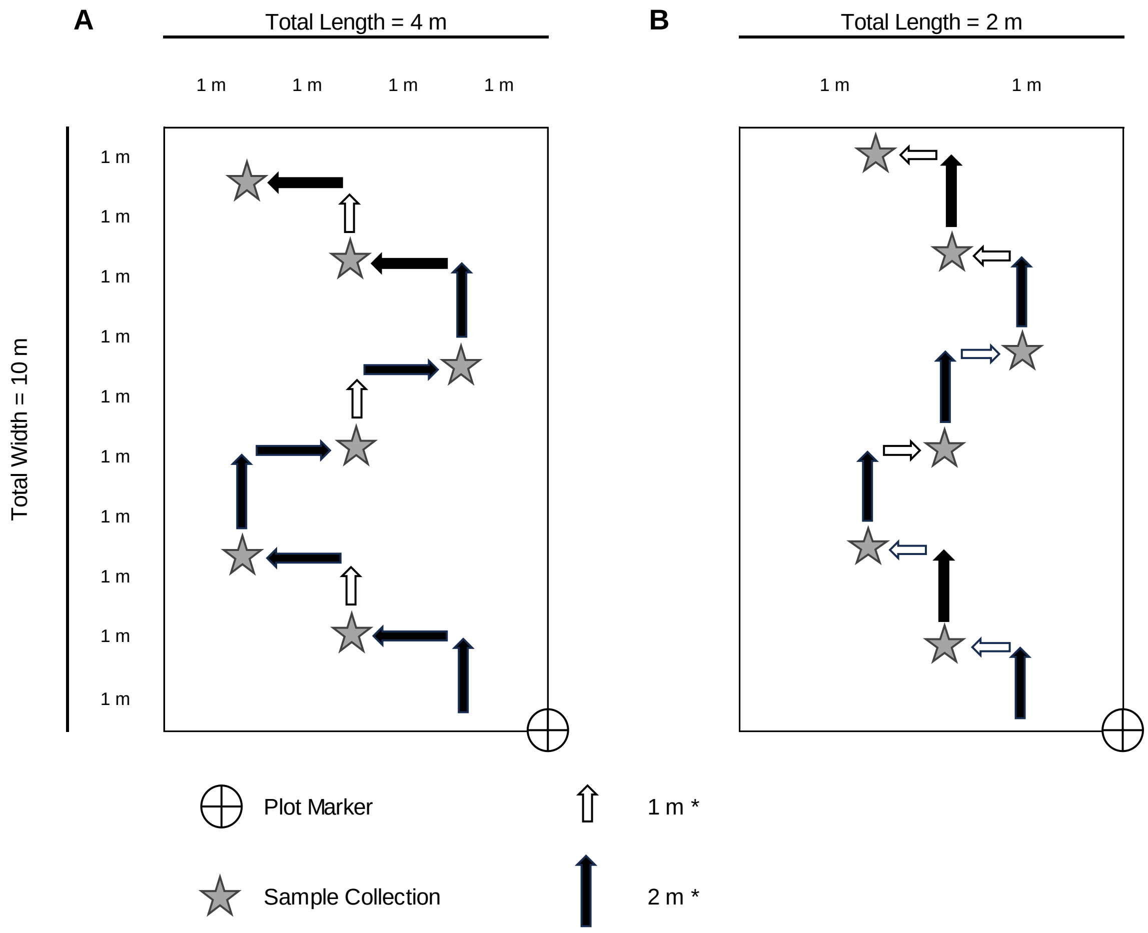

Figure 2.2.4 Diagram indicating switchgrass sampling protocol for **A** split-plots and **B** split-split-plots in years 3 and 4. The distance indicated by the arrows is approximate, measured in footsteps.

2.2.6.3.2 Miscanthus

At the end of each growing season, a sub-sample of miscanthus plants were harvested (tillers cut approximately 5 cm from the base of the plant) per split-plot (or split-split-plot) and collected for DMY analysis. In year 1, eight randomly selected plants per split-plot were collected and subsequently analyzed for DMY. In year 2, only a sub-sample (approximately 150 g) of the pooled sample (six randomly selected plants per split-plot (or split-split-plot)) was collected to calculate DMY. All DMY samples were dried at 70 ºC for at least seven days.

In years 3 and 4, due to the enormity of the miscanthus plants in both density and height, it was unmanageable to collect biomass at random from the middle of the split-plots (or split-split-plots), therefore, the random sampling protocol was amended. Upon cutting down (and discarding) the plant in the edge row (4 m edge), one plant was collected from the next three rows moving into the split-plot from the 4 m side and this same process was repeated at the opposite 4 m side (totalling six miscanthus plants per split-plot or split-split-plot) (Figure 2.2.5). Like previous years, a sub-sample (approximately 100 g) of the pooled sample (six randomly selected plants per split-plot (or split-split-plot)) was collected to calculate DMY. All DMY samples were dried at 70 ºC for at least seven days.

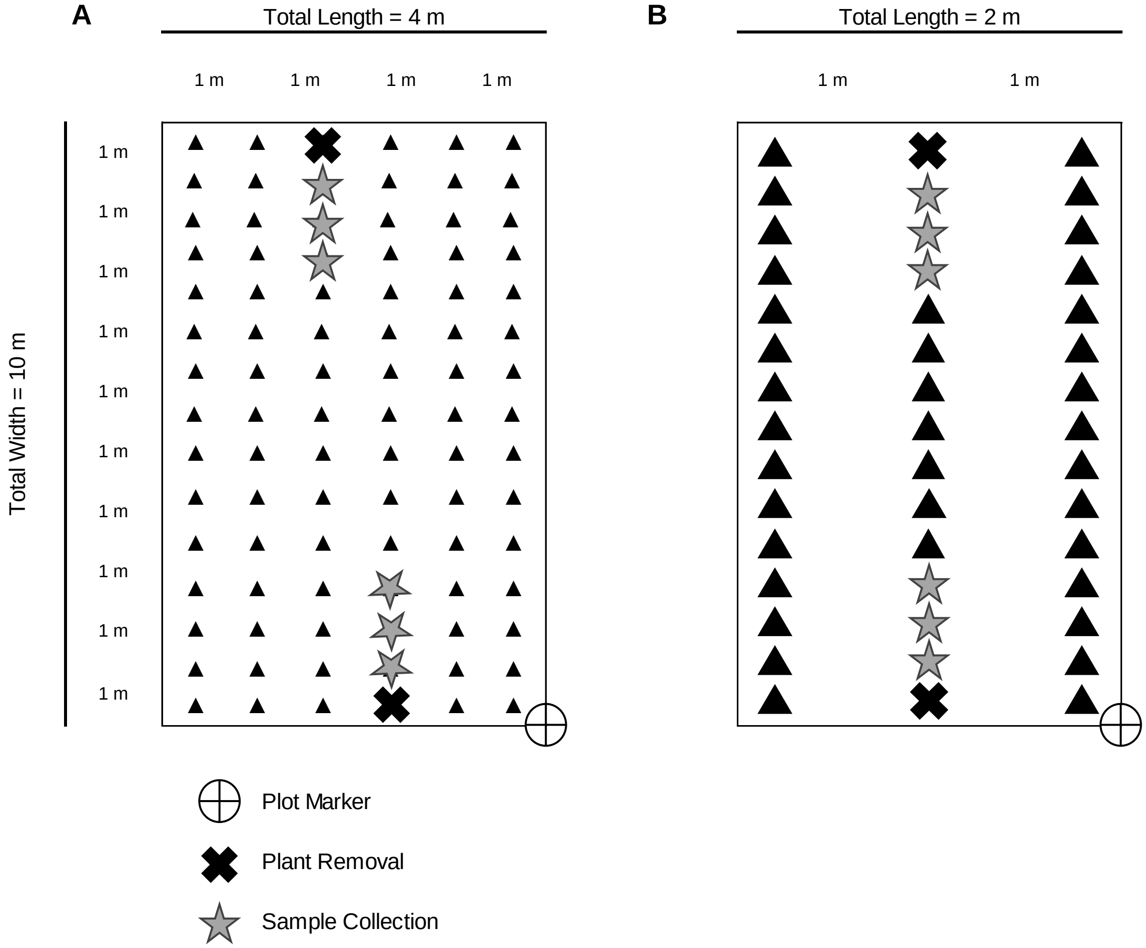

Figure 2.2.5. Diagram indicating miscanthus sampling protocol for **A** split-plots and **B** split-split-plots in years 3 and 4.

2.2.6.3.2.1 Tissue Nutrient Analysis

Upon completion of DMY analysis, dried miscanthus samples were sub-sampled and sent to the Nova Scotia Department of Agriculture Analytical Laboratory (Truro, Nova Scotia, Canada) for nutrient analysis for the first two years of the study.

2.2.6.3.2.2 Tissue Quality Analysis

Dried miscanthus samples collected during the fall harvest in year 3 were sent to Dr. Ajay Dalai at the University of Saskatchewan (Saskatoon, Saskatchewan, Canada) for various tissue quality analyses including cellulose, hemicellulose, lignin, moisture, ash and calorific contents.

2.2.7 Statistical Analyses

Generalized linear models (GLM) can be used when the assumption of normality and homogeneity of variance of response data are violated [100]. Two of the three components of a GLM, the family distribution and the link function are assigned to the model from the outset based on the distribution of the response data. The model is adjusted to reflect the response data, rather than transforming the data to satisfy the assumptions of a model (analysis of variance). Data was analyzed with the assumption of a normal distribution and identity link function unless the response data proved otherwise (via data visualization, normality, and homogeneity of variance testing) [101]. When the data were continuous and positively skewed, the assumption of a Gamma distribution with a log link function was used [102]. Once the GLM was written, an analysis of deviance was performed. When the F-statistic was significant, group means were analyzed using pairwise comparisons with Tukey correction method ($P < 0.05$).

Due to the split-split-plot structure that resulted from the secondary application of DG and SE in year 2, a nested analysis of variance was completed with year of application (year 1 versus year 2) nested within treatment. If there was no significant effect of the nested factor, then the same procedure was completed using pooled response data for DG and SE: a GLM was written, followed by an analysis of deviance and pairwise comparisons with Tukey correction method.

All statistical analyses were performed using R [103] and RStudio© [104]. The following packages were also used: stats [103], car [102] and multcomp [105].

2.3 Results

2.3.1 Dry Matter Yield

2.3.1.1 Year 1

Mean switchgrass DMY across treatments at the Nappan field site was 87.53 kg ha^{-1}, ranging from 67.46 kg ha^{-1} in the CT treatment up to 101.22 kg ha^{-1} in the DG treatment, however there were no statistically significant differences between treatments ($P = 0.6408$) (Figure 2.3.2) (Table A-7). Due to significant weed pressure and minimal switchgrass growth, there was no switchgrass harvest at the Bible Hill field site in year 1.

Mean miscanthus DMY across treatments at the Bible Hill field site was 586.69 kg ha^{-1} while the mean DMY at the Nappan field site was 694.47 kg ha^{-1} (Figure 2.3.3, Figure 2.3.4). Although the PPER treatment showed a numerically higher DMY at both sites, there were no statistically significant differences among soil amendment treatments (Table A-7).

2.3.1.2 Year 2

Mean switchgrass DMY across treatments at the Bible Hill field site was 510.02 kg ha^{-1}, where the CT treatment (598.44 kg ha^{-1}) showed significantly greater DMY than the PPER treatment (378.20 kg ha^{-1}) ($P = 0.08765$) (Figure 2.2.4). At the Nappan field site, the mean switchgrass DMY was 261.09 kg ha^{-1}, ranging from 212.50 kg ha^{-1} in the CT treatment up to 291.25 kg ha^{-1} in the PPER treatment (Figure 2.3.2). There were no statistically significant differences between treatments (Table A-12).

Mean miscanthus DMY across treatments at the Bible Hill field site was 2,672.32 kg ha^{-1}, where the DG treatment (3,607.57 kg ha^{-1}) showed significantly greater DMY than the CT treatment (1,813.67 kg ha^{-1}) ($P = 0.09414$) (Figure 2.3.3). At the Nappan field site, the mean miscanthus DMY was 3,104.22 kg ha^{-1}, ranging from 2,660.43 kg ha^{-1} in the SE treatment up to 4,191 kg ha^{-1} in the PPER treatment (Figure 2.3.4). There were no statistically significant differences between treatments in Nappan (Table A-12).

2.3.1.3 Year 3

Mean switchgrass DMY across treatments at the Bible Hill field site was 2,680.79 kg ha^{-1}, ranging from 2,003.41 kg ha^{-1} in the CT treatment up to 3,006.17 kg ha^{-1} in the PPER treatment (Figure 2.3.1). There were no statistically significant differences between treatments in Bible Hill. At the Nappan field site, the mean switchgrass DMY across treatments was 2,180.58 kg ha^{-1}, where the PPER treatment (2,639.69 kg ha^{-1}) showed significantly greater DMY than the CT treatment (1,676.44 kg ha^{-1}) ($P = 0.1298$) (Figure 2.3.2) (Table A-20).

Mean miscanthus DMY across treatments at the Bible Hill field site was 9,042.93 kg ha^{-1}, where the DG treatment (11,062.31 kg ha^{-1}) showed significantly greater DMY than the PPER treatment (7,400.60 kg ha^{-1}) ($P = 0.1236$) (Figure 2.3.3). At the Nappan field site, the mean miscanthus DMY was 9,277.73 kg ha^{-1}, ranging from 7,229.81 kg ha^{-1} in the SE treatment up to 10,620.61 kg ha^{-1} in the PPER treatment (Figure 2.3.4). There were no statistically significant differences between treatments in Nappan (Table A-20).

2.3.1.4 Year 4

Mean switchgrass DMY across treatments at the Bible Hill field site was 1,575.31 kg ha^{-1}, where the PPER treatment (2,086.48 kg ha^{-1}) showed significantly greater DMY than the CT treatment (867.80 kg ha^{-1}) ($P = 0.095$) (Figure 2.3.1). At the Nappan field site, the mean switchgrass DMY across treatments was 3,539.99 kg ha^{-1}, ranging from 2,858.58 kg ha^{-1} in the

DG treatment up to 4,226.16 kg ha^{-1} in the SE treatment (Figure 2.3.2). There were no statistically significant differences between treatments in Nappan (Table A-22).

Mean miscanthus DMY across treatments at the Bible Hill field site was 10,821.02 kg ha^{-1}, ranging from 10,167.06 kg ha^{-1} in the PPER treatment up to 11,505.27 kg ha^{-1} in the CT treatment (Figure 2.3.3). At the Nappan field site, the mean miscanthus DMY across treatments was 10,285.04 kg ha^{-1}, ranging from 9,364.45 kg ha^{-1} in the SE treatment up to 11,441.63 kg ha^{-1} in the PPER treatment (Figure 2.3.4). There were no statistically significant differences between treatments at either site (Table A-22).

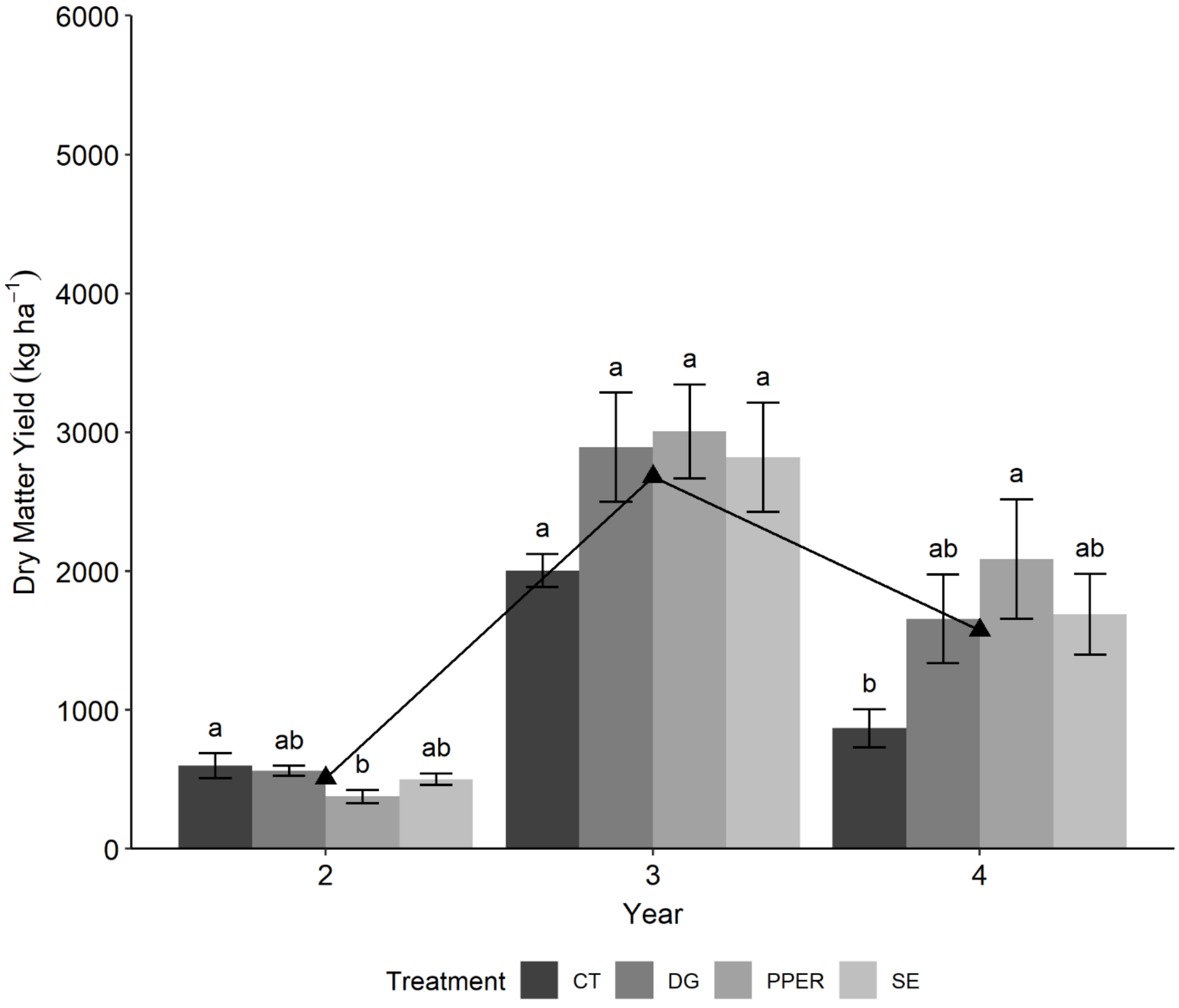

Figure 2.3.1 Mean switchgrass dry matter yield (kg ha^{-1}) by soil treatment for years 2-4 at Bible Hill, Nova Scotia. CT = Control, DG = Digestate, PPER = Pulp and paper mill effluent residue and SE = Seaweed extract. Bars represent the mean value for each treatment, the error terms represent the standard error of the mean (n = 4). Solid triangles represent the mean value across treatments per year. Different letters indicate significant difference within year at $P < 0.05$.

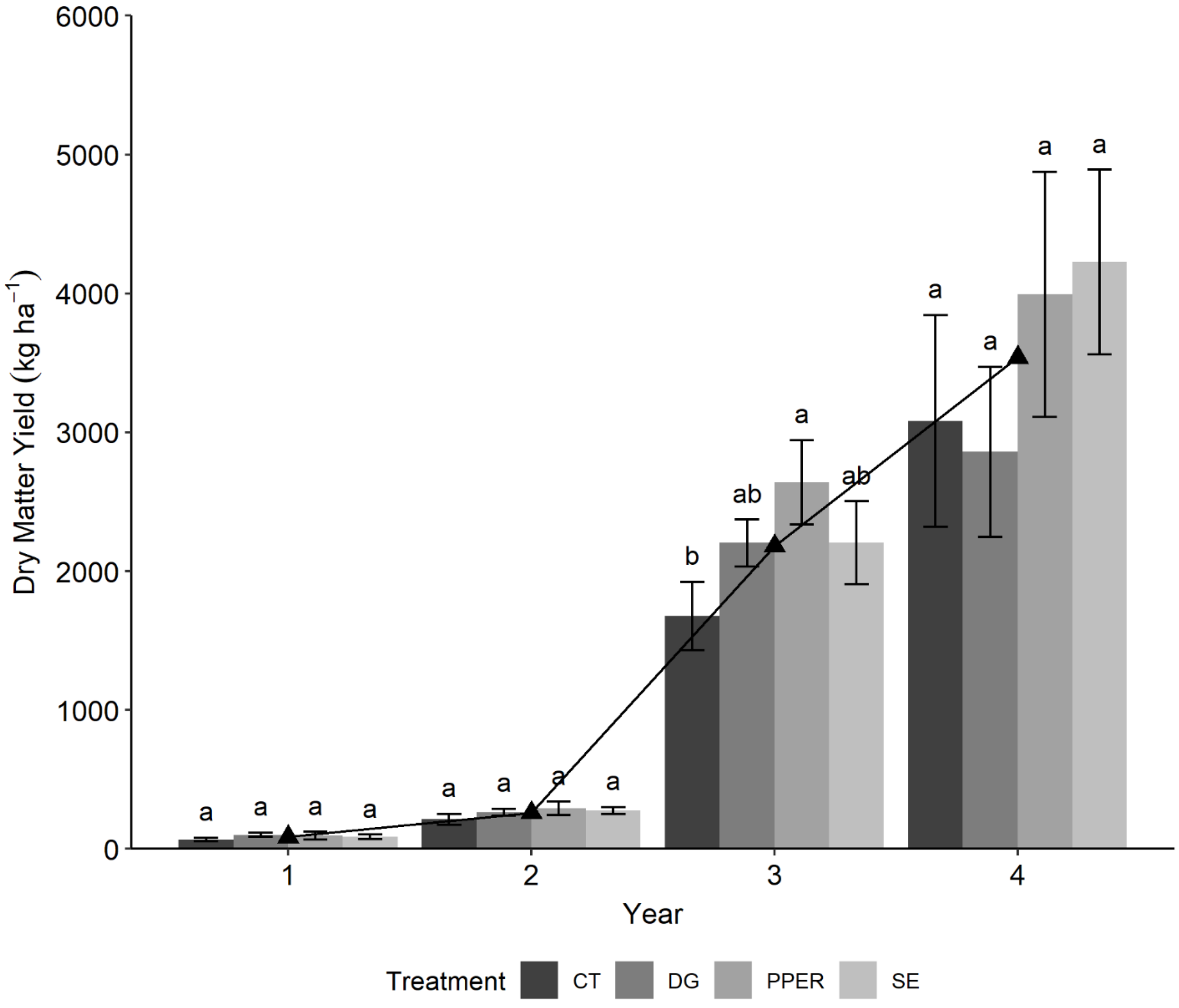

Figure 2.3.2 Mean switchgrass dry matter yield (kg ha^{-1}) by soil treatment for years 1-4 at Nappan, Nova Scotia. CT = Control, DG = Digestate, PPER = Pulp and paper mill effluent residue and SE = Seaweed extract. Bars represent the mean value for each treatment, the error terms represent the standard error of the mean (n = 4). Solid triangles represent the mean value across treatments per year. Different letters indicate significant difference within year at $P <$ 0.05.

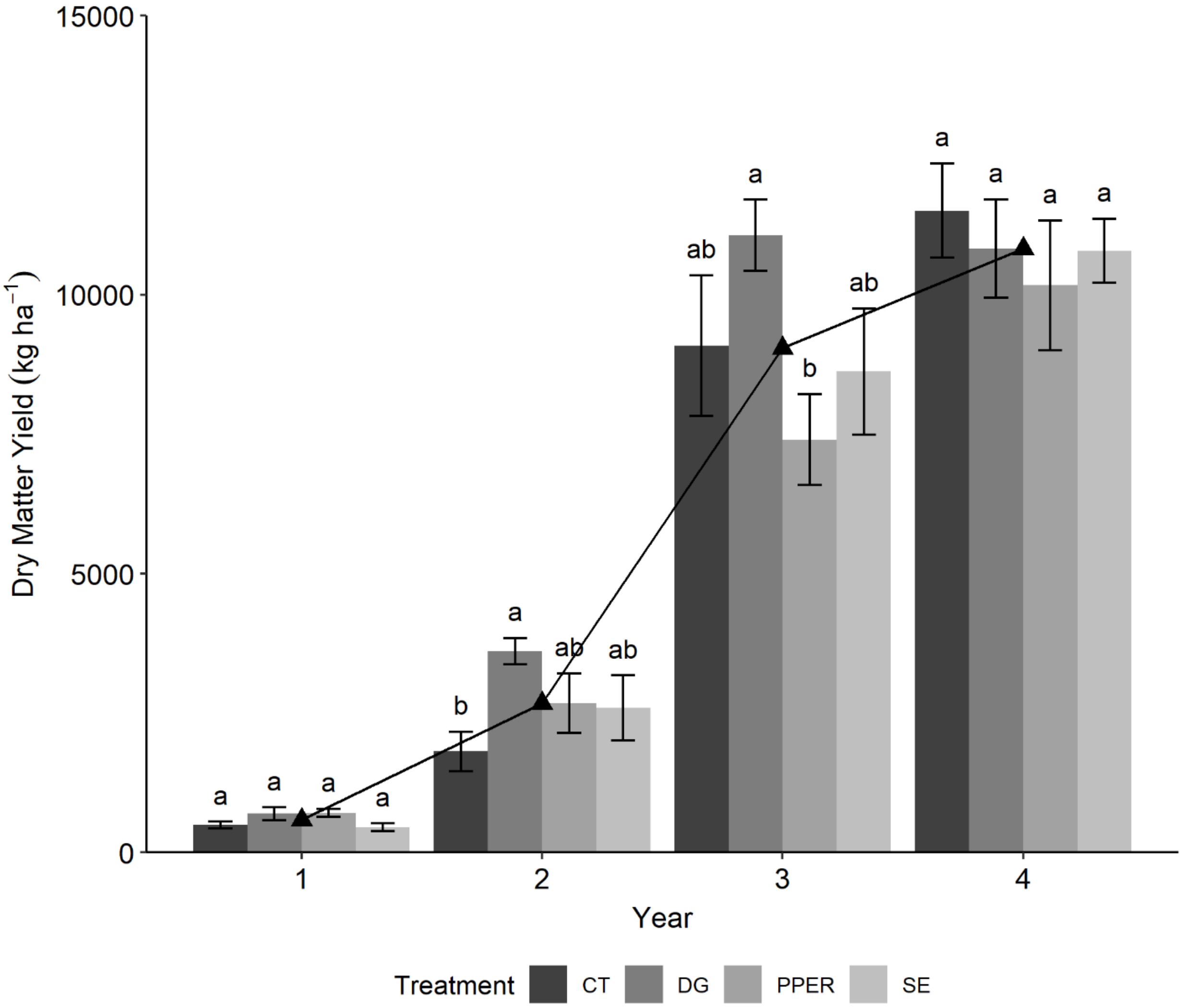

Figure 2.3.3 Mean miscanthus dry matter yield (kg ha^{-1}) by soil treatment for years 1-4 at Bible Hill, Nova Scotia. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill residue. Bars represent the mean value for each treatment, the error terms represent the standard error of the mean (n = 4). Solid triangles represent the mean value across treatments per year. Different letters indicate significant difference within year at $P < 0.05$.

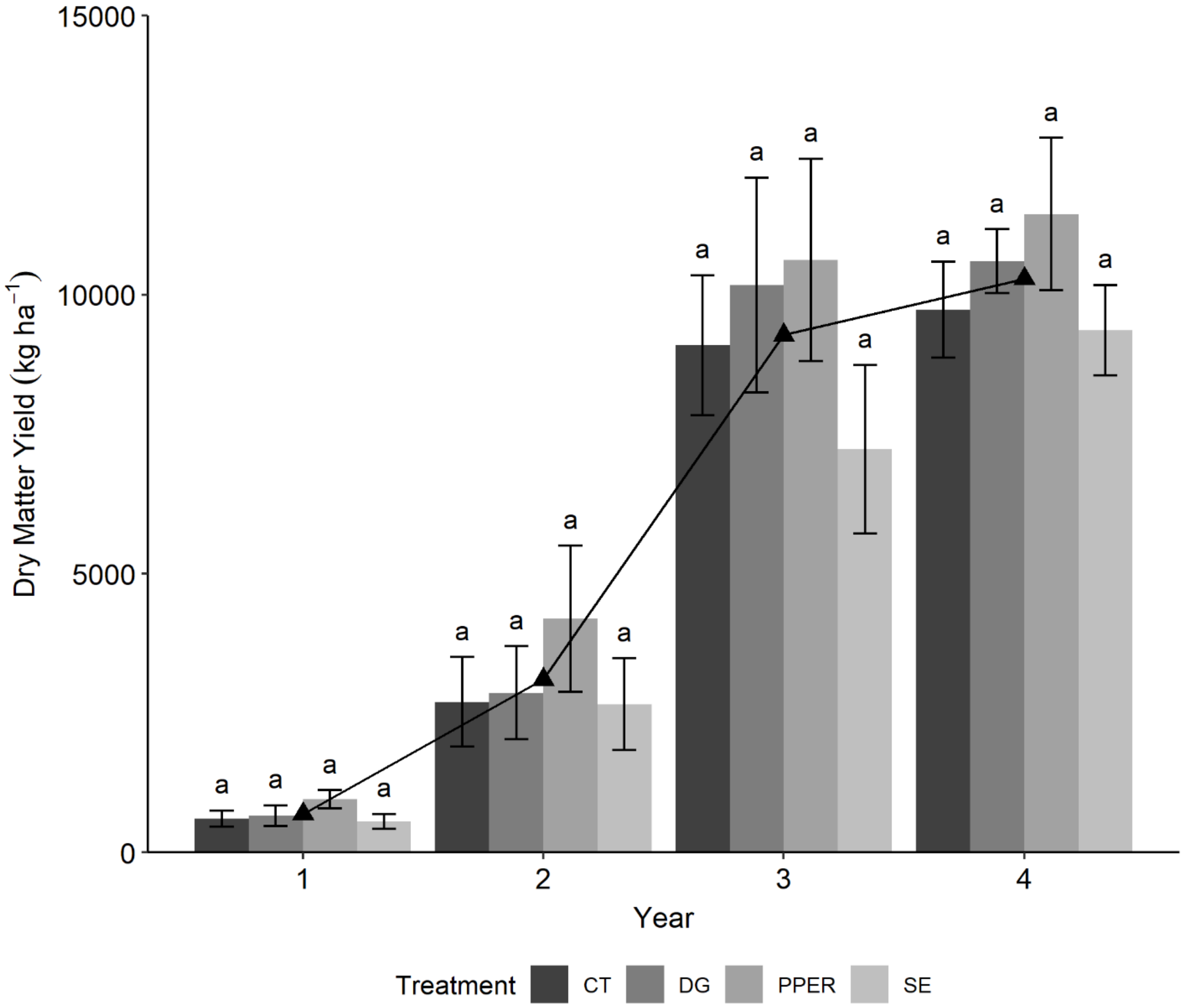

Figure 2.3.4 Mean miscanthus dry matter yield (kg ha^{-1}) by soil treatment for years 1-4 at Nappan, Nova Scotia. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill residue. Bars represent the mean value for each treatment, the error terms represent the standard error of the mean (n = 4). Solid triangles represent the mean value across treatments per year. Different letters indicate significant difference within year at $P < 0.05$.

2.3.2 Tissue Moisture Content

Moisture content of both switchgrass and miscanthus tissues were calculated from year 2 through year 4. There were no statistically significant differences in switchgrass moisture content between treatments at either site in any year. The only statistically significant differences in miscanthus moisture content were found at the Nappan field site in year 2. The moisture content of the DG treatment (36.45 %) was significantly greater than that of the SE treatment (23.76 %) ($P = 0.0772$) (Appendix B).

2.3.3 Mid-Season Data Collection

There were no statistically significant differences to report in miscanthus growth parameters from either the Bible Hill or Nappan field site in year 2 (Table A-19).

2.3.4 Tissue Nutrient Analysis

2.3.4.1 Year 1

2.3.4.1.1 Nutrient Concentration

At the Bible Hill field site, the application of DG significantly increased the iron and zinc concentrations (both significantly greater than the CT tissue, $P = 0.04083$ and $P = 0.06484$, respectively). The application of SE significantly increased the calcium and iron concentrations (both significantly greater than the CT tissue, $P = 0.05832$ and $P = 0.04083$, respectively) (Table 2.3.1, Table A-8).

At the Nappan field site, the application of PPER (and the untreated CT tissue) showed significantly greater calcium concentrations than DG-treated tissue ($P = 0.02549$) while the application of DG significantly increased the potassium concentration (significantly greater than PPER-treated tissue, $P = 0.06102$) (Table 2.3.2, Table A-9).

The manganese concentration in miscanthus tissue was significantly greater in the PPER application at both sites compared to the CT tissue ($P = 0.09161$ at Bible Hill and $P = 0.002978$ at Nappan) (Table 2.3.1, Table 2.3.2). Complete tables of nutrient concentrations can be found in Appendix A.

Table 2.3.1 Select miscanthus tissue nutrient concentrations at Bible Hill, Nova Scotia as measured in the fall of year 1.

	Ca	Fe	Mn	Zn
	(%)		(ppm)	
CT	0.25 ± 0.006 b	39.72 ± 4.64 b	73.78 ± 12.59 b	20.54 ± 1.98 b
DG	0.27 ± 0.009 ab	65.39 ± 5.75 a	83.37 ± 13.20 ab	29.82 ± 2.59 a
SE	0.29 ± 0.007 a	64.35 ± 9.57 a	112.11 ± 10.44 ab	26.14 ± 3.21 ab
PPER	0.26 ± 0.013 ab	54.46 ± 5.52 ab	140.97 ± 30.27 a	28.35 ± 0.37 ab
	P = 0.05832 .	*P* = 0.04083 *	*P* = 0.09161 .	*P* = 0.06484 .

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Table 2.3.2 Select miscanthus tissue nutrient concentrations at Nappan, Nova Scotia as measured in the fall of year 1.

	Ca	K	Mg	Mn
		(%)		(ppm)
CT	0.394 ± 0.016 a	0.58 ± 0.10 ab	0.288 ± 0.015 ab	97.34 ± 5.58 b
DG	0.340 ± 0.011 b	0.78 ± 0.09 a	0.249 ± 0.014 b	98.80 ± 5.67 b
SE	0.358 ± 0.006 ab	0.63 ± 0.05 ab	0.252 ± 0.017 b	117.85 ± 15.32 b
PPER	0.386 ± 0.012 a	0.42 ± 0.07 b	0.332 ± 0.022 a	199.28 ± 37.47 a
	P = 0.02549 *	*P* = 0.06102 .	*P* = 0.01875 *	*P* = 0.002978 **†

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

† Gamma family distribution.

2.3.4.1.2 Nutrient Yield

At the Bible Hill field site, the application of DG significantly increased numerous miscanthus nutrient yields in comparison to the SE-treated tissues: nitrogen (P = 0.0346), sodium (P = 0.05093) and iron (P = 0.06754). The application of PPER significantly increased magnesium (significantly greater than SE-treated tissue, P = 0.042) and manganese yields (significantly greater than all other treatments, P = 0.007164). The potassium and phosphorus yields of PPER and DG-treated miscanthus were significantly greater than SE-treated tissue at the Bible Hill site (P = 0.01372 for potassium and P = 0.006611 for phosphorus).

At the Nappan field site, the application of PPER significantly increased the manganese yield in comparison to the SE-treated tissue (P = 0.05184). There were no other statistical differences to report (Table A-10, Table A-11).

2.3.4.2 Year 2

2.3.4.2.1 Nutrient Concentration

At the Nappan field site, the SE-treated miscanthus tissue showed significantly greater concentrations of nitrogen (significantly greater than CT and PPER-treated tissues, P = 0.007508) and phosphorus (significantly greater than PPER-treated tissue, P = 0.05022). Both SE and DG-treated tissues showed significantly greater concentrations of potassium (significantly greater than CT and PPER-treated tissues, P = 0.002064) and zinc (significantly greater than PPER-treated tissue, P = 0.01822). The untreated control (CT) tissue showed significantly greater concentrations of calcium (significantly greater than all other treatments, P = 0.004197) and magnesium (significantly greater than DG-treated tissue, P = 0.09559) (Table 2.3.3).

There were no statistically significant differences in miscanthus tissue nutrient concentration to report among soil amendment treatments from the Bible Hill field site (Table A-13).

Table 2.3.3 Select miscanthus tissue nutrient concentration at Nappan, Nova Scotia as measured in fall of Year 2[1].

