Open Geospatial Viticulture: Determining the Mesoscale Impact of Climatic Change for Quebec's Winegrowing Bioclimatology

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

The combined utilization of climate scenarios, climate models and Geographic Information Systems [GIS] represent the most reliable tools to spatially determine the potential impacts of climate change in the near to end-of-century time horizons. With affordable computation, massive and open online courses, open access journals, cloud-based data visualization platforms, countless repositories of environmental and climate data available through the Internet, and the Free and Open Source [FOS] software movement, geospatial analysis is becoming an increasingly accessible field for professional researchers, the technically inclined, and the general public.

I present here a Master's thesis that has been developed primarily using FOS software and openly accessible environmental data with few usage restrictions. The analysis is a multi-criteria-based suitability and climate categorization of Southern Quebec for European *V. vinifera* wine grape viticulture. Using several openly available GIS data sources, I identify and categorize the wine regions of Quebec according to a series of climate metrics developed specifically for wine studies. My analysis is based on both NASA Daymet present-day satellite-observed climate grids (Thornton et al., 2015) and ClimateNA (Wang, Hamann, Spittlehouse, & Carroll, 2016), a statistically downscaled gridded data set of 30-year climate normals extending from years 1980 to 2100 for two climate change scenarios, the Representative Concentration Pathways scenarios [RCP] 4.5 and 8.5 (Moss et al., 2010). I perform my analysis by examining the results of these viticultural metrics and climate variables both at the regional scale and at locations of presently-operating vineyards. All results are determined spatially using QGIS (QGIS Development Team, 2016) and other Open Source GNU/Linux utilities (Debian Project, 2015).

My results show that present-day Saint Lawrence Seaway Valley barely exceeds the needed thermal suitability threshold for *V. vinifera* viticulture with most of *Montérégie* and *Estrie* at or below most “Cool Climate” categorizations and other agricultural zones are located well below climatic suitability for European viticulture. For future projections both RCP scenarios mirror an increase of ~200 growing degree-days [GDDs, ºC] from 1981-2010 to the 2011-2040 period and strongly diverging for periods afterwards. Results using the RCP 4.5 “Stabilization” show present-day vineyard locations may experience an increase in climate region category by roughly one or two climate categories (“Temperate” and “Warm”), while the

RCP 8.5 “Business as Usual” scenario shows some present vineyard locations may become unsuitably hot with “Warm” viticultural climates extending above 50 ºN.

I also present an extended literature review and methodology chapter that summarizes and explores my experience in employing almost exclusively FOS software and unrestricted data. This chapter is structured in a non-traditional fashion and is meant to provide an introductory background and discussion of the history of Open Source/Data/Access and Open Government movements. An extended methodology explores FOS software, Open Data resources, and showcases an example methodology for an agriculturally-focused FOS-GIS analysis. While the FOS movement is not presently capable of replacing all proprietary tools or present models of knowledge dissemination, Open Source approaches and a fostering of the Open ecosystem can be greatly beneficial for both the individual and at societal levels.

Acknowledgements

There are many people I'd like to thank for their advice, expertise, moral support, interest, and encouragement that has lead me to this achievement. I begin by thanking the members of the Climate Change Science Impacts and Mitigation Studies (C2SIMS) lab who have provided me with feedback, advice, and encouragement (despite being on the receiving end of some really terrible presentations, including the practice run of this thesis presentation). I'd like to especially thank Donny Seto, for always taking a moment to listen, and whose advice has helped me both academically and professionally. With great admiration, I sincerely thank Professor H. Damon Matthews for his encouragement, support, and – above all – patience in the past several years I have studied under him.

This work could not have been possible without the effort and commitment of developers within the Open Source community, who continuously work to produce reliable and open software to democratize the digital tools for the world peoples. I extend my thanks to Geography, Planning, and Environment Professors Pascale Biron, Sébastien Caquard, and Kevin Gould, as well as the GIS and Data Librarian, Alex Guindon, and Geography, Planning, and Environment Network Administrator, Marco Burelli, for their thoughts, guidance, and support over the course of both my Master and Baccalaureate degrees. I would also like to thank Journalism Professors Fenwick McKelvey of Concordia University and Rob McMahon of the University of Calgary, and Environment and Sustainability Professor David N. Oswald of Royal Rhodes University for the opportunities they presented to me to really delve into the literature on Open Source GIS. I would like to thank Professors Andreas Hamann and Tongli Wang and their research team at the University of Alberta for developing a key data set that my main analysis is built upon. Many thanks to Fabien Gagné of *l'Assocation des Vignerons du Québec* (AVQ) for providing me with Quebec vineyard industry data that was integral to one of my analyses. I'd also like to thank the research funding agencies, FQRNT, NSERC, and CIWESS for considering my wine/GIS analysis a worthwhile application to support throughout the course of my graduate studies.

I would never have settled on this topic if I hadn't met Professor Norman K. Jones at the Wine Studies session held at the Canadian Association of Geographers Conference at Memorial University of Newfoundland in 2013 and would like to thank him for his advice and for being a member of my review committee for the proposal and defence of my thesis. As I happened to be hitchhiking throughout Atlantic Canada that summer, I'd like to sincerely thank those who picked me up on the side of Newfoundland and Labrador Route 1 as I would never have made it to Saint John's in time without their kindness – a special thank you to Angela and Rob Piercey for housing, feeding, and driving me the last leg of that journey.

Much love goes out to Laura Stephanie Roch, best friend slash crazy person, who has had my back for years (despite her better judgment) and remains one of the most important people in my life, David Beauchesne, for all the good advice that I just didn't take (and who would've thought, it figures), Jessica Cabana and Benjamin Prunty, for the use of their living room futon where a significant portion of Chapter 4 was written, and Rebecca Deagle and Marcus Peters, for their help and moral support in the final hours leading up to my thesis defence.

I'd also like to thank Pierson Nettling for convincing me that I am (though I'm reluctant to admit it) a cultural geographer, Kiley Goyette and Noah Cannon for being my all-time biggest fans, Anthony Garoufalis-Auger for his motivating enthusiam, Keroles Riad, for all of his hard work, Julia Gregory for being supermom and an all-around wonderful person, and the members of GEOGRADS, the Concordia Student Union, Divest Concordia, Sustainable Concordia, and QPIRG Concordia for their passionate and tireless efforts to help make Concordia a better university. A special thanks also to Cristine Mongeau, for all the impromptu wine tastings that got me hooked on the stuff.

I wouldn't have been able to write this thesis without the moral support of my wonderful and loving partner, Cassandra Lamontagne, who has endured my anxiety and meltdowns, supporting me every step of the way.

Finally, I would like to dedicate this thesis to my late grandmother, Esther Kronick Smith, whose encouragement, kindness, and personal strength were an inspiration for me to push myself to keep trying, despite everything.

Table of Contents

Index of Figures

Index of Tables

Index of Equations

List of Acronyms

(Non-English names and terms italicized)

- AAFC – Agriculture and Agri-Food Canada
- AOC – *Apellation d'Origine Controllée*
- AVA – American Viticultural Area
- AVQ – *Association des Vignerons du Québec*
- BBL – Branas, Bernon, and Levadoux Hydrothermal Index
- BEDD – Biologically-Effective Growing Degree-Days
- CMD – Climatic Moisture Deficit
- CMIP – Coupled Model Intercomparison Project
- CNI – Cool Night Index
- COP – Conference of the Parties to the UNFCCC
- CPTAQ – *Commission de Protection du Territoire Agricole* (Quebec)
- DEM – Digital Elevation Model
- DI – Dryness Index
- DOCG – *Denominazione di Origine Controllata e Garantita*
- FOS – Free and Open Source
- FSF – Free Software Foundation
- GCM – General Circulation Model or Global Climate Model
- GDAL – Geospatial Data Abstraction Library
- GDD – Growing Degree-Days
- GDI – Geospatial Data Infrastructure
- GIS – Geographic Information System
- GST – Growing Season Temperature
- HI – Huglin Heliothermal Index

- IPCC – Intergovernmental Panel on Climate Change
- ISO – International Organization for Standardization
- LTI – Latitude-Temperature Index
- LULUCF – Land Use, Land Use Change, and Forestry
- MAPAQ – *Ministre de l'Agriculture, des Pêcheries et de l'Alimentation* (Quebec)
- MERN – *Ministre de l'Énergie et des Ressources Naturelles* (Quebec)
- NGO – Non-Governmental Organization
- NRCan – Ministry of Natural Resources Canada
- OGC – Open Geospatial Consortium
- OS – Operating System
- QGIS – Previously “Quantum GIS” Software; Later shortened to “QGIS”
- RCP – Representative Concentration Pathways; RCP 2.6, 4.5, 6.5, and 8.5
- RF – Radiative Forcing (W/m^2)
- SAQ – *Société des alcools du Québec* (liquor commission of Quebec)
- SRES – IPCC Special Report on Emissions Scenarios; SRES B1, A1B, A2, etc.
- StatsCan – Statistics Canada
- UNFCCC – United Nations Framework Convention on Climate Change
- VQA – Vintners Quality Association
- WI – Winkler Growing Degree-Day Index (Growing Degree-Days above Base 10º C)

Foreword

I get asked often how some guy from Quebec who has never once stepped foot in a vineyard decided to spend years examining them virtually. The truth is, like most odd things, it's a long story; my personal justifications for focusing on wine stems from a passion in discovering the intricate complexities of wine and a scholarly interest in developing my aptitude in the geospatial and climate sciences.

The research that I present here is meant to offer a concise examination of a few key areas of interest that center around the themes of climatic change and geospatial agricultural or viticultural analysis techniques, and I have purposely highlighted the near exclusionary use of Open Source software, data and/or materials held in the Public Domain. In performing the background research for this thesis, I was able to immerse myself into these very different yet intersecting topics, was fortunate enough to integrate knowledge gained and data sets discovered in the pursuit of seemingly-unrelated research projects, and found a way to bring this all together using methods and technologies that continue to amaze me. While I recognize that this document is quite long and unnecessarily verbose, this manuscript represents an enormous amount of work, headaches, and perseverance that I am immensely grateful to have had the opportunity to draft it.

Chapter 1 - Introduction

Section 1.1 - Key Concepts

1.1.1 - Tackling Climatic Change

Global scale environmental problems, according to policy researchers, are considered to be "wicked problems" (Ludwig, 2014; Rittel & Webber, 1973): problems with numerous conflicting goals, without clear definitions of success, and without precedents or space for potential replication. Global Warming and Climate Change, the recent global-scale increase in mean annual temperatures worldwide and the resultant climatic anomalies experienced at regional and local scales, are beyond reasonable doubt an observed climatic departure since the last glacial maximum and a problem of anthropogenic origin requiring immediate action (J. Cook et al., 2016; IPCC, 2014a; Marcott, Shakun, Clark, & Mix, 2013).[1] The combined impacts from anthropogenic sources such as increasing levels of industrialization, population affluence, and land use change are together increasing the amount of greenhouse emissions and decreasing the ability of natural sinks to draw down these emissions are contributing to the carbon saturation of the atmosphere and other natural carbon sinks (Rosenzweig, Neofotis, & Vicarelii, 2008). These problems are compounded by the complexity of fragmented global-scale politics/policies and climate mitigation negotiations (Ludwig, 2014; UNFCCC, 2015), a dwindling global carbon emissions allowance (Zickfeld, Eby, Matthews, & Weaver, 2009), and the asynchronous timescales and severity of climate change impacts expected between wealthier and poorer regions (Harrington et al., 2016). Research groups, Non-Government Organizations [NGOs], corporations and government agencies have been increasingly taking part in the adaptation planning process by analyzing, localizing, and planning for the potential dangers of inaction, as they have been comprehensively reviewed by the Intergovernmental Panel on Climate Change (IPCC, 2014a; Warren & Lemmen, 2014; World Bank Group, 2014), as well as accounting for the pledged greenhouse emission reductions following the COP21 meeting in Paris (FAO, 2016; Gignac & Matthews, 2015).

1 A compendium of consensus statements from major research institutions and societies assembled by NASA can be found at the following website: http://climate.nasa.gov/scientific-consensus/

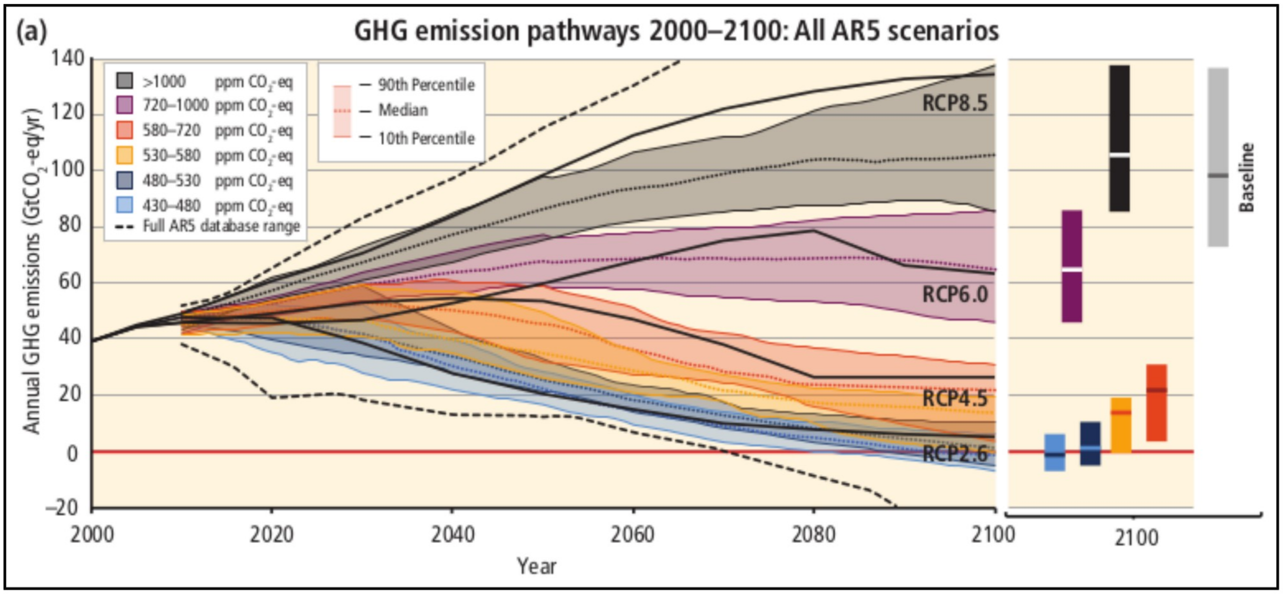

Figure 1-1: Confidence Intervals for Greenhouse Gas Emissions Trends According the the IPCC Representative Concentration Pathway (RCP) Scenarios (IPCC, 2014a, fig. SPM.11-a)

One method proposed by the scientific community as a means of reducing complexity and visualizing the potential policy approaches with regards to climate change mitigation is scenario development (Levin, Cashore, Bernstein, & Auld, 2012; Moss et al., 2010; Nakicenovic et al., 2000). Quantifying and temporalizing the different pathways available for collective global mitigation is particularly useful as a means of weighing the costs and benefits of actions (or inaction). The most recent climate change scenarios adopted by the IPCC, the Representative Concentration Pathways (Moss et al., 2010), provide a set of estimates based on end-of-century anomalies to the global radiation budget [Figure 1-1].[2] Predicting climate impacts using these pathways usually involves climate model simulations at global scales that are then reanalyzed to regional, and/or local scales and for anthropogenic sectors and interests, moving from the abstract/conceptual to the tangible/sensible, with each step introducing parameterizations and new levels of uncertainty (Prather et al., 2009). Caveats aside, these scenarios and their gridded climate model estimations present the most approachable and easily replicable means of performing climate prediction analysis [Figure 1-2].

2 RCPs 2.6, 4.5, 6.0, and 8.5 all refer to potential radiative forcing (W/m^2) anomalies experienced at year 2100, though some scenarios may peak at higher radiative values than their namesake within the century before falling.

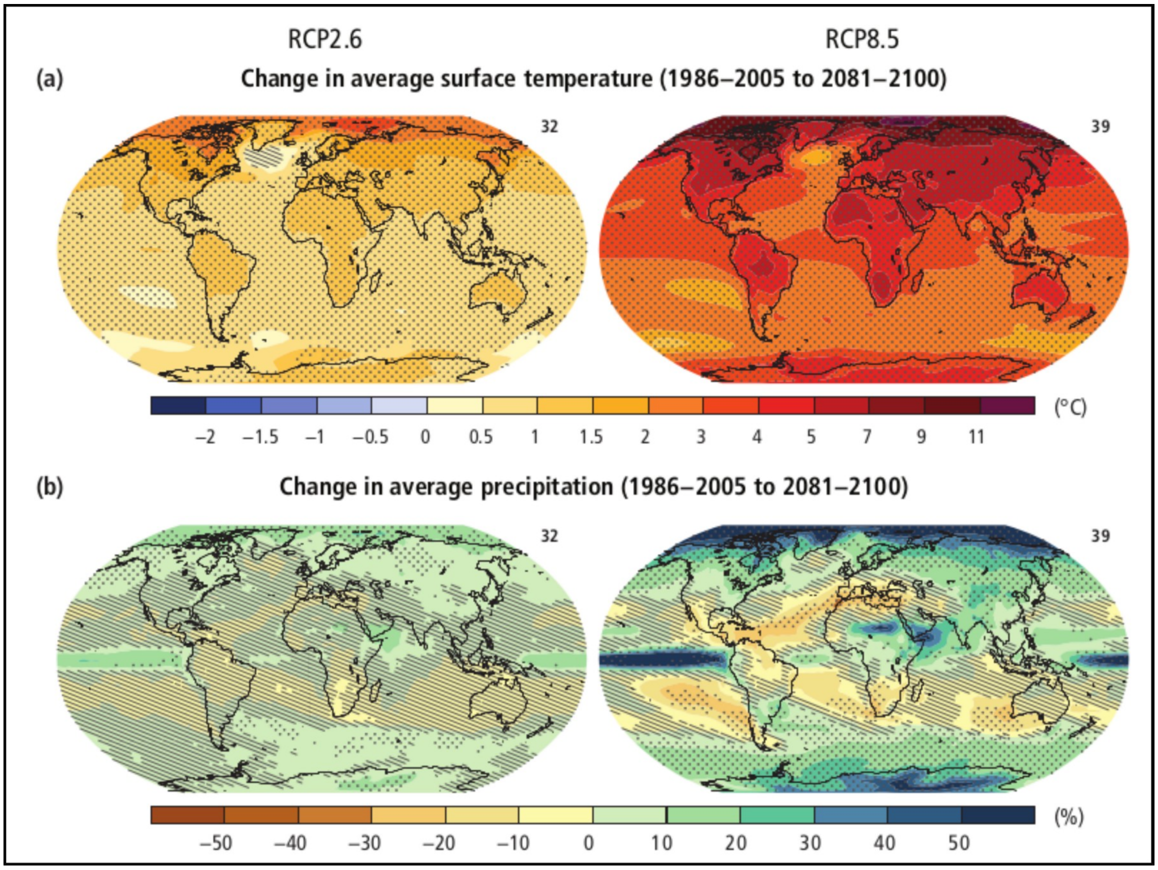

Figure 1-2: Comparison of the Global Temperature and Precipitation Anomalies Anticipated from Strongly Mitigated (RCP 2.6) and Unmitigated (RCP 8.5) Scenarios of Climate Change (IPCC, 2014a, fig. SPM.7)

1.1.2 - *Performing Geospatial (Bio-)Climatology*

One among many major applications of climate model output is to predict potential climatic departures (or anomalies) from present-day and to determine the potential impacts of anomalies on human and environmental systems (e.g. flood risk, labour productivity, agriculture) (Bootsma, Gameda, & McKenney, 2005; Kjellstrom, Kovats, Lloyd, Holt, & Tol, 2009; Muis, Güneralp, Jongman, Aerts, & Ward, 2015). Determining local-scale daily meteorological changes or seasonal trends between multi-decade normalization periods is particular importance in performing agroclimatology – determining the climatic suitability for agricultural production in an area or modelling the shifting of important phenological dates for a major crop species – which focuses not only affects yields but can extend to examine impacts on economic, financial, cultural, and other systems (Bernetti, Menghini, Marinelli, Sacchelli, & Sottini, 2012; IPCC, 2014b; Lesk, Rowhani, & Ramankutty, 2016; Lobell, Field, Cahill, & Bonfils, 2006). Agroclimatic metrics such as growing degree days [GDDs], Growing Season Precipitation [GST], Frost Free Period [FFP], and other biolcimatic indicators that can characterize crop suitability and risk are of immense importance in determining the type, amount, and timing of crop planting and cultivation by agricultural operators (Bryant, Singh, & André, 2007; Mosedale, Wilson, & Maclean, 2015; Shen, Basist, & Howard, 2010). This information can be gathered directly from weather station point sources and then interpolated across landscapes or gathered though raw or processed satellite imagery (remote sensing). For climatology, particular emphasis is placed on multi-decadal periods in order to obtain a statistically representative sample of expected monthly and seasonal precipitations and temperatures that allow for comparisons between other multi-decade periods (normalization periods).

Of particular importance for predictive climatology is that Geographic Information Systems [GIS] can be used in translating coarse global data to finer regional and local levels (Daly, 2006; Daly et al., 2008); As raw general circulation model outputs are coarse in spatial resolution, techniques that integrate local topography, convective patterns, and the existing climate record are used to create predictive masks that aid in translating coarse-scale phenomena (Daly et al., 2008; Wang, Hamann, Spittlehouse, & Aitken, 2006). These masks can then be combined with additional raster and vector data allowing for innumerably diverse and specialized approaches to site characterization and suitability analyses depending on the temporal and spatial scales as well as the technologies (GPS, GIS, satellite imagery) available on hand (Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014; Kurtural, Dami, & Taylor, 2007; Tomasi, Gaiotti, & Jones, 2013; Vaudour & Shaw, 2005). As technologies to perform geospatial viticulture have become more accessible both financially and from a technical perspective (with developments such as cloud-based GIS), these types of viticultural analyses have become more accessible to the scientific and professional communities as well as small-holder vineyard operators (Tomasi et al., 2013).

1.1.3 - Engaging in Free and Open Source GIS

With the rise in popular use in recent decades of GIS techniques and software, methods of integrating and analyzing gridded climate data as well as remotely sensed, locally surveyed, and other cartographic data sets has become a financially affordable and technically accessible approach for establishing spatial relationships and phenomena; on the technical side of this accessibility, this is largely due to the declining cost of computation power, the wide array of available specialized GIS software (OSGeo Contributors, 2013), the enormous number of standardized and open data sets now produced (Hengl et al., 2014; Sinha, 2015), and the expanding availability of high-speed Internet; from the legal and policy side, the development and release of software, data, and knowledge under the principles of “Open Source” – where the source materials or source code, the human-readable basis of software, are available to be distributed, scrutinized, modified, and recompiled with very few restrictions – has revolutionized the way that research and the production of knowledge is performed between individual researchers, institutions, and agencies (Open Knowledge International, 2016a, 2016b). This emerging technical and ideological climate has changed the way that research is performed across the world today.

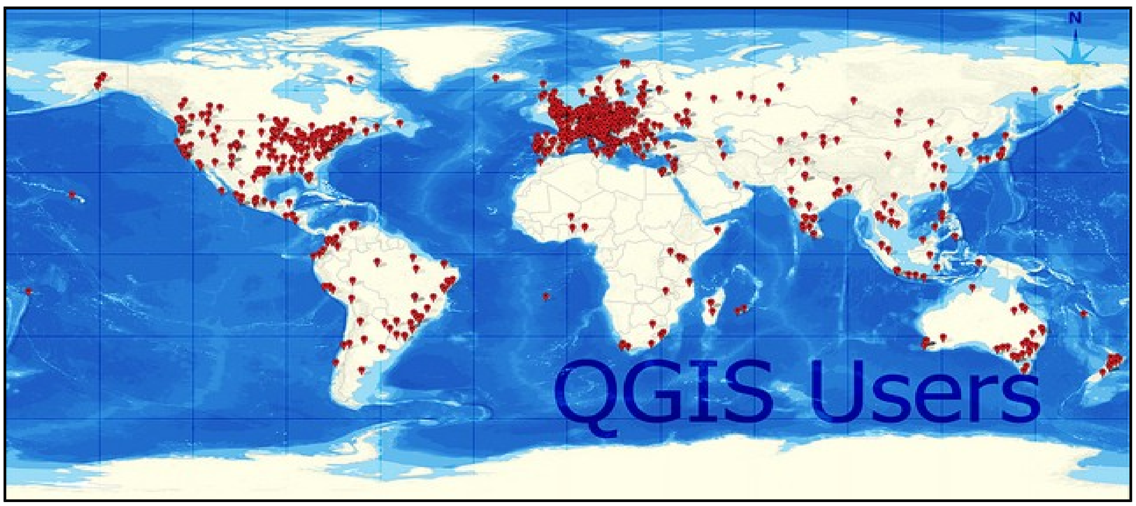

Figure 1-3: Map of QGIS Users by Location throughout the World, circa 2013 (Woodrow, 2013), licensed under CC-BY 2.0

In abandoning the subscription-payment model of proprietary GIS, Free and Open Source GIS [FOS-GIS] analysis is becoming a more widely-adopted skill at the fingertips of those interested, and not so much a specialization unique to geographers and environmental researchers. For general researchers. the number of FOS resources available for spatial analysis and visualization by way of platforms, data sources and accompanying documentation are plentiful. For traditional desktop GIS analyses, QGIS [Figure 1-3] (QGIS Development Team, 2016) and other FOS-GIS platforms are quickly becoming a major competitor to proprietary GIS for education, research, and web services, while written and audiovisual documentation and training resources are being constantly developed and made available for all levels of technical proficiency.

Spatial analysis, and even more so climate-focused spatial analysis, has become more accessible than ever thanks to the rapid development of FOS-GIS and “Open Science”. It is within this context that I present the following thesis and research project that builds upon the themes of climatology, spatial analysis and “Open” approaches. Working from this intersection of disciplines and within the context of the “Open” movement, this research is a summary of approaches and background for performing “Open Science” in geography.

Section 1.2 - Structure of the Thesis

The supporting works and knowledge that builds upon the background necessary in achieving the goals outlined in the previous section, largely borrowed from Climate Change studies, agroclimatology, GIS, and vineyard site suitability, are elaborated on in Chapter 2.

Throughout the entirety of this research, I have pursued where possible to use Free and Open Source software, operating systems, and data. My research concerning the history of the Open Source movement and its influences on creative use rights, government transparency and spatial data infrastructure have been summarized in the first half of Chapter 3. An example for performing a total agricultural extent analysis in Southern Quebec is illustrated in the second half of Chapter 3, ending with some limitations, lessons learned and some comments on Open Source use in academia.

The primary analysis of viticultural physical climate for Southern Quebec, with methods, results and discussion detailing the majority of findings and predictions for viticulture and geospatial bioclimatology are illustrated in Chapter 4.

The thesis concludes with a brief statement stressing the need for greater global cooperation if global societies wish to avert the worst possible outcomes of climatic change in Chapter 5.

Additional tables and example methodologies present in Annexes 1 – 5 are representative of further analyses and additional work that may be part of an upcoming research project extending from Chapter 4. The text of the Creative Commons license that this work is distributed under can be found in Annex 6.

Section 2.1 - Overview

The research reviewed in this section bridges the fields of viticulture, spatial analysis, and climatology, and stems from numerous backgrounds ranging from climate science, biology, statistics, geography, anthropology, history and economics. For the purpose of this research, the literature is categorized as follows: Viticulture, Agriculture and Climate Change; Spatial Analysis and Assessment Techniques; Wine Geography, History & Society; Metrics, Phenology and Horticulture; and General Atmosphere & Earth Science [Figure 2-1].

Figure 2-1: Breakdown of Literature Examined by Topic Categories

2.1.1 - Climate Change and Potential Agricultural Impacts

The beginnings and rise of industrialism, made possible through fossil fuel combustion technology over the course of the past 250 years, has led to a significant release of greenhouse gas emissions, contributing to the enhanced greenhouse effect. Atmospheric loading of greenhouse gases from anthropogenic origin, which alter the radiation budget of Earth by trapping or repelling incoming and outgoing radiation, has resulted in a steady increase in energy retained from the Sun (Ramanathan, 1988). The ongoing and accelerated emissions associated with the need to satisfy demands of energy, transportation, food and societal affluence has resulted in a growing number of adverse effects (Sawyer, 1972). The resultant compounding effects of climatological phenomena on Earth's basic systems are typically referred to as impacts of climate change.

Atmospheric greenhouse loading at the global scale has resulted in an unequivocal rise in global temperatures (IPCC, 2014a; Rosenzweig et al., 2007). The latest Intergovernmental Panel on Climate Change (IPCC) report suggests that the 1880-2012 average global temperature increase was approximately 0.85°C (+0.21/-0.20) above preindustrial temperatures (Stocker et al., 2013), with large variability in its regional distribution. This global temperature increase has resulted in numerous broad-scale changes to physical and biological earth system components (Rosenzweig et al., 2007).

Cryospheric changes from increased temperatures are reduced overall sea ice extent as well as reduced glacial volume. On land, temperature increases have modified drainage systems by increasing snow and ice melt while simultaneously raising water temperatures in lakes and rivers. Ultimately, this has resulted in global decreases in seasonal and annual total frozen water and an influx of water volume to the world oceans, raising sea levels along coasts and in open oceans (Rosenzweig et al., 2007). In North America, for example, climate-induced changes to hydrological systems have in many cases led to enhanced and earlier seasonal snow melt, with resulting average increases in spring runoff and river flows. Meanwhile, areas prone to water deficit have become increasingly stressed (Rosenzweig et al., 2007).

Biological impacts have also been observed. Seasonal changes in climate, hydrological systems and other environmental conditions have impacted phenological cycles, or the seasonal timing of events for plant and animal species (Rosenzweig et al., 2007). Climatic changes expressed through earlier spring and later autumn arrival, coupled with numerous anthropogenic pressures (such as intensive agricultural operations, land-use changes and landscape fragmentation) contribute to shifting animal migration dates and constrict mating opportunities. Among plant species, longer growing seasons and warmer mean monthly temperatures have contributed to altered timings of spring and summer events such as budburst and flowering (Rosenzweig et al., 2007). The shifting of climatic zones towards the poles has been accompanied by a poleward shift of plant and animal species.

As a result of this poleward shift of climatic zones, plant and animal species may experience enhanced climate-based stresses in their current habitats (Easterling et al., 2007). This may affect agriculturally valuable species through variability in the timing and severity of pest events, lower crop yields, and heat and water stress, ultimately resulting in food insecurity (Falloon & Betts, 2010). Among the innumerable plant species that are commercially and culturally important, wine grapes are particularly sensitive to these climatic effects (Duchêne & Schneider, 2005; G. V. Jones, White, Cooper, & Storchmann, 2005).

2.1.2 - Viticulture and North American Oenology

Grapevines (specifically, the "*Vitis*" species of wine grapes) have long been an important agricultural crop for several thousands of years (Dougherty, 2012; Schultz & Jones, 2010). Viticulture (the cultivation of wine grapes), and oenology (the science of winemaking), can be traced back as far as to the Bronze Age and its practices are mentioned in religious texts written thousands of years before present (J. Robinson, 2006; Winkler, Cook, Kliewer, & Lider, 1974). From viticulture's beginnings in Asia Minor, the specific range of agreeable climates for particular grapevine varieties have been ascertained and regimented. This is also reflected in their production standards has lead to strict oversight of viticultural methods. As a result, particular varieties of the European *V. vinifera* have been horticulturally adapted and proliferated throughout most of Western Europe and, more recently, to particular regions within most continents (Dougherty, 2012).

As viticultural regions have expanded and become specialized in their choices of cultivars and their particular winemaking practices in Europe and the Mediterranean (which are commonly referred to as as the "Old World"), knowledge and practices of viticulture and oenology have spread to other continents as well (Dougherty, 2012; J. Robinson, 2006). The "New World" is the common name for winemaking regions outside of the Mediterranean established after the 15th century European explorations (J. Robinson, 2006), and typically refers to bottles produced in the former colonies of South Africa, the Americas, Australia and New Zealand. While endemic grape vines, particularly in North America, were found to grow wild, the first attempts to cultivate the European variety, *V. vinifera*, were not successful, largely due to lack of experience with pests and diseases but primarily due to non-analogous climatic conditions compared to those in the wine regions of Europe (J. Robinson, 2006; Ulin, 2007).

In North America, native *Vitis* varieties that were better adapted to local environmental stresses than imported *V. vinifera* (particularly *V. labrusca* or "Fox Grape") became the subject of oenological experimentation as a means of supplementing growing wine demand not met with European imports (Ackerman, 2007; J. Robinson, 2006; Ulin, 2007). One of the first American successes in winemaking with native species was from Nicholas Longworth's experiments with *V. labrusca* in the early 19th century (Ulin, 2007). Further experimentation led to the development of grafting techniques and hybridized *vinifera x labrusca* varieties organized under the subgroup of *V. labruscana*, such as the Concord, Niagara, Catawba and other varieties in the American Northeast and Southern Ontario (J. Robinson, 2006). Up until the mid-19th century, cold-resistant *V. labruscana* varieties and French vine hybrids[3] were the primary wine grapes cultivated in North America. However, attempts to cultivate true *vinifera* varieties have now begun to show greater successes (Bramble, Cullen, Kushner, & Pickering, 2007; J. Robinson, 2006).

2.1.3 - Wine Geography and "Terroir"

Alongside these developments in North America and abroad, the widespread expansion of viticulture and oenology has led to the development of strong ties between the human and physical realms of geographical research (Dougherty, 2012). Geographical inquiry into local and regional physical and topographical characteristics and their intersection with the cultures of the vine across the globe have invoked cross-disciplinary development in the climatological, pedological and biological sciences with landscapes and societies, contributing to the concept of *terroir* (Burns, 2012; Dougherty, 2012; G. V. Jones, Reid, & Vilks, 2012).

From a winemaker and enthusiast's perspective, *terroir* refers to the most important physical criteria necessary for making a palatable and geographically representative wine (Stevenson, 2005). Latitude, climate, topography and soil are the most common physical

3 The most popular Southern Ontarian and Eastern Canadian varieties of wine grapes include Baco Noir, Marechal Foch, Vidal, Riesling, Chardonnay and Gamay Noir (Shaw, 1999).

characteristics considered to situate a wine within a 'landscape' or 'place'. These factors also determine the suitability of grape vines from an agricultural perspective.

From a scientific research perspective, "*terroir*" is described by Dougherty as a heavily geographical concept in that it "brings together the spatial elements of the natural environment and synthesizes them with the socioeconomic factors..." (2012, p. 22). The term is often employed in the wine industry to denote a geographically defined region with a "...complex interaction among physical, cultural and socioeconomic factors that defines the wine styles and quality that come from a particular region" (Holland & Smit, 2010, p. 131). The contemporary concept of *terroir*[4] is often associated with guaranteed wine quality, a particular variety or sets of grapes cultivated and the particular winemaking practices and production volumes allowed within a specific region. It can be enforced through social conventions or through regimented laws governing delimited viticultural areas, as seen in the *Apellation Origine Controllée* [AOC] system for France, *Denominazione di Origine Controllata e Garantita* [DOCG] for Italy, American Viticultural Areas [AVAs] for the United States, and similar origin certification systems in neighbouring regions (J. Robinson, 2006; White, Whalen, & Jones, 2009). For New World winemaking, regional wine laws are typically not as restrictive, allowing winemakers more freedom to experiment with grape varieties and winemaking practices (Yau, Davenport, & Rupp, 2013). The AOC system is primarily employed in New World winemaking as a method of typifying and codifying wines according to regions that share a generally similar topographical, hydrological and pedological features, as well as a marketing criteria for distinguishing vineyards adhering to a regional association's production standards (Yau et al., 2013). As these *terroirs* and winemaking regions have begun to experience the impacts of climate change, there is great concern over the future viticultural viability of currently established winemaking regions, driving the need for specialized research in this field (Santos, Malheiro, Pinto, & Jones, 2012).

4 The history of *terroir* and its association with quality wines is not without its critics: While one of the main employments of *terroir* in recent years are to base legal controls for fraud and to guarantee wine quality, some authors suggest that its historical usages did not exclude exercising class power over peasant producers by enforcing standards that excluded or quashed smaller-scale winemakers (Ulin, 2007), and to entrench narratives that the best wines were only derived from grapes sown on French soils (White, Whalen, & Jones, 2009)

2.1.4 - Current Research in Wine and Climatic Change

While North American winemakers have been exploring new viticultural and oenological methods since the 18th century, current research in grape and wine can be seen in practice across the world's established winemaking regions. As mentioned earlier, climatic factors have a had a strong influence over the suitability of *V. vinifera* in many regions (Amerine & Winkler, 1944) and the many research approaches performed to determine grape vine suitability are aimed at furthering our understanding of past climatic trends and expected future changes to wine quality and wine-growing regions (Ashenfelter & Storchmann, 2014; Hood, Cechet, Hossain, & Sheffield, 2006; G. V. Jones, Duff, Hall, & Myers, 2010; G. V. Jones et al., 2005; Koufos, Mavromatis, Koundouras, Fyllas, & Jones, 2014; Moriondo, Bindi, Fagarazzi, Ferrise, & Trombi, 2011; Sadras & Petrie, 2011) as well as to the potential of novel viticultural regions under potential climate change (Fraga, Malheiro, Moutinho-Pereira, & Santos, 2012; Gustafsson & Mårtensson, 2005; Hannah et al., 2013a; Kryza et al., 2014; Olsen, Olesen, Breuning-Madsen, & Balstrøm, 2011). Research in adaptation planning specifically for agricultural and viticultural practices also encompasses many facets of socioeconomic and socioecological dynamics, with some studies focusing on the human dimensions of winemaking under uncertain and highly variable future climates (Belliveau, Bradshaw, & Smit, 2007; Bryant et al., 2007; Lereboullet, Beltrando, & Bardsley, 2013; Viers et al., 2013; Viguié, Lecocq, & Touzard, 2014); However, before exploring the particular case studies, it is necessary to establish the base criteria required for viticulture to be conducted within a region.

2.1.5 - Criteria Necessary for Cool Climate Viticulture

The literature on grapevine suitability is focused specifically on *V. vinifera* as this varietal is most often associated with the majority of high quality commercial winemaking efforts. The most important and limiting factors in grapevine cultivation region are climate and soil[5] (Amerine & Winkler, 1944; Fraga et al., 2012; Kurtural et al., 2007; Olsen et al., 2011; Stevenson, 2005; Watkins, 1997; Yau et al., 2013). The oenological goal in cultivating cool climate wine grapes is to achieve a balance of sugar, acid and alcohol content that fosters a

5 The versatility of *V. vinifera* to grow in many different regions adheres to the idea that grapes are infused with the "*gout de terroir*", or the taste of the landscape, which could refer directly to soil but is not necessarily exclusive of other factors (Stevenson, 2005).

“fruity” flavour (Shaw, 1999). As such, careful consideration is placed on optimizing a balance between ensuring adequate heat, available water and maximizing sunshine available to the grapevines in cooler climates throughout the growing season. Thermally, the growing season necessary for a vine to begin grape production requires a minimum consistent daily temperature of 10°C before *V. vinifera* budding (“bud break”) can occur (Amerine & Winkler, 1944; Stevenson, 2005). Areas with risk of temperature extremes in the form of severe frost after budding, and drought-like severe heating are typically avoided as both these occurrences have the potential to decimate crop yields and damage vines (Shaw, 2001; White, Diffenbaugh, Jones, Pal, & Giorgi, 2006; Wolf & Boyer, 2003). Following bud-break, *V. vinifera* grape productivity *c*an be fatally impacted if temperatures consistently drop below -1 to -3° C (Olsen et al., 2011). During winter dormancy, average temperatures that below those limits risk significant damage to the xylem and phloem tissues of most *V. vinifera* vines, with constant temperatures below -20° C seen as the lower limit before plants are destroyed, should they not be adequately insulated or protected (Ashenfelter & Storchmann, 2014; Webb, Watterson, Bhend, Whetton, & Barlow, 2013).

The upper limit of average growing temperatures is also significant to the effectiveness and quality of grape production during the typical growing season (Gladstones, 1992; Gornall et al., 2010; G. V. Jones et al., 2005; Lereboullet, Beltrando, & Bardsley, 2013). While the optimal range of temperatures for most intermediate climate grapevines is suggested at 14-16 °C (Stevenson, 2005), the ideal ranges for most *V. vinifera* grapes can be as high as 20-22 °C (Gladstones, 1992). Consecutive daily temperatures well in excess of 30 °C, exceeding “hot” viticulture climates, have been estimated to have negative impacts on some varieties of *V. vinifera* species (Schultz & Jones, 2010). For most agricultural crops, continuous temperature extremes above 35 °C during the flowering period can damage flowering structures, reducing pollen viability (Wollenweber, Porter, & Schellberg, 2003). These temperature-based particularities thus constrict the *V. vinifera* vine climatic range to regions falling between average growing season temperatures of around 12 – 22 °C [Error: Reference source not found] (G. V. Jones et al., 2012).

For the average grape-growing region, the minimum necessary precipitation to support grapevine production is estimated to be 500 mm for cooler climates and 600 – 750 mm for warmer climates (Gladstones, 1992), while phenological patterns require there to be lower levels of precipitation during the early growing season (to discourage early mildew growth) followed by higher levels of precipitation with greater humidity and more moderate temperatures later on (Yau et al., 2013). Extreme rainfall events also present a major concern for grapevines, as wash-away and water-logging of soils can also lead to structural damage and anaerobic conditions of organic matter, also potentially leading to mildew growth (Gornall et al., 2010; Olsen et al., 2011).

Topographically, slight inclines (3-8.5°) on southward facing (for Northern Hemisphere) slopes are the better candidates for vineyard placement as these terrains provide optimal conditions for soil drainage, maximizing solar radiation, and does not place heavy strain on agricultural machinery (Yau et al., 2013). Other authors, however, suggest that slopes exceeding a range of 12° C can also be appropriate (Olsen et al., 2011). The edaphic components needed for viticulture mainly require good drainage or irrigation to prevent waterlogged soil conditions which can lead to vine mildew and disease (Olsen et al., 2011; Yau et al., 2013). Placement of vineyards in relation to topographical features also plays an important role in the mesoclimatic phenomena that can occur at the smaller scale within vineyards, suggesting that higher elevations and slightly westward slopes are ideal for maximizing solar radiation input in relation to the surrounding topography (Gustafsson & Mårtensson, 2005; Kurtural et al., 2007). While shelter against harsh elements is necessary, shade is generally regarded as an impediment to the potential of grapevines to use solar resources, thus demanding creative and careful placement of vines on the landscape at the smaller scale.

