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Carbon Footprint of Wines from the Finger Lakes Region in New York State

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Abstract: The goal of this study was to evaluate the cradle-to-gate greenhouse gas emissions of Finger Lakes wine using life cycle assessment. It was hypothesized that the carbon footprint of Finger Lakes wines would be lower than that of wines from other regions, based on winery practices and climate conditions. Primary data was collected from three wineries representing a range of production volumes, and sensitivity analyses were also performed. Bottle production contributed the most to the impacts of the wine. Impacts associated with cultivation were highest for the winery with the smallest production volume. The cradle-to-gate greenhouse gas emissions for the three case studies ranged from 0.617 to 1.03 kg CO_{2eq} bottle^{-1}. These results suggest that wines from these three Finger Lakes wineries have among the lowest carbon footprints of wines globally (which range from 0.68 to 2.68 kg CO_{2eq} bottle^{-1}), promoting the need to assess the impacts of other wineries in this wine region.

Keywords: life cycle assessment; carbon footprint; wine; Finger Lakes; New York State

1. Introduction

Life cycle assessment (LCA) as a research methodology to determine environmental impacts of consumer products has become increasingly frequent in the scientific community. This is due to the ever-growing interest of consumers and business-owners alike in the environmental impacts associated with the products they consume and produce. LCA allows for these individuals to determine the impacts of each step of the production process, and from the results, develop suggestions regarding which steps could be improved. A match in scope and the functional unit between LCA studies provides researchers and reviewers the benefit of directly comparing environmental impacts associated with products or processes that provide the same function.

One product that has increasingly received attention from LCA researchers is wine. The carbon footprints or life cycle greenhouse gas (GHG) emissions have been calculated and published for wines from multiple regions: Italy [1–4], Spain [5–7], Portugal [8], France [9], Luxembourg [10], Australia [11], New Zealand [12], and Canada [13]. Variations in scope are evident among these previous wine LCAs. Notably, two LCAs related to wine grapes produced in the United States do not include processes beyond the agricultural phase [14,15]. Furthermore, no LCAs have been published for wine produced in the Northeastern area of the United States, even though New York is the state with the third highest wine production nationally [16]. The Finger Lakes region in central New York State is home to over 100 wineries and boasts a robust tourism industry centered on the natural environment (e.g., Watkins Glen State Park) and the winemaking industry. Four of the eleven Finger Lakes (Canandaigua, Seneca, Cayuga, and Keuka) host their own wine trails. Seneca Lake has nearly 70 wineries, more than 30 of which are members of the Seneca Lake Wine Trail, representing the greatest number of any lake in the Finger Lakes region [17].

The Finger Lakes region presents a distinctive climatic setting for wine production. New York State has winters during which temperatures can reach below negative 17.8 degrees Celsius and summer temperatures that can often exceed 37.8 degrees Celsius [18]. Riesling production in particular has become common in the Finger Lakes wine region, as Riesling grapes prefer cooler growing conditions, having originated from the Rhine region in Germany [19]. The cold temperatures and snowfall in the winter may also reduce the energy needs for cooling during winemaking. Furthermore, the region also benefits from abundant rainfall during the growing seasons of economic crops as well as snowfall in the winter [18], which may contribute to a lower need for irrigation relative to wine regions in arid climates.

In addition to these climatic conditions, the production of Finger Lakes wines may also be currently benefiting from low carbon-emission electricity. It has been estimated that at least 15 percent of wineries in the Finger Lakes have invested in solar energy in the last several years, with the earliest in 2004, which started increasing with a cooperative effort by four of the larger wineries in 2015 [20]. These installations were part of the NY-Sun program by New York State to incentivize community and industry solar panel installation [21]. The NY-Sun program is part of the New York Reforming the Energy Vision initiative, designed to reduce the state's reliance on fossil-fuel-based heat and electricity, increase energy efficiency in systems throughout the state, and reduce greenhouse gas emissions [21]. The adoption of solar energy led to the Finger Lakes Wine Region being awarded the Solar Champion Award by the Solar Energy Industries Association in 2015 [22].

Given the unique conditions available for viticulture and viniculture in New York and the lack of previous LCAs on wines from the region, an LCA is needed to determine the carbon footprint of wines from the Finger Lakes using data from existing wineries. We hypothesize that the carbon footprint of Finger Lakes wines will be lower than that of wines from other regions due to the relatively lower need for irrigation and cooling and the use of renewable energy. This study provides the first carbon footprint analysis for wine produced in the Northeastern United States, and the Finger Lakes region of New York State in particular. Three wineries located on the east and west shores of Seneca Lake volunteered to provide data for this carbon footprint study of Finger Lakes wines. These three wineries represent different production scales and practices and were thus assessed as three separate LCA case studies.

2. Materials and Methods

2.1. Goal and Scope Definition

This goal of this study is to determine the cradle-to-gate greenhouse gas (GHG) emissions of an average 0.75 L bottle of wine produced in the Finger Lakes region of New York through three case studies representing data collected from three participating wineries located around Seneca Lake. The wineries range in annual wine production volumes and are thus referred to as the Small, Medium, and Large wineries to maintain anonymity. The results and recommendations of this study may be utilized by the wineries themselves in order to internally adjust the processes of the wine production life cycle in order to reduce their carbon footprint and for sustainable marketing for the companies. In addition, these results have the potential to encourage the provision of additional incentives for reducing GHG emissions in the New York State wine industry. The methodology outlined within this study can set a precedent for future studies that can include a greater number of wineries in the Finger Lakes area.

The scope of this study is cradle-to-gate, determining the environmental impacts of processes in the winemaking life cycle from grape cultivation and harvest through bottling the produced wine. This is consistent with previously published LCAs of wine (e.g., [7,8,23]), though some do include the distribution and end-of-life phases of the life cycle (cradle-to-grave) (e.g., [1,2,11]). Excluding the distribution phase in wine LCAs eliminates the need to assume distribution trends, as these are highly variable and dependent on the individual winery and individual consumers. Studies that choose to include the distribution phase either have winery- or industry-specific distribution data or must make assumptions. A cradle-to-grave scope also requires data or assumptions on end-of-life management. Furthermore, most steps after bottling are often beyond the control of a winery, and thus broadening the scope past bottling may not provide actionable information for a winery through LCA results. Subsequently, a large number of published wine LCAs chose a cradle-to-gate scope for their analyses instead of a cradle-to-grave scope, or provided results by life cycle process, which could in turn be aggregated to the same scope and be used in a cradle-to-gate comparison [1–3,5,7–9,11,13,23].

In an LCA, all results are scaled to a functional unit, which is a quantitative component that represents the function of the system or process being studied [24,25]. The functional unit for this study is also the most commonly chosen for wine-related LCAs: one 0.75 L bottle of wine [1–13,23,26]. Setting the same functional unit as this precedent allows for comparisons to be made between this study and the wine LCAs that have already been published.

2.2. Inventory Analysis and Impact Assessment

Data collection began with a site visit to each winery to discuss the life cycle of produced wines with contacts who are employed by and who supervise the wineries. A draft of the methods and numerical inputs was provided to these contacts in order to confirm that the models accurately represent conditions at each winery. For this LCA of Finger Lakes wines, most of the life cycle inventory (LCI) data was obtained from the Ecoinvent 3 and USLCI databases using SimaPro 8.2 software (Table A1). The GHG emissions of these LCIs were categorized using the Environmental Protection Agency Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (EPA TRACI) 2.0 life cycle impact assessment (LCIA) method and SimaPro 8.2 software. EPA TRACI is a midpoint LCIA method, which complies with the ISO Standards for LCA practice for describing environmental problems [24,25].

The values used for the life cycle GHG emissions of solar panel-generated electricity were obtained from harmonized LCA results by US National Renewable Energy Laboratory researchers [27]. Additionally, the values used for the life cycle GHG emissions of gelatin were obtained from an LCA in the scientific literature [28], due to the absence of a relevant inventory for gelatin in the databases of the SimaPro 8.2 software package. In the systems of equations developed to model the life cycle GHG emissions of wines from each winery in Python code, the impacts from database LCIs and these two sources for gelatin and solar panel-generated electricity were scaled to the functional unit using winery-specific data provided by each of the wineries. The systems of equations were designed to calculate the life cycle GHG emissions of an average wine from each of the three wineries by each life cycle process from grape cultivation through bottling and to allow for sensitivity analysis.

2.3. Interpretation

Baseline LCA results were analyzed by process and compared against the scientific literature on the carbon footprint of wines. In addition to baseline LCA scenarios, a sensitivity analysis was performed for each winery case study in order to identify the variable input parameters to which the impacts are most sensitive and to subsequently provide suggestions for improvements to each of the participating wineries. This was accomplished by changing one variable parameter at a time to its minimum and maximum value, while keeping all other parameters at their baseline values, thus isolating the effects of a change in a single parameter on the life cycle results.

Because the three case study wineries obtain all of their net electricity from on-site solar panels, ranging from 28- to 151-kW capacity, which may differ from other Finger Lakes wineries not investigated in this study, alternative baseline scenarios were investigated in which the wineries maintain the same practices but obtain all of their electricity needs from the grid. The emissions associated with the current electricity mix were obtained for the area using the Power Profiler tool developed by the United States

Environmental Protection Agency [29]. The baseline values for grid electricity impacts were based on the baseline electricity consumption values provided by the three case study wineries and the carbon emissions per energy unit reported for the region by the Power Profiler tool.

2.4. Assumptions and Limitations

The impacts associated with vine planting were not modeled in this LCA. It was assumed that these GHG emissions scaled to one bottle of wine would be minimal due to the long lifetime of the vines. For example, one LCA notes a lifespan of 30 to 70 years for each vine [5]. Vine planting (which is different from cultivation practices that are performed every year) is frequently excluded in wine LCAs; greenhouse gas emissions specifically allocated to vine planting were only calculated in four studies among all published wine LCAs [2,8,10,23].

The amount of carbon dioxide emitted as a result of fermentation and the amount of carbon dioxide fixed into the biomass of vines and fruit during photosynthesis prior to harvest are excluded from this LCA, as it was assumed that these two quantities would be equivalent [23]. A precedent for this assumption has been set in several wine LCAs [1,3–5,7,10,11,23,30]. The carbon dioxide emissions and storage in the plants remaining on the land after harvest and in the soils are not quantified in this LCA. Prior LCAs have also omitted this potential carbon storage due to lack of data available at this scale [2].

There was limited database information available for the highly specific pesticide, fungicide, and fertilizer data provided by the contacts at the three collaborating wineries. Therefore, proxy data for pesticides and fungicides were selected where the level of detail from the wineries was higher than could be achieved with the databases available. For fertilizers, pesticides, and fungicides, the impacts were calculated based on the production of these compounds, and the impacts associated with application (i.e., via sprayers) were not included due to data limitations.

Other wine LCAs either modeled a proxy compound, modeled only the transportation of the compounds [8,10,13], or omitted the impacts of these compounds in cases where life cycle inventory data availability was inadequate [2–5,7,11,23]. For example, Barry (2011) used Captan as a proxy to represent all fungicides and insecticides used and glycosophate to represent all herbicides used [12]. Similarly, the impacts of yeast are often excluded from LCAs of wine [3–5,7,11,13,23] or only their transportation was modeled [8,10]. However, for the purposes of this study, the value for fodder yeast (which produces ethanol) found in the Ecoinvent 3 database was used as a proxy inventory impact for yeast used during fermentation.

In addition, the impacts associated with the cork, cap, label, and other associated packaging in the bottling phase of the life cycle are excluded from the scope of this study. This is based on a precedent set by several other studies as it has been determined that the impacts from bottling originate primarily from the production of the glass bottles [26]. The impacts of producing the glass bottle are included in the three case studies.

The impacts associated with the production of infrastructure (such as winery buildings) and machinery (such as the mechanical harvesters, tractors, and winemaking machines) were considered outside of the scope based on the lifespan of these technologies. This is similar to the boundaries set by several wine LCA studies, as this infrastructure was only included in two previous studies [7,23]. Still, the impacts of operating these items were included; only the production of their materials and infrastructure were excluded.