	N	Ca	K	Mg	P	Zn
			(%)			(ppm)
CT	0.43 ± 0.04 bc	0.36 ± 0.01 a	0.16 ± 0.006 b	0.137 ± 0.009 a	0.15 ± 0.02 ab	19.82 ± 2.37 ab
DG	0.64 ± 0.10 ab	0.24 ± 0.01 b	0.45 ± 0.099 a	0.093 ± 0.009 b	0.16 ± 0.02 ab	22.36 ± 3.79 a
SE	0.79 ± 0.07 a	0.26 ± 0.009 b	0.48 ± 0.040 a	0.100 ± 0.012 ab	0.20 ± 0.01 a	27.72 ± 2.75 a
PPER	0.32 ± 0.05 c	0.29 ± 0.03 b	0.11 ± 0.015 b	0.117 ± 0.014 ab	0.12 ± 0.01 b	11.38 ± 1.67 b
	P = 0.007508 **	*P* = 0.004197 **	*P* = 0.002064 **	*P* = 0.09559 .	*P* = 0.05022 .	*P* = 0.01822 *

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

2.3.4.2.2 Nutrient Yield

At the Bible Hill field site, the SE treatment showed an overwhelming effect on miscanthus tissue nutrient yield in year 2. SE-treated tissue showed significantly greater calcium ($P = 0.01317$), iron ($P = 0.05872$), and zinc ($P = 0.05451$) contents than all other treatments. Miscanthus tissue collected from SE-1 (first application of SE in 2019) showed significantly greater magnesium ($P = 0.04884$) and phosphorus ($P = 0.09318$) contents than all other treatments (Table A-16). Conversely, the CT and PPER-treated tissues showed significantly greater nitrogen content than SE-treated tissue ($P = 0.08345$) (Table A-15).

At the Nappan field site, the PPER treatment showed a persistent effect on miscanthus tissue nutrient yield in year 2. PPER-treated tissue showed significantly greater iron ($P = 2.523 \times 10^{-8}$), manganese ($P = 1.683 \times 10^{-6}$) and zinc ($P = 2.86 \times 10^{-8}$) contents than all other treatments. Conversely, SE and DG-treated tissues showed greater potassium content than both the CT and PPER-treated tissues ($P = 0.03525$) (Table A-19).

2.3.5 Tissue Quality Analysis

2.3.5.1 Ash Content

Mean ash content of miscanthus tissue from the Bible Hill field site was 3.02 %, ranging from 2.85 % in the PPER treatment up to 3.39 % in the CT treatment. At the Nappan field site, the mean ash content was 3.90 %, ranging from 3.61 % in the DG treatment up to 4.23 % in the PPER treatment. There were no statistically significant differences between treatments at either field site (Table A-21).

2.3.5.2 Caloric Content

Mean caloric content of miscanthus tissue from the Bible Hill field site across treatments was 18.13 MJ kg^{-1}, ranging from 18.06 MJ kg^{-1} in the PPER treatment up to 18.18 MJ kg^{-1} in the CT treatment. At the Nappan field site, the mean caloric content across treatments was 18.19 MJ kg^{-1}, ranging from 18.03 MJ kg^{-1} in the SE treatment up to 18.28 MJ kg^{-1} in the PPER treatment. There were no statistically significant differences between treatments at either field site (Table A-21).

2.3.5.3 Lignin Content

Mean lignin content of miscanthus tissue from the Bible Hill field site across treatments was 8.86 %, ranging from 8.58 in the CT treatment up to 9.06 % in the DG treatment. At the Nappan field site, the mean lignin content across treatments was 8.82 %, ranging from 7.86 % in the PPER treatment up to 8.86 % in the DG treatment. There were no statistically significant differences between treatments at either field site (Table A-21).

2.3.5.4 Cellulose Content

Mean cellulose content of miscanthus tissue from the Bible Hill field site across treatments was 39.32 %, ranging from 38.34 in the CT treatment up to 39.71 % in the DG treatment. At the Nappan field site, the mean cellulose content across treatments was 38.42 %, ranging from 37.13 % in the PPER treatment up to 39.13 % in the DG treatment. There were no statistically significant differences between treatments at either field site (Table A-21).

2.3.5.5 Hemicellulose Content

Mean hemicellulose content of miscanthus tissue from the Bible Hill field site across treatments was 24.96 %, ranging from 24.73 in the DG treatment up to 25.22 % in the SE treatment. At the Nappan field site, the mean hemicellulose content across treatments was 25.83 %, ranging from 25.43 % in the SE treatment up to 26.61 % in the PPER treatment. There were no statistically significant differences between treatments at either field site (Table A-21).

2.4 Discussion

In this chapter, switchgrass and miscanthus were evaluated for their capabilities as biomass crops on marginal agricultural lands in Nova Scotia. Further, the effects of locally sourced soil amendments and a plant biostimulant on early biomass yield, nutrient composition and quality were evaluated.

The successful establishment, overwintering capacity, and post-establishment biomass productivity of miscanthus at both field sites and switchgrass at one field site are major findings of this research. Further, through mid-season growth measurements and subsequent yield calculations, both the pulp and paper mill effluent residue and the liquid anaerobic digestate showed potential to increase the biomass productivity of both miscanthus and switchgrass. The caloric and ash content of the miscanthus tissue closely align with data from the literature, assuring biomass quality for co-firing is attainable in Nova Scotia. Despite the positive findings, the field experiments confirmed Nova Scotia is susceptible to one of the major hurdles for switchgrass establishment: competition with weeds.

2.4.1 Planting Protocols

2.4.1.1 Switchgrass

The switchgrass was seeded into split-plots at a rate of 8 kg ha^{-1}. Prior to the outset of this study, the germination rate of switchgrass was evaluated and found to be low (approximately 30%) [106]. As such, the seeding rate of pure live seed (PLS) was only 2.4 kg ha^{-1} which is at the low end of the recommended seeding rate range of 2.24 to 11.2 kg ha^{-1} of PLS [107]. The low PLS seeding rate combined with a high weed pressure at the Bible Hill site likely stalled the establishment and subsequent growth of the switchgrass stand in the absence of herbicides

(Figure 2.4.1, Figure 2.4.2). Increasing switchgrass seeding density could improve establishment, especially within plots using mechanical-dominant weed management practices [108].

Figure 2.4.1 Switchgrass plot at Bible Hill, NS field site in October 2022 [109].

Figure 2.4.2 Switchgrass plot at Nappan, NS field site in October 2022 [110].

2.4.1.2 Miscanthus

Miscanthus plantlets from *in vitro* propagation overwintered very well after being cut in the establishment year. Typically, the same concern for switchgrass overwintering is present with miscanthus rhizomes, as the initial growth is slow and it takes multiple growing seasons for a miscanthus plant to fully establish [111,112]. Miscanthus survival, as recorded mid-season of year 2, was 95 % and 98 % across all treatments in Bible Hill and Nappan, respectively. Contrary to the results of this study, it has been reported that micro-propagated plantlets have reduced tolerance to sub-optimal growing conditions and overwintering compared to plants grown from rhizomes [111,113].

The typical planting density of miscanthus ranges from 10,000 to 20,000 plants ha^{-1} (2 plants m^{-2}) [73,111,113,114]. The planting density of miscanthus in this study was 22,500 plants ha^{-1} (equivalent to 2.25 plants m^{-2}). The greater the planting density, the greater likelihood of a higher early yield (years 2 through 5) [111,114]. However, there is obviously a higher planting cost associated with a higher planting density, and this cost is not always compensated for in biomass productivity [111,114]. In the early years, before stand maturation, a higher plant density is beneficial for the overall stand as competition for resources is improved over weeds [115]. Conversely, once the miscanthus plants reach maturation, stands with higher planting densities can experience stunted growth due to the very same competition for resources [115–117]. Since the survival rate of the plantlets was incredibly high, the higher planting density in this study could have implications for reduced yield in later years.

2.4.2 Weed Control

An often-described advantage of perennial grasses for biomass is the minimal agronomic inputs required for growth [118,119]. There is still a prevalence of data to support the incorporation of both fertilizers and herbicides to alleviate stresses and encourage maximum establishment and growth, especially on marginal soils [120–122]. Competition with weeds can be a major impediment to establishment for both crops [123–125]. When miscanthus rhizomes are planted, weed management is just as critical as with switchgrass seeds, as the dominant weed species need to be hampered to allow growth of both grasses [123]. In our study, using the miscanthus *in vitro* propagated plantlets rather than rhizomes seemed to enhance the competitive advantage of the miscanthus over the weeds.

Unfortunately, numerous factors including (but not necessarily limited to) low germination and high weed pressure [123] combined to seemingly stall switchgrass establishment at the Bible Hill site, allowing weeds to outcompete the switchgrass. The weed management strategy in this study (mowing twice during the establishment year and once during year 2 followed by an herbicide application), is noted to be a beneficial strategy for switchgrass yield when herbicides are not applied during the establishment year [108]. Although mechanical weed control during the growing season can be effective during switchgrass establishment, inherently, biomass accumulation at harvest will be lower following shortened periods of growth (between mowing and harvest) [126,127]. Given the vast weed pressure at the Bible Hill site, a more proactive, integrated weed management strategy may improve yield. Successful weed management in high weed pressure areas utilizes a pre- and post-emergence herbicide application during the establishment year [125,128].

2.4.3 Precipitation

The precipitation during the establishment year was greater than average at both Bible Hill (18 % greater) and Nappan (39 % greater) (Table 2.2.1) [92,97]. Adequate soil moisture and water availability in the establishment year are necessary for successful establishment of perennial grasses [129], including precipitation from the winter and spring seasons preceding planting [130]. The increased precipitation at Bible Hill may have helped the germination and growth of the weed species more than the switchgrass.

Post-establishment, water availability continues to be a major factor affecting biomass yield in perennial grasses [129,131–133]. Although the deep rooting systems of grasses (compared to SRWC) are beneficial to biomass productivity in water-limited conditions, the presence of higher precipitation (and water availability) during the growing season can be attributed to higher growth rates and ultimately, higher biomass productivity [131–133]. The reduced biomass productivity of both crops at both sites compared to the literature could be attributed to a potential lack of water availability during post-establishment growing seasons, as all subsequent years at Bible Hill and two of three years at Nappan experienced less precipitation than average (Table 2.2.1) [134].

2.4.4 Dry Matter Yields

2.4.4.1 Switchgrass

At the end of the establishment year, there was not enough switchgrass observed in Bible Hill to warrant a harvest, and the incrementally better growth in Nappan wasn't outstanding, with a mean yield across treatments of 87.53 kg ha^{-1}. It is neither recommended [135] nor common in the literature for switchgrass to be harvested in the establishment year, owing to minimal yields, and improving establishment and overwintering of plants [122,136].

Post-establishment, switchgrass is expected to reach maximum yield potential in two to three years [137,138]. The reported biomass yield across treatments at the Bible Hill site is mainly indicative of the growth of the weed species, as the sampling methodology did not allow for differentiation between switchgrass and other species in the collected biomass (Figure 2.3.1). This methodology is most applicable to a producer harvesting switchgrass with a swather; however, this methodology does not allow a truly representative sampling of switchgrass yield in amongst an abundance of weeds.

Reported biomass yield increased year over year as expected at the Nappan site (Figure 2.3.2), but both sites still paled in biomass productivity in comparison to other studies. Mean switchgrass yields across treatments in year 4 were 1,575.31 kg ha^{-1} at Bible Hill and 3,539.99 kg ha^{-1} at Nappan. Two studies with field sites within metres of the Bible Hill site reported switchgrass yields in years 3 and 4 of 7,000 and 4,400 kg ha^{-1}, respectively [122,136]. Similar experimental conditions (namely similar climatic conditions, based on plant hardiness zones [139–141]) show promising results for switchgrass. Switchgrass DMY reported in Ontario under various nitrogen fertilizer applications for year 3 was between 7,000-8,000 kg ha^{-1} [142] and separately reported, yields increased with time (5,860 kg ha^{-1} in year 2, 9,630 kg ha^{-1} in year 3) until year 4 [143]. Switchgrass DMY reported in Manitoba, Canada (cooler climatic conditions than Nova Scotia) for years 3 and 4 ranged from 7,000 kg ha^{-1} to 12,000 kg ha^{-1} [65].

The database of switchgrass biomass yield productivity published by Wullschleger et al. [144] reports the most frequently observed switchgrass yield falls between 10,000 and 14,000 kg ha^{-1}, while the model discussed in Chapter 4 [145] reports a mean switchgrass yield of 10,500 kg ha^{-1} in similar climates to Nova Scotia, both of which are higher than yields reported in this study.

The PPER-treated switchgrass at both sites was consistently numerically greater than the untreated control switchgrass (apart from Bible Hill, year 2) (Figure 2.3.1, Figure 2.3.2). Above average precipitation and increased water holding capacity associated with PPER incorporation into the soil could have could have contributed to increased DMY [134], as both sites experienced between 4-36 % less precipitation during the growing season than average [146,147].

2.4.4.2 Miscanthus

Like switchgrass, miscanthus is expected to reach maximum yield potential three to five years post-establishment [111,148]. The biomass yield of miscanthus across treatments at both sites continually increased with time, appearing to peak between years 3 and 4 around 10,500 kg ha^{-1} (Figure 2.3.3, Figure 2.3.4). Similar experimental conditions (namely similar climatic conditions, based on plant hardiness zones [139–141]) published in the literature could contradict the idea that peak yield was reached in the current study. Separate field trials from Ontario reported miscanthus DMY in years 2 and 3 between 12-25,000 kg ha^{-1} [149], and just under 20,000 kg ha^{-1} in years 4 and 5 [150]. Another study from Ontario reported year 3 miscanthus yields under various nitrogen fertilizer applications between 25,000-43,000 kg ha^{-1} [142]. These studies all reported yields for the same cultivar as the current study (Nagara), but only one reported a similar planting protocol (plantlets) [149]. In Manitoba, although the studied cultivar is different, miscanthus DMY reported for years 3 and 4 (14,000 kg ha^{-1}) are most similar to the yields in the current study [65]. Further, the model developed in Chapter 4 reports a mean miscanthus yield of 15,000 kg ha^{-1} in similar climates to Nova Scotia [145].

Although there were minimal statistically significant differences between treatments at either site, the DG treatment appeared (with two years of the greatest numerical DMY of all treatments) to be the best performing treatment in the miscanthus at the Bible Hill site, while the PPER treatment showed the greatest numerical miscanthus DMY of all treatments in all four years at the Nappan site.

The DG treatment exhibited a positive effect on soil K_2O content at both Bible Hill and Nappan sites, as described in further detail in Chapter 3 [134]. The baseline soil K_2O content (establishment year) was 333 and 164 kg K ha^{-1}, respectively (Table A-1). According to resources from the United Kingdom, given these baseline values, the Bible Hill site is unlikely to exhibit a yield response to added K, while a yield response to added K in Nappan is probable [151]. Conversely, through the application of DG, Bible Hill reported a yield response to added K, while Nappan did not. Despite the substantial drop in soil K_2O content from Bible Hill to Nappan, and the weak relationship between biomass yield and the DG treatment, the Nappan field site produced a considerable miscanthus yield. Shield et al. reported that miscanthus can produce a substantial biomass yield with soil K_2O content between 100 and 198 kg K ha^{-1} [152]. The correlation between soil K_2O content above-ground biomass K content can change the outlook for the intended end-use of the biomass [152,153].

The increased presence of soil K_2O content can increase plant drought tolerance [154], which could be occurring in miscanthus at the Bible Hill field site as the post-establishment growing season precipitation was low, while the soil K_2O content (especially in the DG-treated soils) was high. Further, the presence of an organic fertilizer such as DG could provide additional nutrients to miscanthus, increasing their plant availability [155], benefitting the growth of the plant but also changing the composition of the miscanthus tissue. Like switchgrass, the PPER-treated miscanthus DMY could have benefitted from increased soil water-holding capacity [85–87].

2.4.5 Tissue Nutrient Analysis

2.4.5.1 Nutrient Concentration

The macronutrient concentrations in miscanthus above-ground biomass harvested in November of the establishment year were markedly greater in this study compared to summary values for a similar harvest time on plants in year 3 and beyond reported by Cadoux et al. [156]. Across treatments and sites, the mean N and P concentrations in this study were 1.5 % N and 0.35 % P, compared to 0.5 % N and 0.08 % P [156]. The K concentration across treatments varied substantially between sites in this study, with K concentrations of 1.4 % in Bible Hill and 0.6 % in Nappan. The Bible Hill site reported a higher K concentration than the literature value of 0.88 [156], which was more like the value for Nappan.

In year 2, across treatments and sites, the N concentration (0.63 %) and P concentration (0.17 %) were both less than in the establishment year, and more closely aligned with the literature [156]. Again, the K concentration was variable between sites in year 2, with K concentration at Bible Hill reported at 0.42 % across treatments. At the Nappan site, the K concentration in the DG-treated miscanthus (0.45 %) was significantly greater than the PPER-treated and CT miscanthus (0.11 and 0.16 %, respectively). All K concentrations reported at Nappan in year 2 were lower than those reported for Nappan in year 1, and lower than the value reported in the literature [156].

The variation in macronutrient concentration compared to the literature could be a function of plant maturity: the underground rhizome (responsible for translocation of nutrients) in the establishment year would be substantially smaller than a rhizome in post-establishment years. The high K concentration in the DG-treated miscanthus in Nappan could be indicative of the correlation between the high soil K_2O in DG-treated plots and the uptake of K by miscanthus. A very small proportion (less than 10 %) of potassium in miscanthus samples taken during the middle of the growing season was supplied to the plant by the rhizome [153], demonstrating high nutrient uptake by miscanthus from the soil.

An interesting relationship between K and Mg were identified in the miscanthus tissues in Nappan. In both years 1 and 2, the Mg concentration in the above-ground biomass treated with DG was statistically significantly lower than other treatments, while the K concentration in the same biomass was statistically significantly higher than other treatments. The antagonistic interaction between K and Mg is known to cause Mg deficiency in plants via an abundance of K interfering with the uptake of Mg by plants [157]. Through three years of soil nutrient analysis, the soils at both sites were never technically considered Mg deficient (< 99 kg Mg ha^{-1}) [158]. Further, the ratio of K:Mg in the soil was approximately 1 at Bible Hill while the ratio decreased from 1 to approximately 0.3 at Nappan throughout the study, hovering near the ideal ratio of 0.5 [157]. This does not appear to be directly influencing miscanthus biomass yield, but the interaction should be monitored in the future.

The PPER-treated miscanthus tissue exhibited a significant increase in Mn content in the establishment year at both field sites. The pulp and paper mill effluent residue used in this study has an average Mn content (taken from 113 samples) of 407 mg kg^{-1}, more than one and a half times the average reported by Vasconcelos and Cabral (262 mg kg^{-1} [159] but half as much as reported by Gagnon et al. ((815 mg kg^{-1} [160]). Additional studies have reported an even larger variation in Mn concentrations, ranging from 155 mg kg^{-1} [161] to 1,260 mg kg^{-1} [162]. The variation in nutrient concentration between pulp and paper mill residues accounts for the differing feedstocks, processing and treatments across differing pulp and paper mill operations [87].

Increasing the application rate of 'pulp mill sludge' resulted in decreasing Mn concentrations in leaf tissue of yellow lupin (*Lupinus luteus* L.) plants grown in pots [159]. The Mn tissue concentration reported after the first year of growth for comparable pulp and paper mill residue application rates (10,000 and 30,000 kg ha^{-1} = 662 and 214 ppm, respectively) [159] were substantially higher than those in this study (12,000 kg ha^{-1} = 141 and 199 ppm at Bible Hill and Nappan, respectively). The Mn tissue concentration in this study was well above the accepted Mn-sufficiency range for plants (20 – 30 ppm) [163,164], and could potentially be more concerning in terms of Mn-toxicity. The range for plant Mn toxicity varies between species about as much as the Mn concentration in pulp and paper mill residues, ranging from 150 to 5,000 mg kg^{-1} [165,166]. Symptoms of Mn toxicity in the miscanthus plants during the establishment year were not observed [166], and year 2 tissue analysis indicated much less Mn variation. The spike in Mn concentration in the establishment year could simply reflect the moderate Mn present in the PPER treatment, and with time, the quick decomposition of the pulp and paper mill effluent residue material [87], in combination with the cycling of nutrients throughout the plant regulated the Mn in the harvested tissue.

2.4.5.2 Nutrient Yield

As mentioned, the miscanthus yields in the current study were not as high as those reported in similar climatic conditions, so comparing numerical nutrient content between this study and other studies is not necessarily a fair comparison. However, trends in the nutrient yield can be observed.

Similar to the patterns reported previously in miscanthus biomass yield and tissue nutrient concentrations, the differences between treatments for nutrient content in the establishment year were dominated by DG and PPER. Across sites, the DG and PPER treatments showed significantly greater nutrient contents (N, P, K, Mg, Na) than the SE treatment in the establishment year. In year 2, the SE-treated miscanthus showed significantly greater nutrient contents (P, K, Mg, Ca) than other treatments. The nutrient dynamics of miscanthus suggest that the highest nutrient concentration in the above-ground biomass is in spring, decreasing throughout the growing season until plant senescence, due to nutrient translocation to the underground rhizome. It has been suggested that nutrient yields in above-ground biomass are substantially greater in miscanthus harvested in the fall, rather than the spring [167].

2.4.6 Tissue Quality Analysis

The composition of purpose-grown biomass is important to understand potential market opportunities for the end-use of biomass but can also inform producers of how to modify maintenance and harvest protocols according to desired end-use. Co-firing biomass with coal for electricity production was proposed throughout this dissertation to diversify biomass for electricity. Through the Nova Scotia lens, this intended biomass utilization is simple, as the local bioenergy industry is in its infancy and co-firing is touted for its maximal efficiency with minimal costs [168]. In agreement with Arundale et al. [169], there were neither variations in biomass composition between treatments within this study, nor between this study and others with similar climatic conditions (Table 2.4.1).

2.4.6.1 Ash Content

Ash is an inorganic by-product of burning biomass, composed mostly of potassium, phosphorus, sulfur, and sodium [60,170,171]. The higher the ash content in biomass, the less desirable for fuel, lowering energy density and increasing potential for equipment malfunction [60,77,172,173]. Agricultural biomass ash content ranges from 1 – 18 % [172], but the best quality biomass has an ash content of less than 1 % [60]. Ash contents reported from Nappan and Bible Hill in the current study are higher than 1 %, and higher than values reported from similar climates (Table 2.4.1). This could be a result of the high potassium concentration in the biomass, or an indication that a fall harvest is not optimal for biomass quality for combustion. Ash content can substantially decrease between a fall harvest and a winter harvest [77].

Table 2.4.1 Comparison of miscanthus above-ground biomass tissue composition (ash, caloric, cellulose, hemicellulose and lignin contents) grown in the current study to other studies with similar experimental conditions.

	Location	Plant Hardiness Zone [174]	Age of Stand (Years)	Ash Content (%)	Caloric Content (MJ kg^{-1})	Cellulose Content (%)	Hemicellulose Content (%)	Lignin Content (%)
Current study	Bible Hill, Nova Scotia	5b	3	3.02	18.13	39.32	24.96	8.86
Current Study	Nappan, Nova Scotia	5b	3	3.90	18.19	38.42	25.83	8.82
[171]	Drumbo, Ontario	6a	-	2.08	18.06	-	-	-
[175]	Zamosc, Poland	6b	-	1.60	16.55	-	-	-
[170]	Ontario, Canada	4b – 7a	-	2.7	19.00	-	-	-
[150]	Ontario, Canada	7a	3	-	-	36.00	26.8	7.48
[62]	Gretna, Virgina	7a	2	1.56	-	45.08	29.98	7.55
[172]	Zagreb, Croatia	7b	4	1.20	18.15	49.27	19.30	28.39
[60]	Zagreb, Croatia	7b	10	1.91	17.78	50.45	23.95	13.80

2.4.6.2 Caloric Content

Caloric content is one of the main characteristics used to evaluate the combustion quality of biomass, otherwise known as the heating value [60,176]. The caloric content is also used to compare the energy densities of different fuel sources. The disparity in energy density of raw biomass (15 to 20 MJ kg^{-1} [168]) and coal (25 to 35 MJ kg^{-1} [177,178]) is evident. The nutrient composition, along with moisture content of biomass reduces the calorific value [60,178]. Torrefaction of raw biomass can enhance the energy density (16 to 29 MJ kg^{-1}), through lowering moisture and creating greater uniformity within the biomass [173,178], creating an end-product more like coal. Harvest timing (fall, winter or spring) did not affect the caloric content of miscanthus [32].

2.4.6.3 Lignin Content

The higher the lignin content in biomass, the more desirable for direct combustion [60,77,172]. Lignin, along with ash, are the main characteristics associated with determining the efficiency of the thermochemical conversion of biomass [173]. The lignin content reported in this study (approximately 8.8% (Table 2.4.1)) is most comparable to rice straw [173], while the range of lignin in woody species is 10-15% [178]. Lignin content reported an increase between fall and winter harvests [77].

2.4.6.4 Cellulose and Hemicellulose Content

The lower the cellulose and hemicellulose contents of biomass, the more suitable the biomass is for combustion [60,172]. The values of cellulose and hemicellulose in this study are slightly lower than average values [62], so in terms of combustion, this is more favourable. Cellulose increased between fall and winter harvests, while hemicellulose decreased [77].

2.4.6.5 Moisture Content

The lower the biomass moisture content, typically the more suitable the biomass is for direct combustion [179]. Moisture content of miscanthus reported in the literature (between 6 and 10 %) [175,180] was much lower than values reported in this study (ranging from 23 to 57 %) (Table A-12, Table A-20, Table A-22). The moisture content decreases substantially between fall and winter harvests [77,179], which is optimal from both a combustion efficiency standpoint and a biomass storage and transportation standpoint [172,181].

2.4.7 Biomass Outlook in Nova Scotia

The grasses from this study do not meet the moisture specifications for direct combustion in local facilities. The optimal range of moisture content for these two plants is between 40 and 50 %, as material with lower moisture contents burns too quickly. The average moisture content of the biomass (across species and sites) from year 4 was approximately 33 %. Combining switchgrass and miscanthus from both sites, the total biomass harvested in year 4 was approximately 4,000 kg of green biomass (approximately 1.5 hours of biomass for the Dalhousie Biomass Energy Plant). Substantially increasing the annual volume of grass biomass harvested from miscanthus and switchgrass and modifying the harvesting strategy to increase moisture content should be evaluated moving forward to create an opportunity for switchgrass and miscanthus as a feedstock for combustion in Nova Scotia.

The opportunity for switchgrass and miscanthus biomass as livestock bedding in Nova Scotia has come to light in an effort to create local markets for biomass. Traditional livestock bedding is made up of straw, woodchips/ wood shavings and sawdust, due to low initial moisture content and decent moisture holding capacity. Unfortunately for livestock producers, these bedding materials are some of the most readily available sources for biomass energy [182]. The demand for these materials is increasing, inevitably increasing the cost, creating inaccessibility to producers. If switchgrass and miscanthus are not feasible biomass sources for combustion in Nova Scotia, this biomass could become a locally produced alternative for livestock bedding. Miscanthus can replace straw bedding 1:1 at a moisture content less than 25 % [182]. This supply chain still provides GHG reduction potential.

2.5 Conclusion

There were three objectives of this research: 1) to evaluate the establishment, early growth and DMY of switchgrass and miscanthus on marginal agricultural lands in Nova Scotia; 2) to evaluate the effect of locally sourced soil amendments and a plant biostimulant on the establishment, early growth and DMY of switchgrass and miscanthus and 3) to investigate the quality of miscanthus biomass. The results of this research indicate that switchgrass is slow to establish but can be productive on marginal lands in Nova Scotia. Miscanthus, when planted as plantlets, is highly successful at establishing on marginal lands in Nova Scotia and its biomass productivity can be enhanced with the application of anaerobic digestate and pulp and paper mill effluent residue. Based on the tissue quality characteristics, the fall harvest to maximize yield is suitable for the intended utilization of biomass combustion for electricity generation, however in Nova Scotia's current combustion facilities, switchgrass and miscanthus biomass may be better served as livestock bedding.

Despite favourable results in most conditions, the switchgrass grown in Bible Hill is evidence that these grass crops require a proactive weed management strategy to establish a strong stand from the outset. In areas of strong weed pressure, a pre- and post-emergent application of herbicide, combined with a higher seeding rate in switchgrass could allow for these crops to outcompete weed species and strengthen early biomass productivity.

Chapter 3 Real-world verification of the yield potential of coppiced hybrid-poplar and willow on marginal lands in Nova Scotia.

3.1 Introduction

The forestry industry in Nova Scotia has a rich, extensive history. Starting in 1612, the first sawmill in North America was built in Annapolis County, Nova Scotia [183] and in 1819, the first paper mill was constructed in the province [184]. The forestry industry is a mainstay in the province's economy, providing significant export markets (pulp, paper, and lumber) and rural employment opportunities [185,186]. The reduced societal dependence on paper products [184,187], alongside increasing calls to action from the public for forest protection, has resulted in a shift in the marketplace that has left existing forestry-related infrastructure underutilized. This change in the industry landscape presents what could be a crucial opportunity to expedite the development of the local bioenergy industry.

As per Chapter 2 (Section 2.1), co-firing biomass with coal is a more sustainable and renewable alternative to coal for electricity [188]. Co-firing can be a cost-effective strategy to reduce reliance on and emissions from fossil fuels for electricity [47,48]. To date, the main source of biomass for electricity in Nova Scotia has been forest products [189,190], which in-line with forest protection, has been publicly met with controversy.

Recent amendments to the Renewable Electricity Regulations of the Nova Scotia Electricity Act have required the acquisition of 135 Gigawatt hours (GWh) of dispatchable renewable electricity beginning in 2023 [191]. This amendment is advantageous in shifting toward renewable electricity production, however, the wording in the amendment in combination with the province's history of biomass for electricity has blurred the intent of the act. Under subsection 6AA(3) of the Electricity Act, the renewable electricity must be produced from 'secondary waste by-products' [191]. The tremendous provincial forest biomass reserve [192–194] and comments from industry officials [195,196] have left minimal opportunities for the implementation of alternatives to forest biomass in renewable electricity. The utilization of dedicated energy crops alongside forest waste by-products better aligns forest management protocols to be developed to retain the economical, ecological, and environmental services of productive forests while continuing to develop a supply of diversified renewable biomass for electricity.

Highly productive growth under short-rotation woody coppice (SRWC) with versatility for substantial productivity in substandard growing conditions are the pillars that make coppiced hybrid-poplar (*Populus* sp.) and willow (*Salix* sp.) well suited as dedicated energy crops in Canada [29,30]. Further, evidence shows these species provide additional ecosystem benefits in certain environments, including marginal soils [197–200]. Growing SRWC for biomass on marginal soils counters numerous arguments against large-scale implementation of dedicated energy crops, including the 'food versus fuel' debate [197,201,202], and environmental concerns from land use change [202–205]. In Nova Scotia, only 13% of suitable agricultural land is currently under agricultural production [206]. Based on the Canada Land Inventory (CLI) system, there are no Class 1 lands in Nova Scotia and only 3.1 % of Nova Scotian land falls into Class 2 [206,207]. There are approximately 1.2 million hectares of land which are suitable to grow dedicated energy crops (Classes 3 and 4) [204].

SRWC for biomass are socioeconomically promising on marginal lands and while there is evidence to suggest these crops are productive in lower fertility soils with minimal inputs [30,204,205,208], there is additional evidence to suggest substantial increases in productivity when supplemented with fertilizers [200,201,208,209]. The production, transportation and use of synthetic fertilizers is known for its high rate of energy consumption and greenhouse gas emissions [209], therefore, the application of these fertilizers on SRWC can be counterproductive to the ultimate purpose of a cost-effective emissions reduction alternative to fossil fuels [201,210]. Non-synthetic amendments (such as pulp and paper mill effluent residue, liquid anaerobic digestate and seaweed extract) may provide similar benefits to the crops as synthetic fertilizers with a substantially smaller carbon footprint, as these can be locally sourced in Nova Scotia. A description of the soil amendments and the plant biostimulant in this study can be found in Chapter 2 (Section 2.1) [188].

3.1.1 Objectives

As per Chapter 2 (Section 2.1), the overarching objective of this research is to de-risk biomass feedstock supplies in Nova Scotia to aid in the development of a renewable, dependable source of electricity [188]. This electricity could be implemented immediately with the eventuality of encouraging the start-up of a dedicated biomass refinery (biorefinery). The objectives of this paper are:

1. To evaluate the establishment, early growth and biomass yield of coppiced hybrid-poplar and willow on marginal agricultural lands in Nova Scotia;
2. To evaluate the effect of locally sourced soil amendments and a plant biostimulant on the establishment, early growth and biomass yield of coppiced hybrid-poplar and willow.

3.2 Materials and Methods

3.2.1 Field Site Characterization

Field trials were conducted at two field sites in Nova Scotia, Canada as per Chapter 2 (Section 2.2.1) [134].

3.2.2 Plant Material

Cuttings of the hybrid-poplar clone ‘NM-6’ (*Populus nigra* × *P. maximowiczii* ‘NM-6’) were sourced from nursery stock cultivated at the Agriculture & Agri-Food Canada Nappan Research Farm (Nappan, Nova Scotia, Canada). Cuttings (20 cm) were soaked in water at least 24 hours pre-planting [211]. Cuttings were planted into the soil with approximately 2-5 cm of stem left above the soil surface, with axillary buds oriented upward.

Cuttings of the willow clone ‘SX67’ (*Salix miyabeana* ‘SX67’) were collected from nursery stock owned by Rick Corradini in Falmouth, Nova Scotia, Canada. Willow cuttings were planted following the same protocol as hybrid-poplar.

Hybrid-poplar and willow cuttings were planted following a double row design as described in Lewis et al. [212]: five groups of double rows (13 cuttings per two rows) were planted per split-plot (65 trees per split-plot or 16,250 trees ha^{-1}). Row spacing within the double row was 0.75 m while the spacing between double rows was 1.5 m (Figure 3.2.1).

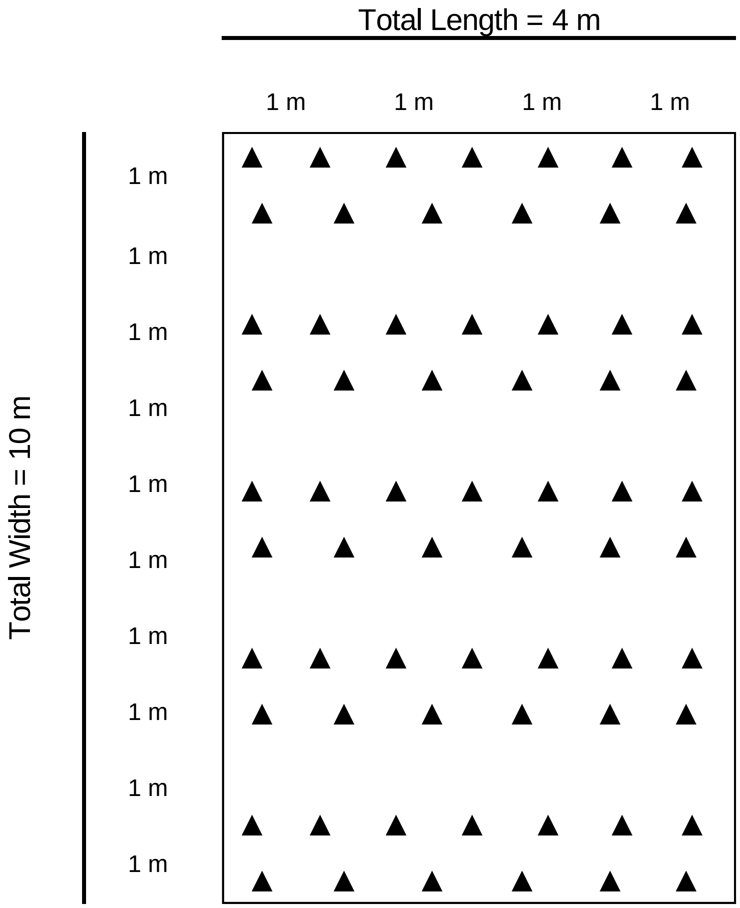

Figure 3.2.1. Diagram indicating double row split-plot design for hybrid-poplar and willow planting at the Bible Hill and Nappan, Nova Scotia field sites.

3.2.3 Soil Amendments and a Plant Biostimulant

Two locally sourced soil amendments (Table 3.2.1) and one plant biostimulant were applied to hybrid-poplar and willow cuttings in the establishment year.

Table 3.2.1 Source and experimental abbreviation of two locally sourced soil amendments and one plant biostimulant applied to hybrid-poplar and willow at the Bible Hill and Nappan, Nova Scotia field sites.

Abbreviation	Material	Commercial Name	Scientific Name	Source
PPER	Pulp and paper mill effluent residue	-	-	Port Hawkesbury Paper, LP
DG	Liquid anaerobic digestate	-	-	T.E. Boyle Farm and Forestry Limited
SE	Seaweed Extract	Stella Maris®	*Ascophyllum nodosum*	Acadian Seaplants Limited

Pulp and paper mill effluent residue was applied to hybrid-poplar and willow during planting in early June of year 1 at both field sites. Amendment application rates were as follows: PPER (~ 12,000 kg ha^{-1}), DG and SE (16,250 L ha^{-1}). For consistency between applications, the application rate of PPER was calculated in litres (Table 3.2.2). Holes (approximate depth of 30 cm) were dug for each cutting, filled with PPER, and subsequently covered with soil once the cuttings were planted into the holes.

Table 3.2.2 Application rate (per plant) of two soil amendments and one plant biostimulant for hybrid-poplar and willow during the establishment year at the Bible Hill and Nappan, Nova Scotia field sites.