2.1.6 - Heat Summation Indexes and Climate-Viticulture Regions

Much of the early and ongoing research into the placement and effectiveness of climatic regions for viticulture relies on techniques to spatially index the thermal and solar capacity of regions according to the dynamics of the growing season for a particular landscape. The most employed metric, in this regard, for determining regional climate classification for grapevines and in general horticulture is the Growing Degree Day [GDD] (Amerine & Winkler, 1944; Winkler et al., 1974). Building upon the basis of de Candolle's research establishing spring temperatures of 10° C as the necessary threshold for the departure of vegetative dormancy, vine growth, budding and fruit ripening (J. Robinson, 2006), the heat summation method proposed by Amerine & Winkler (1944), commonly known as the Winkler Index [WI], summates the averaged daily low and high temperatures between April and October and subtracts a baseline temperature (in the case of *V vinifera*, 10° C): the total of monthly temperature values in exceeding the baseline are then used to typify climatic regions. According to Winkler Viticulture climate zones are broken into several categories ranging from "cool" to "hot", with regions scoring less than 1370° C considered the coolest regions and those in excess of 2200° C the hottest (Amerine & Winkler, 1944; Winkler et al., 1974). The use of growing degree-day functions to categorize climatic regions is a nearly universally-applied method for most vineyard site selection suitability studies (Hood et al., 2006; G. V. Jones et al., 2010; Koufos et al., 2014; Kryza et al., 2014; Kurtural et al., 2007; Yau et al., 2013).

Building upon the GDD equation, more comprehensive indexes began to integrate factors such as: daily (Heliothermal/Huglin Index, [HI]) (Huglin, 1978) and maximum biologically effective degree days [BEDD] (Gladstones, 1992); latitudinal position for more accurate solar radiation calculation (Latitude-Temperature Index, [LTI]) (Kenny & Harrison, 1992); multi-criteria heat indexes that integrate potential soil water balance (Dryness Index, [DI]) and night temperatures (Cool Night Index, [CI]) (Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014; Tonietto & Carbonneau, 2004); and extreme cold and hot events (White et al., 2006). These numerous climate regionalization methods have contributed to the growing number of vineyards and vineyard research assessing the suitability of viticulture in many geographic areas. More importantly, from the perspective of climate change research, these indexes and metrics have been useful in tracking environmental changes within current winemaking regions as they begin to be impacted by the onset of global climate change (Fraga et al., 2012; G. V. Jones et al., 2010; Moriondo et al., 2011; Santos et al., 2012).

2.1.7 - Impacts to Viticulture and Vineyard Systems under Climate Change

The effects of recent climate changes on vineyards and the quality of wine from well-known winemaking regions has already been established in the literature. One study by G. V. Jones et al. (2005) has established an average rise in temperatures for winemaking regions across the globe of around 1.26°C over the period of 1950 to 1999, suggesting that vineyards around the world may already be experiencing anomalous climate conditions from anthropogenic warming. The same study also predicted that temperatures for these regions could potentially further elevate another 0.42°C per decade in subsequent years. Variability in vintage rating (a metric used for the quality of wine produced during a typical growing season) across regions was determined to have been 10-60% attributed to climatic changes (G. V. Jones et al., 2005).

Due to the complexities of climate change impacts on Earth's systems, projected changes are expected to vary significantly between major regions as global temperatures rise (Hannah et al., 2013a). Quantitative studies of climate change impacts on presently-defined vineyard regions have typically relied on raster output from multiple general circulation model [GCM] ensembles and Geographic Information Systems [GIS] approaches to determine a range of estimates for average annual temperature and precipitation levels for both the global regional scale (Gornall et al., 2010; Hannah et al., 2013a; Lereboullet, Beltrando, Bardsley, & Rouvellac, 2013; Lobell et al., 2006; Moriondo et al., 2013; Webb et al., 2013). As the major winemaking regions are distributed across several continents and as the modelling methods strongly differ, unsurprisingly, there is large variability among numerical estimates of physical environmental impacts. An intrinsic factor that also strongly influences future viticulture suitability is the preparedness of operators to tackle climate change as well as the dynamic socioeconomic conditions they operate within (Belliveau et al., 2007; Bryant et al., 2007; Lereboullet, Beltrando, & Bardsley, 2013). For simplicity, I will briefly mention here general trends and common concerns identified as important among a majority of studies.

The most pressing concerns for site suitability of the majority of economically important wine regions have largely to do with changes in global average temperature and temperature variability as well as changes to precipitation and hydrological systems (Hannah et al., 2013a; Lereboullet, Beltrando, Bardsley, et al., 2013; Moriondo et al., 2013). In turn, these factors compound into potential impacts on phenology and crop quality (e.g. growing season variability, shifts in ripening periods, crop yields) (Gornall et al., 2010; G. V. Jones et al., 2005; Sadras & Petrie, 2011), and on socioeconomic dynamics (e.g. globalized markets, crop insurance, farming practices, tourism impacts, legal frameworks), which together increase uncertainty with regards to the operational viability of vineyards (Belliveau et al., 2007; Bryant et al., 2007; Lereboullet, Beltrando, & Bardsley, 2013). While some studies of economically important Mediterranean locations point to the challenges in adhering to strict vinicultural laws and policies covering areas such as region-specific cultivars, yields, irrigation and other winemaking practices (G. V. Jones et al., 2005; Lereboullet, Beltrando, & Bardsley, 2013; Schultz & Jones, 2010), most general studies focused on global trends highlighted the challenges from physical changes to environmental systems and the opportunity costs and competing interests at play in the choice of crop or land development under uncertain climate scenarios (Gornall et al., 2010; Lobell et al., 2006; Webb et al., 2013).

Phenological changes – changes to the seasonal timing of specific agricultural events (e.g. budbreak, *veraison* (ripening), harvest date) for grape species – in many other viticultural areas experiencing the local impacts of global climate change have been well documented in Europe and abroad (Fraga et al., 2012; Hannah et al., 2013a; Koufos et al., 2014). The advancement of bud break dates and the shortening of growing seasons are among many impacts predicted, and observed in some cases, for major agricultural regions (Bock, Sparks, Estrella, & Menzel, 2011; Gornall et al., 2010; Lobell et al., 2006), presenting a challenge for the future well-being of vineyards globally (Hannah et al., 2013a; Webb et al., 2013).

While there are strong uncertainties and concerns over the future viability of global viticulture, it should be noted that not all predictions suggest solely negative impacts from climate change. Many studies agree that as global warming manifests itself in major agricultural regions, climate regions may shift and expand poleward to open new territory for agriculture development (Fraedrich, Gerstengarbe, & Werner, 2001; G. V. Jones et al., 2005; Moriondo et al., 2013; Viers et al., 2013; Webb et al., 2013). For colder viticultural regions like Canada, one study by Holland & Smit (2010) suggests that climate change may help more northern climates in moderating harsh winters by increasing mean growing temperatures, favouring greater production and extent of vineyard suitability. The authors do, however, agree with most prediction studies that finer-scale, regional-level analysis is needed to determine specific environmental variability for specific locations (Daly et al., 2008; Holland & Smit, 2010; Wang et al., 2006).

2.1.8 - Industrial Figures

At the global scale, vineyards in 2012 accounted for 7.528 Million Hectares (M Ha or 75280 Km^2) of the world's arable lands. Global wine production accounts for nearly 252 Million

Hectolitres (MhL), and – if comparing production against world consumption in 2012 (243 MhL) – wine production was recently exceeding overall global demand (OIV, 2013). The Canadian figures for wine suggests that overall production has slightly increased in a relatively unsteady fashion since 1961 (FAO, 2014). While the rise of a globalized economy adds complexity to discerning any trends, this increase in production may have been influenced by both a more favourable climate and individual provincial policies with regard to their respective agricultural and wine industries (Ackerman, 2007; Bramble et al., 2007). One contributing region to this growing trend in Canadian wine production, and the focus of this research project, is the Canadian province of Quebec. As of early 2016, province-wide viticulture has cultivated roughly 640 Ha of planted vines; the membership of the largest vintner association in Quebec, *l'Association des Vignerons de Québec, a*ccount for roughly 365 Ha of this area, producing nearly 11,150 hL of wine (or ~1.5 Million bottles) (Gagné, 2015a).

Section 2.2 - Research Objectives

In this thesis project, I perform climate categorizations of agroclimatic regions as well as site suitability evaluations of the potential for viticulture with respect to other physical characteristics within Southern Quebec. The literature with regards to viticulture suitability suggests that the primary limiting factor to the growth and development of grape vines is air temperature (Amerine & Winkler, 1944; Kurtural et al., 2007), with the growing season length being the most important bioclimatic indicator in achieving grape ripeness (Wolf & Boyer, 2003), and a mean growing temperature of around 12 – 22 ºC typically considered as the ideal range for grape growing (G. V. Jones et al., 2012, 2005). In order to further categorize the areas falling within this zone to define “hot”, “cool”, “humid”, “dry”, and other intermediary climates for viticulture, an array of agricultural indexes based on temperature, precipitation and other annual trends have been developed over the past century (Amerine & Winkler, 1944; Gladstones, 1992; Huglin, 1978). More recent thermal indexes have attempted to integrate factors such as latitude, drought and frost potential, aiding in further specifying spatial areas that would potentially be suitable for grape varietal cultivation (Jackson & Cherry, 1988; Tonietto & Carbonneau, 2004; White et al., 2006). For some researchers, combining these indexes to generate multi-criteria evaluation systems is often used in order to identify terroirs by multiple climate variable patterns producing maps and even more specified methods of categorizing climate regions (Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014; Tomasi et al., 2013; Tonietto & Carbonneau, 2004). Furthermore, specific methodological approaches to viticulture suitability in select regions, with climates categorized as “cool”, have been conducted by national research institutes and general researchers (Hood et al., 2006; Koufos et al., 2014; Moriondo et al., 2011; Olsen et al., 2011). Climate categorization indicators, as expressed through these indexes and supporting methodological approaches, provide for a reliable tool set to identify the spatially-defined extent of these climate regions in Quebec.

My primary analysis climatically categorizes the agricultural areas within southern Quebec for wine grape viticulture. At present, the viability of Quebec viticulture is limited by climatic characteristics of northern latitudes, most notably harsh winters and short growing seasons, constraining the present regional extent of Quebec appropriate for viticulture well below the generally observed upper extent of 50º latitude North (N. K. Jones, 2012; Shaw, 1999). That said, the number of winegrowing operators in the region of Southern Quebec is steadily increasing over time, offering wine from numerous grape varietals that are successfully grown throughout the area (AVQ, 2012a).

In order to evaluate the characteristics and historical conditions of Quebecois viticulture operations, I present an evaluation of present-day and recent-past climate characteristics at vineyard locations and throughout the geography of Quebec. While viticulture is a well established activity in present-day Quebec, the recent re-emergence and growth of the industry spans roughly 40 years (Ackerman, 2007; AVQ, 2012a). Instrumental climate records are available for the region of interest and the entirety of this time period through government agencies (Environment Canada, 2011). Temperature and precipitation anomalies from climate change expressed within the meteorological record during this time period have been established at many weather stations near popular viticulture regions in Southern Quebec from the 1970s to recent years (N. K. Jones, 2012). By establishing the spatial extent of suitable area for viticulture within Quebec across the recent historical record and for present-day, forward projections of climate realizations will be possible to determine the expansion, constriction, and/or shifting of suitable areas or climate regions under future scenarios of climate change (Hannah et al., 2013a; White et al., 2006).

Within the dialogue on future climatology, a large volume of the literature concerning predictions of climate change impacts have either been based on the Special Report on Emissions [SRES] Scenarios (Nakicenovic et al., 2000) and, more recently, the Representative Concentration Pathway [RCP] scenarios (Moss et al., 2010). For the most part, potential trends among global and regional climatic changes are typically for the year 2050 and 2100 time horizons (Bourque & Simonet, 2008; Easterling et al., 2007; van Vuuren et al., 2011; Webb et al., 2013). In addition, finer scale spatial predictions for potential changes in the climatology of North America, Canada and Quebec have been produced with an emphasis on environmental, social and, specifically, agricultural impacts (Bourque & Simonet, 2008; Field et al., 2007; Lobell et al., 2006). A particular study by Hannah et al. (2013a), outlines the future climatological impacts specific to grape vines, suggesting that future outcomes from climate change may render some present-day major viticultural areas unsuitable for winemaking, however there is heated debate as to the effectiveness adaptation measures and the range of suitable average growing season temperatures for major *V. vinifera* varietals (Hannah et al., 2013b; van Leeuwen et al., 2013). The lack of a regional-scale future climate change prediction for viticultural climate and/or suitability in Quebec motivates the secondary objective of the main research.

My next secondary climate analysis determines the spatial extent of regions of Quebec that are predicted to be suitable for viticulture under a selection of possible climate change scenarios for normalization periods hovering around the 2030's (2011-2040), 2050s (2041-2070), and 2080s (2071-2100). This objective is examined through climate model data that has been reanalyzed (downscaled) through spatial interpolation techniques using data from GCMs and high resolution climate conversion grids (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005; Loubier, 2007; Moriondo et al., 2011). The purpose for performing a spatial projection of the possible characteristics of a future Quebec climate is, in a similar method as objective (1.a), to generate a gridded climate geometry that can be integrated along with the spatial components of non-climatic characteristics to determine changing areas of viticulture suitability across time. Focusing specifically on the climatic changes within southern Quebec in considering two RCP realizations (Scenarios 4.5 and 8.5), I will be able to quantitatively and/or qualitatively prediction for the climate anomalies potential climatic suitability and spatial extent for viticulture for normalization years 2030s, 2050s and 2080s.

Extending from the evaluation of recent historical vineyard operations, past viticulture suitability can also be interpreted from practices by vineyard operators and trends observed in the phenological characteristics of cultivated grape vines over time. For example, G. V. Jones et al. (2005) have shown that changing trends in cultivation volumes, lengths of growing seasons and values of wine vintages from across regions and time are useful indicators of impacts of climate change as experienced by vineyards.

Section 2.3 - Research Questions

The emergence of Southern Quebec's wine industry has coincided with climate change in the 20th century, arguably to the benefit of the winemaking and wine tourism industry. Within this context:

1. What will the continuing effects of climate change mean for Quebec's viticultural bioclimatology?
2. How well placed are present day winegrowing operations with regards to climate? How might they be impacted climatically by end of century?

And additionally,

3. What is Free and Open Source Software and Open Data, and how can we integrate Open Source knowledge and Open platforms to better society as well as perform environmental GIS research?

Section 2.4 - The Significance of My Research

The purpose of performing this type of suitability analysis for Quebec's vineyards can be seen from both an industry-focused perspective and climate change mitigation perspective. As mentioned earlier, Quebec's wine industry is relatively new and accounts for a small percentage of the Canadian total of wine production. The potential for the industry to adopt more economically valuable vinicultural grape varietals and to expand potential growing areas poleward hinges upon the characteristics of expected warming regimes from climate change in the region and the availability of agroclimatic information directed at operators.

Additionally, the recent popularity of non-academic articles suggesting that climate change may benefit the wine industry is, in my opinion, providing an oversimplified perspective of the phenomenon. While some warming may be beneficial to some areas – such as Quebec which presently lies at the edge of a suitable climate region – I believe that the distinction must be made that unmitigated carbon emissions and unchecked climate change will negate any potential positives of change that could be realized under more restrictive emissions scenarios.

At the time of my choice to adopt this project, to my current knowledge, there was yet to be performed a comprehensive longitudinal spatial study of the Southern Quebec region from a climate change and viticultural suitability perspective. With this project, I present a relatively parameterized scientific inquiry to base future climate-viticulture projections for industry-focused general information purposes. Ideally, this research would be reproduced at a more comprehensive scale, integrated with a greater economy-based focus on the economic impacts of climate change to the winemaking industry of Quebec.

Chapter 3 - Free and Open Source Software, Data, and Access for Society and Research

My aim in writing a chapter specifically focused on the “Open Source” aspect of my approach is both to dispel the anxiety accompanied by the decision place ones technical research capabilities upon the freedom, technical capability, and altruistic intent of the development community and to promote the value of adopting Open Source tools by researchers, especially those beginning their careers and learning how to employ learned theory using the available tools, both open- and proprietary-developed. I felt that my particular experience in navigating an enormous amount of information concerning geospatial tools, data sources and methods for utilizing Open Source software to the exclusion of most proprietary tools and confidentially held data sets merited an extended chapter. While my initial reasons for adopting “Open” criteria in my research may have been motivated simply by my interest in learning something new, my lessons learned have given me a more concise criticism of the technical and legal challenges as well as ethical dilemmas associated with the proprietary control of knowledge, information and applications within the software realm.

Section 3.1 - Abstract

The Free and Open Source movement, initially championed by firmware and software developers, is a call for the opening of access to source code and the adoption of permissive licensing agreements to challenge the proprietary control and commercialized model of software, data, and information and to empower all. In recent years, government agencies, not-for-profit organizations and researchers have begun to adopt these same principles by opening access of data sets to the general public to encourage usage by users, developers and for the benefit of the general public. In Canada, this has translated into adoption of the Open Government initiative, among others, to provide free-to-use information, reports, and geospatial data for researchers, industry and other Canada-interested parties.

In this mini-chapter, I begin by briefly describing the Open Source ideology and licensing, the Open Government initiative and the Canadian government approach to Open Source geospatial information, and some of the repositories and data sources available for geospatial analysis. I then focus on geospatial data with coverages that encompass Canada, comparing available project data for environmental analyses, the benefits and potential trip-falls in using Open Source or Public Domain data, and the general experience and lessons learned in my decision to almost exclusively use Open Source data and software.

Section 3.2 - Context: The Open Source Ideology

3.2.1 - Open Source and the "Freedoms" of Free Software

The Free (and Open Source) [FOS] software ideology – the policy of releasing the human-readable source code of software and explicitly allowing others to contribute or build upon and redistribute it (and under some conditions, sell it) – is not a new concept. The philosophy behind its approaches and its employment by governments, researchers, librarians, programmers, and other developer communities have helped populate and pioneer the information and idea economy that shape the digital world. Similarly, knowledge of scientific or of any other form would not be possible without the sharing of ideas, methods, and tools that allow us to collectively gather it and build upon established conclusions.

The term "FOS" and what constitutes FOS is a very complex debate[6], with a lot on confusion within and outside of the programmer community; the most reliable approach to understanding what is meant by "Free" is to understand the justification behind its development. A major influence in the development of FOS, the Free Software Foundation [FSF], defines "Free Software" as software adhering to the following four conditions (or freedoms):

1. *The freedom to run the program as you wish, for any purpose (freedom 0).*
2. *The freedom to study how the program works, and change it so it does your computing as you wish (freedom 1). Access to the source code is a precondition for this.*
3. *The freedom to redistribute copies so you can help your neighbor (freedom 2).*
4. *The freedom to distribute copies of your modified versions to others (freedom 3). By doing this you can give the whole community a chance to benefit from your changes. Access to the source code is a precondition for this.*

(Free Software Foundation, 2015)

Software and other products that don't follow these principles don't necessarily imply that the products are commercial but they would be "proprietary" - "non-free" or "owned" - suggesting that the source code is not distributed and only released as a compiled product, or that the code is available to examine but integration/modification/distribution is prohibited (Free Software Foundation, 2015; Steiniger & Bocher, 2009). Proprietary software implies that the

6 For background, a detailed categorization of the definitions of types of free and non-free software is actively maintained by the Free Software Foundation https://www.gnu.org/philosophy/categories.html

algorithms and base code are not openly shared ("closed source") and that payment-based preconditions, such as software purchasing, access fees, or licensing fees, are payment barrier to its use.[7]

For major software developers, closed source approaches reflect the model where – in order to support and finance internal ongoing software development – the one-time or annual licensing of a finished product may be a primary source of revenue, with technical support an ongoing expense. All software undoubtedly contains some degree of unintended behaviour ("bugs") or vulnerabilities and, under this model, the task of identifying the cause and fixing this behaviour falls on the publishers/developers (Raymond, 1999a); one characteristic of this model is that once the product is abandoned or the publishers/developers shutter, the value of these software products drops significantly as their inner workings remain unknowable and the technical support and development base has evaporated (Raymond, 1999b). The FOS model contrasts this approach by shifting development from the "Cathedral" to the "Bazaar" where, rather than having a small group develop software internally and release finished products (the "Cathedral"), software is made available to many in the development stage regularly and the developers rely on strong communication between themselves, beta-testers and other developers to improve the software (the "Bazaar") (Raymond, 1999a).[8][9]

In essence, these criteria attempt to foster a software environment where the monetary value of software isn't derived the sale of finished products; the free software definition fosters an economy where interested developers can examine and contribute to the code base, or where users and agencies who use free software can finance the research, and even help direct developmental progress to better suit the user base and cater better to an enterprise-level need (Raymond, 1999b). These freedoms go so far as to enable software developers to

7 A similar relationship can be found in the dynamics of researchers and journal publishing houses which is largely the focus of the "Open Access" debate.

8 The metaphor for this development approach was coined by Eric S. Raymond (1999a) based on his account of the success of Linus Torvald's development style of the Linux kernel in the early 1990s and his experiences in adopting a similar approach for software development.

9 This essay is famous among FOS advocates and developers for coining the phrase commonly referred to as *Torvald's Law* ("Given enough eyeballs, all bugs are shallow").

sell products stemming from free software such as, for instance, development, distribution, implementation, and management services (Scott, 2002)[10],[11].

3.2.2 - *Open Licensing*

Within the software community, these ideas have been made manifest into numerous practices and models including the practice of relinquishing most copyrights, which gave rise to legal documents like the GNU General Public Licenses [GPL], MIT and BSD licenses and the Creative Commons [CC] sets of licenses (Free Software Foundation, 2015; Lessig, 2004)[12],[13]. These licenses serve different purposes and are targeted for use by programmers, developers, artists, composers and other types of content/software/media creators with varying degrees of openness and restrictions. One defining characteristic for all of these licenses is that they all imply the “free” usage of the intellectual property of the creator for the the usage of anyone, with some restrictions. While some CC and other licenses can be very restrictive on usage (e.g. the CC No-Derivatives licenses) or demand that products built from FOS software may only be released through a FOS license to maintain “Free” cultures (e.g. the GPLv3, CC Share-Alike licenses)[14], even these restrictive options provide more opportunity for users to distribute, share and use source material than what would otherwise be fully rights restricted content.

Justifications for FOS-compatible licensing adoption specifically aimed at software developers – the group that has largely responsible for the development and popularization of these concepts through online discussion and collaboration – cite the economic, ethical, and

10 For some free software developers, the service provider-based approach to FOS has been a very financially successful business model (Canonical Ltd., 2016; Red Hat Inc., 2016).

11 A colloquial saying repeated among free software advocates to demystify these differences is “Free as in 'Freedom', not as in 'Beer'” (Balter, 2015; Free Software Foundation, 2015; Raymond, 1999c; Scott, 2002; Steiniger & Bocher, 2009; Thompson, 2012).

12 All these licenses are hosted online for developers and content creators to use. Full text versions are available through the following references (Creative Commons, 2016; Free Software Foundation & Stallman, 1989, 1991, 2007; MIT, 1988).

13 Steiniger and Bocher (2009), provide a useful analysis of the differences between these licenses and illustrate the major changes between the GPL, LGPL, and works in the Public Domain.

14 An ongoing debate within the Open Source community concerns “CopyLeft” or ensuring that products derived from free software remain as free software. Some licenses thus demand that any derived products must also be released under a compatible open license. For more information: https://www.gnu.org/copyleft/.

professional arguments that benefit end-users, programming communities, societies, governments and the Internet as a whole. The increasing popular use of FOS and open media is seen by some advocates as a response to a philosophical need to decentralize and democratize software and information while dismantling the monopoly of corporate "malware"[15] or, more pragmatically, as communities are recognizing the immediate benefits of its use such as lowering development and maintenance costs, fostering opportunity for integrating end-user feedback, and its increasing democratize software[16].

This approach to and dialogue focused on creation, distribution and easing of restrictions on source materials has had many far-reaching and socially empowering benefits not just for the programmer/end-user communities but also for government/citizen, researcher, and organizational relations.

3.2.3 - "Opening" Government

At the government ministerial level, we see the FOS ideology manifest itself as "Open Government" initiatives (Government of Canada, 2013; Kerski & Clark, 2012; Lenihan, 2015; Statistics Canada, 2014). The "Open Government" approach, comprising three dynamics of sharing between citizens, non-government groups, and government agencies, pays close attention to methods informing government/citizen dialogue, government transparency, and the implementation of technical measures like machine-readable data protocols, typically built upon FOS infrastructure (Lenihan, 2015). From a policy standpoint, enacting measures that favour the release of government information concerning environmental and public health, economy, industry, and inner workings increases the transparency of the government to the general public, reducing the need for redundant or duplicated analyses between otherwise-opaque ministries and organizations, thereby lowering research costs both within and outside of the government, and provides civil society with timely and reliable information for

15 I defer to one FOS movement founder, Richard Stallman, for his usage of the term as "software whose functioning mistreats the user." https://www.gnu.org/proprietary/proprietary.html

16 Many essays that elaborate on these points can be found on the websites of important Open Source advocates like software developer and author Eric S. Raymond (Raymond, 1999b), GNU developer and Free Software Foundation founder Richard Stallman (2015), and GitHub Product Manager Ben Balter (2015).

socioeconomic and environmental decision-making (Kerski & Clark, 2012; Open Government Partnership, 2011)[17].

In the United States, this initiative was formalized with the 2011 Public Online Information Act (POIA) (Kerski & Clark, 2012) while for Canada, the federal government formalized its modern Open Government initiative with the submission of the Open Government Action Plan at the 2012 OGP summit in Brazil (Treasury Board of Canada Secretariat, 2014a). For the Canadian context, the justification for the Open Government approach is perhaps best illustrated from the text of the Open Government Directive definition:

> *"The objective of the [Open Government] directive is to maximize the release of government information and data of business value to support transparency, accountability, citizen engagement, and socio-economic benefits through reuse, subject to applicable restrictions associated with privacy, confidentiality, and security."* (Treasury Board of Canada Secretariat, 2014b, sec. 5.1)

With the intended results of this policy approach being that:

> *"Canadians are able to find and use Government of Canada information and data to support accountability, to facilitate value-added analysis, to drive socio-economic benefits through reuse, and to support meaningful engagement with their government."* (Treasury Board of Canada Secretariat, 2014b, sec. 5.2)

For Canadian citizens and other interested parties, by releasing data concerning environment, economy, and demographic statistics in standardized and online accessible formats, researchers, developers, industries and not-for-profit groups are then able to uptake these files and be better equipped to study, provide services and information that in turn benefit the financial and knowledge economies[18]. One of the most successful case studies of the benefits of Open Source ideology can be seen in the development of Canada's geospatial data infrastructure.

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17 As of the end of 2015, the Open Government Partnership lists 70 countries worldwide as members with varying degrees towards full adoption and implementation of open and online data transparency measures. http://www.opengovpartnership.org/countries

18 At the time of this writing, more than 121,000 open data sets and 170,000 government technical reports were available through open.canada.ca, this number is not inclusive of the preexisting geographic data presently available through Natural Resources Canada, Environment Canada, Statistics Canada, and other government-administered spatial databases.

3.2.4 - *Success Story: Canada's Spatial Data Infrastructure*

The Canadian government has been adept at responding to and keeping pace with the need for accurate, diverse, and openly accessible online geospatial information (Lenihan, 2015). Government-level acknowledgement of the economic value in assembling networked and user-accessible Canadian geodatabases of land, hydrological, soil, weather, climate, administrative, demographics and other geographical characteristics and extents – despite the substantial initial and operational maintenance costs – was acknowledged by at least the late 1990's (Fong, 2000; Johnson & Singh, 2003).

In response to a growing need to standardize Canadian geographic information and faced with the task of compiling data from among federal, provincial, and municipal agencies, the Canadian government established the GeoConnections program under Natural Resources Canada [NRCan] in 1999. The primary goals of this program were enable online accessibility of geospatial information and direct, develop and maintain the Canadian GDI which, prior to the program, was fragmented and largely inaccessible to end-users at the time (GeoConnections, 2005; Johnson & Singh, 2003). The financial cost of performing this task was high due to the expansive geographic extent of Canada and therefore the approach to information collection focused on quality, consistency, reducing redundancy, and compliance with international standards, working closely with groups such as International Organization for Standardization [ISO] and the Open Geospatial Consortium [OGC], both agencies collectively responsible for developing production, storage, and delivery methods for geographic data and metadata (Fong, 2000; GeoConnections, 2005).

By 2005, GeoConnections had largely achieved its initial goals by working alongside many agencies from both within and outside government, establishing the GeoBase data repository, and was continuously innovating on Open Source standardization, and adapting to a changing information needs environment (GeoConnections, 2005). GeoConnections correctly predicted that with the rise in popular use of broadband Internet that “[t]he rapid growth of Web service standards and specifications will tremendously impact geospatial data infrastructures” (GeoConnections, 2005, p. 7). As of 2015, the program has achieved several goals in developing geospatial data access standards, quality, and user accessibility built upon Open Source infrastructure and principles of open access throughout (KPMG, 2016).

This is one example of a GDI initiative that not only solved an issue of researcher and inter-department data access, but also streamlined data delivery methods, fostered a version control method and standardization movement for Canadian geodata and information, and increased the availability of environmental and other information from numerous sources for the general public.

3.2.5 - Adopting Open Source in Environmental Analyses

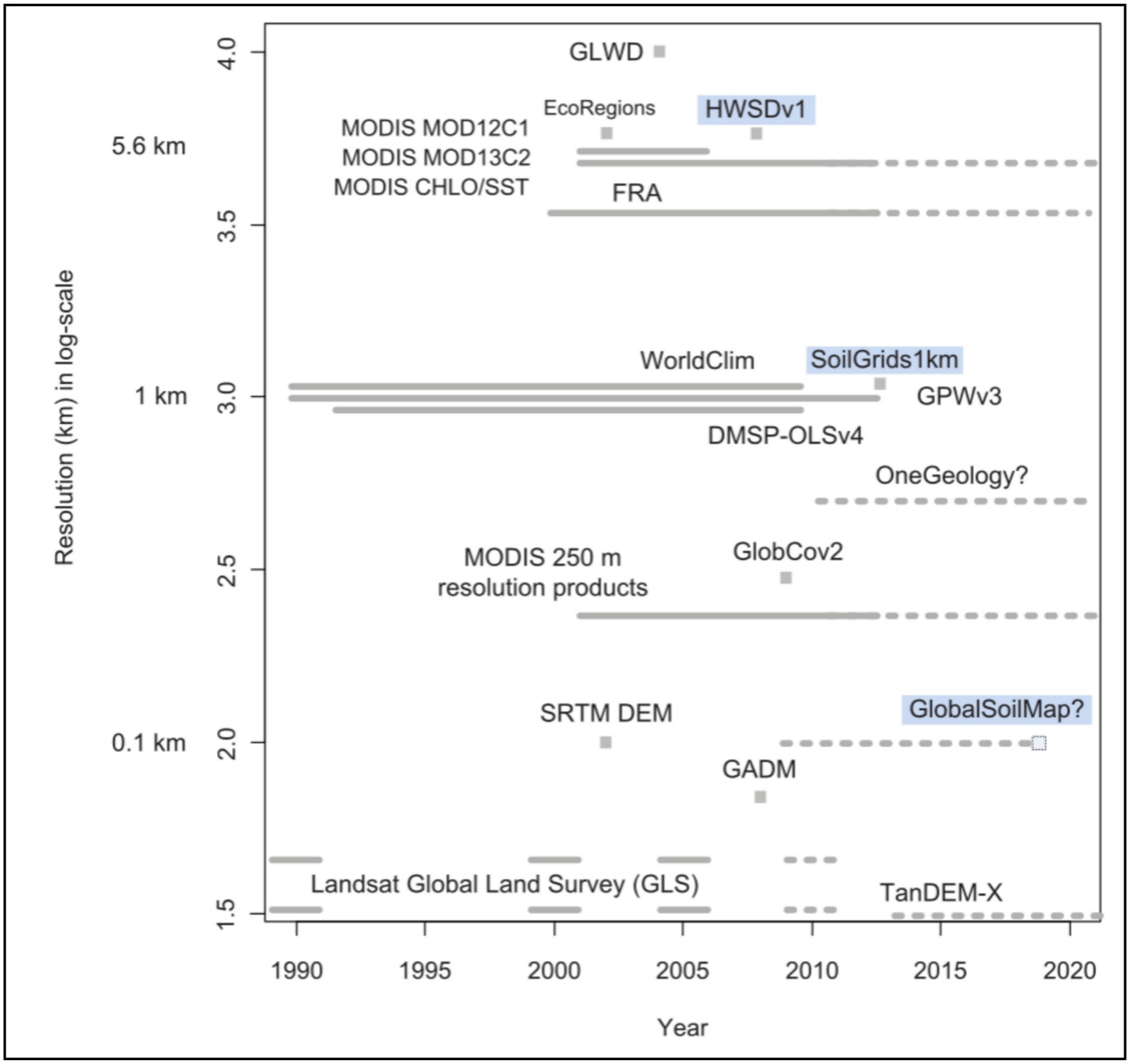

Figure 3-1: Openly-Accessible Global Environmental Data Projects organized by Spatial Resolutions (Hengl et al., 2014, fig. 1), licensed under CC-BY

At the global scale, the proliferation of GDI technology between countries, at sub-national levels, and spanning the Internet has broadened the availability of data on the Internet between researchers, research agencies and government departments. Open Data projects initiated and maintained by government agencies, research groups, and independent researchers are providing valuable and important environmental data for the benefit of all [Figure 3-1]. Environmental agencies and research units such as NASA, the United States

Geological Survey [USGS], the National Center for Atmospheric Research [NCAR], and others are examples of providers for environmental data integral to the research efforts of individuals, universities and other research agencies connected via the Internet.

As mentioned earlier, a major application of this data as well as a major reason for government investment in precise and representative geographic data is for the benefit of the commercial and industrial sectors (Fong, 2000). Agricultural analyses for planning and adaptation is one of the major interests behind Canada's digital investments in GIS and stands out as a major strength of the Canadian GDI (Shen et al., 2010). Using openly accessible GIS data concerning interpolated soil characteristics (Hengl et al., 2014), climate normals and projections (Hijmans et al., 2005), combined with Canadian remotely-sensed land use and topography (Agriculture and Agri-Food Canada, 2015a, 2016; Statistics Canada, 2015), determining the characteristics of agricultural operations is a relatively easy spatial analysis to perform.

To illustrate this point, the second half of this chapter provides an account of my learning process and decisions taken in performing environmental spatial analyses, some of the tools and solutions I've employed in my workflows, some of the data repositories I've referred to in performing environmental GIS research. The section that follows showcases an analysis of how FOS-GIS and Open data can be used for agricultural evaluation. The chapter concludes with a brief discussion of some limitations of the Open movement and some final thoughts.

Section 3.3 - Considerations for FOS software and GIS

3.3.1 - GNU/Linux, FOS-GIS, and Open Ecosystems

FOS-GIS solutions have, in recent decades, become a major component in the geospatial infrastructure around the world. The different types of FOS-GIS available for research institutions, corporations, technicians and other groups and individuals include tools built for visualizing spatial data online, organizing and developing data repositories and geodatabases, and for performing traditional raster and vector data based operations.

In order to perform a good deal of the environmental GIS research I outline in Chapter 4, I relied on as much as possible FOS solutions for my analysis and data needs. Given the robust development and online accessibility of FOS, specifically FOS-GIS, this was easily achievable. My primary software needs for performing research were a FOS-compatible operating system [OS], basic writing/spreadsheet software and a FOS-GIS. Steiniger and Bocher (2009, p. 1354) list some of the dimensions necessary to consider prior to deciding on a FOS-GIS project ecosystem and include the following:

1. Features/Functionality
2. Documentation
3. Modular Software
4. User Community
5. Support
6. Useability
7. Support for OGC Standards
8. A Transparent Development Team
9. Developer Community
10. Software Licence
11. Supported Operating Systems and System Requirements
12. A Functioning and Actively Developed Application Programming Interface [API]

With these consideration in mind, I decided that I wanted to try my hand at using a near-fully open sourced workstation. In order to accomplish this, I opted not to use Apple or Windows systems. In order to satisfy my OS needs, I adopted use of the GNU/Linux OS. GNU/Linux is a universal FOS OS back-end available for virtually all computer architectures with many versions (distributions/”flavours”) available customized for general or specific purposes as well as for varying levels of computer literacy. For standard operations, I chose to use the

Debian GNU/Linux distribution (Debian Project, 2015) whose standard installer image includes many commonly-used desktop utilities such as LibreOffice suite, a file manager, graphical user interface, and programming language compilers[19]. Debian is a customizable and stable distribution that strives to deploy FOS software and drivers wherever possible and has a vibrant online support community, comprehensive support documentation, and an approachable learning curve, making it a good candidate for technical-minded researchers. Additional software, themes, and command libraries are available from the Debian software library via its software package manager "apt" allowing for greater customization and utility. Other software libraries can also be added to enable access to the newest versions of software directly from source providers.

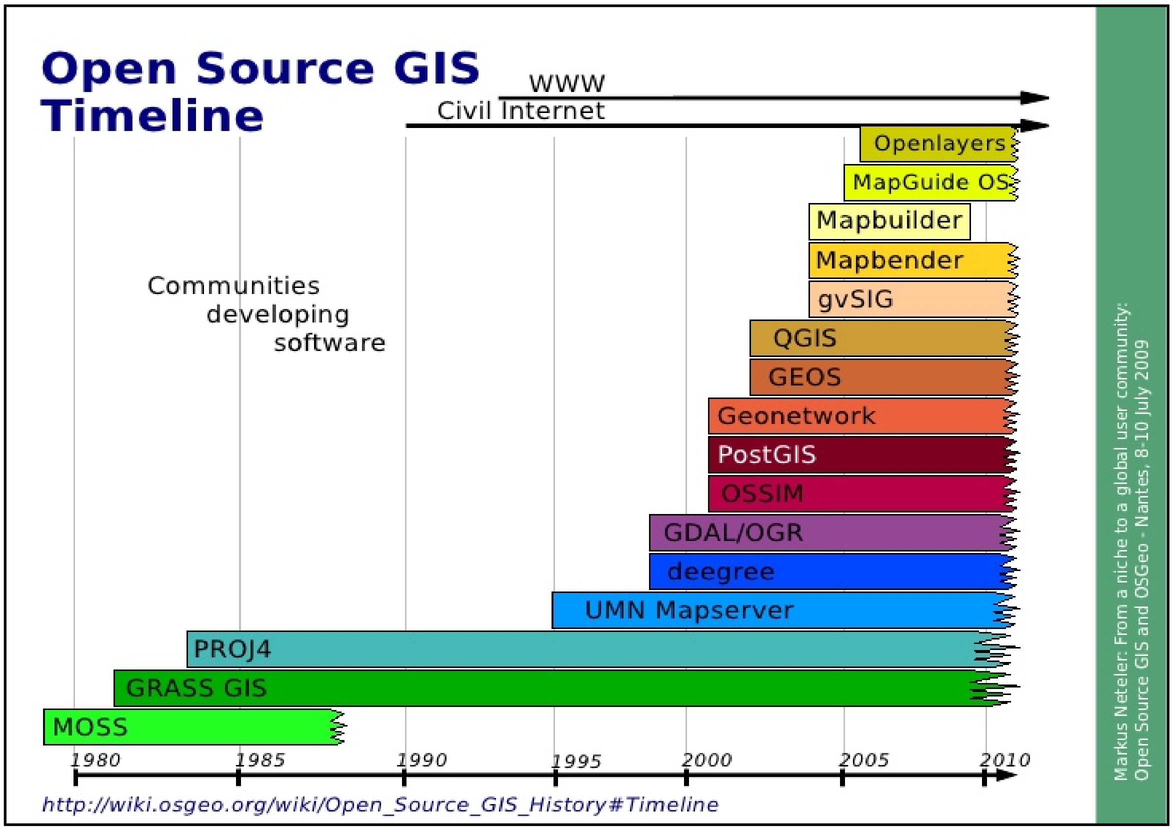

Figure 3-2: Historical Timeline of FOS-GIS Platforms circa 2009 (Neteler, 2009) licensed under CC-BY-SA 2.5

19 This distribution and its software library form the basis of the popular Ubuntu GNU/Linux distribution.

For geospatial analyses, FOS-GIS desktop solutions are numerous[20]. As of the time of this writing, nearly 20 different FOS-GIS clients were completed or in active development, not including Web-Mapping or Web-Feature Services [Figure 3-2].

My research needs required a desktop GIS with functions similar to ESRI's ArcGIS Desktop suite but released under an Open license. In satisfying my FOS-GIS needs, I opted to use QGIS (QGIS Development Team, 2016), a fully featured and modular graphical FOS-GIS built in Python. QGIS includes functions built for several different GIS software such as SAGA (Conrad et al., 2015) and GRASS (GRASS Development Team, 2012) and integrates a model-builder and command-line tools such as the GDAL/OGR raster and vector analysis library (GDAL Development Team, 2013) as well as the statistical programming language, R (R. Development Core Team, 2013). QGIS also includes a plug-in installer providing access to user-built modules that aid in performing specialized analyses, visualizing GIS data, and provide web-GIS functionality among other functions. The software runs natively on Windows, Apple and Linux operating systems and is regularly maintained through contributors on GitHub[21]. In addition to my OS and FOS-GIS needs, I also relied on a number of other FOS software solutions [Table 3-1].

Free and Open Source Software Solutions			
Name	Version	Purpose	Home Page
Debian GNU/Linux	8.5 “Jessie”	Operating System	www.debian.com
GDAL/OGR	2.1.1	GIS Library	www.gdal.org
GRASS	6.4.4 and 7.0.4	GIS	http://grass.osgeo.org
Iceweasel/Firefox	45.3.0	Web Browser	www.mozilla.org/en-US/firefox/new/
LibreOffice	4.3.3.2	Office Utilities	www.libreoffice.org
ownCloud	9.1 Server	Cloud Storage Backup	https://owncloud.org/
QGIS	2.16.1	GIS	http://qgis.org/en/site/
R	3.1.1	Statistical Environment	https://cran.r-project.org/
SAGA	2.1.2	GIS	www.saga-gis.org/
Wine	1.6.2	Windows Application Environment	www.winehq.org

Table 3-1: Examples of Free and Open Source Software used in this Research Project

20 An actively maintained list of GIS software organized by license, operating system, and features can be found at https://en.wikipedia.org/wiki/Comparison_of_geographic_information_systems_software

21 While the Debian software repository includes QGIS and other GIS software, the versions are intentionally held back in order to ensure system stability. The most up-to-date GNU/Linux binaries of QGIS are available directly through the www.qgis.org software repositories.

The software ecosystem I present here is not meant to represent the ideal assemblage of options for performing Open Source GIS analysis, but simply a possible configuration based on needs and preferences. Many programming languages integrate GIS analysis libraries natively (e.g. Java, Python, R) and different Open Source projects are regularly developed from the code bases of existing projects to suit the needs of specific activities/analyses.

Section 3.4 - Extended Analysis: Identifying Agricultural Area in Southern Quebec Using Open Source

3.4.1 - Background

The French concept of Terroir is seen as the characteristic basis for successful viticultural operations, reflecting the climate, topography, soil, and culture of a wine region. While climate is generally considered the most defining factor in performing viticulture, soil, hydrological, and topographical characteristics can also present limitations or heavily influence the grape characteristics of vineyard operations (Barriault et al., 2013; van Leeuwen et al., 2004).