The impacts related to the operation of specific on-site machinery associated with viticulture were not collected from each winery. Therefore, the assumed diesel consumption for a mechanical harvester of 30 L per hectare per growing season was modeled as part of the cultivation stage based on the LCA of New Zealand wine by Barry (2011) [12]. This diesel consumption does not include the fuel consumption of any other on-site cultivation machinery (i.e., sprayers, tractors). Because this value reflects the diesel consumption for a mechanical harvester, it is only included in the calculations which do not harvest by hand (the Medium and Large wineries).

Though 80 percent of grapes are cultivated on-site for the Small winery, all viticulture information is modeled based on the cultivation methods utilized by the Small winery. Therefore, the other 20 percent of grapes imported to the Small winery are assumed to have been cultivated using the same methods, as they are from neighboring farms and growers. While it was not taken into account for the purposes of the assessment, the transportation of the grapes from the local vineyards would also contribute to the life cycle impact of the harvest. For the Medium and Large wineries, 100 percent of the production volume is based on grapes grown on-site.

The impacts associated with water use by the winemaking facilities were excluded from the analysis. This includes any water used for irrigation, cleaning, and inputs into the tanks during winemaking. These values were excluded due to the lack of data collected from the wineries and because these wineries do not frequently irrigate. This is consistent with other LCA studies which also exclude water as an input into the system at any point in the life cycle [4,5]. The impacts of tap water included in the analysis for the Medium winery were solely used in the impact calculations for the fertilizer compounds requiring water inputs for application.

In that only wineries that elected to participate in the study were considered, there could be self-selection bias. For example, there is the chance the wineries that believed they followed sustainable practices participated while those who did not believe this opted out, thus skewing the results away from representing the entire region. One example of the potential differences between the three wineries in this study and the entire Finger Lakes winemaking region is the use of solar panels for electricity. Each of the three participating wineries produces more than enough net electricity from their solar array to maintain their winemaking facilities and tasting rooms, with excess electricity being fed back into the grid. Future studies including a larger number of wineries from the Finger Lakes could alleviate this potential bias and provide results that more comprehensively represent the region as a whole.

Although the information for this LCA originates from a small fraction of the wineries in the region, the wide variation in production volumes (from 21,000 to 775,000 bottles annually) and techniques utilized may approximate general practices in the Finger Lakes winemaking region. However, each vineyard and winery approaches grape growing and winemaking differently, especially in terms of crop management and wine additives, and so the LCA results will not generalize to all of the wineries in the Finger Lakes. This analysis thus presents results by winery before discussing the potential applicability across the region and comparison to the carbon footprint of other wines produced globally.

2.5. Study-Specific Methodology

The three wineries agreed to participate based on a condition of anonymity, and therefore they will be referred to as Small, Medium, and Large for the remainder of this study. Each winery has different methods for producing their wine, particularly in terms of the additives used, the amount and types of fertilizers, pesticides, and fungicides applied to the grape crop, and the volume of wine produced each year. Therefore, in order to provide context for the case studies and their calculated GHG emissions, a detailed winemaking process is described for each of the wineries. Data was obtained on-site in March 2018, and further email correspondence to finalize data collection and to confirm the modeled values and processes continued through June 2018. The winery contacts confirmed the methods prior to obtaining results from the authors. The calculated impacts are intended to represent average conditions and production volumes, understanding that these impacts could vary significantly depending on the harvest year [7].

2.5.1. Small Winery

The Small winery is the smallest of the three vineyards and wineries assessed in this study by production volume. It is located on the east shore of Seneca Lake. This vineyard produces approximately 6.73 Mg/ha of grapes every year, resulting in an annual production between 2200 and 3000 cases of wine (an average of about 21,000 bottles, as each case contains 12 bottles). This range was estimated given the average yield of the vineyard and the area of vineyard cultivated, as well as the mass of grapes required to make a single bottle of wine. The same methodology was used to model the annual number of bottles produced from the area cultivated, mass harvested, and mass of grapes per bottle for each winery.

Eighty percent of the grapes used for wine production are grown on-site, with the other 20% brought in from three other local vineyards. At the Small winery, the lifetime of the vines is approximately 30 years, and 100 to 200 vines require replanting each year, either due to age or winter damage. Dry periods during critical growth stages have previously led to 0.81 ha of this vineyard requiring minimal irrigation. The water used for irrigation is sourced from a spring-fed well connected to a gravity-fed collection tank. A small pump is used in order to direct the flow of water across the 0.81 ha. Water for irrigation goes through a mesh screen to filter out solids before being spread on the vineyard. As irrigation is only utilized during years of extreme drought, this does not represent the average year of production for the Small winery, and therefore this water treatment and provision falls outside the scope of this study.

The entirety of the electricity used by the winery and accompanying tasting room is provided by the 28 kW solar array on site. Excess electricity generated by the array is fed back to the grid, and no natural gas is utilized on-site. The amount of electricity used by the Small winery was used in modeling the impacts of electricity generation; the grid electricity displacement from excess production was omitted from the analysis. Due to limitations in machine-specific data within the winery, the impacts of electricity usage across multiple processes are derived from the total electricity usage of the facility and scaled based on the number of bottles produced on an annual basis. Thus, the impacts of electricity use are not assigned to individual processes, but are instead only included in a separate process for electricity provision (Figure 1). The impacts associated with the other processes do not include energy use. However, they still include the GHG emissions originating from the production and transportation of inputs such as fertilizers, fungicides, pesticides, gases, yeast, and glass bottles. The same separation of energy use impacts applies to all three winery case studies.

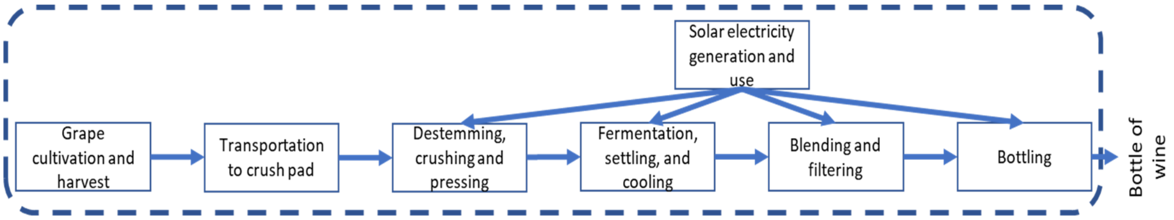

Figure 1. System diagram of cradle-to-gate processes modeled for the Small and Medium wineries.

Approximately 80% of wines produced at the Small winery are white wines, with over 50 percent of production exclusively comprised of Riesling. This study explores the general life cycle of wines produced at this location and therefore, with this ratio of white wine to red wine production, the aging process mainly associated with red wines is not considered. The full production volume of wine was modeled using only the white wine processes (Figure 1).

The modeling of the cultivation step for the grapes produced on-site includes the amount and frequency of fertilizer, pesticide, and fungicide application. The pesticide used is the biologic DiPel, which is targeted to combat grape berry moth infestations and is applied two to three times over the course of the growing season (Valent BioSciences, LLC., Dublin, CA, USA). A wide variety of fungicides are used by the Small winery, in order to combat powdery mildew, downy mildew, *Botrytis cinerea*, black rot, and *Phomopsis*. These are each applied at varying rates that depend on the labeled rates of the targeted compound, as well as the amount of rainfall over the course of the growing season (May to September). During years of heavy precipitation, the fungicides are applied as frequently as every 10 days, while during drier seasons, they are applied more infrequently (every 21 days). This results in a range of applications from four to nine times per year, based on rainfall. The average of the minimum and maximum was chosen as the baseline value for the number of fungicide applications per year.

The fertilizers used by the winery include Timothy hay provided from a neighboring farmer (less than 2 km away) and composted pomace accumulated during crushing and destemming of cultivated grapes. The Timothy hay also provides a mulching benefit for the crop, although the carbon emissions associated with its decomposition in the field are not included in the model. Only the greenhouse gas emissions associated with its production are considered. Due to the wide variety of compounds used as fungicides, many of which are bacteria-based biological controls, and the use of DiPel biological control as a pesticide, this study utilized the life cycle inventory in the Ecoinvent 3 database for unspecified pesticides to calculate the impacts associated with the production of both fungicides and pesticides used at the Small winery. Further iterations of this study could use more specific inventory data if it becomes available in the future.

After cultivation, the grapes are harvested by hand, with the assistance of a small tractor for collection. The tractor utilizes a biodiesel blend called B20 Diesel. Due to limitations in database information regarding this particular blend of diesel fuel, this was not specifically modeled for this study, though future studies could model the use of different biodiesel blends. This tractor brings the grapes to the crush pad, where the grapes, skins, and stems are crushed before being pressed. Pressings are transported to a compost container on-site, and the composted material is used as fertilizer during the following growing season. The juice is fermented in 3785-L (1000-gallon) stainless steel tanks through the addition of yeast, enzymes, sulfites, and diammonium phosphate compounds to assist with the production of alcohol within the juice. The masses of these additives were obtained directly from the Small winery (Table 1). No additional sugar was added in the winemaking process. Following fermentation, the yeast and other solids are settled out of the wine liquid, and these lees are collected, composted on-site, and spread on the vineyard as additional fertilizer.

Table 1. Variable parameter values modeled for stages in the life cycle of a bottle of wine at the Small winery.

Variable Parameter	Minimum	Baseline	Maximum	Units
Mass of fungicide	2.699	3.175	3.651	kg year^{-1}
Mass of pesticide	1.361	4.309	7.257	kg year^{-1}
Number of fungicide applications	4	6.5	9	unitless
Number of pesticide applications	2	2.5	3	unitless
Mass of hay	21,591	25,401	29,211	kg year^{-1}
Area of vineyard	2.43	2.83	3.24	ha
Mass of harvest	5716	6725	7734	kg ha^{-1} year^{-1}
Mass of grape per bottle	0.964	1.134	1.304	kg bottle^{-1}
Distance to crush pad	0.155	0.183	0.210	km
Distance to compost bin	0.233	0.274	0.316	km
Fraction of pomace	0.0255	0.0300	0.0345	unitless
Mass of propylene glycol	62.12	73.08	84.04	kg year^{-1}
Mass of yeast	4.356	5.125	5.894	kg year^{-1}
Mass of Argon gas	89.87	105.73	121.59	kg year^{-1}
Number of filters	233.75	275.00	316.25	filters year^{-1}
Mass of empty bottle	0.440	0.445	0.450	kg bottle^{-1}
Distance to bottling facility	2.05	2.41	2.78	km
Distance transportation of bottle	45.35	47.91	50.48	km
Electricity usage by winery	22,193	26,109	28,233	kWh year^{-1}
Impact of electricity from solar panels	0.026	0.045	0.183	kg CO_{2eq} kWh^{-1}
Impact of electricity from grid (NY)	0.148	0.174	0.200	kg CO_{2eq} kWh^{-1}

In order to stabilize and further settle out solids within the wine, approximately 75.7 L of propylene glycol are pumped through an on-site chiller to quickly cool down the wine (Table 1). This propylene glycol is also the primary means for temperature control over the course of the life cycle of the wine and is first used to remove heat produced by the yeast during fermentation. In order to keep fermentation tanks warm following harvests that occur late in the season, electric heat belts are placed around the tanks, which allow for easy temperature control. Once the wines have been completed, they are blended together to produce the preferred flavors. The wine is then pumped through a plate-and-frame filtering machine, utilizing cellulose pads with decreasing pore size. About 275 filter pads are used by the Small winery each year (Table 1). Each batch of wine is filtered twice before being pumped into small tanks, which are then transported by truck to an off-site bottling facility in small batches. These tanks are transported by pickup truck to the bottling facility.

In previous years, the bottling facility was located approximately 2.41 km away from the Small winery (Table 1). The bottles utilized by this facility are from the "eco-glass" lines of products supplied by a company based in Waterloo, New York. This line is designed to be slightly lighter than conventional glass bottles. Approximately 26 canisters (approximately 2.41 m^3 each) of argon are used as an inert gas to displace air within the bottle in order to preserve the taste and quality of the wine (Table 1). The bottling phase includes the application of the label, which for the purposes of this study has been assumed to be negligible over the life cycle of the wine, as has the production of the cork. Once bottling has been completed, the bottles are packaged, and 30 percent are transported to Clay, New York for storage before distribution. The rest of the wines are either distributed locally or through the tasting room on-site. The distribution of wines is outside the defined cradle-to-gate scope of this study.

