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Review

An Overview of the Impacts of Climate Change on Vineyard Ecosystems in Niagara, Canada

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Abstract: Vineyards are agroecosystems of great importance in the Niagara Region, Ontario (Canada). Due to its microclimate, this region is projected to be impacted by climate change with temperature increases, changes in precipitation patterns in all seasons, and greater frequency of extreme weather events. The aim of this review paper is to summarize which seasonal changes are expected to occur in the Niagara Region and assess how such changes are likely to affect the main components of the vineyard ecosystem (i.e., soil, vines, invertebrates, and pathogens). It is expected that by 2080 the region will experience an increase in temperature in all four seasons; an increase in precipitation during the fall, winter, and spring; and a decrease in precipitation during summer months. Impacts of the projected changes will likely lead to vine water stress, yield loss, increases in incidents of diseases, increases in the spread of new pests, and changes in grape quality ultimately resulting in lower wine quality and/or production. Current management practices will need to be better understood and adaptive strategies introduced to enhance grape growers' ability to minimize these impacts.

Keywords: vineyard; climate change; conceptual model

Citation: Tosato, D.R.; VanVolkenburg, H.; Vasseur, L. An Overview of the Impacts of Climate Change on Vineyard Ecosystems in Niagara, Canada. *Agriculture* **2023**, *13*, 1809. https://doi.org/10.3390/agriculture13091809

Academic Editors: Michael Moustakas and Julietta Moustaka

Received: 13 August 2023
Revised: 10 September 2023
Accepted: 11 September 2023
Published: 14 September 2023

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) in 2021, due to the expected increase in the concentration of greenhouse gases, the world average annual temperature is projected to rise by at least 1.5 °C in the next 20 years, thus affecting agroecosystems [1]. Changes in rainfall patterns and in the frequency of extreme climatic events are also expected [2]. Under current scenarios, agroecosystems must respond to both gradual and abrupt changes [3].

Agroecosystems are ecologically complex with a combination of managed and, in some cases, natural systems [4]. Some studies have taken the approach of examining this complexity but focusing on only a few components such as crop–weed or crop–pest interactions [5,6]. However, a myriad of other biophysical factors, such as soil nutrients and moisture, and multi-trophic interactions among plants, soil microfauna, and invertebrates can also be affected by these climate and environmental changes [6].

Vineyards, either for grape or wine production, are heavily managed perennial agroecosystems of high economic importance. It is estimated that there is a worldwide wine production of 262 million hL [7]. They cover an area of approximately 7.3 million ha of productive land around the globe and are present in six of the seven continents, but most production occurs in Europe, especially Italy, France, and Spain [7].

Vineyards are growing in a broad variety of climates [8,9], mainly in regions with seasonal summer droughts [10,11]. Due to increased gradual changes in temperature and rainfall patterns, some regions may suffer from water stress, a limiting factor in the grape industry [10], while others may benefit from these changes [12].

Upper latitude regions with cool, temperate climate may become more suitable to grapevine production due to an increase in temperature, reducing risks related to adverse weather during flowering, ripening, and harvest stage [12]. In recent years, countries like

Canada, the United Kingdom, and Germany have seen an increase in production [13,14]. In this paper, we provide an overview of how vineyard ecosystems may be affected by climate change by making linkages among the various components of the ecosystem.

The paper focuses mainly on changes in temperature and precipitation regimes as well as extreme weather events and their impacts on the vineyards in the Niagara region, Canada. Other factors such as changes in wind patterns, which may also impact grape production, may have limited information [15]. We also offer insights into what alternative management techniques may help reduce these impacts and further contribute to adaptation. Some of these techniques are already being used in the region on a small scale. Some aspects of the study and conclusions are likely applicable to similar regions of the world.