A major factor important for mitigating the risk of pest outbreaks on newly established vineyards is ensuring that the vineyard site is not situated on newly cleared terrain. Areas that have been consistently used for agricultural operations are favourable in order to prevent the risk of introducing agricultural pests that can thrive for some time after a forest has been cleared (Nowlin & Bunch, 2016; Wolf & Boyer, 2003). For this analysis, I treat viticultural operations as specific type of agricultural activity, albeit with a different set of specific climatic, soil, and topographical criteria[22]. In Quebec, the spatial extent of agricultural operations is roughly limited to the areas residing within the Saint Lawrence Seaway Valley and the southern areas below it – limited by New York, Vermont and Maine – as well as some areas east of Lac Saint-Jean and around Saguenay Valley, some areas bordering the Quebec shore of the Ottawa River, and some areas of the Gaspé Peninsula bordering the Gulf of Saint Lawrence[23]. These areas are identified by many Canadian government data sets and government researchers as suitable for agricultural operations (Agriculture and Agri-Food Canada, 2015b; Lepage, Bourgeois, & Bélanger, 2012; Rochette & Dubé, 1993a, 1993b; Statistics Canada, 2015).

Methods and definitions used for determining the specific boundaries of recognized agricultural areas within this region vary between agencies and at different scales. For instances, the CanSIS Soil Landscapes of Canada data set used in recent editions of the

22 For a detailed table of some criteria for assessing the suitability of a location for viticulture based on soil, and topography see annexed Table 7-3. For a table detailing a multi-criteria system in development for evaluating climate, soil, and topography, see Table 7-16.

23 Due to their remoteness of location, I exclude Anticosti and *Les Îles-de-la-Madeleine* from both major analyses.

Agroclimatic Atlas of Canada ranks soil units at the national scale with “High”, “Medium”, and “Low” agricultural probability based on drainage, soil composition, distance to root restricting layer, and other factors (Canada Soil Information Service, 2013), or based on the National Census of Agriculture (Statistics Canada, 2015). Provincial agencies may base the area of agriculture on reported limits of zoned agricultural and operating areas (Commission de Protection du Territoire Agricole du Québec, 2016), or estimate the area of viable agricultural operations on proximity to modern weather stations (Financière Agricole Quebec, 2016). These different definitions lead to many different zones considered as agricultural areas and are all available as polygons in Shapefile format.

Another method of estimating agricultural land is through remotely sensed data for Land Use, Land Classification, and Forestry [LULUCF], another geospatial data product readily available through open access. AAFC's Canadian Land Use Maps (Agriculture and Agri-Food Canada, 2015a) detailing agricultural operations from land inventories are available for years 1990, 2000, and 2010, while another raster product based on remote sensing of agriculture throughout Canada for recent years (2011 – 2015) is available as the AAFC Annual Crop Inventory (Agriculture and Agri-Food Canada, 2016). Both of these data sets provide gridded geographic extents of agricultural operations as they have been planned and as they have been sensed using satellite imagery and are a valuable resource for specifying agricultural areas based on gridded observations.

3.4.2 - Methodology: Data Treatment and Evaluation

For this analysis I treat the CPTAQ shapefile for present-day agricultural operations as a coarse-scale delimitation of agricultural areas, and consider for the finer scale evaluation of agricultural areas the regions where both land use and land classification rasters are in agreement (ie: pixels identified as either “Agricultural” or “Cropland”). I further limit the region through the negative selection of roads, highways, railways, and waterways.

After comparing the various formats and data types between the agricultural extent shapefiles and gridded data, the final boundaries I used to determine the areas of existing agricultural operations were a combination of both the agricultural boundaries available from Quebec as determined by CPTAQ and a combination of both gridded AAFC products.

I then gathered, compared, and determined the total agricultural area using a combination of vector polygons identifying coarse-scale agricultural, removing roads, highways, and railways, then used land use, land cover and forestry [LULUCF] satellite estimates to determine the exact total agricultural area in Southern Quebec. With this estimate, I integrated elevation, soil and drainage data, and scored these variables according to suitability criteria developed for non-climate spatial components important for common viticultural operations and practices. Using site quality indicators for non-climatic characteristic in a multi-criteria evaluation system, I present here a point-based suitability scoring system for the geometry ensembles to provide relative viticultural favourability across the Southern Quebec region.

The coarse geometry outlining areas of agricultural operations not limited by critical non-climatic variables was developed using both Boolean and weighted multi-criteria analysis operations to delimit suitable areas. I began by combining vector and raster data sources, removing roads, rails and industrial, and urban areas to focus specifically on areas specific to agricultural operations. I then weighed topological, pedological, and hydrological features according to suitability criteria for viticulture operations. The regional suitability values were then examined with the locations of currently operating vineyards to assess non-climate vineyard characteristics from a spatial analysis perspective.

3.4.3 - Results: Identification of Consistent Agricultural Land

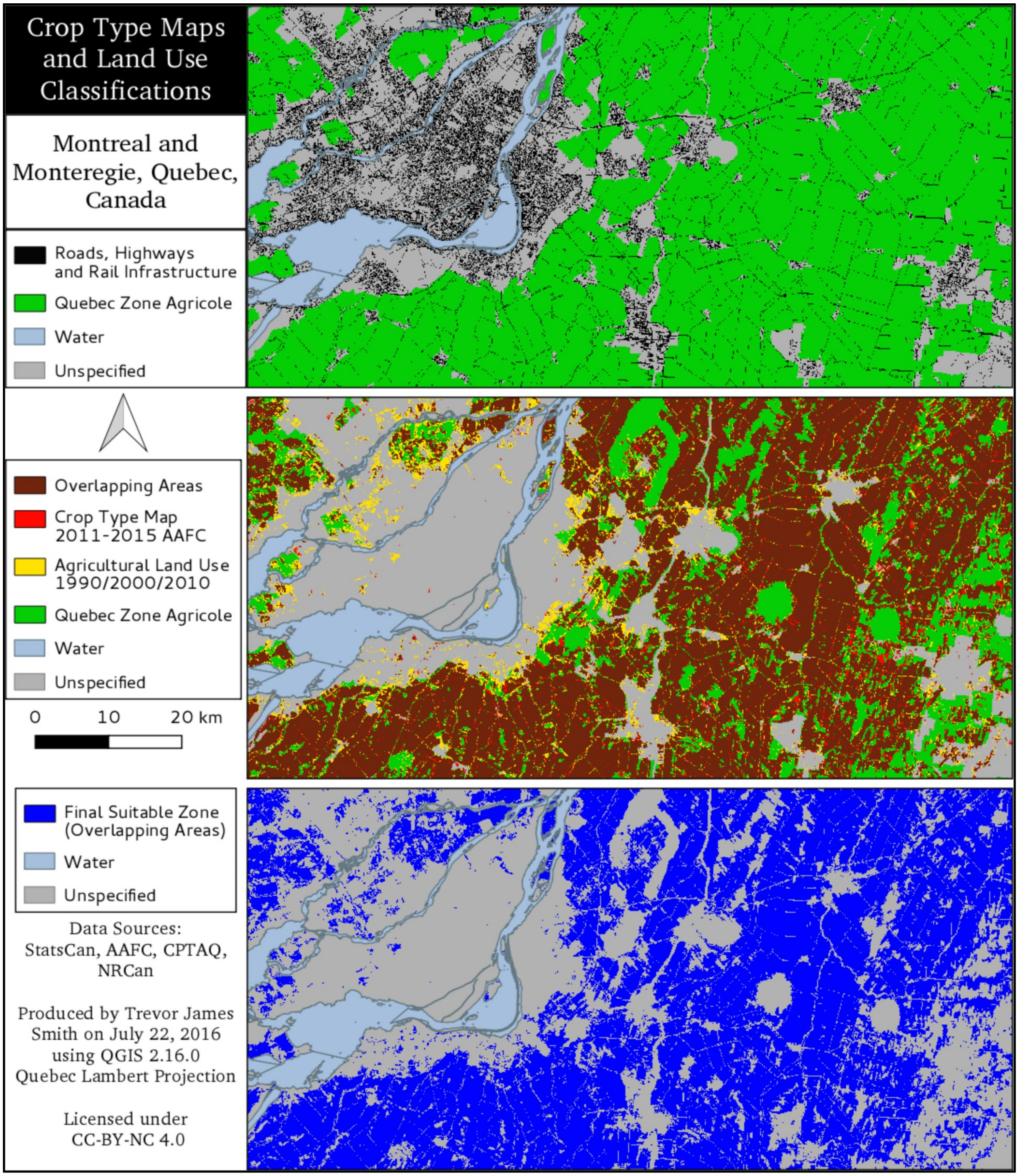

Figure 3-3: Land Use and Crop Inventory Data Overlays Determining Total Agricultural Areas, derived from (Agriculture and Agri-Food Canada, 2015a, 2016; Commission de Protection du Territoire Agricole du Québec, 2016)

As mentioned previously, In order to determine the exact areas recognized as agricultural land, I began with the CPTAQ boundaries (Commission de Protection du Territoire Agricole du Québec, 2016) as the rough estimate of agricultural boundaries with areas that were identified as roads, highways, and rail infrastructure being removed [Figure 3-3, areas in green]. Additionally, areas consistently marked for agricultural land use and recent estimates that consistently identified agricultural operations via remote sensing data were used to determine the exact amount of agricultural area within this region [areas in red, yellow, and brown]. Grid pixels falling outside this region were eliminated. I identify this region as the final suitable zone [areas in blue].

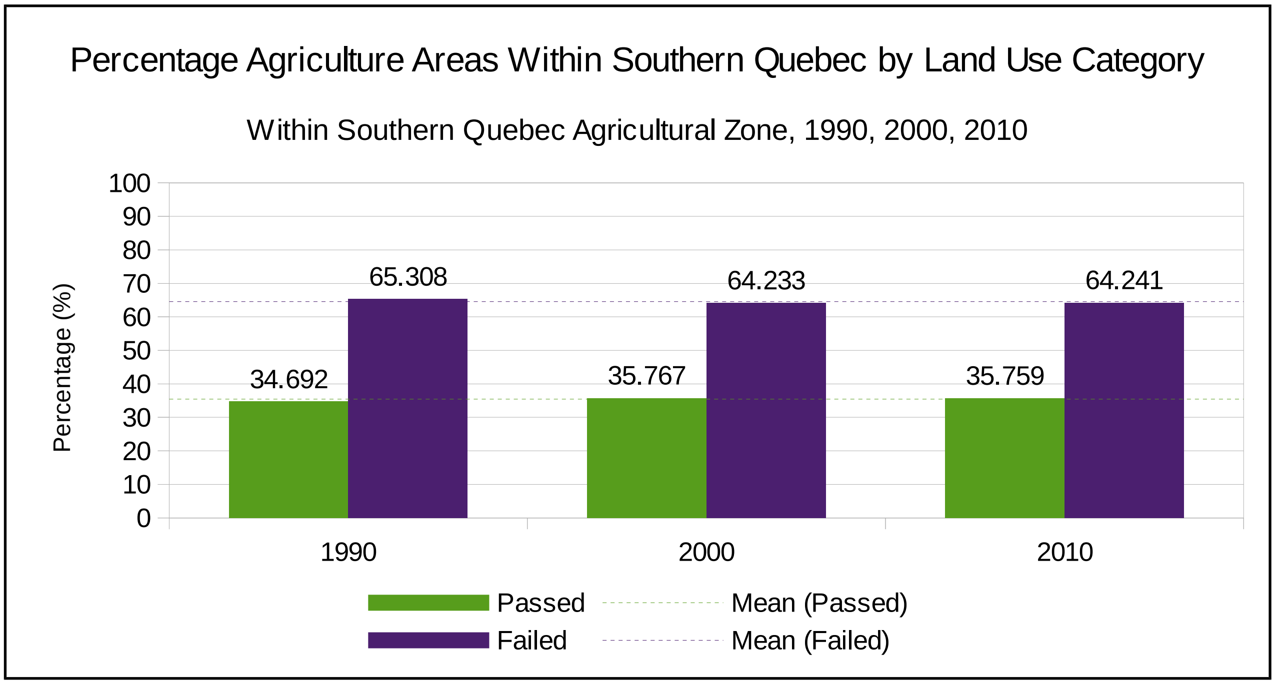

Figure 3-4: Proportion of Actual Agricultural Areas from CPTAQ Agricultural Estimates as determined from Land Use Categories (Agriculture and Agri-Food Canada, 2015a)

[Passing Land Use ("Cropland") Code = 51; All Others Failed]

When comparing the raster-based estimates of agriculture to the region minus roads, highways, and railways, Land Use estimates identifying the agricultural area in Southern Quebec show that agriculture accounts for more than 1/3 of the Southern Quebec CPTAQ region. The region experienced an increase of 1% by way of agricultural land use ("Cropland" = grid value '51') but has stayed roughly at around 35.75% since year 2000.

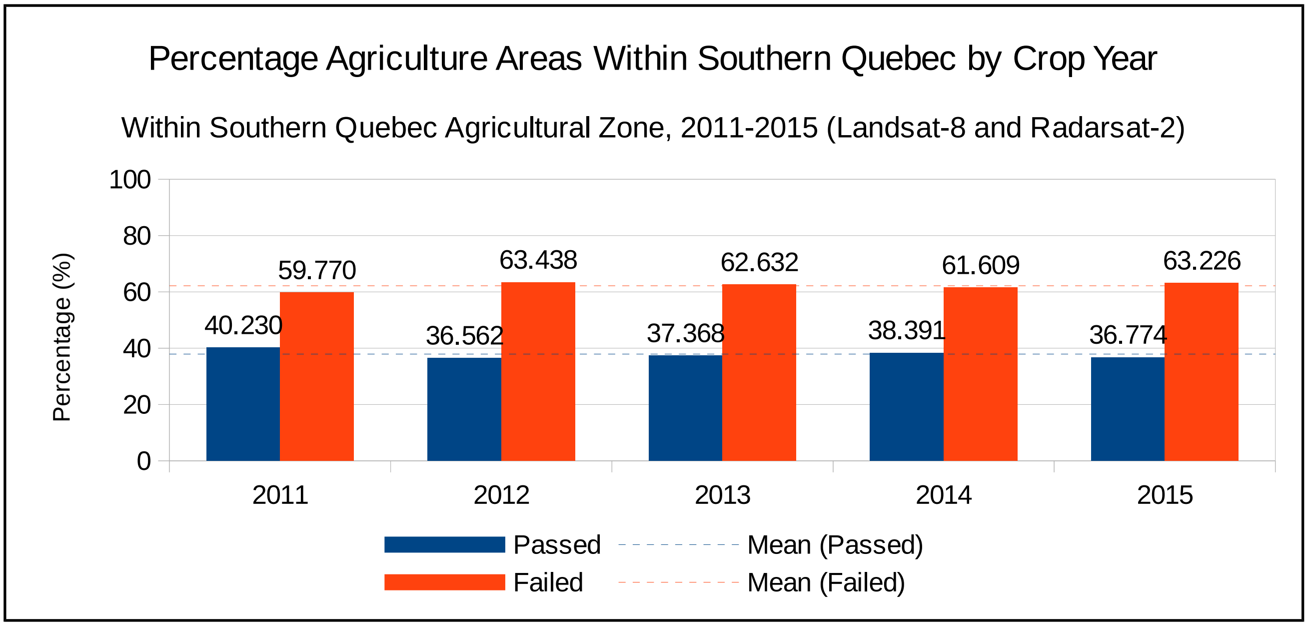

Figure 3-5: Proportion of Actual Agricultural Areas from CPTAQ Agricultural Estimates as determined from remotely-sensed Annual Crop Inventory Data (Agriculture and Agri-Food Canada, 2016)

[Passing Crop Codes = 120 – 199, inclusive ; All Others Failed]

The Annual Crop Inventory data offers much more diversity in the types of agricultural operations measured. Some specific categories include “Cereals” and its subcategories (codes: 132 – 146), as well as categories for “Corn” (code: 147), “Soybeans” (code: 158), and “Hemp” (code: 197).[24] By considering all agricultural operation areas as those with coded for any existing agricultural operations and areas that otherwise would be (e.g. areas too wet to be seeded that season), I determine that agricultural areas have comprised roughly the same proportion of Southern Quebec.

24 While “Vineyards” is a designated crop type category (code = ‘190’), no regions within Southern Quebec are categorized as such. This is likely due to the small and heavily dispersed region failing to be recognized as “Vineyards” in comparison to the provinces of British Colombia and Ontario.

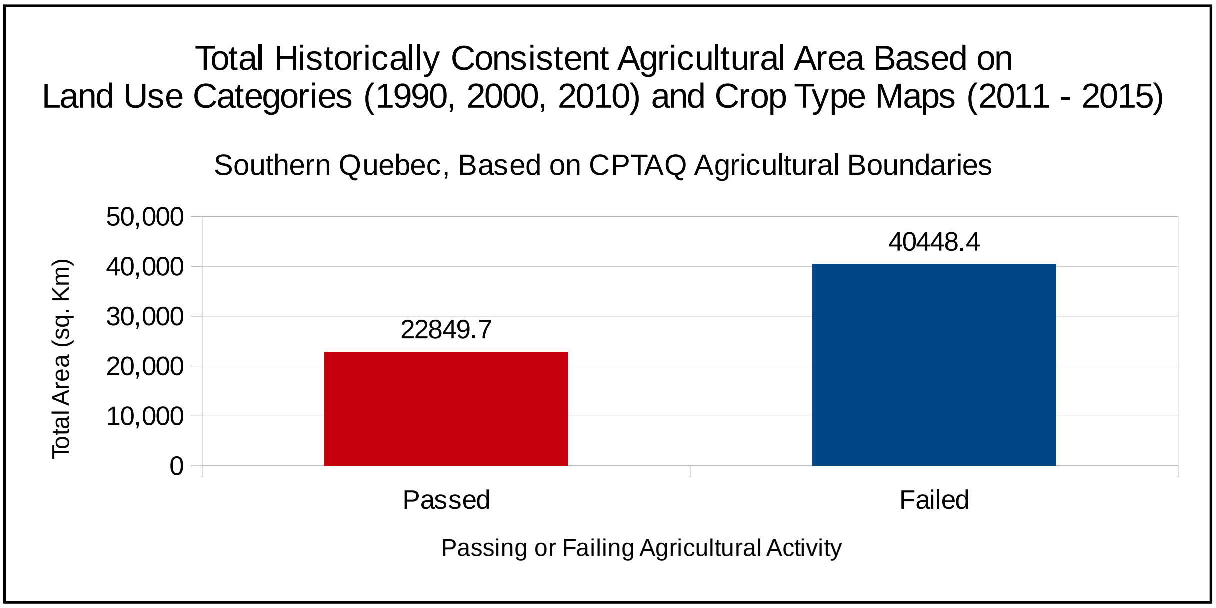

Figure 3-6: Total Agricultural Area as determined by Selective Removal of Rail, Roads, and History of Agricultural Land Use or Crop Inventory

[Area in square Kilometres]

By combining the more recent Crop Year rasters using a Boolean test for agricultural suitability within the CPTAQ region, I determine here that in actuality the five rasters overlap continuously for 36.1% of all areas within the region. This translates to a total area of nearly 22,850 sq. Km with the remaining 40,450 sq. Km identified either as urban, developed, forested, rivers or lakes, or inconsistent and transitioning agricultural land.

Section 3.5 - Conclusion: Open Limitations and Lessons Learned

The popular rise of the FOS ideology have changed a lot of the ways that researchers and developers work together and has the capacity to continue changing major systemic institutions and help build more inclusive societies. That said, the choice to adopt a fully open source approach is not without limitations. The idea of "Opening" science for the benefit of all is limited based on the relative access of the source material, physically, temporally, and intellectually. The more academic-focused "Open Access" movement – whose aims are to "liberate" the wealth of knowledge published in circulated journals by encouraging article authors to release their works under Open licenses – is not focused explicitly on making journal access more accessible to those without the base knowledge necessary to comprehend the material; Open Access is designed to give access to anyone, with the understanding that exclusive access models costly and have few benefits, and that researchers whose work and accomplishments benefit the general audiences which depend on exposure to new literature might make better use of it (Suber, 2012).

Open Access as an academic movement is still a work in development and is not as popular relative to more traditional methods of journal publication due to many factors, such as the added cost of publishing in Open journals, both from a financial sense and from a professional sense (e.g. lower journal impact factors) (Evelith, 2014). Publication rates for Open journal articles and the creation of new Open journals however have been rapidly expanding with publications significantly increasing in numbers since the beginning of the commercial Internet (Laakso et al., 2011).[25]

From a business standpoint, Open Source options have yet to effectively tackle problems of small and medium enterprise operations, due to the speed at which FOS software and solutions are developed and issues of compatibility with Microsoft Windows legacy infrastructure or exclusive software and data formats. While desktop operating systems built on Ubuntu have been deployed as the standard for some government-level desktop operating systems – with some major examples being Andalusia, Spain (Canonical,

25 That said, an up-to-date listing of all reputable Open Access journals online can be found online (https://doaj.org/), identifying 2.4 Million articles across 9,426 journals at the time of this publication.

2010) and Munich, Germany (Heath, 2013)[26] - and Red Hat Inc. provides Linux certification programs (Red Hat Inc., 2017) as well as both desktop and workstation solutions for businesses, some barriers to adoption by other educational and public institutions persist in the costs of conversion, the reluctance of paid developers to release Open code, and perceived reliability, compatibility and maturity of Open Source solutions (Thacker & Knutson, 2015; van Rooij, 2007).

Issues related to the need for capable hardware, reliable network infrastructure, time needed to familiarize oneself with Open models, and language and physical capabilities can also be considered other major limitations of Open media (Suber, 2012). All Open styles of data, development, and knowledge access are built upon and facilitated by Internet infrastructure. For communities without reliable Internet access – due to high access fees, low available speeds, hardware support/needs, lack of social support, or a combination of all these factors – the benefits of these Open approaches are negligible. Where networks speeds and online capabilities have gotten faster and more all-encompassing, regions such as developing countries and rural and remote locations may continue to experience a lack of adequate network infrastructure due to high access fees and persistent low quality connections, contributing to the “Digital Divide” (Graham, 2011); this reality is particularly true for indigenous communities (McMahon, 2014; Samaras, 2005). That said, the arguments for greater Internet access to help bridge the gap in Internet society have been identified for some time (WSIS, 2003) and, for Canada, efforts have been put forward by non-government groups, such as the First Mile Connectivity Consortium and others, to hold government responsible for responsive and self-determined Internet infrastructure development (McMahon et al., 2011).

In many ways, these criticisms of Open movements help us in identifying where the weaknesses lie and where to put forward efforts to make these movements stronger and to have more positive impact for societies and peoples. Open models, licenses, standards and projects are continuously innovating and evolving to better serve communities and reshape

26 At the time of this writing, the city of Munich, Germany was considering shifting from LiMux, a personalized version of Ubuntu to Microsoft Windows 10 due to Information Technology infrastructure problems. It is worth noting that these problems are largely due to the fact that this infrastructure had not been updated during or since the LiMux conversion began in roughly 2006, suggesting that many of the issues are falsely-attributed to LiMux when those problems would have persisted under Windows (Heath, 2017).

the digital landscape both physically and virtually. The sheer quantity of data now openly available is difficult to track and many efforts to provide universal catalogues, or categorization schemes or access mechanisms have further divided the Open environmental data landscapes.[27] As such the need for data curation and management services of libraries and archives are integral to the next steps in the evolution of Open platforms (Recker, Müller, Trixa, & Schumann, 2015); this need extends as well to the systems and principles by which libraries conduct and innovate to remain on the cutting edge of these new digital needs (Thompson, 2012). From an academic standpoint, the universities are in a unique position with regards to Open Source, as they are publicly-funded institutions with archival resources and data needs and should not only pursue a more collective and Open knowledge-sharing but also strive for a more Open education and research pedagogy reliant on FOS solutions (Recker et al., 2015). By supporting those actively using and building upon FOS, universities and research institutions add value and learning experience to the code and knowledge-base which can be beneficial to others in direct and in indirect ways (Recker et al., 2015).

More technically, FOS software and Open standards are moving very fast and the number of solutions and web services built on FOS is already fundamentally changing the software landscape. For GIS, FOS has changed the way we visualize our world and surroundings and given independent researchers and smaller agencies the tools to better represent local-level to global-scale goals and needs. By adopting Open methods and practices, barriers to environmental spatial analysis are significantly lessened. While the knowledge needed to use some FOS software and perform and interpret environmental analyses may be beyond the reach of non-technical users and other independent researchers, resources like online support communities and movements such as Open Access or the popular phenomena of Massive Open Online Courses [MOOCs] provide opportunities for most anyone to learn without payment barriers.

My experience in working in Open Source has changed many of the ways in which I approach technology and society. The knowledge I gained in searching for, using and troubleshooting Open Source solutions for my technical and academic needs has opened for me many opportunities to develop my Informational Technology skills and aid my performance

27 One such active listing of all open environmental GIS data maintained by Dr. Robin T. Wilson that I relied upon and contributed to in my search for data can be found online at http://freegisdata.rtwilson.com/.

and success in the realm of environmental and socioeconomic research. As a movement, I find it inspiring and I hope one day to adequately “commit” myself to it.

Chapter 4 - Manuscript: The Agroclimatic Impacts of Climate Change for Quebec's Physical Viticultural Climate

I present here the main results of my wine climatology research, roughly adapted for future academic publication for perhaps the *Journal of Wine Climatology*, *Regional Environmental Change*, or the universally open access journal, *PLoS One*. This research was built as an comprehensive spatial reproduction of some of the wine climatology studies authored by European and American viticultural researchers, namely Helder Fraga (Universidade de Trás-os-Montes e Alto Douro) and Gregory Jones (Southern Oregon University), and extending upon the research of Canadian geographers professors Norman Jones (Bishop's University) and Anthony Shaw (Brock University) who've speculated on the potential for Southern Quebec to enter the “Big League” of wine producing regions of Canada. This research project would not have came to be without the continuing research and enthusiasm of the Wine Specialty Group of the American Association of Geographers who I had the opportunity to present some of this work to in San Francisco earlier in 2016.

Section 4.1 - Abstract

The anticipated impacts of climate change and global society's ability to adapt to changing and uncertain atmospheric and meteorological conditions suggests that there will be “winners” and “losers”. Future agricultural changes, specifically for viticulture, are expected to significantly impact most “old world” wine countries in negative ways creating non-analogous growing conditions to present, while some viticultural studies suggest that the “new world” wine regions may experience more favourable growing conditions for more marketable European V. Vinifera grape species. In the past 40 years, commercial winemaking in Québec has become popular in corresponding with changes to legal alcohol frameworks and, coincidentally, as the effects of climatic changes have been felt through the region. My research compares historical, present-day and future climatic conditions for an artisan grape-growing and winemaking area located in Southern Québec.

I examine the region's existing and potential viticultural capacity by employing a spatiotemporal climatic analysis using open source GIS software, open data portals and viticultural growing season metrics, incorporating annually-observed and 30-year normalized climate records, as well as regionally downscaled climate model output for two radiative forcing scenarios (RCP 4.5, RCP 8.5). Results suggest that observed changes in the area from climate change are already being experienced throughout the region and that path-dependent scenarios will significantly impact the degree of suitability and agroclimatic stability of the region.

Section 4.2 - Introduction

4.2.1 - Canadian Wine, Québecois Climate

When people think of the culture of Canada and its identity, wine does not immediately come to mind. Despite this absence of cultural tradition, the production of wine and the development of the wine industry has become a strong and distinctive niche within the Canadian milieu throughout the history of the country. Each province has different cultural and historical landscape of production and identity. In Quebec, the history of wine and its production is heavily entwined with the historical prominence of the Catholic Church, the Nation of Quebec, and the traditional French Canadian identity that has developed over 400 years which have all come together, creating a rather unique Canadian region (Ackerman, 2007). The French influence that permeates the province extends well beyond Quebec's borders and Canada's French communities. It therefore should come as no surprise that much like in France, Canada has a vibrant wine culture.

The growth of commercial wine production in Canada is a relatively new phenomenon that was only popularized in the 20th century. The most recent available data from the FAO place Canada's 2012 wine production at 57000 Million Hectolitres (MhL, or 10-1 Tonnes) (FAO, 2014), roughly doubling the wine production 50 years previously [Figure 4-1]. Prior to this period, Canadian winemaking was primarily limited to artisan production. The present-day Canadian industry is dominated by the Okanagan and Fraser Valleys of British Columbia and the Lake Erie North Shore and Niagara Peninsula of Ontario (Shaw, 1999, 2001).

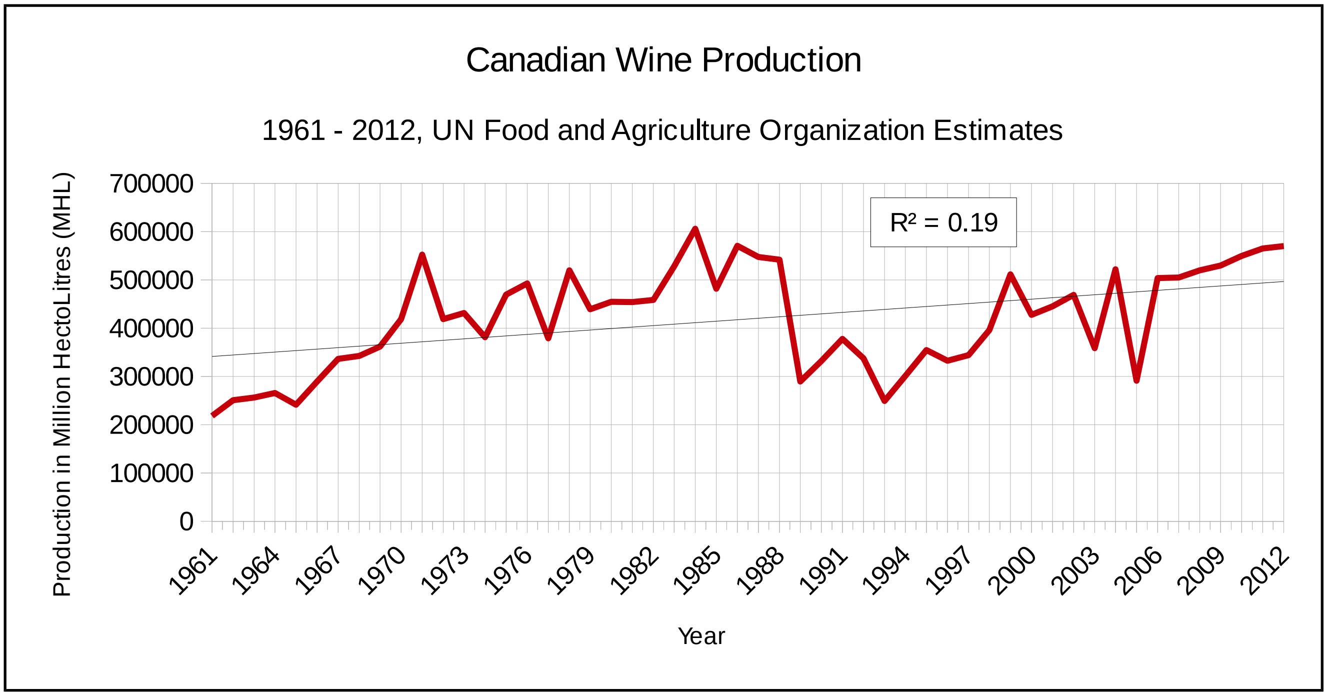

Figure 4-1: Canadian Wine Production, 1961-2012 (adapted from FAO, 2014)

Reflecting on its harsh winters and recent history, Southern Quebec has been called “the least likely of all Canadian wine regions” (J. Robinson, 2006, p. 133), a statement echoed by Shaw (1999). The earliest known attempts to establish European *V. vinifera* vineyards in Quebec can be traced back to a lot founded in Montreal in the late 19th century under the name “Beaconsfield Vineyards” after the British prime minister, Benjamin Disraeli, the Earl of Beaconsfield (Ackerman, 2007; Ville de Beaconsfield, 2012). Within five years, this vineyard was destroyed due to a series of harsh winters and the lot was auctioned by its owner; this is where the current municipality of Beaconsfield is now located (Ville de Beaconsfield, 2012). The first permits for artisan winemaking issued under the newly established provincial liquor commission and corporate distributor, *la Commission de contrôle des permis d’alcool* and *la Société des alcools du Québec* (SAQ), respectively, were only granted in the late 1970's (Ackerman, 2007; AVQ, 2012a). By 1987 a regional wine quality board, the *Association des Vignerons du Quebec* (AVQ), was established in order to certify quality, specificity and the origin of Quebec wines and to negotiate for better government support of the industry (AVQ, 2012a; Ben Hassen & Tremblay, 2016). As of 2014, approximately 64 vineyards registered with AVQ were actively producing wine in southern Quebec, with the highest concentration of operations located in the *Montérégie* and *Estrie* wine regions (40 in total) (AVQ, 2012b).

According to Ben Hassen & Tremblay (2016), AVQ members included, there are presently around 270 wineries throughout Quebec, with around 20 operating under the *Vignerons Indépendants du Québec* and the remaining operating independently. A large portion of Quebecois vineyards are found within the Saint Lawrence river valley and straddling the United States border, between 45 and 45.5°N (N. K. Jones, 2012).

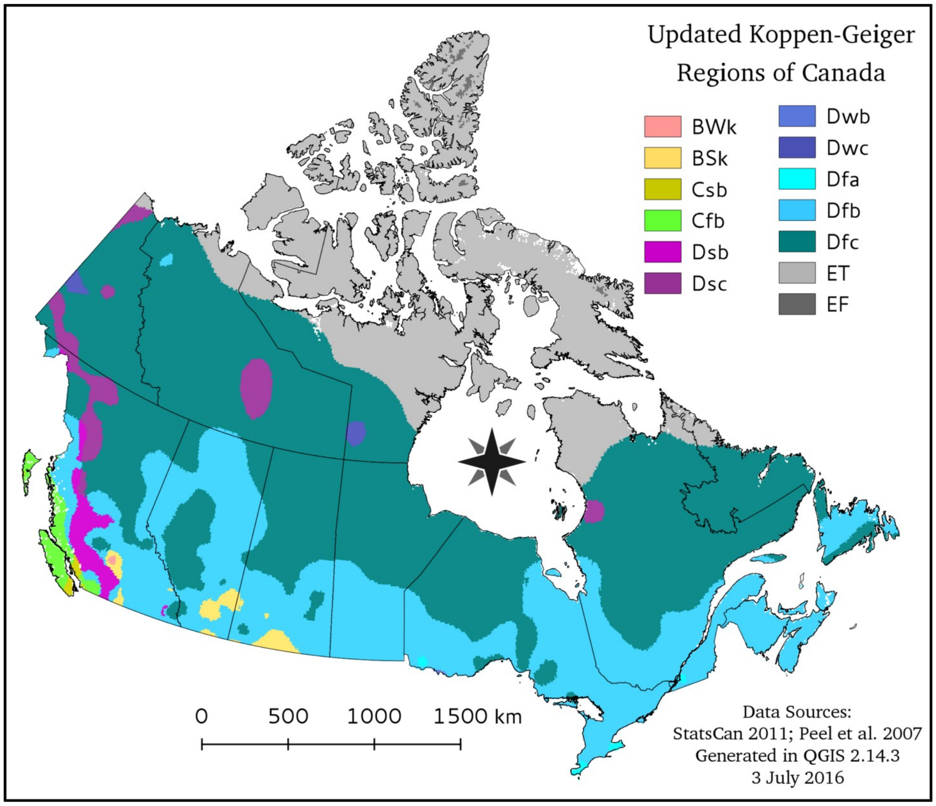

Figure 4-2: Updated Köppen-Geiger Regions of Canada, with Provinces and Territories Outlined (adapted from Peel et al., 2007)

The regional climate of southern Quebec is mostly a 'Dfb' Köppen-Geiger categorized climate [Figure 4-2], well-known for its harsh, snowy winters, hot summers, and short growing season accompanied with late spring intermittent frosts, making viticultural practices, particularly those relying on *V. Vinifera,* a risky investment (Peel, Finlayson, & McMahon, 2007; Shaw, 1999). Vineyard site location in Quebec places emphasis on cultivating vines around topographic features that protect vines from harsh winter and spring elements while attempting to maximize direct insolation on vine foliage (N. K. Jones, 2012; Shaw, 1999). While numerous studies summarized by the IPCC in recent decades have suggested that climate change has already begun to present itself within North America (Field et al., 2007), and many studies have focused on the viticultural and oenological impacts of climate change in many well-established winemaking regions across the world (G. V. Jones et al., 2005), there is a lack of extensive knowledge centered on wine and climate change focused on the relatively new southern Quebec wine region. According to N.K. Jones (2012), some vineyards in the *Montérégie* and *Estrie* wine regions have begun experimenting with European varietals of *V. vinifera* despite the historical hostility of the Québecois climate.[28] The rationale behind this new effort is for vineyard operators to potentially capitalize on what they have observed as longer and warmer growing seasons, likely attributed to the onset of climatic changes from Quebec regional-level warming of the climate system (N. K. Jones, 2012).

Climate change, a direct result of ever-increasing greenhouse gas emissions, is presently affecting numerous atmospheric, biological and hydrological systems that agricultural operations rely upon (Bourque & Simonet, 2008; Rosenzweig et al., 2007). Wine grape (*V. vinifera* and particular to Canada and the American northeast, *V. labrusca a*nd American-European *Labruscana* hybrids) cultivation dates and wine production quantities have historically been used as climate proxies for their phenological sensitivity to climate-dependent growing conditions (Schultz & Jones, 2010; Tonietto & Carbonneau, 2004), particularly mean seasonal temperatures, precipitation and extreme weather events (Holland & Smit, 2010). Numerous studies conducted for regions and *terroirs*, or areas with specific climate, aspect and soil favourable for grapevine cultivation (G. V. Jones, Snead, & Nelson, 2004; Stevenson, 2005) have historically focused on locations throughout Europe, particularly France (Bonnefoy et al., 2013; B. I. Cook & Wolkovich, 2016; Laget, Tondut, Deloire, & Kelly, 2008; Lereboullet, Beltrando, Bardsley, et al., 2013) and in Australia (Hall & Jones, 2009, 2010; Sadras & Petrie, 2011; Webb et al., 2013; Webb, Whetton, & Barlow, 2007, 2011), and the western United States (G. V. Jones et al., 2010, 2004; Watkins, 1997). The region of southern Quebec and its recent emergent commercial wine industry has yet to be comprehensively studied using a Geographic Information Systems-based viticultural categorization analysis approach (Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014; Kurtural et al., 2007; Tomasi et al., 2013; Vaudour & Shaw, 2005).

28 This claim is supported by my personal communications with vineyard operators throughout the region at SAQ-sponsored wine events and agricultural festivals.

In recent years, the spatial extent of vineyards within southern Quebec is primarily located within *Montérégie,* the Eastern Townships (*Estrie*), and neighbouring regions comprising the Saint Lawrence Seaway Valley, constrained by cold weather conditions and comparatively short growing seasons typical of Northern regions (N. K. Jones, 2012; Shaw, 1999). However, under scenarios of future impacts from expected climate change, many studies suggest that anticipated temperatures and precipitation patterns from climate change could alter existing viticulture operations, possibly increasing the potential for greater widespread cultivation of more economically valuable, thermally-demanding grape varietals as well as contribute to the expansion of viticulture climate regions northward from the extent of presently suitable areas (Fraga et al., 2012; Moriondo et al., 2013).

4.2.2 - *Agroclimatic and Viticultural Studies of Quebec*

From a general agroclimatic perspective, historical studies of mid-to-late 20th century Southern Quebec have described the region as one of high climate risk on account of its cold climate with high potential for late spring frost (when temperatures dip below 0 ºC after grapevine budbreak), extreme cold air temperatures, and ground dehardening (based on cumulative degree-days exceeding 0 ºC during the winter season) which combine to make Quebec a very hostile environment for perennial crops that are not well cold-adapted (Lepage et al., 2012; Rochette & Dubé, 1993b, 1993a). That said, many of these agriculturally important indicators are predicted to change under most scenarios of global climate change, potentially becoming more temperate and with less cold- and frost-associated risks (Lepage, Bourgeois, & Bélanger, 2011). The predictive agroclimatic study performed by Lepage *et al.* (2011) using regional-scale climate model data showed that average summer temperatures in Southern Quebec may rise between +1.9 and +3.0 ºC while average winter temperatures may see anomalies exceeding +2.5 to +3.8 ºC by end of century relative to a mid-20th century baseline. For precipitation, trends are much harder to establish using climate models due to the high uncertainty and disagreements between climate models and their outputs however precipitation (rain and snow) patterns may change alongside large regional temperature changes (Lepage et al., 2011).

Focusing specifically on wine, Quebec's viticultural potential has been briefly examined by a handful of scholars in both global-scale climate studies (Tonietto & Carbonneau, 2004; Vaudour & Shaw, 2005) and more extensively in case studies focused specifically on the Southern Quebec region (N. K. Jones, 2012; Shaw, 1999). According to Tonietto and Carbonneau (2004), Quebec is a moist, cold climate wine region, with very cold *veraison* temperatures, a borderline suitable climate for viticulture comparable to regions such as Geisenheim, Stuttgart and Trier in Germany or Maidstone in the UK. Shaw (1999) described Southern Quebec as a continental climate with a very short growing season and an overall poor quality of soil drainage, where viticulture hinges on local knowledge as “...growers must choose sites that will protect the vines in the winter from polar winds and in the spring from frost, and maximize solar energy to prolong the growing season” (1999, p. 89). At the time of writing, Shaw estimated that the total area of vineyard operations comprised 121 Ha, with the most popular hybrid grape varieties being Seyval Blanc, de Chaunac, Vidal, Maréchal Foch and Geisenheim clones, with some cold-adapted *V. Vinifera* (Riesling, Cabernet Franc, Gamay and Merlot) experimental plots found in a select few locations (Shaw, 1999, p. 90). While vineyards in Quebec have risen in number in recent years (Ben Hassen & Tremblay, 2016), many of the same grape varietals remain in high production today among the AVQ membership [Figure 4-3] (Gagné, 2015b). The majority of these grape varietals and most others typically grown in Quebec require a growing season ranging from between 850 to 1250 growing degree-days, achievable by regularly cold northeastern climates [Figure 4-4] (Dubé & Turcotte, 2011).

