When and Where Can Farm-level Life Cycle Assessments be Used to Predict Aggregate Food System Contributions to Global Warming?

Honours Thesis

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Abstract

Food production is a key anthropogenic system driving global warming, biodiversity loss, land use change, and biogeochemical cycle disruption. Food system sustainability is a field of research dedicated to addressing these issues, ultimately motivated to meet human needs within biophysical planetary boundaries. One of the many tools that have emerged in food system sustainability research is the life cycle assessment (LCA). Though not without limitation, individual farm-level LCAs and the works that synthesize them are extremely valuable, as they characterize system contributions to environmental concerns and resource depletions. Drawing from published LCAs, previous meta-analyses have demonstrated that food production systems and their associated contributions to environmental concerns can be highly variable between producers of the same product, between products, and between geographies, among other factors, and that there is more to be understood with regard to both food systems and LCA methods. This exploratory research investigates how and why farm-level production systems vary in their contributions to environmental concerns within and between production regions. Separately, this work also assesses whether life cycle assessments have thus far been undertaken systematically to geographically represent production patterns. With these objectives in mind, a review and comparison of available wine LCA data was conducted, as well as a systematic wine LCA literature inventory. Results indicate that wine grape production system contributions to global warming can be highly variable within and between production locales, and that LCA research has not been undertaken systematically to geographically represent production patterns. These conclusions are intended to help inform future food system sustainability research methods, thus contributing to the sustainable development of our food systems.

Chapter 1: Introduction

1.1 Motivation

Food production is a key anthropogenic system driving global warming, biodiversity loss, land use change, and biogeochemical cycle disruption. In 2018, food system contributions to global greenhouse gas (GHG) emissions were estimated to be roughly 26% (Poore and Nemecek, 2018). As of 2021, this estimate is now approximately 34% of global anthropogenic GHG emissions (Crippa et al., 2021). Based on current climate change projections, radical mitigation efforts within food systems are needed to avoid further transgressing earth's biophysical planetary boundaries and permanently altering the earth's capacity to sustain human life (Campbell et al., 2017).

Food system sustainability is a field of research dedicated to addressing these issues, ultimately motivated to meet human needs within the earth's biophysical planetary boundaries. Within the field of food system sustainability research, life cycle assessments (LCA) have become a common tool used to quantify and characterize production system contributions to these large-scale environmental concerns. Food system LCAs target individual production systems with the purpose of quantifying their contributions to environmental concerns, thus facilitating shifts towards more sustainable production practices and decision making. In a broader context, food LCAs can be synthesized to answer questions of aggregate production and consumption impact contributions, as well as inform policymaking and consumer behaviours. They are therefore extremely valuable, but are also not without limitations. For example, the comparability of LCA findings is often limited by inconsistencies in the practitioner decisions and assumptions behind the LCAs (Scrucca et al., 2020).

This research consists of two components: a review and comparison of available wine LCA data, and a systematic wine LCA literature inventory. Ultimately, the goal of this project is to shed light on how and why LCA results vary across geographies, and to assess the degree to which the current breadth of LCA research collectively represents production patterns geographically. These conclusions are intended to help inform future food system sustainability research methods by contributing to our current understanding of farm-level LCA research and the associated implications for meta-analyses and LCA data synthesis projects. Thus, the primary motivation of this research is to enhance research development within the field of food system sustainability.

1.2 Background

Food systems encompass all components of food production and consumption, connecting all disciplines that relate to food, such as governance, agriculture, nutrition, and resource management, among others, though one single term. Food system sustainability is a field of research dedicated to optimizing these food systems in ways that can be sustained long-term to ultimately support the growing human population now and in the future. One of the most prominent challenges that food system sustainability addresses is the degree to which food systems are currently degrading the environment. Food production has been identified as the single most extensive form of anthropogenic land use on earth (Foley et al., 2005), and is responsible for roughly 70% of global water withdrawals (Poore and Nemecek, 2018). With food systems also being responsible for over a third of anthropogenic greenhouse gas emissions, the majority of which being attributed to agriculture and land-use (Crippa et al., 2021), food systems have been deemed a key driver of global warming. The heavy resource use and harmful emissions of food systems are causing major environmental repercussions, such as biodiversity loss (Maxwell et al., 2016), unstable and extreme weather patterns, and a substantial loss of ecosystem productivity and services (Campbell et al., 2017). For a few environmental challenges, such as destabilized nutrient cycling, climate change, and the loss of genetic diversity, radical mitigation efforts within food systems are needed to avoid further transgressing the earth's biophysical planetary boundaries and permanently altering the earth's capacity to sustain human life (Campbell et al., 2017). Thus, food system sustainability research is vital, now more than ever.

One of the ways in which the environmental impacts of food systems are quantified is though life cycles assessments (LCA). The life cycle assessment is a biophysical accounting framework used to measure the material and energy flows involved in a product or service's life cycle, typically communicated as contributions to a range of global-scale resource depletions (e.g. water use, cumulative energy use, etc.) and environmental concerns (e.g. climate change, eutrophication, etc.). These assessments target individual production systems with the purpose of quantifying their contribution to environmental concerns, thus facilitating shifts towards more sustainable practices and decision making. Typical motivations for food-specific LCA research include, but are not limited to, characterizing the environmental performance of commercial-scale production practices, novel or other experimental production techniques, alternate scenarios that have been or could be applied, or the consequential changes in flows that result from possible decisions.

Within the field of food system sustainability, the results of LCAs have a variety of applications, such as pointing to inefficiencies within production systems, informing impact mitigation policy, and informing consumer behaviours and choices, among other uses. Life cycle assessments are thus recognized as an important and useful tool, though not without limitations, and are being conducted at an increasing rate. From this growing breadth of LCA literature, researchers have also been able to use LCA results to draw conclusions about the environmental impacts of aggregate systems, such as national scale production and diet level impact assessments (Aleksandrowicz et al., 2016; Clune et al., 2017; Notarnicola et al., 2017). These reviews and meta-analyses are integral to food system sustainability research (Poore & Nemecek, 2018), as they not only help to characterize the environmental impacts of food systems, but also shed light on emission patterns and trends. For example, the meta-analysis of Poore and Nemecek (2018) demonstrates that the environmental impacts of food systems can be highly variable between geographies, products, and producers, as can be mitigation opportunities between geographies and production systems. Geographic variables in particular have been found to influence system contributions to environmental concerns (Steenwerth et al., 2015; Tabatabaie & Murthy, 2017), though these patterns are not yet fully understood (Clune et al., 2017).

Though extremely useful, life cycle assessments and the works that synthesize them are, as mentioned above, not without limitations. According to Clune et al (2017), among many other works (Röös et al., 2011; McAuliffe et al., 2016), LCAs are not suitable for comparisons due to the influence of methodological variation. Despite these suggestions, researchers continue to attempt LCA comparisons, syntheses, and aggregations because of their centrality to food system sustainability research (Clark & Tilman, 2017; Poore & Nemecek, 2018; Clune et al., 2018;

Richie et al., 2018). Differences between LCAs can arise from a range of factors, including the underlying motivations of the assessments, mentioned above, as well as the methodological choices of the author. For every LCA, the author must define the system boundaries of the production chain, the method for allocating aggregate contributions to a single functional unit, the environmental concerns and resource depletion categories of interest, the databases used to inform the results, and so on (Guinée & Heijungs, 2017). Inconsistencies in the underlying methods and decisions behind LCAs are often raised as an issue in systematic reviews (Heller et al., 2013; Clune et al., 2018), as this is a substantial source of uncertainty for aggregate food system impact estimations.