2.5.2. Medium Winery

The Medium winery is a medium-sized vineyard and winery on the west shore of Seneca Lake. This vineyard produces 4.48 to 11.2 Mg/ha of grapes every year, resulting in an annual production between 68,000 and 190,000 bottles of wine (approximately 5600 to 15,800 cases of 12 bottles). Considering that the assumed lifetime of the vines at the Medium winery is 15 to 20 years, replanting is not considered for the purposes of this analysis, though it should be noted that around three to four percent of vines need to be replanted each year due to losses from winter damage and age.

Due to its location, there is no irrigation requirement for the vineyard during the growing season, which falls between May (bud break) and November (when senescence occurs in the leaves). This means that the water required for maintaining the health of the grapevines is regularly provided by rainfall. During years with less precipitation, the reduced water availability presents a challenge to vine growth and health, often leading to smaller harvests. Despite this, additional irrigation would not be reasonable to undertake at the Medium winery due to the infrequency of drought-stress years (once every four to five years). Additionally, due to the slope of the land on which the vineyard is located, necessary drainage is minimal. There is a rudimentary drain tile system installed, though there remain some vineyard blocks where water is held in the soils in periods of high precipitation, due mainly to the heterogeneity of the soil in the region. The impact of this drainage system is assumed to be negligible over the course of the wine life cycle.

The operations of the winery and the adjacent tasting room are facilitated entirely through the electricity generated by the 151 kW solar array on-site. Due to limitations in machine-specific data within the winery, the impacts of electricity usage for the life cycle of a bottle of wine is represented by the electricity used by the winery as a whole and is scaled to the functional unit based on the number of bottles produced on an annual basis.

Overall, approximately 65 to 70 percent of the wine produced at the Medium winery is white wine, which is more commonly produced than red wines in colder climates like the Finger Lakes. The differences in impacts between the two types of wine are assumed to come mainly from the impacts of the barrel in which aging occurs. The other differences are primarily in order of processes (i.e., red wine grapes ferment with the skins before being pressed, while white wine grapes are pressed before fermentation). For the purposes of this study, therefore, it is assumed that the full production volume is appropriately represented by the white wine processes (Figure 1).

The modeling of the cultivation step for the wine grapes includes the amount and frequency of fertilizer, pesticide, and fungicide application. For this winery, these compounds are applied according to the labeled recommended rate for each, and not exceeding the maximum recommended application. For each compound used by the Medium winery, the application rates were obtained from the specifications available on the companies' websites (Loveland Products, Inc., Loveland, CO, USA; Valent BioSciences, LLC., Dublin, CA, USA; Syngenta International AG, Basel, Switzerland; and Arysta LifeScience Corporation, Cary, NC, USA). For a majority of the compounds used, the labeled rates were described as a range of values, and thus this range provided the maximum and minimum values modeled for each of the application rates (Table 2). The baseline values for those compounds were assumed to be the average of the maximum and minimum values. For those compounds that only provided a baseline application, a range of plus or minus 15 percent was assumed, unless a maximum seasonal application was provided, which also determined the number of applications if present. The compounds with maximum seasonal application rates are Sniper (0.468 L/ha), Danitol (0.673 kg ai./ha), Captan (16.8 kg/ha), and Roper (26.9 kg/ha).

Table 2. Application rates of compounds associated with grape growing at the Medium winery.

Compound	Compound Type	Minimum	Baseline	Maximum	Units
Sniper (Loveland Products, Inc., Loveland, CO, USA)	Pesticide	0.22	0.35	0.44	kg ha^{-1}
Danitol (Valent BioSciences, LLC., Dublin, CA, USA)	Pesticide	0.12	0.17	0.25	kg ha^{-1}
Captan (Arysta LifeScience Corp., Cary, NC, USA)	Fungicide	2.37	2.79	3.21	kg ha^{-1}
Revus Top (Syngenta International AG, Basel, Switzerland)	Fungicide	0.12	0.15	0.17	kg ha^{-1}
Rampart (Loveland Products, Inc., Loveland, CO, USA)	Fungicide	3.39	6.77	10.18	kg ha^{-1}
Roper (Loveland Products, Inc., Loveland, CO, USA)	Fungicide	1.68	3.09	4.47	kg ha^{-1}

At the Medium winery, the Captan fungicide is applied approximately eight times per year, which was then assumed to be the number of applications for any compound without a maximum seasonal application rate. In calculating the inventory impacts of the fertilizers used by the Medium winery (Table 3), the individual chemical components for each compound were identified from the Material Safety Data Sheet (MSDS) and label. Each fertilizer's composition is presented as a range of percentages for the ingredients. Borosol is comprised of 45 to 60 percent boric acid, 15 to 30 percent monoethanolamine, and 15 to 25 percent water, while Lokomotive is 40 to 70 percent water, four to six percent urea, and six to eight percent potassium acetate ("Loveland Products|Get Growing," 2018). The GHG emissions of these composites were calculated based on these ranges of percentages, as well as the LCI values for these compounds (Table 3). For example, the maximum inventory value for the impact of Borosol is based on a composition of 30 percent monoethanolamine, 15 percent water, and 55 percent boric acid. The composition for potassium acetate in Lokomotive was determined from a study which reports that potassium acetate is derived from 50 percent potassium hydroxide and 50 percent acetic acid [31].

After cultivation, the grapes are harvested by machine and transported 0.161 to 0.402 km into the winemaking facility, where they are crushed, destemmed, and pressed (Table 3). The waste stems, skins, and seeds (also known as pomace), which account for 10 to 12 percent of the mass of grapes harvested, are then transported 0.20 km by truck to a nearby field (Table 3), where they are spread on the ground and subsequently decompose. The separated juice is then pumped into several sizes of stainless-steel tanks to ferment.

The juice is fermented for a short time after the addition of yeast. Once the juice has reached the desired sugar content, white wines are either fermented to dryness or rapidly cooled. Those white wine styles which are fermented to complete dryness do not require cooling, as the yeast has no substrate on which to survive and therefore stops production. Cooling is required for the styles which contain residual sugars as the sudden drop in temperature halts further fermentation. Once fermentation is completed, the dead yeast and other solids, known collectively as the gross lees, settle out. The cloudy wine is then racked (separated) from the gross lees into new tanks, and the lees are discarded. Following the racking of gross lees, the wine is fined with bentonite and seeded with cream of tartar (at the rates in Table 3), in order to further settle out solids and to prevent the creation of crystals in finished wines. Each batch of wine is cooled in large stainless-steel tanks in order to stabilize.

Table 3. Variable parameter values modeled for the life cycle assessment (LCA) case study of a bottle of wine from the Medium winery.

Variable Parameter	Minimum	Baseline	Maximum	Units
Number of pesticide applications	1	2	2	unitless
Number of fertilizer applications	6	7	8	unitless
Number of fungicide applications	2	5	8	unitless
Mass of pesticide	0.346	0.519	0.692	kg ha^{-1}
Mass of fungicide	7.59	12.82	18.06	kg ha^{-1}
Application rate of Borosol	4.67	8.18	11.69	L ha^{-1}
Application rate of Lokomotive	4.67	11.69	18.71	L ha^{-1}
Calculated impact of Lokomotive	0.908	1.089	1.264	kg CO_{2eq} kg^{-1}
Calculated impact of Borosol	0.260	0.314	0.369	kg CO_{2eq} kg^{-1}
Area of vineyard	18.2	19.2	20.2	ha
Mass of harvest	4483	7846	11,208	kg ha^{-1} $year^{-1}$
Mass of grape per bottle	0.91	1.20	1.36	kg $bottle^{-1}$
Distance to crush pad	0.16	0.28	0.40	km
Distance to field	0.18	0.20	0.23	km
Fraction of pomace	0.10	0.11	0.12	unitless
Mass of bentonite	38.56	45.36	52.16	kg $year^{-1}$
Mass of propylene glycol	88.4	104.0	119.6	kg $year^{-1}$
Mass of sugar	3856	4536	5216	kg $year^{-1}$
Mass of yeast	0.00016	0.00019	0.00022	kg $bottle^{-1}$
Mass of nitrogen gas	908	1044	1200	kg $year^{-1}$
Mass of CO_2 gas	1346	1514	1682	kg $year^{-1}$
Number of filters	1700	2000	2300	filters $year^{-1}$
Mass of empty bottle	0.49	0.50	0.51	kg $bottle^{-1}$
Distance to transport empty bottle	337	1320	4200	km
Electricity usage by winery	133,950	141,000	148,050	kWh $year^{-1}$
Impact of electricity from solar	0.026	0.045	0.183	kg CO_{2eq} kWh^{-1}
Impact of electricity from grid (NY)	0.148	0.174	0.200	kg CO_{2eq} kWh^{-1}

In the years during which winter temperatures are sufficiently low, wine is pumped to several tanks located outside in order to complete stabilization, thus reducing the overall electricity demand of the winery. When the temperatures are not appropriate for stabilization outdoors, and for wines that are prepared exclusively indoors, between 85 and 115 L of propylene glycol (Table 3) is pumped around the surface of the tanks for several days, after which the waste solids (including potassium bitartrate, the product resulting from the addition of cream of tartar) settle out, remaining in the tanks when the liquid is pumped to new tanks. This same propylene glycol is also used earlier in the life cycle for refrigeration, in order to clarify the wine and to prevent the reproduction of microbes that naturally occurs on grapes, as well as to halt fermentation in wines with residual sugars. The pumps operate on a closed loop, so the volume of propylene glycol remains constant throughout the life cycle of the winery. The settled waste is disposed of into the winery's septic system, though some of the waste yeast is used in the personal compost of the winemaker.

Once the wines have been completed, they can be blended together to produce the preferred styles. Rarely, sugar is added during this step to assist in the balancing of flavor, though this is not the case for all styles. A minimum of 100 (8.5 m^3 at standard temperature and pressure) canisters of nitrogen gas per year are introduced into the tanks during this step to roll and mix the wine (Table 3). Further filtering is then accomplished using a plate-and-frame filtering machine, and each of the three filtering phases increases in granularity in order to remove any remaining solids, resulting in a clear wine ready for bottling. Over the course of a single production year, about 2000 filter sheets are used, totaling approximately 0.008 filter sheets per bottle (Table 3). The Medium winery utilizes BECO Steril

40 filter sheets, which amount to approximately 0.215 kg of cellulose fiber per sheet ("BECO® Standard Range," 2018).

The bottling is also performed on-site with glass bottles with an average mass of 500 g shipped in from Mexico, Pennsylvania, Illinois, and Europe. For the purposes of this study, the distance that bottles are transported were limited to those produced in North America, as 85 to 90 percent of bottles used by the Medium winery are from facilities in North America, and therefore these distances are more representative of an average bottle of wine produced by the Medium winery. Bottling occurs approximately 40 to 50 days over the course of the year. Between 80 and 100 (8.5 m^3) canisters of carbon dioxide per production year are used as an inert gas to displace the air within the bottle and to keep air from being introduced as the wine travels between the tanks during the blending stage (Table 3). The bottling phase includes the application of the label, which for the purpose of this study has been assumed to comprise a negligible impact over the life cycle of the wine, as has the production of the cork. Once bottling has been completed, the bottles are packaged and either sold through the tasting room or distributed elsewhere. The distribution of wines is outside the defined cradle-to-gate scope of this study.

2.5.3. Large Winery

The Large winery is a vineyard and winery with a relatively high production volume on the east shore of Seneca Lake. This vineyard produces 6.73 to 17.9 Mg/ha of grapes annually, depending on the variety, resulting in an annual production between 291,000 and 775,000 bottles of wine. This vineyard experiences an approximate loss of 8% of vines each year due to winter damage, but annual replanting requirements are not included in the overall carbon footprint.