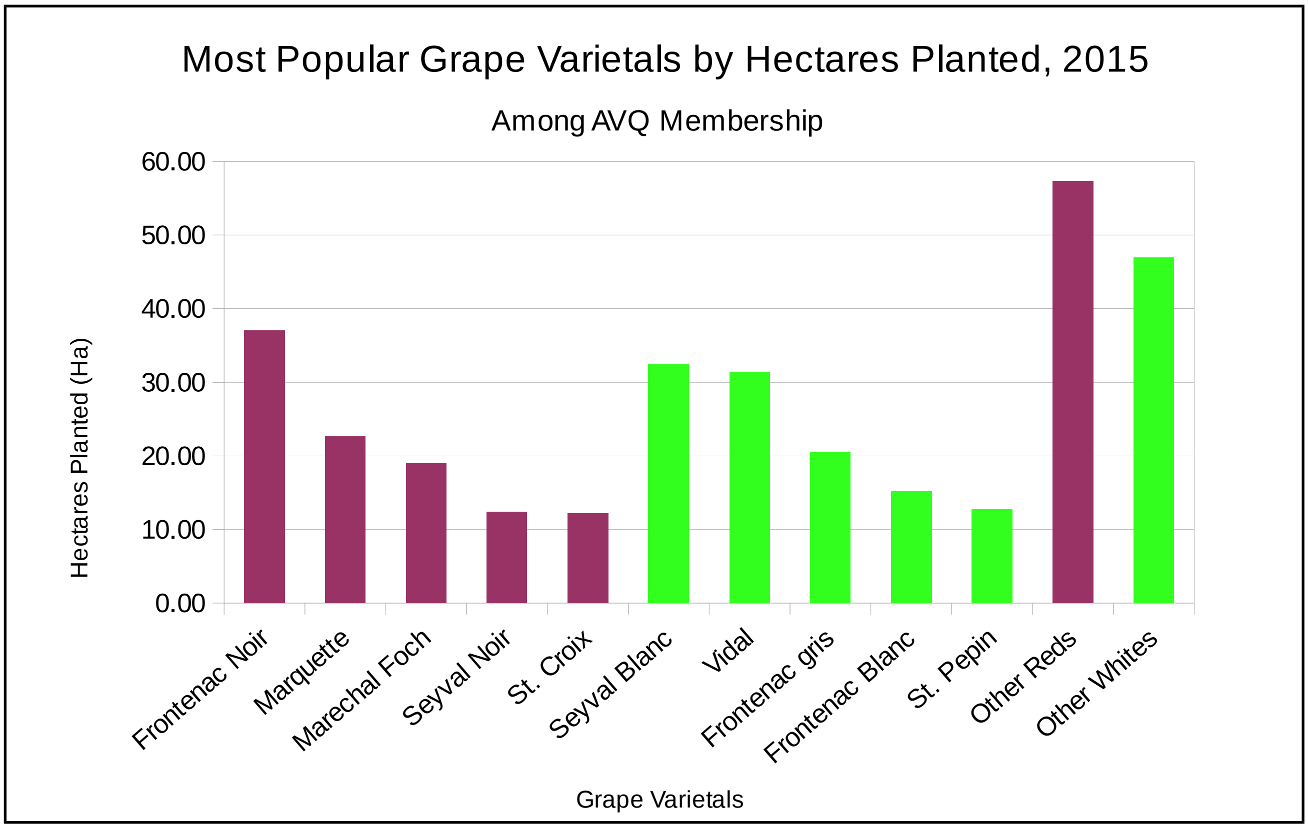

Figure 4-3: Most Popular Grape Varietals Among the Membership of the AVQ, 2015 (adapted from Gagné, 2015b)

[Red wine grapes in maroon; White wine grapes in green]

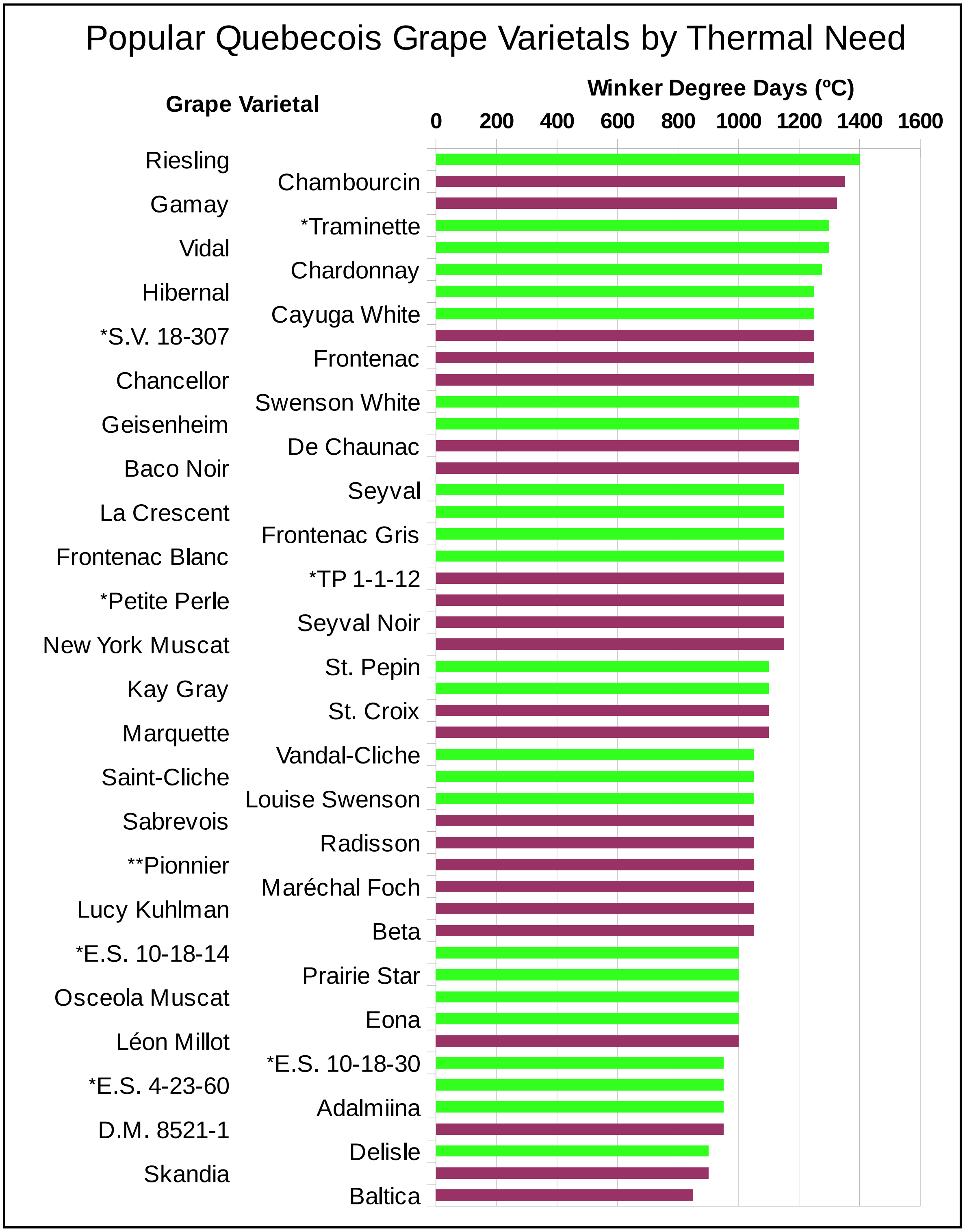

Figure 4-4: Thermal Needs for Most Popular Quebec Grape Varietals to Achieve Veraison (onset of ripening) (adapted from Dubé & Turcotte, 2011)

[Red wine grapes in maroon; White wine grapes in green]

The study presented by N.K. Jones (2012) established statistically that some present-day vineyard regions have begun to experience a trend consistent with climate warming for many bioclimatic indicators important for viticulture, namely higher growing degree-days, fewer winter chilling days, warmer mean minimum temperatures, and a longer frost free growing season throughout the 1979 – 2009 climate period. These conclusions were not organized spatially nor were they extrapolated into the future using climate modelling and are also limited to a select few weather stations representative of the majority of vineyards in the Southern Quebec region. In order to determine a spatial pattern of climatic and bioclimatic changes for the region, I present here a new methodology and analysis of the Southern Quebec viticultural climate using GIS and climate model projections.

4.2.3 - Research Goals

My research goals here are to contribute t the Quebec climate-viticulture by estimating and projecting climatic suitability of the Southern Quebec region for viticultural operations for present-day and future climate scenarios, using a range of bioclimatic indicators and climate-viticulture metrics.

In the following sections, I present: a spatial analysis of the extent of thermal region categories that delimit the suitability of southern Quebec to accommodate present-day viticultural operations; the spatial extent of thermal regions of Quebec that are predicted to be suitable for viticulture under a selection of possible climate change scenarios for 30-year periods spanning from 2010 to 2100; and a validation and contextualization of my results by examining these climatic variables at Québecois vineyard locations to determine common characteristics for the Quebec vineyard industry.

Section 4.3 - Research Methodology

4.3.1 - Overview of Methods

The general aim of my research methodology was to develop a regional climate estimation of viticultural suitability defined by favourable and unfavourable characteristics for viticulture in the southern Quebec region. In order to perform this, I applied approaches and techniques borrowed from the supporting literature within the disciplines of agriculture, climatology, geographical information science and remote sensing. The approach can be summarized in the following steps:

1. I examined temperature and precipitation data using viticulture-specific climate criteria (cumulative Growing Degree Days Above 10°C and other similar climate indices) to determine the current spatially-defined climate-only potential of viticulture operations within southern Quebec (roughly below 52° North). Using spatially interpolated historical observed and modelled temperature and precipitation data from 30-year intervals spanning the previous 50 years, I performed a climatic suitability analysis of Southern Quebec to establish baseline climatic conditions. This methodology was performed for a pseudo-climatology of the 5-year period from 2011-2015 to establish 30-year normalized climate conditions for the present-day period, and for the recent historical (1961 – 1990 and 1981 – 2010) and future periods (2011 – 2040, 2041 – 2070, and 2071 – 2100) projected using the Representative Concentration Pathways [RCP] scenarios for 4.5 W/m^2 (“Stabilization”) and 8.5 W/m^2 (“Business as Usual”) to year 2100. To categorize the viticultural climate regions between periods and data sets, I employed a set of accepted climate classification systems and multi-criteria-based classification system used for categorizing viticulture climate regions.
2. My climate suitability analysis continues by considering present-day locations of vineyards and their potentials for changes to climate and bioclimatic conditions. Using the climate results determined for the Quebec region and data acquired through web scraping techniques, I then geolocated vineyards and related local climate predictions to determine the climatic suitability of present-day winegrowing locations and how these areas and vineyards may undergo climatic changes from present-day climate conditions.

Throughout, I have adhered to the principles of Open Source, and have ensured that all data sets and analysis tools used here are available via free and Open Access policies, under Open Source licenses, or through the public domain. Thanks in part to Canadian Open licensing policies (Government of Canada, 2013) and the wealth of data released by individual researchers and agencies under similar Open-style licenses (for example, see Creative Commons, 2015), it was fairly effortless to achieve the coverage required for the region in question. In addition, I opted to, where feasible, exclusively use Free and Open Source [FOS] software and GIS platforms to conduct all analyses. As such, QGIS (QGIS Development Team, 2016), an open source GIS built in Python that integrates mapping libraries of GDAL/OGR (GDAL Development Team, 2013), GRASS (GRASS Development Team, 2012), SAGA (Conrad et al., 2015), R (R. Development Core Team, 2013), and other analysis programs was used exclusively throughout the research for data formatting, analysis and visualization.

4.3.2 - Defining the Area of Interest

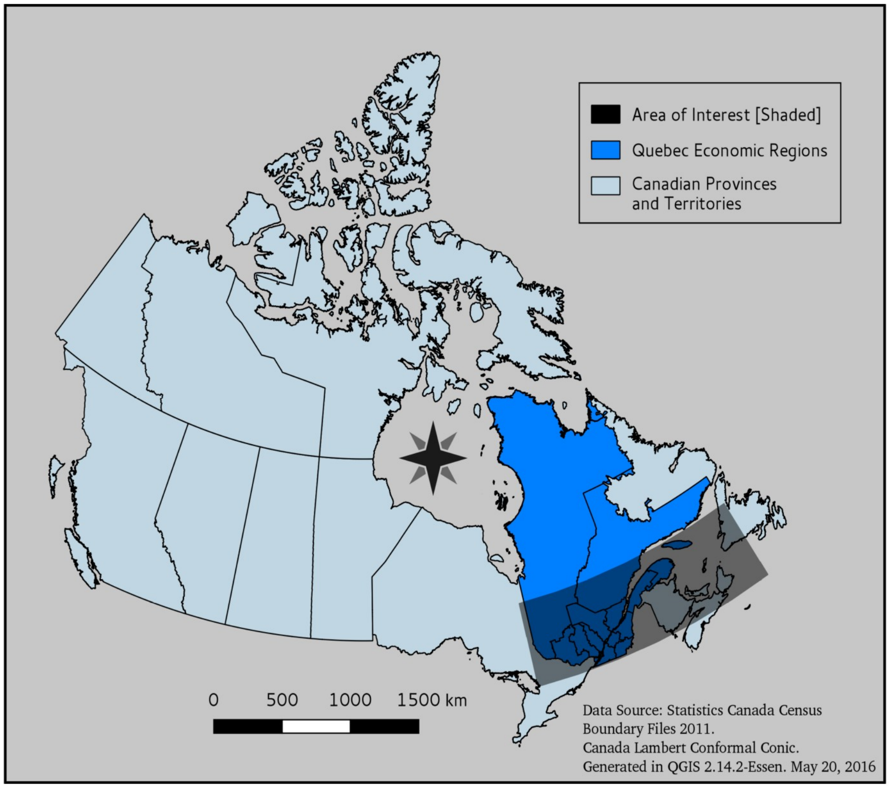

Figure 4-5: Case Study Area of Interest within Canada (Light Blue = Rest of Canada; Dark Blue = Province of Quebec; Shaded Areas = Quebec areas below 50º N)

The area of interest for the main climate analysis is the southern portion of Quebec [Figure 4-5], encompassing primarily all southern regions up to *Sept-Îles*, roughly the northern shore of Quebec bordering the Gulf of Saint Lawrence (around 50 degrees North). While interpolated climate coverages available for Quebec extend beyond this boundary, the density of weather stations North of the Saint Lawrence Valley quickly drops off for the sparsely populated interior areas of Northern Quebec, reducing the reliability of climate variable surfaces from historical climate records.

4.3.3 - Historical and Present Climate Data

For the historical portion of my analysis, I considered climate data from the WorldClim database which maintains relatively high-resolution historical and projected raster tiles for many climate and basic bioclimatic variables (Hijmans et al., 2005), the NASA Daymet project which offers daily and monthly temperature and precipitation estimates based on satellite observations (Thornton et al., 2015), and the Quebec Agroclimatic Atlas which offers climate and bioclimatic estimates focused on the recent 30-year normal period for Southern Quebec (Agriculture and Agri-Food Canada, 2015b).

From the WorldClim, Daymet, and Quebec Agroclimatic Atlas data sets, I collected monthly averaged maximum and minimum temperature and average monthly precipitation grids for several different time periods (30-year normals and measured months) which were then used to create the tools for calculating most viticulture-climate metrics. While these three data source options presented me with many time periods to proceed with my formal analysis, I elected to use solely the NASA Daymet data to examine near-recent climate trends and relied on another data set, ClimateNA (Wang et al., 2016), for two historical climate normalization periods (1961 – 1990 and 1981 – 2010).

I treat the time period of 2011-2015 as an example of present climate conditions and monthly observation from this time period were extracted from the NASA Daymet data set and used to calculate a pseudo-climatology of monthly averages. It should be noted that while these climate conditions represent the most recent five years, the short time period considered is not reflective of normal trends, as interannual variability and compounding factors such as the El Niňo Southern Oscillation and the influence of solar cycles have not been controlled for.

Future Climate Data and Precalculated Climate Indices

For the future analysis, I considered two potential realizations of climate change from the IPCC-developed Representative Concentration Pathways [RCP] scenarios (van Vuuren et al., 2011): RCP 4.5 (Thomson et al., 2011) and RCP 8.5 (Riahi et al., 2011). The numerical naming conventions for these scenarios refer to the total radiative forcing [RF] anomaly predicted at the end of year 2100 given different assumptions of decarbonization, green energy developments, and international cooperation on climate. I refer to these scenarios as "Stabilization" (in reference to stabilized radiative forcing levels by 2050) and "Business as Usual" (in reference to continuous carbon emission growth), respectively.[29]

I sourced climate data for the RCP scenarios from the ClimateNA North American climate project (Wang et al., 2016). ClimateNA is freely accessible via University of Alberta and which provides ensemble averages of spatially downscaled climate and bioclimatic variables, generated from 15 atmosphere-ocean general circulation models. The project's aim is to create regionally downscaled and ensemble averaged temperature, precipitation, and other climate grids from climate models of the Coupled Model Intercomparison Project [CMIP5] that most accurately portray historical climate conditions across North America (Wang et al., 2016).[30] These models are averaged for monthly climate conditions according to two historical normal periods (1961 – 1990, 1981 – 2010) and three future periods (2011 – 2040, 2041 – 2070, 2071 – 2100) and downscaled using the PRISM technique (Daly et al., 2008) to account for orographic and topographical influences on local climate. The results are available for all land areas of North America at the 1 Km spatial resolution.

In addition to monthly averages for temperature and precipitation, I also relied on precalculated indices determined through the ClimateNA project. In order to determine factors such as soil moisture demand and other agriculturally important climate indicators, I use the bioclimatic indicators provided by ClimateNA, specifically soil moisture demand as the

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29 Both of these scenarios suggest an end of 21st century climate warming at or in excess of 2 °C. While the goal of maintaining the global climate anomaly below 2 °C is necessary to prevent harmful climate system interruption, in my opinion the RCP 2.6 "Peak and Decline" scenario is unachievable under present-day climate change mitigation leadership.

30 The CMIP5 models used to create ensemble averages are CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO Mk 3.6, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R.

Climatic Moisture Deficit [CMD], extreme minimum temperature [EMT], average length of the frost free period [FFP], and precipitation in the form of snow [PAS].[31]

The CMD is a monthly calculated index for normalization periods that uses the modified Penman-Monteith soil moisture approximation outlined by Hogg, Barr, and Black (2013) that examines baseline soil moisture as a function of climate-based reference evaporation (E_{ref}, mm) and precipitation (P, mm). Where precipitation exceeds potential evaporation, no deficit is recorded, and where evaporation is equal to or exceeds precipitation the amount of moisture required for vegetation from non-precipitation sources to prevent soil desiccation or drought, the value is recorded as a positive integer [Equation 4-1].

$$\mathrm{CMD} = \begin{cases} 0, E_{ref} < P_m \\ E_{ref} - P, E_{ref} \geq P_m \end{cases}$$

Equation 4-1: The Climatic Moisture Deficit Index

The remaining indices are calculated annually and are approximations of the bioclimatic conditions experienced in the average year for the normalization period of interest.

31 For more information, the calculations for CMD, EMT, FFP, and PAS are detailed in-depth in the appendix section of Wang, Hamann, Spittlehouse, and Murdock (2011).

4.3.4 - *Climate Metrics and Parameterizations*

All climate metrics used in this study rely on temperature (ºC) and/or precipitation (mm) at various scales (daily, monthly, and/or annual).[32] The gridded climate data I used included only monthly averages; in cases where the calculation of climate metrics required accumulated daily values (e.g. for accumulated growing degree days), I approximated daily values by multiplying monthly data by the number of Julian calendar days in each month. All climate metrics were programmed using the QGIS graphical modeller using combinations of GDAL, GRASS, and SAGA algorithms, and were saved as Python scripts.

Growing degree-days [GDDs] with a threshold temperature of 10 ºC, generally referred to as the Winkler Index [WI] (Winkler et al., 1974), is a standard wine bioclimatic metric for determining the category of growing season that an area experiences based solely on mean and max monthly temperatures (T) [Equation 4-2].

$$WI = \sum_{April}^{October} \left(\frac{T_{max} + T_{min}}{2} - 10 \right)$$

Equation 4-2: The Winkler Index for Growing Degree-Days

The Huglin Heliothermal Index [HI], another popular metric for wine bioclimatology, considers daily average max and mean temperatures between April and September and relies on a latitude-based modifier (k) in order to account for longer day length experienced during the growing season at higher latitudes (Hall & Jones, 2010; Huglin, 1978) [Equation 4-3].

$$HI = \sum_{April\,1}^{September\,30} \left(\frac{(T_{max} - 10) + (T_{average} - 10)}{2} \right) * k$$

Equation 4-3: The Huglin Heliothermal Index for Growing Degree-Days

The “true” curve of this value is non-linear and heavily dependent on latitude, angle of incidence with the Sun, and the number of days within the growing season. For the sake of

32 These climate categorizations as presented among the source literature can be found in tabular format throughout Annex 3 – Climate Indexes and Climate Scoring Tables.

simplicity, I forwent the calculation presented in Hall and Jones (2010) and approximated a pseudo-exponential curve based on the original formula by Gladstones (1992) that assumes k = 1.04 at 45º N, 1.06 at 50º N, 1.10 at 55º N, and 1.15 at 60º N (the northern limit of present-day Quebec agriculture doesn't exceed 52º N).[33]

Another wine climate metric developed by specifically by Gladstones (1992) considers the mean diurnal temperature ranges in addition to an adjustment for latitude. For the Biologically-Effective Growing Degree-Days [BEDD] metric, daily temperature ranges below 10 ºC and above 13 ºC are emphasized using conditional modifiers to approximate the curve of daily temperatures [Equation 4-4 and Equation 4-5].

$$BEDD = \sum_{April\,1}^{October\,31} max\left(min\left(\left(\frac{(T_{max}-10)+(T_{min}-10)}{2}\right),0\right)*k+TRadj,9\right)$$

Equation 4-4: The Biologically Effective Growing Degree-Days Index

Where:

$$TRadj\begin{cases} 0.25[T_{max}-T_{min}-13],[T_{max}-T_{min}]>13 \\ 0, 10<[T_{max}-T_{min}]<13 \\ 0.25[T_{max}-T_{min}-10],[T_{max}-T_{min}]<10 \end{cases}$$

Equation 4-5: The BEDD Temperature Range Adjustment

Another major climate metric I considered is the Latitude-Temperature Index [LTI] (Jackson & Cherry, 1988) [Equation 4-6]. This metric is based solely on the Mean Temperature of the Warmest Month [MTWM] of growing season (June, July, or August in the Northern Hemisphere) and latitude.[34]

33 The full equations used by Hall and Jones (2009) for calculating day length and twilight period are available here: http://herbert.gandraxa.com/length_of_day.xml

34 In order to calculate latitude at pixels, I generated a shapefile of latitudinal lines in the NAD83(CSRS) projection and interpolated a grid of latitudinal values per pixel extending along the East/West longitude of Quebec.

$$LTI = MTWM * (60 - Latitude)$$

Equation 4-6: The Latitude-Temperature Index

As this metric is typically based on point measurements at weather stations to determine the warmest month, for spatial calculations I performed a test to return the highest monthly value of LTI determined at each location.

Another climate metric shown to be effective at categorizing winegrowing regions is based on mean temperatures of the growing season [GST] (Hall & Jones, 2009; G. V. Jones et al., 2005), considering the growing season as the period where daily average temperatures regularly meet or exceed 10 ºC [Equation 4-7].

$$GST = \frac{\sum_{April\,1}^{October\,31} \left(\frac{T_{max} + T_{min}}{2}\right)}{n}$$

Equation 4-7: Average Growing Season Temperature

Where 'n' is the number of number of days in the growing season. In an article by Hall and Jones (2009), the authors combined this climate metric with BEDD and the results of GST alone were shown to be just as reliable of an indicator (G. V. Jones et al., 2005).

While not a true heat summation metric for establishing wine regions, I also perform calculations for the Branas, Bernon, and Levadoux Hydrothermal Index [BBL] (Branas, Bernon, & Levadoux, 1946) [Equation 4-8]. This metric has historically been used to approximate for the risk of mildew as a function of monthly temperature and precipitation (P).[35]

35 Criticisms of this metric due to its dependence on total monthly precipitation rather than soil moisture conditions, as well as due to the complexities of climate modelling for rainfall patterns (Lorenzo, Taboada, Lorenzo, & Ramos, 2012) increase metric uncertainty and reduce the reliability of some estimates of negative growing conditions based on this metric alone. This metric is described here for general information purposes.

$$\mathrm{BBL} = \sum_{April}^{August} T_{Mean} * P_{Total}$$

Equation 4-8: The Branas, Bernon, and Levadoux Hydrothermal Index

[36]

36 I am looking into making these Python and QGIS models available online through a GitHub repository and/or through the Concordia University Spectrum research archive http://spectrum.library.concordia.ca/.

4.3.5 - Multi-Criteria Classification Systems

For bioclimatic analyses, a single climate metric is often not sufficient to determine areas suitable for viticulture. As such, several studies present multi-criteria systems for determining suitable viticultural regions (Blanco-Ward, Queijeiro, & Jones, 2007; Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014; Kurtural et al., 2007; Mills-Novoa, Pszczólkowski, & Meza, 2016; Nowlin & Bunch, 2016; Tonietto & Carbonneau, 2004). The second objective of my analysis, to determine the multi-criteria-based suitability of viticulture in Quebec, relies on additional bioclimatic variables and multi-criteria weighting systems. My approach to this objective was to perform a spatial analysis using the Categorized Index for Viticultural Climates [CatI, Equation 4-9] as presented by Fraga et al. (2014) based on the GeoViticulture Multi-Criteria Classification System [GeoVitMCC] developed by Tonietto and Carbonneau (2004) [Table 4-1]. Both of these classification system rely on the HI Index (Huglin, 1978) as well as a Soil Dryness Index [DI, Equation 4-10] (Riou et al., 1994) and a Cool Night Index [CNI, Equation 4-12] (Tonietto & Carbonneau, 2004). The CatI Index (Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014) divides climate categories into 16 general regions according to different thresholds exceeded for the aforementioned climate indexes, while the GeoVitMCC index provides options for more distinct climate categories:

$$\mathrm{CatI} \simeq \mathrm{GeoVitMCC} = HI + DI + CNI$$

Equation 4-9: The Categorized Index for Viticultural Climates

where DI, an approximation of soil moisture is reliant on Initial soil water reserves (W_O, mm) as well as seasonal values for precipitation (P, mm), transpiration (T_V, mm), and evaporation (E_S, mm).

$$\mathrm{DI} = W_O + P - T_V - E_S$$

Equation 4-10: The Dryness Index

For the calculation of DI, I needed to make a few assumptions. I began by setting the initial soil W_O for all areas to 200 mm while monthly values for P, E_S and T_V were included to determine the soil water budget. Where E + Tv surpassed P for a given month, I assume that water demand is met through depletion of the initial soil reserve. As I did not have these variables in a gridded format, I substituted E + Tv for the modified Penman-Monteith estimation of Climatic Moisture Deficit [CMD] (Hogg et al., 2013) as calculated in the ClimateNA data set (Wang et al., 2016) [Equation 4-11];

$$\mathrm{DI} \simeq W_O - CMD$$

Equation 4-11: Approximation of the Dryness Index

For the CNI value, Tonietto and Carbonneau (2004) suggest using the minimum average temperature (Tmin) observed during the ripening period (September in the Northern hemisphere) [Equation 4-12].

$$\mathrm{CNI} = T_{min}(September)$$

Equation 4-12: The Cool Night Index

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Category	Huglin Index (°C units) (Huglin 1978)	Dryness Index (mm) (Riou et al. 1994)	Cool Night Index (°C units) (Tonietto and Carbonneau 2004)	Description
0	<900	<−100		Unsuitably cold or excessively dry
1	900–1,500	−100 to 50	<14	Cool, dry with cool nights
2			>14	Cool, dry with warm nights
3		> 50	<14	Cool, humid with cool nights
4			>14	Cool, humid with warm nights
5	1,500–2,100	−100 to 50	<14	Temperate, dry with cool nights
6			>14	Temperate, dry with warm nights
7		>50	<14	Temperate, humid with cool nights
8			>14	Temperate, humid with warm nights
9	2,100–2,700	−100 to 50	<14	Warm, dry with cool nights
10			>14	Warm, dry with warm nights
11		>50	<14	Warm, humid with cool nights
12			>14	Warm, humid with warm nights
13	>2,700	−100 to 50	<14	Very warm, dry with cool nights
14			>14	Very warm, dry with warm nights
15		>50	<14	Very warm, humid with cool nights
16			>14	Very warm, humid with warm nights

Table 4-1 : The Categorized Index for Viticultural Climates (Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014 Table 1), adapted from the GeoViticulture Multi-Criteria Classification system (Tonietto & Carbonneau, 2004), licensed under CC-BY

4.3.6 - Vineyard-Scale Analysis

The second portion of the climate evaluation involved examining the climate conditions for existing vineyards through Southern Quebec. While I expect that global warming will fundamentally change the grape-growing climate for all southern areas of Quebec, evaluating these changes at specific locations where vineyards are presently operating can help in better understanding impacts to the industry and vineyard operators.

In order to do this, a data set of existing vineyards with their addresses and geographic locations was necessary. To build this data set, I began by consulting the *Association des Vignerons du Quebec* [AVQ] and obtained a comprehensive data set from them (n = 192) which included all AVQ member vineyards as well as all vineyards listed on the Google search engine that claim to be producing wine grapes.[37][38] For this data set, all locations contained measurements of vineyard sizes by hectares determined from measurements of the size of vineyard plots in Google Earth.

While exact geographic coordinates for the centres of plots were provided for many locations, other locations were only available as street addresses and needed to be geocoded. In order to add geographic coordinates to these addresses I geocoded them using QGIS with the Google Maps API and ground-truthed using Google Satellite Imagery to determine the accuracy of the tool at determining exact vineyard locations and modified point placement by hand where it seemed appropriate.

37 Quebec wines produced from fruits such as raspberries, blueberries, and strawberries are typically advertised by operators, in addition to other alcoholic beverages such as apple cider, craft beer, and mead. While grape-based wine has become popular pursuit in contemporary for Southern Quebec agricultural producers, wine-grape viticulture accounted for only ~0.6% of all fruit production by tonnage in Quebec in 2015 (Statistics Canada, 2016).

38 This number includes all commercially-operated wineries under the AVQ, the members of the Canadian Vintners Association, and the members of *les Vignerons Indépendants du Québec* (VIQ) asd well as small producers that offer on-site vineyard tours, typically *auberges,*

Section 4.4 - Results: Regional-Scale Climate Conditions

4.4.1 - Climate and Bioclimatic Condition Anomalies

Climatic conditions between the earlier historical (1961 – 1990) and more recent historical (1981 – 2010) periods show indications of an average warming trend with a slight rise in the average expected Extreme Minimum Temperature [EMT, Figure 4-6], a decrease in the annual average of Frost Free Period [FFP, Figure 4-7], and decreases in the average annual Precipitation as Snow [PAS, Figure 4-8] throughout the region, with changes most notable in the southern and southwestern agricultural region. The Climatic Moisture Deficit index [CMD, Figure 4-9] which approximates expected soil moisture need does not show change over this time period. The Branas, Bernon, and Levadoux Hydrothermal Index [BBL, Figure 4-10], an indicator for potential mildew incidence, shows a slight expansion of heightened mildew risk extending around *Estrie*, with some novel higher risk areas near Quebec City.

Focusing on conditions in future periods, we can see that for most indicators, both RCP scenarios are strikingly similar in the 2011–2040 period. An average rise of +2.5 ºC in EMT can be seen throughout the the northern Quebec interior, *Montérégie* and the Gaspé Peninsula with lesser gains throughout the Saint Lawrence Valley. An increase in FFP and CMD can also be seen during this period throughout the entire province, particularly in southwestern Quebec. PAS shows marked decreases throughout most of northern Nunavik during this period while a large area of heightened mildew risk emerges from *Estrie* stretching north towards *Saguenay – Lac-Saint-Jean* and encompasses most of *Montérégie*.

The climate scenarios begin to diverge for the bioclimatic variables during the 2040–2070 period, becoming very distinct by the end-of-century. For the RCP 4.5 “Stabilization” scenario, climatic changes continue to follow a warming trend with EMT for areas below the 50 degree latitude line no longer experiencing temperatures below -35 ºC while FFP in this area begins to exceed 140 for most Southern Quebec areas as well. Areas bordering James Bay and the Ottawa River see some decline in PAS, with *Montérégie* and western *Estrie* experiencing declines exceeding 60 mm in most affected areas, while a similar trend in CMD can be seen for this region, with some moisture deficit extending from the Saint Lawrence Valley towards *Saguenay – Lac-Saint-Jean.* The BBL mildew risk for Southern greatly expands during this time period, comprising most of the populated areas of Southern Quebec, extending westward from the Gaspé Peninsula to easternmost areas of Abitibi-Témiscamingue and portions of southwest Quebec.

The RCP 8.5 “Business-as-Usual” scenario replicates many of the same patterns seen by end-of-century in the “Stabilization” scenario, except these changes are realized in the earlier 2041–2070 period. By end-of-century, bioclimatic changes accelerate and show the strongest anomalies as compared to the 1981–2010 period. For northern Nunavik and Southern Quebec, this scenario predicts substantial reductions in PAS as well as elevated EMT surpassing temperatures found throughout present-day Southern Quebec. Regions south of 50 degrees are by this point well established with annual FFP exceeding 170 days. Predictions for CMD show much elevated soil water depletion may occur due to high water demand from potential evapotranspiration and reductions in PAS. Reading for BBL indicate that most areas below the 52 degree latitudinal line may experience elevated mildew risk not seen in present-day Southern Quebec, with most of the *Montérégie, Estrie*, and Quebec City regions experiencing the highest potential of mildew risk in the region.

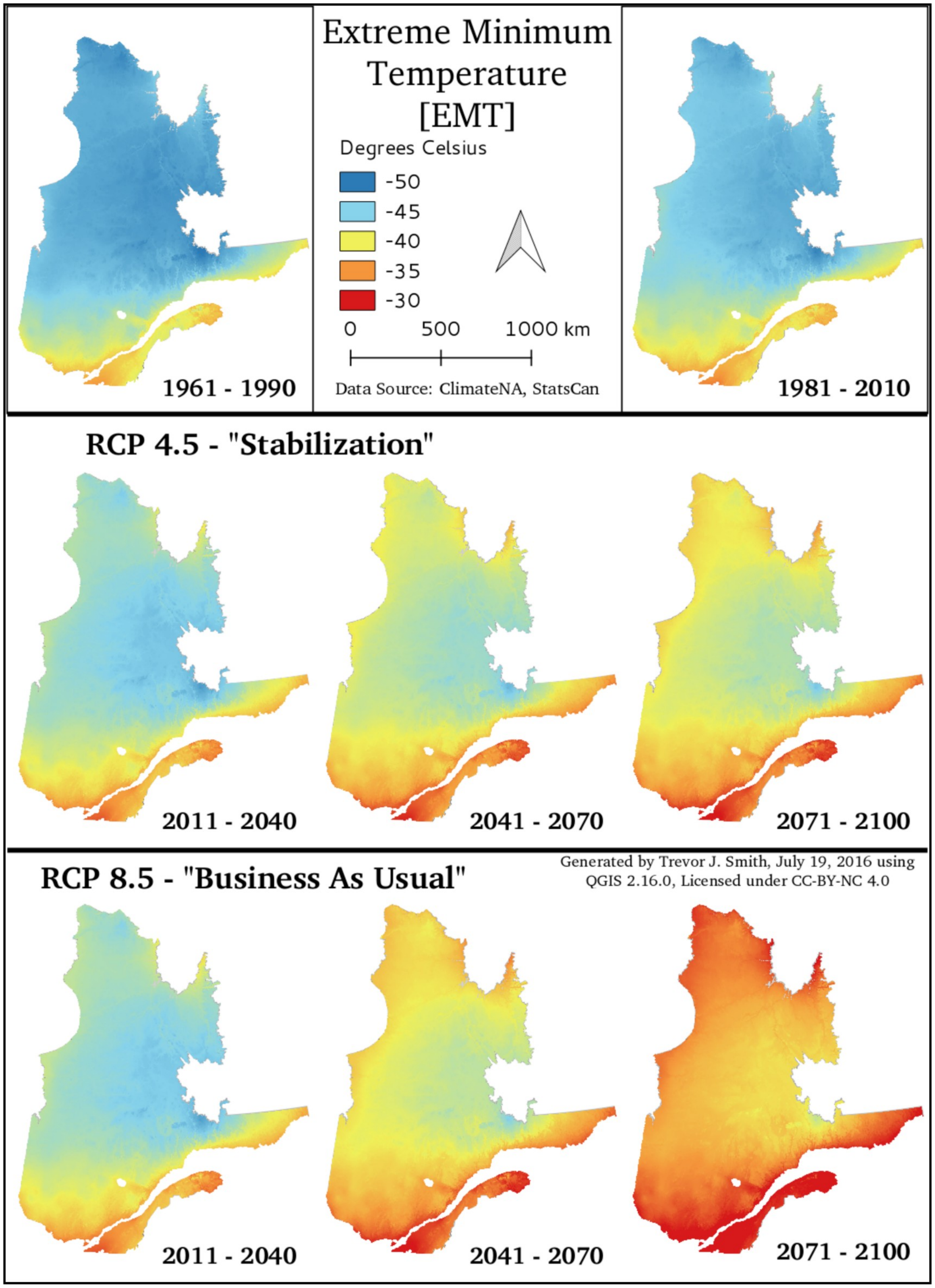


Figure 4-6: Extreme Minimum Temperature [EMT] Conditions for Historical periods, RCP4.5 and RCP8.5 Projections

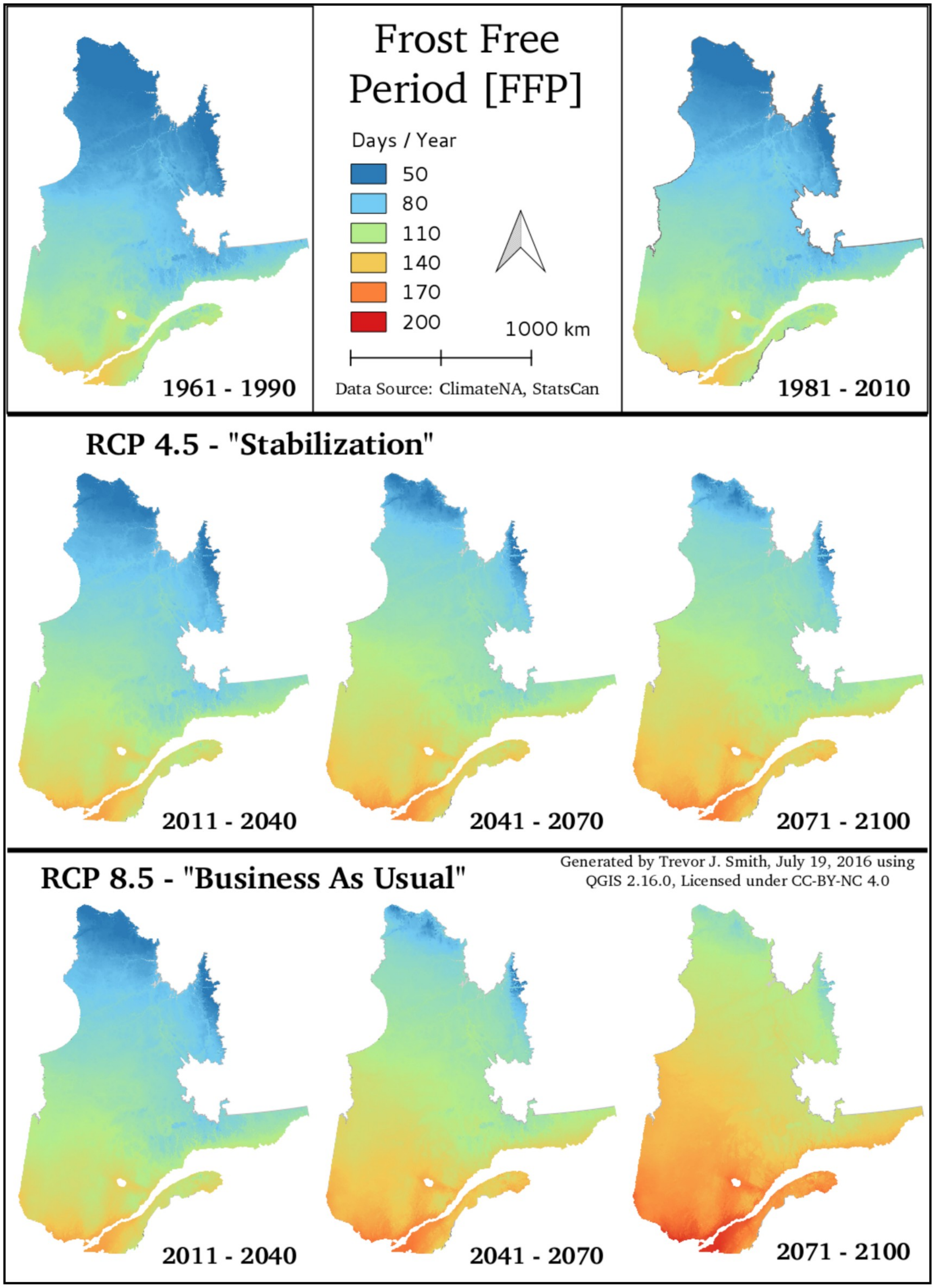


Figure 4-7: Average Annual Frost Free Period [FFP] for Historical periods, RCP4.5 and RCP8.5 Projections

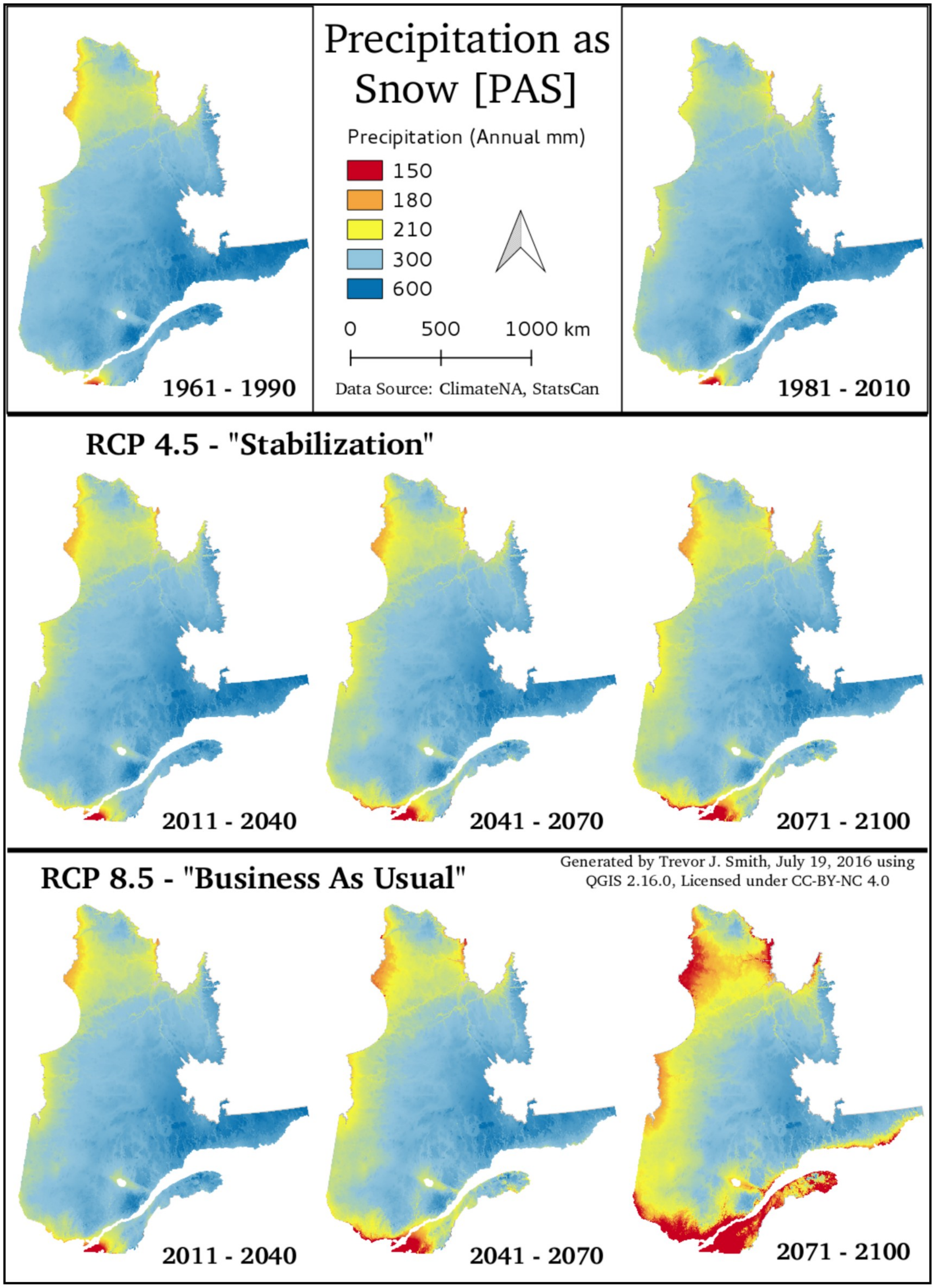


Figure 4-8: Average Annual Precipitation as Snow [PAS] for Historical periods, RCP4.5 and RCP8.5 Projections