Food system LCA results may be highly variable for a number of reasons, including differences between systems as well as between the methodological decisions of the LCA practitioners (Scrucca et al., 2020). Thus, aggregate food system impact assessments must air on the side of caution when sampling life cycle assessments. Further complicating these challenges, LCA practitioners and food system impact assessment researchers must also be wary of the underlying sampling patters of food system LCA research, as it is unclear whether the current breadth of LCA literature is geographically representative of food production patterns. There are many reasons for which food LCAs are undertaken, some having very little to do with representing production patterns. For example, LCAs are conducted for reasons such as personal interests, accessibility, private funding, institutional support, and so on. Together, the above points suggest that we are not yet able to utilize or interpret food production LCAs to their full potential due to the uncertainty surrounding LCA sampling patterns as well as the variability of emission patterns and trends, highlighting that more research is needed.

1.3 Summary of literature

Many of the ideas I explore in this research were inspired by the findings of Poore and Nemecek (2018), who conducted a meta-analysis of food system life cycle assessments to study the environmental impacts of food production at a global scale and to facilitate the implementation of systemic mitigation strategies. Their work was undertaken with the intention of characterizing the variability of impacts between production systems, focussing on system contributions to a range of environmental concerns and resource depletions. They present their results by looking at the degree to which these contributions can vary between producers of the same product, between products, and between geographies, among other factors. Poore and Nemecek (2018) conclude that the environmental impacts associated with food production are highly variable, as are mitigation opportunities between producers and also between geographies. The work of Poore and Nemecek is central to my research because it demonstrates that food production systems and their associated contributions to environmental concerns are heterogeneous across many variables, indicating that there is room for expanded understanding with regard to food system LCAs and how they can be utilized effectively at a larger scale.

The second publication that informed this research was a life cycle assessment conducted by Steenwerth et al. (2015) on wine production systems in California. This work compared the greenhouse gas emissions attributed to producing one ton of grapes from cradle-to-farm gate in two different wine growing regions of California: Napa and Lodi. This study found that emissions per metric ton of grapes were almost twice as great in Napa compared to Lodi, which was largely attributed to harvesting techniques and lower yields per area. This re-enforces Poore and Nemecek's (2018) conclusion that contributions to environmental concerns are highly variable between producers of the same product as well as between geographies, and also extends these conclusions to wine and grape production specifically.

Together, these articles illustrate that the results of food system life cycle assessments are inconsistent between systems, which has implications for public and private decision-making around emission reduction strategies as well as implications for emission reporting to downstream parties (e.g. retailers, consumers, etc.). It also means that, in efforts to aggregate LCA data, it may be problematic to assume that LCA literature is currently representative of larger areas and system contributions to environmental concerns. In conclusion, food LCA research, production system LCA sampling patterns, and food system impacts patterns must be further explored.

1.4 Study introduction

The purpose of this exploratory research is to further investigate how and why farm-level production systems vary in their contributions to environmental concerns by assessing their variance both within and between major production regions. Separately, this work also aims to assess whether life cycle assessments have thus far been undertaken systematically to geographically represent production patterns, or whether the alternative motives behind life cycle assessment research may be causing geographic over-representation or under-representation in the literature, relative to production patterns. To do so, this work has drawn from published wine grape LCAs to answer the following two research questions: First, are conventional, commercial scale, grape production system contributions to environmental concerns more similar within production locales than between, specifically exploring production locales identified in Southern Europe, where broadly methodologically consistent wine LCAs have been conducted? Second, has wine LCA research been undertaken systematically to geographically represent large-scale production patterns? The objective of the first research question was to assess the variability of greenhouse gas emission values and source contributions to emissions attributed to the production of one kg of grapes from cradle-to-farm gate, comparing values both within and between identified production locales. This was done while controlling for methodological difference during LCA sampling and standardizing for a consistent unit of output during data extraction. The second objective of this research was to compare national wine production volumes for the world's top wine producing countries in kt per year relative to the degree that wine LCA research has thus far been conducted in these countries, with the intention of determining whether there is geographic over-representation or under-representation occurring in LCA literature.

Given that these topics could be explored though a wide variety of domains within food production, I have chosen to focus on grapes in order to narrow the scope of my project. Although the project is not specifically motivated to understand the environmental impacts of grape and wine production, and is rather meant to address the emission patterns identified by food production LCA research and the sampling patterns that have informed them, my focus on wine is nevertheless important. Generally, discretionary food products have received less attention from food production impact assessment research than foods and food systems that are nutritionally dense (Friel, 2015), and are thus a more novel lens though which food system sustainability can be explored. Despite not being nutritionally valuable, wine is heavily consumed in many cultures and societies, and must therefore be addressed in order to properly characterize the impacts of food production and consumption.

1.5 Summary of approach

The first component of this research, the review and comparison of available wine LCA data, began with purposive non-probabilistic case study sampling. This sampling process was strategically designed to produce a sample set of methodologically consistent grape LCA case studies that could be compared. In order to achieve this, a specific set of inclusion criteria were applied to all potential case studies identified in Scopus, and conversion factors were used to standardize all functional units. Within the sample set, studies were grouped together into production locales based on their spatial distribution as well as the pre-established grape growing regions of the area. The data extracted from the studies included the total GHG emissions (g CO_2 eq) attributed to the production of one kg of grapes from cradle-to-farm gate, as well as the quantified material and energy flows of production and the emission contributions of major production substages, all for the standardized unit of output. These values were then compared within production locales to assess the variability of system emissions within regions, and were aggregated to create generalized emission profiles for each production locale, which were then further compared to assess the variability of systems between production regions.

The second component of this research was a systematic literature inventory conducted to assess the geographic sampling patterns of grape and wine LCA research undertaken to date. This process also began with a literature search in Scopus, which aimed to create a comprehensive list of published wine and grape LCAs. From each study, the country in which the studied vineyards were located was documented. Additionally, wine production data from the Food and Agriculture Organization of the United Nations (FAO) were extracted for the years 2016, 2017, and 2018. A tornado chart was created in excel to illustrate the wine production volumes of each country relative to the extent that the country has been addressed by wine LCA research. The results were examined to identify any countries where LCA research has been disproportionately undertaken in relation to national wine production volumes.

In summary, the goal of this research was to assess how wine production system contributions to environmental concerns vary within and between regions, and to better understand the sources of variation across geographies. As well, to study the sampling patters of wine LCA literature with the intention of determining whether case studies are systematically undertaken to collectively be geographically representative of production patters, or whether other motives may be contributing to geographic over-representation and under-representation. The conclusions of this research will help inform future food LCA sampling methods and aggregate food production impact assessment research methods, thus contributing to the sustainable development of our food systems.

Chapter 2: Literature review

2.1 Overview

This chapter focuses on peer-reviewed publications drawn from a variety of academic databases and other accessible repositories such as journals, and was limited to articles, conference presentations, and credible databases presented in English. Google Scholar, Scopus, and Web of Science were the primary search engines used to conduct this review. Search results were supplemented with literature provided by Dalhousie-based associates working within the field of food system sustainability research.

The purpose of this literature review is to broadly overview the work that has been done within the field of food system impact assessment research to date. More specifically, the development of food LCA research, and the methods that food system LCA aggregations have followed. First, the environmental impacts of food-systems and the associated repercussions are overviewed in a global-scale context, and the history, development, and standards of the life cycle assessment framework are discussed using foundational LCA literature. Next, the current strengths and pitfalls of food system LCA research are reviewed, highlighting the data and knowledge gaps that are currently acting as sources of uncertainty. The motivations and major conclusions of aggregate food LCA research is then defined, focusing on pivotal and well-cited meta-analyses and systematic reviews. Literature exploring the relevance of geographic to the LCA framework is then outlined, including the debates that have emerged from the topic. Knowledge gaps that have been identified in the literature are reviewed, with a focus on geographic over-representation, under-representation, and sampling biases as potential sources of uncertainty. Last, I review the current state of knowledge and future research directions that should be taken within the field of food production LCA research.