Due to its location and the slope of the vineyard land, there is no irrigation requirement for the Large winery during the growing season (May to October). Indeed, removing excess water is a more pressing need. To accomplish this, the Large winery utilizes a pattern tiling drainage system with approximately 750 m of 15.2 cm corrugated run tile per hectare. The associated GHG emissions of these tiles are included in the grape cultivation phase of the wine life cycle.

The operations of the winery and the on-site tasting room are facilitated entirely through the electricity generated by the facility's 93 kW solar array, with the exception of the heating required for wine storage as well as the fuel for on-site vehicles, which are provided by two propane tanks. Excess electricity generated by the solar panels that is not used by the winery is fed back into the grid. The same method was also utilized to calculate the impacts from electricity for the other two case studies.

The wine production at the Large winery is 70% white (primarily Riesling and Chardonnay), and therefore this study focuses on the general production steps associated with white wine as representative of the winery's total production (Figure 2).

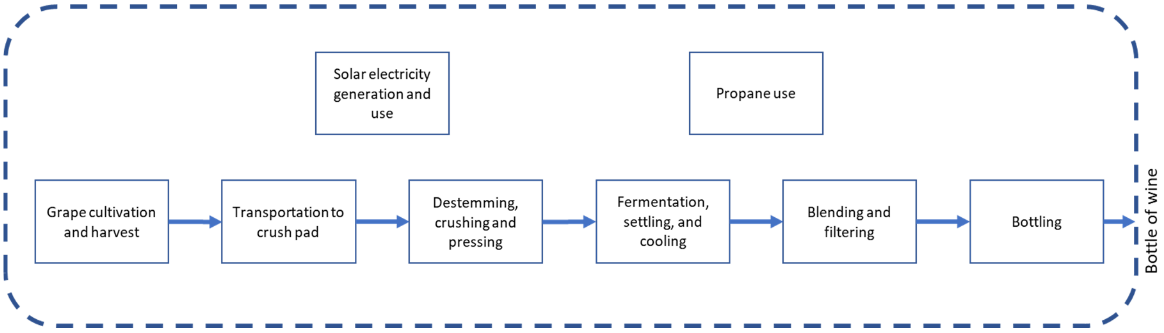

Figure 2. System diagram of cradle-to-gate processes modeled for the Large winery.

For those variable parameters for which only baseline values were provided, minimum and maximum values were assumed to be plus or minus 15% of the baseline value. For those variables for which a range was given, the baseline value was assumed to be the average of the two values (Table 4). The modeled ranges were then verified by the winery contact.

Table 4. Variable parameter values modeled for stages in the life cycle of a bottle of wine at the Large winery.

Variable Parameter	Minimum	Baseline	Maximum	Units
Mass of sulfur (fungicide)	1166	1372	1578	kg year^{-1}
Mass of hay	129,546	152,407	175,269	kg year^{-1}
Area of vineyard	41.3	48.6	49.0	ha
Lifetime of pattern tile	50	75	100	years
Mass of harvest	6725	12,329	17,934	kg ha^{-1} year^{-1}
Mass of grape per bottle	0.9550	1.1235	1.2920	kg bottle^{-1}
Distance to crush pad	1.163	1.368	1.573	km
Distance to compost bin	0.181	0.213	0.245	km
Fraction of pomace	0.1751	0.2060	0.2369	unitless
Mass of yeast	11.57	13.61	15.65	kg year^{-1}
Mass of gelatin	0.000064	0.000075	0.000086	kg bottle^{-1}
Number of filters	47.6	56	64.4	filters year^{-1}
Mass of empty bottle	0.425	0.445	0.475	kg bottle^{-1}
Distance to transport empty bottle	41.04	41.68	45.38	km
Mass of propane	24,463	28,780	33,097	kg year^{-1}
Electricity usage by winery	110,466	129,960	149,454	kWh year^{-1}
Impact of electricity from solar panels	0.026	0.045	0.183	kg CO_{2eq} kWh^{-1}
Impact of electricity from grid (NY)	0.1480	0.1741	0.2002	kg CO_{2eq} kWh^{-1}

The modeling of the cultivation step for the wine grapes includes the amount and frequency of fertilizer, pesticide, and fungicide application. The fertilizers used at this winery include Timothy hay, which is applied at an amount of 3.14 Mg/ha on a case-by-case basis to account for nitrogen deficiencies in the soil, as well as compost produced on-site. The Large winery utilizes a sulfur spray as a fungicidal treatment ten times per growing season (approximately once every 14 days) (Table 4). As for pesticides, there are no preventative sprays or compounds introduced for the entirety of the crop, as outbreaks are handled on a case-by-case basis (and often solely vine-by-vine).

Once the grapes reach optimal ripeness, they are harvested from the vine. Ninety-five percent of harvesting is done by machine, and the other five percent is performed by hand. These grapes are brought to the crush pad and presses where approximately 17.5 to 24 percent of the harvested mass is removed in the stems and skins (Table 4). The waste skins and stems (as well as other lees produced through the winemaking life cycle) are then transported by forklift to a composter on-site. The produced compost is used as fertilizer on-site for future harvests. The juice from pressing is pumped into the 5678 L stainless-steel tanks. The juice is inoculated with yeast to assist with fermentation, though some varietals are left to spontaneously ferment. Fermentation proceeds until the yeast dies, as the Large winery specializes in producing dry wines. Additionally, due to this preference, no additional sugar or sweeteners are added during the winemaking process.

In order to remove the solids from the juice, 500 g of gelatin are added to each 5678-L stainless-steel tank to act as a flocculant, and nitrogen gas is injected into the juice to keep air from accumulating as well as to assist in settling out the solids. Once settled out, the lees are racked and added to the compost pile. The wines are then blended to achieve the desired flavor profiles, with argon gas displacing the air within the tanks.

The Large winery utilizes approximately 29 canisters of argon and nitrogen, which each contain approximately 8.5 m^3 of gas, per production year (Table 4). Once the wines have been blended, they are brought down to the proper temperature while still in the stainless-steel tanks. These tanks are cold stabilized all together in one room through ambient temperature controls powered by electricity.

Once cooled, the wines are run twice through a plate-and-frame filtering machine, which uses cellulose pads at 0.4 to 0.5 micron fine pores.

Bottling is also completed on-site, using bottles from the same bottle manufacturer located in Waterloo, New York as the Small winery. For different types of wine, the bottles are various shapes (all containing 0.75 L of wine), thus the mass of an empty glass bottle used by the Large winery ranges from 425 to 475 g (Table 4). This is consistent with the values reported by other studies which state the masses of their bottles [3–5,7,10,23]. The bottling phase was calculated in the same way as for the other two case studies, excluding the production and application of the cork, label, and other packaging components, but including the impacts of producing and transporting the bottle to the winery. Additionally, the distribution of wines is outside the defined cradle-to-gate scope of this study.

2.6. Main Differences between Case Studies

While each of these wineries have very distinct production methods, there are key aspects of the winemaking process for each that can be considered as major differences in the carbon footprint calculation model (Table 5). These aspects include the production volume (in terms of the number of 0.75 L bottles produced annually), the size (and subsequently, electricity generation) of the on-site solar array, the compounds used as fertilizers, pesticides, and fungicides, waste management (in terms of treatment of pomace), the source of glass packaging bottles and location of bottling, as well as the proportion of production volume based entirely on on-site grapes.

Table 5. Major differences in production methods modeled between the three case study wineries.

Characteristic	Small Winery	Medium Winery	Large Winery
Annual wine production volume	Approximately 21,000 bottles year^{-1}	68,000 to 190,000 bottles year^{-1}	291,000 to 775,000 bottles year^{-1}
Capacity of on-site solar array	28 kW	151 kW	93 kW
Fertilizers used	Timothy hay; compost	Borosol; Lokomotive	Timothy hay; compost
Fungicide and pesticide life cycle inventories used in the model	"Undefined" pesticides to capture general pesticides	Captan	Sulfur
Pomace management	Composted on-site	Deposited on nearby field (~0.2 km away)	Composted on-site
Source of bottles	Local manufacturer	Various locations (337 to 4200 km from winery)	Local manufacturer
Bottling location	Off-site facility (approximately 2.41 km from winery)	On-site	On-site
On-site grape production for wines	80% of production from on-site grapes	100% of production from on-site grapes	100% of production from onsite grapes

3. Results and Discussion

3.1. Baseline Results by Finger Lakes Case Study

The life cycle GHG emissions of each process in the cradle-to-gate production of a bottle of wine and the total carbon footprint result were calculated for each of the three Finger Lakes wineries.

For the Small winery, the life cycle GHG emissions of an average bottle of wine were 1.03 kg CO_{2eq} bottle^{-1}. The highest impacts were associated with cultivation, which provides 46% of the total life cycle GHG emissions, and with bottling, which provides 45% of the total life cycle GHG emissions (Figure 3). The impacts associated with the cultivation process are due almost entirely (97%) to the high mass of Timothy hay applied per hectare over the course of a growing season.

The bottling process includes the transportation of the wine to the bottling facility and the production of the glass bottles. This does not include the impact of the electricity used for bottling, as the impact from electricity use was calculated separately for the entire winery instead of separated by process. The Small winery is the only one of the three case study wineries that bottles off-site, and therefore the impacts of bottling included the transportation of the bottle from the bottling manufacturer as well as the transportation of the wine to the bottling facility. Despite this additional transportation impact, the impacts associated with the production of the glass bottle represents over 99.5% of the GHG emissions contributed by the bottling process.

The third highest impact for the Small winery stemmed from the production of electricity generated for winery operation, accounting for 5.45% of the total. This impact represents a smaller proportion of the life cycle impact than that of the Medium winery, mainly owing to a lower amount of electricity required for the production of each bottle of wine at the Small winery and due to differences in impacts from other processes. The absolute impacts of electricity generation per bottle are nearly equal between the two wineries, differing by less than 0.006 kg CO_{2eq} bottle^{-1}, and are slightly higher for the Small winery.

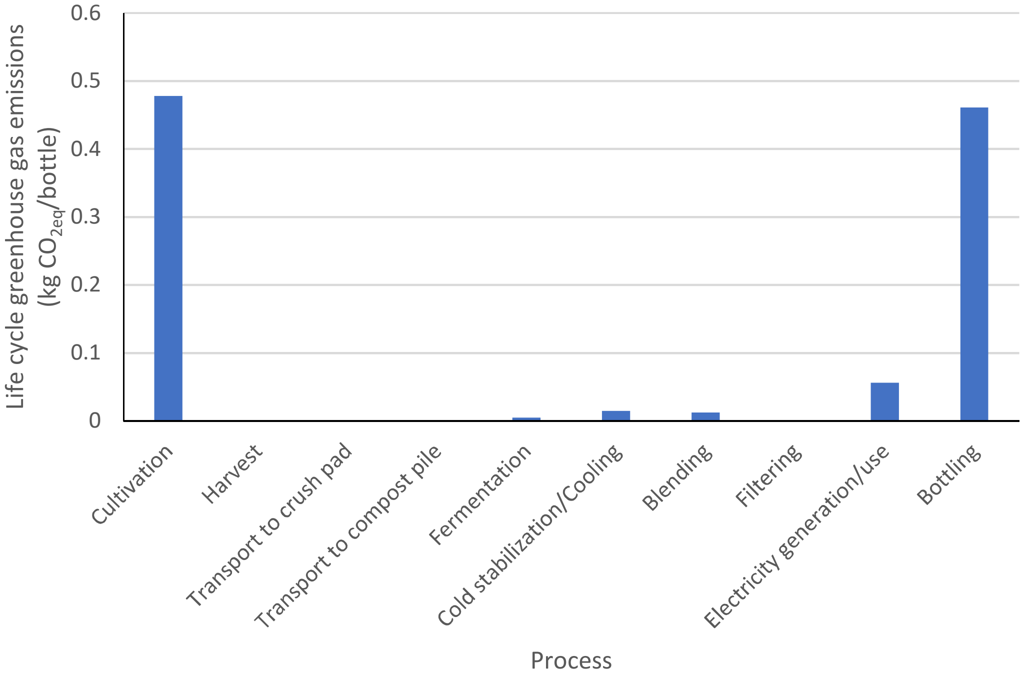

Figure 3. Baseline life cycle greenhouse gas (GHG) emissions of a bottle of wine produced by the Small winery.