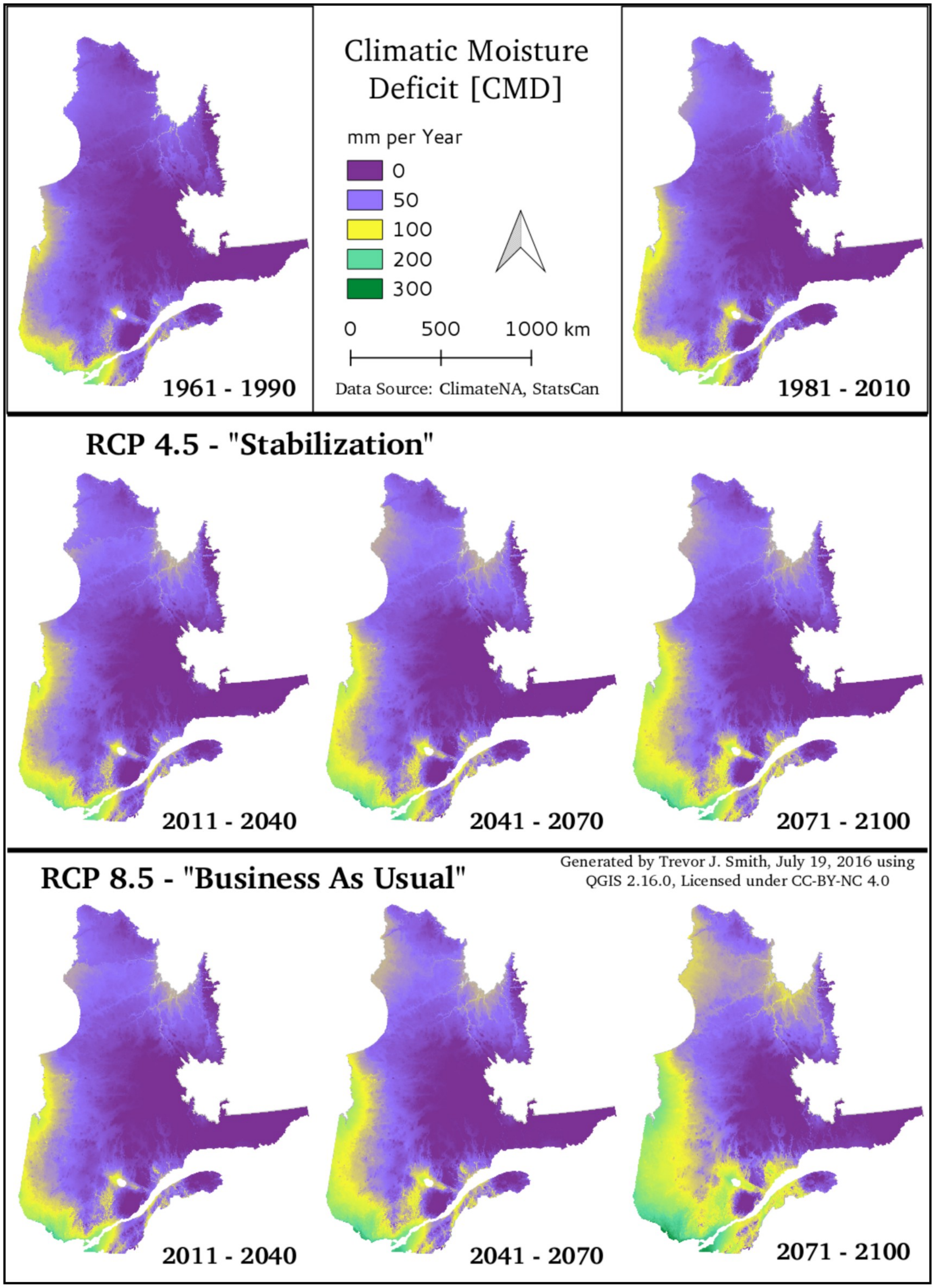


Figure 4-9: Modified Penman-Monteith Climatic Moisture Deficit [CMD] Values for Historical periods, RCP4.5 and RCP8.5 Projections

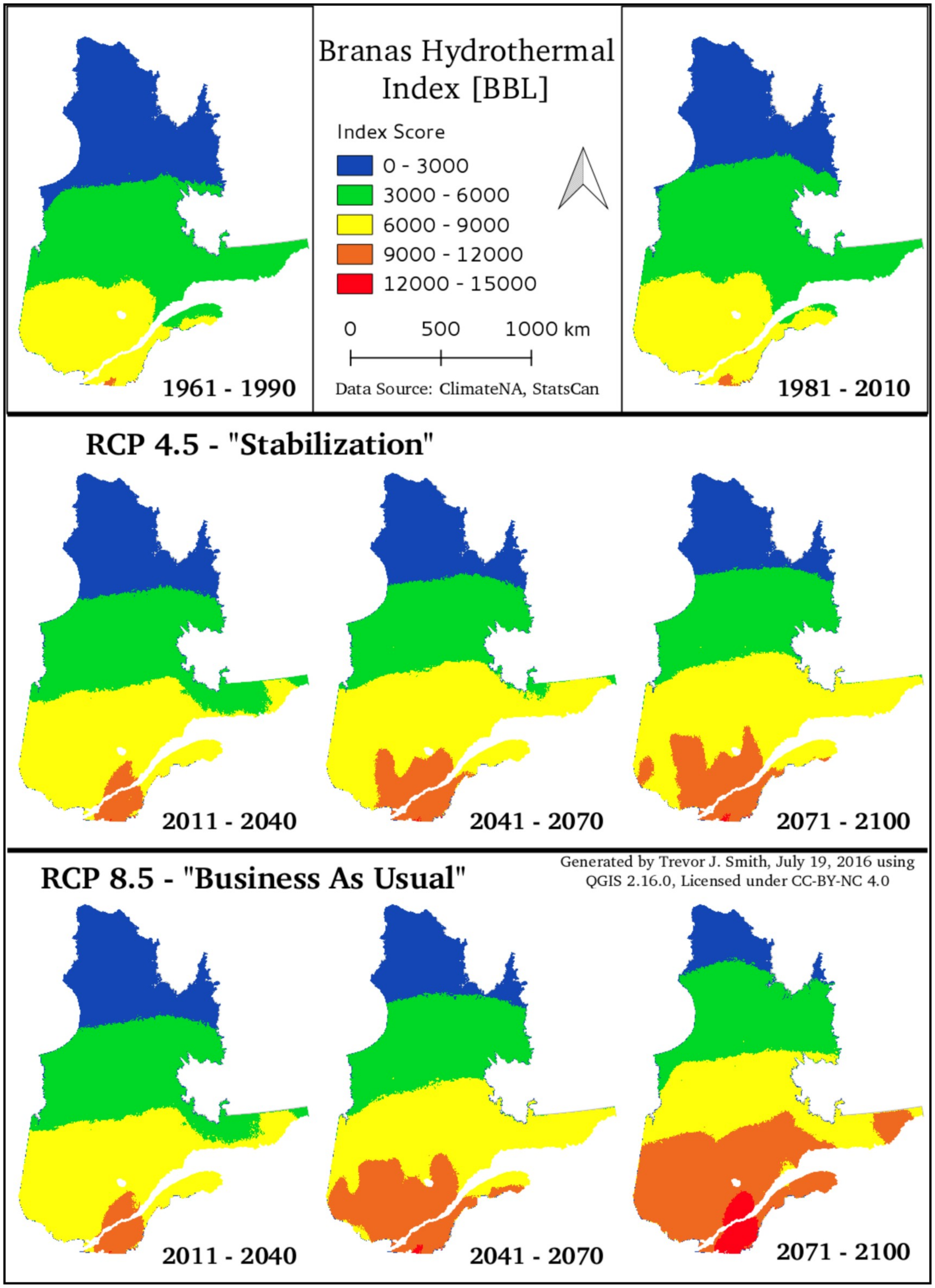


Figure 4-10: The Branas, Bernon, and Levadoux Hydrothermal Index [BBL] for Mildew Risk for Historical Periods, RCP4.5 and RCP8.5 Projections

4.4.2 - Recent Historical, Present, and Near Future Climate Index Comparisons for Modelled and Observed Climate Data

Results from the initial climate metric analyses of the recent historical normal period (1981 – 2010), a pseudo-climatology of the last 5 years (2011 – 2015), and the near future RCP 4.5 normal period (2011 – 2040) all denote a progressive warming trend [Figure 4-11]. The historical and future periods are calculated from the ClimateNA ensemble average data set, while the pseudo-climatology is developed from an average of the Daymet SRTM-based data set.

The normal periods for 1981 – 2010 and 2011 – 2040 show a warming progression extending along the Saint Lawrence Valley from Montreal towards Quebec City, towards the North above the Ottawa River and Eastward throughout *Montérégie* and *Estrie*. For the HI, LTI and WI indexes, *Saguenay – Lac-Saint-Jean* region and the region extending southward through *La Tuque* to *Trois-Rivières* begin to show signs of warming, becoming much more pronounced in the 2011-2040 period. Areas of the Southern Gaspé Peninsula along the border of Maine and New Brunswick also begin to show borderline climate suitability for the 2011 – 2040 period.

Present-day viticultural climate regions show an expansion of present-day climate conditions eastward throughout *Montérégie* and Estrie with areas south of Montreal showing a transitional change from a cooler climate region to a warmer one in all metrics from present-day to the 2011 – 2040 period.

LTI-based Climate category values for the Daymet data, however, shows a few departures from the recent historical period with colder areas seen for more mountainous terrain and warmer areas extending from *Saguenay – Lac-Saint-Jean* to *Abitibi-Témiscamingue*.[39] Additionally, this climate index suggests that much more of Southern Quebec has been climatically suitable for viticulture in the historical period compared to other metrics with many regions proximal to populated zones categorized as Climate Region B or C.

39 A lack of weather stations records reduces the reliability of Daymet v2.0 data estimates above 50 degrees North.

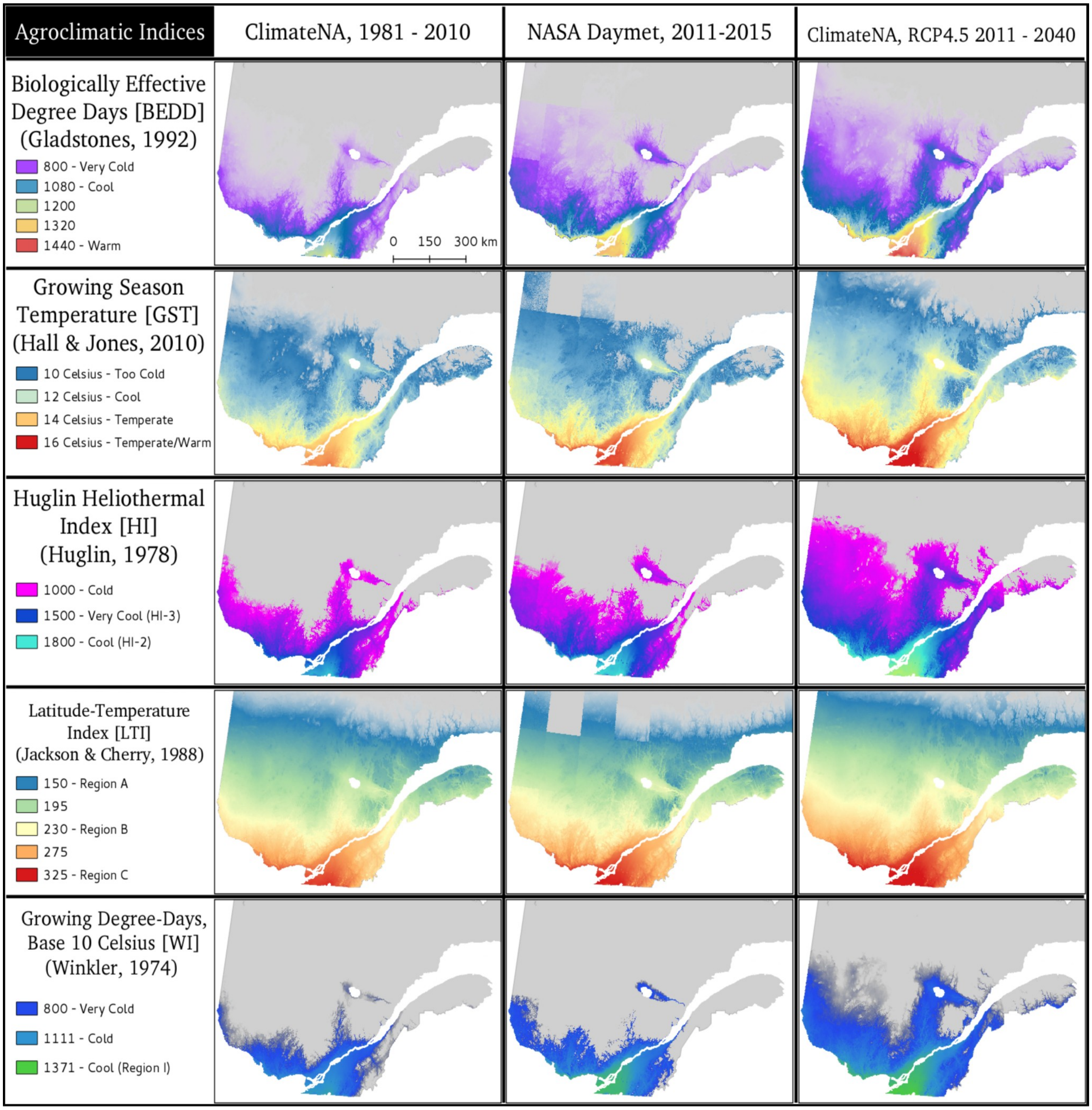


Figure 4-11: Climate Index Comparisons for Present, Recent-Past, and Near-Future for Southern Quebec (Daymet derived from Thornton et al., 2015; ClimateNA derived from Wang et al., 2016)

4.4.3 - Winkler Index Comparisons

In this and the following section, I focus on the Winkler Index as being representative of the changes captured by the metrics shown previously [Figure 4-11]. Looking at spatiotemporal changes exclusively from the Winkler Index, the ClimateNA data presents us with normal periods for recent historical and future projections [Figure 4-12]. From visual examination, the WI Index shows very marginal changes to climate for the 1961 – 1990 to 1981 – 2010 historical periods. Most regions besides *Montérégie* are unsuitably cold and *Montérégie* barely registers a Winkler Category 1 climate during the 1981 – 2010 period.[40]

Upon examining the end of century changes to regions and RCP scenario differences, changes become striking by end of century. For both the RCP 4.5 and 8.5 scenarios in the 2011 – 2040 period, the WI index shows that viticulture climate regions greatly expand along the Saint Lawrence Valley, and south throughout *Montérégie*. Divergence becomes noticeable in 2041 – 2070 normal periods, with the Business As Usual scenario showing the *Saguenay – Lac-Saint-Jean* region establishing itself as a Region 1 Winkler climate and *Montérégie* surpassing a Region 2 Winkler climate.

Differences between scenarios become most striking for the 2071 – 2100 period as viticultural thermal climate for the Business As Usual scenario show Gaspé Peninsula becoming a Region 1 Winkler climate, western *Montérégie* nearly crossing into a Region IV Winkler climate and most other regions increasing by one thermal region prior to the last normal period. On visual inspection, the thermal regions determined for the Stabilization scenario for this period strongly resemble the 2041 – 2070 Business As Usual scenario.

40 Although this region the region at this time was not suitable for *V. vinifera* viticulture, hybrid grape varietals and other species endemic to North America were successfully ripening with climate categories barely exceeding 800 degree-days.

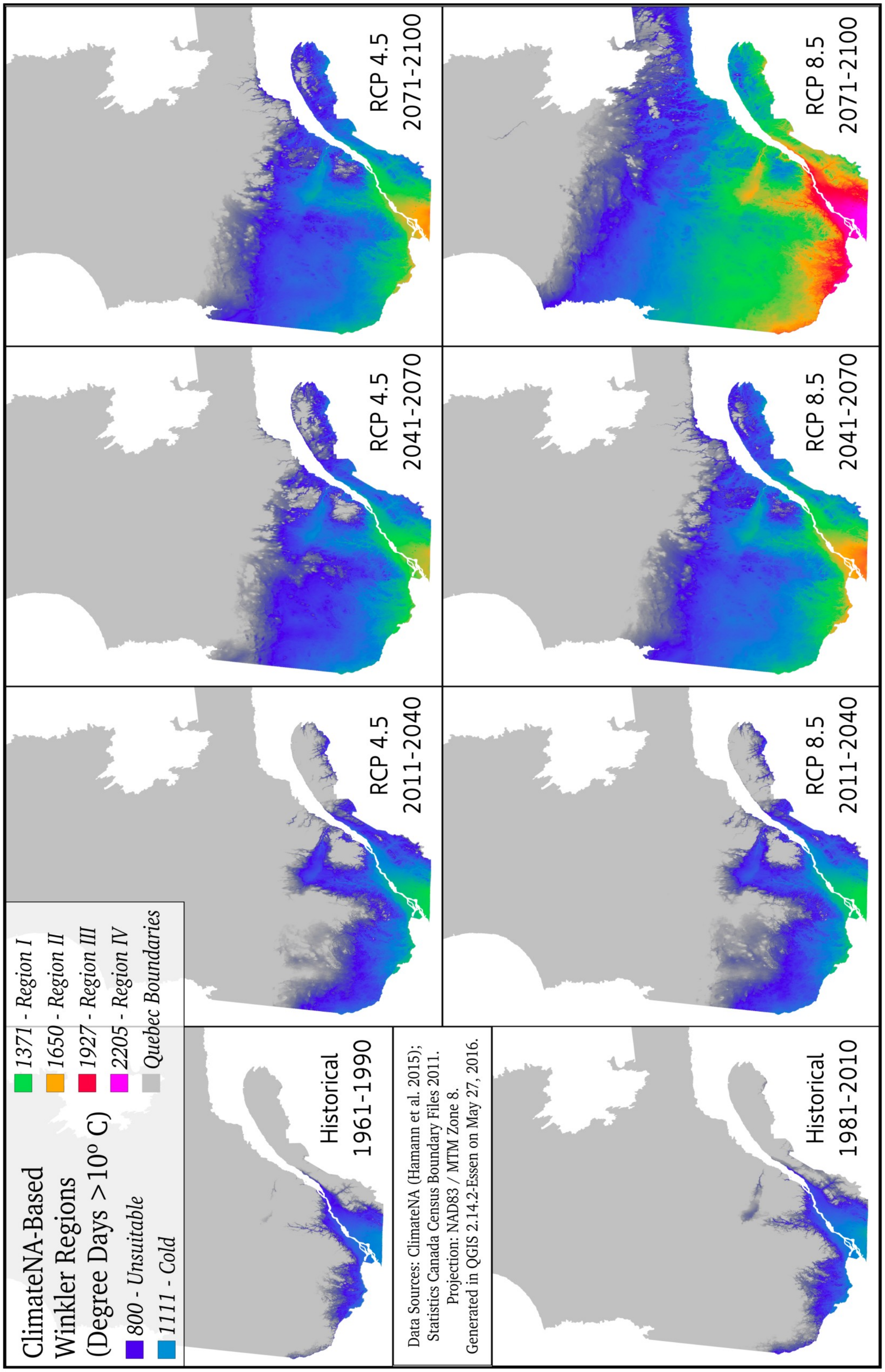


Figure 4-12: Winkler Index Calculations for RCP 4.5 and 8.5 Projected Climate Change Scenarios (ClimateNA data derived from Wang et al., 2016)

4.4.4 - Inter-Period Degree-Day Anomalies

The next analysis of the WI index shows the average anomalies relative to the previous period, organized for each scenario [Figure 4-13]. By comparing the anomalies, temporal progressions between scenarios show a decreasing trend in degree days gained between periods for the Stabilization scenario, with *Montérégie* experiencing a gain of ~+200 degree-days in the 2011 – 2040 period, while the Business As Usual values show areas at or exceeding gains of +240 degree-days from the historical period. Most areas northward of 50 degrees latitude experience some (<100 degree-day) thermal gains before tapering off at 60 degrees latitude.

The same thermal gains are seen in the Stabilization scenario for the 2041 – 2070 period. Changes in the Business As Usual however show sharp gains of nearly +200 degree-days between 50 – 52 degrees latitude, and average gains of +310 degree-days for areas directly north of the Saint Lawrence Valley. *Montérégie* experiences the highest thermals gains with roughly a +350 degree-day anomaly from the previous period.

By end of century, the scenario comparison is most contrasted. Climatic change in the Business As Usual scenario shows accelerated changes, with southernmost areas between *Montérégie* and Quebec City eliciting gains exceeding +500 degree-days. Northernmost regions of Nunavik (North Shore) experience gains of +100 degree-days while regions delimited by James Bay, The Saint Lawrence Valley and the Laurentian Mountains experience gains between +375 and +450 degree-days. The Stabilization scenario for this period shows some positive anomaly from the previous period but overall warming is less by comparison to both previous periods with no region exceeding +125 degree-days.

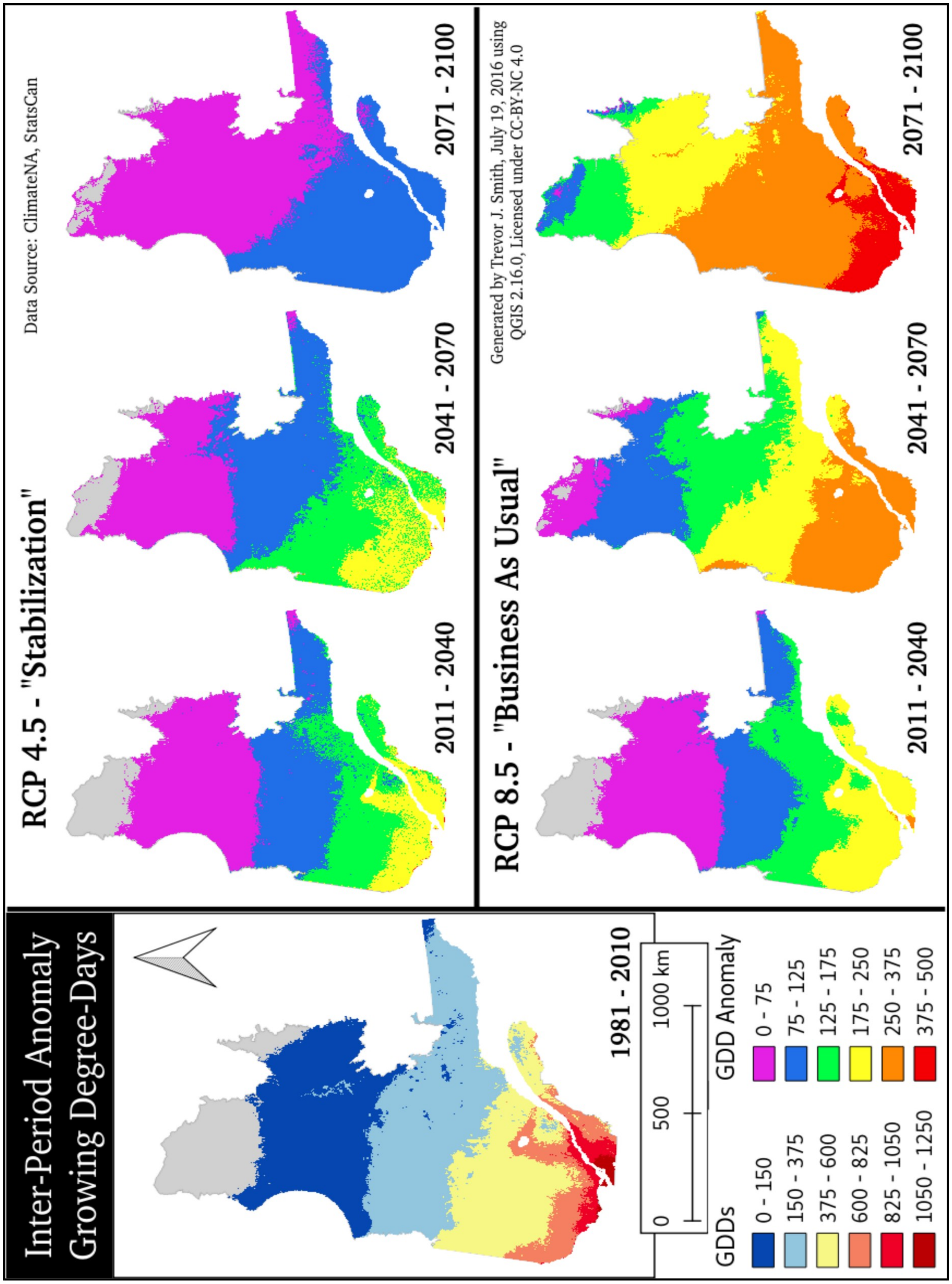


Figure 4-13: Inter-Period Growing Degree Day Anomalies for RCP 4.5 and RCP 8.5 Projected Climate Change Scenarios

4.4.5 - Multi-Criteria Climate Evaluations

Results from the CatI index for viticulture regions [Figure 4-14] shows the same shift in regional climates that is shown for most other climate metrics. CatI region values are non-linear with primary colour groupings referring to thermal regions (Cool: 1 – 4 ; Temperate: 5 – 8; Warm: 9 – 12; Hot: 13 – 16) which are then subdivided according to growing season soil moisture conditions and the threshold for average minimum temperature in September surpassing 14 ºC (Tmin <14 ºC: Odd numbers; Tmin >14 ºC: Even numbers).

For the historical period, *Montérégie* shows the warmest category for the regions (5: “Temperate, Dry, with Cool Nights; and 7:“Temperate, Dry, with Cool Nights”) while most areas outside of *Montérégie* can be classified as a colder viticulture region (3: “Cool, Humid, with Cool Nights”). It's worth noting that this climate-viticulture region extends Northwest to James Bay and North, eventually surrounding the Lac Saint-Jean region, westernmost areas of Gaspé Peninsula. All areas outside these climate regions are categorized as having a CatI value of 0 (“Unsuitably Cold and/or Excessively Dry”).

The 2011 – 2040 climate periods show an expansion of the warmer categories already present in *Montérégie* and eastward along the Saint Lawrence Valley. Notably, the areas surrounding Ottawa undergo enough warming to be reclassified as regions 5 and 7, while westernmost areas of Estrie experience a warming shift in their HI index category [see Table 4-1]. Gaspé Peninsula also experiences novel expansions of viticulture climate regions in its Southernmost areas along the Maine-New Brunswick borders.

The 2040 – 2071 period begins to show a departure of the RCP 8.5 “Business as Usual” scenario from the RCP 4.5 “Stabilization” pathway. Both scenarios show a complete climate warming shift in CatI index for regions outside *Montérégie* relative to earlier periods; for “Stabilization”, most areas that were categorized as CatI region 3 in the 1961 – 1990 period are now CatI region 5, 7 or higher, while for “Business as Usual” the same is true except in reference to the more recent 1981 – 2010 climate period. During this period we see a major shift in *Montérégie* as both scenarios suggest September temperature minimum rising above 14 ºC and Huglin degree-days exceeding 2100 throughout the growing season (CatI regions 10 and 12); the “Business as Usual” scenario sees this warming extend northward to westernmost areas of the Saint Lawrence Valley.

The end of century period shows the most marked contrast between scenarios. The “Stabilization” scenario results strongly resemble the 2041 – 2070 “Business as Usual” climate conditions, with the warmer areas of *Montérégie* extending slightly northward. The “Business as Usual” climate categories show the most drastic CatI value change from present-day. All the previous period's viticultural areas experience a shift to a warmer thermal region, particularly *Montérégie* which experiences the highest thermal conditions in excess of 2700 Huglin degree-days. Most continental interior areas below 52 degrees latitude and the 1981 – 2010 agricultural regions exhibit temperate and humid climate conditions while the Gaspé Peninsula shows potential for temperate viticulture throughout the entire region.

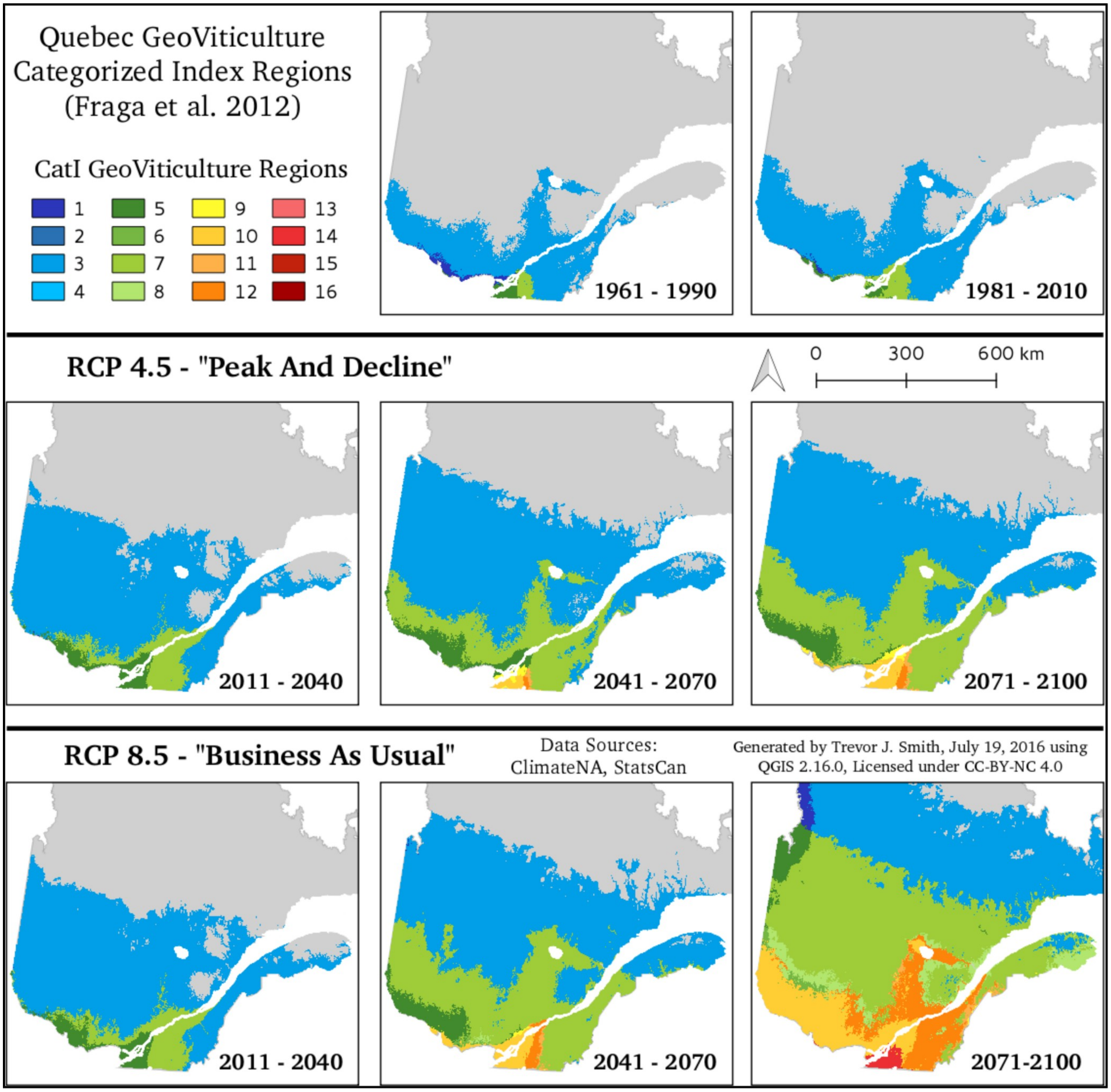


Figure 4-14: The GeoViticulture Multi-Criteria Classification System Categorized Index values for Southern Quebec (Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014; Tonietto & Carbonneau, 2004; Climate data derived from Wang et al., 2016)

Section 4.5 - Results: Vineyard Location Climate Evaluation

In this section I evaluate climate changes at the locations of presently-operating vineyards throughout Quebec. As regional changes to the agroclimatic conditions of Quebec will impact all crops grown throughout the area, determining the environmental conditions where vineyards have been operating for several decades can provide greater insight into the degree and time-line over which operators can be expected to experience climate changes in the future.

4.5.1 - Distributions and Locations

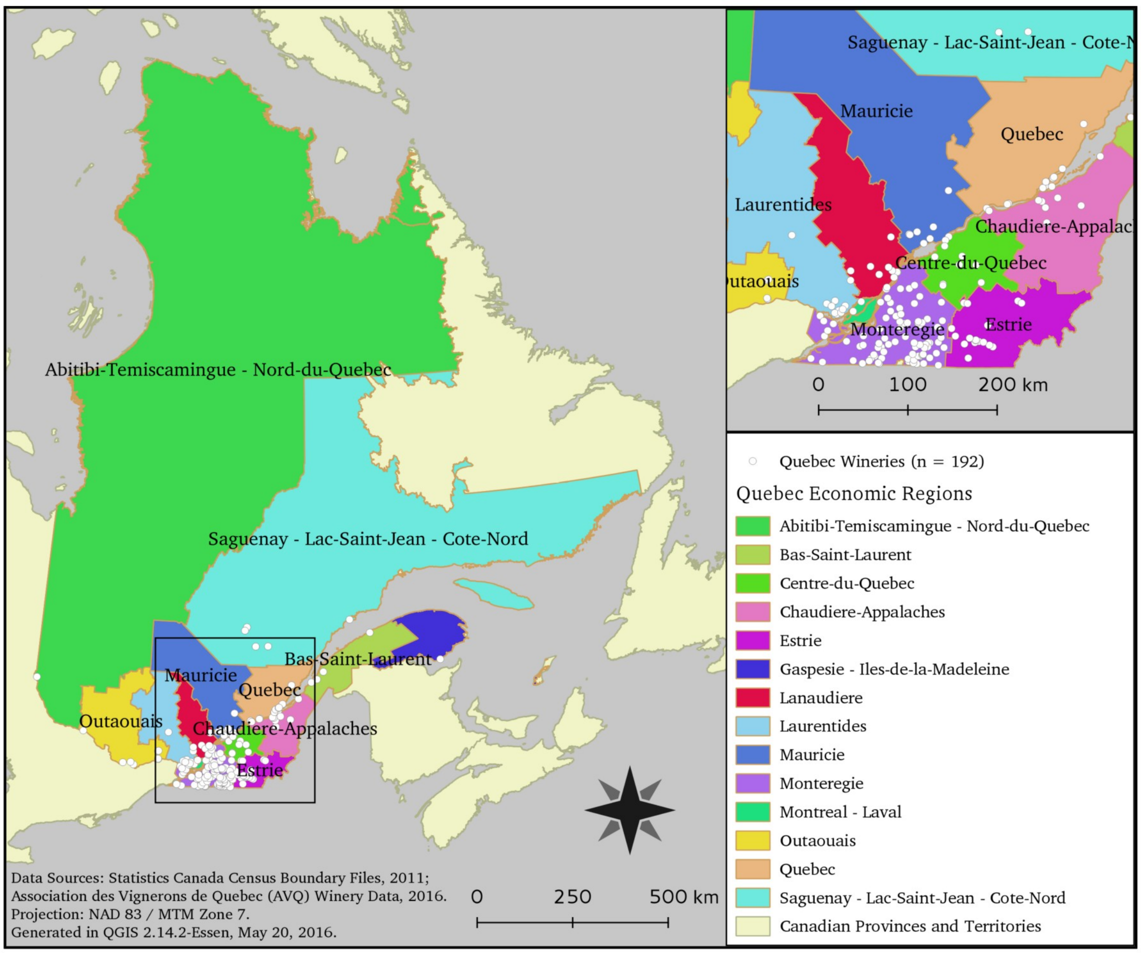


Figure 4-15: Map of Quebec Economic Regions and Vineyard Locations

Using a combination of methods mentioned earlier I was able to identify vineyard locations (n = 192) throughout Southern Quebec [Figure 4-15].

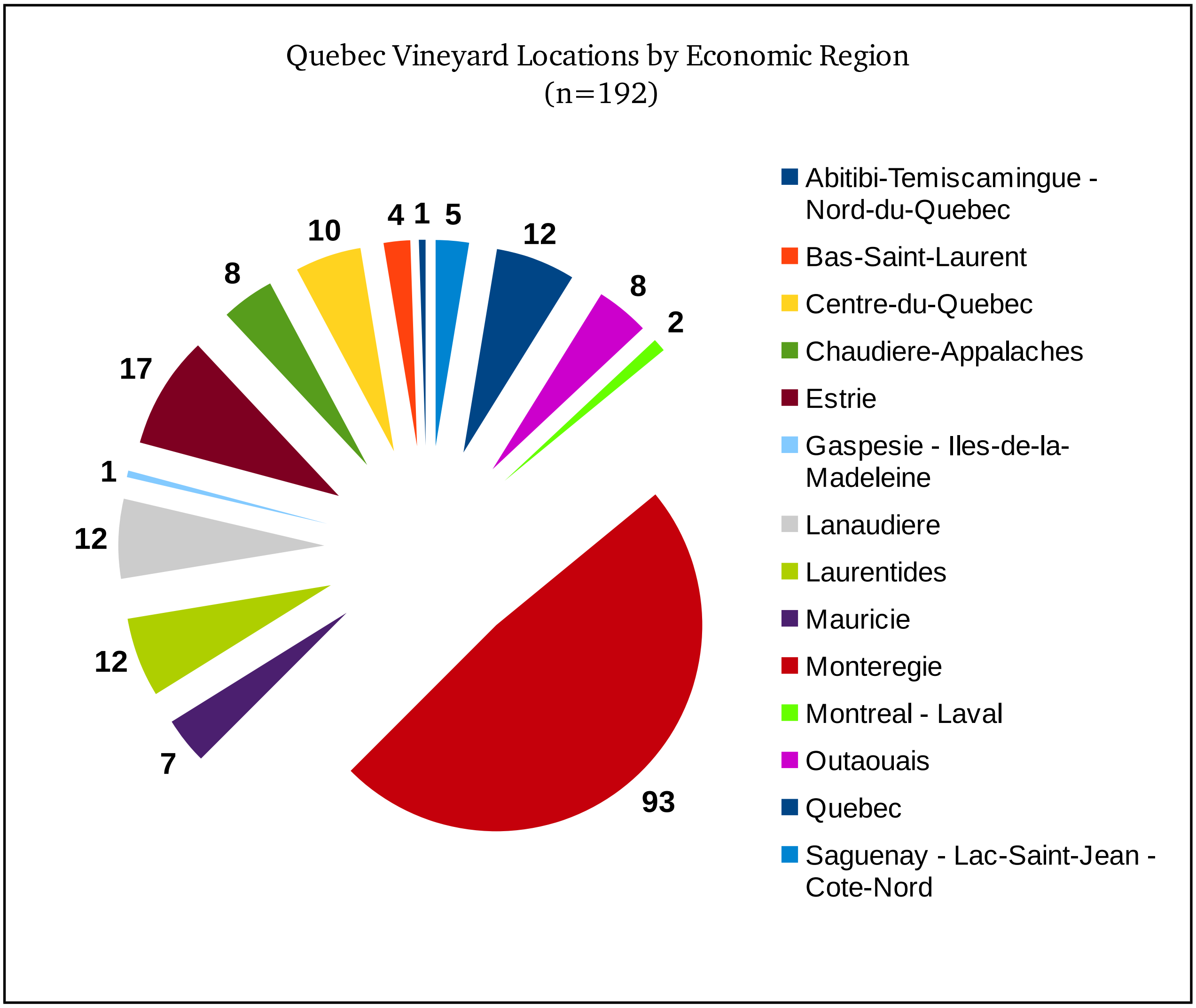


Figure 4-16: Quebec Vineyards (2016) organized by Economic Regions (derived from Statistics Canada, 2015)

As shown in Figure 4-16, the vast majority of present-day vineyards tend to be distributed within *Montérégie* (n = 93) and neighbouring *Estrie* (n = 17), with most remaining vineyards grouped in along the Ottawa River, and throughout the Saint Lawrence Valley near Montreal, *Trois Rivières*, and Quebec City. The most Northern vineyards can be found near Lac Saint-Jean and along the eastern shores of the Saint Lawrence River (n = 6), while the easternmost and westernmost vineyards are found on the south side of Gaspé Peninsula and on *L'Île-du-Collège*, on the Ontario border, respectively.

4.5.2 - *Temporal Change in Viticulture Climate Metrics*

For the following charts, climate metric values for each vineyard in the 1981 – 2010 reference period are plotted along the horizontal axis, with the warmer vineyards generally found throughout *Montérégie* clustered further along the axis. The anomalies at these vineyards as modelled using the “Low” RCP 4.5 (“Stabilization”, square symbols in blue) and “High” RCP 8.5 (“Business-as-Usual”, diamond symbols in Red) scenarios are plotted along the Y-axis for several time periods (2030s, 2050s, and 2080s). An estimate of present-day metric values based on NASA Daymet climate data is shown alongside the future scenario to illustrate average conditions during 2011 – 2015 relative to the 1981 – 2010 baseline (ribbon symbols in green). Each set of vertically-stacked symbols therefore represents all potential changes experienced at at an individual vineyard location depending on time period and climate scenario.