2.2 Food systems and their contributions to environmental concerns

Since the industrial revolution, food production has developed to become one of the most environmentally taxing anthropogenic activities that humans depend on (Campbell et al., 2017). In 2015, Steffen et al. created an updated framework of planetary boundaries – thresholds of anthropogenic impacts on the environment that should not be transgressed if humanity is to remain within what is described as a 'safe operating space', based on Rockstrom et al's (2009) earlier work on planetary boundaries. These concepts were updated by Steffan et al. in 2015, concluding that four boundaries have already been transgressed: Climate change, biosphere integrity, biogeochemical flows, and land use change. Campbell et al. (2017) extend these concepts to food systems by demonstrating that the inputs and outputs of agriculture are key drivers of planetary boundary transgression, where agriculture is identified as the most prominent driver of land use change, biogeochemical flows, freshwater use, and a significant contributor to climate change. These effects are major, as the land use change component of food production alone has already compromised the biosphere's productive capacity to the point where it may no longer be able to sustain the global human population in the long run (Foley et al., 2005; Myers et al., 2017). Furthermore, the implications of food production extend far beyond the direct impacts to society. In 2016, Maxwell et al. conducted an in-depth analysis assessing the degree to which anthropogenic activities threaten biodiversity. Their results illustrate that food production, specifically agriculture, is the second most prevalent threat to biodiversity loss on earth, closely following over-exploitation. Given that Steffen et al. (2015) suggest biosphere integrity has already been transgressed as a planetary boundary, these results are particularly troubling. In summary, this literature illustrates that the environmental impacts of food systems must be addressed to mitigate anthropogenic impacts on the environment and the associated repercussions, including the biosphere's capacity to sustain human life.

2.3 Life cycle assessments

2.3.1 Development

One of the ways in which the environmental impacts of food systems are quantified is through life cycle assessments (LCA). LCA is a biophysical accounting framework used to measure the material and energy flows involved in a product's life cycle, typically communicated as contributions to environmental concerns (e.g. climate change, eutrophication, etc.) and resource depletions (e.g. freshwater use). An LCA is a valuable tool for quantifying the environmental impacts of food systems and for identifying opportunities for impact mitigation, but is not without limitations. The first documented LCA case studies, though not at the time described as such, date back to the 1960's and early 1970's, when critical resource depletion concerns and environmental conservation first emerged as issues of public concern (Guinee & Heijungs, 2012). Since then, the LCA framework has come a long way. In 2006, the International Organization for Standardization (ISO) published an updated and standardized methodological framework for life cycle assessments, outlining the tool's strengths and weaknesses (ISO 14040, 2006). As suggested by the ISO (2006), LCAs are useful for identifying mitigation opportunities, informing decisions within industries, governments, and non-government organizations, and for outlining appropriate environmental indicators and standards for emission and output regulation. On the other hand, LCAs are limited in their ability to inform decisions because their scopes rarely extend to economic and social considerations, and because they often cannot be compared due to methodological and contextual inconsistencies (Scrucca et al., 2020). Though currently limited, Finnveden et al. (2009) suggest that the applications and methodologies of LCAs are in a constant state of standardized development and improvement, and thus hold the potential for a wider range of applications in the future. In conclusion, life cycle assessments are an extremely useful tool for understanding some key resource depletion measures and environmental impacts from a systems-thinking perspective, and should be used to sustainably develop food systems and mitigate agri-food impacts. That being said, their current shortcoming should not be ignored.

2.3.2 The LCA framework

A traditional life cycle assessment is comprised of four phases: The goal and scope, the inventory analysis, the impact assessment, and interpretation (Guinee & Heijungs, 2012). The goal and scope phase of an LCA is primarily intended to define the boundaries of the system being assessed and the functional unit of production. A functional unit refers to the quantity of product being assessed, and the system boundaries of the study outline the cut-offs of the system. Once the goal and scope of the assessment are established, an inventory analysis is typically conducted to quantify the material and energy flows involved in the life cycle (e.g. amount of pesticides) per unit of production. These inputs and outputs then inform the impact assessment, where impact values are calculated to represent the product's contributions to environmental concerns and resource depletions. The final phase of the life cycle assessment is interpretation, where the output of the assessment can be discussed in a variety of ways. Some common means of interpretations are to compare the system to others with a common functional unit and to discuss mitigation measures that would improve the sustainability of the system. Though this is listed as the last phase of the LCA, interpretation typically occurs throughout the entire assessment rather than solely at the end.

2.4 Using LCAs for agricultural production systems

2.4.1 Applications

In application, agricultural life cycle assessments can be used to inform decisions from either a supply perspective or a demand perspective. On the production side, LCAs are often used to compare production methods or strategies for improving eco-efficiency, and to perform hotspot analyses to identify sub-systems or activities contributing disproportionately to overall environmental concerns (Heller et al., 2013). On the consumption side, food production LCAs can be used to inform consumer choices though comparisons of meal and/or ingredient options as well as diet level comparisons (Heller et al., 2013).

With the increasing urgency of sustainability and environmental conservation, LCAs have grown in popularity and have become much more prevalent. As a result, the breadth of published LCA case studies has become extensive, leading to the emergence of LCA aggregations and large-scale impact assessments. Often taking the form of meta-analyses and systematic reviews, these aggregate studies often synthesize the results of life cycle assessments to inform inferential analyses regarding the impacts of broader systems, such as national dietary patterns (Hellweg & Canals, 2014).

An example of this is a study by Martin and Brandão (2017), which drew from various published food LCAs to quantify and examine the environmental implication of Swedish dietary patterns, ultimately motivated to help influence the environmental impacts of food consumption in Sweden in a controlled manner. Similarly, Tillman and Clark (2017) also drew from published food LCA data for their research, where they drew connections between health trends and sustainable food consumption in order to promote large-scale dietary change. These conclusions and methods are further supported by the work of Ritchie et al (2018), who assessed the environmental impacts attributed to healthy diet recommendations from around the world. As predicted by Ritchie et al. (2018), current dietary guidelines were not deemed compatible with future carbon budget goals, ultimately suggesting that production systems and social norms both require dramatic re-framing. Another pivotal publication in this field is the meta-analysis of Poore and Nemecek (2018), covering a wide breadth of products and geographies. The work of Poore and Nemecek (2018) demonstrates that synthetic LCA research is not only helpful for identifying inefficiencies and mitigation strategies, but can also be used to better understand the variability of food systems and the relative effectiveness of mitigation across different systems and areas. Last, Willet et al.'s (2019) well-cited systematic review explores the extent to which food systems are negatively impacting human health, acknowledging the direct impacts that consumptive choices can have on the human body, as well as the environmental consequences associated with producing these foods. Willet et al. (2019) use their findings to create mitigation strategies that can be applied by producers, as well as dietary recommendations for consumers. These are just a few of many aggregate assessments that have drawn upon LCA literature to better understand large-scale food system contributions to environmental concerns. In summary, synthetic food system impact assessments are a vital component of sustainable development research, as their results can be used to inform dietary recommendations, supply chain improvements, and decision maker choices. Generally, they point to a clear need for shifts in consumer awareness and production system efficiency at a global scale.

In addition to broadening our understanding of how large-scale consumption and production choices contribute to environmental concerns and resource depletion, aggregations of food system LCA research can also be used in an exploratory fashion to help us better understand patterns within production systems that can point to potential mitigation opportunities for individual systems. For example, the study of Poore and Nemecek (2018) highlighted some key hot spots that were contributing disproportionate to emissions relative to other emission sources of production, such as fertilizer use and fuel consumption. Tough these patterns were deemed to be highly variable, even within producers of the same product, these conclusions nevertheless suggest that LCA aggregations and synthesis can be used to point to common patterns across production systems, which can then be used to address mitigation at the farm level (Poore & Nemecek, 2018).