2. The Niagara Region of Ontario, Canada

Canada ranks 12th for wine consumption worldwide, with a consumption per capita of 13.1 L, and 27th for production, with an area of 12,742 ha in 2021 [7]. The province of Ontario grows over 7284 ha of grapes for wine production [16]. Over 76% of the Ontario vineyards are in the Niagara region [16]. The Niagara region is ideal for grape growing due to its temperate, cool meso-climate created by the presence of the Niagara escarpment [17]. The proximity of Lake Erie and Lake Ontario alleviates the harsh winter conditions [18], especially due to Lake Ontario prevailing winds [19]. During the growing season (April–October), the region averages 500 mm of rainfall [18], but due to its location, polar and tropical air masses bring constant changes to the weather conditions [20].

The annual average temperature in the Niagara region is 10.5 °C, with summers averaging 22 °C and winters reaching −2.3 °C [21]. Summers are warm; winters are cold, snowy, and windy; while springs and falls are characterized by cloudiness, rainfall, and cooler temperatures. July is the hottest month of the year, with temperatures reaching as high as 35 °C, while January marks the coldest month, with temperatures dropping to −15.6 °C on the coldest day. The region experiences an average of 194.3 frost-free days, which has increased by 7.4 days since 1976 [21]. Between 1976 and 2005, the average annual precipitation in the Niagara region was 876 mm [21,22].

3. Changes in Climate in the Niagara Region

The Niagara region is already experiencing the effects due to climate change, especially in average annual temperature, with an increase of almost 2 °C since 1976 [21,23]. Moreover, the region has averaged 157 wet days per year, encompassing both rain and snowfall. The Great Lakes region has witnessed an increase of nearly 10% in heavy precipitation events during this period [22].

Figure 1 provides a conceptual diagram illustrating the anticipated changes in temperature and precipitation across the seasons in the Niagara region. To create this conceptual diagram, data projections from the Prairie Climate Centre (PCC) in the highest greenhouse gas emission scenario (RCP 8.5) were used [21]. The PCC research shows yearly and seasonal projections for the Niagara Region until 2080. The projections include rainfall change, temperature change, precipitation, frost days, and extremely hot days, among other agricultural climate factors. In this paper, the projected changes will be divided into spring and fall, summer, and winter (Figure 1).

Current projections indicate that the average annual temperature in the Niagara region may rise to 11.4 °C by 2050 and 13.2 °C by 2080 [21]. By 2050, it is also anticipated that the region will experience an average of approximately 159 wet days [21]. These temperature increases will have implications, including changing in freeze–thaw cycles. As temperatures rise, the frequency of rain events is expected to increase due to moisture accumulation in the atmosphere, particularly influenced by the presence of Lakes Ontario and Erie [22]. Furthermore, greater variability in weather conditions is likely to result in an increased frequency of extreme events, such as thunderstorms, snowstorms, ice storms, high winds, and hailstorms [24,25]. Furthermore, the number of frost-free days is projected to increase significantly. By 2080, there could be an additional 42 days without frost, resulting in a frost-free season lasting for 231 days [21]. Cheng et al. suggest that by the end of the 21st century, the Niagara region may experience more wind gust events than at any other time in Canadian history, although this has not been confirmed in other studies [26].