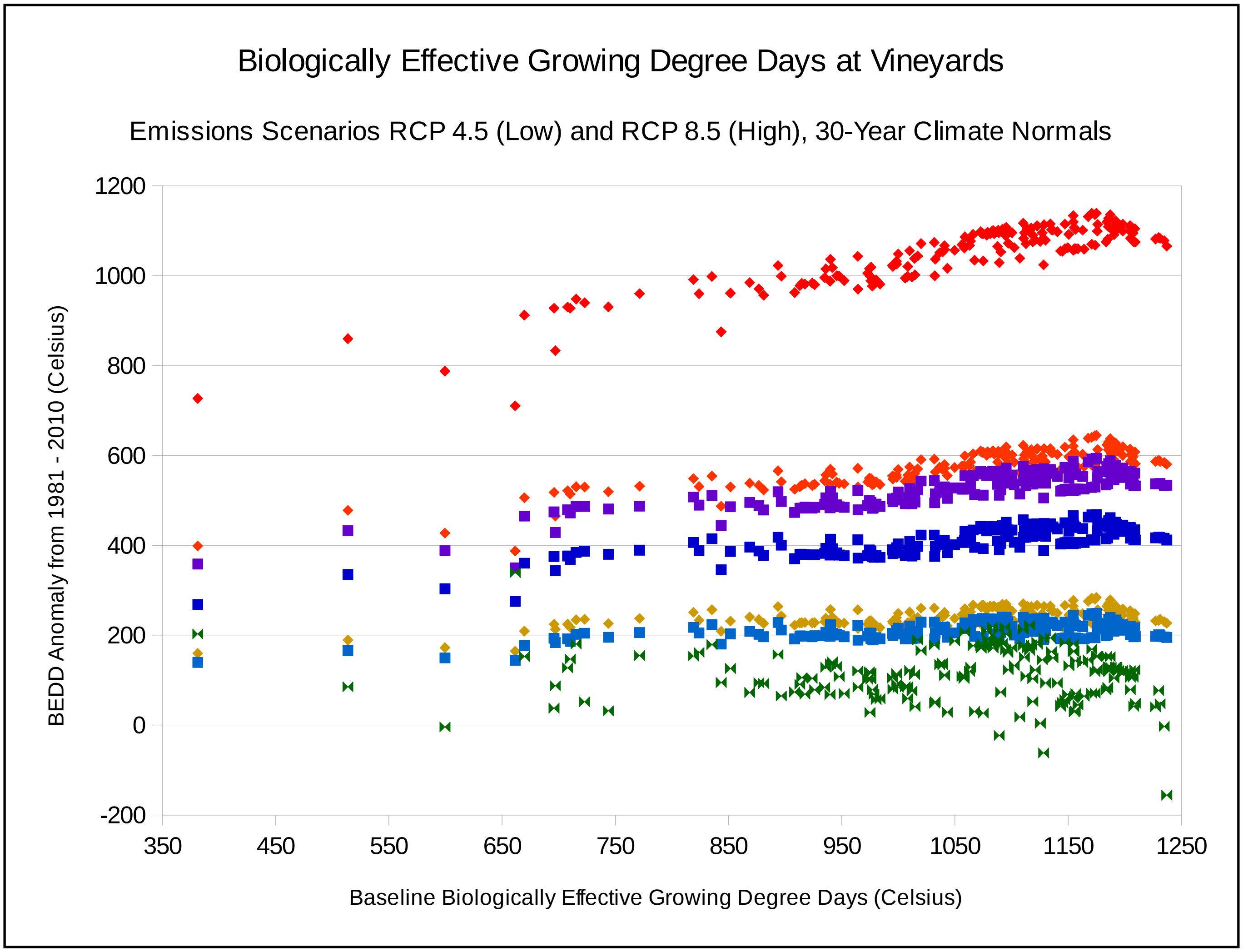
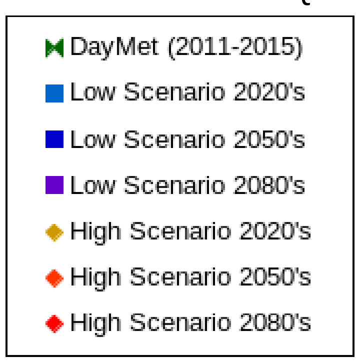


Figure 4-17: Biologically Effective Growing Degree-Day Anomalies for "Stabilization" and "Business-as-Usual" Scenarios at Quebec Vineyards



For the BEDD metrics [Figure 4-17], the 1981 – 2010 conditions illustrate that the majority of vineyards tend to experience around 825 to 1250 degree-days on average. The Daymet data shows average anomalies of +120+/-100 BEDD with some outliers at -156 and -61 BEDD's. For the “Stabilization” emissions scenario, end of century estimates see the warmest vineyards experiencing between +500 and +600 BEDD gains with cooler vineyards gaining between +400 and +500 BEDD's; changes in the “Business-as-Usual” emissions scenario are more pronounced with vineyards at present with 1000 BEDD's or more experience gains in excess of 1000 – 1100 BEDD's, while the vineyards below 700 BEDD's at present see less total gains, relative gains in BEDD's vary between 130% – 200% from present-day.

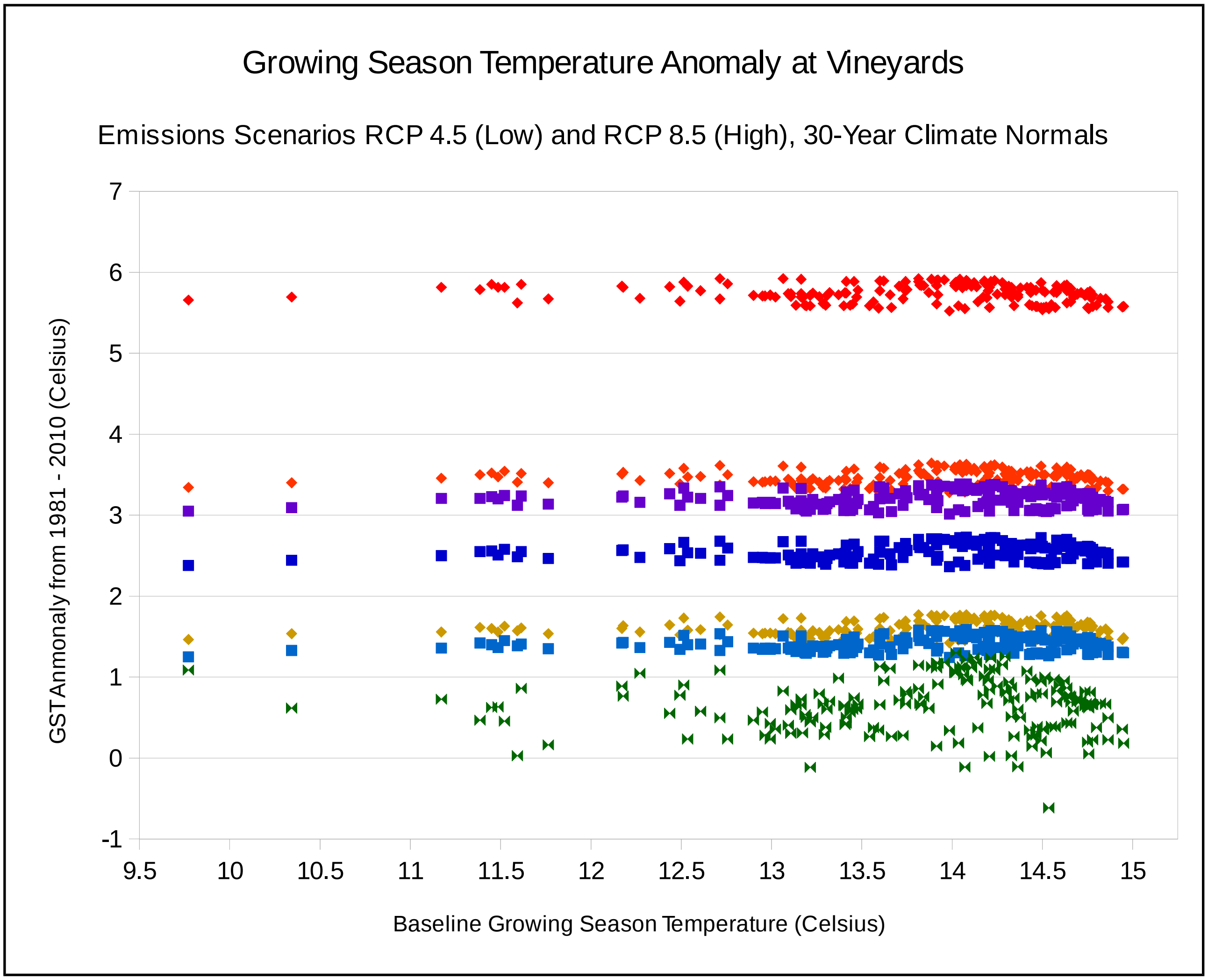
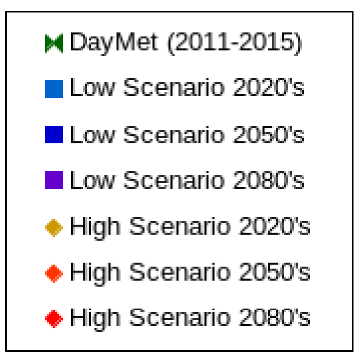


Figure 4-18: Growing Season Temperature Anomalies based on "Stabilization" and "Business-as-Usual" Scenarios for Quebec Vineyards



The GST values show the average increase of max and min temperatures between April and October [Figure 4-18]. Values here show an increase of ~1.5 ºC for the 2030's in both scenarios relative to the reference period, while Daymet values suggest average temperatures may already have increased relative to the reference period with anomalies as high as 1.25 ºC for some vineyards. For the "Stabilization" scenario, end-of-century warming predicts average increases of 3.25 ºC across vineyards, while "Business-as-Usual" scenario predicts an increase of nearly 5.85 ºC by end of century, with mid-century anomalies surpassing the "Stabilization" period for end-of-century by 0.25 ºC.

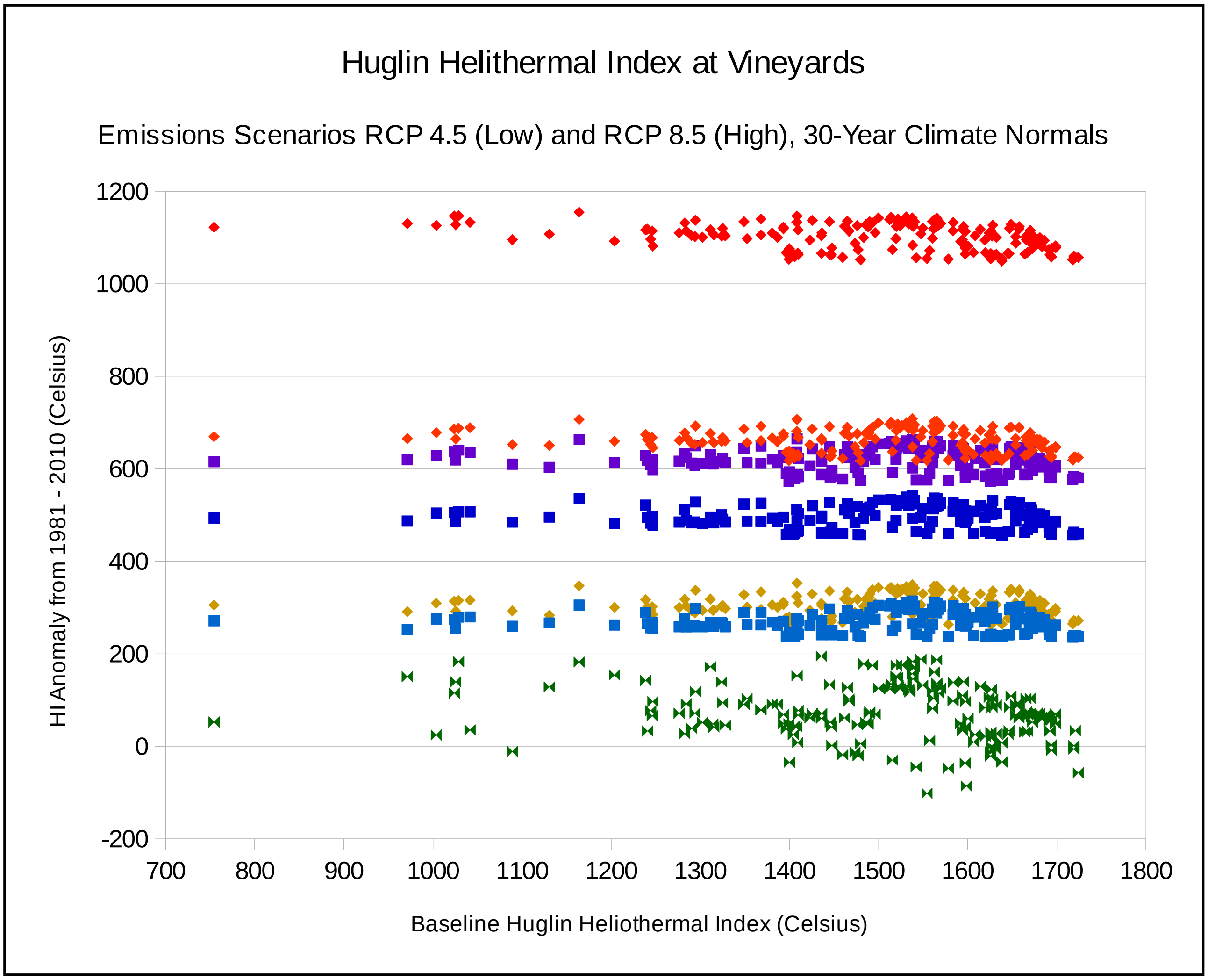
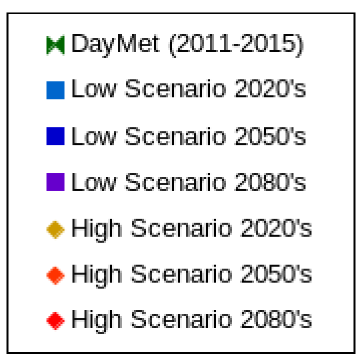


Figure 4-19: Huglin Heliothermal Index Anomalies for "Stabilization" and "Business-as-Usual" Scenarios at Quebec Vineyards



The HI Index values [Figure 4-19] show roughly uniform increases of HI between periods for all scenarios. Daymet values for 2011 – 2015 average +75 with a margin of +125/-175, suggesting that most vineyards have already seen a measurable increase in latitude-adjusted degree-days since 1981 – 2010. While warming trends are very close for the 2011 – 2040 period between scenarios, the “Business-as-Usual” scenario register an average gain of +25 over the “Stabilization” scenario. Overall warming trends for end of century shows vineyards gaining between +580 and +675 in HI for the “Stabilization” scenario, and nearly +1120 in HI for the “Business-as-Usual” scenario.

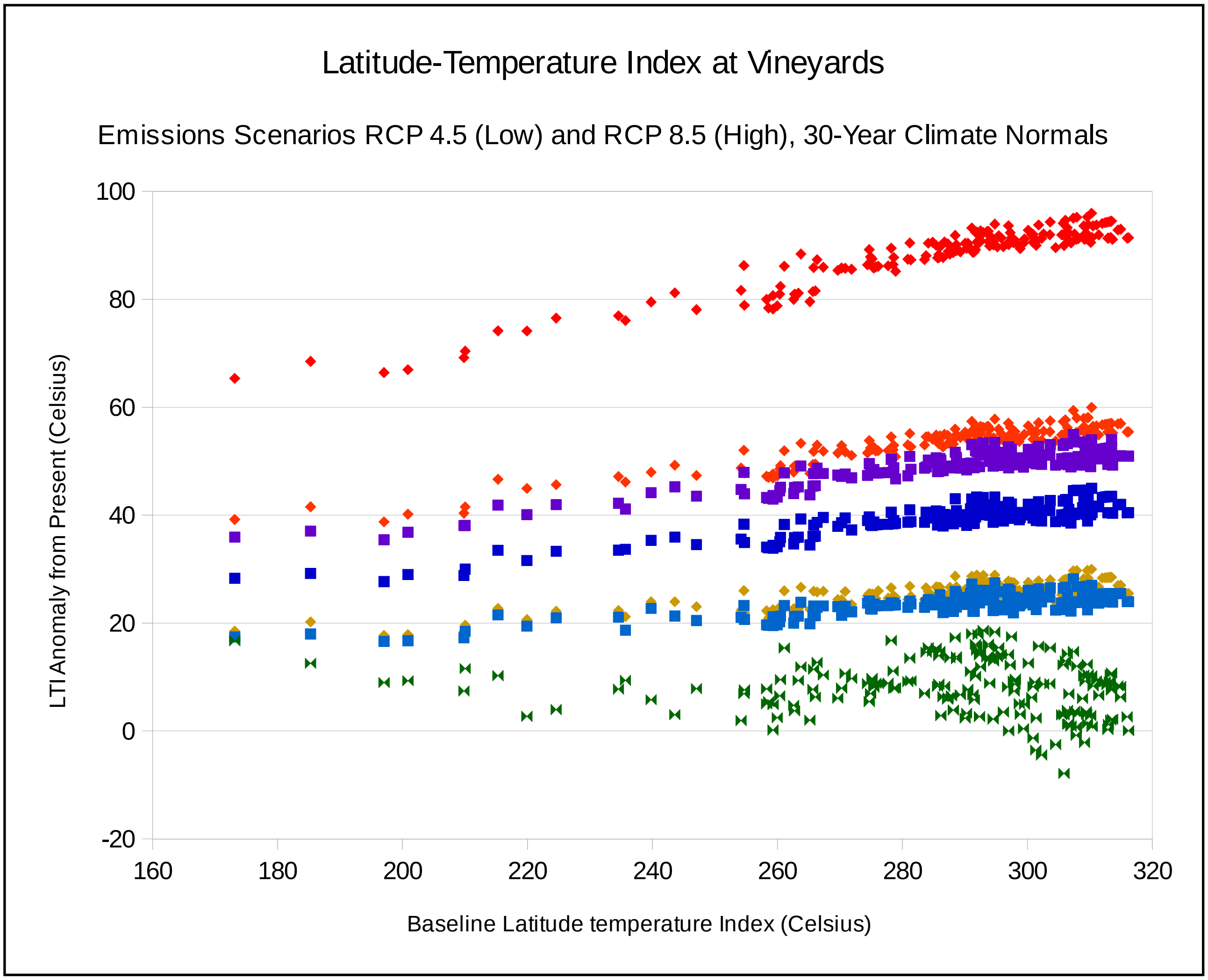
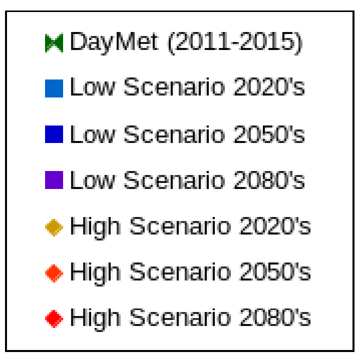


Figure 4-20: Latitude-Temperature Index Anomalies for "Stabilization: and "Business-as-Usual" Scenarios and Quebec Vineyards



The LTI index [Figure 4-20] shows an increasing trend that is markedly similar to values obtained for the BEDD index. Most vineyards presently range in LTI regions from the lower 'B' (200 – 275) to mid-'C' (275 – 375), with some outliers in the coldest 'A' region (below 195)

(Jackson & Cherry, 1988). Daymet values indicate an average increase of ~7 LTI units, with high variation for warmer vineyards. For the “Stabilization” scenario, end-of-century estimates show average gains of ~55 LTI units, while the “Business-as-Usual” scenario estimates average gains of 90 LTI units. Across data points, the high scenario gains reflect average increases of 25% to 35% for most vineyards.

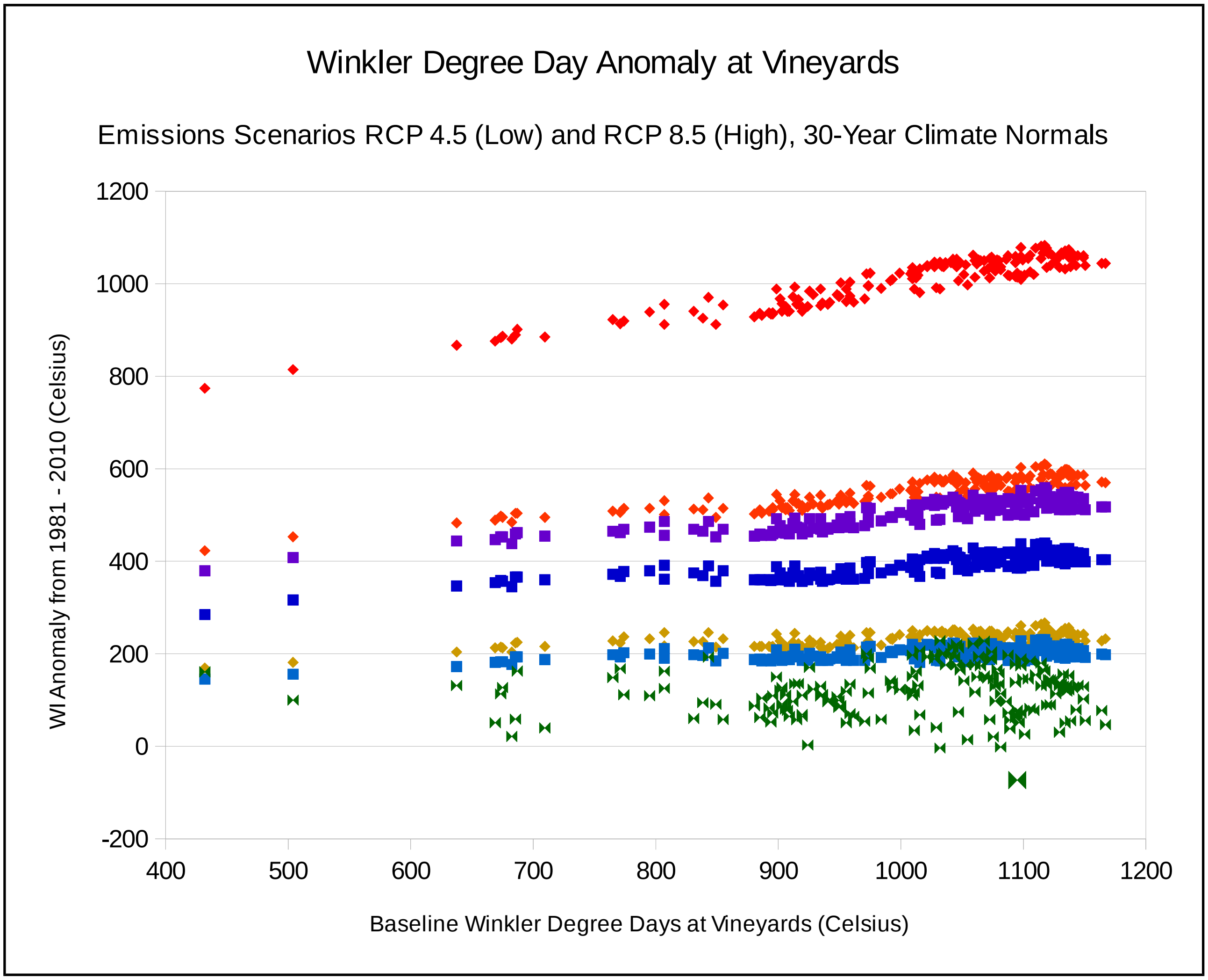
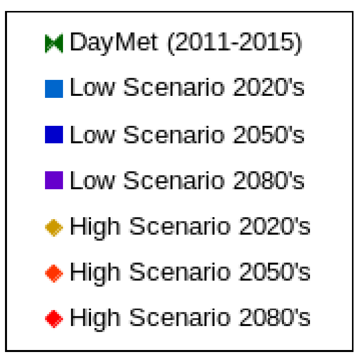


Figure 4-21: Winkler Growing Degree-Day Anomalies for "Stabilization" and "Business-as-Usual" Scenarios at Quebec Vineyards



The WI index [Figure 4-21] shows an increasing degree-day trend with value ranges similar to that of the BEDD calculations. The 1981 – 2010 period shows a more constrained range for WI values, with most vineyards experiencing around 850 to 1150 degree-days on average.

The Daymet average shows vineyards experience +140 with a margin of +220/-150 WI degree-days with one outlier at -70 WI units from the reference period. For the “Stabilization” emissions scenario, similar to end of century estimates for the BEDD index, the warmest vineyards experiencing between +450 and +550 WI degree-day gains with cooler vineyards gaining between +390 and +500 WI degree-days; the “Business-as-Usual” emissions scenario registering 1000 WI degree-days or more in 1981 – 2010 experience gains in excess of 1000 – 1100 WI degree-days. Again, the coolest vineyards today see much greater proportional gains in WI degree-days with some vineyards experiencing +130% to +190% gains from the reference period.

4.5.3 - Temporal Changes to Categorized Index Values

The changes experienced by vineyards according to Categorized Index values illustrates the fundamental type of climate that Quebec vineyards may need to operate and plan for. Figures 4-22 and 4-23 show the first two historical climate periods (1961 – 1990, 1981 – 2010) and then future periods for the RCP 4.5 “Stabilization” scenario [Figure 4-22] and the RCP 8.5 “Business-as-Usual” scenario [Figure 4-23]. While 16 categories are listed, some climate categories (e.g. CatI values of 2, 6, 8, 13, and 15) within thermal regions (1 – 4, 5 – 8, 9 – 12, and 13 – 16) are seldom experienced at vineyards within Quebec. NULL values shown here are due to edge-case suitability conditions (e.g. too cold, too dry) or due to vineyards being located beyond the spatial region of the data set (particularly true for coastal and island locations).

Examining solely the historical periods, vineyards have already undergone some degree of change to growing conditions, with 27 vineyard locations upgrading from a Cool to Temperate climate region between 1961 – 1990 and 1981 – 2010 and overall fewer vineyards experiencing humid growing conditions. These trends continue at different rates depending on the scenario examined.

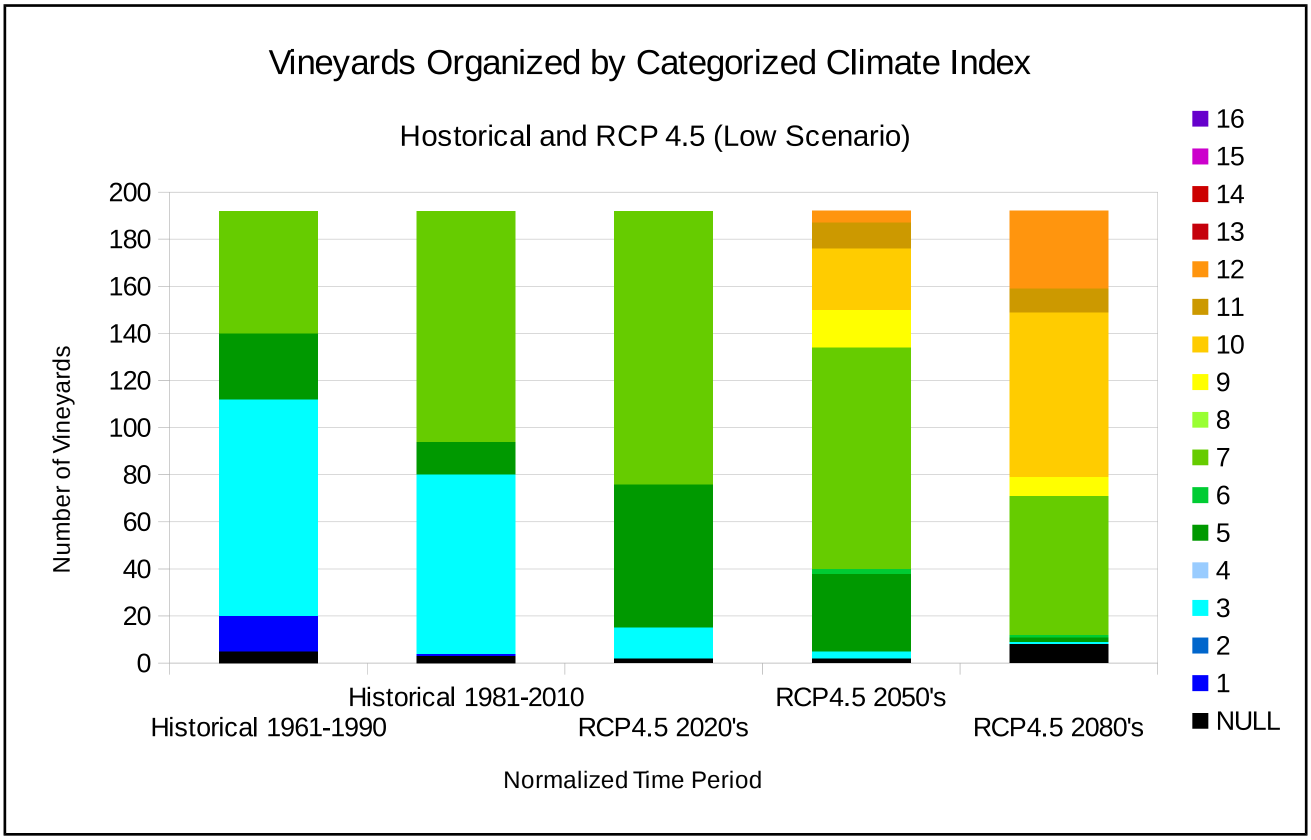


Figure 4-22: The Categorized Index Values for Vineyards (Historical – 2100) under Low Emissions Projections

For the "Stabilization" scenario [Figure 4-22], changes between the 1981- 2010 reference period and the 2021 – 2040 period show a marked decline in the number of Cool climate vineyards, with more locations experiencing Temperate and drier growing conditions (n = 177, up from 112 locations). The 2041 – 2070 period shows warming at 58 locations that causes them to upgrade their status to a "Warm" climate region with relatively the same proportion of vineyards experiencing humid growing conditions. We also see an emergence of locations with "Warm Nights" near the warmer end of the spectrum as September minimum temperatures begin exceeding 14 ºC. The end of century period (2071 – 2100) shows a widening of the number of locations with "Warm, Dry and Cold/Warm Night" growing conditions, while the number of Temperate locations decreases. Only one vineyard location continues to experience 'Cool" growing conditions during this period.

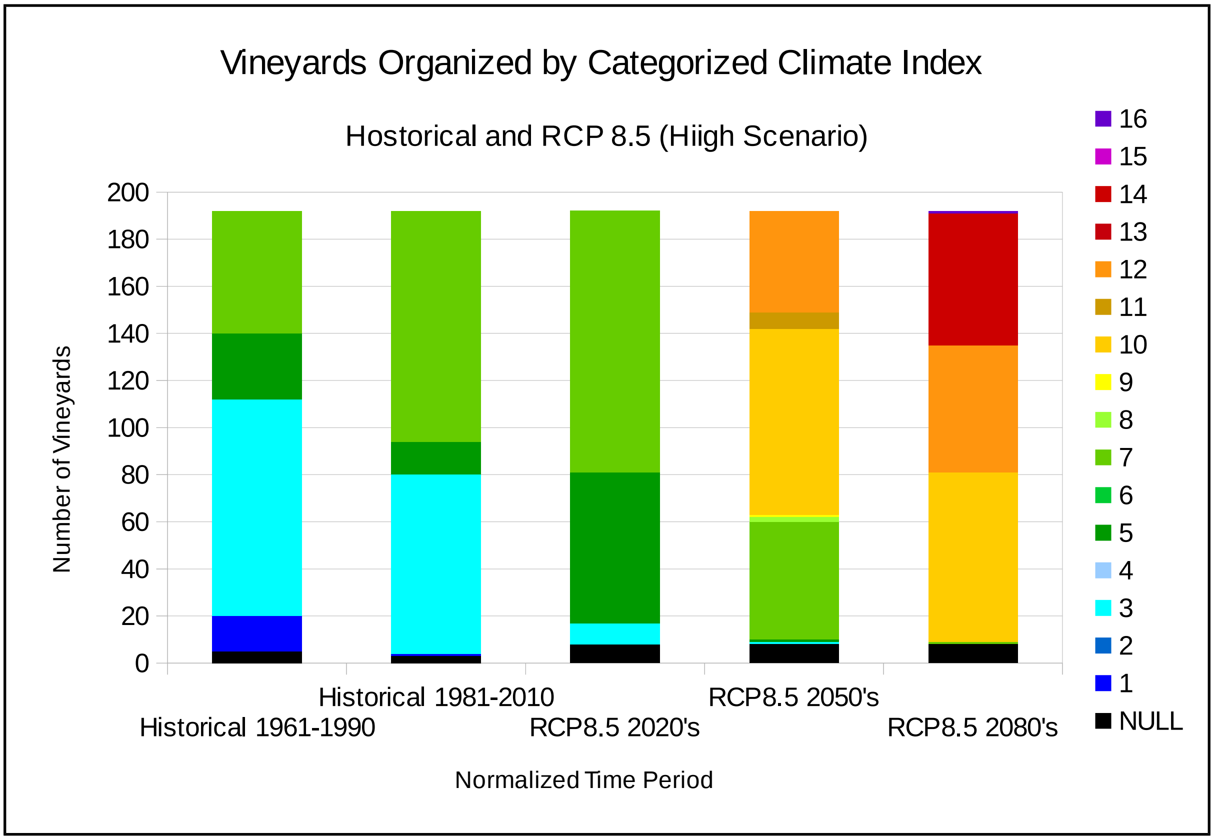


Figure 4-23: The Categorized Index Values for Vineyards (Historical – 2100) under High Emissions Projections

For the "Business-as-Usual" scenario [Figure 4-23], we can see that the number of "Temperate" climate vineyards in the 2011 – 2040 period increases in size and dry/humid proportion similarly to the "Stabilization" scenario (RCP8.5: 175 versus RCP4.5: 177). For the 2041 – 2070 period, a very noticeable shift in climate categories can be seen in the rapid growth of "Warm" climate vineyards. These "Warm" vineyards also overwhelmingly shows September minimum temperatures above 14 ºC. This also marks a climatic departure from the stabilization scenario (RCP8.5: 130 locations versus RCP4.5: 58 locations). The end-of-century period sees this warming trend accelerate, as the number of "Temperate" locations drops to 1 with the remainder exhibiting climate that are either "Warm, humid or humid, with warm nights" (n = 136) or "Very Warm, dry, with warm nights" (n = 56). By this time period, there are no "Cool" climate locations.

Section 4.6 - Discussion

4.6.1 - Overview

The discussion here is based on the results from all of my analyses and is divided into four main sections:

1. Agroclimatic changes to the southern Quebec regions based upon bioclimatic variables calculated by Wang et al. (2016) and through viticulture-specific climate metrics.
2. Potential direct and indirect risks due to climate change specifically for vineyards and some considerations for adaptive planning.
3. Technical strengths, limitations and potential complexities associated with my research approach.
4. Conclusions and next steps in building upon the viticulture-climate analysis and expanding the research beyond regional physical climate modelling.

4.6.2 - Potential Bioclimatic Changes and their Impacts on Agriculture throughout Southern Quebec

From my analyses using a combination of regional-scale indices of bioclimatic change as determined from the ClimateNA data set (Wang et al., 2016) and climate indices calculated using a number of viticulture-specific categorization metrics, I am able to illustrate here some of the potential future changes to agricultural operations in Quebec, as a function of various models of future climate change pathways.

The ClimateNA bioclimatic indicators which comprised surfaces for average expected Extreme Minimum Temperate [EMT, Figure 4-6]; the modified Penman-Monteith method for Climatic Moisture Deficit [CMD, Figure 4-9] (Hogg et al., 2013); the average annual Frost Free Period length [FFP, Figure 4-7]; and the amount of Precipitation As Snow [PAS, Figure 4-8], all showed trends associated with that of a region undergoing warming climatic changes. Areas experiencing longer frost-free periods, much less precipitation as snow, and higher minimum temperatures will experience to a more temperate winter season, with longer growing seasons and less risk of extreme low temperatures damaging cold-sensitive vegetation.

These changes to bioclimatic variables correspond with Canada-wide (Qian, Zhang, Chen, Feng, & O'Brien, 2009) and provincial (N. K. Jones, 2012) historical trends, showing that these patterns are not solely limited to the southernmost areas of Quebec where higher numbers of vineyards are presently operating. In fact, many of these changes can be seen operating at much higher latitudes, leading to major anomalies from present-day climatic norms in Nunavik, along the shores of Hudson Bay and Ungava Bay. While these areas are not viable for traditional agriculture, severe and rapid climatic changes, such as the ones shown for the high emissions scenario (see Figures 4-6 and 4-7 in particular) may prove disastrous for phenological patterns (ie: reproduction and migration cycles) of arctic species that the Nunavik peoples rely upon (Berteaux, Réale, McAdam, & Boutin, 2004).

Hydrological changes seen in the CMD estimates show that due to a combination of warmer temperatures and longer growing seasons, soil water reserves may become stressed due to higher potential evapotranspiration in the future, particularly for all present-day agricultural areas west and northwest of *Estrie*. For most areas of Quebec, soil moisture and river flow are strongly influenced by snow melt and thus regions experiencing much less precipitation as snow may need to employ water conservation techniques or irrigation to fulfill the demands of longer, warmer growing seasons (Gornall et al., 2010). While it is difficult to determine whether drought conditions may occur on the basis of period-normalized model ensemble estimates for the region, the risk of drought under a much warmer climate is higher as the environmental conditions that preclude drought may occur more often, while increased precipitation variability may contribute to drought conditions where they currently aren't common (Trenberth et al., 2013). Because of warmer temperatures, agricultural managers will need to take into account water demand and risk of drought conditions, as well as the risk of atypically wet growing seasons, considering their crop mix or planting schedule (Bradshaw, Belliveau, & Smit, 2012).

This warming trend greatly increases the area and number of regions for agricultural operations as unfavourably cold climates become less and less a limiting factor in the delimitation of agricultural areas. As most existing agricultural areas tend to be within the warmer and lower elevation areas such as along the Saint Lawrence Lowlands, western GaspéPeninsula, and around *Lac-Saint-Jean*, there will be greater agricultural potential along the North Shore of the Gulf of Saint Lawrence under even moderate scenarios of climate change. These observations by and large agree with previous estimates for agricultural potential due to greenhouse gas induced climate change throughout Quebec (Singh & Stewart, 1991). The many limiting factors for agriculture throughout Quebec's Canadian Shield region to the north of the Lowlands, such as lower population density, public (“Crown”) land, and expansive boreal forested areas, with large areas under environmental protection status (“*Zones d'Exploitation Controllées*”), will probably prevent agricultural expansions to this region even under a warming climate. Additionally, the topography of the shield, with greater variation in relative elevation, places potential vineyard sites at risk of sudden frosts due to cold air drainage which can be devastating to vineyards (Dietrich & Böhner, 2008; Olsen et al., 2011).

A major factor evident from Figure 4-13 is the path-dependent nature of inter-period climatic changes. The relative gain of thermal degree-days over subsequent 30-year periods may contribute to environmental stresses if the rate of change is greater than the ability of the socioecological system to acclimatize. For agricultural operators who rely on a few varieties of annual crops, making informed choices of crops requires extensive information and tools such as preexisting knowledge of local-level climate trends, a degree of climate forecasting knowledge, capital to adapt to a changing environment, and the financial and insurance mechanisms in place to endure a few potentially "bad years" (Bradshaw et al., 2012). Environmental risks to operators can also stem from the potential for new and emergent crop diseases as well as the migration of pests, both of which are associated with atypical warmer climates (Gornall et al., 2010; Shannon & Motha, 2015). While both high and low emissions scenarios may result in damaging effects, the higher degree of climate variability associated with much warmer environmental conditions will likely exacerbate all of these problems.

An additional concern associated with more extensive climate changes projected for end-of-century are the risks associated with extreme weather events and their impacts on agricultural yields. While some agricultural crops that are presently limited by short growing season may see some more favourable growing seasons in the near to mid-term, extreme heat waves can decimate a season's harvest and kill livestock even with adequate precipitation and irrigation (Lesk et al., 2016; Shannon & Motha, 2015). Additionally, under more extreme warming scenarios, crops may experience negative impacts to potential yields because photosynthesis and productivity are strongly impacted by high temperature growing conditions, as can be seen for many agricultural areas in the United States (Lobell et al., 2006; Schlenker & Roberts, 2009).

For agricultural operations in *Montérégie*, *Estrie*, and the lower Saint Lawrence Valley, winters that are less severe and growing seasons that are longer and warmer reduce the need for agricultural managers to rely on cold-hardy cash crops that are optimized for quicker yields but produce less quantity. The choice of crop will ultimately need to reflect these changing climate anomalies and more research in the field of agricultural modelling will need to be met with operator experiences and adaptation measures for the industry to successfully adapt to the new normal (Bradshaw et al., 2012; Challinor, Smith, & Thornton, 2013; Rosenzweig et al., 2014).

While conventional cash crop agricultural operations may experience some more favourable near- and mid-term conditions with longer growing seasons and less severe winters, other season-dependent industries may experience negative impacts. Reduced snowfall and warmer winter temperatures could have direct and indirect impacts on the potential for winter tourism activities such as skiing and skating as well as the service industry that is based around it (Damyanov, Matthews, & Mysak, 2012). These impacts extend to other economically important seasonal activities such as maple syrup production, which is strongly influenced by the temperature seasonality, snow cover, and tree health (Skinner, DeGaetano, & Chabot, 2010). As seasonal tourism throughout the region may be impacted by climatic, the impacts on loosely related sectors may be compounded, which is of particular concern for Quebec's wine country.

4.6.3 - Wine Climatology and Adaptation Considerations for Viticulture

The majority of Quebec's vineyard operations, situated throughout *Montérégie* and *Estrie* [Figure 4-15,Figure 4-16], are in a region that is not only currently the warmest, but has the potential to undergo some of the highest warming anomalies under scenarios of extreme climate change by the end of this century; for other vineyards throughout Southern Quebec which are presently located at the climatic threshold for grape production, they can expect to see warmer conditions compared to present-day conditions, in some places and under warmer scenarios, even surpassing the warmest areas today [Figure 4-18].

A major interest on the part of the industry is to increase the acreage of more economically sought after grapes like European *V. vinifera*. Unfortunately, true forms of these varietals have a high thermal need typically not experienced even throughout the warmest areas of Quebec. For present-day operators, most wine grapes cultivated in Quebec, a mix of cold hardy *V. labrusca* and American-European *Labruscana* hybrids, tend to require between 800 and 1250 WI degree days to reach *veraison* (onset of ripening) [Figure 4-4]. Many of these varietals are specifically adapted to the northeastern North America region and their characteristic and growing habits are well documented (Dubé & Turcotte, 2011). The interest here, with the potential of a warming regional climate, is the possibility of introducing "true" *V. vinifera* into a novel *terroir* and advance Quebec's wine industry (Patriquin, 2013).

As expressed in a number of studies, climatic changes are expected to translate into poleward shifts in the latitudinal isotherms of the ~12 – ~22 ºC average growing season in both hemispheres (G. V. Jones et al., 2012; Moriondo et al., 2013). The significance of these isotherms are that they represent the lower and upper thresholds for successful European-style viticulture, as shown in Error: Reference source not found (G. V. Jones et al., 2005). We can already see in the warming patterns from Canadian wine climatologies (N. K. Jones, 2012; Rayne & Forest, 2016) and from visual comparisons between modelled and remotely-sensed climate data [Figure 4-11] that the changing values for most bioclimatic metrics that Southern Quebec are beginning to show areas exceeding the base thermal need thresholds needed for European *V. vinifera* viticulture. For most climate metrics, this shift is seen early on along the Saint-Lawrence Lowlands, and North of Ottawa, expanding around the Lac-Saint-Jean area and extending along the Gaspé Peninsula.

As mentioned earlier, changes in CMD, PAS, EMT, and FFP as bioclimatic indicators all have resounding impacts on vegetative performance, agricultural management and risk of cold damage and yield loss (Davenport, Keller, & Mills, 2008; Mosedale et al., 2015; Qian et al., 2009). At present, the major deterrents to operators adopting European *V. vinifera* viticulture are harsh cold temperatures and the risk of late spring frost events. Cold hardy endemic grapes such as *V. Labrusca* and European-American hybrid varietals tend to fare much better under colder average conditions, but their wines are less sought after for their perceived inferior wine quality (Köse, 2014; J. Robinson, 2006; Shaw, 1999). Under climatic change, these limiting factors become less of a hindrance, presenting new opportunities for operators to try their hand at *V. vinifera* viticulture.