2.4.3 Shortcomings

Although aggregate assessments are a valuable food system and impact mitigation modeling tool, they are associated with high levels of uncertainty that can only be mitigated with more research focus. In 1998, Huijbregts analyzed key concerns amongst LCA experts regarding high levels of uncertainty, specifically highlighting that some practitioners believe high uncertainty may render LCA results insignificant and meaningless. In a systematic review by Clune et al (2017), four key shortcomings of LCA research are discussed. First, that LCA methods are highly inconsistent across farm-level LCAs, raising questions of whether they can effectively be compared (Röös et al., 2011; McAuliffe et al., 2016). Second, the current body of LCA literature is not comprehensive, lacking data for many food products and production regions (Clune et al., 2017). This relates closely to the third issue bought up by Clune et al., (2017) which refers to a clear lack of publicly accessible LCA synthesizing resources, creating challenges for those who want to utilise LCAs for decision making. Last, life cycle assessments and systematic LCA reviews often fail to report on all relevant impact categories (Röös et al., 2011), which may be misleading to readers. The relationship between impact indicators can often times be negative, meaning that a system contributing substantially to one environmental concern cannot be assumed to be highly impactful in other impact categories as well. Generally, these issues suggest that drawing conclusions about food system contributions to environmental concerns with confidence and accuracy is currently a challenge in food system sustainability research.

A poster presentation from Nicole Arsenault (2020) at the International Food LCA 2020 conference addressed the challenge of uncertainty by highlighting the need for a more structured and systematic approach to LCA aggregations. In assessing the transparency and repeatability of published aggregate LCA works, Arsenault concluded that a significant proportion of studies provided inadequate information and details, and were therefore deemed non-replicable. Similarly, Finnveden et al. (2009) outline the uncertainties in LCA research that stem from the data, the author's decisions, and the various characterization models. These uncertainties range from potentially erroneous datasets to the inherently unreliable relationship between outputs and impacts. In conclusion, for many, the LCA is a powerful tool used to better understand the impacts of the world's industrial systems. However, the LCA framework cannot be harnessed without the acknowledgment of uncertainty and limitation. The uncertainty associated with synthetic and aggregate impact assessments requires more attention, as it is a key limitation reducing the significance of this important research.

2.5 Data gaps

As mentioned in Clune et al's (2017) systematic review, there are geographic gaps in LCA literature where little is known about regional production systems. These gaps do not necessarily correlate to lower regional production outputs, and could thus be leading to the under-representation of certain regional systems in LCA literature. Clune et al. (2017) note in their review that the LCA data they have drawn from is European centric, though their objective was to study global food systems. This issue is mentioned again in their discussion, where they suggest that there is a European dominance in LCA literature (Clune et al., 2017). In 2019, the Food LCA Database was created by Robert Parker at Dalhousie University to synthesize food system life cycle assessment research. Though this database remains incomplete, as of late 2020 it contained detailed information on approximately 1,000 food system-related case studies drawn from over 600 publications. As seen in Figure 1, which was pulled from the database's summary information, the distribution of LCAs documented within the Food LCA Database (2020) is currently heavily concentrated in the industrialized regions of the world. In particular, this concentration appears to be European centric, supporting the observations of Clune et al (2017). This suggests that there could be significant under-representation and over-representation occurring within LCA research, though this is a newer idea that has only briefly been mentioned in the above literature.

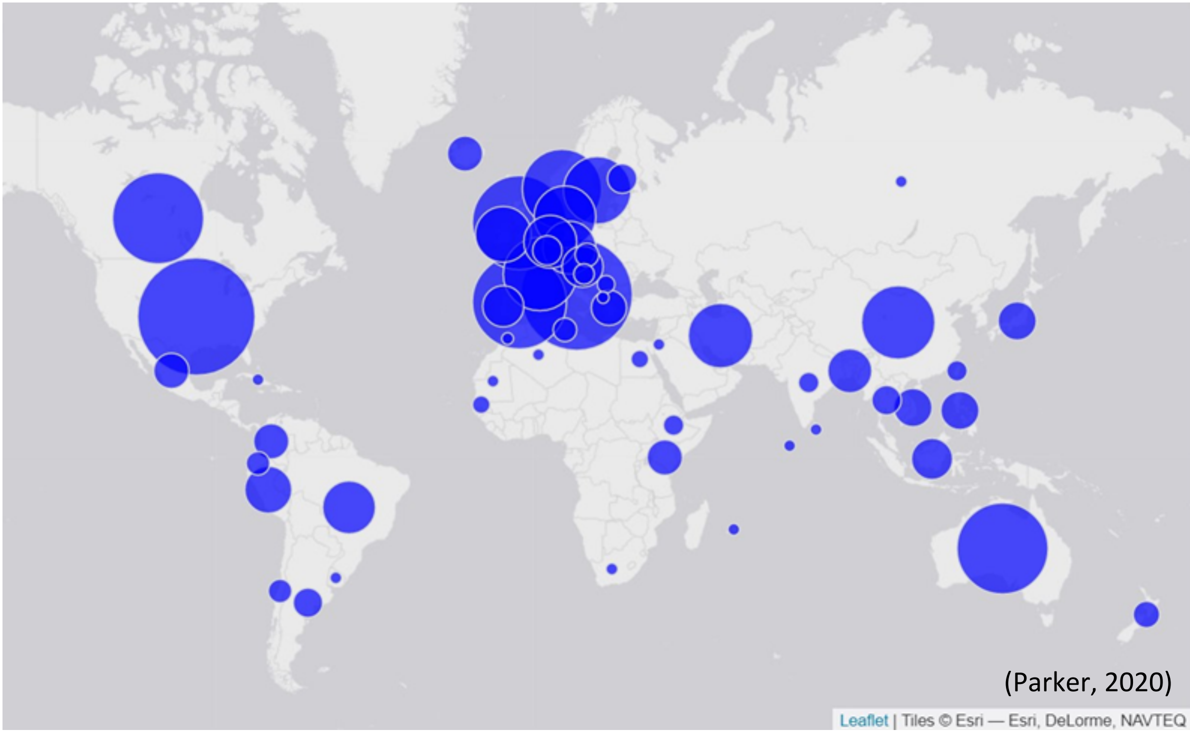

Figure 1. The global distribution of food LCA case studies documented within the Food LCA Database, retrieved from Food LCA Database summary information page in November 2020 (Parker, 2020). One of the objectives of this database is to synthesize food production LCA research at a global scale, and is thus motivated to eventually represent all parts of the world. Thus far, however, the LCAs included in the database appear to be concentrated in some regions and lacking in others. In particular, the concentration of research in industrialized regions, specifically in Europe, is noteworthy.

Similarly, Parker and Tyedmers (2015) developed a fishing fleet fuel consumption database from primarily publicly available sources (e.g. government reports, peer-reviewed articles), which aimed to compile data on the relative energy performance of fisheries to facilitate analyses of patterns between fisheries and over time. This database pointed to a clear concentration of fuel consumption data and impact assessment studies in European countries due to robust analyses within those regions. A 2011 review by Mila I Canals et al. relates to these observations by assessing the consequences of geographic LCA data gaps as well as the mitigation strategies used by LCA practitioners. Mila I Canals et al. (2011) suggest that, when dealing with data gaps, LCA researchers will often turn to proxy datasets, extrapolate data from other regions, or leave the gaps as they are. The review concludes that more research is needed to develop a better approach for addressing geographic data gaps in LCA research, given that the above management strategies can be erroneous, and are associated with high uncertainty. In summary, it appears as though food system LCAs are not being undertaken in a coordinated or systematic way to represent global production patterns, leaving geographic data gaps in published LCA data. As suggested by Heller et al. (2013) these data gaps remain a prominent challenge for large-scale environmental impact assessments.