The processes of cooling, blending, and fermentation are the next highest impacting parameters, imparting an aggregate 3.10% of the total life cycle impacts. However, considering that only the electricity usage for the winery as a whole was modeled, the impacts for these processes were based entirely on the impacts of their inputs. Thus, in spite of this aggregate impact, these processes realistically cannot be considered negligible in terms of influence on the total environmental impact. All other processes together amount to 0.004% of the total GHG emissions.

The baseline life cycle GHG emissions of a 0.75 L bottle of wine from the Medium winery was 0.742 kg CO_{2eq} bottle^{-1}. The highest impact among the processes was associated with the bottling process, which includes the production and transportation of the glass bottle (Figure 4). Bottling contributes 79.3% of the total life cycle GHG emissions for wines produced by the Medium winery. As the bottles are transported between 337 and 4200 km to the winery, in addition to being the heaviest bottles of the three case study wineries (at 0.500 kg), it is reasonable that the Medium winery had the highest climate change impact for bottling between the three wineries (0.589 kg CO_{2eq} bottle^{-1}). However, it should also be noted that the transportation of the bottles represents only 12.1% of the impact of the bottling phase; the other 87.9% can be attributed to the production of the glass bottles.

The second highest impact stemmed from the grape cultivation process, which contributes 8.39% of the total impact. This is consistent with previous wine LCAs, as viticulture is often attributed as one of the highest impacts. This can be primarily attributed to the amount of fungicide, pesticide, and fertilizer compounds required to maintain the health of the crops [26].

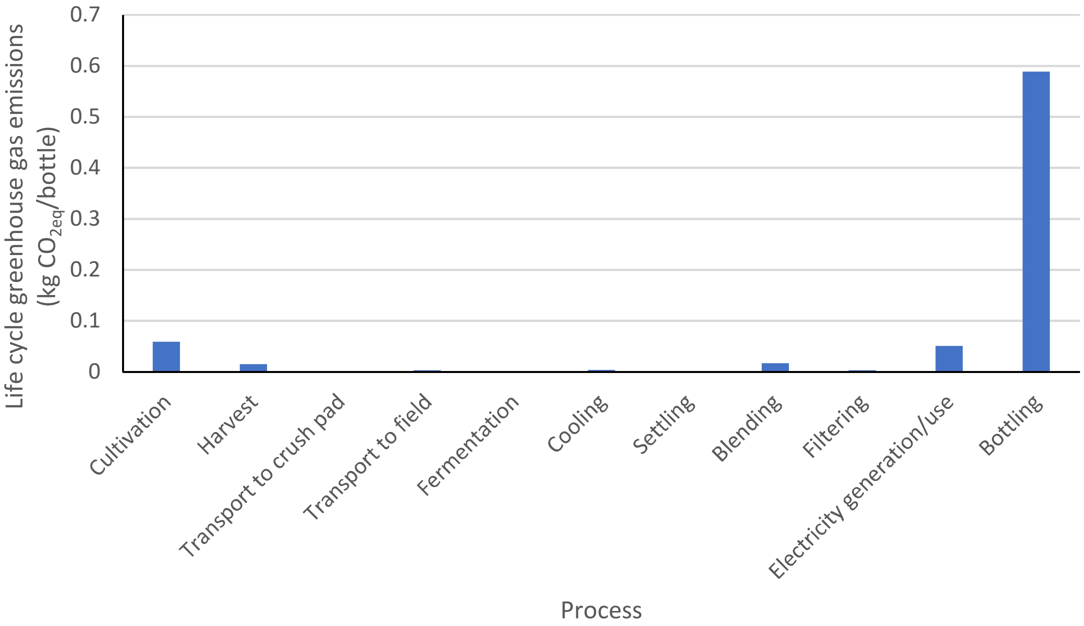

Figure 4. Baseline GHG emissions of a bottle of wine produced by the Medium winery.

The third highest impact was associated with the production of electricity for winery operations. This was the case primarily due to the electricity generation by the 151 kW solar array that provided all of the winery's electricity needs overall. Compared to the other two wineries in this study, the Medium winery had the highest electricity consumption per bottle of wine. This results in the electricity generation and consumption impacts comprising nearly 7% of the total climate change impact of the wines produced at the Medium winery. The processes for blending the finished wine as well as harvesting the grapes from the vineyard were the next two highest impacts, although their impacts each only amount to 2% of the aggregate GHG emissions of an average bottle of wine produced by the Medium winery. The rest of the processes from cradle to gate together contribute to just over 1% of the total impact.

For the Large winery, the total GHG emissions associated with the production of an average bottle of wine is 0.617 kg CO_{2eq} bottle^{-1}, which is the lowest result of the three Finger Lakes case studies (Figure 5). The Large winery produces an average of more than 500,000 bottles of wine per year, a much higher production volume than either of the other two wineries. This suggests an economies of scale effect for the climate change impact of a bottle of wine produced using the practices of the three wineries investigated.

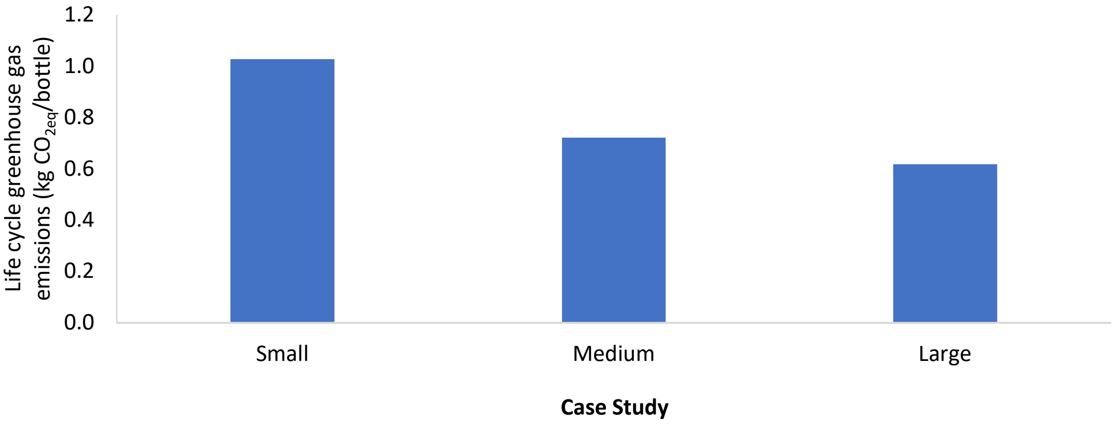

Figure 5. Comparison of baseline cradle-to-gate GHG emissions of wine from the three case study wineries in the Finger Lakes.

The highest impacts for the Large winery can be attributed to the bottling phase, which includes the production of the glass bottle as well as the transportation of the bottles from the manufacturer to the bottling location on-site. This is often the highest contributor to greenhouse gas emissions in wine LCAs, due to the impacts of producing the glass material [26]. The process modeled in this study represents 75.0% of the total cradle-to-gate impacts (Figure 6), with 99.6% of the process emissions resulting from the glass bottle production.

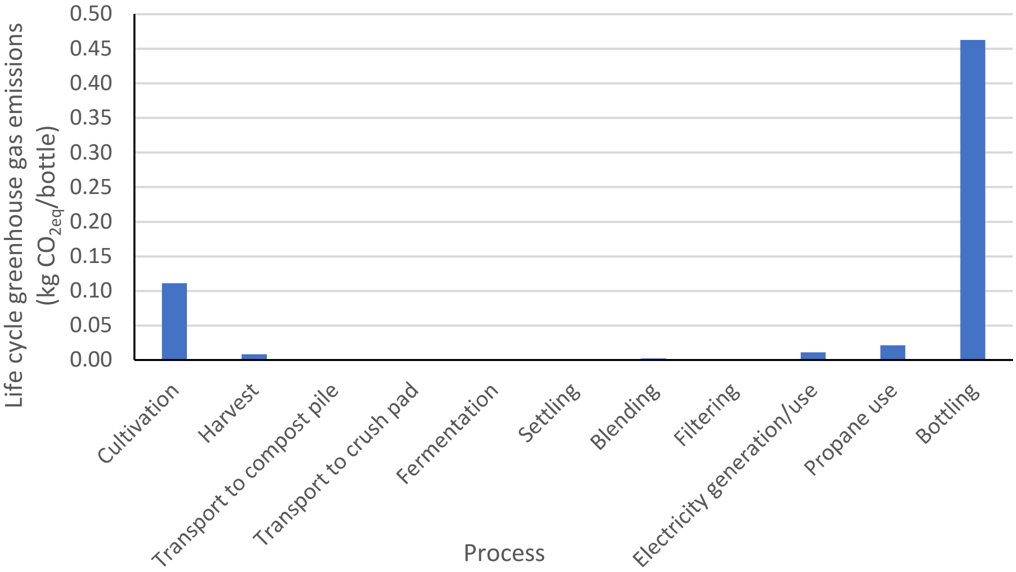

Figure 6. Baseline GHG emissions of a bottle of wine produced by the Large winery.

Transporting the bottles to the winery can present significant impacts, as seen with the Medium winery, which transported an average of 1278 km farther than the Large winery. However, despite also including the transportation of the bottles to the Large winery, the impact of bottling is only 0.0016 kg CO_{2eq} bottle^{-1} higher than the bottling impact of the Small winery. This indicates that the impacts associated with transporting bottles the distance between the Large winery and the bottle manufacturer are minimal compared to those of other processes. In the results for all three wineries, the production of the glass bottle represents the overwhelming majority of the life cycle GHG emissions of a 0.75 L bottle of wine from this region.

The second highest impact for wines from the Large winery is associated with the cultivation process, which comprises 18.0% of the aggregate climate change impact (Figure 6). This can be directly attributed to the amount of Timothy hay used for fertilizer on the vineyard and the use of sulfur as a broad-spectrum fungicide. The Large winery is also the only one of the three Finger Lakes sites for which the existing drainage system was modeled due to sufficient detail, although with the long lifetime of the high-density polyethylene (HDPE) pattern tile, the impacts associated with this system only contributed 0.0012 kg CO_{2eq} bottle^{-1}. Despite being the second most impactful process, the impacts of viticulture are four times lower than those at the Small winery.

The third highest impact for the Large winery results from the winery's use of propane for heating and as a fuel for various pieces of machinery (such as forklifts) on-site. The Large winery was the only winery in this study to use propane in its operations. The impacts associated with the use of the propane amount to approximately 0.021 kg CO_{2eq} bottle^{-1}, which is just over 3% of the life cycle impact of a bottle of wine (Figure 6).

While electricity generation by solar panels is the next highest impact for the Large winery, this impact contributes a lower percentage of the life cycle GHG emissions than the same process for the other two Finger Lakes wineries. The impacts associated with this solar electricity generation add less than 2% of the cumulative impacts, the equivalent of under 0.011 kg CO_{2eq} bottle^{-1}. This is a direct result of the relatively lower electricity consumption by the Large winery per bottle of wine, which amounts to approximately 0.25 kWh per bottle of wine. This is much lower than the electricity consumption of the Small and Medium wineries at 1.24 and 1.12 kWh per bottle, respectively. It must be noted here, however, that the Large winery does include propane as an additional energy input, which has the potential to account for this discrepancy. The remaining parameters combined represent less than 2% of the total life cycle GHG emissions of a bottle of wine produced at the Large winery.

In addition to the analysis based on the current operating conditions at each of the three case study wineries, alternate scenarios substituting the solar panel-generated electricity with the electricity mix from the regional grid were modeled in order to determine the influence of solar power in winemaking processes for these wineries relative to utilizing electricity from the grid. For the Small winery, having electricity provided by the grid increases life cycle GHG emissions by 0.127 kg CO_{2eq} bottle^{-1} or 12.3% from the baseline. For the Medium winery, grid-based electricity leads to a 0.145 kg CO_{2eq} bottle^{-1} or 19.5% increase. For the Large winery, a 0.031 kg CO_{2eq} bottle^{-1} or 5.02% increase can be observed when switching from solar-based electricity to grid-sourced electricity. The carbon emission intensity of electricity from the grid in the Finger Lakes is relatively low compared to other regions of the United States because of the prevalence of hydropower and nuclear energy, followed by natural gas [29]. Although these changes in carbon footprint are modest, this suggests that increasing the use of solar panels for electricity could be advantageous in the Finger Lakes winemaking facilities to reduce their GHG emissions.