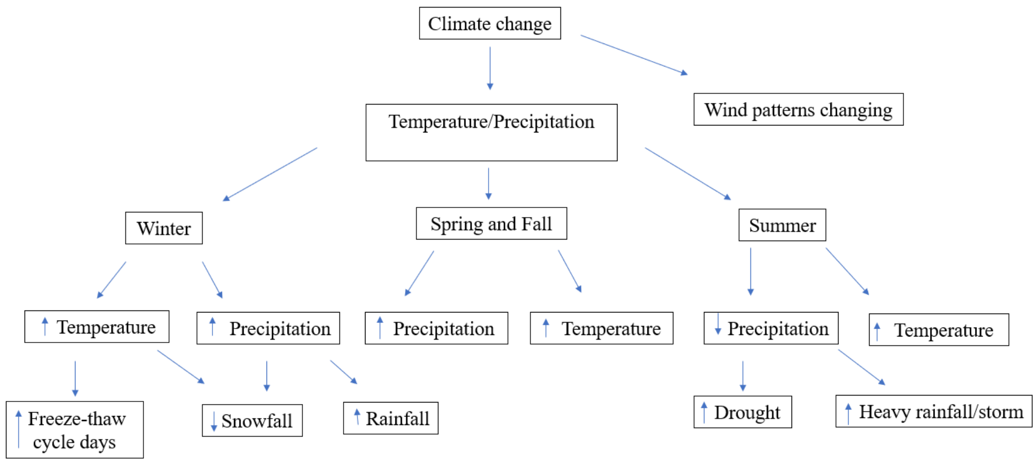

Figure 1. General conceptual model of the impacts of climate change in the weather in the Niagara region, Ontario, Canada. Each box presents the projected changes according to IPCC [1]. The arrows inside the boxes represent the trend expected for those factors if increases or decreases occur.

3.1. *Spring and Fall*

In the fall and spring seasons, mean temperatures are expected to increase by approximately 3.5 °C, with fall temperatures rising from 11.3 °C and spring temperatures from 7.3 °C by 2080 [21]. These projections coincide with anticipated changes in precipitation patterns. Specifically, there is expected to be an increase in precipitation during the spring, with levels rising from 232.4 mm to 253 mm by 2080 [21]. Similarly, fall precipitation is projected to increase from currently 228 mm to 235 mm by 2080 [21].

According to reports from the Intergovernmental Panel on Climate Change, a significant increase in the frequency (2.7 times greater than current conditions) of heavy rainfall events is expected for the Niagara region [1]. These events are expected to be particularly prominent during the winter and spring seasons. Additionally, changes in frost patterns are also predicted. The last spring frost, which historically took place on 20 April between 1976 and 2005, is projected to occur earlier, by 3 April by 2080 [21]. Conversely, the first fall frost, which previously arrived on 31 October, is expected to be delayed, occurring on around 23 November by 2080 [21,22].

3.2. *Summer*

Projections indicate a significant upward trend in summer temperatures for the Niagara region. Between 1976 and 2005, average summer temperatures stood at 20.8 °C, but by 2050–2080, they are expected to rise to 25.2 °C. This rise is accompanied by a remarkable increase in the number of days exceeding 30 °C, soaring from 15.5 to 62.9 days per summer [21].

The anticipated warmer weather conditions also bring about other changes such as potential wind gust events of over 30% [26]. Summers are likely to experience a decrease in precipitation ranging from 5% to 15% by 2100 [22]. These alterations in rainfall patterns can lead to the occurrence of extreme weather conditions, including flash floods during heavy rainfall events or wind funnels. Extreme agricultural droughts, currently occurring once every 10 years, are projected to increase in frequency [1].

3.3. *Winter*

In the coming years, the winter season in the Niagara region is projected to undergo significant changes. The average winter temperature is expected to rise by 4.6 °C, reaching a winter average of 2.3 °C by 2080 [21]. A decrease in the occurrence of extremely cold days is anticipated, with a decline from 7.3 to 0.3 days with temperatures less than −15 °C [21].

The warming trend during the winter can have significant implications for the Great Lakes region. As temperatures rise, ice cover on the lakes is expected to diminish [27]. This reduction in ice cover can lead to heat distribution over the lakes and increased moisture in the air, potentially resulting in greater precipitation in the form of either snow or rain, depending on the prevailing temperature [22]. Winter rainfall is likely to increase by approximately 18% (around 37 mm) by 2080 with a decrease in snow fall [25].

The combination of elevated precipitation and warmer temperatures may have implications for agriculture in the Niagara region [22]. One potentially beneficial change is the freeze–thaw cycles, which are anticipated to decline from 57 to 34.7 days by 2080 [21].