2.6 The relationship between system locations and their contributions to environmental concerns

2.6.1 Geographic influences

The environmental impacts measured by LCA research can vary greatly depending on where the system is located. This has been demonstrated by the work of Poore and Nemecek (2018), where it was determined that contributions to environmental concerns are highly variable between systems and geographies, as is the potential for impact mitigation in different regions. In their figure 2 (Figure 2), Poore and Nemecek (2018) illustrate that the underlying processes and inputs that dictate the GHG emission values of high-performing wheat farms vary substantially in different regions.

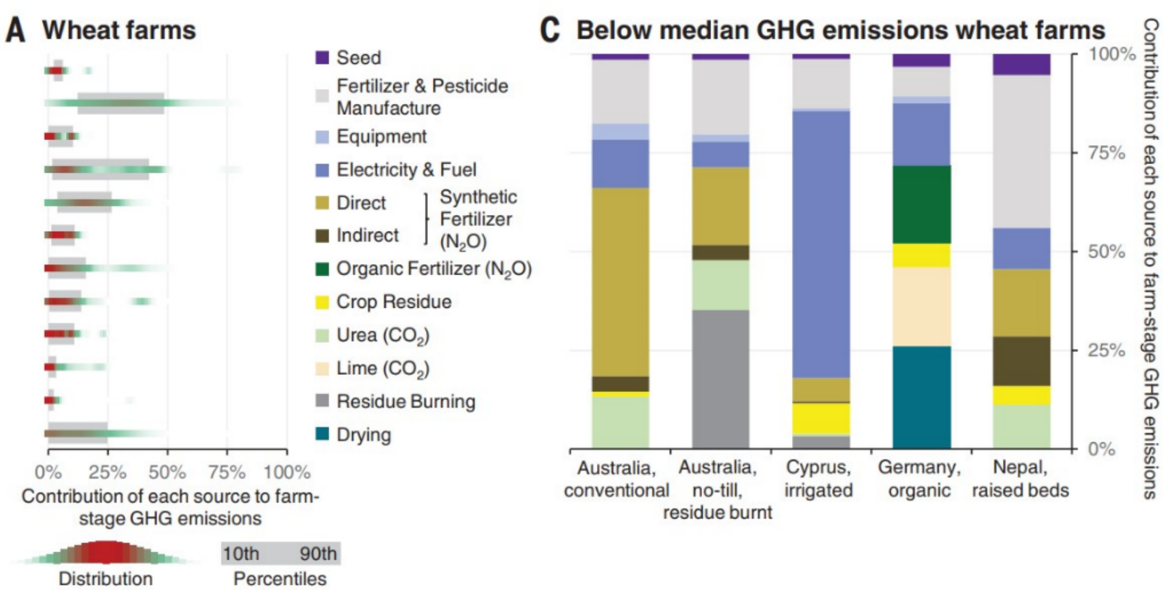

Figure 2. Poore and Nemecek's (2018) depiction of contributions of emission sources to total farm-stage GHG emissions. More specifically, panel C depicts the contributions of emission sources for example producers with below-median GHG emissions, illustrating the variability of these underlying emission sources across different systems, even when comparing systems that perform relatively similarly in terms of their total GHG outputs.

Similarly, a case study by Tabatabaie and Murthy (2017) has demonstrated that the contributions to environmental concerns associated with producing camelina in the Northwestern United States vary significantly by production locale as a result of varying environmental factors such as weather patterns, field management practices, and ecosystem services. Last, Steenwerth et al. (2015) suggest that the environmental impacts of wine production can vary significantly by region because of varying management goals, soils, and climates. This study compares GHG emissions resulting from viticulture undertaken in the Napa and Lodi grape growing regions of California to illustrate that system outputs can vary between regions, as do the system's environmental impacts. The findings of Steenwerth et al. (2015) are illustrated in the top two rows of Figure 3, where the total CO_2 equivalent emissions associated with the cultivation of one metric tonne of grapes is significantly higher in Napa than in Lodi, California. Furthermore, the sub-stages of cultivation that are contributing to greenhouse gas emissions are also dramatically different.

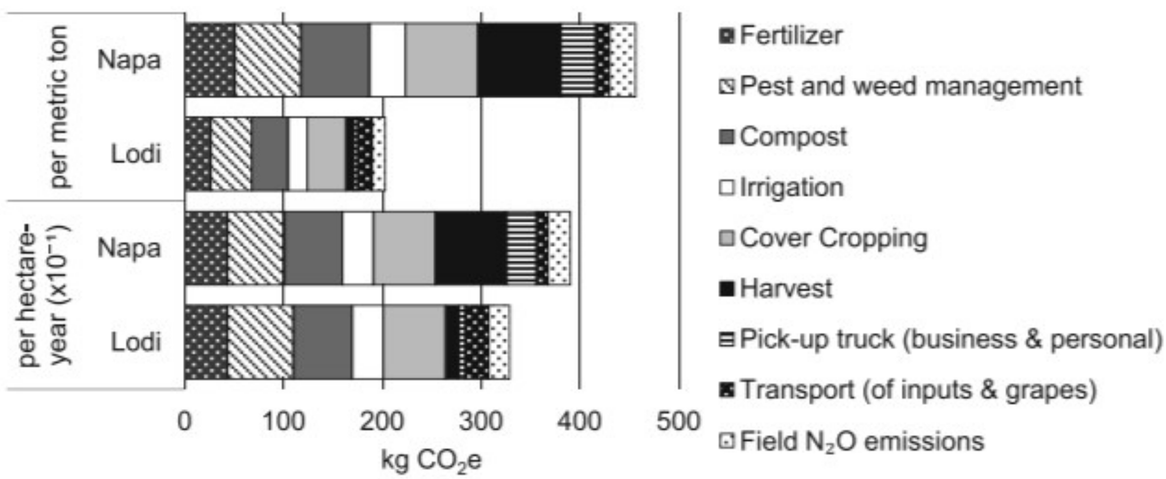

Figure 3. Steenwerth et al's (2015) comparison of global warming potential (GWP) values attributed to the production of one metric ton of grapes from cradle-to-farm gate in Napa and in Lodi, California. More specifically, this figure also shows the absolute contributions of each emission source of production to the total GWP for one metric ton of output, illustrating variable contributions between the two systems, specifically for harvesting emissions and personal transport.

In conclusion, comparisons of the results from LCAs undertaken on seemingly very similar systems from different locales have revealed that results can vary by region due to differences in climate, agricultural practices, and environmental conditions, among other factors.

2.6.2 Regionalization

The spatial dimension of LCAs has been debated since the framework was originally developed in the late 1960's. Some argue that localized characterization is essential for reducing uncertainty (Potting & Hauschild, 1997), while others suggest that this is not in line with the objective of the assessment framework (Perriman, 1995). The LCA framework was originally developed to quantify contributions to global impacts, and therefore had no need for spatial impact specificity. Since then, the framework's applications have shifted to encompass localized production systems as well as large scale supply chains. In addition, some phenomena of global-scale concern, such as nutrient leeching (Steffen et al., 2015), are experienced very differently across the globe depending on the conditions of the receiving environment. This has sparked debate about whether spatial dimensions should be adopted into the LCA framework, and if so then how (Hauschild, 2006). Finnveden et al. (2009) suggest that these framework developments will significantly complicate the LCA framework, and will require much more information and transparency. The above conclusions indicate that the spatial dimension of LCA research has been well addressed in the literature, yet it remains an area of debate and uncertainty due to its complexity.