In addition to unfavourable climate, challenges in introducing *V. vinifera* can also be attributed to the these vines' higher susceptibility to mildew conditions and pest-born diseases such as Phylloxera and Pierce's Disease (Nowlin & Bunch, 2016; Rayne & Forest, 2016). Endemic North American and hybridized grape species, particularly *V. riparia*, are naturally resistant not only to cold temperatures, but wines made from these species are not sought after due their “foxy” flavour (J. Robinson, 2006). The Branas, Bernon, and Levadoux Index (Branas et al., 1946)(Branas, Bernon, & Levadoux, 1946) is an approximation of mildew and pest outbreak risk for vineyards. The results [Figure 4-10] from this index suggest that the *Montérégie* region has experienced a moderate amount of mildew and disease risk likely due to comparatively higher temperatures as compared to other Quebec regions.

For the present-to-near future period, the expected climatic changes for normal periods in the Southern Quebec region do not show much path-dependency, decreasing the level of uncertainty associated with shorter-term climate predictions [Figure 4-12, Figure 4-22, and Figure 4-23]. The presently-defined cool climate growing areas in the Saint Lawrence River Valley will increase in overall area while the annually expected Growing Degree Days (GDDs) in the southern valley region will shift to a warmer growing category, which would likely contribute to earlier onset of ripening in present-day grape vines (Sadras & Petrie, 2011) or allow for operators to cultivate different, more thermally demanding, varietals for at vineyards. If we consider only the average expected climate conditions, the Southern Quebec region may become more amenable to European *V. vinifera* viticulture, even under high emissions climate scenarios in the near future [Figure 4-14]. Within a context of the vineyard-specific growing season, changes determined from the Categorized Index for viticultural climates (Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014) further illustrate the potential for higher numbers of humid and temperate growing conditions and many fewer cool climate wineries throughout the 2010 – 2040 period compared to previously[Figure 4-22,Figure 4-23]. Much of this change can be attributed to a longer and warmer growing season (a decreasing FFP and an increasing GST), providing more opportunity for vineyard locations to amass the necessary GDDs to meet the thermal requirements for most European vines to produce fruit and reach *veraison*.

Spring frost events are typically disastrous to vine buds and can set back grape production or, in extreme cases, destroy vines, ruining growing seasons (Stafne, 2008). While the rise in GDDs and a warming growing season will likely have an impact on grapevine phenology (Köse, 2014), there is some debate as to the impact these changes may have on the risk of spring frost events (Kartschall et al., 2015; Molitor et al., 2014; Mosedale et al., 2015; Roy, 2017 (Personal Communication)). Some research shows signs of risk increase for German and French terroirs (Kartschall et al., 2015; Molitor et al., 2014) as risk of future spring frost events will largely be dependent upon the continentality of local climate, with risk potential particularly high for extreme warming scenarios; meanwhile forthcoming research using modelling ensemble results for Quebec suggest that warmer growing conditions and an advancing budbreak date has very little impact on the risk of spring frost events (Roy, 2017); finally Mosedale et al. (2015) predict that for the UK that while grapevine frost risk is dependent on choice of varietal, this risk may generally decrease under extreme warming scenarios. More research is needed on these changes as spring frost can be economically devastating for vineyards, particularly for smallholder operations (Bradshaw et al., 2012).

Regional estimates for all viticultural climate metrics – the BEDD, HI, GST, LTI, and WI indices (Gladstones, 1992; Hall & Jones, 2009; Huglin, 1978; Jackson & Cherry, 1988; Winkler et al., 1974) – show that southernmost areas of Quebec might expect to see a continued warming trend not unlike the warming trend observable by comparing of the downscaled 1981 – 2010 period to the 2011 – 2015 remotely sensed climate [Figure 4-11]. Basing the estimates of climatically suitable areas from these indices, it comes as little surprise that many regions predicted to become ideal areas for cool or temperate climate viticulture, namely the *Saguenay – Lac-Saint-Jean* area, the western Gaspé Peninsula (Singh

& Stewart, 1991), and areas to the north of Ottawa are all locations of some newly-established vineyards [Figure 4-15].

For longer term climate projections, the potential for a climate-aided wine industry begins to look less promising. The RCP climate scenarios begin to drastically diverge by the end of century, with the high emissions scenario showing a potential for much warmer temperatures compared to present day and the lower emissions scenario showing very little progression from mid-century warming estimates [Figure 4-12]. Integrating other bioclimatic indicators, as is performed for the Categorized Index (Fraga, Malheiro, Moutinho-Pereira, Jones, et al., 2014), we can see how average growing conditions may dramatically change over time for most already-established vineyard locations [Figure 4-22 and Figure 4-23]. Where the majority of vineyards in Quebec are typically “Cool” climates at this point in time, mid-century and end-of-century projections show the predominance of “Warm” with some “Temperate” growing conditions for the lower emissions scenarios, while the higher emissions scenarios see a complete drop-off of “Temperate” climates and nearly a third of wineries showing indications of “Very Warm/Hot” growing conditions. In addition, for the higher emissions scenario, these changes are accompanied by much drier soil conditions, reflecting the changes seen in potential evapotranspiration from hotter, more productive growing conditions [Figure 4-9].

Present-day Quebec wineries experience a temperature range of roughly 11 ºC to 15 ºC as their average GST, with the majority of vineyards warmer than 12.5 ºC [Figure 4-18]. Under climate change, the expected anomalies for GST range between a minimum change by 2100 of roughly +3 to +3.5 ºC for lower emissions scenarios, with higher emissions scenarios showing changes in excess of +5.75 ºC. As such, the warming presented in both of these scenarios has the potential to drastically alter the bioclimatic characteristics of the growing season at all vineyards within Southern Quebec, rendering present-day grape varietals climatically incompatible with future growing conditions.

Jones (2005) and Hall & Jones (2009, 2010) present a classification method based on average GST as an index for identifying the optimal *V. vinifera* grape vines for a range of climates [Figure 4-24]. While this classification system is relatively simplistic and fails to integrate many important bioclimatic variables, it serves as useful proxy for viticultural planning within a context of macro-scale, long-term environmental changes.

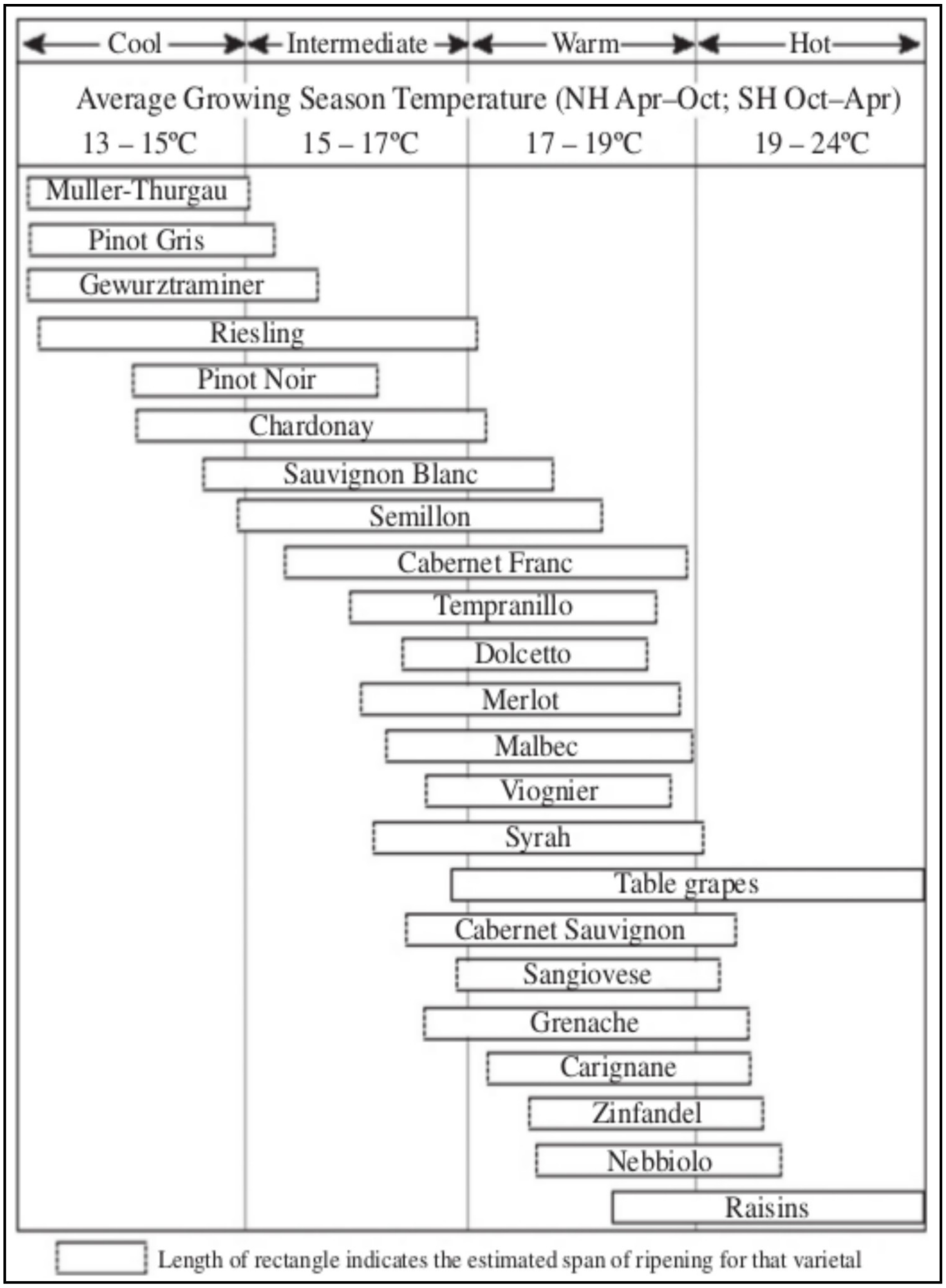


Figure 4-24: Wine Grape Average Growing Season Thermal Needs (Fraga et al., 2012, fig. 4; originally adapted from G. V. Jones, 2006) licensed under CC-BY

According to the GST index, under present climate conditions, the majority of Quebec's warmest vineyards fall into the range of "Cool" considered adequate enough to grow grape species such as Müller-Thurgau (white), Pinot Gris (white), Gewürztraminer (white), Riesling (white), Pinot Noir (red), and possibly Chardonnay (white). While the thermal requirements for

V. vinifera species may technically be met under present-day conditions, most of the grapes cultivated in Quebec are European-American hybrids owing largely to their resistance to harsh winters and pest diseases, as mentioned earlier (Davenport et al., 2008; Nowlin & Bunch, 2016). As of mid 2014, only a handful of operators claimed to be cultivating "true" Pinot Noir grape vines (*personal communication*).[41] Given these limitations, pest management and cold protection techniques would technically provide the opportunity for operators to introduce these varietals: a possible motivating factor behind the modern experimentation in cultivating "true" *V. vinifera*.

Under moderate climate change, the majority of Quebec vineyard operators will likely need to change the type of grape vines they presently cultivate. Again referring to the GST index [Figure 4-24], it is reasonable to suggest that should changes be limited to +3.25 ºC by end-of-century, most of the less thermally demanding, cold-hardy vines might fade from viticultural practices among operators, as warmer climates might give way to cultivation of higher valued, more chemically complex European grape vines. One present-day *V. vinifera* varietal cultivated in present-day Quebec that might remain under lower emissions scenarios is Riesling, which has a broad range of acceptable climates mostly within "Cool" and "Temperate" zones.

Moderate and extreme scenarios of climate change will likely see the introduction of a broad range of different *V. vinifera* grapes, many of them presently cultivated throughout southern areas of Europe, as operators attempt to capitalize on warmer temperatures propelling the climate from "Cool" to "Warm" or "Very Warm", encouraging experimentation and adaptation techniques as climatic changes create never-before-seen growing conditions.

Environmental risks in the form of mildew diseases will greatly impact the suitability for new grape varietals. The BBL Index results [Figure 4-10] for end-of-century scenarios suggest that even under moderate scenarios of climatic change the risk of mildew-based vine diseases is expected to increase drastically, particularly for *Estrie* and neighbouring regions. The extreme scenario suggests that mildew potential will exceed even higher thresholds. Several detractors already present in current-day beyond mildew and pest risk will need to be

41 Even then, these claims are dubious at best as Pinot Noir-based hybrids such as Baco Noir are known to be a popular grape vine producing wines of very similar taste to its parent varietal but are benefited by a much higher cold resistance (Shaw, 2012).

mitigated, as the drastic departures expected for both moderate and extreme climate scenarios for agricultural operations will foster an enormous degree of complex risks.

For both scenarios, from many studies, a strong relationship has been established between advance of harvest date and the increasing amount of thermal units accumulated during the growing season (Köse, 2014; Molitor et al., 2014; Ruml, Korać, Vujadinović, Vuković, & Ivanišević, 2015; Webb et al., 2011). Within this context, another concern stems from the relationship between phenological shifts and bioclimatic changes; as bioclimatic anomalies contribute to a set of non-analogous climate conditions, potentially causing vine buds to appear early in the growing season, operators will need to plan carefully when it comes to the overwintering and the risk of frost during early bud-burst periods for grape vines. (Ruml et al., 2015; Singh & Stewart, 1991)

Regardless of the degree to which these climate scenarios may reflect the realized future climate, operators will need to constantly be adapting and innovating; the ways in which the lessening amount of snowfall, hydrological system changes, the advance of the beginning of growing seasons, warmer thermal potential changes, the lessening risk of extreme cold events, and the heightening risk of pest and vine diseases are factors that all need to be considered by operators when choosing an appropriate wine grape to cultivate (Bryant et al., 2007; Holland & Smit, 2010). At present, these warming climatic changes have already begun to show the early signs of negative impacts for some ice wine producers in Quebec (CBC News, 2015) (as well as in Germany for their *eiswein* (Webb et al., 2013)) and positive impacts for some small-holder vineyards (Zarrinkoub, 2016), while the risks associated with hydrological system variability are beginning to show new challenges in the practice of grape vine overwintering (Piché, 2014). The practice of viticulture is also strongly tied to culture and socioeconomic choices in addition to climate conditions; on-the-ground adaptation practices, technological innovations as well as predictive crop modelling integrating socioeconomic information and non-climate environmental information will be necessary to provide reliable information to inform choices (Challinor et al., 2013; Nicholas & Durham, 2012). A continued and accelerating warming trend (as can be seen for the higher emissions scenario [Figure 4-13]) may contribute to the decoupling of climate and hydrological systems that could affect grape vine phenology in hard-to-predict ways, or drastically alter the operational capabilities and context, contributing to a more complex socio-ecological system compared present and forcing operators to adapt to rapidly changing environmental and operational conditions that are extremely difficult to operate within (B. I. Cook & Wolkovich, 2016; Easterling, Seipt, Terando, & Niu, 2012).

4.6.4 - Strengths, Limitations, and Research Considerations

The main research I present here is based on a large array of different climate model data as well as remotely-sensed climate data, and vineyard locations extracted from online databases. Each data source introduces or is subject to uncertainties and for each data type, the relative applicability to agricultural/viticultural planning needs to be contextualized and considered for its strengths and limitations.

Normalized Climate Data

The ClimateNA data set (Wang et al., 2016), which uses model ensembles and PRISM-like dynamical downscaling is particularly useful for determining average trends over 30-year normalization periods. Average estimates over these time-spans helps in understanding and planning for the impacts of short-term regional effects of climate forcings such as the El Niño Southern Oscillation, solar cycles, and natural variability which can influence average climate conditions over multi-annual time periods. That said, the effects of climate change as estimated by ClimateNA using model averages and PRISM-like downscaling methods cannot effectively capture or represent changes experienced at scales below the 1 Km grid resolution; Wang et al. (2016) also rely on some simplifications in modelling vegetation and the local effect of topography (slope, aspect) This data set, an expansion of the ClimateBC and ClimateWNA projects (Hamann & Wang, 2005; Wang, Hamann, Spittlehouse, & Murdock, 2011), is reliant on the availability of weather station data to generate an interpolated surface of temperatures and other climate variables that comprise the baseline of the delta method applied in modelling the climate anomalies of general circulation models [GCMs]; as a result, this approach is not as reliable in assessing northern and remote areas with sparse weather station distribution.[42]

Comparing ClimateNA data against the Daymet data (Thornton et al., 2015) shows how variable climate measurements can be at locations according to shorter-term pseudo-climatologies, as is the case for Quebec's vineyards. This data set was included to illustrate that the impact of climate variability and multi-year climate forcings can result in large fluctuations above or below the mean climate average for several consecutive years at a time,

42 The data set authors however estimate that the average error for monthly temperatures compared to similar gridded climate projects is small (+/- 0.77 °C) (Wang, Hamann, Spittlehouse, & Carroll, 2016).

obfuscating conclusions drawn from them. With this in mind, I must clarify that though the Daymet pseudo-climatology (2011 – 2015) is reflective of average temperatures during this short time period, this is not a statistically valid sample on which to generate a baseline or normalization period and any results drawn from it are likely dominated by natural variability.

Climate estimates that reduce the impacts of signal noise and uncertainty are useful for long-term estimates, and are generally useful for determining trends and curves for the purpose of regional long-term planning. When considering the needs of industry operators however, information that is timely and considers inter-annual variability is necessary for short-term agricultural management and decision-making on activities such as choice of crop sub-species, quantities, and insurance coverage (Bradshaw et al., 2012; Dunn, Lindesay, & Howden, 2015). In order to provide the best information for planning by operators, an approach that statistically integrates data from daily observations to determine potential variability is necessary for the information to be useful for operators who work within shorter time-horizons (Dunn et al., 2015).

Climate Scenarios

It is also worth mentioning again that the path-dependent nature of climate change prediction introduces an inescapable uncertainty in the quantifying of how global-scale climate change mitigation plans will be actualized, their relative effectiveness, and the overall climate response from these actions. The RCP scenarios that my research is based on are highly educated guesses as to how organized and motivated the global community will be in tackling climate change (Moss et al., 2010). As such, it's likely that the resulting RF experienced at the end of century may not precisely reflect the results of either the RCP 4.5 or RCP 8.5 scenarios.[43] Instead, I present the results of these analyses as the upper and lower boundaries of what regional climate change may look like given varying degrees of effort to address carbon emissions, with “Stabilization” as a pragmatically optimistic goal for end-of-century efforts (Thomson et al., 2011). The path dependent climate impacts from these two scenarios may also only become clear once RF anomalies begin increasing either marginally or drastically from present-day. This would suggest that the reliability of climate models may

43 As both of these scenarios reflect a >2 ºC world, a decisive and organized global movement to drastically curb emissions could potentially lead to more optimistic scenario forecasts, such as those outlined in RCP 2.6 .

be held as the dominant source of uncertainty in climate predictions in short term planning, while the accuracy of RCP scenarios in predicting global climate trends presents the greater amount of uncertainty in long term planning. For on-the-ground operators, this climate prediction information will need to be contextualized and communicated regularly to provide operators with benefits in the agricultural or viticultural planning and in the development of climate adaptation efforts at the seasonal to multi-year scales (Bradshaw et al., 2012; Dunn et al., 2015).

Vineyards and Geocoding

When determining vineyard locations, I relied mainly on manually entered centroid of plots for a significant portion vineyards (n = 82) and the geocoded addresses of vineyards for the majority remaining (n = 110). For aggregated analyses at the regionally scale this is adequate, but for finer-scale site suitability analysis, as would be necessary for activities such as precision agriculture, this approach is insufficient. There is a degree of uncertainty in the geocoding process as addresses are typically placed a certain distance along a center line (e.g. roads) as an interpolated estimate of distance between known addresses. While this method is relatively accurate for urban centres, according to one study, rural areas can experience geocoded positional errors in excess of 3 Km from their true location (Cayo & Talbot, 2003). In addition, the placement of geocoded points along roads requires further post-processing to adjust location potentially hundreds of meters to the location of the vineyard plot. Given that the highest grid resolution for both major climate data sets was roughly ~1 Km, and the positional uncertainty presented by geocoded vineyard locations, meso-to-microscale variability in terrain were not considered in the climate analysis.

Viticulture-Climate Metrics

For the agroclimatic metrics, the thermal thresholds set in the literature defining viticultural climate indices are all used to denote the regions that best accommodate different varieties of grapes used in winemaking. Each of these climate metrics are adapted to and aim to reflect the climates that they were built to describe, typically regions of western Europe (Huglin, 1978; Jackson & Cherry, 1988; Winkler et al., 1974) and in few instances Australia (Gladstones, 1992; Hall & Jones, 2010). As such, the relative accuracy and applicability of many of these climate metrics, is limited for use in Quebec due to its largely continental climate and by the high latitudinal profiles of most vineyards operating throughout the region. That said, the LTI index might be better suited for determining viticulture climates at higher latitudes than the WI Index due in part to their inclusion of a simple latitudinal modifier (Huglin, 1978; Jackson & Cherry, 1988; Rayne & Forest, 2016), however the HI and BEDD Indices use a similar method to Winkler for heat summation in addition to a more comprehensive latitude modifier function (Gladstones, 1992; Huglin, 1978); this partly why Tonietto and Carbonneau integrate HI into their Geo-viticulture Multi-Criteria Climate classification system over other heat summation metrics (Tonietto & Carbonneau, 2004).

While many of these indices can provide in-depth recommendations of the most appropriate wine grape to cultivate based on climate characteristics, I defer to the GST metric for assessing the *V. vinifera* grapes based on regional GST (Fraga et al., 2012; Hall & Jones, 2009, 2010). This is largely due to the fact that most other viticulture-climate metrics are specifically to categorize *V. vinifera* varietals grown within specific environmental conditions typically found in Europe and fail to include factors such as frost, mildew and pest risks which are region-specific – and of particular concern for Quebec – and not well understood within the emerging context of global climate change. As such, the on-the-ground choices of grape species will need to carefully planned and experimented with by vineyard operators and horticulturists as climatic and other growing conditions evolve.

Ground-Truth and Operator Experiences

For the entirety of this research, my approach has relied on readily-available remotely-captured Open data processed using GIS with very little verification from operators on-the-ground. While multi-criteria evaluations using the best available climate data represents a “best guess” in objectively determining present and future climate conditions, this approach fails to capture cultural contexts and operator-held knowledge that is of key importance to determining the “ground-truth” of performing viticulture in Quebec. Climatic variability and specific bioclimatic indicators that greatly influence vineyard operations require not only precise data collected at the micro-scale, but also the observations and experiences of the operators themselves.

Agricultural and Viticultural Practice Changes

When considering vineyard locations and industry conditions projected forward to the end-of-century, a major assumption taken is that present-day agricultural areas will remain the same throughout time. In practice, changes to rural land use planning, seasonal climate trends and industrial economic conditions greatly impact the extents of agricultural areas on long time scales as well as inter-annually.[44] The present-day placement of vineyards throughout *Montérégie* and southernmost regions of Quebec arguably reflects the operator need to seek out the warmest regions of Quebec to satisfy the thermal needs of *V. vinifera* and other hybrid grape species. As the region becomes warmer, traditional practices and grape varietals will need to be adapted and a degree of risk due to inter-annual climate variability and other environmental concerns will need to be planned for. These changes may require operators to purchase crop insurance plans, dissuading smaller operators from attempting to experiment or engage in the wine-growing industry.

Additionally, as these present-day warm regions in particular become much warmer, accelerating the inter-period heating potential for most viticulture-climate metrics, regions that better reflect climate conditions of today may be more sought-after for their capability to sustain varietals developed for present-day climates. While warming in Quebec may shift the suitability of climates to reflect those of warmer areas, climates present throughout already warm areas of the United States are already nearing threshold where further warming may result in negative impacts to yields for already-established crops and fruits; extreme heating events could mimic these conditions in the short-term and overall warmer average conditions could exacerbate the situation (Lepage et al., 2011; Lobell et al., 2006). Phenological modelling, using multiple bioclimatic indicators and Bayesian statistical methods are thus necessary to determine species-specific development and fruition patterns with a measure of certainty (Köse, 2014). More information is thus needed from operators themselves, from instrumental records and personal observations and experiences, to understand their perceptions of climate risk and considerations when developing agricultural plans (Belliveau et al., 2007; Bradshaw et al., 2012)

44 For an in-depth example of some of these changes for Southern Quebec see Chapter 4, section 3.4.

4.6.5 - Summary of Conclusions and Avenues for Further Research

To conclude my analysis, I have determined that Southern Quebec can expect to experience some climatic changes in the near and distant future that may be of concern to vineyard operators throughout the region. Climate model ensembles compared to satellite-determined average of the previous five years of climate conditions show that this region may have already experienced visible warming from the 1981 – 2010 reference period and if these trends continue, observed warming will likely resemble average climate conditions for both RCP 4.5 and 8.5 scenarios in the short term. In the near future, present-day suitable climates may extend to the North-East following the Saint Lawrence River, with the vineyard-populated *Montérégie* region experiencing the warmest average climate conditions. These changes may create opportunities for operators to experiment more with more economically sought-after European grape species that typically have greater thermal demands than endemic or hybridized wine grape species. In the longer term, climatic changes will become more path-dependent, diverging according to the relative successes of the global community to curb carbon emissions and mitigate climatic change. Gradual and stabilizing climatic conditions may yield a Southern Quebec that is moderately warmer than present-day and better suited to more temperate viticultural activities while a climate reflecting more accelerated inter-period warming may contribute to environmental condition that prove difficult to plan for when it comes to agricultural practices that demand long-term investments such as viticulture. Under higher emissions scenarios, drastic changes to growing season conditions may risk negatively impacting other annual and perennial crops as well fundamentally changing the agricultural landscape of Southern Quebec and the provincial food and tourism economy. This analysis can be considered the first step in the broader challenge of performing regional-scale, projected viticulture-climate assessments in Quebec.

Moving forward from here, several methods of following up on this research are necessary in order to derive greater utility to industry and operators. The development of much more sensitive phenological models using daily weather and normalized climate data is necessary in order to better understand the unique local climate conditions necessary for growth for specific grape vines (Köse, 2014; Webb et al., 2007); this of particular importance for economically valuable *V. vinifera* as well as endemic and hybridized varietals that vineyards presently rely upon. Information like this will be essential to determine the species-specific responses to greater heating degree-days and the particularities of frost risk with an advancing start to the growing season (Molitor et al., 2014; Mosedale et al., 2015). While multi-variable crop models have been developed for particular species of *V. vinifera*, more research would be needed to assess their applicability for modelling typical Quebec-specific grape varietals, and such an analysis could serve as an interesting follow-up to this work. Knowledge of vineyard-scale data, such as phenological dates of importance, annual yields and production values, and local-level weather data would be of key importance to the development of these models. Much of this work would need to be conducted by contacting individual operators and academics who maintain agricultural/viticultural research relationships with commercial vineyards. Data sets pertaining to grape and wine production held by MAPAQ and the AVQ might also be useful to determining industry-level trends in annual wine production, however individual vineyard-level data would be more reliable in determining smaller-scale trends by local area or region.

Another potential follow-up to much of this work would be to facilitate the sharing much of the technical methodologies and tools I've developed throughout the course of this project, including but not limited to metric calculation scripts, data formatting models, listings of technical resources, and documentation of pre- and post-processing techniques. These GIS script resources could be shared online as scripts via developer platforms such as GitHub, or compiled into a QGIS plug-in specifically built for viticulture-climate analysis while documentation and methods could be explicitly summarized in a working paper or article released under an Open Access license or published in an Open academic journal such as PLoS One. Many of my scripts have been developed to use monthly averaged data, so a potential follow-up of this work would be to expand these scripts to accept daily values summarized in spreadsheet or raster data. There are many technical avenues of expansion that I could consider.

Chapter 5 - Conclusion

Throughout this thesis, I have presented research within the overlapping fields of bioclimatology, spatial analysis and open science. Focusing on the very niche topic of wine studies, I hope I have provided a case example that adds to the growing body of literature on Quebec, an emerging and promising zone for viticulture. The prospects for growth in this industry under low greenhouse emission scenarios is great and with adequate planning and coordination, viticultural operators have the potential to proliferate and establish the *Québecois Terroir*.

This research project shows the possibility of adopting newer, more accessible methods of performing traditional spatioclimatic analyses. By focusing on the history of Open Source/Data/Access, I hope here to inspire other researchers to exercise their agency in this digital social movement, to consider integrating Open methods into their practices and to introduce these approaches into their respective disciplines. Just as the academic community has benefited from the sharing of knowledge, dismantling the barriers of access and reclaiming the tools to build upon knowledge from proprietary controls can change not only the way research is performed but the model upon which societies can participate be better informed.

Much of the debate concerning climate change and the future of wine focuses on how the Old World will be able to maintain their traditional viticultural practices and how the New World can benefit under new climate regimes. In both cases, our opportunity to gain from any potential benefits hinges on the global effort to prevent climate change from getting worse. Under the worst possible scenarios, socioeconomic challenges at the global scale brought on by a drastically changing climate have the potential to deepen the divide between developed and developing nations, displacing nations and forever altering the lives of those less fortunate as today's global problems are exacerbated by a runaway global climate. In order to achieve the best possible scenario, sustainably developing and decarbonizing the global economy will need to happen, and soon. Only in a world where all peoples lives are considered worth the political effort of preventing environmental disaster will societies still plan for the future of a luxury commodity such as wine.

Chapter 6 - References

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Chapter 7 - Indexes

Annex 1 – Additional Methodologies

7.1.1 - Climate Data Projections

Due in part to the standardized and consistent formatting decisions adopted by the Canadian geospatial data authorities (Johnson & Singh, 2003), spatial data for most Canadian shapefiles is typically available in the NAD83 Canadian Spatial Reference System (CSRS) projection (EPSG: 4617). For Canadian gridded data sets, such as the Land Use and Crop Type raster grids, areas are made available according to UTM zone and projected according to the respective UTM zone.[45] In order to have continuous surfaces encompass the agricultural region of Southern Quebec, I warped grid tiles to the NAD83 (CSRS) projection, merged, and clipped to the spatial extent of Quebec, removing Ontario and New Brunswick.

For most other environmental data sets coming from international agencies, data and grids were made available in the WGS84 or NAD83 projection. In these cases, I did not reproject grids unless there were combined with Canadian spatial data, in which case I warped them to the NAD83(CSRS) projection to maintain consistency.

For some climate data, the standard projection did not adhere to a geographic coordinate system and needed to be defined and projected to common reference system before analysis. For the ClimateNA grids, the projection custom Lambert Conformal Conic projection which needed to be defined for QGIS. The projection definition I used to set the proper coordinate system was as follows:

- ClimateNA Lambert Conformal Conic Projection

+proj=lcc
+lat_1=49
+lat_2=77
+lat_0=0
+lon_0=-95
+x_0=0
+y_0=0
+datum=WGS84
+units=m
+no_defs

45 The agricultural areas of Quebec encompass UTM zones 17 thru 20 North.

The Daymet raster tiles also used a specific Lambert Conformal Conic projection that needed to be defined as well before they could be processed.

- Daymet Lambert Conformal Conic Projection

+proj=lcc
+lat_1=25
+lat_2=60
+lat_0=42.5
+lon_0=-100
+x_0=0
+y_0=0
+ellps=WGS84
+towgs84=0,0,0,0,0,0,0
+units=m
+no_defs

Using these projections, I reprojected a shapefile of Quebec Provincial Boundaries and used the QGIS graphical modeller to batch process these grids before merging.[46]

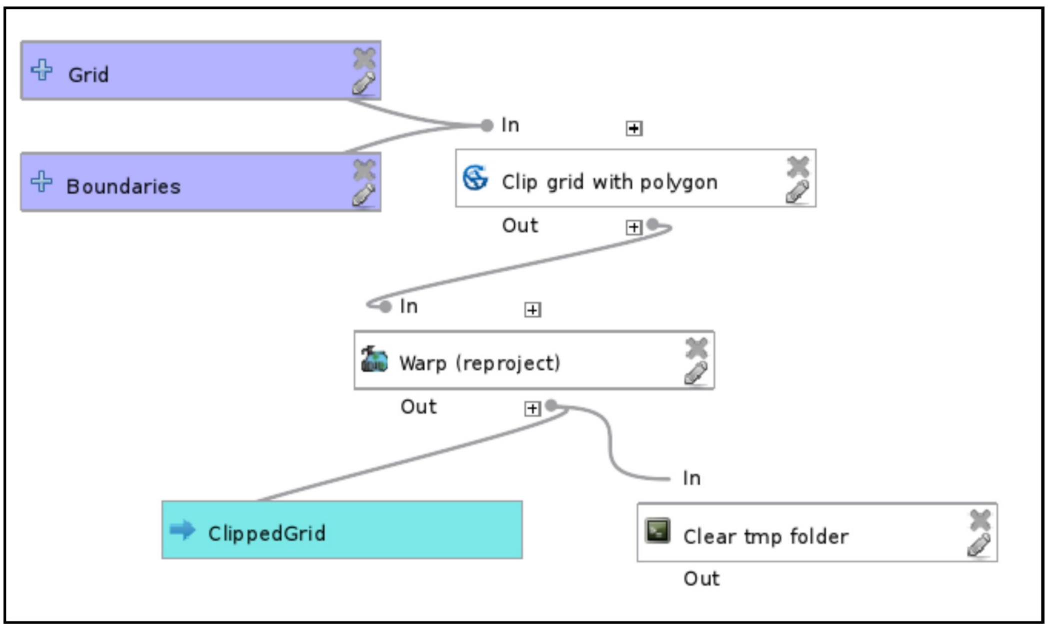

Figure 7-1: QGIS Graphical Model for Batch Clipping and Warping Raster Grids

46 In order to prevent RAM overflow when processing hundreds or more climate grids, I needed to program a script ("Clear tmp folder") to remove temporary files generated by SAGA that ran the Python "shutil" library on my '/tmp' folder after every model run iteration.

Despite the superior usability of NetCDF data containers for performing multidimensional analyses (Wilhelmi, Sampson, & Boehnert, 2015), all climate grids used in the analyses were downloaded in the GeoTIFF format. This was in part to the fact that earlier versions of QGIS did not handle NetCDF format natively during my data acquisition phase. In lieu of this, monthly climate grids representing annual time periods were merged into multi-band rasters to achieve similar functionality.

For DEM-derived products such as Aspect, Slope, and Topographic Indexes, I employed a combination of GRASS-derived ("r.slope", "r.aspect") and GDAL-derived ("TPI Topographic Position Index") analyses.[47] In order to determine USDA soil categorizations based off of soil grid percentages of silt, sand, and clay compositions, these grids were processed together using the GRASS function "r.soils.texture"

47 When calculating slope, warping DEMS to a projected coordinate reference system or setting a Z-value multiplier was not necessary as GRASS converts all Z units to degrees before calculating slope.

7.1.2 - Sources and Consideration for Non-Climate Data

To build a multi-criteria analysis many data sets are needed to assemble the many components of a non-climatic suitability. These variables include soil components, drainage characteristics, relief (elevation, slope, aspect, and topographic indexes), roadways, railways, and water networks. In limiting my sources to Open Data, I had expected that there would be few options available for satisfying my data needs but this turned out not to be the case.

For hydrological and pedological data sets, I considered both the CanSIS Soil Landscapes of Canada data set and the ISRIC SoilGrids 250m data set (Canadian Soil Information Service, 2013; Hengl et al., 2014). As the soil surveys available through CanSIS is organized by vector polygons that contain soil horizons that begin and end at different depths, I suggest using the ISRIC data. The grids available through ISRIC are composed of interpolated textures and soil types at globally consistent depths (0cm, 5cm, 15cm 30cm, 60cm, 1m, and 2m) and extend to have global coverage. In addition, these grids integrate the CanSIS and other soil surveys in their interpolations for soil characteristics throughout Canada and elsewhere. Based on the literature the main soil components consider for the analysis were percentages of silt, sand, and clay as well as percentages of organic carbon and soil pH.

Given that Canadian drainage surveys were only available through CanSIS surveys, I refer to these estimates for applicable regions and exclude drainage from my analyses for areas residing outside of the CanSIS regions due to the limited coverage and inadequate spatial resolution (1 : 250,000).

For elevation data and for analyses of topographic features (slope, aspect, terrain ruggedness index), I considered the following Digital Elevation Models [DEMs] [Figure 7-2]:

- The GeoGratis Canadian DEM data set at 0.75 arc-second (~30m) resolution (Natural Resources Canada, 2013),
- The NASA and Japan Ministry of Economy, Trade, and Industry-produced Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER] Global DEM at 30m resolution (NASA & METI, 2016),
- The NASA Shuttle Radar Topography Mission [SRTM] DEM at 90m resolution (Farr et al., 2007), and

- The EarthEnv DEM90 void-filled SRTM-ASTER hybrid raster at 90m resolution (N. Robinson, Regetz, & Guralnick, 2014).

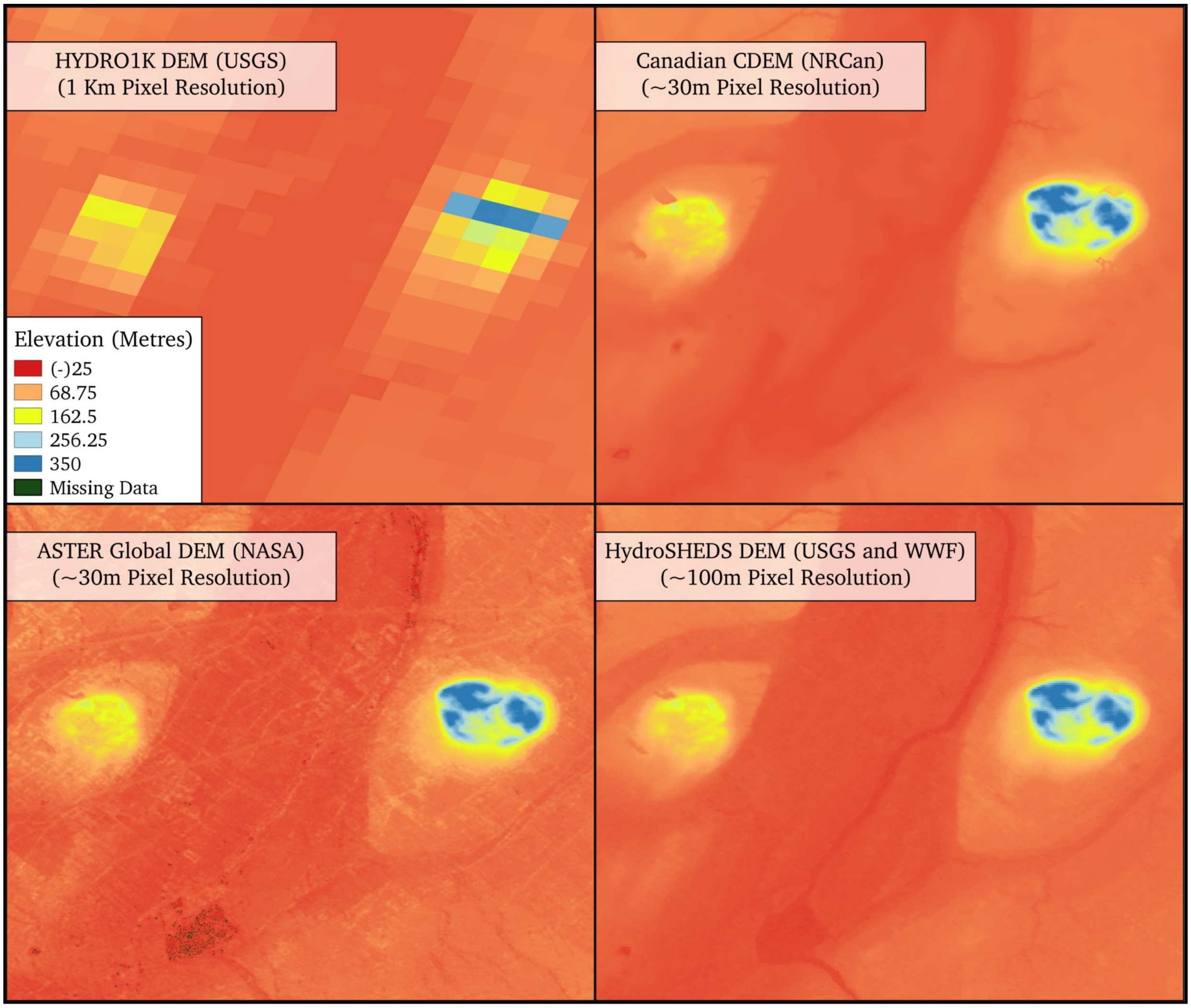

Figure 7-2: Comparison of Different Elevation Models showing Resolution differences and Artifacts

While all the DEMs I consider have continuous Canadian coverage, I would suggest the EarthEnv DEM90 for regional analyses. The main benefits of this data set over others is the claim of high error-removal by using the combination of SRTM and ASTER DEMs, as well as the slightly coarser resolution which allows for quicker processing times with typical consumer hardware specifications.

Vector shapefiles for Canadian roads, highways, railways, and waterways are available via the data sets produced by Natural Resources Canada, specifically the National Hydro

Network (Government of Canada & Natural Resources Canada, 2016a), the National Railway Network (Government of Canada & Natural Resources Canada, 2016b), and the National Road Network (Government of Canada & Natural Resources Canada, 2016c). These were converted to raster files to allow for easier analysis with the AAFC data products.

Other boundaries such as Economic Regions and the Quebec Provincial Boundaries are accessible as part of the StatsCan Census Boundary files for 2011 (Statistics Canada, 2015) and the Municipal Regions of Quebec hosted on GeoBase (Government of Canada & Natural Resources Canada, 2010).

By applying a set of categorization schema to these data sets based on best practices and assumptions followed in other studies, it is possible to identify the most and least suitable locations for vineyards based on physical characteristics. Where regions fall far from meeting the topographical or other components (e.g. bare bedrock, very severe slopes, poorly drained soils, roads, etc.), pixels and polygons are labelled “unsuitable”. Combining this scoring system alongside methods for distinguishing the exact areas where agricultural/viticultural operations have operated both historically and for present-day. It would be feasible to assess relative suitability of soil, hydrography, and topography, limited to agriculturally important areas throughout Quebec.