4. Connecting Climate Change to Niagara Vineyards: A Conceptual Model

The projected climatic changes can have a considerable impact on grape production and greater uncertainty regarding wine production and industry viability in the Niagara region. In this section, we examined how these changes may impact the following components and their interactions: soil, vines, invertebrates, and pathogens. To quantify the impact of grape production, the consequences in grape quality and quantity were observed. Figure 2 illustrates the interactions among these components as a simplified model. The following section makes connections between Niagara's projections (Figure 1) and the interacting components that could be the most impacted (Figure 2).

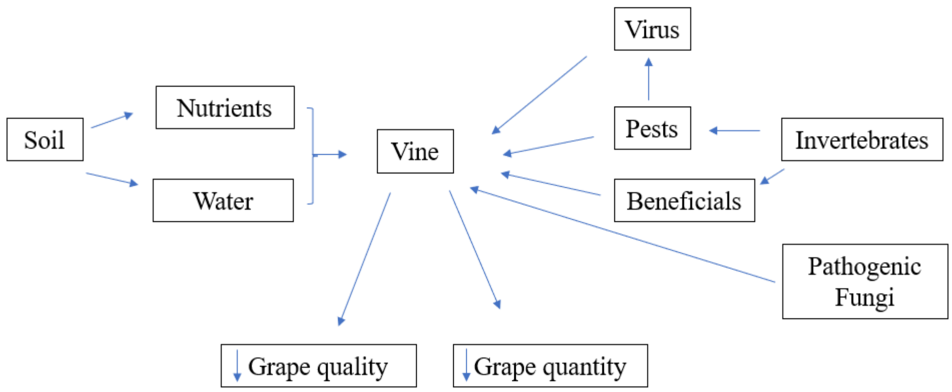

Figure 2. Simplified diagram of the most important interactions within a vineyard. The boxes represent the vineyard components and the arrows the direction of effects between them. Arrows found within the boxes indicate expected component increases or decreases. The component of the soil influences the growth and quality of the vines. The vines are also impacted by the invertebrates, which can provide a positive relationship when they are beneficial or negative when they are pests, virus vectors, or pathogenic fungi. The interaction within the vineyard will results in changes in grape quality and quantity.

4.1. Soil

Soil plays a vital role in vineyards, exerting a direct influence on production outcomes, and climate change can have profound consequences on nutrient cycling, water quantity and quality, and the diverse community of soil organisms [28,29]. Changes in rainfall patterns can significantly impact the growing season, as moisture plays a crucial role in the various stages of grape growth, including flowering and veraison. Water content in the soil has a significant influence on shoot growth, with soil high moisture levels stimulating vigor, leading to increased vine size and berry weight [30,31]. In the Niagara region, it has been observed that years with higher precipitation result in larger vines across all cultivars, indicating a positive correlation between soil water content, yield, and vine size [31]. However, extreme rainfall events and subsequent flooding can lead to soil moisture saturation, resulting in oxygen deprivation and hindered nutrient transport and absorption by plants [32,33]. Waterlogging in the spring or the summer can have adverse effects on photosynthesis, vine growth, and berry size. Kobaiashy et al. reported that constant water saturation of the soil may delay berry growth and veraison of Cabernet Sauvignon but may not necessarily impact berry quality [33]. However, it does lead to a decrease in the anthocyanin content in the berry skin, which is an important element in red wine production. On the other hand, drought conditions and limited soil moisture can impact soil structure, leading to erosion and affecting the microbiota [34]. These effects can have a negative impact on vine growth by hampering nutrient diffusion and absorption, especially in the case of potassium uptake by vines [34]. Studies have shown that soil with low water content induces plant stress, affecting vine physiology and impeding the photosynthetic process, as demonstrated in European vineyards [35].