Overall, for the wineries included in the Finger Lakes case study, the process in the life cycle of a bottle of wine which contributes the most to climate change is bottling, and in the case of the smallest wineries, cultivation, in the way that the processes were defined (Figure 7). This is consistent with the conclusions of previously published wine LCAs and supports the basis for studies that evaluate the influence of lightweight packaging and alternatives to glass, as well as organic and low-intensity agricultural practices (e.g., [11,13]). However, organic and low-intensity agricultural practices might not be as influential in reducing GHG emissions, as the Small winery most closely follows these practices compared to the Medium and the Large winery, and because this may have led to the relatively lower yield of grapes per hectare per year reported by the Small winery. This in turn affects the life cycle climate change impact of wine. The results also suggests an economy of scale effect, where intensification may reduce life cycle GHG emissions.

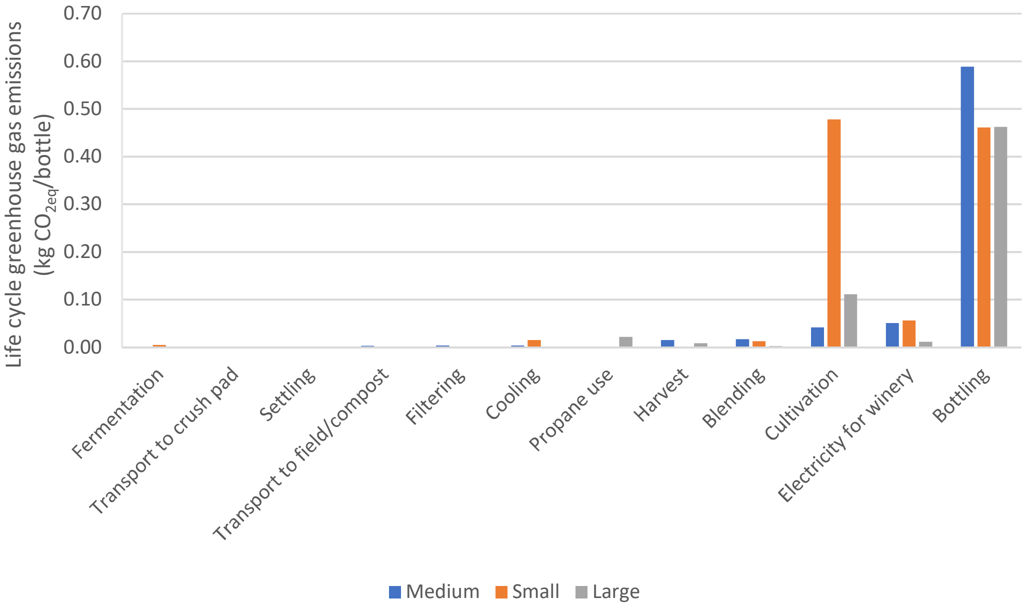

Figure 7. Comparison of impacts by process for each of the three Finger Lakes wineries.

3.2. Sensitivity Analyses

A sensitivity analysis was performed for all variable input parameters for each of the three wineries by changing each input, one at a time, to its maximum and minimum value and evaluating the subsequent change in the life cycle environmental impacts of a bottle of wine. Similarly, six other wine LCA studies performed sensitivity analyses to determine the impacts of changing system inputs [1,3,4,6,8,11].

The results of the Small winery case study are most sensitive to the life cycle climate change impact of solar-generated electricity (Figure 8). If the impact per kilowatt-hour were at the maximum value modeled (0.183 kg CO_{2eq}/kWh), the life cycle climate change impact for the Small winery would be 16.7% higher than the baseline impact. The amount of electricity used in the production of one bottle of wine is just barely (0.82 kWh bottle^{-1}) higher than the electricity used per bottle for the Medium winery, so investment in higher-efficiency machinery may be a worthwhile endeavor to reduce the carbon footprint of wines from the Small winery in the future.

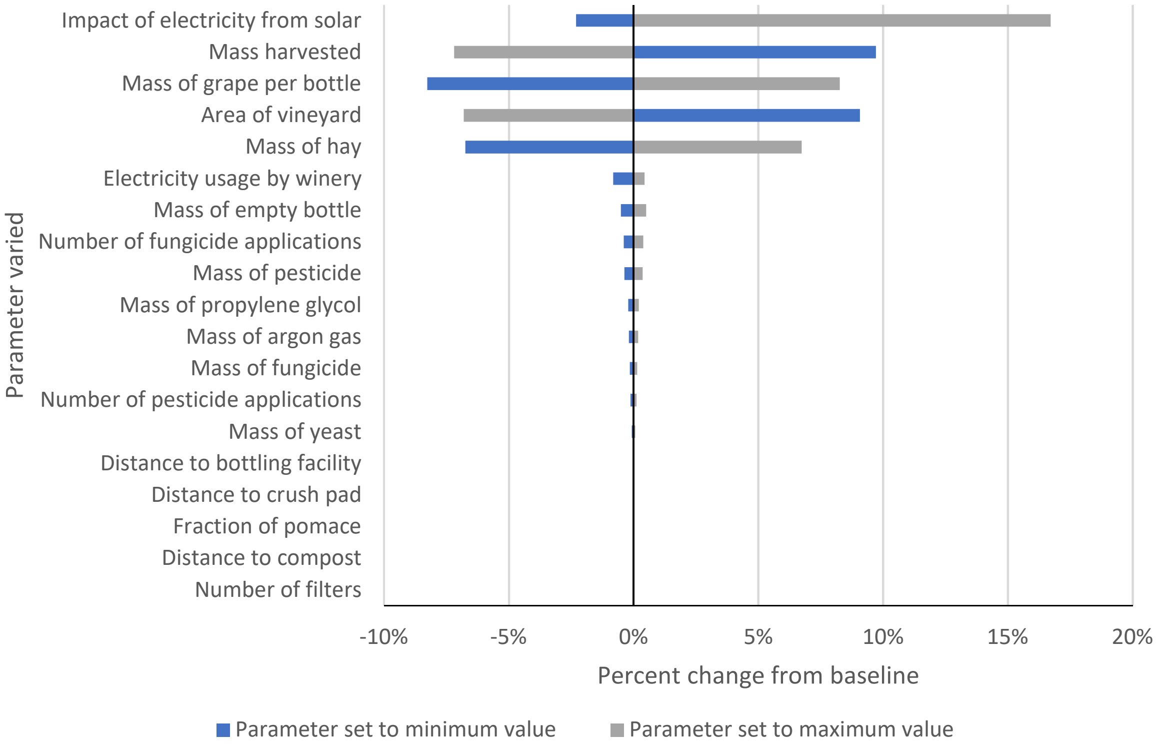

Figure 8. Sensitivity analysis results for the Small winery.

The second most sensitive variable parameter for the Small winery is the mass of grapes harvested per hectare per year. As this is one of the parameters involved with the calculation to determine the number of bottles produced in a year, the sensitivity of this variable parameter is unsurprising. With the maximum mass harvested per hectare modeled in this LCA case study, the total climate change impact decreases 7.18% from the baseline. In order to minimize the life cycle greenhouse gas emissions associated with the production of their wines, the Small winery may prioritize maximizing the mass of grapes harvested from each hectare. However, reaching this goal may involve implementing different cultivation practices which would themselves affect the life cycle climate change impact of the system. Furthermore, this yield per hectare may be difficult for the winery to control, and efforts to maximize this value are typically already undertaken for economic reasons, regardless of environmental impacts.

The third most sensitive variable parameter for the Small winery is the mass of grapes needed to produce one finished bottle of wine. This correlation is logical, in that the more grapes required per bottle of wine, the higher the GHG emissions associated with the production of the bottle of wine. The baseline value for the Small winery was 1.134 kg of grapes per bottle; this was varied to 0.964 and 1.304 kg of grapes per bottle for the sensitivity analysis. The Medium and Large wineries used a slightly lower mass of grapes per bottle at 1.20 and roughly 1.12 kg bottle^{-1}, respectively. These masses of grapes may be higher in wines from the Finger Lakes region than those used for other wines; for example, a study of French and Spanish wines indicated that each kilogram of grape was considered equivalent to a 0.75 L bottle of wine [9]. However, these wines were mostly red wines instead of the white varietals common to the Finger Lakes. Still, the amount of grapes required to produce a bottle of wine in the style of the winery in question is often something that cannot be readily changed without altering the flavor profile and style associated with the wine, and therefore minimizing this value would likely be unrealistic for the Small winery to undertake.

The next two most sensitive input parameters are the area of the vineyard itself and the mass of the Timothy hay utilized as fertilizer on this vineyard. The sensitivity of the area of the vineyard is due to the range of values assumed—the area of vineyard utilized was increased slightly in 2014, though the newest land is the area that occasionally requires irrigation. Therefore, for the purposes of this study, the minimum value for the area of the vineyard was assumed to be the area of land that was vined before 2014, as if there had been no land added. As the intention was to determine the environmental impacts of the average bottle of wine produced at the Small winery, the lower value was assumed to represent the impacts of wines produced before the expansion. If 100% of the vined area (the maximum value for the variable parameter) produced the modeled baseline mass of grapes per hectare, the overall environmental impacts would be lowered by 6.81% (Figure 8).

Although the carbon footprint of wines from the Small winery is sensitive to the mass of Timothy hay used, the Timothy hay is intended to account for nitrogen deficiencies in the soil and reducing the amount of fertilizer has the potential to lead to smaller harvests. This would in turn lead to a higher environmental impact. In addition, the Small winery only spreads hay on every other row, so it is reasonable to assume that the amount of hay applied for fertilizer is necessary to meet the nutritional needs of the vines. The rest of the modeled input parameters showed minimal influence on the total GHG emissions, affecting these impacts by 0.82% at most when changed to their minimum or maximum values.

For the Medium winery, the cradle-to-gate GHG emissions of a bottle of wine were most sensitive to the distance that the empty bottles were transported from a supplier to the winery (Figure 9). This was expected, as the bottles were sourced from a wide range of locations, from as close as Pennsylvania to as far as Mexico. At the maximum transportation distance for the bottle (4200 km, from Mexico), the baseline LCA results increased by 18.5%. At the minimum distance (337 km from Pennsylvania), the impacts of a bottle of wine decreased 6.14% from the baseline LCA result. In order to reduce the carbon footprint of their wines, the Medium winery could source their bottles from locations that are a smaller distance from the winemaking facility. There is potential to locate suppliers in the region, as the Small winery and the Large winery both utilize a single bottle manufacturer which would be less than 32 km away from the Medium winery.

The second most sensitive parameter for the Medium winery is the life cycle climate change impact of the electricity generated from their solar panels. The range of values for this parameter was obtained from a harmonized LCA of electricity generation from crystalline silicon solar photovoltaic systems [27]. If the value for the impact of solar power were assumed to be the maximum (0.183 kg CO_{2eq} kWh^{-1}), the life cycle GHG emissions increase by 20.8% (Figure 9). The sensitivity of the impacts of electricity generation for the Medium winery emerges from the relative demand on electricity for winemaking processes, as the electricity usage per bottle is the highest of any of the three Finger Lakes wineries being studied. Its influence suggests that performing regular maintenance on solar panels in order to extend their lifetime and maximize efficiency, installing higher-efficiency machinery for winemaking processes, and increasing the capacity for passive processes (i.e., the outdoor cold stabilization tanks) could reduce the carbon footprint of wines from the Medium winery.