Crop	Number of Plants per Split-plot	Application Rate (L plant^{-1})		
		Pulp and paper mill effluent residue	Anaerobic Digestate [a]	Seaweed Extract (1 mL L^{-1}) [a]
Hybrid-poplar	65	5.0	0.96	0.96
Willow	65	5.0	0.96	0.96

[a] Application rates were the same in Year 1 and Year 2.

Liquid anaerobic digestate and seaweed extract were applied as a soil drench treatment post-planting. The initial application of these treatments occurred in mid-August of year 1 at both field sites. A second application (following application rates from year 1) was applied in July to compensate for the late application in the establishment year. Split-plots from year 1 were divided in half lengthwise (2 m × 10 m) to create split-split-plots.

3.2.4 Experimental Setup

Each field site followed the same randomized complete block design split-split-plot structure, with hybrid-poplar and willow as two of four biomass crops planted. Four crops were planted (treatment factor A, ‘plot’) and treated with two soil amendments, one plant biostimulant and one untreated control (treatment factor B, ‘split-plot’). Two amendments (liquid anaerobic digestate and seaweed extract) received a secondary application in year 2, creating treatment factor C (‘split-split-plot’). Each block (four block replicates total) contains all levels of all treatment factors (Figure 2.2.3). Prior to field site establishment, plots were prepared by spraying

Roundup® herbicide (according to the manufacturer's recommendation) followed by ploughing the soil to a depth of approximately 30 cm followed by harrowing.

3.2.5 Field Site Maintenance

Moderate to high weed pressure was observed at both Bible Hill and Nappan field sites approximately four weeks post-planting. To aid crop establishment, weeds were mechanically removed using a combination of mowing, trimming, hoeing, and hand-pulling. Weed removal occurred once per growing season at the Nappan field site and twice per growing season at the Bible Hill field site (apart from only one weeding session in year 3) (Chapter 2, Section 2.2.5 [188]). At the Bible Hill field site, an electrified deer fence was installed in year 2 as per Chapter 2, Section 2.2.5 [188].

3.2.6 Data Collection

3.2.6.1 Year 1

Soil cores (0 – 15 cm and 16 – 30 cm) across the field sites were collected prior to planting to establish baseline soil characteristics (Table A-1). At the end of the season (November), tree survival rate (the ratio of presently living trees to the total number of trees initially planted [213]) was recorded prior to harvest. All stems from the primary cuttings were cut following a typical coppicing methodology (stems cut approximately 5 cm from the base any remaining leaves were detached) to create a 'stool' from which new secondary stems will grow. Stems were collected from ten randomly selected trees per split-plot and dried at 70 ºC for at least seven days to measure dry matter yield. By coppicing hybrid-poplar and willow in 2019 (year 1), a three-year coppice cycle would end in 2022 (year 4).

3.2.6.2 Years 2 and 3

Due to the three-year coppicing cycle, there were no biomass harvests completed in years 2 and 3. To evaluate the early effects of the soil amendments and plant biostimulant, growth parameters were measured twice in year 2 (mid-season and end of season) and once again in year 3 (end of season).

Soil samples were collected from within each split-plot (or split-split-plot) after the secondary application of DG and SE. To collect a representative composite sample for each split-plot (or split-split-plot), soil cores (0 – 15 cm) were collected within and between the double rows of trees, equidistant between trees. Tree survival rate was recorded again in year 2 to evaluate overwintering capacity. Ten randomly selected hybrid-poplar and willow trees per split-plot were selected as sub-samples for all data collection. In hybrid-poplar, number of stems per tree (defined as growth from the primary cutting or the coppiced secondary stems), total length of stems (measured from base to tip), number of leaves per tree and leaf area (per one stem) were measured while in willow, number of stems per tree, total length of stems, number of leaves per tallest stem and leaf area were measured. Stem lengths were measured with a metre stick, and leaf areas were measured using a LiCor LAI03300C Plant Canopy Analyzer. Due to the morphology of willow leaves, a sub-sample of leaves was removed from the tallest stem of each sub-sampled tree and measured for leaf area. All mid-season sampling occurred in August of year 2 at both Bible Hill and Nappan field sites.

At the end of the year 2 growing season, data were collected from the ten previously selected trees for the CT and PPER split-plots. In the DG and SE split-plots, data were collected from the ten previously selected trees and from an additional ten trees randomly selected to evenly distribute ten sampled trees per split-split-plot. Number of stems per tree, total length of stems and stem diameter (measured 5 cm from the base of all stems with a digital caliper) were measured in both hybrid-poplar and willow in November of year 2 at both field sites. Only secondary stems (coppiced from the original cutting) and tertiary stems (growth from previously coppiced stems) were selected for measurement in the fall. At the end of the year 3 growing season, the same growth parameters were measured at both sites in November. Due to the increasing size of the trees, only eight randomly selected hybrid-poplar and willow trees per split-plot (or split-split-plot) were selected as sub-samples for data collection.

From the data collected in years 2 and 3, tree stem volume (TSV) was estimated using the formula:

$$\mathrm{TSV} = [\mathrm{SV}_1 = (\pi r^2{}_1 \times L_1/3] + [\mathrm{SV}_2 = (\pi r^2{}_2 \times L_2/3] + \ldots\ [\mathrm{SV}_x = (\pi r^2{}_x \times L_x/3]$$

where TSV is the sum of the volume of each stem [$SV_{(1\ldots x)}$] as calculated from the area of the base of an individual stem [$\pi r^2_{(1\ldots x)}$] multiplied by the length of the same stem [$L_{(1\ldots x)}$] divided by 3. This formula assumes each stem is a cone with a decreasing diameter from base to tip.

3.2.6.3 Year 4

Soil samples and tree survival rate were collected prior to harvesting at the end of the growing season in November from both Bible Hill and Nappan field sites. All stems from the primary cutting were cut approximately 5 cm from the base. Stems were collected from eight randomly selected trees per split-plot (or split-split-plot) and dried at 70 ºC for at least seven days to measure dry matter yield.

3.2.7 Statistical Analyses

As per Chapter 2, Section 2.2.7 [188], all statistical analyses were performed using R and RStudio©.

3.3 Results

3.3.1 Tree Survival

Tree survival as measured at the end of the establishment year for hybrid-poplar was 92% and 97% across treatments at Bible Hill and Nappan, respectively, while willow survival was 86% and 96% across treatments at Bible Hill and Nappan, respectively (Table B-1). Over the course of the coppice cycle, there were some estimation errors of counting tree survival in the field (e.g. the survival rate was sometimes numerically higher in 2020 than in 2019), likely due to different individuals counting over the course of the study. Nonetheless, by the year of the coppice harvest (year 4), survival of the CT treatment declined in all crops across all sites (Figure 3.3.1). Tree survival in the CT treatment dropped nearly 30% in hybrid-poplar at Bible Hill, and 15% in Nappan. In willow, the decline in CT survival was much less at both sites (less then 15% from year 1 at both sites). Hybrid-poplar survival across treatments in year 4 was 68% at Bible Hill, while willow survival across treatments was 84% (Table B-10). At the Nappan field site, the tree survival in year 4 across treatments was 91% for hybrid-poplar and 93% for willow.

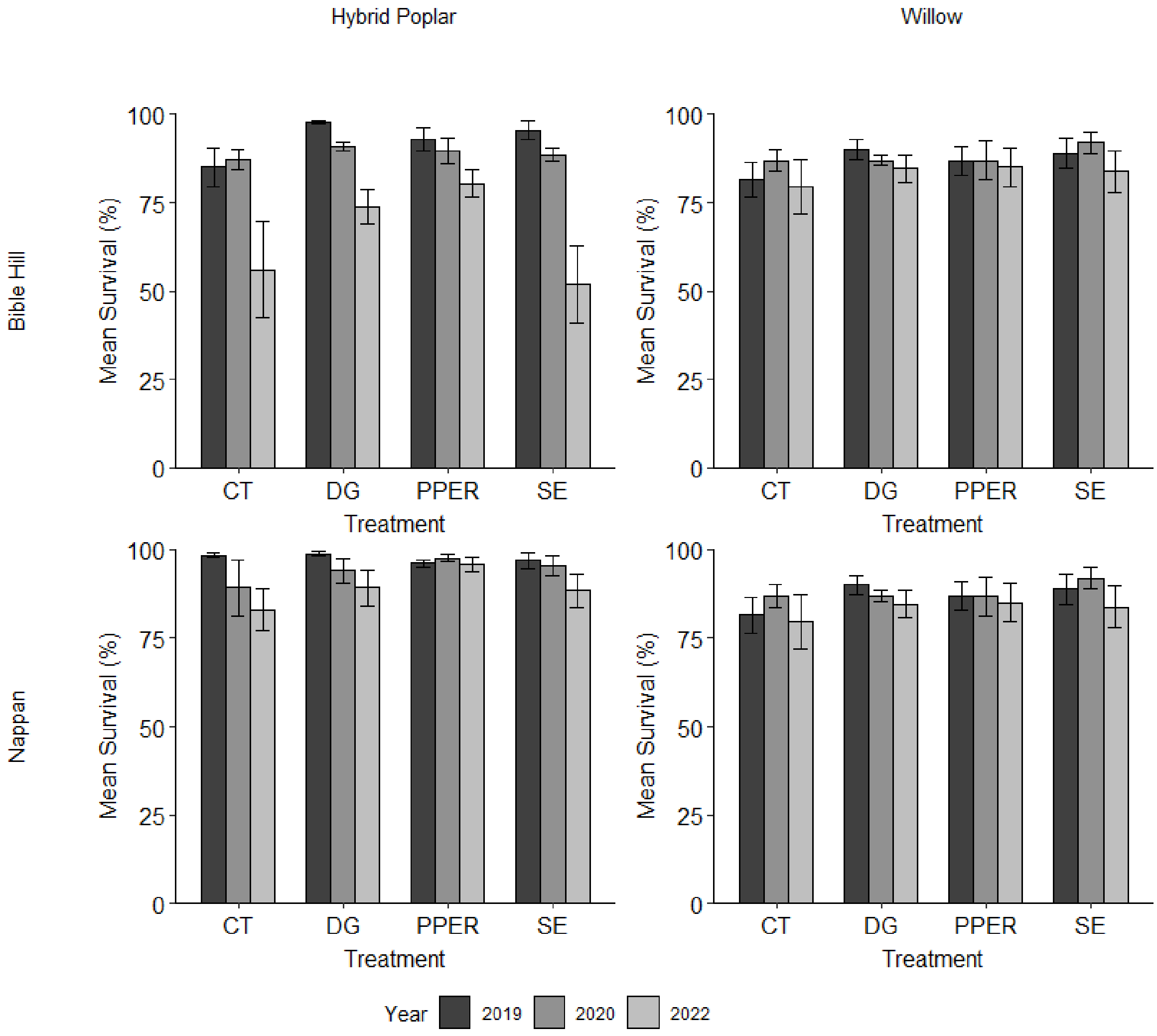

Figure 3.3.1 Mean tree survival of hybrid-poplar and willow from the establishment year (2019) to the first coppice harvest (2022, year 4) by soil treatment. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill effluent residue. Bars indicate standard error.

3.3.2 Dry Matter Yield – Year 1

Mean hybrid-poplar DMY across treatments at the Bible Hill field site was 29.85 kg ha^{-1}, where the PPER treatment (58.47 kg ha^{-1}) showed significantly greater DMY than the CT treatment (P = 0.06881). At the Nappan field site, the mean hybrid-poplar DMY was 59.68 kg ha^{-1}, where the PPER treatment (180.27 kg ha^{-1}) was significantly greater than all other treatments (P = 0.01053) (Figure 3.3.2) (Table B-1).

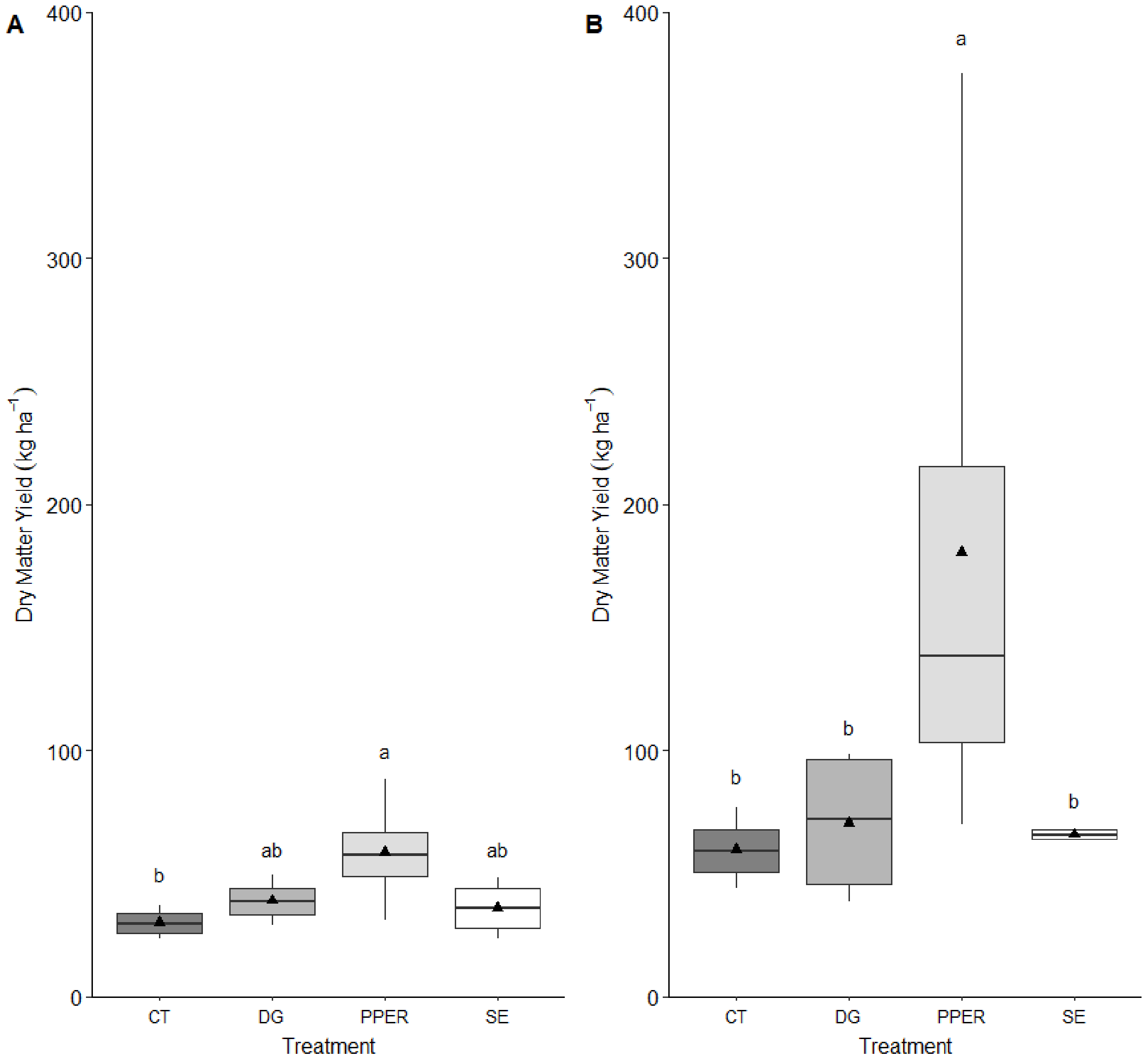

Figure 3.3.2 Mean hybrid-poplar dry matter yield (kg ha^{-1}) by soil treatment at **A** Bible Hill and **B** Nappan, Nova Scotia in year 1. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill effluent residue. The median value for each treatment is represented by a bold horizontal line, while the mean value is represented by a filled triangle. The range (excluding outliers) is represented by the whiskers, while outliers are represented by filled circles (n = 4). Different letters indicate significant difference within site at $P < 0.05$.

Mean willow DMY across treatments at the Bible Hill field site was 92.14 kg ha^{-1}, where the SE treatment (161.49 kg ha^{-1}) showed significantly greater DMY than the DG treatment (27.07 kg ha^{-1}) ($P = 0.02345$). At the Nappan field site, the mean willow DMY was 75.08 kg ha^{-1}, where the PPER treatment (160.80 kg ha^{-1}) was significantly greater than all other treatments ($P = 1.1674 \times 10^{-5}$) (Figure 3.3.3) (Table B-1).

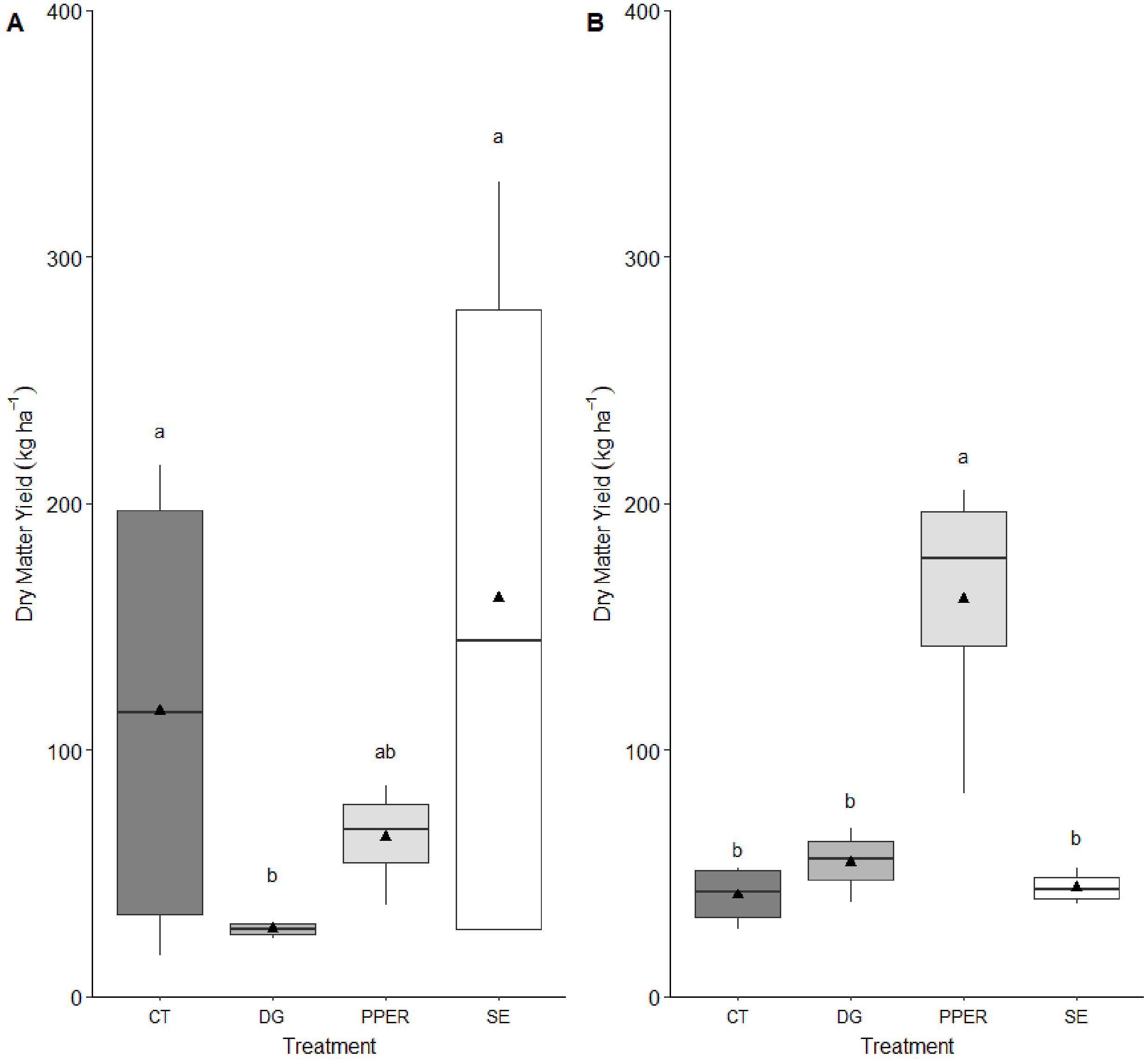

Figure 3.3.3 Mean willow dry matter yield (kg ha^{-1}) by soil treatment at **A** Bible Hill and **B** Nappan, Nova Scotia. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill effluent residue. The median value for each treatment is represented by a bold horizontal line, while the mean value is represented by a filled triangle. The range (excluding outliers) is represented by the whiskers, while outliers are represented by filled circles (n = 4). Different letters indicate significant difference within site at $P < 0.05$.

3.3.3 Mid-Season Growth Measurements – Year 2

At the Bible Hill site, there was a statistically significant positive effect of the PPER treatment on all measured hybrid-poplar growth parameters except area per leaf in comparison to all other treatments (Table 3.3.1). Conversely, in Nappan, there was only a statistically significant positive effect of the PPER treatment on area per leaf compared to the CT treatment.

For willow growth parameters, the PPER treatment showed a statistically significant effect on total stem length and area per leaf compared to the SE treatment at both the Bible Hill and Nappan field sites (Table 3.3.1).

Table 3.3.1 Mean values of dependent variables (stems per tree, total length of stems, leaves per tree, area per leaf and total leaf area) as measured in August (mid-season) of year 2 at Bible Hill and Nappan, Nova Scotia.

		Stem Count [a]	Stem Length [a] (cm)	Leaf Count [b]	Area per Leaf (cm^2)	Total Leaf Area per Tree [c] (cm^2)
Bible Hill						
Hybrid-poplar	CT	4 ± 0.4 b	118.75 ± 29.78 b	47 ± 8 b	15.33 ± 0.61 a	735.16 ± 151.6 b
	DG	4 ± 0.2 b	130.75 ± 19.37 b	50 ± 4 b	15.64 ± 1.64 a	795.85 ± 121.88 b
	SE	4 ± 0.2 b	83.00 ± 22.18 b	40 ± 7 b	13.65 ± 1.86 a	591.06 ± 186.32 b
	PPER	7 ± 0.6 a	247.75 ± 24.88 a	82 ± 10 a	17.49 ± 1.26 a	1,435.47 ± 207.94 a
Willow	CT	6 ± 0.9 a	209.75 ± 57.28 b	35 ± 7 a	5.35 ± 1.09 ab	-
	DG	8 ± 1.0 a	352.25 ± 41.09 ab	44 ± 1 a	7.08 ± 0.26 ab	-
	SE	6 ± 1.4 a	223.75 ± 43.76 b	36 ± 2 a	4.99 ± 0.62 b	-
	PPER	9 ± 0.3 a	427.00 ± 60.08 a	44 ± 4 a	8.115 ± 0.83 a	-
Nappan						
Hybrid-poplar	CT	3 ± 0.9 a	136.00 ± 44.9 a	46 ± 13 a	15.84 ± 1.26 b	780.44 ± 269.54 a
	DG	3 ± 0.8 a	161.5 ± 40.43 a	50 ± 11 a	19.38 ± 3.91 ab	1067.37 ± 414.20 a
	SE	3 ± 0.9 a	175.75 ± 59.91 a	57 ± 15 a	17.94 ± 2.91 ab	1137.2 ± 492.83 a
	PPER	4 ± 1.0 a	286.00 ± 59.38 a	86 ± 21 a	27.53 ± 2.51 a	2534.88 ± 857.1 a
Willow	CT	2 ± 0.5 a	172.25 ± 40.31 ab	40 ± 4 a	6.41 ± 0.85 b	-
	DG	2 ± 0.3 a	194.00 ± 27.89 ab	43 ± 5 a	8.73 ± 1.4 ab	-
	SE	2 ± 0 a	141.50 ± 19.16 b	38 ± 5 a	5.56 ± 0.59 b	-
	PPER	2 ± 0.5 a	269.00 ± 40.59 a	51 ± 4 a	10.43 ± 0.45 a	-

[a] All stems per tree. [b] Leaf count per hybrid-poplar tree; leaf count per tallest willow stem.

[c] Total leaf area per tree not available for willow because leaf count was only measured on the tallest stem, not all stems.

Means followed by the same lowercase letters within a crop and site are not significantly different at $P = 0.05$.

3.3.4 End of Season Growth Measurements – Years 2 and 3

3.3.4.1 Growth Parameters – Years 2 and 3

Hybrid-poplar stem count (secondary and tertiary stems) in the PPER treatment was significantly greater than the SE and DG treatments, while the PPER treatment showed significantly greater total length of stems than all other treatments at Bible Hill (Table 3.3.2). There were no statistically significant differences to report in hybrid-poplar from the Nappan field site.

Willow stem count (secondary and tertiary stems) and total length of stems in the PPER treatment were both significantly greater than the SE and CT treatments at Bible Hill. Total length of stems was significantly greater in the PPER treatment than the SE treatment at the Nappan field site (Table B-7).

There were no statistically significant differences to report in hybrid-poplar or willow growth parameters from either the Bible Hill or Nappan field sites in year 3 (Table B-8).

Table 3.3.2 Mean values of dependent variables, stems per tree, total length of stems and stem diameter as measured in November (end of season) of year 2 at Bible Hill and Nappan, Nova Scotia.

		Stem Count [a]	Stem Length [a] (cm)
Bible Hill			
Hybrid-poplar	CT	3 ± 0.5 ab	107.00 ± 22.88 b
	DG	3 ± 0 b	121.00 ± 19.73 b
	SE	2 ± 0.3 b	74.75 ± 18.58 b
	PPER	4 ± 0.3 a	191.50 ± 15.00 a
Willow	CT	3 ± 0.3 b	210.00 ± 63.14 b
	DG	4 ± 0.6 ab	271.25 ± 33.46 ab
	SE	3 ± 0.8 b	224.00 ± 37.30 b
	PPER	6 ± 0.6 a	439.25 ± 61.6 a
Nappan			
Hybrid-poplar	CT	3 ± 0.7 a	135.50 ± 39.67 a
	DG	3 ± 0.4 a	152.25 ± 41.95 a
	SE	3 ± 0.8 a	154.00 ± 54.47 a
	PPER	4 ± 0.8 a	271.5 ± 54.51 a
Willow	CT	3 ± 0.6 a	235.50 ± 60.89 ab
	DG	3 ± 0.5 a	248.50 ± 60.00 ab
	SE	3 ± 0.3 a	189.75 ± 23.21 b
	PPER	5 ± 0.8 a	422.25 ± 54.34 a

[a] Secondary and tertiary stems per tree.

Means followed by the same lowercase letters within a crop and site are not significantly different at $P = 0.05$.

3.3.4.2 Tree Stem Volume – Years 2 and 3

Although the PPER treatment consistently had the numerically highest tree stem volumes in both tree species at both sites, there were no statistically significant differences among soil amendment treatments in either the hybrid-poplar or the willow tree stem volume from either the Bible Hill or Nappan field sites in years 2 or 3 (Table B-9).

3.3.5 Dry Matter Yield – Year 4

Mean hybrid-poplar DMY across treatments at the Bible Hill field site was 2,861.58 kg ha^{-1}, where the PPER treatment (5,243.30 kg ha^{-1}) showed significantly greater DMY than the SE treatment (1,098.46 kg ha^{-1}) ($P = 0.06408$). At the Nappan field site, the mean poplar DMY was 3,099.44 kg ha^{-1}, where the PPER treatment (6,314.64 kg ha^{-1}) was significantly greater than all other treatments ($P = 0.006087$) (Figure 3.3.4) (Table B-10).

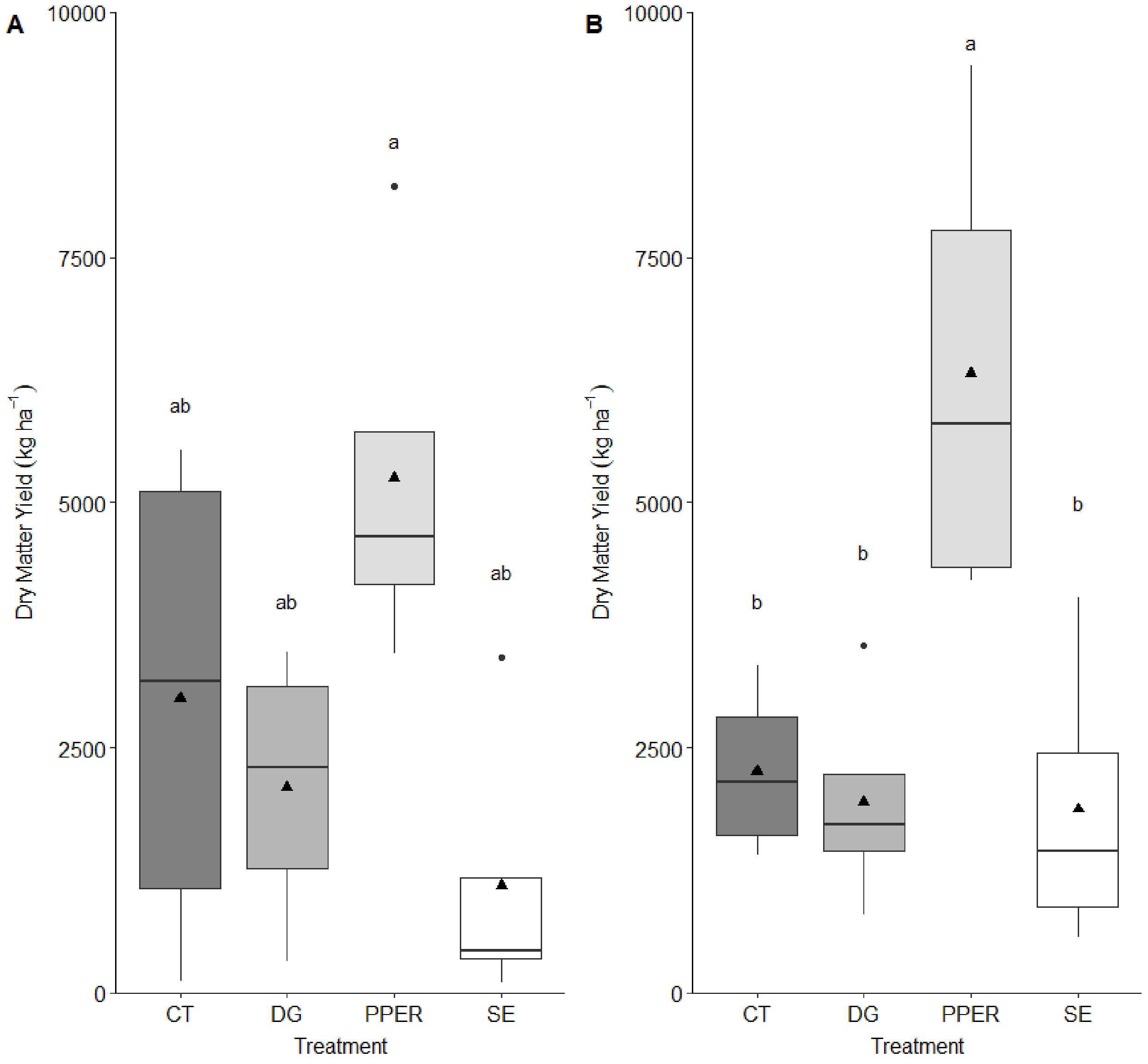

Figure 3.3.4 Mean hybrid-poplar dry matter yield (kg ha^{-1}) by soil treatment at **A** Bible Hill and **B** Nappan, Nova Scotia in year 4. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill effluent residue. The median value for each treatment is represented by a bold horizontal line, while the mean value is represented by a filled triangle. The range (excluding outliers) is represented by the whiskers, while outliers are represented by filled circles (n = 4). Different letters indicate significant difference within site at $P < 0.05$.

Mean willow DMY across treatments at the Bible Hill field site was 7,119.73 kg ha^{-1} with no statistically significant differences between treatments ($P = 0.4748$). At the Nappan field site, the mean willow DMY was 10,598.74 kg ha^{-1}, where the PPER treatment (19,024.045 kg ha^{-1}) was significantly greater than the SE treatment (4,454.97 kg ha^{-1}) ($P = 0.04777$) (Figure 3.3.4) (Table B-10).

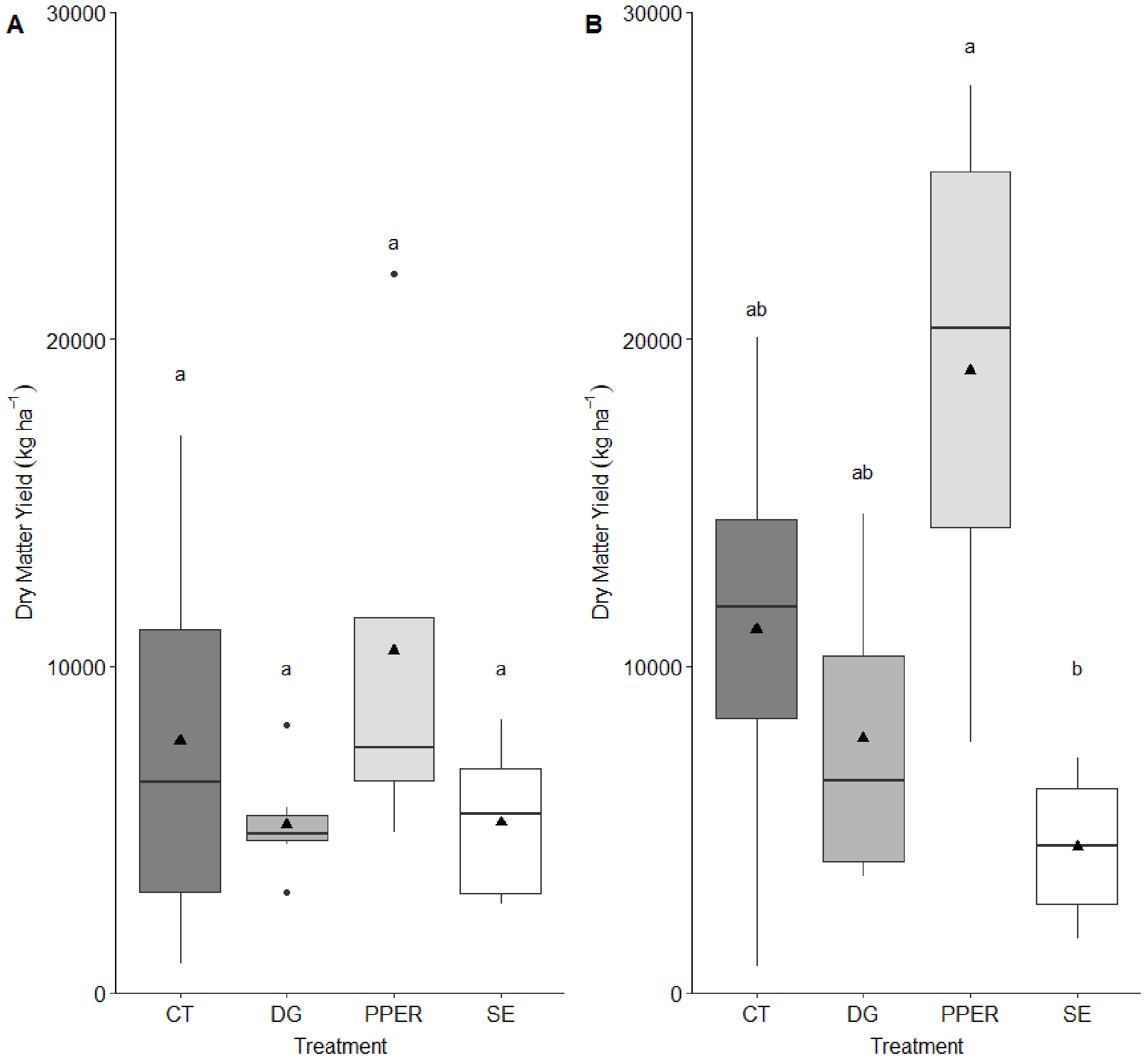

Figure 3.3.5 Mean willow dry matter yield (kg ha^{-1}) by soil treatment at **A** Bible Hill and **B** Nappan, Nova Scotia in year 4. CT = Control, DG = Digestate, SE = Seaweed extract and PPER = Pulp and paper mill effluent residue. The median value for each treatment is represented by a bold horizontal line, while the mean value is represented by a filled triangle. The range (excluding outliers) is represented by the whiskers, while outliers are represented by filled circles (n = 4). Different letters indicate significant difference within site at $P < 0.05$.

3.3.6 Soil Nutrients – Year 2

At the Bible Hill field site, the application of DG significantly increased the potassium (significantly greater than the PPER-treated soil, *P* = 0.05225) and sodium contents (significantly greater than all other treatments, *P* = 0.01316). The DG treatment also significantly increased the sulfur content compared to the CT treatment at the Nappan field site (*P* = 0.03336) (Table A-4, Table A-5, Table A-6).

3.3.7 Soil Nutrients – Year 4

At the Bible Hill field site, the application of DG significantly increased the soil potassium content (significantly greater than SE-treated soil, *P* = 0.02881). The DG treatment also showed a very interesting effect in Nappan on soil potassium. The soil collected from DG-2 (second application of DG in year 2) was significantly greater than all other treatments excluding the single application of DG-1 (*P* = 0.0033589) (Figure 3.3.6). Organic matter was also impacted at the Nappan field site, with a significantly positive effect of the PPER-treated soil compared to the SE-treated soil (*P* = 0.0824) (Table B-2, Table B-3, Table B-4, Table B-5).