During the summer, higher soil temperatures play a positive role in the nutrient uptake of grapes, specifically magnesium, nitrogen, calcium, and potassium during veraison [35,36]. This occurs due to heightened microbial activity, leading to the decomposition of soil organic matter, as well as the dehydration of clay minerals in the soil [36]. However, elevated summer temperatures greater than the seasonal average can also result in increased soil evapotranspiration, thus reducing water availability for plants and soil organisms l [29]. Areas with bare soil are particularly vulnerable to the impact of high temperatures compared to vegetated areas due to their higher albedo [29,37]. The ground vegetation blocks and decreases the amount of sunlight reaching the soil, slowing the ground temperature increase [29].

In the winter, in cold climate regions like the Niagara, ground vegetation acts as a protective layer for the soil, shielding it from extreme cold temperatures [38]. As higher temperatures are projected in Niagara, reduced snow cover during this season is accompanied by more frequent episodes of rain or freezing rain [22,25]. Bare soil may be exposed to temperature fluctuations and increased water saturation due to the reduction in snow cover [39].

In the face of climate variability and gradual changes in temperature and precipitation, soil fertility becomes a critical factor directly and indirectly influenced by water availability. The importance of studying the interactions among soil characteristics including microfauna and nutrient availability, temperature, and water is underscored by their significant impact on vine development [40].

4.2. Vines

Air temperature is a critical factor that significantly impacts the length of the growing season in vineyards, as well as the development and reproduction stages of grapevines. Numerous studies have highlighted the influence of temperature on phenophases, including bud break, flowering, veraison, and ripeness [41–43]. Additionally, dry atmospheric conditions during the maturation stage of grapes have been found to be particularly beneficial for wine production [41,44].

In the Niagara region, temperature increase is predicted to advance bud break by 45 days, flowering by 19 days, and veraison by 37 days in temperate areas. Fluctuating spring temperatures, however, may have the potential to impact bud break due to late frost and reduced cold hardness of grapevines [18,21,45].

Extreme cold snaps (which can occur all year around in Niagara) pose additional challenges for winegrowers as they can damage vines and reduce yield per vine [28,46]. Moreover, increased rainfall and humidity during the spring can lead to water stress, which stimulates excessive vine growth, resulting in a larger canopy leaf area and higher transpiration losses [29,47]. Water stress can also impact flower cluster formation, leading to a reduction in the number of flower clusters and lower berry quantity [41,45].

Low temperatures can also increase the probability of hailstorms [28,42]. This weather event can both break the vines due to the impact and strip the vines from fruits and leaves, decreasing yield per vine [46].

High temperatures and low precipitation in the summer predicted in Niagara can lead to heat stress in vines. Heat stress negatively affects photosynthesis by reducing water use efficiency due to stomatal closure [29,35]. High evaporative demand (dry, warm air) and soil water deficit cause plant tissues to undergo dehydration, resulting in metabolic decline, changes in leaf structure, and reduced production and berry quality [34,48–51].

Summer temperature fluctuations, including heat waves, can exacerbate water stress and adversely impact vine metabolism, development, and grape quality [52–55]. Heat stress during the veraison stage affects the synthesis of anthocyanins, leading to changes in grape color, and downregulates carbohydrate production, resulting in decreased sugar accumulation in grapes [56,57]. Colder years in the Niagara region have been observed to delay Cabernet Sauvignon veraison, reducing the growing season length and negatively affecting grape maturity [53].

Water availability is another crucial factor that significantly influences grape composition. Cool climate wine regions have experienced varying degrees of water stress over the past two decades, impacting berry weight, yield, and composition, thereby affecting wine quality and quantity [28,52,53]. Water deficit can result in smaller grapes, and the level of stress directly affects berry weight [58–60]. It also can, particularly during veraison, dilute the sugar content in grapes, reduce color intensity, and impact berry maturation [61], resulting in unbalanced and flat-tasting wine [50,62,63]. Projections of low summer precipitation levels may result in prolonged drought periods, causing yield loss, inhibiting leaf growth, and producing smaller shoots [10,61,64]. Drought conditions can also lead to photoinhibition in vine leaves [34,65].