Geography has been identified as an important variable in LCA research, but the focus of this thinking has been geared towards the spatial variability of localized impacts, as discussed above, rather than the geographic variability of contributions to environmental concern. In 2018, Patouillard et al. carried out a critical review of propositions for integrating a spatial dimension into the LCA framework. Although this was a review of all geography related LCA recommendations, the majority of the propositions reviewed in this assessment were focused on mitigating the issue of inventory regionalization, rather than the potential for outputs to vary between regions. Similar to the work of Patouillard et al. (2018), Mutel et al. (2019) broadly overviewed recommendations for regionalized life cycle impact assessments. Many reviews of this nature have been done, most of which focus on the issue of regionalized inventory characterization as opposed to regional output quantification. In conclusion, the reviews that address the spatial component of LCA have heavily favoured the issue of regionalized inventory data, and have not yet addressed geographically variable results or the implications of this variability within the context of aggregate food-system research.

2.7 Knowledge gaps

Although some of the spatial dimensions of LCA are well recognized, the literature surrounding the LCA framework has a long way to go before farm-level LCAs can effectively be used to inform our understanding of aggregate food system impacts as well as contributions to large scale environmental challenges. Little is known about how well the current body of published LCA literature is geographically representative of global food production patterns, and whether geographic over-representation and under-representation hold the potential to affect the results of aggregate food system impact assessments. In 2013, Heller et al. published a review of emerging challenges in diet-level LCA studies, highlighting that it is a relatively young methodology, and is still undergoing significant development. Further, the review also acted as a call for database developments and a more sophisticated and systematic research approach. Green et al. (2020) expand upon these statements by proposing seven future research areas to develop the robustness and transparency of diet-level LCA methodology. Their conclusions were threefold: (a) Geographic information science (GIS) has not yet been adequately applied to the diet-level LCA framework, (b) methods must not only be standardized but also enhanced, and (c) the availability and quality of data must be enhanced so that gaps can be filled, such as the geographic data gaps mentioned above. In conclusion, steps must be taken to address the challenges that exist for LCA data syntheses and aggregations.

2.8 Conclusions

In Chapter 2, the relevant developments and challenges of food system impact assessment research were reviewed. In summary, food-system impact assessments hold the potential to catalyze global-scale food system sustainable development, though the framework is complex and constantly developing in response to uncertainty. These framework developments are important because they address limitations in LCA research. Although methodological developments in LCA research have received a lot of attention from practitioners and experts, there are areas of uncertainty that have not yet been well addressed, such as geographic sampling biases. As geographic data gaps in LCA literature emerge, it is important to address the potential over-representation and under-representation of production locales.

In addition to LCA developments, this literature review aimed to better understand aggregate food system analyses and synthetic impact assessments. Synthetic food system impact assessments draw on LCAs to help inform predictions of aggregate system outputs. Although it has been demonstrated that impacts can be highly variable between systems and production locales, many synthetic works fail to consider potential LCA sampling biases when predicting aggregate impacts, compromising the reliability and accuracy of their conclusions. This chapter points to a clear knowledge gap in the literature, where neither LCAs nor aggregate impact assessments have assessed the importance of representative geographic sampling. The spatial component of LCA research must therefore be further examined so that the uncertainty attributed to aggregate impact predictions can be mitigated.

Chapter 3: Methods

3.1 Overview

The following research methods were designed with two objectives in mind. The first was to analyze the variability of GHG emissions for grape cultivation within and between production locales within which numerous wine grape LCA studies have been conducted. This process began with purposive non-probabilistic case study sampling, drawing from published wine and grape LCA literature to create a sample set of grape LCAs that were broadly methodologically consistent, and all assessed conventional grape production systems from cradle-to-farm gate. This was followed by a data extraction process in which all values were standardized for a consistent unit of output. Data extracted from these studies were compared within and between common production locales, where similarities and differences were communicated with data visualization methods such as proportional stacked bar charts, following a similar formatting approach to Poore and Nemecek (2018). The goal of this process was to examine emission patterns both within and between production locales to assess the variability of total emissions, emission source contributions, and the underlying material and energy flows of the systems.

The second component of this research was a systematic literature inventory conducted to assess the geographic sampling patterns of grape and wine LCA research undertaken to date. The objective of this assessment was to compare global wine production patterns relative to the extent that the countries have been addressed by wine LCA research. First, an advanced search in Scopus was conducted, intended to form a comprehensive list of published and accessible wine LCA case studies that have been undertaken to date. The results of this search were output to Excel, where the countries in which the studies took place were recorded. National wine production volume data was downloaded from the Food and Agriculture Organization (FAO) and documented in a similar fashion. Using a tornado chart, production volumes were compared relatively to national wine LCA research focus, with the purpose of illustrating whether over-representation or under-representation has occurred.

3.2 Review and comparison of available wine LCA data methods

3.2.1 Procedures

As overviewed above, this research began with a systematic and comprehensive literature search. Wine LCA case studies were identified in Scopus, Elsevier's academic literature database, using the following search term: 'TITLE-ABS-KEY ("Life cycle assessment" OR "life cycle analysis" OR "lca" AND "viticulture" OR "wine*" OR "grape*") AND DOCTYPE(ar)'. From this search, conducted in November 2020, 143 articles were identified, and their titles and abstracts were read to positively identify those studies in which the results of grape or wine LCAs were reported. The output of this process was 58 wine LCA studies, which were then exported in an Excel-readable format. Details retained included author names, year of publication, article title, and article link. Non-probabilistic case study sampling was then carried out to create a methodologically consistent dataset of wine LCA case studies, where case studies were assessed against seven pre-determined inclusion criteria. Inclusion criteria were as follows:

- Results must quantify global warming potential (GWP) in CO_2 equivalents
- Functional unit must be one kg of grapes (wet weight) or must be accompanied by a conversion factor between grapes and wine and/or employ a functional unit that can be easily converted to one kg of grapes (e.g a 0.75 L bottle of wine)
- Data from cradle (cultivation) to farm gate can be extracted to stand alone
- The study must be published no earlier than 2010
- The study must avoid significant system expansion allocation
- The production system must be characterized as conventional/commercial
- The study must be published in English

As the majority of the remaining studies were undertaken in Italy, Spain, and Cyprus, these locations were chosen as the areas in which studies would be retained for further analyses, and other studies were discarded. Within each of the three countries, sub regions were identified based on well-established wine production regions, and case studies that occurred within the same sub-region were grouped together. For this project, the production locales identified included Northern Spain (Galicia and Asturias), Central Italy (Tuscany and Umbria), Sardinia in Italy, and Cyprus as its own production locale. Data from the remaining studies were also extracted for the purpose of better understanding system patterns within the three countries, but were not included in any group comparisons.

3.2.2 Area of interest

My research was focused on LCAs conducted on commercial scale, conventional, wine production systems from Italy, Spain, and Cyprus. These regions were selected for this research because advanced literature searches in Scopus indicated that, in the case of wine, these production locales have received significantly more LCA attention than other regions. For other regions of the world, it was unclear whether the LCA data would have been abundant enough to support my analyses. Italy is currently the world's leading wine producer, exporting the most wine of any country in 2019 (FAO, 2020). Italy is described as having a Mediterranean climate, where summers are hot and dry, and winters are cooler and damp. Spain is also among the world's top three wine producers in gross output, competing closely with France for second place (FAO, 2020). Spain has the greatest vineyard surface area of any country, encompassing a variety of climatic zones. Also classified as a Mediterranean climate, summers can range from hot and dry to cool and damp along the Atlantic Coast, and winters vary from cool and damp to cold and wet (NOAA, 2020). The third country of interest, Cyprus, does not contribute significantly to the global wine sector, but produces a notable quantity of wine on a per-capita basis. Cypriot vineyards contribute significantly to the national economy, which may explain why, to date, numerous wine grape LCAs have been undertaken in this Country. Cyprus has a warm temperate climate with dry summers that range from warm to hot (Kottek et al., 2006).