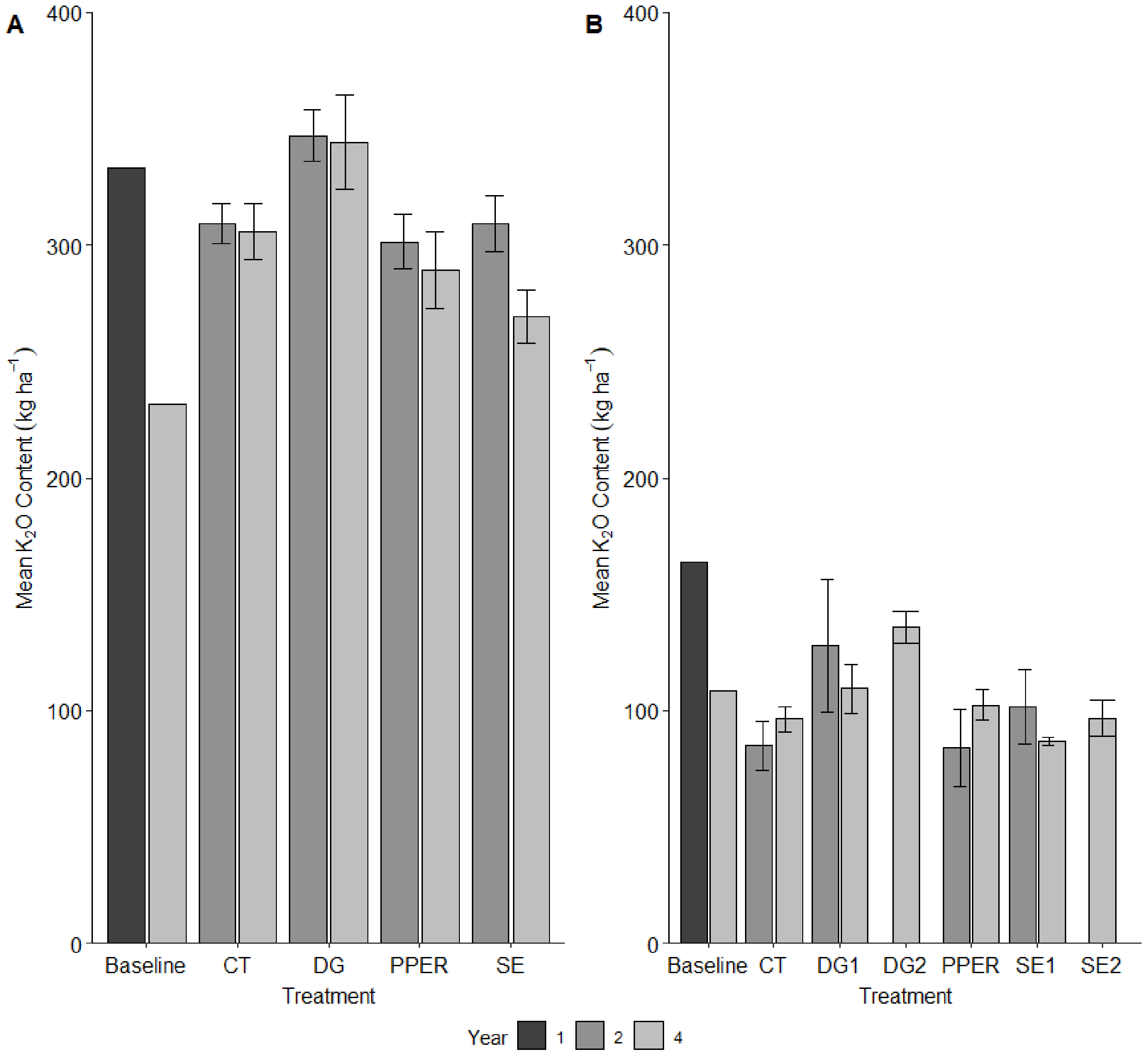

Figure 3.3.6 Mean K_2O content (kg ha^{-1}) in the soil (0-15 cm) from the establishment year to the first coppice harvest (year 4) by soil treatment at **A** Bible Hill and **B** Nappan, Nova Scotia. CT = Control, DG1 = Digestate (year 1), DG2 = Digestate (year 2), SE1 = Seaweed Extract (year 1), SE2 = Seaweed Extract (year 2), PPER = Pulp and paper mill effluent residue. Bars indicate standard error.

3.4 Discussion

In this chapter, hybrid-poplar and willow were evaluated for their capabilities as biomass crops on marginal agricultural lands in Nova Scotia. Further, the effects of locally sourced soil amendments and a plant biostimulant on establishment, early growth and biomass yield were evaluated.

Two major findings of this research include the successful establishment of hybrid-poplar and willow on marginal agricultural lands across Nova Scotia and the potential for soil amendments, particularly pulp and paper mill effluent residue, to enhance establishment and subsequent biomass productivity of these crops. However, the field experiments indicated a substantial increase in stool mortality over the four-year course of study despite the favorable effects of the soil amendments.

3.4.1 Stool Mortality

Mean stool mortality across treatments over the four years of the study was 32 % in hybrid-poplar and 16 % in willow at the Bible Hill site, while at the Nappan site, hybrid-poplar stool mortality was 9 % and willow was 7 % (Table B-10). Higher mortality rates are more typical in the establishment year for various reasons, including poor cutting quality and competition with weeds [214–218]. The Bible Hill site exhibited moderate to high stool mortality in the establishment year in both hybrid-poplar (8 %) and willow (13 %) [213,219] (Table B-1). There was extensive weed growth in the establishment year at the Bible Hill site that was mechanically tended to twice during that growing season. The smaller cuttings that were planted (~ 20 cm) combined with early large-scale mechanical weed control could have inflicted damage to the cuttings prior to rooting.

However, mortality in the establishment year at the Bible Hill site was more likely caused by deer grazing [220,221]. Initial remedial action via chemical deterrent was introduced later in the establishment year, followed by the installation of an electrified fence in the spring of year 2, leaving the hybrid-poplar relatively unprotected from browsing over the winter season between years 1 and 2 [221,222]. Aside from costly physical barriers to the plantation, deer grazing could be minimized by planting larger cuttings, known as whips. If the initial planting is above the browse line, damages to the trees could be minimized [221,222].

A considerable rise in mortality rate in hybrid-poplar at Bible Hill (nearly 30 %) was observed just before the harvest in year 4 (Table B-10, Figure 3.3.1). This rise in mortality could be a long-term symptom of deer grazing during the establishment year [220,221]. Or, the seemingly delayed mortality could be indicative of the inability of this hybrid-poplar clone to adapt to the specific climatic or edaphic conditions at the Bible Hill site [223,224]. The ‘NM-6’ clone used in this study is known for its strong establishment capabilities and productivity in northern climates [225,226], however, the Bible Hill site could have presented additional unfavourable microclimatic conditions for long-term adaptability. In future, it should be noted if the stool mortality in this study continues to decline into the second rotation, or if it stabilizes. If stabilization occurs, the stool mortality rate of poplar can be used to adjust the planting density to optimize biomass productivity.

3.4.2 Precipitation

As previously mentioned in Chapter 2, the growing season precipitation during the establishment year at both Bible Hill and Nappan field sites were greater than average, 18 % and 40 % increases, respectively (Table 2.2.1) [92,134]. It was deduced that cumulative water availability (precipitation and irrigation, when used) in the first two years of growth is essential not only to the survival of both hybrid-poplar and willow, but also to biomass productivity [219]. Conversely, all subsequent years at the Bible Hill site and two of three years at Nappan experienced less precipitation than average (Table 2.2.1). This potential lack of water availability during post-establishment growing seasons could explain the rise in mortality at the Bible Hill site, as adequate precipitation becomes one of the most limiting factors for growth of SRWC post-establishment [213,216,227].

3.4.3 Dry Matter Yield

In coppice systems, the above-ground biomass is cut approximately 5 cm from the stool in the first year to regenerate multiple new shoots from the original cutting [228], inherently increasing future biomass productivity. First year biomass is typically not collected for further use. However, as an indication of early growth, establishment year DMY was measured in this study. Both sites exhibited a significant positive effect of the PPER treatment on hybrid-poplar DMY compared to the CT treatment: 96 % increase in Bible Hill and 202 % increase in Nappan. The same trend occurred in the willow at Nappan, with the PPER treatment exhibiting a 292 % increase in DMY over the CT treatment (Figure 3.3.2 and Figure 3.3.3). Above average precipitation and increased water holding capacity associated with PPER incorporation into the soil could have propelled biomass productivity in the establishment year [146,147].

After the first rotation (year 4), DMY was measured again. At the Bible Hill site, there was less variation between soil amendments in both hybrid-poplar and willow, although there was persistent evidence of a positive effect of PPER in hybrid-poplar, with a 74 % increase in DMY compared to the CT treatment (Figure 3.3.4). At the Nappan field site, the PPER treatment exhibited a significant positive effect on hybrid-poplar DMY compared to the CT treatment (179

% increase) and on willow DMY compared to the SE treatment (76 % increase) (Figure 3.3.5). The smaller variation between soil amendments in year 4 versus year 1 could be indicative of increasing stool mortality with stand age. Further, any effects on early plant growth from the single application of PPER in the establishment year could be waning by year 4. Perhaps the ability of PPER to increase water-holding capacity of the soil contributed to the increased DMY, as both sites experienced less than average growing season precipitation [87,229].

There is a large range of average biomass production of hybrid-poplar reported in the literature, from 1.0 – 25.0 Mg ha^{-1} year^{-1} [230]. Labrecque and Teodorescu reported an average yield of 18.05 Mg ha^{-1} year^{-1} for the NM-6 clone after four years of growth (harvested annually) in Quebec, Canada [231]. The average across soil amendments in this study was 0.95 Mg ha^{-1} year^{-1}, with the PPER-treated hybrid-poplar at both sites reporting the highest yields (1.7 and 2.1 Mg ha^{-1} year^{-1} at Bible Hill and Nappan, respectively). The relatively lower yields reported in this study in comparison to the literature could be explained by plantation management. Many SRWC studies encourage fertilizer and/ or irrigation applications to trees to increase biomass productivity. The Labrecque and Teodorescu study [231] was very similar in management to this study (planting density, nutrition regime) apart from the annual harvesting, which could be accountable for the substantial rise in biomass productivity.

The average biomass production of willow in Canada reported in the literature is less variable than hybrid-poplar. [202] reported an average biomass yield of 3.5 Mg ha^{-1} year^{-1} based on the first rotation of growth in Saskatchewan, while specifically for the SX-67 clone, Labrecque and Teodorescu reported a yield of 9.44 Mg ha^{-1} year^{-1} after four years of growth (harvested annually) in Quebec, Canada [231]. The average across soil amendments in this study ranged from 2.3 Mg ha^{-1} year^{-1} (Bible Hill) to 3.5 Mg ha^{-1} year^{-1} (Nappan), with the PPER-treated willow in Nappan reporting a massive 6.3 Mg ha^{-1} $year^{-1}$ biomass yield. The similar yields reported between the literature and this study could be indicative that willow is more viable as a dedicated energy crop in Nova Scotia than hybrid-poplar.

3.4.4 Soil Nutrients

The only amendment to have a significant effect on the soil throughout the course of the study was the liquid anaerobic digestate (DG). The nutrient composition of anaerobic digestate, including K_2O content, is directly correlated to the original nutrient composition of the feedstocks used in the digestion process [232–234]. The nature of digestion offers an increase in plant-available nutrients in the digestate [233–236], suggesting that animal manure digestates are more suitable for crops requiring high levels of potassium [232]. The digestate in this study is derived from dairy manure and crop residues, exhibiting a relatively high K_2O content of 3.5 % (dry weight) [237] (Table A-3), which evidently increased the soil K_2O content (Figure 3.3.6).

At both sites, the baseline K_2O content (collected from within the plots prior to treatment in year 1, and near plots in year 4) was noticeably less in year 4 than in year 1 at both sites. The behaviour of the ‘baseline’ soil gives a good indication of the losses of soil potassium from erosion, leaching or runoff, as these areas are well-trodden and lesser maintained than the study plots. Interestingly, the CT plots at both Bible Hill and Nappan did not exhibit the same losses in K_2O content, although the only difference between the ‘baseline’ and the CT soils is the presence of the trees.

In year 2, the single DG application showed a significant positive effect on soil K_2O content compared to PPER treated soil at the Bible Hill site and non-significant positive effects compared to all other treatments at both sites (Table A-4, Figure 3.3.6). Further, in year 4, the

DG application (pooled across single and dual applications) at the Bible Hill site showed a non-significant positive effect on K_2O compared to all other treatments (significant positive effect compared to SE treatment). At the Nappan site in year 4, there was a significant interaction effect between application (year 1 versus year 2) with respect to K_2O soil content. The dual application of DG showed a significant positive effect on K_2O soil content compared to all other treatments except for the single application of DG (Table B-3). Perhaps the combination of the lower-than-average precipitation over the course of the study combined with the high concentration of potassium in the DG enhanced the soil K_2O, although it is likely the increased K_2O is not within the soil solution [154,238].

The effect of DG on the soil K_2O content is interesting and could aid in future drought tolerance. The DG did not positively impact the biomass yield of hybrid-poplar or willow in this study. For purposes of biomass collection, it would be important to complete a tissue analysis on the hybrid-poplar and willow biomass to assess the K_2O content, as high potassium content is undesirable for combustion-bound biomass, as potassium negatively impacts combustion equipment [239].

3.4.5 Biomass Outlook in Nova Scotia

After consultation with two local biomass burning facilities (Dalhousie Agricultural Campus' Biomass Energy Plant in Bible Hill, Nova Scotia, and Port Hawkesbury Paper's (PHP) Biomass Plant), the tree biomass from this study meets one of the most important specifications for these direct combustion applications: moisture content. The average moisture content of the tree biomass (across species and sites) from year 4 was between 47-50 %, falling within the optimal range of moisture content for these two facilities.

Combining the hybrid-poplar and willow from both sites, the total biomass harvested in year 4 was approximately 2,000 kg of green biomass. Although this volume is a mere fraction of what either of these facilities consume (Dalhousie Biomass Energy Plant consumes 60,000 kg of green biomass per day, while the PHP plant consumes a whopping 100,000 kg of green biomass per hour), substantially increasing the annual volume of tree biomass harvested from SRWC could seamlessly feed into either of these operations.

3.5 Conclusion

There were two objectives of this research: 1) to evaluate the establishment, early growth and DMY of coppiced hybrid-poplar and willow on marginal agricultural lands in Nova Scotia and 2) to evaluate the effect of locally sourced soil amendments and a plant biostimulant on hybrid-poplar and willow establishment and growth. The results of this research are indicative that these hybrid-poplar and willow clones can successfully establish and grow on marginal lands in Nova Scotia, and that pulp and paper mill effluent residue can enhance hybrid-poplar growth and biomass productivity. Within Canadian studies, the biomass productivity of hybrid-poplar in this study was substantially low, while the biomass productivity of willow was on the higher end of the spectrum [231,240,241].

The findings of this research are helpful in many ways. Despite successful establishment of both hybrid-poplar and willow at both sites, and favourable effects of the pulp and paper mill effluent residue, some aspects of plantation management could be adjusted to enhance the production of these crops in Nova Scotia. In areas where deer are present, the installation of a deer fence prior to planting would be beneficial. If fence installation is deemed too costly, the plantation of larger plants (above the browse line) could also detract from grazing and bolster establishment and subsequent growth. To further evaluate the feasibility of these crops for co-firing, crop productivity should be evaluated for subsequent growth rotations, and tissue nutrient analysis should be completed for the biomass.

Chapter 4 Predictive yield modelling of switchgrass and miscanthus in Nova Scotia.

4.1 Introduction

Anthropogenic climate warming and the societal pressures to deal with it have the demand for non-fossil, sustainable energy and materials rising. Biomass is an abundant global resource and can be used directly or indirectly (converted to other forms) as an energy alternative and as a material for bioproducts [9,242].

Canada's annual supply of lignocellulosic biomass from agricultural and forestry residues, accounting for natural variation, ranges from 64-561 million dry Mg per year [9]. Approximately 27 million dry Mg of these residues are currently used to produce bioproducts [9]. Although numerous confounding factors are present, between 20-50 % of above-ground agricultural and forestry residues should remain uncollected from fields and managed forests, respectively to address ecological concerns, including soil preservation [9,39,41,243]. Citing Oo et al., [39] the quantity of agricultural residues available from Canadian farms to be sustainably harvested (30 million Mg) [40] is just about the same as the current quantity of residues used for bioproducts. Others have indicated the quantity of forestry residues available in Canada including considerations for ecological and technical restrictions is 20 million Mg [41]. Further depleting agricultural and forestry residues for bioenergy and bioproducts could be environmentally and socially detrimental, thus, additional sources of sustainable biomass on top of current societal requirements need to be explored [9,244].

A well-known debate associated with bioenergy and bioproducts from dedicated crops is the 'food versus fuel' debate. This debate encompasses two scenarios: the first, using food and/

or feed crops for bioenergy or bioproducts rather than for food and feed. The production of first-generation biofuels has historically reduced food supply, increased food prices, and provided negligible GHG emissions reductions [9,20]. The second scenario deals with the conversion of agricultural land designated for food and feed production into biomass production for energy or materials [9,245,246]. The Canada Land Inventory (CLI) system classifies agricultural lands as classes 1 through 7 based on suitability of the land for agricultural production [93]. Class 1 and 2 lands are typically (and rightfully) designated for food and feed production (although there are no Class 1 lands in Nova Scotia and only 3.1% of land falls into Class 2 [206,207], forcing Nova Scotians to rely on Class 3 and 4 lands). The use of higher-class soils to produce dedicated, non-food (lignocellulosic) crops for bioenergy and bioproducts inherently fuels the ‘food versus fuel’ debate from another angle: displacing food production land while simultaneously raising other concerns, including issues with soil carbon sequestration and limited GHG emissions reductions (depending on production practices) [9,245,246].

Biomass supply for bioenergy and bioproducts can be increased without forfeiting ecological functions of agricultural and forestry residues or triggering the ‘food versus fuel’ debate. The production of dedicated lignocellulosic crops on underutilized agricultural and marginal lands has the potential to provide ecological and environmental services as well as supplying biomass to fill voids in the bioeconomy [245,246]. Nova Scotia has approximately 300,000 hectares of Class 2, 3 and 4 lands (unforested land in agricultural production) [206] that could be sustainably repurposed to grow dedicated bioenergy crops, including switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* × *giganteus*).

As mentioned in Chapter 2 [188], there is history of growing switchgrass and miscanthus as bioenergy crops in Canada, and even more locally, switchgrass has been grown in Nova

Scotia [122,136]. Growing these crops for biomass in Nova Scotia would increase both the volume of biomass available and the diversity of biomass (sources/ suppliers), increasing the competitiveness of the local bioeconomy (Rod Badcock, personal communication). Inherently, this development can increase societal dependency on local Nova Scotian resources compared to imported, fossil fuel resources [9].

Predicting biomass yields through mathematical models is not a new practice as the foundation of agricultural modeling can be traced back to the 1950s [247]. Productivity models of both miscanthus [248,249] and switchgrass [144] have been created for other geographical areas. This research serves to identify the productivity of these dedicated grasses on underutilized lands in Nova Scotia to sustainably produce biomass for bioenergy and bioproducts, as there is a dearth of local data available. Quantifying the potential productivity of biomass crops in Nova Scotia could help address the need to sourcing sustainable biomass for the development of a local bioeconomy.

4.1.1 Objectives

The overarching objective of this research is to de-risk purpose-grown biomass feedstock in Nova Scotia to diversify both local biomass suppliers and sources and increase the competitiveness of the Nova Scotia bioeconomy. There are numerous end-uses for purpose-grown biomass, but the supply volume is crucial to identifying the best opportunities that could grow the bioeconomy. The objectives of this paper are:

1. To identify, through scientific literature, the climatic and edaphic conditions that have the greatest impact on biomass productivity of potential purpose-grown grasses, switchgrass and miscanthus in Nova Scotia;
2. To compile electronic databases of the climatic and edaphic conditions that are comparable to conditions in Nova Scotia, Canada;
3. To create predictive yield models for each crop based on the electronic databases.

The creation of these databases provides a central collection of pertinent purpose-grown biomass production data for Nova Scotia for easier accessibility in the future.

4.2 Materials and Methods

4.2.1 Database Creation

The creation of statistical models in this context involves collecting data from the literature. Google Scholar was used to conduct a search of peer-reviewed studies, using a combination of keywords including “switchgrass” or “miscanthus” and at least one of the following terms associated with biomass, including “biomass”, “bioenergy”, or “yield”. Data were also collected for local field trials through personal communication. The studies were sorted by crop, and the electronic databases for each crop were populated with pertinent data.

To create applicable databases and predictive yield models to Nova Scotia, the locations within each study was classified within the databases using plant hardiness zones [17,250]. Hardiness zones in Nova Scotia range from zones 5a through 7a (minimum temperatures of -28.9 to -15.0 ºC) [140,251]. While miscanthus natural populations have been reported up to 50ºN [252], overwintering success is variable in hardiness zones below zone 6 [252–254]. Switchgrass accessions that originate in lower hardiness zones (zones 2-5) typically have greater overwintering success than those originating from higher hardiness zones [255]. The inclusion of data reported from warmer plant hardiness zones inherently introduces more room for error as overwintering ability significantly impacts the productivity of these grasses.

4.2.2 Model Creation

The data collected in the databases are interpreted as predictor variables, as it is these variables that are manipulated to predict biomass yield. Based on biological relevance and end-use of the models, not all variables from the database can or should be incorporated. The end-use of these models is to predict the biomass productivity of switchgrass and miscanthus in Nova

Scotia as a low-cost, sustainable supply of biomass. Evidently, exogenous fertilization can increase biomass productivity and could be included as a predictor variable in the model. However, synthetic fertilization can be economically and environmentally costly [81,119], therefore, it is important to determine a baseline biomass productivity without the inclusion of exogenous inputs. Further, consistent availability of data throughout the literature is also important for inclusion into the predictive yield models: in the case of insufficient data for a predictor variable, it is preferable to exclude the variable from the model than to include it and reduce the model's predictive ability.

4.2.2.1 Model Format

A linear mixed-effects (LME) model was chosen for the predictive yield models to be able to incorporate factors that both directly and indirectly effect the predictive ability of biomass yield. The formulae of a linear mixed-effects model is:

$$y \sim x_1 \times x_2 + (1 \mid a/b))$$

where y is the response (predicted) variable, x_1 and x_2 are fixed effects, and a and b are random effects. Crawley [256] notes that fixed effects are informative factors that influence the mean of the response variable while random effects are less informative factors that influence the variance of the response variable. The random effects (a/b) are listed from left to right in declining order of spatial scale [256].

4.2.2.1.1 Fixed Effects

4.2.2.1.1.1 Precipitation

Biomass productivity as a function of precipitation is seemingly intuitive: plants need water to grow. However, there are many other sub-factors of precipitation that may be specified that impact growth and biomass productivity differently. Total growing season precipitation (mid-April through mid-October in Nova Scotia) was included in the model databases. Given the climatic conditions in Nova Scotia, it is assumed that a single annual harvest of switchgrass and miscanthus would be typical. Studies reporting multiple-cut harvests per year were excluded from the database.

Based on plant growth stage and time of year, the timing and sizing of major rainfall events could help or be the demise of switchgrass or miscanthus biomass productivity. Unfortunately, this specific information is often not accessible in the literature, but it is important to consider the potential of these events when establishing grass crops on marginal agricultural lands.

4.2.2.1.1.2 Growing Degree Days (GDD)

Temperature is another seemingly intuitive variable that directly relates to biomass productivity. Like precipitation, there are numerous sub-factors of temperature that may be specified for their differing effects on plant growth and biomass productivity. Maximum temperature during the growing season, minimum temperature during the off-season and timing of extreme events are all important for consideration. Temperature is an especially important consideration in more northern climates like Nova Scotia, because the ‘shoulder seasons’ of the growing season are typically longer, affecting growing time. When grasses are seeded in the spring, the cooler the air temperature (and cooler soil temperature), the longer it will take for the seeds to establish and germinate. When harvesting in late fall, a slower transition from cool to cold temperatures is ideal to increase biomass quality (moisture content, nutrient content) and induce nutrient translocation [257].

Growing degree days (GDD) is the sum of temperature degrees that contribute to plant growth based on a specified base temperature. The calculation for GDD is:

$$\mathrm{GDD} = \frac{(\mathrm{T_{MAX}} + \mathrm{T_{MIN}})}{2} - \mathrm{T_{BASE}}$$

where $\mathrm{T_{MAX}}$ is the maximum daily temperature (°C), $\mathrm{T_{MIN}}$ is the minimum daily temperature (°C) and $\mathrm{T_{BASE}}$ is the base temperature (°C), representing the lowest possible temperature where plant growth still occurs. $\mathrm{T_{BASE}}$ is variable between plant species and geographical locations. For this project, $\mathrm{T_{BASE}}$ = 5 °C was used to accumulate maximal GDD available as well as to maintain a non-species-specific value that can be applied across crops within this context.

Data for GDD calculations were found using historical data from the National Oceanic and Atmosphere Administration (NOAA) National Centers for Environmental Information, the NOAA Global Historical Climatology Network (GHCN), the European Centre for Medium-Range Weather Forecasts (ECMWF) and Agriculture & Agri-Food Canada. GDD were calculated from planting date to harvest date, where available in the literature. In subsequent years after planting, April 15 was used as the commencement of the growing season and October 15 was used as the end of the growing season, when no harvest date was specified in the literature [144]. April 15 was used to capture more positive GDD values for the shortened Nova Scotia growing season that would contribute to early crop growth.

4.2.2.1.1.3 Stand Year

The time from establishment of switchgrass and miscanthus to the time of maximum biomass yield is substantial (i.e., 3-5 years) [74,111,137,148]. Annual yields normally increase substantially during this period. As such, it is important to include the stand year (i.e. years from establishment) in the predictive yield models to differentiate that yields reported during maximum biomass yield are not compared equally to years prior to full stand development [62,132]. Data reported for the establishment year (year = 1) was not included in model development because the grasses are still in the establishment phase, and typically this biomass would not be collected for end-utilization.

4.2.2.1.2 Random Effects

4.2.2.1.2.1 Study and Location

Although the study itself does not impact biomass productivity, and it could simply be considered as the means to the data, it is important to include this variable as a random effect in the predictive yield model. The locations within studies have more biologically relevant impacts on biomass productivity, as precipitation and GDD, along with other climatic and edaphic conditions differ between geographic locations. Often in the literature, there are multiple annual yields reported for multiple locations within one study (i.e. harvest data was collected for four years at two locations within one study). If a separate study reported harvest data for two different years at the same location, it is expected that yields would be similar but study-specific conditions (planting density, stand management, etc.) would make a difference. This is known as a nested classification, where location is nested within study [258].

4.2.2.1.3 Other Variables Considered in Preliminary Modelling Efforts

Many predictor variables aside from the above-stated fixed and random variables were included in the databases and in preliminary model development. The analyses of models including variables with insufficient replication within the training dataset indicated no significant positive effects on predictability, and in some cases, negative effects on model predictability.

4.2.2.1.3.1 Soil Quality

Soils play many vital ecological roles, but of greatest significance in this context are the roles of soil as a growing medium for plants, as a regulator of water and a recycler of nutrients [138,259]. Soil quality is a major factor of agricultural production that can be divided into three sections: physical quality, chemical quality, and biological quality [260].

Rate of exogenous fertilization is important to include in the electronic databases but is not necessary for the creation of the predictive yield models, as mentioned at the outset (Section 4.2.2). Fertilization contributes to soil quality and can drastically improve crop yield. The exclusion of fertilization in current model development is intended to help identify a baseline biomass yield in Nova Scotia.

4.2.2.1.3.2 Soil Suitability

A soil suitability matrix was created for growing hemp (*Cannabis sativa* L.) in Nova Scotia [261] and was later adapted to create a soil suitability matrix for switchgrass production in Ontario, Canada [262]. Factors contributing to soil suitability in these matrices include crop-specific factors, such as soil texture and drainage, as well as management-specific factors, such as suitability for mechanized harvest (stoniness, slope, etc.) [261,262].

Soil drainage and texture were both included in the electronic databases for switchgrass and miscanthus but were not incorporated into the final versions of the predictive yield models for numerous reasons. These two factors are not independent of each other: there is a distinct correlation between soil texture and soil drainage, resulting in collinearity. Including correlated factors in a statistical model can potentially increase the standard error of the model coefficients and ultimately reduce the predictive ability of the model. Insufficient data was available from the studies for proper replication of soil texture and drainage in the creation of the predictive yield models. Finally, exclusion of soil texture and drainage from the yield models in this context comes down to common sense. The soil variability between locations in the database is vastly different, yet all studies reported switchgrass and miscanthus biomass yields, concluding that soil of any reasonable quality for growing plants should produce some yield of switchgrass and miscanthus.

4.2.2.2 Model Development

There were three steps involved in developing the predictive yield models. Step 1 was creating the databases and building the initial models based on the databases. The notation for continuous predictor variables were identified, followed by an iterative process for simplifying the models. Step 2 involved running the models with Nova Scotia data not previously included in the databases. Step 3 was updating and refining the existing models (developed in Step 1) by including the Nova Scotia data in the databases.

4.2.3 Statistical Analyses

To determine the notation of each variable within the model, the variable was plotted against the biomass yield and a LOESS (locally weighted smoothing) plot was created to visualize the relationship.

All statistical analyses were performed using R [103] and RStudio© [104]. The following packages were also used: agricolae [263], lme4 [264], nlme [265,266], boot [267,268], stats [103], performance [269].

4.3 Results

4.3.1 Switchgrass

4.3.1.1 Model Development

4.3.1.1.1 Database Creation and Model Building

Following extensive searches of the peer-reviewed literature, the switchgrass database contains 118 biomass yields from nineteen studies across twenty-seven different locations within the United States of America and Canada [270].

The first step of model creation is to visualize the relationship of each continuous predictor variable (growing season precipitation and GDD) with the predicted yield variable (yield). This visualization is used to identify the notation of each predictor variable within the LME model. Upon completion of a non-parametric smoothing, the LOESS plots show that growing season precipitation and the GDD data appear to have quadratic relationships with biomass yield (Figure 4.3.1, Figure 4.3.2)

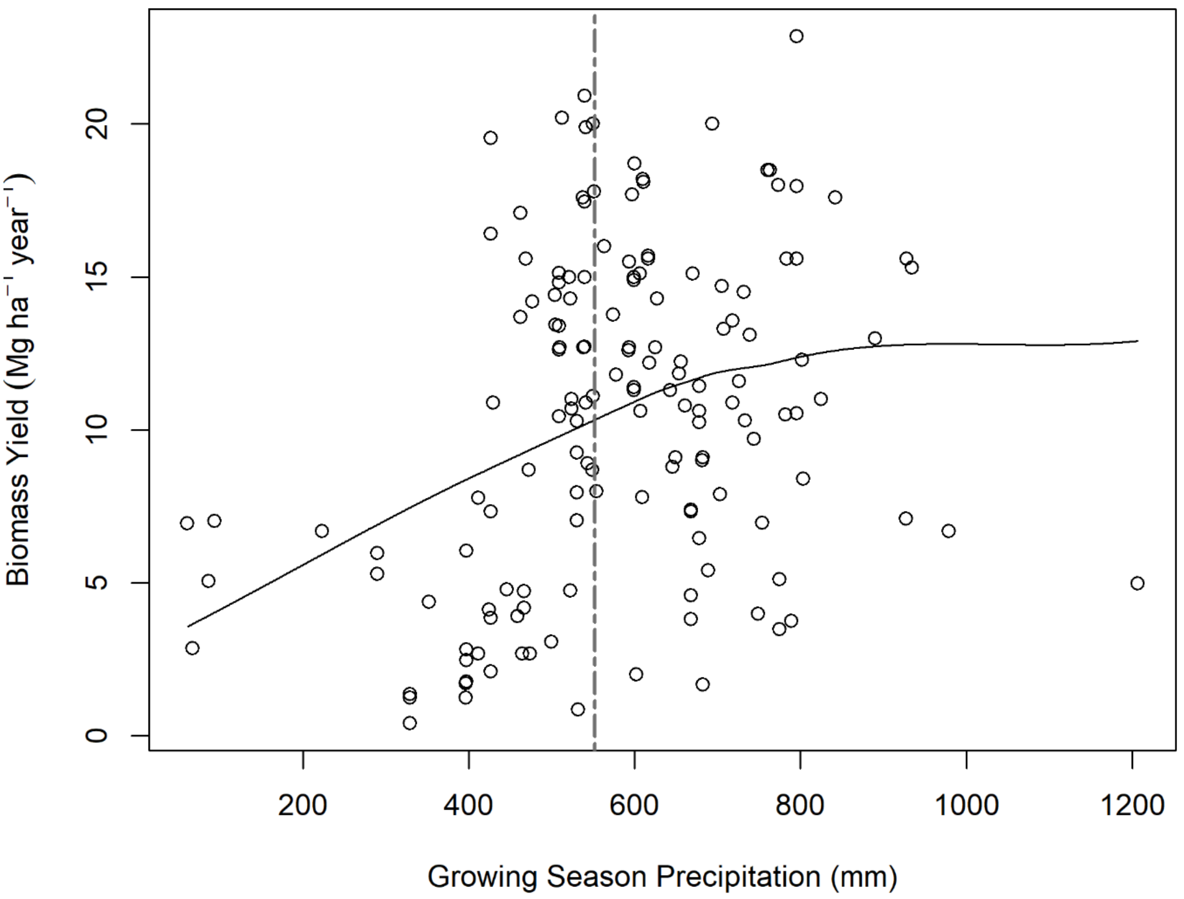

Figure 4.3.1 Scatterplot of switchgrass biomass yield (Mg ha^{-1} year^{-1}) against growing season precipitation (April through October, unless otherwise stated in the literature). Mean Nova Scotia growing season precipitation = 571 mm, represented by the vertical gray dashed line [97].

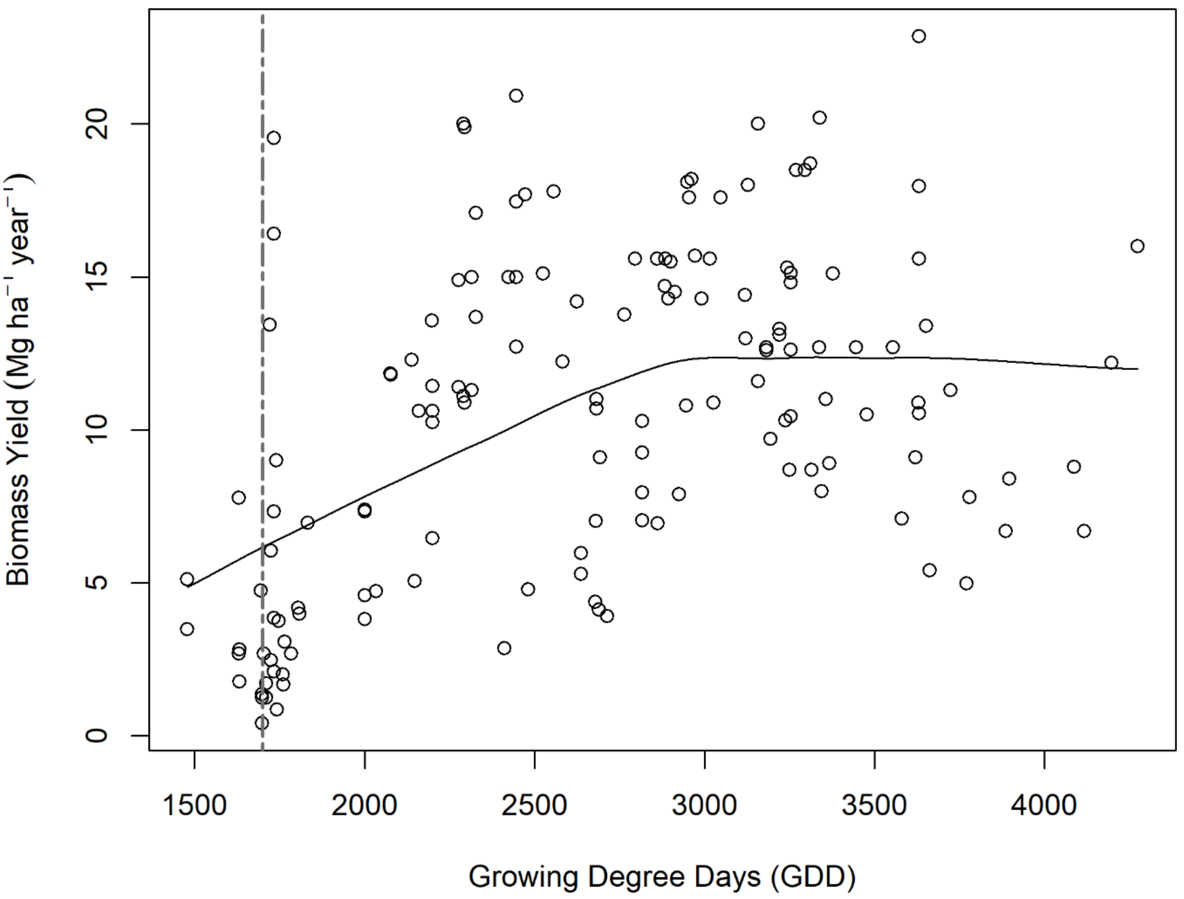

Figure 4.3.2 Scatterplot of switchgrass biomass yield (Mg ha^{-1} year^{-1}) against growing season growing degree days (GDD) (April through October, unless otherwise stated in the literature). Mean Nova Scotia growing season GDD = 1,700 mm, represented by the vertical gray dashed line [97].