Vine water status also influences berry composition, with a higher skin to pulp ratio leading to increased skin tannin and anthocyanin contents, which contribute to more flavorful and concentrated wines [10,66,67]. The excess of water can lead to reduced berry color and sugar content, affecting wine acidity [10,68].

Strong winds can pose a threat to grapevines, particularly during the flowering and fruit set stages, by breaking the vines and stripping them from flower and fruits, potentially resulting in decreased yields and lower-quality grapes [15].

Early fall frost can have consequences for carbohydrate production within the vine, making it more susceptible to impact from low temperatures in the subsequent winter season [67]. This vulnerability to low temperatures can have implications for the vine's overall health and resilience.

In Canada, the concern for grape growers lies in the occurrence of extreme low temperatures and winter frosts. While low temperatures can inflict harm on the vines, prolonged exposure to extreme cold can prove fatal [67]. This poses a significant challenge, especially in regions like the Niagara region, known for its production of ice wine. The rising temperatures and milder winters with warmer days can lead to delayed harvests. If the harvest extends beyond January or later, there is an increased risk of crop loss due to factors such as heavy winter winds and rot [19].

Conversely, warmer winters with fewer days of extreme low temperatures can reduce the risk of bud damage. Different grape varieties have varying thresholds for cold tolerance, with Chardonnay being susceptible to damage at around −24 °C and Riesling at around −25 °C [69].

The expected increase in rainfall during the winters in Niagara may impact the vine's winter hardiness. According to Jasinski et al., the Riesling vine's low water status may have an advantage regarding winter hardiness in Ontario, improving the ability of these plants to survive during the extreme low winter temperatures [70].

4.3. Invertebrates and Pathogens

Ontario's vineyards are confronted with significant challenges posed by 13 prominent insect pests that have reached pest status in the province. These pests include both native species such as *Paralobesia viteana* and *Pseudococcus maritimus* as well as invasive species like *Popillia japonica* [71]. They can cause extensive damage to various parts of the vine, including leaves, buds, small shoots, and berries, posing a serious threat to vineyard health and crop yield. The occurrence and severity of these pest infestations are influenced by multiple factors, with temperature playing a particularly crucial role. As temperature patterns continue to change, there is a high likelihood of new pests and vectors emerging in the region [71], such as spotted lanternfly (*Lycorma delicatula*).

The increase in temperature has the potential to significantly alter the global distribution of pests [72], possibly at a similar or even greater level than the anticipated changes in suitable areas for viticulture [6]. Simulations regarding the European grapevine moth (*Lobesia botrana*), for example, have revealed a projected northward shift of its distribution range by 11 degrees by 2055 [73]. Furthermore, depending on future climatic conditions, the distribution range of Mediterranean and tropical insect species is expected to expand into temperate regions [6]. With increased temperatures and longer growing seasons, the number of generations per year may increase.

Another example is the leafhopper species *Homalodisca coagulate*. This insect poses a significant and new threat to grape production both in North America and worldwide. Anas et al. reveal that rising temperatures during winter enable this leafhopper species, which serves as a vector for Pierce's disease, to survive in cooler climates, adapt to lower temperatures, and spread the bacterium across the United States [74]. The threat of this leafhopper species is not limited to North America but extends to South America, Africa, and Europe as well [6]. As a result, the implications of *Homalodisca coagulata* and its ability to transmit Pierce's disease may become a significant concern for grape production globally.

Alterations in grapevines' photosynthetic activity during spring and summer can lead to an increase in the plant's carbon/nitrogen ratio, resulting in reduced nutritional value for herbivorous organisms, prompting them to increase their feeding to meet their nutritional needs [6,75,76]. Additionally, the rise in environmental CO_2, a major contributor to climate change, can suppress the hormone jasmonic acid, responsible for plant defense, rendering plants more susceptible to insect damage [77].