Annex 2 – Source of Climate and Other Environmental Data Sets

Climate Data Sets				
Name	*Type*	*Resolution*	*Years Available*	*Data Source*
Canada Plant Hardiness Zones	Observed (Interpolated)	Polygons (1:1,000,000)	1930 – 1960, 1961 – 1990, Averages	Natural Resources Canada (NRCan)
Canadian Climate Future Estimates	Historical and Projected (RCP 2.6, 4.5, and 8.5)	Points (User-Specified)	1901 – 2100, 30-year Monthly Normals	Natural Resources Canada (NRCan)
Canadian Regional Climate Model	Historical and Projected (SRES A2)	Gridded Points (0.5 Degree intervals)	1980 – 2099, 30-year Monthly and Annual	Environment Canada (Canadian Regional Climate Model v4.2.3)
Canadian Weather Stations	Observed (points)	Points (1:50,000)	1960 – 1990, 1970 – 2000, 1980 – 2010, Monthly Normals	Environment Canada (EC)
ClimateNA	Historical and Projected (RCP 4.5 and 8.5)	~1 Km (0.5 Minutes intervals)	1961 – 1990, 1981 – 2010, 2011 – 2040, 2041 – 2070, 2071 – 2100, Monthly Normals	University of Calgary, Hadley (CRU-TS 3.22, CMIP5)
Daymet	Observed (Interpolated Grid)	1 Km	2006-2015, Monthly	NASA (World Meteorological Organization; WMO)
Drought Watch Interactive Mapping Derived Climate	Observed (Interpolated Grid)	10 Km	1971-2000, Monthly	Agriculture and Agri-Food Canada (AAFC)
Quebec Agroclimatic Atlas	Observed (Interpolated Grid)	10 Km	1974 – 2003, 1978 – 2008, Monthly and Seasonal	Agriculture and Agri-Food Canada (AAFC)
WorldClim	Historical	~1 Km (0.5 Minute intervals)	1950 – 2000, Monthly Normals	Global Historical Climatology Netw ork, FAO, WMO

Table 7-1: Examples Climate Data Sets Considered with Measured Variables, Scopes, and Sources

Soil and Topographic Data Sets				
Name	*Type*	*Resolution*	*Variables of Interest*	*Data Source*
Agricultural Ecumene Boundary Files, 2011	Vector (Points, Lines, Polygons)	1:50,000	Agricultural Extent	Statistics Canada
ASTER Global DEM	Raster Grids	30 m	Elevation, (Aspect, Slope, Terrain Position Index)	United States Geologic Survey (USGS)
Canadian Digital Elevation Model	Raster Grids	0.75, 1.5, 3, and 6 Second intervals	Elevation, (Aspect, Slope, Terrain Position Index)	Natural Resources Canada (NRCan)
Census Divisions and Economic Regions of Quebec	Vector (Polygons)	1:50,000	Regional Extents	Statistics Canada
Crop Type Maps	Raster Grids	30 m	Zoned Agricultural, Forest, Urban, and other areas	Agriculture and Agri-Food Canada (AAFC)
EarthEnv – DEM90	Raster Grids	90 m	Elevation, (Aspect, Slope, Terrain Ruggedness)	Robinson et al. 2014
Land Use 1990, 2000, 2010	Raster Grids	30 m	Zoned Agricultural, Forest, Urban, and other areas	Agriculture and Agri-Food Canada (AAFC)
National Hydrological Network	Vector (Points, Lines, Polygons)	1:50,000	Major Water Bodies, Water Lines	Natural Resources Canada (NRCan)
National Road Network	Vector (Points, Lines, Polygons)	1:50,000	Major Transit, Roads	Natural Resources Canada (NRCan)
Soil Landscapes of Canada v3.2	Vector (Polygons)	1:50,000	Agricultural Extent, Soil Carbon, Clay Content, Sand Content, Silt Content, Soil pH	Canadian Soil Information Service (AAFC, NRCan)
Territoires des Stations Météo	Vector (Polygons)	Not Specified	Weather Station Proximity	Financiere Agricole Quebec [FAQ]
World Soil Grids	Raster Grids	250 m	Soil Carbon, Clay Content, Sand Content, Silt Content, Soil Depth, Soil pH	ISRIC – World Soil Information
Zone Agricole du Quebec	Vector (Polygons)	Not Specified	Agricultural Extent	Commission du Protection Agricole du Quebec [CPTAQ]

Table 7-2: Example Land, Soil and other Non-Climate Data Sets Considered with Data Types, Scales, and Sources

Non-Climate Suitability Criteria			
Criteria	*Derived from*	*Data Source*	*Support*
Agricultural Land Use/Classification	Land Use	AAFC Land Use Grids 1990/2000/2010, AAFC Crop Type Inventory 2011-2015	(Hansen et al., 2013),
Low Available Water Content	Soil	ISRIC World Soil Grids	(Nowlin & Bunch, 2016)
Low-Neutral pH	Soil	ISRIC World Soil Grids	(Joneset al., 2004; Nowlin & Bunch, 2016; Wolf & Boyer, 2003)
Relatively Elevated Land Parcels	Elevation	Topographic Position Index, derived from EathEnv-DEM90 using [r.topidx] (GRASS)	(Joneset al., 2004; Nowlin & Bunch, 2016)
Slight/Moderate Slopes	Elevation	Slope, derived from EarthEnv-DEM90 using [r.slope] (GRASS)	(Joneset al., 2004)
Soil Carbon between 2% to 4%	Soil	ISRIC World Soil Grids	(Barriault, Michaud, Bourgeois, Grenon, & Plouffe, 2013)
Southward-Facing Slopes (in Northern Hemisphere)	Elevation	Aspect, derived from EarthEnv-DEM90 using [r.aspect] (GRASS)	Many Studies
Unrestricted Soil Depth > 80 cm	Soil	ISRIC World Soil Grids	(Barriault, Michaud, Bourgeois, Grenon, & Plouffe, 2013)
Well Drained Soils	Soil	CANSIS Soil Landscapes of Canada v3.2	Many Studies

Table 7-3: Viticulture Suitability Criteria accorded to Non-Climatic Variables and their Supporting Literature

Annex 3 – Climate Indexes and Climate Scoring Tables

Climate Categorization Indices and Criteria					
Name	*Criteria Evaluated*	*Equation*	*Period (Northern Hemisphere)*	*# of categories*	*Developed by*
Biologically Effective Growing Degree Days	Temperature, Latitude	Σ min[max ([T max + T min] / 2) – 10, 0] * k + TRadj, 9]; where k = multiplier for day length according to latitude and TRadj is an adjustment for temperature range	April 1 – October 31, Daily	Varies	(Gladstones. 1992)
Continentality Index	Temperature	MTWM – MTCM; where MTWM = Mean Temperature of the Coldest Month, MTCM = Mean Temperature of the Coldest Month	June and January, Monthly Averaged	N/A	(Gladstones. 1992)
Cool Night Index	Temperature	T min	September, Monthly Average	4	(Tonietto & Carbonneau, 2004)
Dryness Index	Precipitation, Potential Evapotranspiration, Soil moisture	Σ [Wo + Precipitation – (Tv + E)]; where Wo = Initial Soil Water Reserve, Tv = Transpiration, E = Evaporation	April 1 – October 31, Monthly Averaged	4	(Tonietto & Carbonneau, 2004)
Frost Free Period	Temperature	n, where n = Total # of consecutive days days where Tmin > 0ºC	Annually	Varies	(Jones et al. 2004)
Growing Degree Days (Winkler Index)	Temperature	Σ [([T max + T min] / 2) – 10]	April 1 – October 31, Monthly Averaged	6	(Amerine & Winkler, 1944; Winkler et al., 1974)
Growing Season	Temperature	Σ [(T max + T min) / 2] / n; where n = number of days	April 1 – October 31, Monthly Averaged	6	(Hall & Jones, 2009; G. V. Jones et al., 2005)
Huglin Heliothermal Index	Temperature, Latitude	Σ (([T mean – 10] + [T max – 10]) / 2) * k; where k = multiplier for day length according to latitude	April 1 – September 30, Daily	6	(Huglin, 1978)
Hydrothermal Index	Temperature, Precipitation	Σ [T mean * Precipitation]	April 1 – October 31, Monthly Averaged	3	(Branas, Bernon, & Levadoux, 1946)
Latitude-Temperature Index	Monthly Temperature, Latitude	MTWM * [60 – Latitude]; where MTWM = Mean Temperature of the Warmest Month	June/July/August, Monthly Averaged	4	(Jackson & Cherry, 1988)
Spring Frost Index	Temperature	[(T max + T min) / 2] - Tx min; where Tx min = Extreme Minimum Temperature	April, Extreme Minimum and Monthly Average	3	(Wolf & Boyer, 2003)

Table 7-4: Climate-based Indices, their source literature and their specific criteria examined

Biologically Effective Growing Degree Days (Gladstones 1992; Adapted from Mills-Novoa et al. 2016)		
Criteria (Degree Days)	Classification	Value/Score
< 800	N/A	0
800 thru 1020	Class 1	1
1021 thru 1080	Class 2	2
1081 thru 1140	Class 3	3
1141 thru 1200	Class 4	4
1201 thru 1260	Class 5	5
1261 thru 1320	Class 6	6
1321 thru 1380	Class 7	7
1381 thru 1440	Class 8	8
1441 thru 1500	Class 9	9

Table 7-5: The Biologically Effective Growing Degree Days Index (developed by Gladstones, 1992; adapted from Mills-Novoa et al., 2016)

Latitude Temp Index (Jackson & Cherry, 1988)		
Criteria (Index)	Classification	Value/Score
< 99	N/A	0
100 – 195	Region A	1
196 thru 275	Region B	2
276 thru 370	Region C	3
371 thru 500	Region D	4

Table 7-6: The Latitude Temperature Index (adapted from Jackson & Cherry, 1988)

Winkler Celsius Categories (Winkler et al. 1974)		
Criteria (Degree Days, Celsius)	Classification	Value/Score
< 800	Unsuitable	NULL
801 thru 1100	"Very Cold"	0
1101 thru 1390	Region I	1
1391 thru 1670	Region II	2
1671 thru 1940	Region III	3
1941 thru 2220	Region IV	4
2221 thru 3000	Region V	5

Table 7-7: The Winkler Degree-Day Index (developed by Amerine & Winkler, 1944; adapted from Winkler et al., 1974)

Growing Season Temperature (Hall & Jones, 2009)		
Criteria (degrees Celsius)	Classification	Value/Score
< 10	Unsuitably Cold	0
10 thru 13	Very Cool	1
13 thru 15	Cool	2
15 thru 17	Intermediate	3
17 thru 19	Warm	4
19 thru 21	Hot	5
21 thru 24	Very Hot	6

Table 7-8: The Average Growing Season Temperature Index (adapted from Hall & Jones, 2009)

Huglin Index (Tonietto and Carbonneau, 2004)		
Criteria (Degree Days)	Classification	Value/Score
< 1000	Unsuitable	NULL
1001 thru 1500	Very Cool (HI-3)	0
1501 thru 1800	Cool (HI-2)	1
1801 thru 2100	Temperate (HI-1)	2
2101 thru 2400	Temperate-Warm (HI+1)	3
2401 thru 3000	Warm (HI+2)	4
3001 thru 3600	Very Warm (HI+3)	5
> 3600	Unsuitable	NULL
Huglin Index (Fraga et al. 2014)		
Criteria (Degree Days)	Classification	Value/Score
< 900	Unsuitable	0
901 thru 1500	Cool	1
1501 thru 2100	Temperate	2
2101 thru 2700	Warm	3
2701 thru 3600	Very Warm	4

Table 7-9: Huglin Index (adapted from Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014; developed by Huglin, 1978; adapted from Tonietto & Carbonneau, 2004)

Cool Night Index (Tonietto and Carbonneau, 2004)		
Criteria (degrees Celsius)	Classification	Value/Score
<]12	Very Cool	0
12 thru]14	Cool	1
14 thru]18	Temperate	2
> 18	Warm	3
Cool Night Index (Fraga et al. 2014)		
Criteria (degrees Celsius)	Classification	Value/Score
<]12	Cool Nights	0
> 12	Warm Nights	1

Table 7-10: Cool Night Index (adapted from Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014; adapted from Tonietto & Carbonneau, 2004)

Dryness Index (Tonietto and Carbonneau, 2004)		
Criteria (mm)	Classification	Value/Score
< -100	Very Dry	0
-100 thru 50	Dry	1
51 thru 150	Sub-Humid	2
> 150	Humid	3
Dryness Index (Fraga et al. 2014)		
Criteria (mm)	Classification	Value/Score
< -100	Excessively Dry	0
-100 thru 50	Dry	1
> 50	Humid	2

Table 7-11: The Seasonal Soil Dryness Index (adapted from Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014; developed by Riou et al., 1994; adapted from Tonietto & Carbonneau, 2004)

Branas, Bernon, and Levadoux Hydrothermal Index (Branas et al. 1946)		
Criteria (Index Value)	Classification	Value/Penalty
< 2500	Least Risk	0
2500 thru 5100	Moderate Risk	1
5100 thru 10000	High Risk	2
10000 thru 12600	Highest Risk	3
> 12600	Unsuitable	4

Table 7-12: Hydrothermal Index (adapted from Branas et al., 1946)

Spring Frost Index (Wolf & Boyer 2003)		
Criteria	Classification	Value/Penalty
0 thru 17	Optimal	0
17 thru 18	Low Risk	1
18 thru 19	Lower Risk	2
19 thru 20	Moderate Risk	3
20 thru 22	High Risk	4
> 22	Highest Risk	5

Table 7-13: The Spring Frost Index, categories modified to reflect variations within the Quebec climate (adapted from Wolf & Boyer, 2003)

Extreme Min Temp		
Criteria (degrees Celsius)	Classification	Value/Score
-50 thru -35	Too Cold	0
-35 thru -30	High Risk	1
-30 thru -25	Medium Risk	2
-25 thru -20	Small Risk	3

Table 7-14: Extreme Minimum Temperature Categories (loosely based on Gustafsson & Mårtensson, 2005)

Frost Free Period		
Criteria (Days)	Classification	Value/Score
0 thru 119	Not Suitable	0
120 thru 139	Very Short	1
140 thru 159	Short	2
160 thru 179	Medium	3
180 thru 199	Long	4
200 thru 240	Longest	5

Table 7-15: Frost Free Period Categories (adapted from G. V. Jones et al., 2004; developed by Wolf & Boyer, 2003)

Annex 4 – Non-Climate Criteria Scoring Tables

Soil, Topography, and Climate Scoring Grid					
Type	Character	# of Categories	Max Points	Weight (%)	Total
Climate	Latitude Temperature Index	5	4	30.0%	50.0%
	Growing Season Temperature	6	5	20.0%	
	Branas Hydrothermal Index	5	(-) 4	-15.0%	(-22.5%)
	Spring Frost Index	6	(-) 5	-7.5%	
Topography	Aspect	9	3	10.0%	30.0%
	Elevation	3	2	10.0%	
	Slope	3	3	5.0%	
	Topographic Position	3	3	5.0%	
Soil	Available Water Content	5	2	2.5%	20.0%
	Drainage	8	4	7.5%	
	Soil Carbon	5	2	5.0%	
	Soil pH	5	2	2.5%	
	Soil Texture	5	2	2.5%	
					100.00%

Table 7-16: Aggregated Climate, Topography, and Soil Scoring Grid, allowing for rapid comparison of data sets across time and from different sources (Work in Progress)

Slope Suitability		
Criteria (Degrees from Horizon)	Classification	Value/(Score)
< 1	Flat	0 (0)
1 thru]4.5	Slight Slope	1 (1)
4.5 thru]13.5	Sloped	2 (2)
13.5 thru]18	Steep Sloped	3 (1)
18 thru 30	Severe Slope	4 (-1)
> 30	Unsuitable	NULL

Table 7-17: Slope Suitability Categories in Horizontal degrees (adapted from G. V. Jones et al., 2004)

Aspect Suitability		
Criteria (Degrees Clockwise from North)	Classification	Value/(Score)
0	Flat	0 (-1)
1 thru 22.5	North	1 (0)
22.5 thru 67.5	North-East	2 (0)
67.5 thru 112.5	East	3 (1)
112.5 thru 157.5	South-East	4 (2)
157.5 thru 202.5	South	5 (3)
202.5 thru 247.5	South-West	6 (2)
247.5 thru 292.5	West	7 (1)
292.5 thru 337.5	North-West	8 (0)
337.5 thru 360	North	9 (0)

Table 7-18: Aspect and Cardinal Direction Categories (adapted from G. V. Jones et al., 2004)

Elevation Suitability		
Criteria (m)	Classification	Value/(Score)
< 0	Below Sea Level	0 (-1)
0 thru]53	Very Low	1 (0)
53 thru]114	Low	2 (1)
114 thru]176	Slightly Low	3 (2)
176 thru]249	Optimal	4 (3)
249 thru]301	Slightly High	5 (2)
301 thru]366	High	6 (1)
366 thru 732	Very High	7 (0)
> 732	Unsuitable	8 (-1)

Table 7-19: Elevation Above Sea Level Suitability (developed by G. V. Jones et al., 2004; adapted from Nowlin & Bunch, 2016)

Topographic Position Index		
Criteria (Index)	Classification	Value/(Score)
-120 thru -2 = -1	Valley	0 (-1)
-2 thru -0.5 = 0	Lower Slope	1 (0)
-0.5 thru 0.5 = 2	Middle	2 (2)
0.5 thru 1.5 = 3	Upper Slope	3 (3)
1.5 thru 5 = 1	Ridge	4 (1)
5 thru 10 = 0	Mount	5 (0)
10 thru 200 = -1	Unsuitable	6 (-1)

Table 7-20: Topographic Position Index values, categories modified to accommodate for best practices in vineyard site suitability (developed by Wilson, O’Connell, Brown, Guinan, & Grehan, 2007)

Drainage Suitability		
Criteria (Drainage Code)	Classification	Value/(Score)
-	Not Classified	0 (0)
VP	Very Poorly Drained	1 (0)
P	Poorly Drained	2 (0)
I	Incompletely Drained	3 (1)
MW	Moderately Well Drained	4 (2)
W	Well Drained	5 (3)
R	Rapidly Drained	6 (4)
VR	Very Rapidly Drained	7 (5)

Table 7-21: Soil Drainage Categories (adapted from Kurtural et al., 2007; developed by MacDonald & Valentine, 1992)

Available Water Content		
Criteria (%)	Classification	Value/Score
0 thru 10	Very Low (Optimal)	2
10 thru 15	Low	1
15 thru 40	High	0

Table 7-22: Available Water Content based on Soil Texture (developed by G. V. Jones et al., 2004; adapted from Nowlin, 2013)

USDA Soil Categories (Soil Survey Service, 1993; p63-65)			
Texture Code	Classification	Value/Score	Available Water Content (%)
1	Heavy Clay	0	15**
2	Silty Clay	N/A	16
3	Clay	N/A	15
4	Silty Clay Loam	N/A	20
5	Clay Loam	1	20**
6	Silt	-1	17
7	Silty Loam	N/A	20
8	Sandy Clay	N/A	16
9	Loam	2	17
10	Sandy Clay Loam	N/A	15
11	Sandy Loam	N/A	12
12	Loamy Sand	1	8
13	Sand	N/A	6

Table 7-23: USDA Soil Texture Categories based on Clay, Sand, and Silt constituencies (AWC adapted from Natural Resources Conservation Service, 1997 table 2-1; classes adapted from USDA Soil Survey Division, 1993 p63-65)

Soil pH		
Criteria (pH * 10)	Classification	Value/Score
0 thru 40	Acidic	0 (0)
40 thru 55	Slightly Acidic	1 (1)
55 thru 65	Optimal	2 (2)
65 thru 75	Slightly Alkaline	3 (1)
75 thru 100	Alkaline	4 (0)

Table 7-24: Soil pH Suitability Categories (adapted from G. V. Jones et al., 2004)

Soil Organic Carbon		
Criteria (Parts Per Thousand)	Classification	Value/(Score)
0 thru 10	Deficient	0 (0)
10 thru 20	Low	1 (1)
20 thru 40	Optimal	2 (2)
40 thru 50	High	3 (1)
50 thru 100	Unsuitable	4 (0)

Table 7-25: Soil Organic Carbon Content Categories (developed by G. V. Jones et al., 2004; adapted from Kurtural et al., 2007)

Annex 5 – Additional Analysis Figures

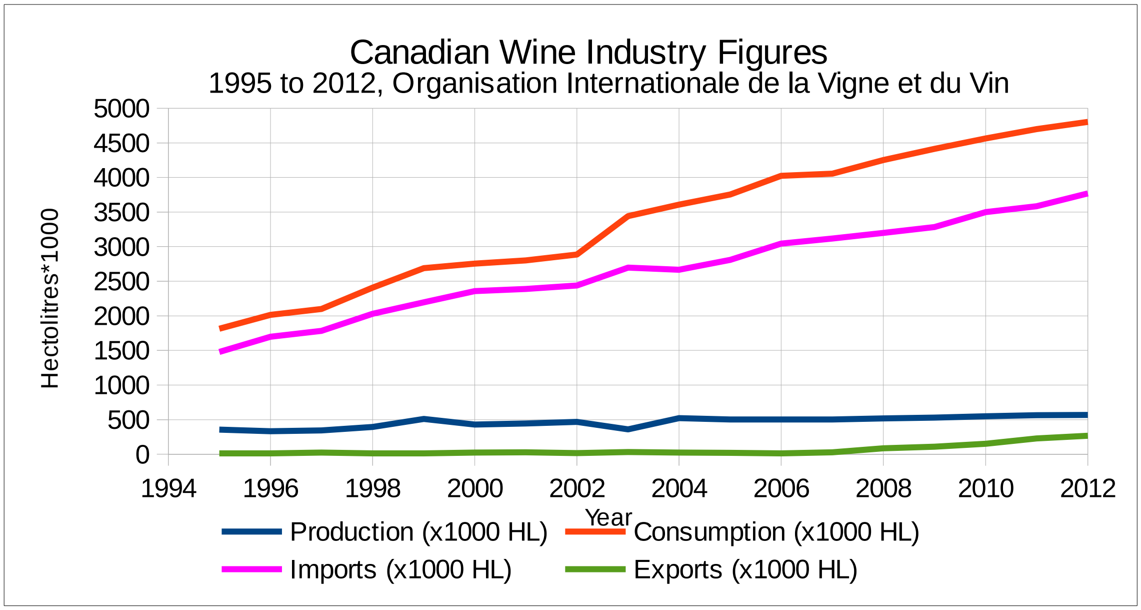

Figure 7-3: Canadian Wine Statistics from 1995 to 2012 (last year of availability) (adapted from OIV, 2016)

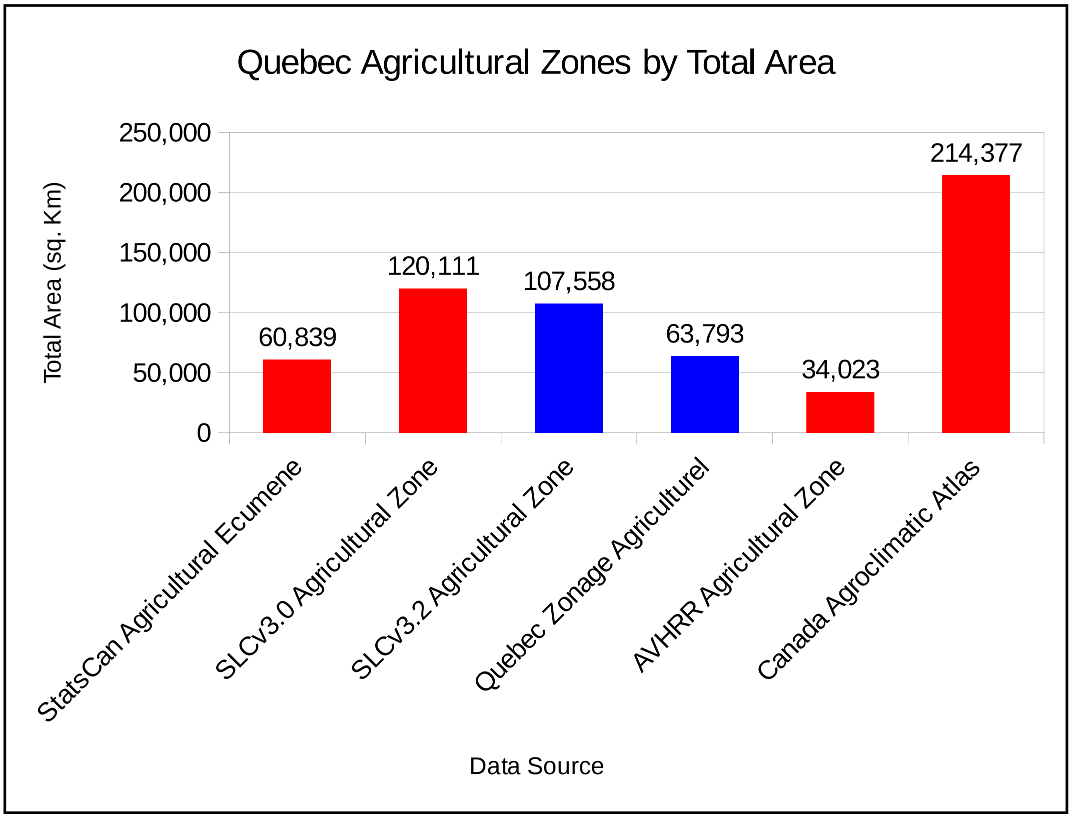

Figure 7-4: Quebec Agricultural Area Polygons adapted from (Agriculture and Agri-Food Canada & Government of Canada, 2013; Commission de Protection du Territoire Agricole du Québec, 2016; MacDonald & Valentine, 1992; Statistics Canada, 2015)

(Blue = Data sets used in analysis, Red = Other data sets shown for comparison)

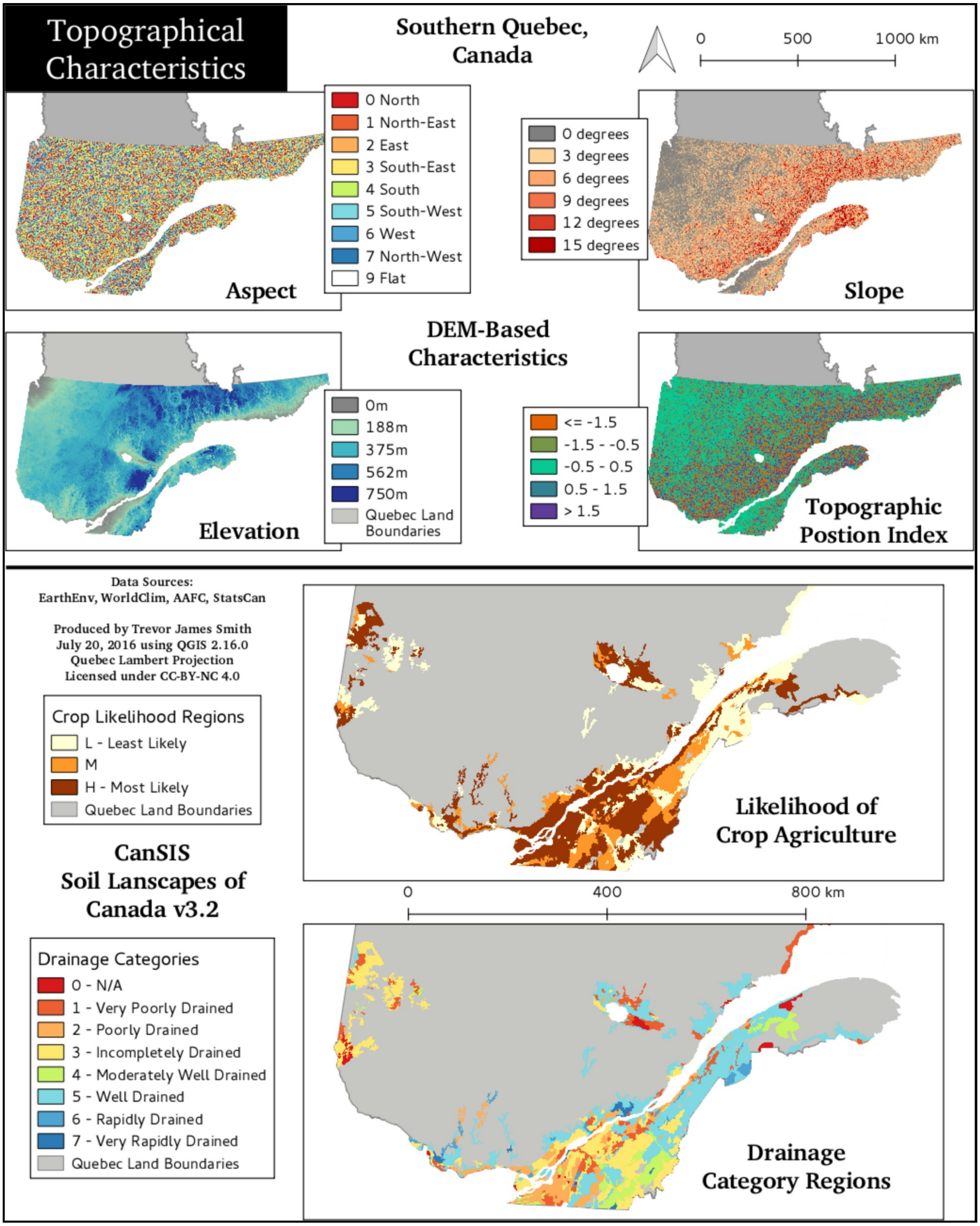

Figure 7-5: Example Soil and Topographic Analyses for Southern Quebec Using Open Data Repositories (Soil data derived from MacDonald & Valentine, 1992; DEMs derived from N. Robinson et al., 2014)

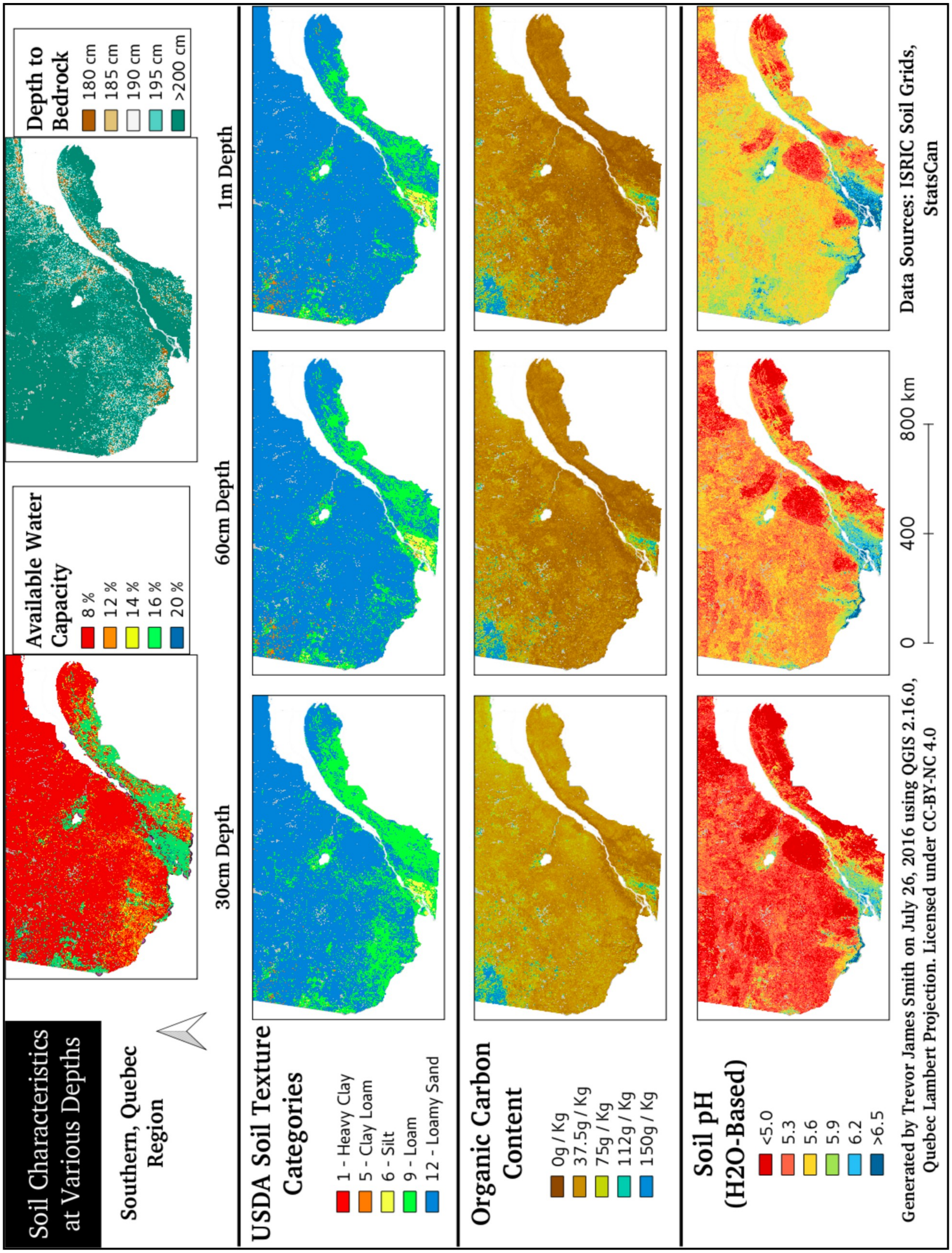

Figure 7-6: Example Soil Characteristics at Varying depths for Southern Quebec (Below 52º

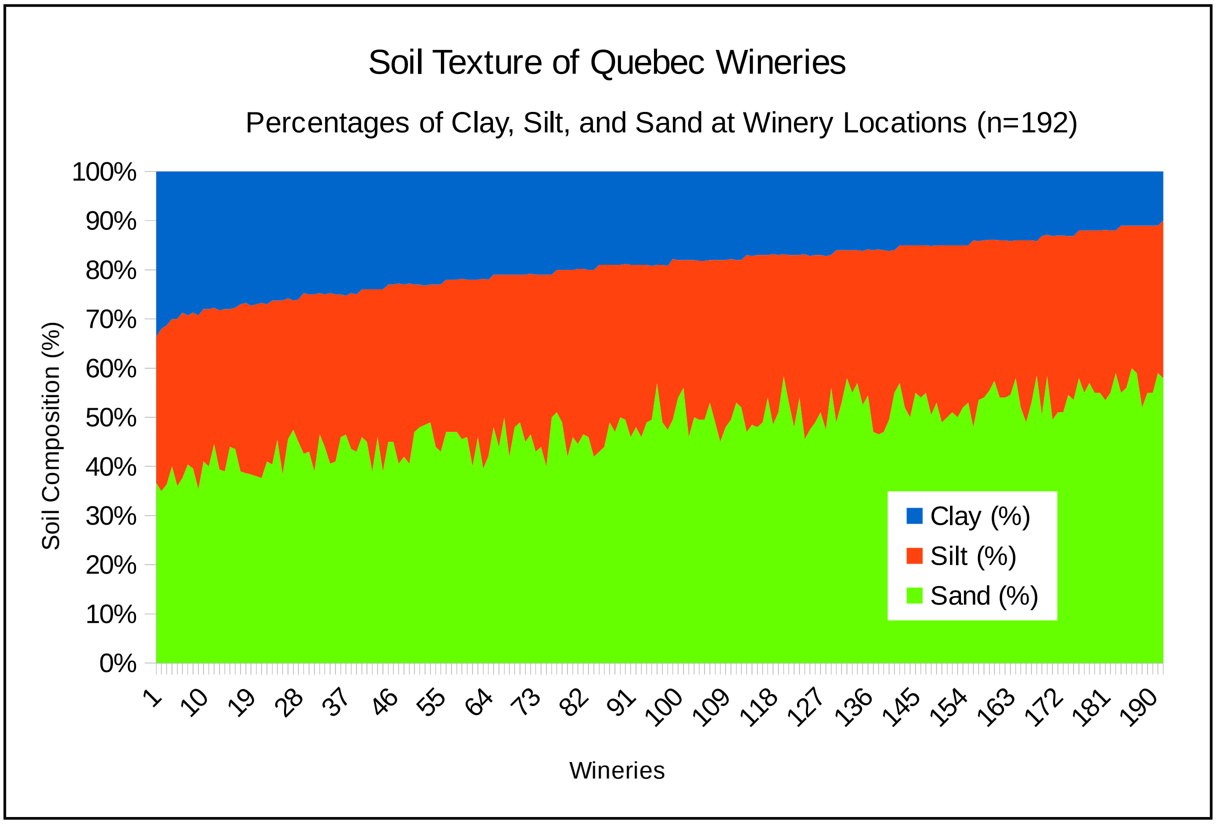

Figure 7-7: Soil Compositions of Quebec Wineries at Depth of 1 Metre

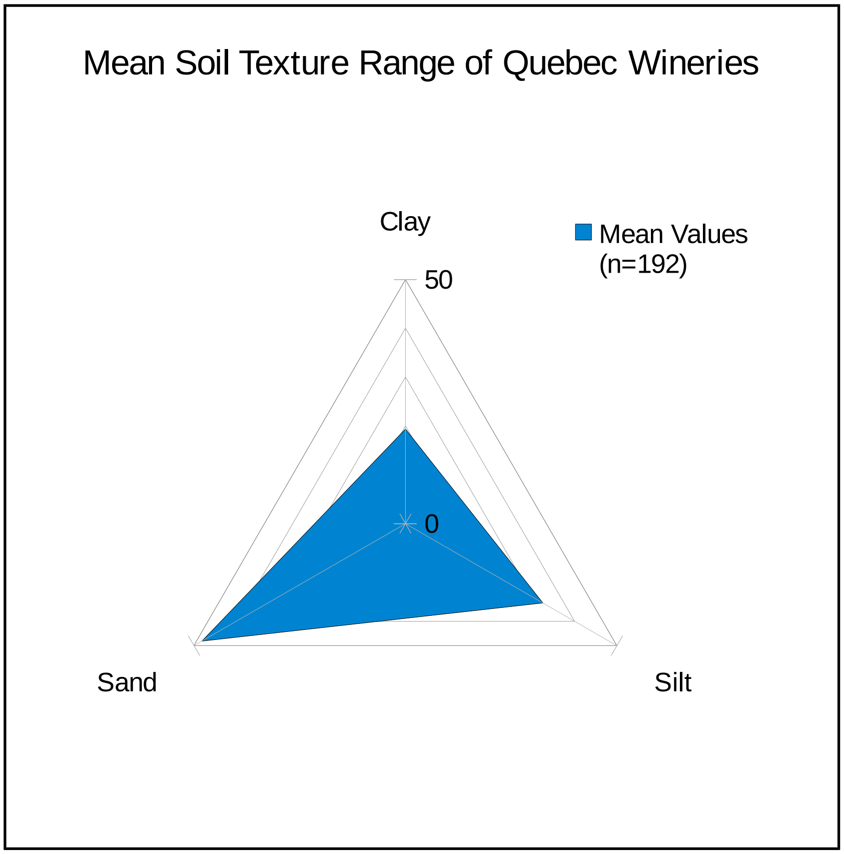

Figure 7-8: Soil Composition Range for Quebec Wineries

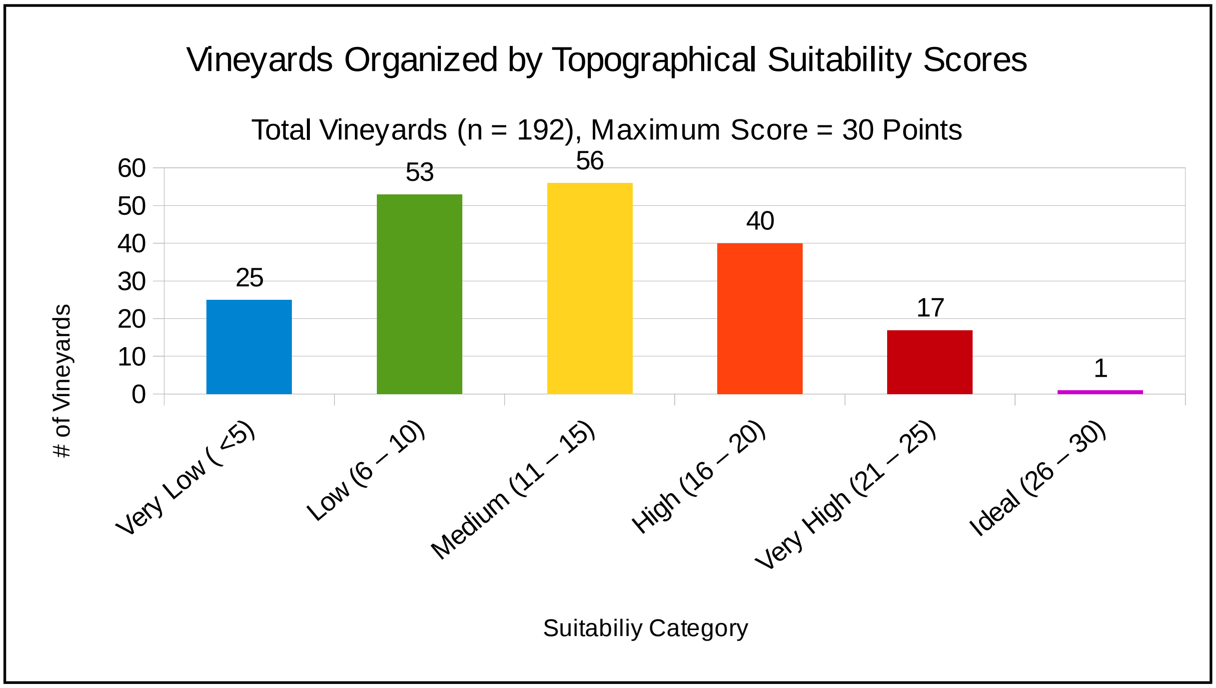

Figure 7-9: Vineyards Organized by Suitability According to Topographical Scores

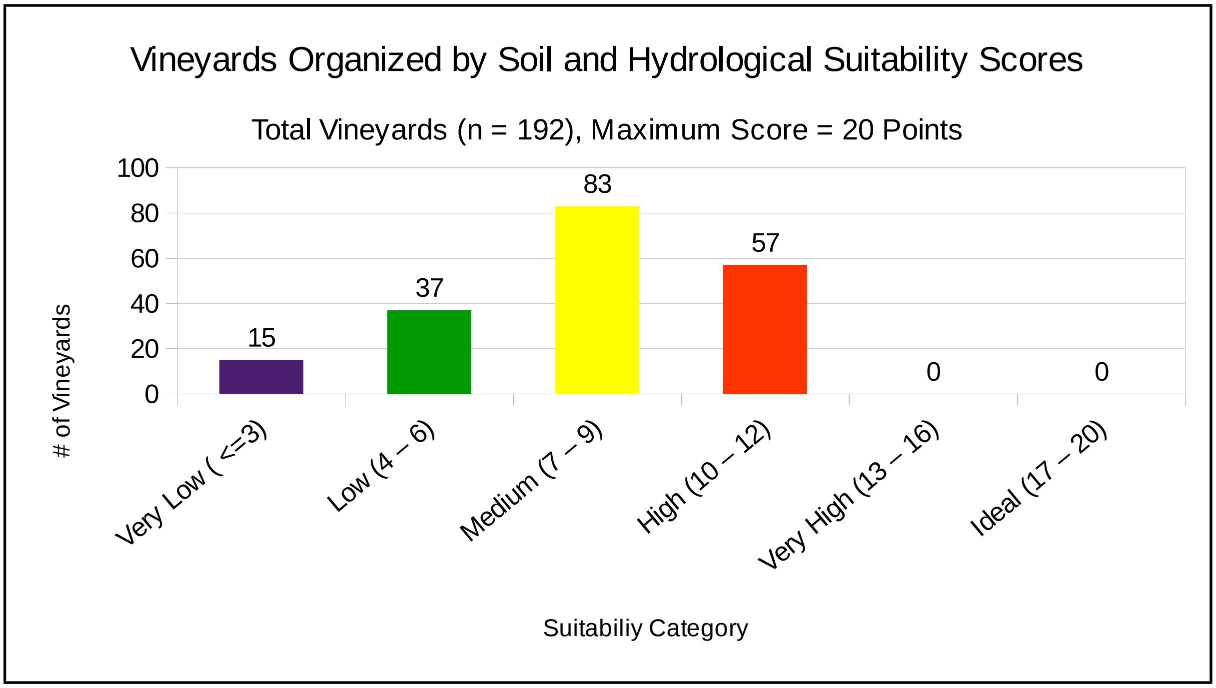

Figure 7-10: Vineyards Organized by Suitability According to Soil and Hydrological Suitability Scores

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