After identifying the notation for the continuous predictor variables, all continuous data (growing season precipitation, growing season GDD and biomass yield) were standardized to Z-score values to ensure consistent orders of magnitude.

There were six predictive yield model iterations created for switchgrass (Table 4.3.1). The additional fixed effects/ predictor terms ‘Precipitation^2’ and ‘GDD^2’ were added to the model to address the loosely negative quadratic relationship identified between precipitation and biomass yield and GDD and biomass yield (Figure 4.3.1, Figure 4.3.2). The ‘Stand Year’ term was added to the predictive yield model so comparisons of biomass yield between stand years would be compared appropriately (Section 4.2.2.1.1.3).

Table 4.3.1 Comparison and naming conventions of switchgrass linear mixed-effects model iterations. The asterisk symbol (*) denotes the inclusion of interaction terms whereas the plus sign (+) denotes the exclusion of interaction terms [271].

Model Description	Model Number	Model Format
2020 Maximal	1	Yield ~ Precip × Precip^2 × GDD + (1 | Study/ Location)
2020 Simplified	2	Yield ~ Precip + Precip^2 + GDD + (1 | Study/ Location)
2022 Maximal	3	Yield ~ Precip × Precip^2 × GDD × GDD^2 + Stand Year + (1 | Study/ Location)
2022 Simplified	4	Yield ~ Precip + Precip^2 + GDD + GDD^2 + Stand Year + (1 | Study/ Location)
2022 Maximal 2.0	5	Yield ~ Precip × Precip^2 × GDD + Stand Year + (1 | Study/ Location)
2022 Simplified 2.0	6	Yield ~ Precip + Precip^2 + GDD + Stand Year + (1 | Study/ Location)

Precip = Precipitation

Table 4.3.2 List of predictor terms in the six model iterations for switchgrass, as described in Table 4.3.1. Models 1, 3 and 5 (maximal models) contain all predictor interaction terms.

Model Number	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Terms	Precip Precip^2 GDD Precip:Precip^2 Precip:GDD $\text{Precip}^2\text{:GDD}$ $\text{Precip:Precip}^2\text{:GDD}$	Precip Precip^2 GDD	Precip Precip^2 GDD GDD^2 Stand Year Precip:Precip^2 Precip:GDD $\text{Precip}^2\text{:GDD}$ Precip:GDD^2 $\text{Precip}^2\text{:GDD}^2$ GDD:GDD^2 $\text{Precip:Precip}^2\text{:GDD}$ $\text{Precip:Precip}^2\text{:GDD}^2$ Precip:GDD:GDD^2 $\text{Precip}^2\text{:GDD:GDD}^2$ $\text{Precip:Precip}^2\text{:GDD:GDD}^2$	Precip Precip^2 GDD GDD^2 Stand Year	Precip Precip^2 GDD Stand Year Precip:Precip^2 Precip:GDD $\text{Precip}^2\text{:GDD}$ $\text{Precip:Precip}^2\text{:GDD}$	Precip Precip^2 GDD Stand Year
Number of Predictor Terms	7	3	16	5	8	4

Precip = Precipitation

As per Table 4.3.2, the maximal switchgrass models (Models 1, 3 and 5) contain all predictor interaction terms. Through stepwise model simplification, highest-order interaction terms are removed first until the minimal adequate model is reached (Models 2, 4 and 6) [271].

When comparing the 2020 models the Akaike Information Criterion (AIC) value was lower for Model 2, favouring the simpler model (removal of all predictor interaction terms) (Table C-1).

The first model iterations from 2022 (Models 3 and 4) included updates to the 2020 model to include two additional predictor terms: GDD^2 and Stand Year. The comparison of Models 3 and 4 again favoured the simpler model, Model 4, without any predictor interaction terms (Table C-2). Finally, after further dissemination, the second iterations of the model from 2022 (Models 5 and 6) included the removal of the GDD^2 predictor term. The comparison of these two models favoured Model 6, the model without predictor interaction terms (Table C-3).

Of these models, the simplified models are favoured over the maximal models. When the simplified models are all compared, the indices of model performance are very similar (

Table 4.3.3) [269]. A ‘spiderweb’ plot is a visual representation of the comparison of model indices where the larger the ‘web’, the better the model performance [272]. Similar to the tabular comparison, Models 2 and 6 are very similar in their performance, but Model 4 appears to be the lesser performing of the three (Figure 4.3.3).

Table 4.3.3 Comparison of model performance indices between three iterations of the switchgrass predictive yield model.

Model	AIC	Marginal R^2	Conditional R^2	RMSE
2	283.3	0.110	0.686	0.471
4	284.8	0.149	0.679	0.469
6	283.1	0.147	0.682	0.467

AIC = Akaike Information Criterion; RMSE = Root Mean Square Error.

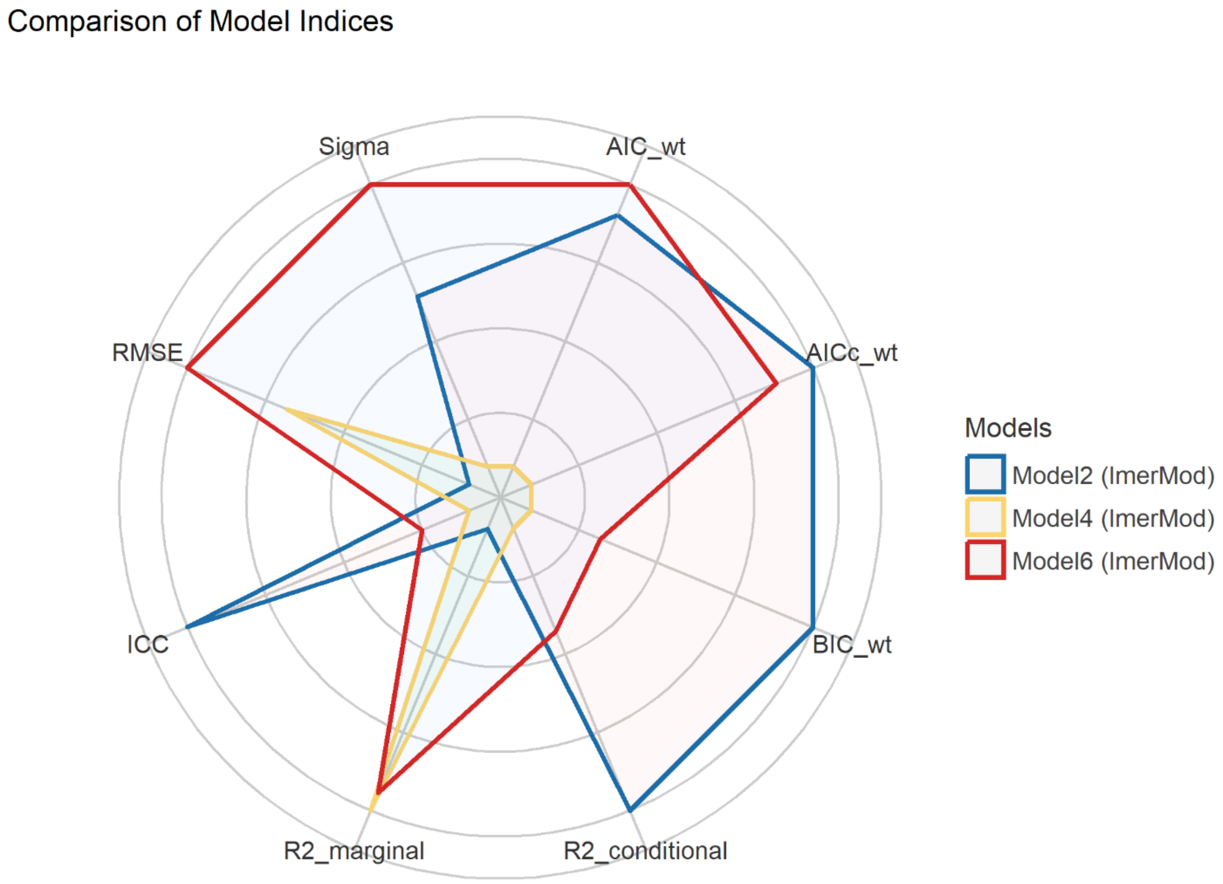

Figure 4.3.3 “Spiderweb” plot comparing the model indices of three iterations of the switchgrass predictive yield model.

The decision between Model 2 and Model 6 for the switchgrass predictive yield model comes down to the incorporation of the ‘Stand Year’ predictor term. Therefore, Model 6 was chosen for the switchgrass predictive yield model.

Table 4.3.4 Predictor term estimation (based on Z-score standardized data) for the switchgrass predictive yield model (Model 6 in Table 4.3.1).

Parameter	Estimate	Std. Error
Intercept	-0.22876	0.23620
Precipitation	0.16930	0.08262
Precipitation^2	-0.12443	0.04099
GDD	0.02400	0.11462
Stand Year	0.05785	0.04059
R^2	0.79	

4.3.1.1.2 Model Visualization

Switchgrass research conducted within this project (BioMass Canada Project 6), within previous Vessey research projects, and with other collaborators has been compiled to add 30 switchgrass biomass yields reported across five different locations within Nova Scotia to the database [270]. These data points were added to the original database to evaluate the predictive ability of the original model (Model 6) using the Nova Scotia data (Table C-4). The model was then updated to include these additional Nova Scotia data to refine the switchgrass model (Section 4.3.1.1.3).

4.3.1.1.3 Model Update

After running the model with the Nova Scotia data to evaluate the model’s predictive ability, the Nova Scotia data were incorporated into the existing model for refinement of the model. The incorporation of the Nova Scotia data increased the R^2 value of the 1:1 fit line (R^2 = 0.88) (Figure 4.3.4).

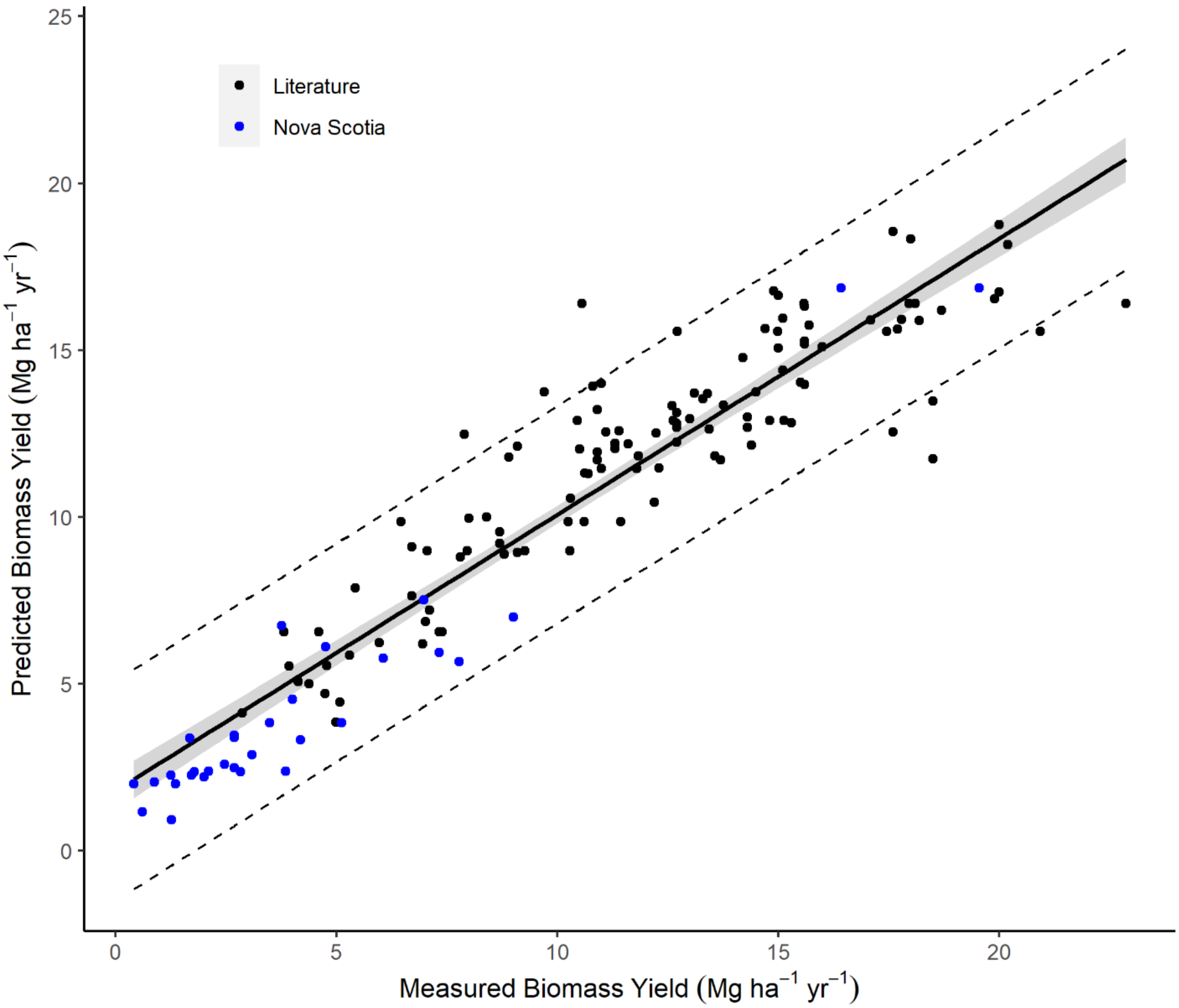

Figure 4.3.4 Predicted switchgrass biomass yield versus measured biomass yield calculated from the linear mixed-effects model. Data points based upon switchgrass yield studies conducted in Nova Scotia are indicated in blue and those from outside Nova Scotia are in black. The dashed lines represent the 95 % prediction interval, while the shaded area represents the 95 % confidence interval. The bold line represents the 1:1 fit (R^2 = 0.88) (n = 148).

4.3.2 Miscanthus

4.3.2.1 Model Development

4.3.2.1.1 Database Creation and Model Building

Following extensive searches of the peer-reviewed literature, the miscanthus database contains 39 biomass yields from six studies across fourteen different locations within Europe, the United States of America and Canada [270,273].

The relationships between miscanthus biomass yield and growing season precipitation and GDD are both indicative of a linear relationship (Figure 4.3.5, Figure 4.3.6). The Z-score (standardized score) values for precipitation, GDD and yield data were utilized throughout model creation to ensure consistent orders of magnitude. The ‘Stand Year’ term was added to the predictive yield model so comparisons of biomass yield between stand years would be compared appropriately (Section 4.2.2.1.1.3).

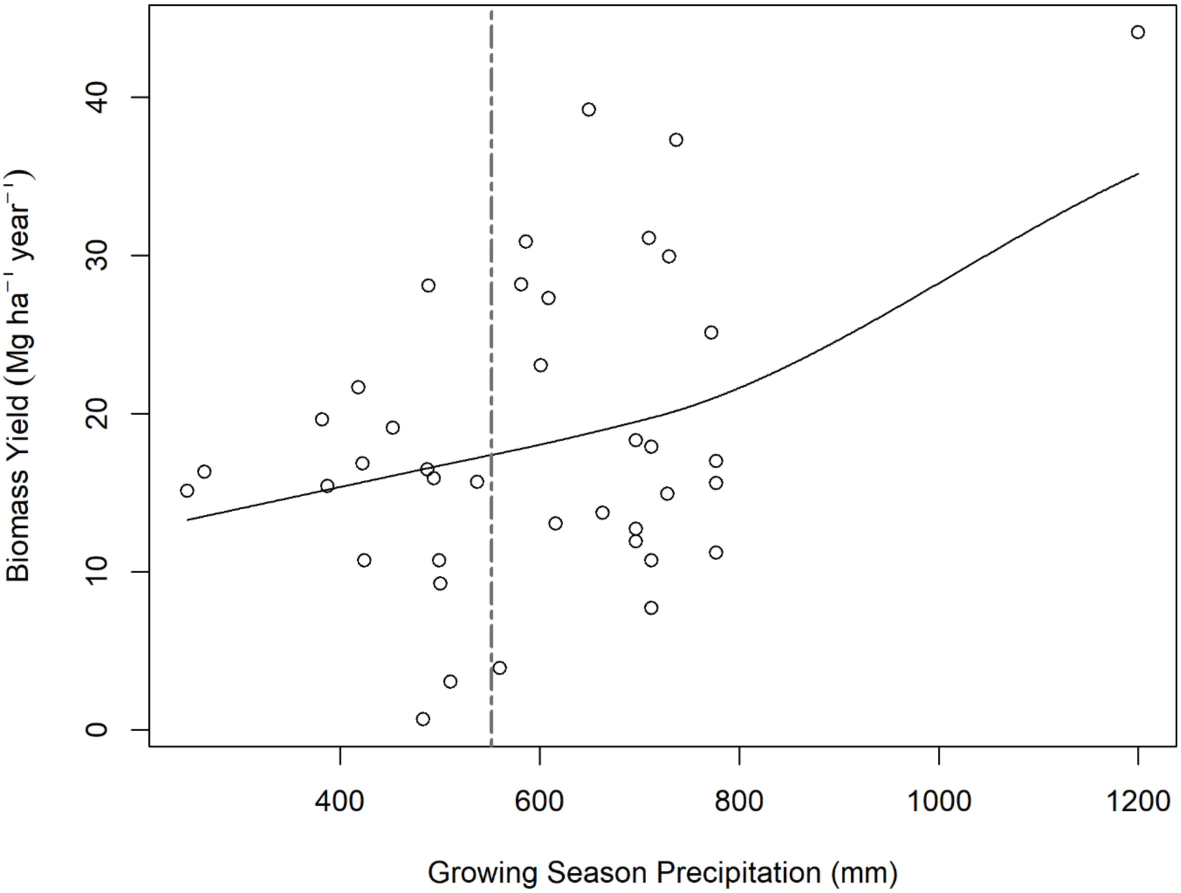

Figure 4.3.5 Scatterplot of miscanthus biomass yield (Mg ha^{-1} year^{-1}) against growing season (mid-April through mid-October) precipitation (mm) overlaid with a LOESS regression curve. Mean Nova Scotia growing season precipitation = 552 mm, represented by the vertical dashed gray line [97].

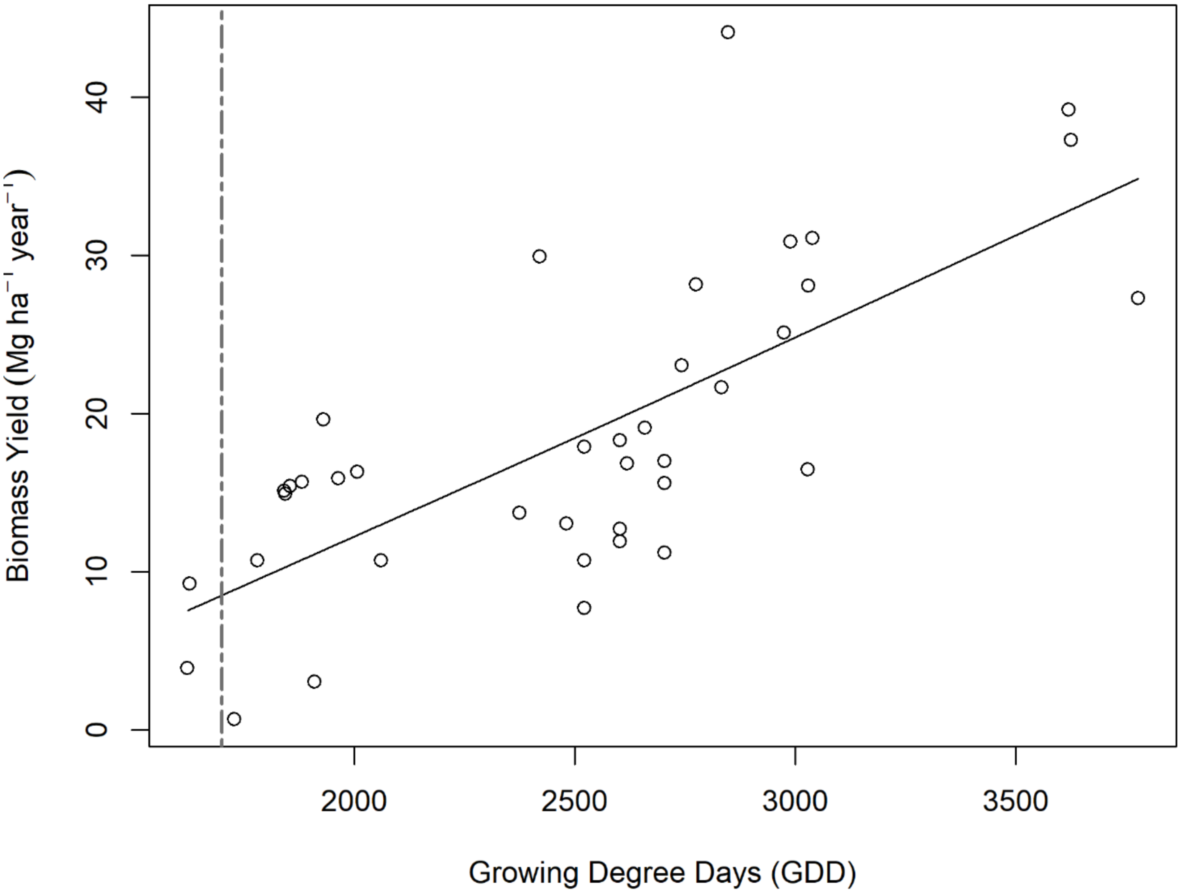

Figure 4.3.6 Scatterplot of miscanthus biomass yield (Mg ha^{-1} year^{-1}) against growing degree days (mid-April through mid-October) (GDD) overlaid with a LOESS regression curve. Mean Nova Scotia GDD = 1,700, represented by the vertical dashed gray line [97].

Based on the AIC values between the maximal and minimal adequate models, in addition to the minimal adequate model suffering from singularity, the maximal miscanthus model was selected for further utilization in model development (Table C-5).

Table 4.3.5 Estimates of model parameters (based on Z-score standardized data) as defined for the maximal miscanthus model. The asterisk symbol (*) denotes the inclusion of Precipitation, GDD and the interaction whereas the plus sign (+) denotes the inclusion of only Precipitation and GDD [271].

Maximal miscanthus model: Yield ~ Precipitation * GDD + Stand Year + (1 | Study/ Location)		
Parameter	Estimate	Std. Error
Intercept	-0.65508	0.33747
Precipitation	0.28494	0.09422
GDD	0.55993	0.11464
Stand Year	0.13786	0.06082
Precipitation:GDD	0.27922	0.10458
R^2	0.9	

4.3.2.1.2 Model Visualization

Miscanthus research conducted within this project (BioMass Canada Project 6) and with other collaborators has been compiled to add 15 miscanthus biomass yields reported across five different locations within Nova Scotia to the database [273]. These data points were added to the original miscanthus database to evaluate the predictive ability of the maximal miscanthus model using the Nova Scotia data (Table C-6). The model was then updated to include these additional Nova Scotia data to refine the miscanthus model (Section 4.3.2.1.3).

4.3.2.1.3 Model Update

After running the model with the Nova Scotia data to evaluate the model's predictive ability, the Nova Scotia data was incorporated into the existing model for refinement. The incorporation of the Nova Scotia data increased the R^2 value of the 1:1 fit line ($R^2 = 0.91$) (Figure 4.3.7).

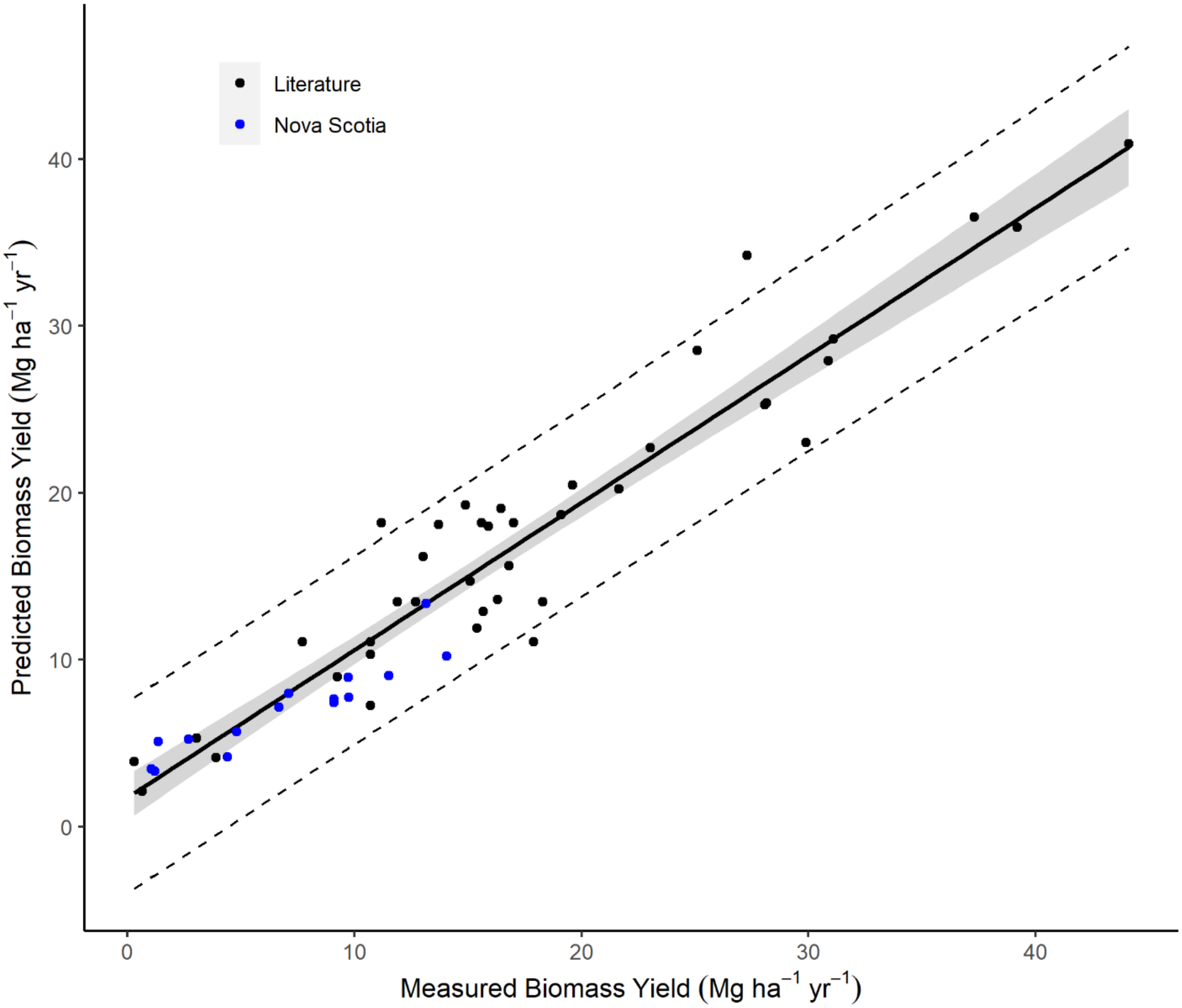

Figure 4.3.7 Predicted miscanthus biomass yield versus measured biomass yield calculated from the linear mixed-effects model. Data points based upon miscanthus yield studies conducted in Nova Scotia are indicated in blue and those from outside Nova Scotia are in black. The dashed lines represent the 95 % prediction interval, while the shaded area represents the 95 % confidence interval. The bold line represents the 1:1 fit (R^2 = 0.91) (n = 54).

4.4 Discussion

In this chapter, predictive models were developed for switchgrass and miscanthus from peer reviewed literature to quantify biomass productivity of these crops on underutilized lands in Nova Scotia. To create the most comparable datasets to Nova Scotia, publications from plant hardiness zones the same as or colder than Nova Scotia were included.

It is important to be considerate of limitations to descriptive/statistical models. Although the predictive ability of both models is high, the models are inherently operating on numerous assumptions, or unnamed/random effects [274].

4.4.1 Stand Year

One of the characteristics of perennial grasses that have been identified as important for sustainability is their long productive lifespans after initial planting. Switchgrass and miscanthus establishment are long, taking upwards of 4 years post-planting to reach full potential biomass productivity [67,68,275]. Once a stand reaches the full potential productivity, switchgrass can have an economic lifespan up to 15 years while miscanthus can have an economic lifespan between 15 and 20 years [275,276]. In this paper, stand year was identified in each model as a fixed effect so peak biomass yields were not mistakenly compared with establishment biomass yields. Further, the planting year was not included in the analysis (Section 4.2.2.1.1.3). After these details were built into the model, there are other aspects of stand year that should be considered. First, as explained in the context of soil suitability (Section 4.2.2.1.3.2), adequate replication is crucial to improve the predictability of a model. Although stand year is considered a continuous variable, a substantial number of measured yield observations is needed for each level of stand year to fulfill the predictive ability of the model. In this study, there were minimal measured miscanthus yields reported for early and later stand years, which potentially impacts the predictive ability of the model for those years. The comparison of the measured yield and the predicted yield of Nova Scotia miscanthus data illustrates the increased accuracy of the model in stand years with more measured yield observations (Table 4.4.1).

Table 4.4.1 Miscanthus measured yields from Nappan and Bible Hill, Nova Scotia across three stand years compared to the predicted yields from the model.

	Nappan, NS		Bible Hill, NS	
Stand Year	Measured Yield (Mg ha^{-1})	Predicted Yield (Mg ha^{-1})	Measured Yield (Mg ha^{-1})	Predicted Yield (Mg ha^{-1})
2	2.70	5.24	1.36	5.09
3	9.09	7.42	9.09	7.64
4	9.73	8.94	11.51	9.06

Another aspect of stand year that is not considered in the miscanthus model is the miscanthus planting protocol. The establishment stage of miscanthus referenced in this study and most often discussed in the literature is based on rhizome planting. As detailed in Chapter 2 the miscanthus planted at the field sites in this research were planted using *in vitro* propagated plantlets [188]. Long term miscanthus yields are not significantly affected by propagation method [277], but differences in survival and early above-ground biomass productivity favour plantlets over rhizomes [278]. This could explain the model's underestimation of the miscanthus yields for Nova Scotia field sites. Sufficient data collection with measured yield observations from both planting protocols could warrant adding another fixed effect to the model.

4.4.2 Soil Suitability

As previously mentioned (Section 4.2.2.1.3.2), the logic for excluding soil suitability from the predictive models was most notably due to insufficiency of data to fully satisfy all levels of the soil suitability matrix [262]. Additionally, the basis of this model is to quantify potential productivity given certain fixed effects, not the lack of potential productivity. Unfortunately, from a model development standpoint, it is too difficult to incorporate soil suitability in the models themselves, but this should be a major consideration alongside model use (in conjunction with good judgment) in real-time. For example, the standalone models can predict the biomass yields of switchgrass or miscanthus regardless of soil suitability given a value for precipitation and GDD. The switchgrass grown at the Bible Hill field site is a perfect example of an imperfect model. The measured switchgrass yield values for Bible Hill are not that dissimilar from the predicted yield values on paper (Table 4.4.2) but witnessing the switchgrass plots in person tells a whole other story of the establishment and productivity of switchgrass at this field site. As was mentioned in Chapter 2, the immense weed pressure during establishment likely stalled growth in comparison to other sites (Figure 4.4.1, Figure 4.4.2). There was some successful establishment and productivity of switchgrass in Bible Hill, but over the four-year course of the field research in this study, the switchgrass productivity paled in comparison to other crops at this field site and to switchgrass plots at other field sites (Chapter 3, Figures 3.4.1 and 3.4.2). Based on the sampling method, there was likely a lot of non-switchgrass biomass in the biomass samples used to calculate yield.

Table 4.4.2 Switchgrass measured yields from Nappan and Bible Hill, Nova Scotia across three stand years compared to the predicted yields from the model.

	Nappan, NS		Bible Hill, NS	
Stand Year	Measured Yield (Mg ha^{-1})	Predicted Yield (Mg ha^{-1})	Measured Yield (Mg ha^{-1})	Predicted Yield (Mg ha^{-1})
2	1.26	1.03	0.60	1.17
3	1.68	3.40	2.00	2.21
4	3.08	2.91	0.87	2.05

Figure 4.4.1 Drone picture of the Bible Hill field site in October 2022. White squares indicate switchgrass plots [279].

Figure 4.4.2 Drone picture of the Nappan field site in October 2022. White squares indicate switchgrass plots [280].

4.5 Conclusion

There were three objectives of this research: 1) to identify, through scientific literature, the climatic and edaphic conditions that have the greatest impact on biomass productivity of potential purpose-grown grasses, switchgrass and miscanthus in Nova Scotia; 2) to compile an electronic database of the climatic and edaphic conditions that are comparable to conditions in Nova Scotia, Canada and 3) to create predictive yield models for each crop based on the electronic database. The results of this research show that growing season precipitation and GDD are very informative in terms of predicting switchgrass and miscanthus biomass yield with a predictive linear mixed-effects model. Both models developed in this research account for a large portion of the variability in the data (80 % and 91 % for switchgrass and miscanthus, respectively) but also have additional aspects of biomass production to consider, including soil suitability and miscanthus planting protocol.

Switchgrass and miscanthus have a lengthy history of production for bioenergy in Canada and should be explored on a greater scale in Nova Scotia. The incorporation of these predictive yield models into an interactive mapping tool could provide all stakeholders with information to progress the local bioeconomy.

Chapter 5 Predictive yield modelling of hybrid-poplar and willow in Nova Scotia.

5.1 Introduction

Global deforestation, the permanent conversion of forested land to other land uses, is happening at an alarming rate, approximately 10 million hectares per year, with Canada being responsible for the deforestation of 37,500 ha per year [281,282]. The main reasons for deforestation are to utilize forest resources and to utilize the forested land for other purposes [282]. Deforestation is detrimental to numerous facets of the environment, including biodiversity, soil dynamics (soil carbon sequestration and erosion) and GHG emissions (the annual anthropogenic GHG emissions associated with global deforestation range from 12-25 %) [283–285]. To meet the growing global demand for woody biomass without a) direct or indirect land use change to forestry land or b) disrupting current markets for woody biomass, short rotation woody crops (SRWC) grown on marginal agricultural lands could be a sustainable solution [284].

Research on fast-growing/short rotation tree plantations (SRWC) in Canada is extensive, dating back to the 1920's, however the implementation of operational-scale plantations in this country have been minimal [286–288]. Stakeholders have shown reluctance with adoption of purpose-grown trees for bioenergy and bioproducts for several reasons, including uncertainty surrounding the economics of SRWC production and the unreliable biomass market, as well as the long-term commitment associated with SRWC production with limited practical experience [284,289,290]. From the biorefinery/investment perspective, the largest obstacle to commercialization is access to a consistent, low-cost source of biomass [98,291].

As mentioned in Chapter 4, the volume of agricultural and forestry residues available annually in Canada is roughly equivalent to the volume currently utilized for bioproducts [145]. The growing societal and environmental demand for renewable energy requires a sustainable supply of biomass above and beyond that currently supplied by agricultural and forestry residues, creating market space for SRWC production. It has been suggested in the literature that available agricultural land (converted arable, abandoned or marginal) in Canada feasible for SRWC production is in the range of 5.3 million to 30 million hectares [292–294], with subsequent productivity estimates ranging from 9 to 433 million Mg of biomass per year. Although it may be considered a ‘conservative’ estimate, it is a hugely wide range and with minimal ‘proof-of-concept’ throughout the country, the estimate does not hold much weight with potential producers. The variable local conditions (climatic, edaphic, and economic) are major factors that determine the efficacy of a SRWC system, and that efficacy does not necessarily correlate across localities [295].

This research serves to identify the productivity of coppiced hybrid-poplar and willow on marginal lands in Nova Scotia to sustainably produce biomass for bioenergy and bioproducts. Quantifying the potential productivity of these crops in Nova Scotia could help address the lack of data available regarding biomass productivity in the region. Predicting biomass yields of SRWC in Nova Scotia could inform producers, investors, and the government of the yield potential of these crops in local environments, thus enabling the further development of the supply chain.

5.1.1 Objectives

The diversification of purpose-grown biomass in Nova Scotia is crucial to increase the competitiveness of the local bioeconomy. Similarly to Chapter 4, the objectives of this paper are:

1. To compile electronic databases, through the scientific literature for hybrid-poplar and willow, of the climatic and edaphic conditions that are comparable to conditions in Nova Scotia, Canada;
2. To create predictive yield models for each crop based on the electronic databases.

The creation of these databases provides a central collection of pertinent purpose-grown biomass production data for Nova Scotia for easier accessibility in the future.

5.2 Materials and Methods

5.2.1 Database Creation

A database was created for each crop from the literature, following the methodology outlined in Chapter 4 [145]. Google Scholar was used to conduct a search of peer-reviewed studies using a combination of keywords including “hybrid-poplar”, “coppiced willow” or “short rotation woody crops” and at least one of the following terms associated with biomass, including “biomass”, “bioenergy”, or “yield” [145]. Only studies with study locations located within the Nova Scotia plant hardiness zones (5a through 7a) or colder were included in the databases [140,145,251].