Phenological shifts in grapevines and insects caused by temperature increase can disrupt the synchronicity between different trophic levels within the ecosystem, consequently influencing the effectiveness of biological control in vineyards [6]. For example, warmer fall conditions can decrease the activity of generalist predators, including spiders and earwigs, which are natural enemies of grape pest insects [6]. The reduced activity of these predators can disrupt their role in maintaining biological control in vineyards, resulting in an increase in the population of pest insects that they would typically prey upon, affecting yield [6].

As mentioned previously, the increase in spring precipitation can lead to water stress, which in turn can result in the formation of a denser canopy for vines. This denser canopy creates shaded areas on lower leaves, inflorescences, and grapes, contributing to the development of fungal diseases due to the continuous humidity and limited air movement within the canopy [47,61,78]. Warmer and wetter soils in the fall can contribute to higher risk of infestation by grape fungus Botrytis bunch rot (*Botrytis cinerea*) [39], which is responsible for one of the most devastating diseases in vineyards [79]. This pathogen affects the berry cluster, leaves, and shoots, impacting the vine integrity, yield, and quality of ice wine [80].

High humidity combined with low temperature can also contribute to increased outbreaks of powdery mildew (*Uncinula necator*) [67,79]. Carrol and Wilcox show a clear impact on grape leaves in all scenarios of precipitation increase during spring [81]. Higher humidity levels up to 85% are associated with higher incidence of fungus disease; thus, any alterations in the plant's microclimate can elevate the risk of pathogen infection [6]. Considering the expected increase in rainfall during spring and fall in the Niagara region, an increase in fungal disease outbreaks is expected during these seasons. On the other hand, the decrease in precipitation during summer may avoid the spread of fungal diseases [67].

Grapevines also serve as hosts for a diverse array of viruses, which reduce vine longevity, yield, and quality of berries. The most common virus-related diseases affecting vineyards are grapevine leafroll, grapevine fanleaf, and the most recently identified red blotch [79]. In red grape varieties, infections caused by the red-blotch-associated virus (GRBaV) lead to the emergence of red patches on the leaves, veins, and petioles. In white grape varieties, the virus manifests as irregular chlorotic areas on the leaf blades. The long-term effects are similar to grapevine leafroll disease, caused by the grapevine leafroll associated virus (GLRaV), with higher berry acidity, uneven ripening, and reduced sugar [79,82]. These viruses became a serious concern in Canada, including in the Niagara region. They can be found in many grapevine varieties in Ontario vineyards, such as Chardonnay and Cabernet franc [83,84].

A recent example of new diseases in the Niagara region is causing a decline in the vigor of Syrah vines with a consistent decrease in berry yield and quality each year, and some vines become unable to withstand the freezing temperatures during winter [85]. This phenomenon, known as Syrah decline, shows damage to the trunk as a primary symptom, particularly around the graft union, which includes swelling, cracks, grooves, and necrosis. Secondary symptoms include a uniform red discoloration of leaves and canopy, typically starting in late summer or early fall, and eventually leading to the death of the infected vine [85]. Even though Grapevine rupestris stem pitting-associated virus (GRSPaV) is a suspected influence, there is still not a defined single cause for this infection of concern [85].

5. Management Alternatives

According to van Leeuwen et al. (2019), as climate conditions shift, it is inevitable that grapes will undergo changes, potentially affecting wine production [42]. However, by implementing appropriate adaptations and management techniques within vineyards, these impacts can be minimized.

Cover cropping is one of the main agricultural techniques used in vineyards [86]. The most common studied benefit from cover crops is soil protection with improvement in soil carbon content and soil erosion control [87–89]. In addition to soil protection, there is a large diversity of ecosystem services delivered by cover crops in vineyards, such as weeds [90,91], increase in beneficial arthropod diversity, regulation of water availability, pest regulation, and soil biodiversity [92–94].