3.2.3 Analysis

Following a similar process to that of Poore & Nemecek's meta-analysis (2018), detailed greenhouse gas emission data were pulled from each case study for a standardized unit of output. For the purpose of this study, one kg of grapes was selected as the functional unit, measured as a wet weight. Based on observation, one kg appears to be the most common functional unit used in horticulture LCA's (Food LCA Database, 2019), and thus allows for the greatest sample of consistent wine-grape LCAs. Where studies reported their results using another volumetric or mass based functional unit, and a conversion basis was recorded (e.g. kilograms of grapes to bottles of wine) or standard unit conversions could be applied (e.g. tonnes to kilograms grapes), GHG emission rates were converted to the one kilogram standard used in this study.

Following the life cycle assessment framework (Guinée and Heijungs, 2012), comparisons were undertaken for both the inventory analysis and the impact assessment phases of the LCA case studies. For the inventory analysis, GHG emission source material and energy inputs were extracted from the inventory analysis section of the case studies, communicated as raw values per kg of grape output. Inventory items of interest include fossil fuels, synthetic fertilizes, organic fertilizers, and pesticides. For the impact assessment phase, the GWP of each production system was extracted from the case studies, communicated as grams of CO_2 equivalents per kilogram of wet-weight grape output. Focus was then shifted to the impact assessment phase of the case studies, where the GWP of one kg of grape production was extracted from each study, and substage contributions to total GHG emissions were extracted wherever possible. For the purpose of comparisons, conversion factors were used to compute all GWP values to a standardized FU as described above, and impact contributions by substage were standardized to include four substages: Fuel use and field operations, fertilization, pesticides, and contributions from unknown or other substages. Proportional stacked bar graphs were used to compare the GHG emission contributions by substage relative to one kg of grapes produced up to farm gate for each of the cases included. To characterize typical or average sub-system emission contributions within production locales, percent contributions were pulled from local studies providing sufficient data, and omitted where data was not available. The purpose of these comparisons was to explore the greenhouse gas emission patterns of grape production systems within identified regions, as well as differences in emission patterns between production locales. Together, these analyses illustrate the degree to which environmental impacts can vary across regions.

3.3 Systematic literature inventory methods

3.3.1 Procedures

The second objective of this research was to compare the national wine production volumes of the world's top wine producing countries to the amount of LCA research attention the country has received. Scopus, Elsevier's academic literature database, was mined using the same search term used to address my first research question, outlined above (section 3.2.1), to create a comprehensive dataset of wine case studies published as peer-reviewed articles in academic journals. All wine case studies identified in Scopus were exported into Excel, and assessed under the following inclusion criteria: Must use wine grapes or wine as the functional unit, and must be a life cycle assessment under ISO 14040 standards. For each study, the country where the vineyards were located was identified. Next, national wine production volume data was extracted from the FAO's open access agriculture database. Wine production quantities were downloaded for the world's major grape producer countries identified in the 2019 Statistical Report on World Vitiviniculture (OIV, 2018). Wine production volumes were extracted for the years 2016, 2017, and 2018, then averaged across all years.

3.3.2 Analysis

The goal of this analysis was to produce a visual comparison of national wine production volumes in kt/year relative to the frequency that wine LCA research was conducted in these countries. Data was shown for all countries that produced at least 1 million tons of wine in 2018 (OIV, 2019), as well as all countries in which LCA case studies have been conducted. A tornado bar chart was created in Excel displaying country names in the center column, wine production volumes in kt/year on the right, and LCA research focus as a count of published studies on the left. It is worth noting that this is not a conventional application for a tornado chart, as they are traditionally used to depict the results of sensitivity analyses.

3.4 Limitations

3.4.1 Delimitations

It is important to note that when reviewing and comparing available wine LCA results, this research focuses solely on greenhouse gas emissions. This means that conclusions cannot be drawn with regard to any other impact categories or indicators (e.g. eutrophication). The choice to study only GHG emissions was made based on the assumption that GWP is the most commonly studied impact category, and would thus allow for the greatest case study sample size.

Another delimitation of the review and comparison of available wine LCA results is the deliberate focus on wine-grape LCAs with system boundaries from cradle-to-farm gate. The choice to focus on wine-grapes was made from an observation that the wine supply chain has received a sufficient amount of LCA attention to support a project of this scale, but has not yet been subject to much synthetic work. Additionally, systems were only assessed from cradle-to-farm gate because this research was focused on agricultural contributions to environmental concerns, rather than the entire life cycle of the product.

3.4.2 Limitations of reviewing and comparing available wine LCA results

This research was limited by a few notable factors, such as data availability, assumptions, and uncertainty, among other factors. One of the most prominent limitations of this research is the uncertainty associated with comparing LCAs from various practitioners (Scrucca et al., 2020). For the purpose of this research, I assume that controlling for methodological differences will eliminate the inconsistencies in major methods applied between sampled case studies. In reality, however, differences in the approaches, perspectives, and objectives of these LCA practitioners are all potentially significant sources of inconsistency and thus uncertainty (Hallstrom et al., 2014).

As mentioned above, this uncertainty was mitigated, to the extent possible, by controlling for methodological inconsistencies through non-probabilistic case study sampling, involving specific inclusion criteria applied to all case studies. Though effective for reducing uncertainty, this approach exacerbated limitations associated with data availability. The resulting sample consisted of 27 LCA case studies, drawn from 20 journal publications. Ideally this sample would have been larger, particularly because the case studies were later divided into sub-samples of studies for which larger groups would have been beneficial. Additionally, the geographic scope of this research was limited by the current breadth of LCA literature, which is concentrated in Southern Europe (Figure 8). This limited the scope of this research to Italy, Spain, and Cyprus, ultimately limiting the geographic variability of the production locales being compared. As a result, this study may not have been able to fully capture the extent to which wine-grape production systems vary between geographies in their contributions to global warming.

It is also important to note that only wine LCA case studies written in English were considered in this research, and that relevant studies in other languages may have thus been omitted. This is particularly relevant because this research assesses case studies from other regions of the world where institutions do not publish in English.

3.4.3 Limitations of the systematic literature inventory

The research methods used to systematically conduct an inventory of current wine LCA literature were also limited by numerous factors, including uncertainties associated with the literature as well as limited data availability. Most notably, this research used the abundance of LCA studies conducted in each country as a proxy for the LCA research focus the countries have received. In reality, life cycle assessments are undertaken at a variety of scales and geographic ranges, and can vary greatly in terms of geographic representativeness. For example, some studies may choose to assess numerous systems within a given region, while others will focus on only one system. For this reason, it must be noted that this exploratory research aimed to identify general sampling patters, but not to determine the precise degree to which production systems have been assessed within given geographies.

Data accessibility was another limitation to consider when interpreting the results of this research. This literature inventory focused on LCA literature published in credible academic journals. Publicly accessible literature that was not published in academic journals, such as master's theses documents made available to the public through institutional websites, were thus omitted from the sample to avoid bias.

3.4.4 Mitigating limitations

To mitigate the uncertainty associated with comparing LCAs, inclusion criteria were pre-determined prior to case study sampling, and were strategically designed to produce a methodologically consistent sample. This helped to ensure that case studies were selected as consistently as possible, and with minimal sampling bias. In response to residual uncertainty and the effects of limited data availability, statistical significance testing was omitted from the analyses. Due to the exploratory nature of the project, data visualisation methods were deemed to be the best fit for communicating results, as they illustrate key findings without requiring a normally distributed and adequately sized sample of case studies. Last, to increase the size of my case study sample without compromising methodological consistency, conversion factors were used to manually alter functional units and associated data to meet the inclusion criteria. This was applied to case studies where an alternative functional unit was used, such as a bottle of wine, and where a conversion factor was provided.