5.2.2 Model Creation

As in Chapter 4, the data collected in the databases are interpreted as predictor variables that can be manipulated to predict biomass yield [145]. The intention of these models is to predict the biomass productivity of hybrid-poplar and willow under a coppice management regime in Nova Scotia.

5.2.2.1 Model Format

The format for the hybrid-poplar and willow predictive yield models is the same LME format as outlined for the switchgrass and miscanthus models in Chapter 4 [145]. As the number of studies to fit the criteria of this research (coppiced hybrid-poplar and willow systems in plant hardiness zones below 7) is fairly low, the number of predictor variables was kept simple based on predictive ability of those variables and availability of data.

5.2.2.1.1 Fixed Effects

5.2.2.1.1.1 Precipitation

Cumulative water availability, either naturally through precipitation or mechanically through irrigation, is a known limiting factor for hybrid-poplar and willow establishment and biomass productivity [213,216,227,296]. Where this research is focusing on low-input management, the relationship between precipitation and biomass yield are important as this is the only source of water for the plants. Timing of rainfall events (or lack thereof) with respect to the plant growth cycle are relevant for predicting biomass productivity [297,298], these details are not typically specified across studies. Total growing season precipitation (mid-April through mid-October in Nova Scotia) was included in the model databases [145].

5.2.2.1.1.2 Growing Degree Days (GDD)

Numerous aspects of temperature are directly related to biomass productivity in SRWC. During establishment and early growth of SRWC, soil temperature is important to consider for the potential of frost heaving. Frost heaving is the process of soil water freezing, increasing the volume of solid and liquid water in the soil, creating an upward movement of the uppermost soil layer [299–301]. This process can push immature tree seedlings or cuttings completely out of the soil, subjecting them to at minimum, significant frost damage if not death [300,301]. Typically, given the proper water availability, higher air temperatures (GDD) throughout the growing season leads to greater biomass productivity [297].

GDD data was collected in the same way outlined in Chapter 4, using a base temperature of 5 ºC and limiting the growing season from mid-April to mid-October [145].

5.2.2.1.1.3 Rotation

Rotation is the number of years or growing seasons between harvests. In a coppice system, the rotation length can be anywhere between 2 to 6 years, depending on the species.

Biomass yields of hybrid-poplar and willow increase with successive rotations [298,302]. This is the only predictor variable that differs between the grass models [145] and the tree models, due to the coppicing system. It is important to include rotation in the predictive yield models to differentiate biomass yield attributed to a single growing season versus yield attributed to multiple growing seasons.

5.2.2.1.1.4 Stand Year

Stand year is an even more specific refinement of the rotation cycle for SRWC. However, because the length of rotation cycles can differ between studies, it is important to identify the length of growing season(s) prior to the harvest. Data reported from the establishment year (year =1) was not included in model development because year 1 biomass is only a function of the coppicing of the trees in preparation for the first rotation.

5.2.2.1.2 Random Effects

5.2.2.1.2.1 Location

In the grass models in Chapter 4, geographic location (‘Location’) was nested within ‘Study’ and represented the total random effects of the models [145]. ‘Study’ was included as a random effect to account for differing study-specific conditions at the same location [145], however, with smaller training datasets for hybrid-poplar and willow, it is less likely that there will be multiple geographic locations reported across different studies. Therefore, the random effects structure in the tree models does not include ‘Study’, as this could lead to overfitting the predictive yield model. ‘Location’ effects should be included in the predictive yield model, as climatic and edaphic characteristics of a location can have significant impacts on biomass yield.

5.2.2.2 Model Development

After developing predictive yield models for switchgrass and miscanthus in Nova Scotia, the protocol for model development in this research is straightforward [145]. The initial models were built around databases comprised of data pulled from peer-reviewed studies, followed by an iterative process for simplifying the model was completed. The initial models were used to predict biomass yields of Nova Scotia data not previously included in the databases. Finally, the initial models were updated by incorporating the Nova Scotia data into the databases [145].

5.2.3 Statistical Analyses

Statistical analyses were performed using R [103] and RStudio [104], and numerous packages outlined in Chapter 4 [145].

5.3 Results

5.3.1 Hybrid-poplar

5.3.1.1 Model Development

5.3.1.1.1 Database Creation and Model Building

Following extensive searches of the peer-reviewed literature, the hybrid-poplar database contains 24 biomass yields from six studies across ten unique locations [303].

Model building in this study followed the same process as outlined in Chapter 4 [145]. The relationships between each continuous predictor variable (growing season precipitation and GDD) and the predicted variable (yield) were visualized to identify the most appropriate notation for each variable in the predictive yield model. This visualization showed that growing season precipitation and the GDD data appear to have linear relationships with biomass yield (Figure 5.3.1, Figure 5.3.2).

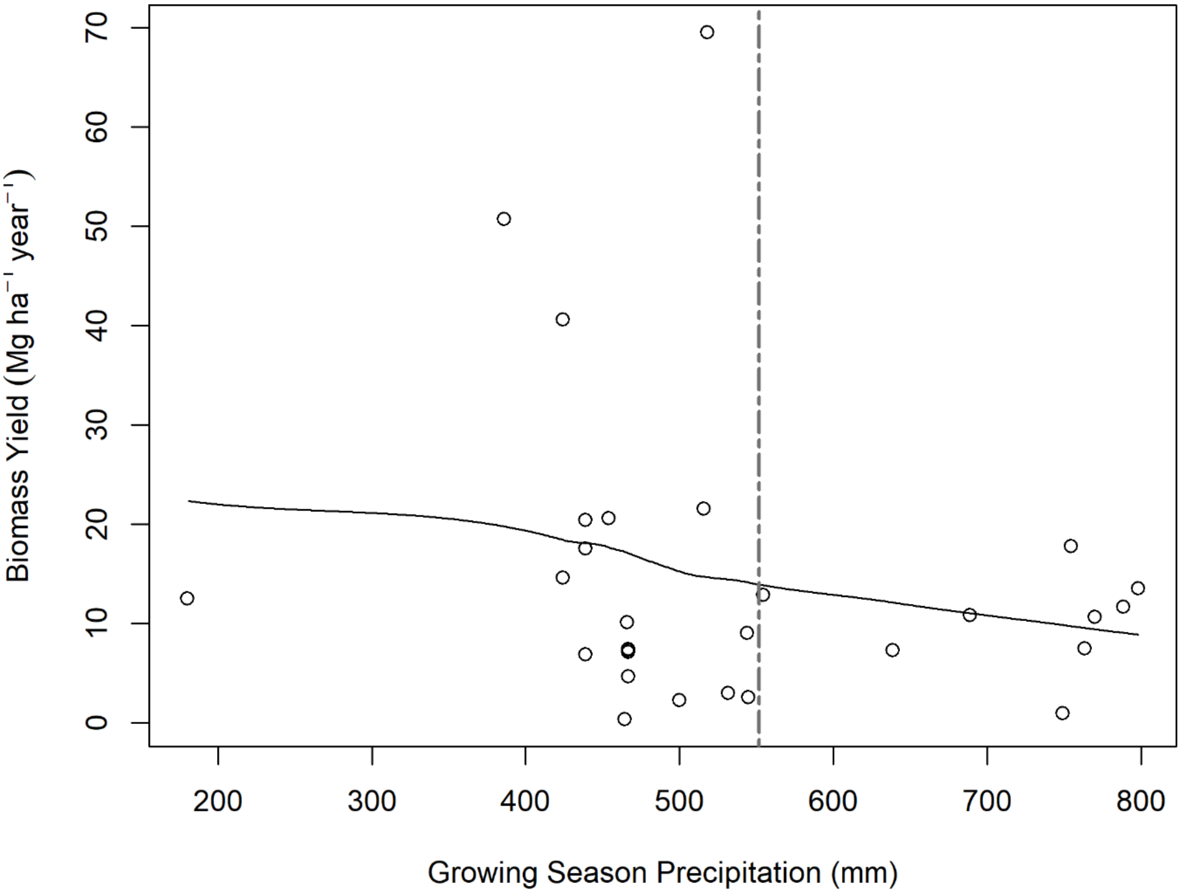

Figure 5.3.1 Scatterplot of hybrid-poplar biomass yield (Mg ha^{-1} year^{-1}) against growing season precipitation (April through October, unless otherwise stated in the literature). Mean Nova Scotia growing season precipitation = 571 mm, represented by the vertical gray dashed line [97].

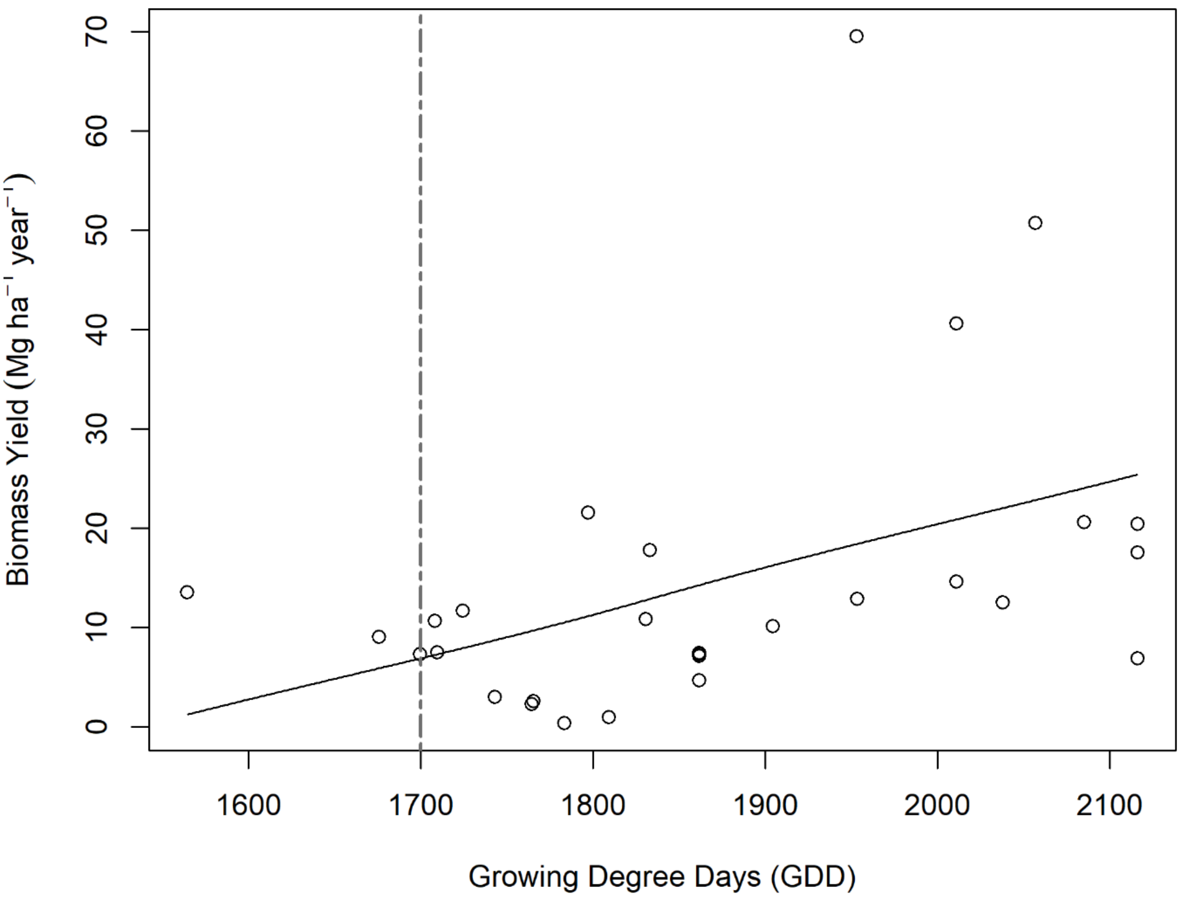

Figure 5.3.2 Scatterplot of hybrid-poplar biomass yield (Mg ha^{-1} year^{-1}) against growing season growing degree days (GDD) (April through October, unless otherwise stated in the literature). Mean Nova Scotia growing season GDD = 1,700 represented by the vertical gray dashed line [97].

As per Chapter 4, after identifying the notation for the continuous predictor variables, all continuous data (growing season precipitation, growing season GDD and biomass yield) were standardized to Z-score values to ensure consistent orders of magnitude [145].

The predictor terms within the hybrid-poplar yield model are based upon the iterative process outlined in Chapter 4 [145,271]. Model 2 indicates the removal of the interaction term between 'Precipitation' and 'GDD' from Model 1 (Table 5.3.1) [271].

Table 5.3.1 List of predictor terms in the maximal hybrid-poplar model (Model 1) and Model 2, a simplified iteration in which the interaction term was deleted. The asterisk symbol (*) denotes the inclusion of Precipitation, GDD and the interaction whereas the plus sign (+) denotes the inclusion of only Precipitation and GDD [271].

Model 1: Yield ~ Precipitation * GDD + Rotation + Stand Year + 1 | Location	Model 2: Yield ~ Precipitation + GDD + Rotation + Stand Year +1 | Location
Precipitation	Precipitation
GDD	GDD
Rotation	Rotation
Stand Year	Stand Year
Precipitation:GDD	

The AIC value decreased from Model 1 to Model 2, penalizing Model 1 for the interaction term and preferring the simplicity of Model 2 (Table 5.3.2) [271]. Model 2 was selected for further utilization (Table 5.3.3).

Table 5.3.2 Comparison of model performance indices between two iterations of the hybrid-poplar predictive yield model.

Model Format	Random Effects	AIC	Marg. R^2	Cond. R^2	RMSE
Model 1: Yield ~ Precipitation × GDD + Rotation + Stand Year	Location	85.704	0.077	0.545	0.589
Model 2: Yield ~ Precipitation + GDD + Rotation + Stand Year	Location	82.795	0.062	0.513	0.605

Cond. R^2 = Conditional R^2; Marg. R^2 = Marginal R^2; AIC = Akaike Information Criterion; RMSE = Root Mean Square Error.

Table 5.3.3 Predictor term estimation (based on Z-score standardized data) for the hybrid-poplar predictive yield model (Model 2 in Table 5.3.2).

Predictor Term	Estimate	Std. Error
Intercept	-0.21949	0.52080
Precipitation	0.23921	0.31561
GDD	0.32840	0.32999
Rotation	-0.06679	0.13262
Stand Year	0.05523	0.09199
R^2	0.63	

5.3.1.1.2 Model Visualization

Hybrid-poplar research conducted within this project (BioMass Canada Project 6) has been compiled to add 5 biomass yields across five different locations within Nova Scotia to the database. These data points were used as ‘new data’ to evaluate the predictive ability of the hybrid-poplar model (Model 2) using Nova Scotian biomass yields (Table D-1).

5.3.1.1.3 Model Update

After running the model with the Nova Scotia data, the Nova Scotia data were incorporated into Model 2 for model refinement. The incorporation of the Nova Scotia data increased the R^2 value of the 1:1 fit line ($R^2 = 0.68$) (Figure 5.3.3).

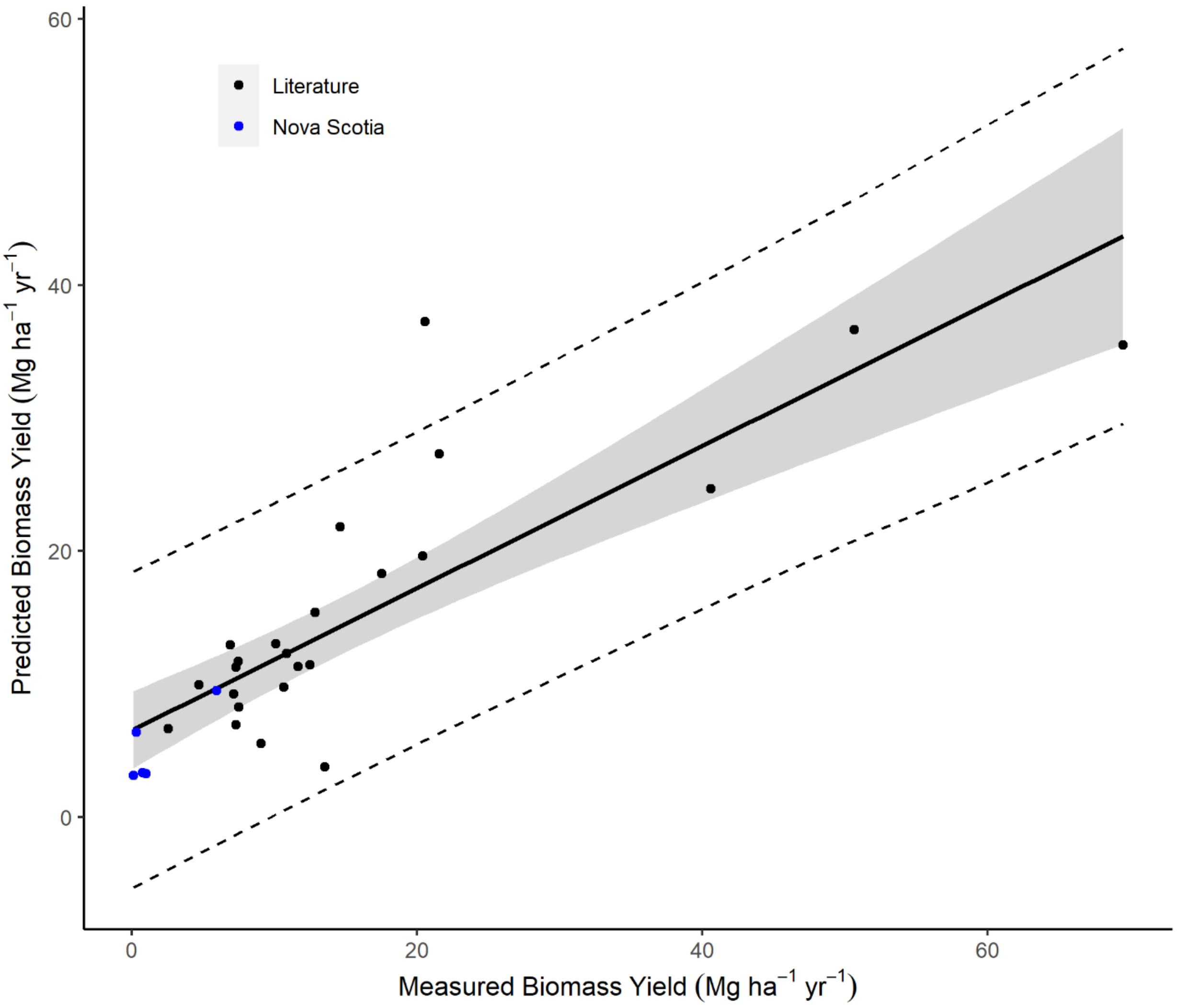

Figure 5.3.3 Predicted hybrid-poplar biomass yield versus measured biomass yield calculated from the linear mixed-effects model. Blue circles represent hybrid-poplar yields from Nova Scotia based studies and black circles represent hybrid-poplar yields from the peer-reviewed literature. The dashed lines represent the 95 % prediction interval, while the shaded area represents the 95 % confidence interval. The bold line represents the 1:1 fit ($R^2 = 0.68$) (n = 29).

5.3.2 Willow

5.3.2.1 Model Development

5.3.2.1.1 Database Creation and Model Building

Following extensive searches of the peer-reviewed literature, the willow database contains 36 biomass yields from nine studies across sixteen unique locations [304].

As per Section 5.3.5.1.5, upon completion of a non-parametric smoothing, LOESS (locally weighted smoothing), the growing season precipitation and the GDD data appear to have linear relationships with biomass yield (Figure 5.3.4, Figure 5.3.5).

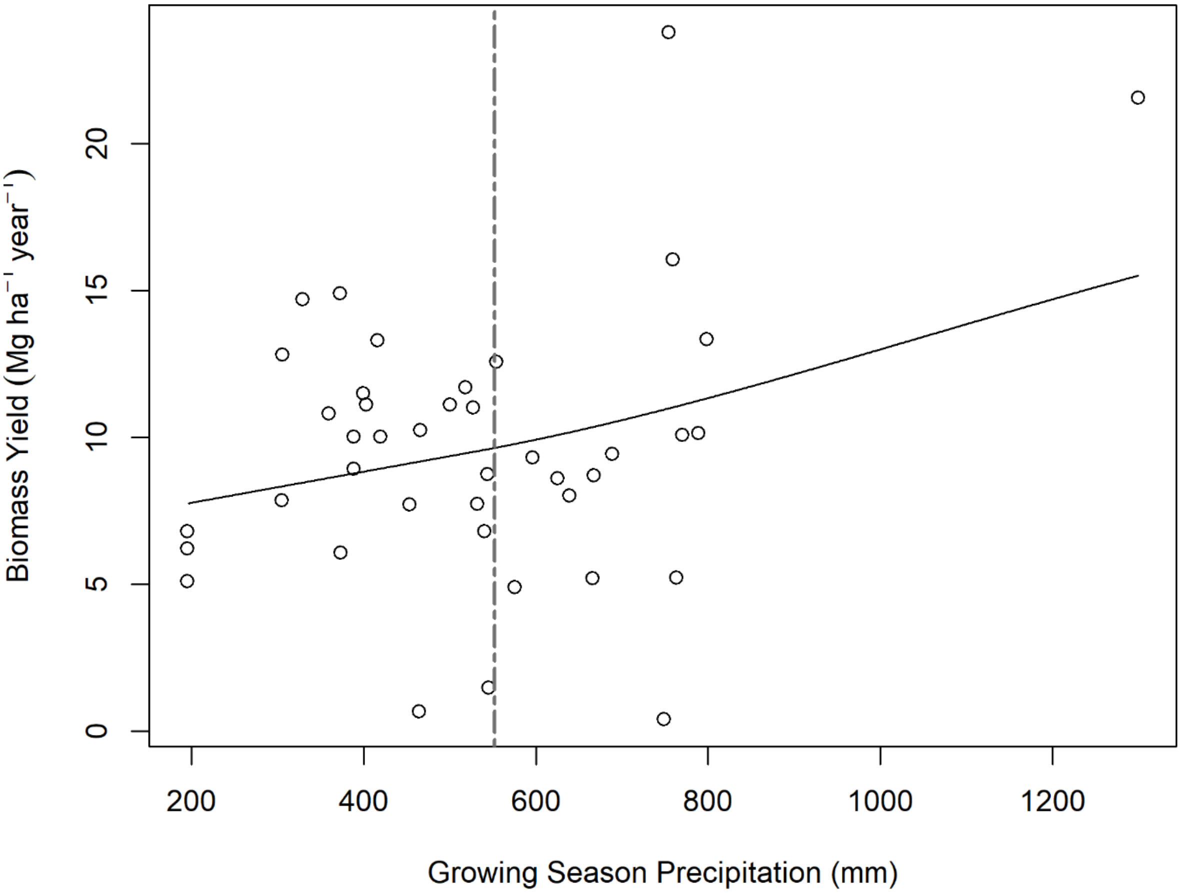

Figure 5.3.4 Scatterplot of willow biomass yield (Mg ha^{-1} year^{-1}) against growing season precipitation (April through October, unless otherwise stated in the literature). Mean Nova Scotia growing season precipitation = 571 mm, represented by the vertical gray dashed line [97].

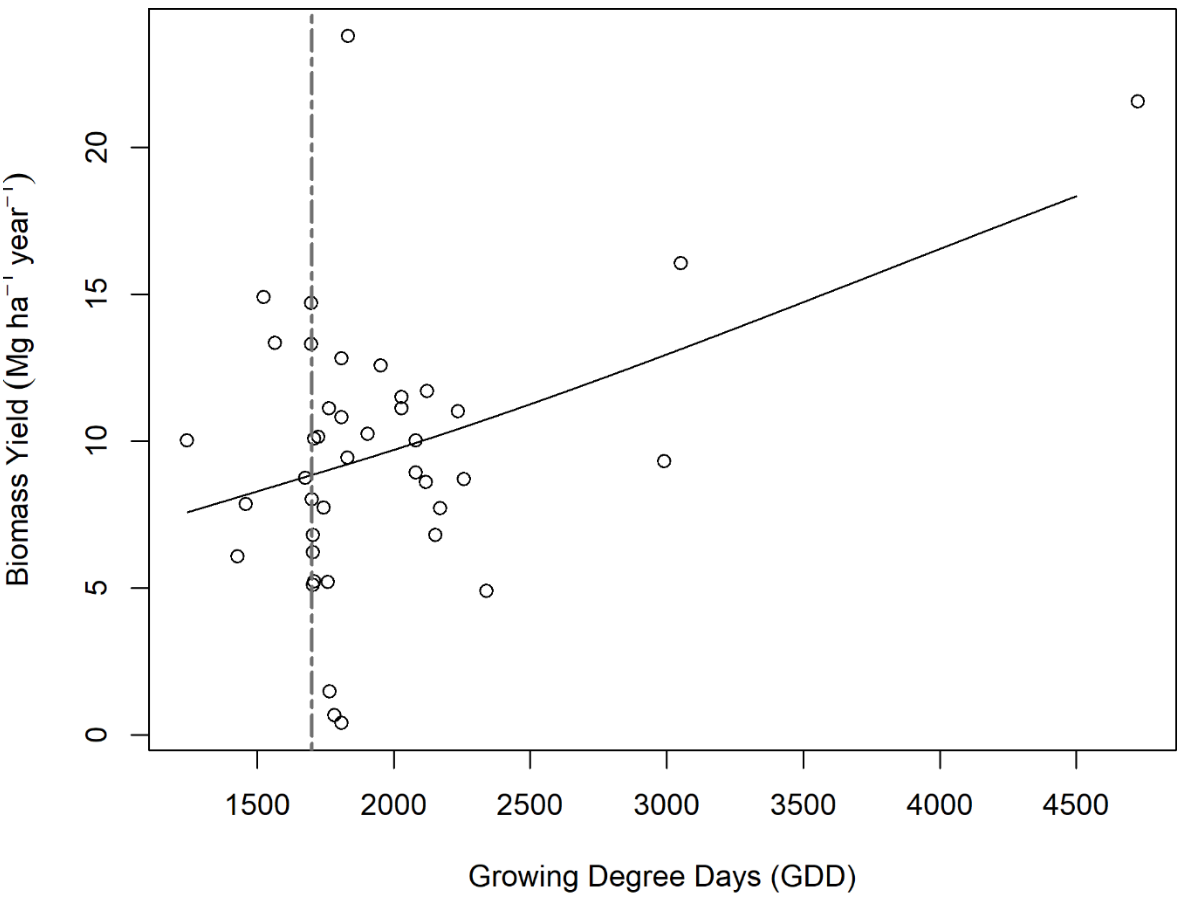

Figure 5.3.5 Scatterplot of willow biomass yield (Mg ha^{-1} year^{-1}) against growing season growing degree days (GDD) (April through October, unless otherwise stated in the literature). Mean Nova Scotia growing season GDD = 1,700 represented by the vertical gray dashed line [97].

The predictor terms within the willow predictive yield model are based upon the iterative process previously outlined in this chapter (Section 5.3.1.1.1), and in Chapter 4 [145]. Like the hybrid-poplar database, the willow database is comprised of less peer-reviewed literature compared to the switchgrass database, the predictor terms in the willow models are the same as outlined in Table 5.3.1.

The AIC value decreased from Model 1 to Model 2, penalizing Model 1 for the interaction term and preferring the simplicity of Model 2 (Table 5.3.4) [271]. Model 2 was selected for further utilization (Table 5.3.5).

Table 5.3.4 Comparison of model performance indices between two iterations of the willow predictive yield model.

Formula	Random Effects	Cond. R^2	Marg. R^2	AIC	RMSE
Model 1: Yield ~ Precipitation × GDD + Rotation + Stand Year	Location	0.583	0.207	110.760	0.523
Model 2: Yield ~ Precipitation + GDD + Rotation + Stand Year	Location	0.606	0.203	106.950	0.520

Cond. R^2 = Conditional R^2; Marg. R^2 = Marginal R^2; AIC = Akaike Information Criterion; RMSE = Root Mean Square Error.

Table 5.3.5 Predictor term estimation (based on Z-score standardized data) for the willow predictive yield model (Model 2 in Table 5.3.4).

Predictor Term	Estimate	Std. Error
Intercept	0.55417	0.71327
Precipitation	0.09805	0.22328
GDD	0.23508	0.20349
Rotation	-0.83268	0.59566
Stand Year	0.10571	0.06465
R^2	0.74	

5.3.2.1.2 Model Visualization

Willow research conducted within this project (BioMass Canada Project 6) has been compiled to add 5 biomass yields across five different locations within Nova Scotia to the database. These data points were used as ‘new data’ for Model 2 to evaluate the predictive ability of the willow predictive yield model using Nova Scotia data (Table D-2).

5.3.2.1.3 Model Update

As per Section 5.3.1.1.3, Model 2 was refined through the incorporation of the Nova Scotia data into the original database. The incorporation of the Nova Scotia data increased the R^2 value of the 1:1 fit line ($R^2 = 0.81$) (Figure 5.3.6).

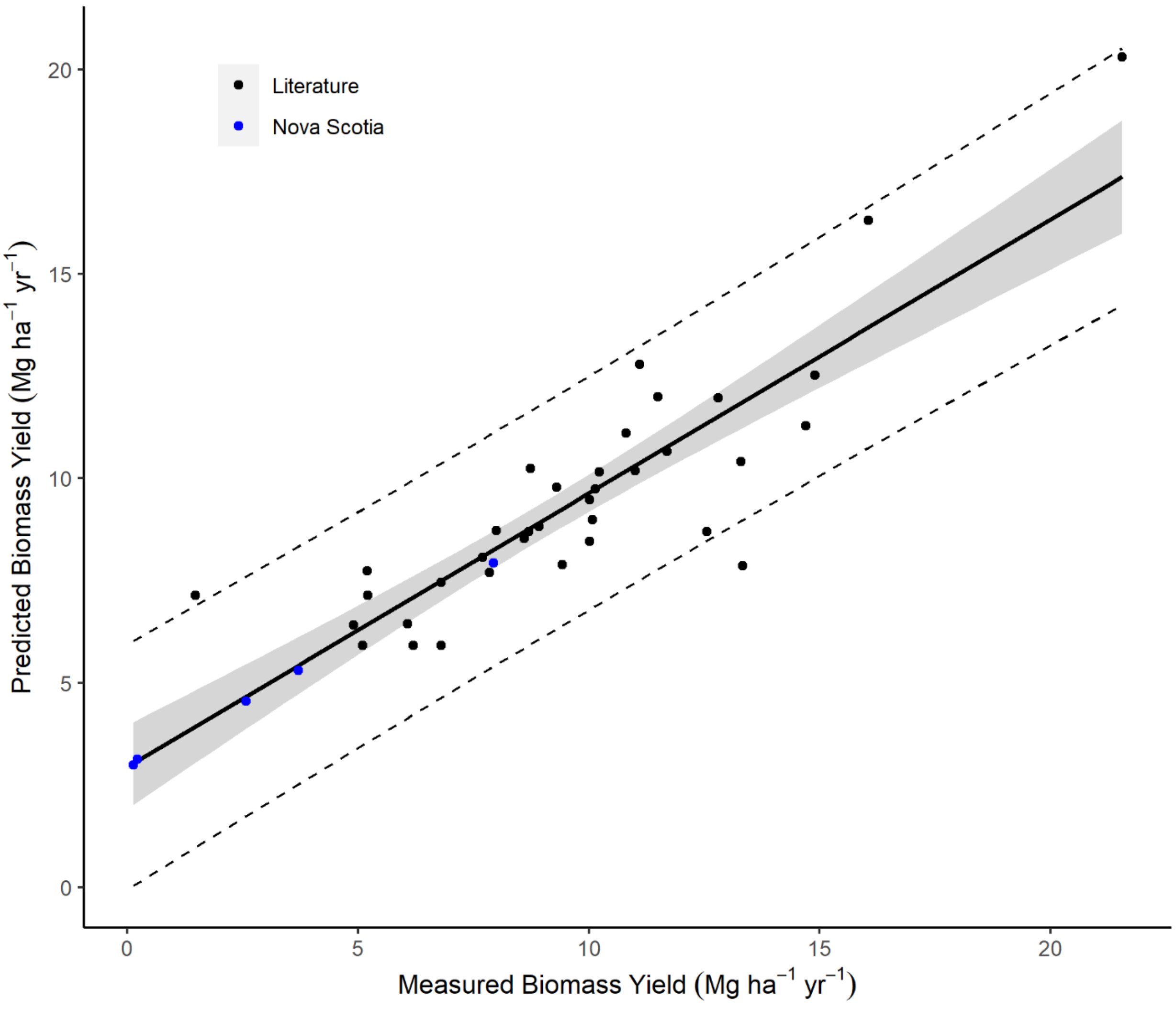

Figure 5.3.6 Predicted willow biomass yield versus measured biomass yield calculated from the linear mixed-effects model. Blue circles represent willow yields from Nova Scotia-based studies and black circles represent willow yields from the peer-reviewed literature. The dashed lines represent the 95 % prediction interval, while the shaded area represents the 95 % confidence interval. The bold line represents the 1:1 fit ($R^2 = 0.81$) (n = 41).

5.4 Discussion

In this chapter, predictive models were developed for hybrid-poplar and willow from peer reviewed literature to quantify biomass productivity of these crops under a coppice management system on marginal lands in Nova Scotia.

Developing predictive yield models for Nova Scotia is an important co-step (alongside real-world data collection) to address limitations in the production of SRWC for bioenergy and bioproducts in a local bioeconomy. There are some limitations to this specific study that should be discussed.

5.4.1 Rotation

One of the most important sustainability characteristics of SRWC production, like purpose-grown perennial grasses [145], is the potentially long stand productivity/ lifetime prior to replanting (20-25 years) [33,296,297]. However, there are minimal published studies to demonstrate long-term SRWC biomass productivity, recounting the limited practical experience discussed previously. In one study, under minimal exogenous inputs, the fifth and sixth 3-year rotations (lifetime of 18 years) produced average poplar yields (across four poplar clones and three sites) of 6.4 and 7.3 Mg ha^{-1} year^{-1}, respectively) [213]. Only one clone was equally or more productive in these later rotations than in previous rotations [213]. In another study, three consecutive three-year harvests of poplar and willow on marginal land were investigated [305]. By the third rotation, the biomass yield of both poplar and willow decreased significantly, citing that perhaps the poor soil quality was the reason for the shortened lifespan of the plantation [305]. In a study evaluating the difference in poplar biomass yield between annual, biennial, and triennial rotation lengths, the yield was highest during the first harvest in both biennial and triennial harvest systems, decreasing in subsequent harvests [306]. Across four locations, poplar biomass yields increased rapidly in the first and second rotations of 3-4 years followed by less rapid increases or decreases in rotations three and four [307].

In one long-term willow coppice study, biomass yield from the first rotation to the second rotation increased 42 % (rotation length was 3 years) [308]. The authors noted the biomass yield fluctuated from rotation 2 to 6, indicating neither a great increase or decrease (between 11.3 and 13.5 Mg ha^{-1} $year^{-1}$) [308]. In another study on different willow clones, between two rotation regimes (three-year rotations versus two-year rotations), there was a 6 % increase in biomass using the longer rotation after the first 6 years and a 14.8 % increase after the second 6 years [309]. Again, the data show that there was neither a great increase nor decrease in willow yield in later years.

All above cited studies about rotation length and the effect on poplar and willow biomass yield reported significant effects between clones. Aside from clonal differences, rotation length could change depending on the end-use of the biomass or access to harvesting equipment. Northern climates typically benefit from longer rotation lengths to maximize biomass yield and improve biomass quality [310]. Further, stool mortality typically increases with short rotations due to more frequent harvesting [306,311].

In relating this information about rotation length effect on biomass yield back to the predictive yield models, it is important to clarify that the main criterion for data to be included into these predictive yield model databases was the plant hardiness zone of the study location (plant hardiness zone 7 and below) (Section 5.2.1). There were no studies with long-term yields reported in these data, apart from one study harvested annually for 10 years [312] (Figure 5.4.1).

The predictive ability of the models is reduced for these longer-term scenarios because there is no precedent in the database to build off. This brings up the question of whether hybrid-poplar and willow coppice systems should be marketed in Nova Scotia for lifetimes longer than 12 years.