Irrigation is another management technique that can impact vineyards positively. Since soil water content affects vine growth, yield, and grape quality, the use of irrigation in scenarios of low precipitation and high temperatures will increase water in the agroecosystem [95]. Among different irrigation types, drip irrigation is generally considered the most efficient method for conserving water [43]. Drip irrigation systems deliver water directly to the root zone of the vines, minimizing water loss through evaporation or runoff. This targeted approach ensures that vines receive the necessary water while optimizing water usage and reducing waste [43].

Reynolds et al. (2007) demonstrate in a study in the Niagara region that the use of irrigation can increase vine transpiration, soil moisture, and leaf potential, resulting in higher berry weight and increase in yield and amount of berry cluster per vine [96]. During winter, water status may also influence cold injury on the vines [70].

Another management alternative is the use of different rootstocks as a method of mitigating soil-related issues such as texture, pH, density, pathogens, and replanting challenges under climate change [97]. Different rootstock varieties are chosen based on specific needs, such as addressing salinity [98,99], enhancing vigor [100], promoting nutrient uptake [101], and providing resistance to diseases and pests [102]. Furthermore, the choice of rootstock is influenced by the environmental conditions of the region in which the vineyard is established. Since these conditions significantly vary, there is no universal rootstock variety or clone that can be used as a one-size-fits-all solution [42].

According to Bucur and Dejeu, selecting rootstocks is crucial for ensuring resistance to drought and high temperatures [95]. These factors are particularly significant for late-ripening grape varieties, as their ripening process must be preserved without compromising quality. However, it is essential to take preventive measures to not increase the risk of viruses in the vineyards. For this, it is necessary to choose the rootstocks only after they are tested for propagation materials of virus [103].

In Ontario, where the winter is extreme cold and can cause injuries in the vineyard, strategies to target and avoid cold hardness are especially necessary. Wind machines, for example, work by modifying the temperature at ground level forcing air circulation. They pull the warmer air from above the field and mix it with the cold air that circulates the vine, helping to avoid winter injuries [104]. Other techniques, like pruning, can help the vines return to full health after winter injury [104].

Furthermore, the diversity of vine varieties also plays a significant role as an alternative for adapting to the challenges posed by climate change [95,105]. With the changing climatic conditions, having a wide range of vine varieties available provides flexibility and options for vineyards to respond effectively [95].

6. Conclusions

Changes in temperature, precipitation, wind patterns, and frequency of extreme events such as hailstorms, drought, and flood will continue affecting vineyard soil, invertebrates, grapevines, and berries. An overall increase in precipitation is anticipated for the Niagara region, except during the summer months, along with an increase in temperature. Therefore, the impacts on vineyard ecosystems could encompass soil erosion, an upsurge in pests and disease outbreaks, reduced yields, and compromised grape quality due to water stress and shifts in temperature.

Management techniques that can mitigate or adapt to the impacts of climate change in vineyards in temperate regions with specific microclimates, like the Niagara region, need to be tested. In this region where viticulture is economically and culturally important, research is needed to develop new management strategies to improve the sustainability of the industry in the face of climate change. Some management strategies are already being discussed and implemented, such as the introduction of more adaptive cover crops, use of irrigation, and introduction of new rootstocks. However, considering the interactions among the various components in the ecosystem, any modification of one element of the vineyard may have an impact on another component. A better understanding of the ecosystem as a complex entity, in addition to increased research focusing on techniques to be able to determine impacts on grape production on a local level, may help define long-term solutions and adaptation strategies.

Author Contributions: Conceptualization: L.V. and D.R.T.; investigation: D.R.T.; writing—review and editing: D.R.T., H.V. and L.V.; funding acquisition: L.V.; project administration: H.V. and L.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Organic Science Federation Cluster III supported by the AgriScience program under Agriculture and Agri-Food Canada's Canadian Agricultural Partnership, project number ASC-13.

Data Availability Statement: Not applicable.

Acknowledgments: We acknowledge the support of the two grape growers with whom we have been working with on this project.

Conflicts of Interest: The authors declare no conflict of interest.

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