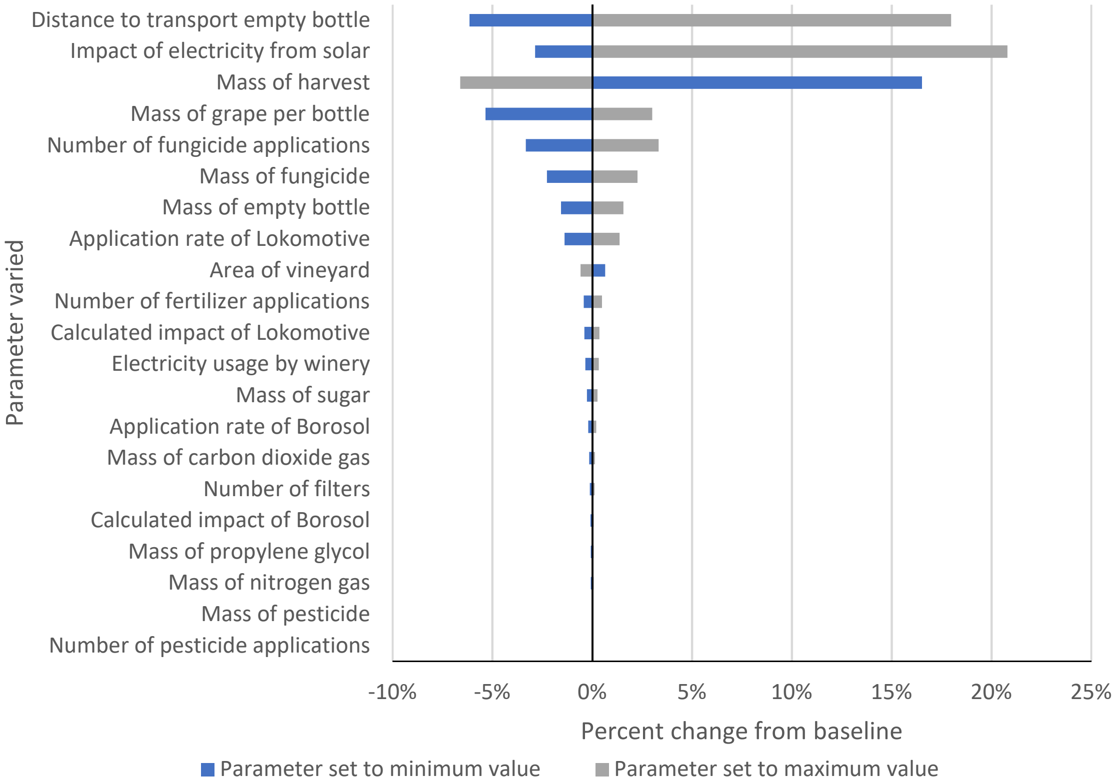

Figure 9. Sensitivity analysis results for the Medium winery.

The third most sensitive variable parameter for the Medium winery is the mass harvested per hectare each year. This parameter directly influences the production volume, with smaller harvests resulting in a lower total number of bottles produced. If the winery experiences a year in which the harvest yield matches the minimum value modeled of 4.48 Mg ha^{-1} year^{-1}, 16.5% higher life cycle GHG emissions per bottle of wine result. Therefore, the Medium winery may also prioritize efforts that maximize the amount of grape harvested from each hectare of vineyard. However, the size of the viable crop is dependent on several factors outside of the winery's control as well (e.g., level of precipitation, unusually cold seasons, etc.) and therefore the mass harvested can be controlled by the Medium winery to a limited extent.

The mass of grapes used in each bottle, the number of fungicide applications and mass of fungicides used, and the mass of the empty bottle also influence the life cycle GHG emissions of wines from the Medium winery. A decrease in any of these values leads to a corresponding decrease in the carbon footprint. Therefore, the Medium winery could reduce its carbon footprint by reducing these masses and the number of fungicide applications. However, higher priority should be placed on the more sensitive parameters of the bottle transportation distance, electricity generated from solar panels, and the mass of grapes harvested per year. The rest of the parameters that were varied in the sensitivity analysis resulted in a less than 0.65% difference from the baseline LCA results when changed to their minimum and maximum values.

The most sensitive parameter for the Large winery is the mass of grapes harvested annually per hectare. This variable is influential in determining the number of bottles produced each year, and thus it affects the life cycle GHG emissions that are scaled to one bottle of wine. If the mass of the annual harvest decreases by 15% (to the minimum value modeled), the overall GHG emissions associated with the life cycle of a bottle of wine increase by 20.8% (Figure 10).

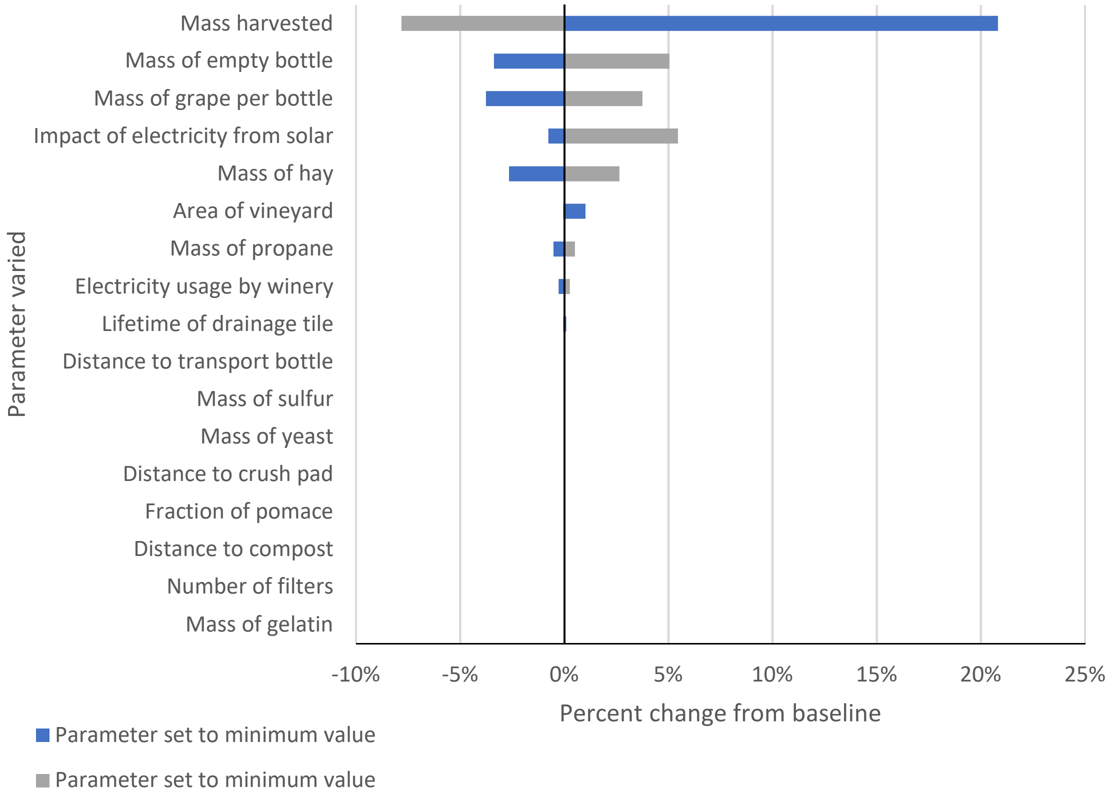

Figure 10. Sensitivity analysis results for the Large winery.

The second most sensitive parameter for the Large winery is the mass of the empty wine bottle. While the impacts of transportation are minimized due to the location of the bottle manufacturer in a neighboring town, the impacts associated with transportation are still dependent on the mass of the bottle, as is the production of the glass in the first place. The lightest bottle used by the Small and Large wineries has a mass of 425 g, which is slightly lighter than the masses given in previously published studies. This is due to the design by the manufacturing company, which advertises an "eco-glass" product line of bottles that is lighter than conventional glass (Waterloo Container, Waterloo, New York, NY, USA). The Small winery explicitly mentioned the "eco-glass" line of bottles from this manufacturer as the source of their product, which has the same mass as the bottle weighed on-site at the Large winery. Therefore, it is assumed that the bottles used by the Large winery are also from this product line and are already lighter than conventional bottles. When the impacts associated with a finished bottle of wine are calculated using the minimum value for the mass of the glass bottle, they are 3.37% lower than the baseline impact, whereas if the maximum bottle mass is used, the impacts increase by 5.05% (Figure 10). In order to minimize impacts associated with the mass of the wine bottle, the lightest viable option should be the one selected.

The last three parameters which have considerable sensitivity for the Large winery are three of the same seen for the Small winery: the mass of grapes used in a single bottle of wine, the carbon footprint of electricity generated by solar panels, and the mass of Timothy hay used for fertilizer. The lower sensitivity to the impacts associated with solar energy are likely driven by the fact that the Large winery uses approximately 80% less electricity per bottle than the other two wineries studied. However, the Large winery does use propane for energy on site in addition to electricity from solar panels and diesel in vineyard equipment. For the use of Timothy hay for fertilizer, changing the amount used to its maximum or minimum value only results in an impact that is 2.65% higher or lower than baseline GHG emissions (Figure 10). The minimum amount of hay needed to maintain reasonable nitrogen levels in the soil should be what is applied, but efforts to reduce the carbon footprint of wines from the Large winery should prioritize more sensitive parameters.

4. Comparison to Other Studies

In order to account for the variation in scope among wine LCAs, and to more directly and fairly compare the impacts associated with the life cycle of a bottle of wine, the cradle-to-gate impacts were determined from published wine LCAs and compared against the three Finger Lakes case studies with the same scope (Figure 11). These impacts were either reported by the individual studies which also have a cradle-to-gate scope, or were determined using the results of those studies which allocated impacts per stage in the life cycle. The phases that were used to determine these cradle-to-gate impacts were the same phases modeled in the Finger Lakes case studies (viticulture/harvest, viniculture, and bottling), in order to provide contextual comparisons between each of the studies and to avoid overestimating the sustainability of Finger Lakes winemaking processes. The four studies that only reported aggregate results were not included in this comparison [4,6,10,12].

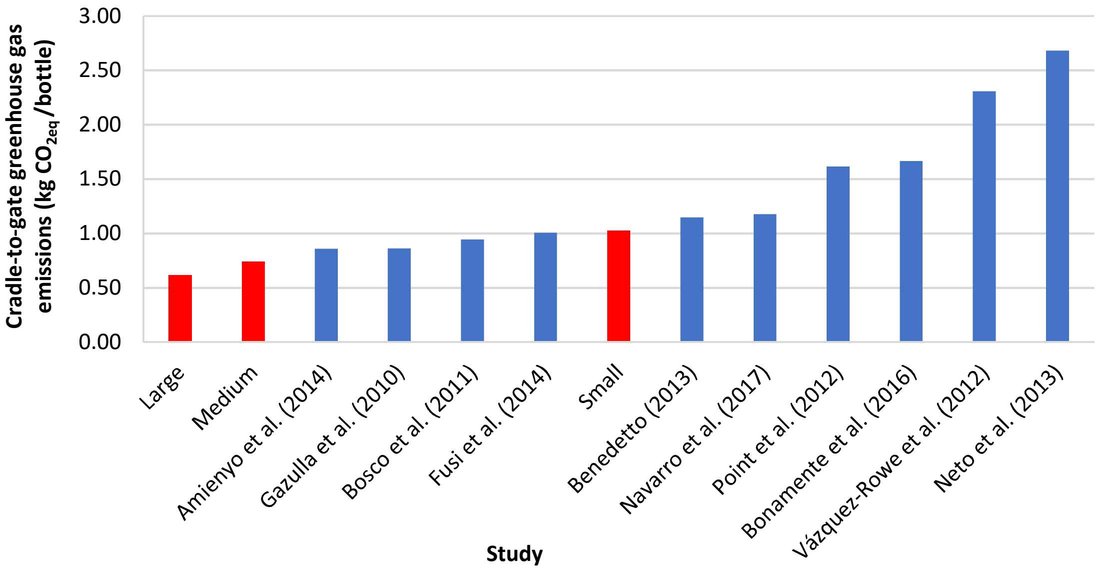

Figure 11. Life cycle GHG emissions of the Finger Lakes wineries in comparison to the cradle-to-gate results described by the other studies. The red bars indicate the three NY wineries.