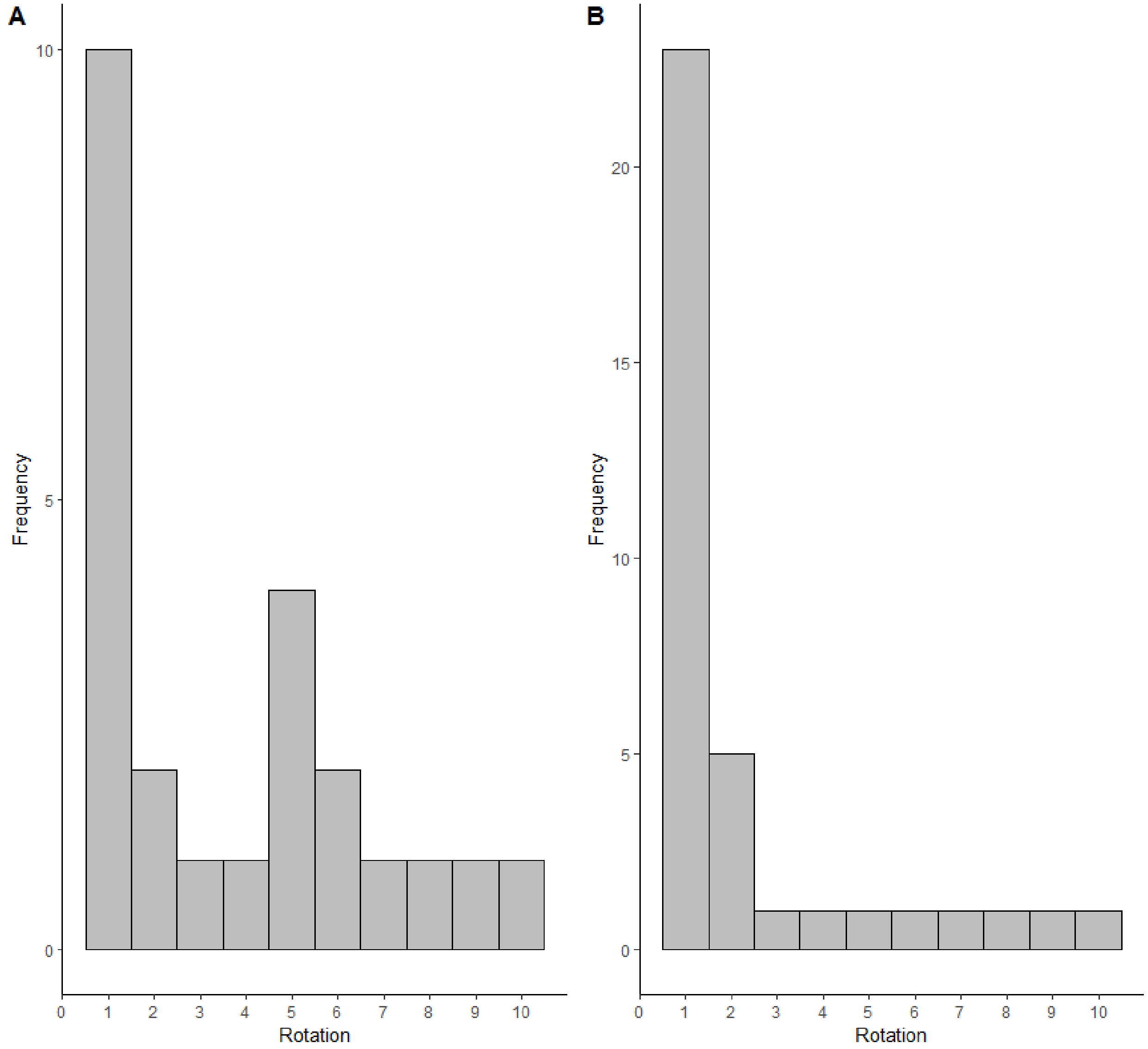

Figure 5.4.1 Frequency distribution of the number of rotations reported in the **A** hybrid-poplar (n = 24) and **B** willow (n = 36) predictive yield databases.

5.4.2 Soil Suitability

Although the predictive yield models for hybrid-poplar and willow have reasonably good predictive power, there are limitations to these models and assumptions that the models are operating upon that are not explicitly outlined (i.e., random effects). Building these predictive yield models occurred through trial and error, and with the concurrence of field data collection in Nova Scotia, more information can be gleaned out of the field work to help better explain the limitations of the models.

Model development and subsequent simplification follow the principle of parsimony, the simpler model the better [271]. This was a favourable principle to follow when many biologically relevant predictor terms originally included in the model (i.e. soil texture, drainage, etc.) were removed due to data insufficiency. It was assumed that these 'unnamed' variables would be captured within the random effect ('Location') of each predictive model. While this may be true in some cases, two field sites were examples of how the removal of certain predictor terms are not necessarily captured in the random effects.

There is sufficient peer-reviewed evidence (previously discussed), as well as research done within this project, to support the growth of hybrid-poplar and willow on marginal lands [106,313]. Given the five field sites established as a concurrent part of BioMass Canada Project 6, the predicted yield values (based on values of precipitation and GDD) of both hybrid-poplar and willow overestimated the measured yields at two of the five sites, East Gore and Port Hood (Table 4.4.1). Although there is some overestimation occurring in the willow predictive yield model, it is interesting to note that the rank order of the predicted yields correlates well with the measured yields (Skye Glen is the highest yielding, Bible Hill and Nappan are intermediary and East Gore and Port Hood are the lowest yielding).

The overestimation could be indicative that other conditions inhibited productivity that were not necessarily captured by the models [106]. The disparity between the measured poplar biomass yield and the predicted yield at both East Gore and Port Hood sites could be accounted for by stool mortality and weed pressure. These two predictor variables could be categorized by soil suitability.

Table 5.4.1 Hybrid-poplar and willow measured yields from five field sites across Nova Scotia after one coppice cycle (year 4) compared to the predicted yields from the predictive yield models.

	Hybrid-Poplar		Willow	
Location	Measured Yield (Mg ha^{-1} year^{-1})	Predicted Yield (Mg ha^{-1} year^{-1})	Measured Yield (Mg ha^{-1} year^{-1})	Predicted Yield (Mg ha^{-1} year^{-1})
Bible Hill	0.76	3.31	3.70	5.30
Nappan	1.00	3.24	2.57	4.55
East Gore	0.32	6.35	0.13	2.99
Port Hood	0.12	3.12	0.22	3.13
Skye Glen	5.93	9.51	7.93	7.92

5.4.2.1 Stool Mortality

As discussed for the two local field sites, Bible Hill and Nappan, Nova Scotia in Chapter 4 [134], there was a considerable rise in stool mortality from establishment to the first coppice cycle harvest. The Port Hood site experienced minimal establishment success, as there was evidence at the end of the establishment year growing season of stool injury and upheaval. Overwintering survival in both hybrid-poplar and willow after the establishment year (across treatments, stool mortality was approximately 66 % and 44 %, respectively). Further, the Port

Hood site experienced a dramatic increase in stool mortality in both hybrid-poplar and willow across treatments over the first coppice rotation. The stool mortality reported in Port Hood just before harvest in year 4 was 84 % for hybrid-poplar and 78 % for willow. The substantial stool mortality reported for this site shows the need to somehow address the potential for stool mortality in SRWC and its effect on biomass productivity.

5.4.2.2 Weed Pressure

Weed pressure and its effect on biomass productivity is a consistent theme throughout this project. There was significant weed pressure at both Port Hood and East Gore sites in the establishment year and year 2, perhaps inhibiting biomass productivity of hybrid-poplar and willow as after coppicing at the end of the establishment year, the growth of new stems would be competing with annual weeds. In comparison, there was minimal weed pressure at the Skye Glen site during the establishment year, and the biomass productivity was surprisingly incredible at this site (Table 4.4.1, Figure 5.4.2, Figure 5.4.3). Weed pressure can and should be controlled chemically and mechanically to aid SRWC development and growth, but the soil suitability of a location within the context of a predictive yield model could include an index of weed pressure to identify the level of concern the weeds on a certain parcel of land raise for producing SRWC.

Figure 5.4.2 Hybrid-poplar at the Port Hood, NS field site in September 2019 [314].

Figure 5.4.3 Hybrid-poplar at the Skye Glen, NS field site in September 2019 [315].

5.5 Conclusion

There were two objectives of this research: 1) to compile electronic databases based on scientific literature of the climatic and edaphic conditions comparable to Nova Scotia, Canada of variables associated with biomass productivity of SRWC hybrid-poplar and willow and 2) to create predictive yield models for each crop based on these electronic databases. Utilizing growing season precipitation and GDD, along with ‘Rotation’ and ‘Stand Year’, predictive linear mixed-effects models were developed with the ability to account for a moderate (67 %) and large (85 %) portion of the variability in the data for hybrid-poplar and willow, respectively.

There were more limitations to these models in comparison to the grass models in Chapter 4 [145]. The incorporation of soil suitability predictor variables, once data for these variables is sufficient, will very likely account for a greater proportion of the variation in the data, and will improve the predictive ability of the models for future use. By quantifying the biomass potential through a combination of predictive modelling (training data) and real-world data collection (testing data), the groundwork can be laid for infrastructure and policy to develop for a successful bioenergy and bioproducts industry in Nova Scotia.

Chapter 6 Summary and Future Outlook

6.1 Summary of Work Completed

There are currently too many uncertainties in the development and deployment of a local bioeconomy in Nova Scotia to get key stakeholders interested enough to buy in, so the central objective of this research was to de-risk some of the components of the bioeconomy. As mentioned in Chapter 1, the local bioeconomy is caught in a causality dilemma due to high uncertainty and high risk. Field trials in this research have validated the establishment and early growth of four dedicated energy crops (switchgrass, miscanthus, coppiced hybrid-poplar and willow) on marginal land in Nova Scotia. The development of statistical predictive yield models investigated the relationships between Nova Scotian climatic factors and the biomass yield of these four crops.

6.1.1 Field Research

The establishment of two field sites in Bible Hill and Nappan, Nova Scotia containing the four dedicated energy crops were successful. Hybrid-poplar and willow were coppiced and subsequently grown for the first three-year rotation in this research. Both species performed well across sites, but there was substantially greater stool mortality over the four-year period at the Bible Hill site compared to the Nappan field site. As theorized in Chapter 2, the stool mortality in Bible Hill could be a long-term symptom of deer grazing during the establishment year.

Switchgrass at the Bible Hill site was the weakest crop/site mixture, but as theorized in Chapter 3, the reactive weed management strategy across sites was incapable of controlling the extensive weed presence in Bible Hill, delaying the growth of switchgrass. The miscanthus was the most productive of the grass species planted at both sites and showed impressive establishment and subsequent growth from *in vitro* plantlets. Further investigation of miscanthus tissue harvested in year 3 shows similar tissue composition to miscanthus grown in similar experimental conditions with the exception of the tissue in this research having a higher ash content, which is undesirable for combustion.

6.1.1.1 Limitations and Future Research

The field trials conducted in this research serve as the very first step of de-risking the development of a local bioeconomy on dedicated energy crops by asking and answering the question of “will it grow here”. However, there are limitations to discuss with the extrapolation of knowledge collected from the field trials.

The intention of the field trials in this research was to establish the four dedicated energy crops on ‘marginal’ lands, as the land use change (LUC) of land suitable for food and feed production to biomass production spurs detrimental impacts to the sustainability of the production system. Since there are no Class 1 lands in Nova Scotia, a relatively small portion of Class 3 and 4 lands are actively in agricultural production and based upon the degree of limitations for crop production of these Class 3 and 4 lands [316], there is a highly variable area of ‘marginal’ land available in Nova Scotia. Moving forward, in order to fully understand the establishment and growth potential of these dedicated energy crops on marginal lands in Nova Scotia, the crops should be established in a variety of ‘marginal’ soils to evaluate wide-scale adoption. In addition to the soil status of the field trials, these crops were purposely established under a low-input management system, to minimize the footprint of the production system. However, had a more proactive weed management strategy occurred at the Bible Hill site, potential increases in switchgrass biomass yield may balance out the use of herbicides.

Ultimately, future field experiments should explore best management strategies with non-synthetic fertilizers and herbicides.

Data was only collected from the first four years of these crops (only one rotation for the tree species) in this research, therefore insight into the longer-term productivity of these crops in Nova Scotia is still unknown. The continuation of data collection from these experiments is important to inform key stakeholders of the productive lifespan of these crops in the Nova Scotian climate. It is evident that the miscanthus *in vitro* plantlets were highly successful in establishment and early yield in Nova Scotia, but these plantlets are much more expensive (and time consuming) to produce than rhizomes. The longer the productive lifespan of the plantlets, the more cost-effective.

The field trials outlined in this research were part of a larger experiment (BioMass Canada Project 6), with seven field sites across the province of Nova Scotia. These field sites were all planted and harvested manually, requiring extensive time and physical labourers. By the end of data collection (year 4), the manual harvesting of all four dedicated energy crops became increasingly labour intensive due to the massive size of the crops (Figure 6.1.1). To scale up production of dedicated energy crops, specialized equipment would need to be acquired for planting, harvesting, chopping, and baling, depending on the end-use of the biomass. The analysis of the larger experiment (seven field sites) as a whole should give a better assessment of the biomass potential across the entire Province.

Figure 6.1.1 Miscanthus at the Bible Hill field site in the fall of year 5 [317].

6.1.2 Yield Modelling

Four predictive yield models were created for the dedicated energy crops of interest in this research using a combination of local Nova Scotian data and data from other locations with similar plant hardiness zones to Nova Scotia. The development of the models was a good exercise to understand the relationship between climatic conditions and biomass yield in Nova Scotia’s continental climate and resulted in a few strong models (Chapter 4 and 5). The grass models explained greater proportions of the total variance compared to the tree models, but all models exhibited high goodness-of-fit [318].

6.1.2.1 Limitations and Future Research

The predictive yield models developed in this research serve as a concurrent step to the field trials in de-risking the local bioeconomy in Nova Scotia by attempting to answer the question “what is the annual provincial supply of dedicated energy crop biomass”. There are numerous limitations to communicate regarding the yield modelling.

There are numerous assumptions made throughout the model development undertaken in this research. These assumptions, not clearly communicated, can increase uncertainty in the model output and jeopardize ensuing value of the models [27]. The creation of training datasets (to develop the models) of mostly non-Nova Scotian data, followed by the use of Nova Scotian testing datasets (to refine the models) to develop Nova Scotia-specific predictive yield models relies on a massive assumption that the spatial extrapolation of dedicated energy crop yields based solely on PHZ is feasible. This could be considered a ‘scenario analyses’, where the model is exploring general responses rather than location-specific responses [52]. This assumption can be justified biologically, as plants rely on the same resources for growth regardless of location.

However, the models in tandem with this assumption without real-world evidence of crop success in Nova Scotia leads to a lot of uncertainty in the model output.

There is an inherent balance in model development between overfitting and predicting. From a biological perspective, there is a greater value in crop growth models when as much growth limiting information as possible can be included in the statistical models to best inform the predictions [53]. This is also true from a statistical perspective, however, if there is not enough variation across the training dataset within variables, the inclusion of these variables invokes overfitting. The initial thought process in this research was the biological perspective, to include as many biologically relevant parameters as possible to best inform the predictions. Once the databases were being populated, the specificity of PHZ reduced data availability and ultimately condensed variability across discrete parameters such as soil characteristics. The exclusion of these characteristics, in addition to fertilizer applications, were justified from both a biological and statistical perspective. Models developed in this research were done so with the idea that dedicated energy crops in Nova Scotia would be grown under a low-input management system, therefore, predicting more of a “baseline” biomass yield rather than a maximum yield. Under this assumption, crop yields would not be reported in the literature on incapable soils, so all yields must be accompanied by reasonable quality soil. Statistically, the exclusion of soil characteristics (without sufficient replication) improved the predictability of the model and avoided overfitting. Ultimately, the application of these models in the real-world requires some caveats, which can be addressed by continuing to collect data from real-world field trials in Nova Scotia.

The combination of the real-world field trials in Nova Scotia and the predictive yield models into an interactive mapping tool was proposed early on in this research but was deemed to be outside the scope of this thesis. This tool could be extremely useful in future work to understand the productivity of lands surrounding a specific area where a biorefinery may be located.

6.2 Future Research

The objectives of this 'use-inspired basic research' were to develop basic scientific understanding, through statistical predictive yield model development and agricultural field trials, to start to address a real-world problem, de-risking the local bioeconomy [319]. This research is only one small step towards the deployment of a sustainable local bioeconomy in Nova Scotia. This research does not provide any insight or knowledge towards the economical perspective of the dedicated energy crop production system, nor does it provide any insight into policy that could be introduced to accelerate the growth of the bioeconomy. With this research, we have evidence to support the successful establishment and early yields of dedicated energy crops in Nova Scotia, so now the other facets of the supply chain need to be explored.

For the interim end-use of this dedicated energy crop biomass (until local biofuel refining facilities are confirmed) as an alternative to coal for electricity generation, the grass biomass is not compatible with current combustion practices in local facilities, but the tree biomass could be (based mainly on moisture content). An alternative end-use for the grass biomass could be animal bedding, as there has been increased demand and decreased supply locally. These interim end-uses would provide a market for biomass while long-term field trials are evaluated in the local climate, concurrently exhibiting the provincial dedicated energy crop biomass supply to biorefineries [289].

6.3 Knowledge Transfer Plan to Key Stakeholders

In tandem, the statistical predictive yield models and field trials should corroborate the biomass potential of the four dedicated energy crops on marginal lands in Nova Scotia. The knowledge gained through this research could dispel the causality dilemma between agricultural producers and biorefineries/industry officials.

6.3.1 Agricultural Producers

With real-world evidence of the success of these dedicated energy crops in Nova Scotia, current agricultural producers may be less averse to diversifying their operations to include these crops. Armed with this local evidence, producers must be surveyed to identify additional barriers to adoption. The interim end-uses of the biomass could provide an initial market for the biomass while the high-volume supply necessary for a biorefinery is established.

6.3.2 Biorefinery/Industry Officials

In order to establish a multi-million-dollar biorefinery in Nova Scotia, there are many details that need to be confirmed. First and foremost, in order to sustain a biorefinery, a stable, high volume biomass supply on a long-term basis is required. The statistical predictive yield models in this research can be used to extrapolate the supply from these dedicated energy crops in Nova Scotia and set a biomass procurement cost. After discussions with industry officials, to consider a location for a biorefinery, there must be evidence of a stable supply of good quality biomass within a certain radius.

6.3.3 Biomass "Brokers"

As part of the biomass supply chain, there is typically a 'middleman' to bring the agricultural producers and the biorefinery together. The 'middleman' would be an individual (or group) with industry knowledge connecting the two groups of stakeholders. This group would likely be the only stakeholder group to use the statistical predictive yield models first-hand.

6.3.4 Energy Recipients

With the intended short-term/interim end-use of the dedicated energy crop biomass, at least from the tree species, being electricity generation in Nova Scotia, any individual benefitting from electricity generation in the province is considered a stakeholder who could be informed about this research.

6.3.5 Provincial Government

The main message to the provincial government from this research is about investing in the local bioeconomy. This research provides evidence to support that dedicated energy crops will grow in Nova Scotia on marginal lands. However, because there is limited practical experience and a very undeveloped market in Nova Scotia and Canada, the government can use the information from this research to incentivize further development. Funding could be allocated for future research in other areas of the supply chain, such as technoeconomic analyses (TEA) and life-cycle assessments (LCA) of the production systems and supply chains. Further, incentives could be created for both agricultural producers and biorefineries/industry officials to create some momentum in development of the bioeconomy. The majority of dedicated energy crop production costs lies within the establishment, so there needs to be an incentive for producers to 'buy in' until the economic benefits can be realized.

6.4 Conclusion

Recent experience within our research group, along with the knowledge gained through this dissertation research suggests that Nova Scotia is well-suited to explore the development of a local bioeconomy. Through short-term, interim end-uses (animal bedding, coal alternative for electricity generation), the provincial supply of dedicated energy crop biomass can be built up in order to attract a biorefinery for higher-valued bioproducts, including biofuels. The development of a local bioeconomy will allow Nova Scotians to depend on local resources, providing job security, especially in rural communities and cleaner, dependable energy.

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Appendix A Chapter 2 Supplementary Material

Table A-1 Baseline soil analysis at Bible Hill and Nappan, Nova Scotia as measured in spring of the establishment year[1]. Measurements taken at 1-15 cm and 16-30 cm depths.

	Bible Hill		Nappan	
Parameter	1 – 15 cm	16 – 30 cm	1 – 15 cm	16 – 30 cm
pH (pH Units)	5.83	6.29	6.49	5.98
Buffer pH (pH Units)	7.59	7.62	7.55	7.43
Nitrogen (%)	0.17	0.11	0.33	0.22
Nitrate-N (ppm)	35.42	10.31	31.59	6.19
Organic Matter (%)	3.4	2.7	6.1	4.3
P_2O_5 (kg ha^{-1})	743	614	222	68
K_2O (kg ha^{-1})	333	205	164	82
Calcium (kg ha^{-1})	2263	2015	3700	1729
Magnesium (kg ha^{-1})	380	371	127	80
Sodium (kg ha^{-1})	< 16	< 16	22	< 16
Sulfur (kg ha^{-1})	19	20	20	19
Aluminium (ppm)	1515	1576	1189	1361
Boron (ppm)	< 0.50	< 0.50	0.57	< 0.50
Copper (ppm)	1.18	0.83	0.9	0.64
Iron (ppm)	237	225	234	258
Manganese (ppm)	62	55	76	49
Zinc (ppm)	1.25	0.83	0.89	0.62
CEC (meq 100 g^{-1})	10.9	9.9	13.6	9.3

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Table A-2 Typical composition of pulp and paper mill sludge (PPER) produced at Port Hawkesbury Paper LLP.

Parameter[1]	Value[1]
Moisture Content[1] (%)	71
Total Organic Carbon (TOC) (%)	42.7
Total Inorganic Carbon (TIC) (%)	3.9
C:N	2,241.9
pH (pH Units)	6.15

[1] Data provided by Port Hawkesbury Paper LLP.

Table A-3 Nutrient compositional analysis of anaerobic digestate (DG) sourced from T.E. Boyle Farm and Forestry Limited. Analyses completed on samples from batches applied in the field in year 1 and year 2[1].

	2019	2020	
Parameter	Digestate	Digestate 1	Digestate 2
Dry Matter (%) [2]	9.40	7.37	8.17
Nitrogen (%)	2.30	2.19	1.93
Calcium (%)	1.874	2.553	2.419
Potassium (%)	3.043	3.951	3.667
Magnesium (%)	0.704	0.843	0.811
Phosphorus (%)	0.808	0.801	0.758
Sodium (%)	3.336	5.759	5.370
Boron (ppm)	40.51	42.03	41.42
Copper (ppm)	182.49	490.23	438.82
Iron (ppm)	5,005.81	2,216.20	2,363.06
Manganese (ppm)	318.73	256.06	249.82
Zinc (ppm)	154.90	212.48	196.90

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

[2] Dry matter is reported as the percentage of solids in the digestate.

Table A-4 Soil analyses at Bible Hill and Nappan, Nova Scotia as measured in year 2[1]. Measurements taken at 1-15 cm.

		pH (pH Units)	Organic Matter (%)	NO_3-N (ppm)	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Bible Hill						
	CT	5.99 ± 0.04 a	3.08 ± 0.05 a	9.16 ± 1.12 a	772.75 ± 27.50 a	309.25 ± 8.78 ab
	DG	6.04 ± 0.06 a	3.25 ± 0.09 a	9.53 ± 1.09 a	802.25 ± 34.95 a	347.00 ± 11.16 a
	SE	5.95 ± 0.05 a	3.25 ± 0.09 a	8.79 ± 1.21 a	774.75 ± 42.60 a	309.25 ± 12.23 ab
	PPER	6.04 ± 0.09 a	3.23 ± 0.02 a	7.76 ± 0.98 a	789.75 ± 20.85 a	301.50 ± 11.76 b
		P = 0.6837	*P* = 0.2453	*P* = 0.6929	*P* = 0.907	*P* = 0.05225 .
Nappan						
	CT	5.79 ± 0.05 a	2.42 ± 0.05 a	1.38 ± 0.43 a	486.75 ± 14.14 a	85.00 ± 10.64 a
	DG	5.87 ± 0.03 a	2.60 ± 0.05 a	2.59 ± 0.88 a	497.75 ± 27.76 a	127.88 ± 28.69 a
	SE	5.81 ± 0.06 a	2.50 ± 0.04 a	1.43 ± 0.38 a	476.00 ± 20.05 a	101.75 ± 16.07 a
	PPER	5.82 ± 0.03 a	2.50 ± 0.09 a	1.30 ± 0.32 a	490.50 ± 16.26 a	84.00 ± 16.53 a
		P = 0.6007	*P* = 0.3029	*P* = 0.3358	*P* = 0.8922	*P* = 0.3704

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Table A-5 Soil analyses at Bible Hill and Nappan, Nova Scotia as measured in year 2[1]. Measurements taken at 1-15 cm.

		Ca (kg ha^{-1})	Mg (kg ha^{-1})	Na (kg ha^{-1})	S (kg ha^{-1})
Bible Hill					
	CT	2,135.50 ± 117.15 a	350.75 ± 21.10 a	20.00 ± 1.08 b	20.75 ± 0.25 a
	DG	2,244.12 ± 115.67 a	356.62 ± 17.63 a	37.88 ± 9.54 a	21.62 ± 0.24 a
	SE	2,055.50 ± 161.49 a	334.00 ± 17.81 a	20.75 ± 0.85 b	21.75 ± 0.85 a
	PPER	2,178.50 ± 145.01 a	352.00 ± 22.62 a	22.75 ± 0.85 b	21.25 ± 0.25 a
		P = 0.7988	*P* = 0.8619	*P* = 0.01316 *	*P* = 0.4761
Nappan					
	CT	1,816.00 ± 58.57 a	248.75 ± 13.12 a	33.50 ± 4.33 a	24.50 ± 0.87 b
	DG	1,867.00 ± 52.25 a	264.38 ± 11.69 a	45.00 ± 6.26 a	27.38 ± 0.55 a
	SE	1,818.25 ± 52.81 a	252.25 ± 11.95 a	35.25 ± 3.28 a	25.25 ± 0.48 ab
	PPER	1,837.00 ± 66.60 a	260.25 ± 11.56 a	35.25 ± 2.87 a	25.25 ± 0.48 ab
		P = 0.9171	*P* = 0.7906	*P* = 0.2842	*P* = 0.03336 *

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Table A-6 Soil analyses at Bible Hill and Nappan, Nova Scotia as measured in year 2[1]. Measurements taken at 1-15 cm.

		Al (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)
Bible Hill						
	CT	1,423.75 ± 36.17 a	1.22 ± 0.04 a	231.00 ± 11.42 a	58.25 ± 1.32 a	1.55 ± 0.04 a
	DG	1,428.62 ± 30.36 a	1.30 ± 0.02 a	233.12 ± 16.24 a	60.88 ± 1.62 a	1.70 ± 0.03 a
	SE	1,436.00 ± 54.04 a	1.22 ± 0.07 a	240.25 ± 16.93 a	61.00 ± 3.85 a	1.60 ± 0.07 a
	PPER	1,434.25 ± 38.24 a	1.26 ± 0.04 a	236.25 ± 14.70 a	61.00 ± 2.48 a	1.64 ± 0.09 a
		P = 0.9969	*P* = 0.6526	*P* = 0.9738	*P* = 0.832	*P* = 0.4098
Nappan						
	CT	1,160.00 ± 41.64 a	0.76 ± 0.04 a	200.00 ± 6.28 a	73.00 ± 4.30 a	1.45 ± 0.11 a
	DG	1,220.25 ± 35.80 a	0.82 ± 0.07 a	200.00 ± 10.49 a	76.75 ± 7.54 a	1.44 ± 0.11 a
	SE	1,157.75 ± 20.13 a	0.76 ± 0.05 a	200.75 ± 5.07 a	79.25 ± 5.31 a	1.38 ± 0.06 a
	PPER	1,111.50 ± 24.93 a	0.76 ± 0.05 a	199.50 ± 3.97 a	72.25 ± 4.27 a	1.36 ± 0.06 a
		P = 0.1727	*P* = 0.788	*P* = 0.9994	*P* = 0.7875	*P* = 0.8326

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Table A-7 Mean values of grass dry matter yield (kg ha^{-1}) measured in the fall of Year 1 and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Dry Matter Yield (kg ha^{-1})
Bible Hill		
Miscanthus	CT	490.53 ± 61.31 a
	DG	695.91 ± 113.98 a
	SE	449.95 ± 71.40 a
	PPER	710.36 ± 75.76 a
		P = 0.09513 .
Nappan		
Miscanthus	CT	608.28 ± 146.75 a
	DG	659.19 ± 187.98 a
	SE	554.71 ± 134.37 a
	PPER	955.69 ± 161.53 a
		P = 0.3278
Switchgrass	CT	67.46 ± 12.38 a
	DG	101.22 ± 14.63 a
	SE	87.10 ± 16.35 a
	PPER	94.34 ± 28.90 a
		P = 0.6408

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Table A-8 Miscanthus tissue nutrient concentration at Bible Hill, Nova Scotia as measured in fall of Year 1[1].

	N	Ca	K	Mg	P	Na
			(%)			
CT	1.51 ± 0.04 a	0.25 ± 0.006 b	1.81 ± 0.04 a	0.142 ± 0.008 a	0.355 ± 0.015 a	0.021 ± 0.003 a
DG	1.60 ± 0.04 a	0.27 ± 0.009 ab	1.39 ± 0.05 a	0.155 ± 0.004 a	0.353 ± 0.017 a	0.027 ± 0.003 a
SE	1.45 ± 0.07 a	0.29 ± 0.007 a	1.18 ± 0.10 a	0.160 ± 0.005 a	0.329 ± 0.038 a	0.019 ± 0.001 a
PPER	1.38 ± 0.10 a	0.26 ± 0.013 ab	1.21 ± 0.05 a	0.161 ± 0.005 a	0.343 ± 0.026 a	0.021 ± 0.002 a
	P = 0.2579†	*P* = 0.05832 .	*P* = 0.1161	*P* = 0.1585	*P* = 0.8847	*P* = 0.199

	Fe	Mn	Zn
		(ppm)	
CT	39.72 ± 4.64 b	73.78 ± 12.59 b	20.54 ± 1.98 b
DG	65.39 ± 5.75 a	83.37 ± 13.20 ab	29.82 ± 2.59 a
SE	64.35 ± 9.57 a	112.11 ± 10.44 ab	26.14 ± 3.21 ab
PPER	54.46 ± 5.52 ab	140.97 ± 30.27 a	28.35 ± 0.37 ab
	P = 0.04083 *	*P* = 0.09161 .	*P* = 0.06484 .

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-9 Miscanthus tissue nutrient concentration at Nappan, Nova Scotia as measured in fall of Year 1[1].

	N	Ca	K	Mg	P
			(%)		
CT	1.43 ± 0.11 a	0.394 ± 0.016 a	0.58 ± 0.10 ab	0.288 ± 0.015 ab	0.38 ± 0.05 a
DG	1.43 ± 0.12 a	0.340 ± 0.011 b	0.78 ± 0.09 a	0.249 ± 0.014 b	0.35 ± 0.04 a
SE	1.48 ± 0.11 a	0.358 ± 0.006 ab	0.63 ± 0.05 ab	0.252 ± 0.017 b	0.38 ± 0.03 a
PPER	1.38 ± 0.17 a	0.386 ± 0.012 a	0.42 ± 0.07 b	0.332 ± 0.022 a	0.29 ± 0.04 a
	P = 0.9648 †	*P* = 0.02549 *	*P* = 0.06102 .	*P* = 0.01875 *	*P* = 0.4176

	Fe	Mn	Zn
		(ppm)	
CT	57.83 ± 6.17 a	97.34 ± 5.58 b	17.95 ± 3.09 a
DG	52.40 ± 3.09 a	98.80 ± 5.67 b	16.58 ± 1.66 a
SE	66.68 ± 5.11 a	117.85 ± 15.32 b	17.03 ± 1.41 a
PPER	50.98 ± 6.99 a	199.28 ± 37.47 a	13.27 ± 0.92 a
	P = 0.2299	*P* = 0.002978 **†	*P* = 0.3866

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

† Gamma family distribution.

Table A-10 Miscanthus nutrient yield at Bible Hill, Nova Scotia as measured in fall of Year 1[1].

	N	Ca	K	Mg	P	Na
			(kg ha^{-1})			
CT	7.44 ± 1.00 ab	1.22 ± 0.17 a	6.21 ± 0.93 ab	0.74 ± 0.08 ab	1.86 ± 0.25 ab	0.12 ± 0.03 ab
DG	10.87 ± 1.60 a	1.86 ± 0.34 a	10.04 ± 1.83 a	1.13 ± 0.22 ab	2.48 ± 0.28 a	0.18 ± 0.01 a
SE	6.37 ± 0.79 b	1.28 ± 0.21 a	5.22 ± 0.51 b	0.72 ± 0.11 b	1.42 ± 0.06 b	0.09 ± 0.02 b
PPER	10.40 ± 1.07 ab	1.94 ± 0.16 a	9.27 ± 0.74 a	1.24 ± 0.11 a	2.62 ± 0.21 a	0.16 ± 0.02 ab
	P = 0.0346 *†	*P* = 0.09455 .	*P* = 0.01372 *†	*P* = 0.042 * †	*P* = 0.006611 **	*P* = 0.05093 .

	Fe	Mn	Zn
		(kg ha^{-1})	
CT	0.022 ± 0.006 b	0.035 ± 0.005 b	0.01 b
DG	0.045 ± 0.006 a	0.052 ± 0.005 b	0.02 a
SE	0.030 ± 0.006 ab	0.052 ± 0.013 b	0.01 b
PPER	0.040 ± 0.004 ab	0.110 ± 0.026 a	0.02 a
	P = 0.06754 .	*P* = 0.007164 ** †	*P* = 2.2×10^{-16} *** †

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-11 Miscanthus nutrient yield at Nappan, Nova Scotia as measured in fall of Year 1[1].

	N	Ca	K	Mg	P	Fe	Mn	Zn
					(kg ha^{-1})			
CT	8.30 ± 1.45 a	2.39 ± 0.57 a	3.20 ± 0.40 a	1.75 ± 0.41 ab	2.11 ± 0.22 a	0.032 ± 0.009 a	0.062 ± 0.020 a	0.0125 ± 0.0025 a
DG	9.41 ± 2.48 a	2.30 ± 0.71 a	4.95 ± 1.11 a	1.72 ± 0.56 ab	2.22 ± 0.52 a	0.035 ± 0.010 a	0.065 ± 0.020 a	0.0075 ± 0.0025 a
SE	8.27 ± 2.02 a	1.98 ± 0.46 a	3.45 ± 0.76 a	1.40 ± 0.35 b	2.03 ± 0.38 a	0.035 ± 0.006 a	0.072 ± 0.024 a	0.0075 ± 0.0025 a
PPER	13.10 ± 2.15 a	3.66 ± 0.55 a	4.00 ± 0.78 a	3.07 ± 0.31 a	2.68 ± 0.42 a	0.050 ± 0.010 a	0.206 ± 0.075 a	0.0150 ± 0.0029 a
	P = 0.3421	*P* = 0.2338	*P* = 0.4546	*P* = 0.06608 .	*P* = 0.6831	*P* = 0.5406	*P* = 0.05184 .†	*P* = 0.1568

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-12 Mean values of grass dry matter yield (kg ha^{-1}) and moisture content (%) measured in fall of Year 2 and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Dry Matter Yield (kg ha^{-1})	Moisture Content (%)
Bible Hill			
Miscanthus	CT	1,813.67 ± 352.11 b	43.22 ± 2.26 a
	DG	3,607.57 ± 235.35 a	38.40 ± 1.30 a
	SE	2,592.30 ± 583.88 ab	38.7 ± 4.34 a
	PPER	2,675.72 ± 534.00 ab	38.79 ± 3.02 a
		P = 0.09414 .	*P* = 0.6228
Switchgrass	CT	598.44 ± 90.12 a	57.90 ± 4.83 a
	DG	561.60 ± 36.53 ab	58.04 ± 1.75 a
	SE	501.85 ± 42.07 ab	59.57 ± 1.94 a
	PPER	378.20 ± 47.21 b	59.14 ± 2.58 a
		P = 0.08765 .	*P* = 0.9735
Nappan			
Miscanthus	CT	2,700.19 ± 802.43 a	34.21 ± 0.51 ab
	DG	2,865.27 ± 830.10 a	36.45 ± 2.64 a
	SE	2,660.43 ± 821.98 a	23.76 ± 5.08 b
	PPER	4,191.00 ± 1,309.36 a	35.45 ± 0.51 ab
		P = 0.6439	*P* = 0.0772 . †
Switchgrass	CT	212.50 ± 40.90 a	24.20 ± 7.86 a
	DG	263.13 ± 25.67 a	35.75 ± 2.05 a
	SE	277.50 ± 24.28 a	26.00 ± 2.58 a
	PPER	291.25 ± 49.26 a	35.90 ± 2.65 a
		P = 0.4771	*P* = 0.2959 †

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-13 Miscanthus tissue nutrient concentration at Bible Hill, Nova Scotia as measured in fall of Year 2[1].

	N	Ca	K	Mg	P	Fe	Mn	Zn
	(%)					(ppm)		
CT	0.69 ± 0.05 a	0.257 ± 0.009 a	0.36 ± 0.03 a	0.09 ± 0.006 b	0.18 ± 0.01 a	26.63 ± 1.56 a	84.32 ± 19.31 a	23.59 ± 2.84 a
DG	0.80 ± 0.04 a	0.263 ± 0.017 a	0.42 ± 0.04 a	0.09 ± 0.006 b	0.17 ± 0.01 a	30.79 ± 0.90 a	96.82 ± 23.01 a	21.86 ± 2.81 a
SE	0.76 ± 0.14 a	0.273 ± 0.018 a	0.55 ± 0.12 a	0.11 ± 0.009 a	0.21 ± 0.02 a	26.61 ± 4.54 a	69.07 ± 23.45 a	26.39 ± 5.21 a
PPER	0.61 ± 0.08 a	0.240 ± 0.015 a	0.35 ± 0.01 a	0.09 ± 0.000 b	0.17 ± 0.01 a	21.36 ± 2.01 a	83.40 ± 23.73 a	21.77 ± 2.40 a
	$P = 0.4756$	$P = 0.4867$†	$P = 0.2108$	$P = 0.05923$.	$P = 0.156$	$P = 0.1735$	$P = 0.8554$	$P = 0.7689$

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at $P = 0.05$.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-14 Miscanthus tissue nutrient concentration at Nappan, Nova Scotia as measured in fall of Year 2[1].

	N	Ca	K	Mg	P	Fe	Mn	Zn
			(%)				(ppm)	
CT	0.43 ± 0.04 bc	0.36 ± 0.01 a	0.16 ± 0.006 b	0.137 ± 0.009 a	0.15 ± 0.02 ab	30.03 ± 1.38 a	105.20 ± 22.61 a	19.82 ± 2.37 ab
DG	0.64 ± 0.10 ab	0.24 ± 0.01 b	0.45 ± 0.099 a	0.093 ± 0.009 b	0.16 ± 0.02 ab	26.35 ± 2.64 a	88.77 ± 24.41 a	22.36 ± 3.79 a
SE	0.79 ± 0.07 a	0.26 ± 0.009 b	0.48 ± 0.040 a	0.100 ± 0.012 ab	0.20 ± 0.01 a	25.08 ± 2.63 a	73.17 ± 18.17 a	27.72 ± 2.75 a
PPER	0.32 ± 0.05 c	0.29 ± 0.03 b	0.11 ± 0.015 b	0.117 ± 0.014 ab	0.12 ± 0.01 b	26.20 ± 2.77 a	111.94 ± 41.50 a	11.38 ± 1.67 b
	P = 0.007508 **	*P* = 0.004197 **	*P* = 0.002064 **	*P* = 0.09559 .	*P* = 0.05022 .	*P* = 0.5315	*P* = 0.7686	*P* = 0.01822 *

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-15 Miscanthus nutrient yield at Bible Hill, Nova Scotia as measured in fall of Year 1[1].

	N	Ca	K	Mg	P	Fe	Mn	Zn
				(kg ha^{-1})				
CT	11.23 ± 1.57 a	4.15 ± 0.43 b	5.89 ± 0.88 a	See Table A-16	See Table A-17	0.04 ± 0.006 b	0.14 ± 0.04 a	0.040 ± 0.006 b
DG	14.65 ± 3.42 ab	4.77 ± 1.00 b	8.24 ± 2.67 a			0.06 ± 0.014 ab	0.17 ± 0.05 a	0.037 ± 0.009 b
SE	27.80 ± 7.87 b	9.92 ± 1.94 a	20.98 ± 7.77 a			0.10 ± 0.022 a	0.26 ± 0.12 a	0.097 ± 0.027 a
PPER	11.50 ± 0.51 a	4.62 ± 0.45 b	6.75 ± 0.84 a			0.04 ± 0.006 b	0.16 ± 0.05 a	0.040 ± 0.000 b
	P = 0.08345 .	*P* = 0.01317 *	*P* = 0.1014			*P* = 0.05872 .	*P* = 0.6753	*P* = 0.05451 .

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-16 Miscanthus tissue magnesium yield (kg ha^{-1}) at Bible Hill, Nova Scotia as measured in the fall of Year 2[1].

	Magnesium (kg ha^{-1})
CT	1.48 ± 0.21 b
DG-1	1.62 ± 0.36 b
SE-1	3.97 ± 0.50 a
PPER	1.74 ± 0.26 b
DG-2	2.00 ± 0.30 ab
SE-2	2.30 ± 0.74 ab
	P = 0.04884 *

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Table A-17 Miscanthus tissue phosphorus yield (kg ha^{-1}) at Bible Hill, Nova Scotia as measured in fall of Year 2[1].

	Phosphorus (kg ha^{-1})
CT	2.90 ± 0.34 b
DG-1	2.95 ± 0.55 b
SE-1	7.58 ± 1.49 a
PPER	3.24 ± 0.35 b
DG-2	3.66 ± 0.49 ab
SE-2	4.62 ± 1.34 ab
	P = 0.09318 *

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Table A-18 Miscanthus nutrient yield at Nappan, Nova Scotia as measured in fall of Year 2[1].

	N	Ca	K	Mg	P
			(%)		
CT	9.19 ± 2.18 a	8.00 ± 2.53 a	3.50 ± 1.08 b	3.05 ± 0.86 a	3.15 ± 0.62 a
DG	13.93 ± 1.82 a	5.62 ± 1.25 a	9.70 ± 1.85 a	2.00 ± 0.30 a	3.66 ± 0.49 a
SE	17.09 ± 2.60 a	5.70 ± 1.23 a	10.39 ± 1.60 a	2.30 ± 0.74 a	4.62 ± 1.34 a
PPER	12.87 ± 4.93 a	11.41 ± 3.69 a	4.33 ± 1.33 ab	4.69 ± 1.63 a	4.58 ± 1.57 a
	$P = 0.4086$	$P = 0.345$	$P = 0.03525$ *	$P = 0.3036$	$P = 0.7415$

	Fe	Mn	Zn
		(ppm)	
CT	$6.67 \times 10^{-2} \pm 2.18 \times 10^{-2}$ b	$0.27 \pm 1.47 \times 10^{-1}$ b	$0.043 \pm 8.82 \times 10^{-3}$ b
DG	$5.67 \times 10^{-2} \pm 8.82 \times 10^{-3}$ b	$0.20 \pm 6.36 \times 10^{-2}$ b	$0.047 \pm 8.82 \times 10^{-3}$ b
SE	$5.67 \times 10^{-2} \pm 6.67 \times 10^{-3}$ b	$0.14 \pm 8.82 \times 10^{-3}$ b	$0.060 \pm 1.00 \times 10^{-2}$ b
PPER	$1.03 \times 10^{3} \pm 3.18 \times 10^{2}$ a	$5{,}019.71 \pm 2.90 \times 10^{3}$ a	$452.77 \pm 1.60 \times 10^{2}$ a
	$P = 2.523 \times 10^{-8}$ *** †	$P = 1.683 \times 10^{-6}$*** †	$P = 2.86 \times 10^{-8}$ ***

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[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at $P = 0.05$.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

† Gamma family distribution.

Table A-19 Mean values of dependent variables (tillers per plant, length of tallest tiller per stem and area per leaf) as measured in November of Year 2 at Bible Hill and Nappan, Nova Scotia.

		Tiller Count [a]	Tiller Length [b] (cm)	Area per Leaf [b] (cm^2)
Bible Hill				
Miscanthus	CT	13 ± 1.9 a	133.35 ± 7.55 a	76.29 ± 6.02 a
	DG	17 ± 1.5 a	155.30 ± 5.89 a	94.63 ± 5.30 a
	SE	13 ± 1.0 a	135.70 ± 8.20 a	81.33 ± 5.64 a
	PPER	14 ± 1.4 a	142.48 ± 8.42 a	85.83 ± 5.97 a
		P = 0.2062	*P* = 0.2220	*P* = 0.1938
Nappan				
Miscanthus	CT	15 ± 2.02 a	134.85 ± 11.35 a	79.20 ± 3.93 a
	DG	16 ± 2.69 a	144.15 ± 14.77 a	82.13 ± 10.08 a
	SE	14 ± 2.33 a	131.95 ± 11.56 a	78.41 ± 8.70 a
	PPER	18 ± 3.75 a	157.20 ± 14.12 a	87.50 ± 7.11 a
		P = 0.7946	*P* = 0.5376	*P* = 0.8397

[a] All tillers per rhizome.

[b] Longest tiller per rhizome.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Table A-20 Mean values of grass dry matter yield (kg ha^{-1}) and moisture content (%) measured in fall of Year 3, and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Dry Matter Yield (kg ha^{-1})	Moisture Content (%)
Bible Hill			
Miscanthus	CT	9,085.43 ± 1,258.88 ab	57.00 ± 1.57 a
	DG	11,062.31 ± 640.42 a	56.40 ± 1.21 a
	SE	8,623.38 ± 1,131.40 ab	55.02 ± 1.09 a
	PPER	7,400.60 ± 816.05 b	57.40 ± 1.13 a
		P = 0.1236 †	*P* = 0.5852
Switchgrass	CT	2,003.41 ± 119.43 a	60.54 ± 5.11 a
	DG	2,893.58 ± 392.02 a	53.99 ± 3.18 a
	SE	2,819.99 ± 391.97 a	56.41 ± 3.84 a
	PPER	3,006.17 ± 337.70 a	52.49 ± 4.27 a
		P = 0.1792	*P* = 0.5627
Nappan			
Miscanthus	CT	9,091.89 ± 1,252.45 a	49.44 ± 1.97 a
	DG	10,168.61 ± 1,927.58 a	46.40 ± 1.55 a
	SE	7,229.81 ± 1,510.31 a	48.15 ± 2.71 a
	PPER	10,620.61 ± 1,811.92 a	46.67 ± 0.64 a
		P = 0.4983	*P* = 0.6398
Switchgrass	CT	1,676.44 ± 246.99 b	40.32 ± 4.98 a
	DG	2,203.00 ± 169.22 ab	39.72 ± 5.03 a
	SE	2,203.17 ± 298.98 ab	35.33 ± 3.19 a
	PPER	2,639.69 ± 302.69 a	32.06 ± 3.63 a
		P = 0.1298	*P* = 0.5046

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

† Gamma family distribution.

Table A-21 Miscanthus tissue quality characteristics at Bible Hill and Nappan, Nova Scotia as measured in fall of Year 3[1].

		Ash Content (%)	Caloric Content (MJ kg^{-1})	Lignin Content (%)	Cellulose Content (%)	Hemicellulose Content (%)
Bible Hill						
	CT	3.39 ± 0.29 a	18.18 ± 0.40 a	8.58 ± 0.18 a	38.34 ± 0.49 a	24.87 ± 0.53 a
	DG	2.92 ± 0.10 a	18.15 ± 0.167 a	9.06 ± 0.15 a	39.71 ± 0.28 a	24.73 ± 0.43 a
	SE	2.90 ± 0.06 a	18.12 ± 0.11 a	8.99 ± 0.33 a	39.69 ± 0.56 a	25.22 ± 0.30 a
	PPER	2.85 ± 0.24 a	18.06 ± 0.12 a	8.82 ± 0.33 a	39.52 ± 0.54 a	25.03 ± 0.25 a
		P = 0.2295	*P* = 0.9822	*P* = 0.5149	*P* = 0.1865†	*P* = 0.8356
Nappan						
	CT	3.79 ± 0.75 a	18.27 ± 0.36 a	8.79 ± 0.35 a	38.82 ± 1.33 a	25.62 ± 0.73 a
	DG	3.61 ± 0.47 a	18.18 ± 0.25 a	8.86 ± 0.43 a	39.13 ± 1.01 a	25.67 ± 0.85 a
	SE	3.96 ± 0.33 a	18.03 ± 0.19 a	8.71 ± 0.41 a	38.60 ± 1.34 a	25.43 ± 0.52 a
	PPER	4.23 ± 0.60 a	18.28 ± 0.39 a	7.86 ± 0.38 a	37.13 ± 1.47 a	26.61 ± 0.79 a
		P = 0.8818†	*P* = 0.9353	*P* = 0.2896	*P* = 0.7101 †	*P* = 0.6777†

[1] Analyses completed by Dr. Ajay K. Dalai of the University of Saskatchewan in Saskatoon, SK, Canada.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution.

Table A-22 Mean values of grass dry matter yield (kg ha^{-1}) and moisture content (%) measured in the fall of Year 4, and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Dry Matter Yield (kg ha^{-1})	Moisture Content (%)
Bible Hill			
Miscanthus	CT	11,505.27 ± 845.66 a	47.47 ± 1.44 a
	DG	10,825.77 ± 883.08 a	46.97 ± 0.97 a
	SE	10,785.97 ± 572.80 a	47.66 ± 1.31 a
	PPER	10,167.06 ± 1,163.51 a	44.75 ± 1.76 a
		P = 0.7716	*P* = 0.4612
Switchgrass	CT	867.80 ± 139.17 b	24.42 ± 6.22 a
	DG	1,656.64 ± 319.84 ab	24.53 ± 3.02 a
	SE	1,690.31 ± 290.45 ab	29.85 ± 6.26 a
	PPER	2,086.48 ± 429.69 a	20.88 ± 1.75 a
		P = 0.095 .	*P* = 0.6227
Nappan			
Miscanthus	CT	9,737.23 ± 861.22 a	38.96 ± 2.77 a
	DG	10,596.86 ± 572.70 a	37.43 ± 1.49 a
	SE	9,364.45 ± 809.45 a	37.37 ± 1.50 a
	PPER	11,441.63 ± 1,367.13 a	39.53 ± 2.97 a
		P = 0.4434	*P* = 0.8725
Switchgrass	CT	3,081.24 ± 761.70 a	19.70 ± 1.81 a
	DG	2,858.58 ± 611.81 a	20.71 ± 2.12 a
	SE	4,226.16 ± 664.58 a	20.19 ± 0.61 a
	PPER	3,993.96 ± 882.90 a	18.09 ± 1.68 a
		P = 0.5034	*P* = 0.7105

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Appendix B Chapter 3 Supplementary Material

Table B-1 Mean values of tree survival and dry matter yield (kg ha^{-1}) measured in November of year 1, and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Survival[1]	Dry Matter Yield (kg ha^{-1})[2]
Bible Hill			
Hybrid Poplar	CT	0.85 ± 0.05 a	29.85 ± 3.02 b
	DG	0.98 ± 0.004 a	38.88 ± 4.41 ab
	SE	0.95 ± 0.03 a	35.89 ± 5.75 ab
	PPER	0.93 ± 0.03 a	58.47 ± 11.75 a
		P = 0.9144	P = 0.06881 .
Willow	CT	0.82 ± 0.05 a	115.49 ± 51.08 a
	DG	0.90 ± 0.03 a	27.07 ± 1.50 b
	SE	0.89 ± 0.04 a	161.50 ± 78.85 a
	PPER	0.87 ± 0.04 a	64.51 ± 10.48 ab
		P = 0.9864	P = 0.02345 *
Nappan			
Hybrid Poplar	CT	0.98 ± 0.006 a	59.68 ± 7.14 b
	DG	0.99 ± 0.007 a	70.19 ± 15.69 b
	SE	0.97 ± 0.02 a	65.79 ± 1.18 b
	PPER	0.96 ± 0.01 a	180.27 ± 67.60 a
		P = 0.9936	P = 0.01053 *
Willow	CT	0.96 ± 0.01 a	40.97 ± 6.18 b
	DG	0.96 ± 0.02 a	54.40 ± 6.57 b
	SE	0.95 ± 0.02 a	44.16 ± 3.24 b
	PPER	0.96 ± 0.02 a	160.80 ± 27.78 a
		P = 0.9997	$P = 1.1674 \times 10^{-5}$ ***

[1] Chi-squared test.

[2] F test.

Means followed by the same lowercase letters within a crop and site are not significantly different at $P = 0.05$.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Table B-2 Soil analyses at Bible Hill and Nappan, Nova Scotia as measured in year 4[1]. Measurements taken at 1-15 cm.

		pH (pH Units)	Organic Matter (%)	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Bible Hill					
	CT	6.08 ± 0.08 a	2.89 ± 0.09 a	672.50 ± 22.24 a	305.88 ± 11.9 ab
	DG	6.12 ± 0.05 a	2.96 ± 0.09 a	736.19 ± 49.82 a	344.19 ± 20.31 a
	SE	6.04 ± 0.06 a	2.85 ± 0.07 a	672.81 ± 29.04 a	269.25 ± 11.25 b
	PPER	6.19 ± 0.08 a	2.94 ± 0.08 a	766.00 ± 47.63 a	289.25 ± 16.33 ab
		P = 0.6054	*P* = 0.7974 †	*P* = 0.2612	*P* = 0.02881 *
Nappan					
	CT	6.01 ± 0.04 a	2.55 ± 0.05 ab	424.13 ± 17.16 a	-
	DG	6.09 ± 0.04 a	2.61 ± 0.06 ab	440.88 ± 20.05 a	-
	SE	5.99 ± 0.02 a	2.46 ± 0.02 b	408.94 ± 7.71 a	-
	PPER	6.08 ± 0.05 a	2.63 ± 0.04 a	418.75 ± 12.67 a	-
		P = 0.2244	*P* = 0.0824 .	*P* = 0.5272	-

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

† Gamma family distribution and 'log' link function.

Table B-3 Soil potassium content analysis at Nappan, Nova Scotia as measured in year 4[1]. Measurements taken at 1-15 cm.

	K_2O (kg ha^{-1})
CT	96.25 ± 5.52 b
DG-1	109.38 ± 10.38 ab
SE-1	86.75 ± 1.53 b
PPER	102.38 ± 6.60 b
DG-2	135.88 ± 7.01 a
SE-2	96.75 ± 7.67 b
	P = 0.0033589 *

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters are not significantly different at *P* = 0.05.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Table B-4 Soil analyses at Bible Hill and Nappan, Nova Scotia as measured in year 4[1]. Measurements taken at 1-15 cm.

		Ca ($kg\ ha^{-1}$)	Mg ($kg\ ha^{-1}$)	Na ($kg\ ha^{-1}$)	S ($kg\ ha^{-1}$)
Bible Hill					
	CT	1,923.75 ± 80.99 a	325.38 ± 13.08 a	17.63 ± 0.80 a	20.50 ± 1.06 a
	DG	2,062.00 ± 152.80 a	330.63 ± 12.58 a	19.50 ± 1.36 a	23.19 ± 0.56 a
	SE	1,893.19 ± 128.18 a	319.75 ± 22.16 a	18.00 ± 1.36 a	21.44 ± 0.87 a
	PPER	2,163.25 ± 146.93 a	354.50 ± 12.32 a	17.13 ± 0.72 a	22.88 ± 0.99 a
		$P = 0.457$	$P = 0.4426$	$P = 0.486$	$P = 0.1695$
Nappan					
	CT	1,731.00 ± 59.39 a	236.88 ± 6.92 a	31.25 ± 0.92 a	20.75 ± 0.60 a
	DG	1,741.75 ± 69.88 a	262.88 ± 16.65 a	31.13 ± 1.56 a	22.63 ± 1.47 a
	SE	1,667.94 ± 36.99 a	230.94 ± 9.13 a	30.69 ± 1.07 a	21.25 ± 0.83 a
	PPER	1,733.00 ± 57.18 a	268.13 ± 9.76 a	31.50 ± 1.67 a	21.88 ± 0.72 a
		$P = 0.7872$	$P = 0.09067$.	$P = 0.9779$	$P = 0.5539$ †

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at $P = 0.05$.

Significance codes: 0'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

† Gamma family distribution and 'log' link function.

Table B-5 Soil analyses at Bible Hill and Nappan, Nova Scotia as measured in year 4[1]. Measurements taken at 1-15 cm.

		Al (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)
Bible Hill						
	CT	1,336.13 ± 53.23 a	1.16 ± 0.05 a	229.00 ± 17.93 a	51.13 ± 3.80 a	1.14 ± 0.06 a
	DG	1,379.13 ± 14.5 a	1.24 ± 0.04 a	216.06 ± 12.2 a	50.56 ± 3.14 a	1.39 ± 0.08 a
	SE	1,354.88 ± 35.49 a	1.17 ± 0.04 a	216.13 ± 16.75 a	50.19 ± 4.44 a	1.20 ± 0.08 a
	PPER	1,400.75 ± 63.65 a	1.27 ± 0.04 a	218.13 ± 16.75 a	52.75 ± 4.48 a	1.35 ± 0.10 a
		P = 0.7689	*P* = 0.2704	*P* = 0.9287	*P* = 0.9698	*P* = 0.1707
Nappan						
	CT	1,161.63 ± 24.24 a	0.73 ± 0.05 a	200.38 ± 8.69 a	59.25 ± 4.16 a	1.07 ± 0.08 a
	DG	1,126.31 ± 11.96 a	0.82 ± 0.07 a	199.81 ± 9.46 a	62.06 ± 3.58 a	1.06 ± 0.07 a
	SE	1,118.94 ± 22.86 a	0.75 ± 0.04 a	197.63 ± 6.04 a	61.94 ± 3.37 a	1.20 ± 0.11 a
	PPER	1,101.25 ± 26.02 a	0.71 ± 0.04 a	190.25 ± 9.13 a	58.75 ± 5.54 a	1.00 ± 0.06 a
		P = 0.314 †	*P* = 0.4573	*P* = 0.821	*P* = 0.9155	*P* = 0.3876 †

[1] Analyses completed by Nova Scotia Department of Agriculture Laboratory Services in Truro, NS.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

† Gamma family distribution and ‘log’ link function.

Table B-6 Mean values of tree survival in spring of year 2, and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Survival[1]
Bible Hill		
Hybrid Poplar	CT	0.87 ± 0.03 a
	DG	0.91 ± 0.01 a
	SE	0.88 ± 0.02 a
	PPER	0.90 ± 0.04 a
		P = 0.9988
Willow	CT	0.87 ± 0.03 a
	DG	0.87 ± 0.01 a
	SE	0.92 ± 0.03 a
	PPER	0.87 ± 0.05 a
		P = 0.9944
Nappan		
Hybrid Poplar	CT	0.89 ± 0.08 a
	DG	0.94 ± 0.03 a
	SE	0.95 ± 0.03 a
	PPER	0.98 ± 0.01 a
		P = 0.9653
Willow	CT	0.88 ± 0.07 a
	DG	0.94 ± 0.02 a
	SE	0.93 ± 0.04 a
	PPER	0.93 ± 0.04 a
		P = 0.9885

[1] Chi-squared test.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Table B-7 Mean values of dependent variables (stems per tree, total length of stems) as measured in November (end of season) of year 2 at Bible Hill and Nappan, Nova Scotia.

		Stem Count[1]	Stem Length[1] (cm)	Stem Diameter[1] (mm)
Bible Hill				
Poplar	CT	3 ± 0.5 ab	107.00 ± 22.88 b	0.375 ± 0.08 a
	DG	3 ± 0 b	121.00 ± 19.73 b	0.350 ± 0.03 a
	SE	2 ± 0.3 b	74.75 ± 18.58 b	0.325 ± 0.05 a
	PPER	4 ± 0.3 a	191.50 ± 15.00 a	0.400 ± 0.04 a
Willow	CT	3 ± 0.3 b	210.00 ± 63.14 b	0.375 ± 0.05 a
	DG	4 ± 0.6 ab	271.25 ± 33.46 ab	0.450 ± 0.03 a
	SE	3 ± 0.8 b	224.00 ± 37.30 b	0.425 ± 0.03 a
	PPER	6 ± 0.6 a	439.25 ± 61.6 a	0.450 ± 0.03 a
Nappan				
Poplar	CT	3 ± 0.7 a	135.50 ± 39.67 a	0.350 ± 0.03 b
	DG	3 ± 0.4 a	152.25 ± 41.95 a	0.425 ± 0.05 b
	SE	3 ± 0.8 a	154.00 ± 54.47 a	0.375 ± 0.05 b
	PPER	4 ± 0.8 a	271.5 ± 54.51 a	0.575 ± 0.03 a
Willow	CT	3 ± 0.6 a	235.50 ± 60.89 ab	0.400 ± 0.04 a
	DG	3 ± 0.5 a	248.50 ± 60.00 ab	0.425 ± 0.05 a
	SE	3 ± 0.3 a	189.75 ± 23.21 b	0.412 ± 0.07 a
	PPER	5 ± 0.8 a	422.25 ± 54.34 a	0.475 ± 0.02 a

[1] Secondary and tertiary stems per tree.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Table B-8 Mean values of dependent variables (stems per tree, total length of stems as measured in November (end of season) of year 3 at Bible Hill and Nappan, Nova Scotia.

		Stem Count[1]	Stem Length[1] (cm)	Stem Diameter[1] (mm)
Bible Hill				
Poplar	CT	1 ± 0.3 a	134.50 ± 28.65 a	0.75 ± 0.06 a
	DG	1 ± 0.2 a	164.75 ± 27.57 a	0.80 ± 0.07 a
	SE	1 ± 0.2 a	121.25 ± 48.46 a	0.70 ± 0.08 a
	PPER	2 ± 0.4 a	222.5 ± 58.97 a	0.90 ± 0.04 a
Willow	CT	1 ± 0.3 b	314.25 ± 70.59 a	1.050 ± 0.16 a
	DG	2 ± 0.3 ab	428.50 ± 50.87 a	1.275 ± 0.05 a
	SE	1 ± 0.3 b	371.00 ± 69.64 a	1.150 ± 0.06 a
	PPER	3 ± 0.0 a	528.00 ± 73.05 a	1.125 ± 0.08 a
Nappan				
Poplar	CT	2 ± 0.7 a	221.75 ± 73.16 a	0.825 ± 0.05 b
	DG	1 ± 0.5 a	224.25 ± 62.00 a	0.925 ± 0.02 ab
	SE	1 ± 0.5 a	226.00 ± 64.37 a	0.850 ± 0.05 b
	PPER	2 ± 0.3 a	338.00 ± 51.21 a	1.050 ± 0.06 a
Willow	CT	2 ± 0.4 a	411.75 ± 77.61 a	1.100 ± 0.11 a
	DG	2 ± 0.5 a	517.00 ± 119.30 a	1.175 ± 0.09 a
	SE	2 ± 0.0 a	364.50 ± 59.94 a	1.050 ± 0.09 a
	PPER	2 ± 0.5 a	581.75 ± 133.85 a	1.225 ± 0.05 a

[1] Secondary and tertiary stems per tree.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Table B-9 Mean values of tree stem volume (cm^3 m^{-2}) as measured in November (years 2 and 3 at Bible Hill and Nappan, Nova Scotia.

		Tree Stem Volume (cm^3 m^{-2})[1]	
		Year 2	Year 3
Bible Hill			
Hybrid-poplar	CT	8.73 ± 3.50 a	40.01 ± 13.80 a
	DG	11.78 ± 3.27 a	57.21 ± 17.40 a
	SE	5.13 ± 2.94 a	40.62 ± 27.69 a
	PPER	19.59 ± 5.82 a	82.34 ± 26.42 a
		P = 0.1278	*P* = 0.6143
Willow	CT	29.92 ± 9.83 a	180.54 ± 71.11 a
	DG	32.80 ± 3.65 a	295.49 ± 56.02 a
	SE	27.77 ± 5.12 a	270.11 ± 85.22 a
	PPER	60.07 ± 20.05 a	302.53 ± 92.05 a
		P = 0.2213	*P* = 0.6718
Nappan			
Hybrid-poplar	CT	12.31 ± 6.33 a	92.90 ± 47.04 a
	DG	19.56 ± 9.88 a	105.34 ± 22.08 a
	SE	17.52 ± 11.36 a	122.33 ± 63.28 a
	PPER	52.64 ± 14.58 a	276.13 ± 78.60 a
		P = 0.2218	*P* = 0.1327
Willow	CT	23.79 ± 9.70 a	245.58 ± 76.10 a
	DG	32.12 ± 12.08 a	402.01 ± 141.02 a
	SE	27.29 ± 12.83 a	210.78 ± 70.81 a
	PPER	58.16 ± 14.00 a	453.18 ± 159.35 a
		P = 0.3711	*P* = 0.3546

[1] Based on 2020 survival data.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Table B-10 Mean values of tree survival and dry matter yield (kg ha^{-1}) measured in November of year 4, and significance levels from analysis of deviance for generalized linear model (GLM) fits.

		Survival	Dry Matter Yield (kg ha^{-1})
Bible Hill			
Hybrid Poplar	CT	0.85 ± 0.05 a	3,004.40 ± 1,329.32 ab
	DG	0.98 ± 0.004 a	2,112.44 ± 495.51 b
	SE	0.95 ± 0.03 a	1,093.99 ± 517.72 b
	PPER	0.93 ± 0.03 a	5,243.30 ± 1,036.56 a
		P = 0.7963[1]	*P* = 0.008693 **[2]
Willow	CT	0.82 ± 0.05 a	7,719.35 ± 3,544.46 a
	DG	0.90 ± 0.03 a	5,207.45 ± 562.95 a
	SE	0.89 ± 0.04 a	5,074.75 ± 1,087.95 a
	PPER	0.87 ± 0.04 a	10,477.38 ± 3,892.29 a
		P = 0.9969	*P* = 0.4748
Nappan			
Hybrid Poplar	CT	0.98 ± 0.006 a	2,262.82 ± 444.98 b
	DG	0.99 ± 0.007 a	1,946.73 ± 574.6 b
	SE	0.97 ± 0.02 a	1,873.58 ± 773.34 b
	PPER	0.96 ± 0.01 a	6,314.65 ± 1,254.35 a
		P = 0.9474	*P* = 0.006087 **
Willow	CT	0.96 ± 0.01 a	11,110.71 ± 3,958.27 ab
	DG	0.96 ± 0.02 a	7,805.23 ± 2,566.94 ab
	SE	0.95 ± 0.02 a	4,454.97 ± 1,271.34 b
	PPER	0.96 ± 0.02 a	19,024.05 ± 4,469.00 a
		P = 0.9552	*P* = 0.04777 *

[1] Chi-squared test.

[2] F test.

Means followed by the same lowercase letters within a crop and site are not significantly different at *P* = 0.05.

Significance codes: 0’***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1

Appendix C Chapter 4 Supplementary Material

Table C-1 Comparison of model performance indices between switchgrass Models 1 and 2.

Model	AIC	Marginal R^2	Conditional R^2	RMSE
1	289.5	0.122	1.725	0.457
2	283.3	0.110	0.686	0.471

Table C-2 Comparison of model performance indices between switchgrass Models 3 and 4.

Model	AIC	Marginal R^2	Conditional R^2	RMSE
3	301.7	0.179	0.695	0.464
4	284.8	0.149	0.679	0.469

Table C-3 Comparison of model performance indices between switchgrass Models 5 and 6.

Model	AIC	Marginal R^2	Conditional R^2	RMSE
5	290.1	0.140	0.722	0.455
6	283.1	0.147	0.682	0.467

Table C-4 Mean measured switchgrass biomass yield (Mg ha^{-1} $year^{-1}$) from Nova Scotia and predicted switchgrass biomass yield from the original model (Model 6).

Study	Location	Stand Year	Precipitation (mm)	GDD	Measured Yield (Mg ha^{-1} $year^{-1}$)	Predicted Yield (Mg ha^{-1} $year^{-1}$)
[320]	Nappan, NS, CA	2	522.30	1695.6	4.75	4.02
[320]	Nappan, NS, CA	3	788.90	1746.8	3.76	3.66
[320]	Nappan, NS, CA	4	681.50	1740.7	9.00	4.58
[320]	Nappan, NS, CA	5	426.40	1733	7.33	4.20
[321]	Nappan, NS, CA	2	426.40	1733	19.55	3.46
[321]	Nappan, NS, CA	2	426.40	1733	16.42	3.46
[322]	Nappan, NS, CA	2	426.40	1733	3.85	3.46
[322]	Nappan, NS, CA	3	396.60	1711	1.72	3.40
[322]	Nappan, NS, CA	4	397.10	1631.7	2.83	3.55
[322]	Nappan, NS, CA	5	774.80	1479.3	5.12	3.93
[322]	Nappan, NS, CA	6	329.30	1699.2	1.36	3.34
[322]	Nappan, NS, CA	2	426.40	1733	2.10	3.46
[322]	Nappan, NS, CA	3	396.60	1711	1.25	3.40
[322]	Nappan, NS, CA	4	397.10	1631.7	1.78	3.55
[322]	Nappan, NS, CA	5	774.80	1479.3	3.49	3.93
[322]	Nappan, NS, CA	6	329.30	1699.2	0.41	3.34
[323]	Nappan, NS, CA	2	329.30	1699.2	1.26	2.35
[323]	Nappan, NS, CA	3	682.10	1761.4	1.68	4.36
[323]	Nappan, NS, CA	4	499.90	1764.4	3.08	4.50
[323]	Bible Hill, NS, CA	3	602.20	1760.1	2.00	4.51
[323]	Bible Hill, NS, CA	4	531.60	1743.1	0.87	4.61
[323]	East Gore, NS, CA	2	466.81	1805.1	4.18	3.86
[323]	East Gore, NS, CA	3	473.76	1703.8	2.69	4.03
[323]	East Gore, NS, CA	4	748.88	1809.4	4.00	4.31
[323]	Port Hood, NS, CA	2	411.53	1629.6	2.68	3.19

Study	Location	Stand Year	Precipitation (mm)	GDD	Measured Yield (Mg ha^{-1} $year^{-1}$)	Predicted Yield (Mg ha^{-1} $year^{-1}$)
[323]	Port Hood, NS, CA	3	396.81	1724.2	2.47	3.42
[323]	Port Hood, NS, CA	4	464.22	1783.6	2.69	4.31
[323]	East Skye Glen, NS, CA	2	411.53	1629.6	7.78	3.19
[323]	East Skye Glen, NS, CA	3	396.81	1724.2	6.06	3.42
[323]	East Skye Glen, NS, CA	4	754.10	1833.1	6.97	4.30

Table C-5 Comparison of model performance indices between miscanthus Models 1 and 2.

Model	AIC	Marginal R^2	Conditional R^2	RMSE
1	83.78	0.574	0.855	0.315
2	85.18	0.774	N/A	0.362

Table C-6 Mean measured miscanthus biomass yield (Mg ha^{-1} year^{-1}) from Nova Scotia and predicted miscanthus biomass yield from the maximal miscanthus model.

Study	Location	Stand Year	Precipitation (mm)	GDD	Measured Yield (Mg ha^{-1} year^{-1})	Predicted Yield (Mg ha^{-1} year^{-1})
Vessey et al., 2022	Nappan, NS, Canada	2	329.30	1699.2	2.70	3.29
Vessey et al., 2022	Nappan, NS, Canada	3	682.10	1761.4	9.09	9.32
Vessey et al., 2022	Nappan, NS, Canada	4	499.90	1764.4	9.73	7.61
Vessey et al., 2022	Bible Hill, NS, Canada	2	459.10	1651	1.36	2.34
Vessey et al., 2022	Bible Hill, NS, Canada	3	602.20	1760.1	9.09	8.19
Vessey et al., 2022	Bible Hill, NS, Canada	4	531.60	1743.1	11.51	7.16
Vessey et al., 2022	East Gore, NS, Canada	2	466.81	1805.1	1.20	7.27
Vessey et al., 2022	East Gore, NS, Canada	3	473.76	1703.8	4.41	4.65
Vessey et al., 2022	East Gore, NS, Canada	4	748.88	1809.4	6.67	14.31
Vessey et al., 2022	Port Hood, NS, Canada	2	411.53	1629.6	1.07	1.96
Vessey et al., 2022	Port Hood, NS, Canada	3	396.81	1724.16	4.82	4.72
Vessey et al., 2022	Port Hood, NS, Canada	4	464.22	1783.6	9.75	7.73
Vessey et al., 2022	East Skye Glen, NS, Canada	2	411.53	1629.6	7.11	1.96
Vessey et al., 2022	East Skye Glen, NS, Canada	3	396.81	1724.16	14.07	4.72
Vessey et al., 2022	East Skye Glen, NS, Canada	4	754.10	1833.1	13.15	16.17

Appendix D Chapter 5 Supplementary Material

Table D-1 Mean measured hybrid-poplar biomass yield (Mg ha^{-1} $year^{-1}$) from Nova Scotia and predicted hybrid-poplar biomass yield from Model 2.

Study	Location	Rotation	Stand Year	Precipitation (mm)	GDD	Measured Yield (Mg ha^{-1} $year^{-1}$)	Predicted Yield (Mg ha^{-1} $year^{-1}$)
Vessey et al. 2022	Nappan, NS, CA	1	4	499.90	1764.4	0.76	3.31
Vessey et al. 2022	Bible Hill, NS, CA	1	4	531.60	1743.1	1.00	3.24
Vessey et al. 2022	East Gore, NS, CA	1	4	748.88	1809.4	0.32	6.35
Vessey et al. 2022	Port Hood, NS, CA	1	4	464.22	1783.6	0.12	3.12
Vessey et al. 2022	Skye Glen, NS, CA	1	4	754.10	1833.1	5.93	9.51

Table D-2 Mean measured willow biomass yield (Mg ha^{-1} $year^{-1}$) from Nova Scotia and predicted willow biomass yield from Model 2.

Study	Location	Rotation	Stand Year	Precipitation (mm)	GDD	Measured Yield (Mg ha^{-1} $year^{-1}$)	Predicted Yield (Mg ha^{-1} $year^{-1}$)
Vessey et al. 2022	Nappan, NS, CA	1	4	499.90	1764.4	3.70	5.30
Vessey et al. 2022	Bible Hill, NS, CA	1	4	531.60	1743.1	2.57	4.55
Vessey et al. 2022	East Gore, NS, CA	1	4	748.88	1809.4	0.13	2.99
Vessey et al. 2022	Port Hood, NS, CA	1	4	464.22	1783.6	0.22	3.13
Vessey et al. 2022	Skye Glen, NS, CA	1	4	754.10	1833.1	7.93	7.92