Overall, when comparing the results to those of published LCAs on wine, the three wineries in the Finger Lakes contributed lower greenhouse gas emissions than their counterparts in other regions with the exception of the Small winery, which has higher impacts than several of the other studies (Figure 11). Two of these are from Italy [2,3], one is from Spain [5], and one examined Australian wine production [11]. Due to the individual life cycle stage impacts not being reported for the Australian study [11], it is difficult to pinpoint which phases contributed the highest impacts, and how these compare to the impacts indicated in the other publications as well as the Finger Lakes case study. Still, conclusions can be drawn from phase-specific results of the three European studies. The highest impacts associated with grape cultivation and harvest were found in the Spanish study, which produced about 0.50 kg CO_{2eq} bottle^{-1} (nearly 60% of the total carbon footprint) [5]. This impact is similar to the 0.478 kg CO_{2eq} bottle^{-1} produced by the Small winery for the same life cycle stage.

For the actual winemaking processes, many previous studies have found that the associated impacts are quite low relative to the entirety of the life cycle of the wine [26]. This is likewise seen in this Finger Lakes wine LCA. For viniculture stages at the three Finger Lakes wineries, the GHG emissions are lower than all published LCAs with the exception of the study done by Benedetto et al.

(2013), which is lower than all three [23]. The use of solar energy at the Finger Lakes wineries assessed may contribute to this result. In addition, the impacts calculated for viniculture in the Bonamente et al. (2016) study were lower than those determined for the Medium winery and the Small winery but were almost equivalent to the impacts for the Large winery [1]. Still, these winemaking processes were separate from the impacts of electricity and propane provision for all processes from cradle to gate in this analysis, and the GHG emissions resulting from viniculture may be higher than reported when the energy needs are allocated to their corresponding processes.

Another feature of the three Finger Lakes wineries assessed that differs from some of the other wine regions is the absence of irrigation. However, a few studies highlighted wineries under similar conditions. Only one of the four wineries utilized any irrigation in the Bosco et al. (2011) wine LCA [2]. The wineries assessed by Gazulla et al. (2011) and Bonamente et al. (2016) did not use any artificial irrigation due to adequate rainfall in their regions [1,5]. No irrigation systems are in place at any of the 12 assessed Nova Scotian wineries in the LCA by Point et al. (2012) due to abundant rainfall [13]. However, the true impact of irrigation on the carbon footprint of wines may be difficult to ascertain because, when water consumption has been included in previously published wine LCAs, it is aggregated as water consumption for all viticulture processes including irrigation [3,4,10,11].

Like the majority of wine LCAs [2,3,5,6,10,13,23], the Finger Lakes case studies determined that bottling (in particular, the production of the glass bottle) and cultivation are the two processes which contribute the most to the cradle-to-gate climate change impact of wine. A recent review of wine LCAs has also determined that the primary environmental impacts stem from the viticulture phase (due to fuel consumption and the production of fertilizers and pesticides) as well as the production of primary packaging including glass bottles [26]. In one study, it was determined that the production of the glass bottle represented between 43% and 82% of the total carbon footprint, depending on the production system [10]. Some potential mitigation strategies have been discussed in the literature, including increasing the percentage of recycled glass within a wine bottle, utilizing lighter-weight bottles (as two of the wineries in this study had implemented), and potentially using cartons as opposed to traditional bottles [11].

As this study also aimed to evaluate the representative impacts of the Finger Lakes region as a whole, the average of the results for the three case study wineries was calculated, resulting in a regional impact of approximately 0.795 kg CO_{2eq} bottle^{-1} per bottle of wine. This was then compared on a regional basis to the previously published literature, in order to determine if the Finger Lakes could be considered a sustainable wine region in relation to other established wine regions on a global scale and in the context of producing wines with a low carbon footprint (Figure 12). However, it should again be noted that these three wineries might not be fully representative of wineries in the Finger Lakes region due to potential self-selection bias and their maximized use of on-site solar power, as well as the fact that there exist dozens more wineries whose carbon footprints could be individually assessed in the future. Furthermore, some studies reported combined LCA results for wineries across nations, such as Navarro et al. (2017) who assessed 18 different wineries in both Spain and France [9].

The values for this regional comparison were determined by taking the average of cradle-to-gate impacts calculated by the articles for each country. For Australia, Canada, and France, there was only one published LCA representing each region, while Spain and Portugal have three studies and Italy has four reporting with either the cradle-to-gate scope or results that can be interpreted from a cradle-to-gate perspective. This may have an influence on the average impacts for the region, should one study conclude a relatively high result. Overall, the averaged result of three case studies suggest that the Finger Lakes wine region contributes on the lower end of greenhouse gas emissions compared to other wine regions around the world (between 7.5% and 59.2% lower on a regional basis).

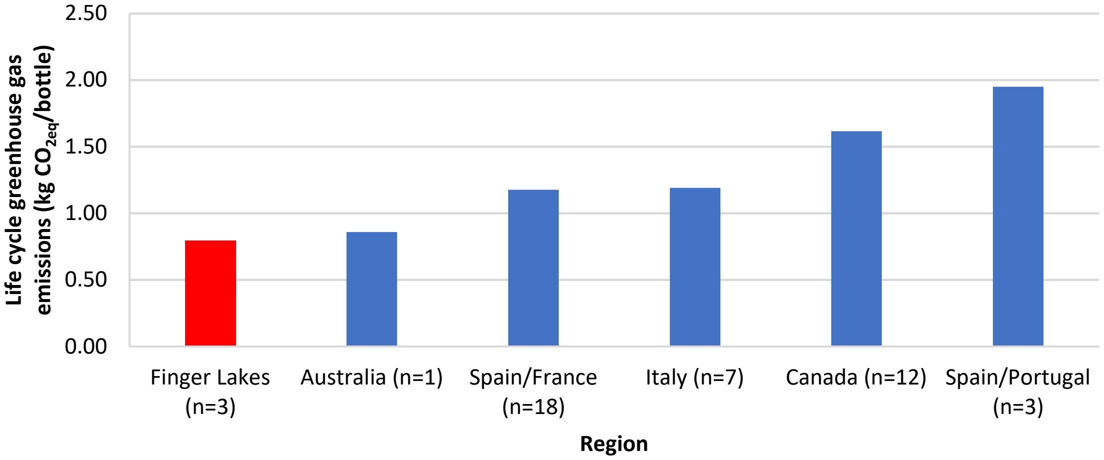

Figure 12. Life cycle GHG emissions of the Finger Lakes wine region as compared to the winemaking regions in other countries as described by published LCAs. The red bar indicates the average impact associated with Finger Lakes wines, as determined by averaging the impacts of the three Finger Lakes case study wineries. n equals the number of wineries referenced, or the wine region as a whole, depending on the information provided by each study.

The representation of other regions in the United States in the wine LCA literature would also provide a useful context for the Finger Lakes' place among leaders in low-carbon winemaking practices. Although Steenwerth et al. (2015) and Venkat (2010) evaluated the GHG emissions of wine-related activities in the United States, their scopes were limited to agricultural processes [14,15], and therefore are not directly comparable to the impacts described by this study, which included viniculture processes.

5. Limitations and Future Work

Because the sensitivity analyses performed in this study do not cover interactions between parameters as they all vary from the baseline values simultaneously, future iterations of this LCA could investigate these interactions with Monte Carlo uncertainty analyses, which would be possible with greater detail on the probability distributions of input parameters by winery. In order to more accurately represent the impacts associated with pesticide, fungicide, and fertilizer application during viticulture, the availability of life cycle inventories of these compounds would benefit future studies. More data is also needed on carbon stored in soils and vegetation in a vineyard in order to include this aspect in future LCAs. Because crop productivity may differ from year to year and the carbon footprint of wine is sensitive to the yield of grapes per unit of cultivated area [6,7], data collection over a longer set of production years may better highlight the variability in the carbon footprint of wine from the region.

Future iterations of this study may also determine the impacts of red versus white wines, though for previous wine LCAs, their carbon footprints have been found to be similar [26]. The scope of this study was established as determining the carbon footprint of Finger Lakes wines. Because GHG emissions are not the only environmental pathway through which environmental impacts occur, additional life cycle environmental impacts could be determined, such as water footprint, life cycle ecotoxicity impacts, life cycle eutrophication potential, and other categories.

In this study, electricity consumption data was provided at the scale of the full winery operations instead of divided by process along the winemaking life cycle. The impacts related to electricity provision were thus separated from the processes that use electricity, and the process-level impacts were based on the GHG emissions associated with other inputs during each process (such as fertilizers, glass bottles, yeast, etc.). Future work could involve further data collection to separate the energy inputs by process at each studied winery to improve recommendations for improving the carbon footprint of high-impact stages in the life cycle of wine. In addition, further research into the prevalence of solar electricity generation for Finger Lakes wineries is needed, in order to determine if this LCA can be considered fully representative of the entire region. Although this LCA represents results based on information from only three wineries, the span of annual production volumes and differences in grape cultivation and winemaking practices provides insight into the range of conditions that can represent the life cycle of wine from Finger Lakes wineries.

6. Conclusions

The life cycle GHG emissions of a bottle of wine produced by the three wineries assessed in the Finger Lakes region of New York are, on average, in the lower end of the impacts of wines produced elsewhere in the world. The winery with the largest annual production volume had the lowest carbon footprint, while the winery with the smallest annual production volume had the highest carbon footprint. These impacts were primarily influenced by the mass of grapes harvested per hectare of vineyard, as well as the mass of grapes used to produce a single bottle of wine. In addition, the impacts associated with electricity use contributed notably to the life cycle GHG emissions of a bottle of wine. This impact would have resulted in a higher carbon footprint if the wineries sourced their electricity from the grid instead of on-site solar panels, but the increase would be modest due to the low carbon intensity of the grid in the region. The bottling process, which includes the production of the glass bottle, and the cultivation process are the highest-impacting stages, which is consistent with other wine LCAs. The high impact from bottle production observed in the wine LCA literature still occurred despite two of the wineries using bottles that have a lower mass than conventional glass bottles. These first carbon footprint results for wineries in the Finger Lakes add to our understanding of the range of the life cycle GHG emissions of wine production and how they differ by production practices and by region.

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

Appendix A

Table A1. Life cycle inventories used and their database sources. RoW represents "rest of world" when a corresponding country- or region-specific inventory is also available.

Life Cycle Inventory Name	Source
Activated bentonite (RoW)| production	Ecoinvent 3
Propylene glycol, liquid (RoW)| production	Ecoinvent 3
Fodder yeast (RoW)| ethanol production from whey	Ecoinvent 3
Sugar, from sugarcane (RoW)| cane sugar production with ethanol by-product	Ecoinvent 3
Cellulose fibre, inclusive blowing in (RoW)| production	Ecoinvent 3
Packaging glass, green (RoW)| production	Ecoinvent 3
Carbon dioxide, liquid (RoW)| production	Ecoinvent 3
Nitrogen, liquid (RoW)| air separation, cryogenic	Ecoinvent 3
Captan (RoW)| production	Ecoinvent 3
Pesticide, unspecified (RoW)| production	Ecoinvent 3
Boric acid, anhydrous, powder (RoW)| production	Ecoinvent 3
Monoethanolamine (RoW)| ethanolamine production	Ecoinvent 3

Table A1. *Cont.*

Life Cycle Inventory Name	Source
Tap water (RoW)| tap water production, conventional treatment	Ecoinvent 3
Potassium hydroxide (RoW)| production	Ecoinvent 3
Urea, as N (RoW)| production	Ecoinvent 3
Argon, liquid (RoW)| production	Ecoinvent 3
Hay (RoW)| production & Hay, organic, intensive (RoW)| production (averaged)	Ecoinvent 3
Propane (RoW)| natural gas production	Ecoinvent 3
Sulfur (RoW)| natural gas production & Sulfur (RoW)| petroleum refinery operation (averaged)	Ecoinvent 3
Transport, combination truck, average fuel mix	USLCI
Diesel, combusted in industrial equipment	USLCI
Acetic acid, at plant	USLCI
Polyethylene, high density, resin, at plant, CTR & Recycled postconsumer HDPE pellet (averaged)	USLCI

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