Chapter 4: Results I – Review and Comparison of Available Wine LCA Data

4.1 Overview

The LCAs selected for this research included 27 grape cultivation case studies undertaken in Italy, Spain, and Cyprus. By mapping the study sites of these case studies, common production locales became apparent, as seen in Figure 4 below. The Italian case studies revealed two prominent production locales within which studies have been undertaken: Central Italy (Tuscany and Umbria), where seven case studies took place, and Sardinia, where three case studies took place. Meanwhile, Spanish studies were more dispersed, and revealed only Northern Spain as a prominent production locale with representation amongst the studies that met my inclusion criteria, where four studies took place. Cyprus, being significantly smaller than Italy and Spain, was considered to be one stand alone production locale, encompassing the study sites of four case studies from my sample. The remaining seven case studies that met my inclusion criteria were too geographically distributed and isolated to be grouped with others, and were thus excluded from all comparisons. Nevertheless, their data were mined and shared in the inventory analysis to provide supplementary data for Italy and Spain.

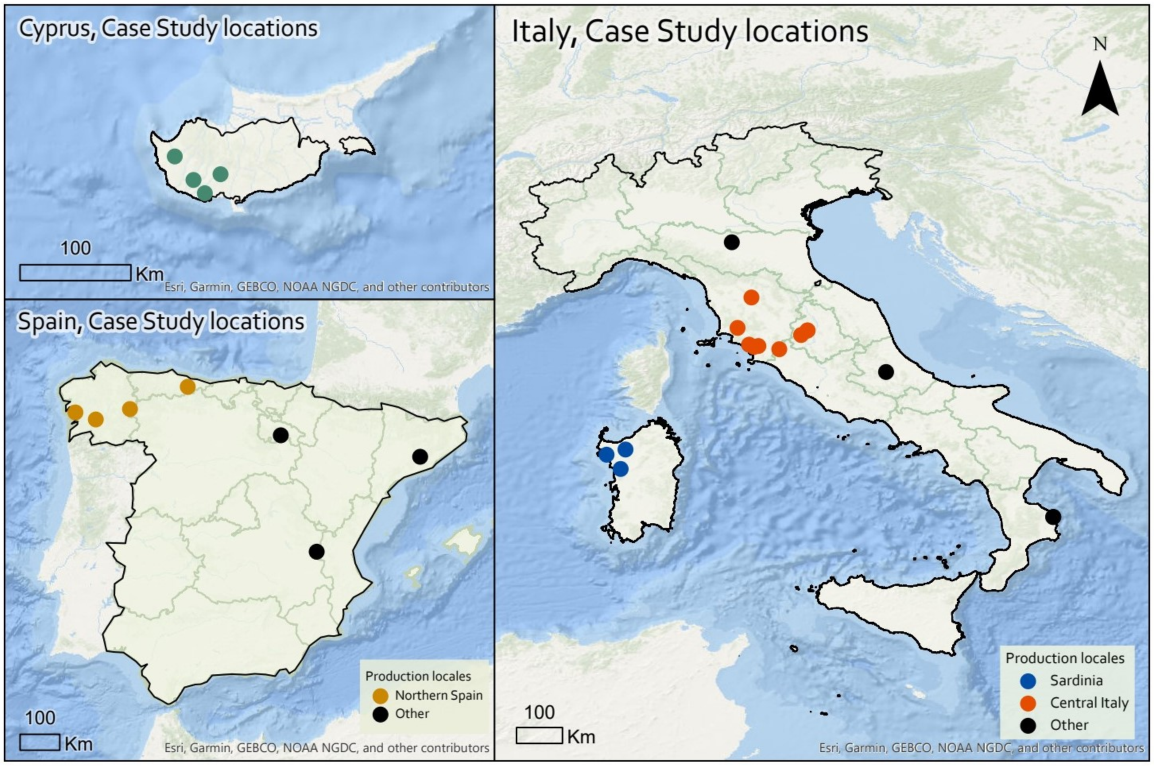

Figure 4. A map identifying each study site for the sample set of wine-grape LCAs conducted in Italy, Spain, or Cyprus, where studies have been colour coordinated based on production locale. Production locales were determined based on the existing boundaries of local wine production regions, as well as the spatial distribution of the case studies in the sample set.

The mean GWP of all 27 case studies was 395 g CO2 eq/ kg grapes produced up to the farm gate. The distribution of these values was found to be positively skewed, where no values below the mean deviated by more than one standard deviation (Figure 5). This suggests the presence of unusually high GWP values at the upper tail of the distribution. The highest of these outliers was recorded in Northern Spain, as was the second highest GWP value as well. Of the two remaining studies from Northern Spain, another also reported a GWP that was above the sample mean, ranking 7th of 27 case studies (Table 1). In contrast, 8 of the 9 studies that took place in Central Italy reported GWP values that were well below the sample mean. Though these examples indicate that emission patterns may be more similar within regions than across, the results also indicate significant differences within production locales as well. In Cyprus, two studies report high GWP values, ranking 4th and 5th highest amongst the entire sample set, while the remaining two Cypriot studies fell below the mean. The range of GWP values reported in

Cyprus is 560 g CO_2 eq per kg grapes, which is notable considering the average GWP of all the systems is 395 g CO_2 eq per kg grapes.

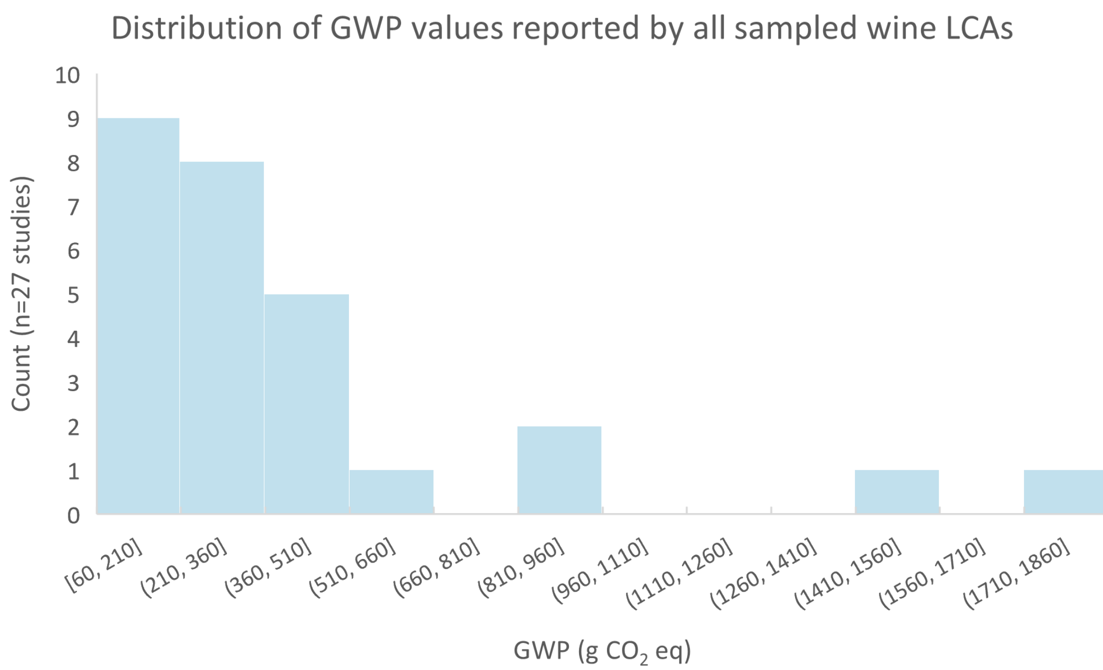

Figure 5. Distribution of GWP values from sampled wine LCA case studies (n=27), all screened for broad methodological consistency, and all assessing the global warming potential attributed to grape production from cradle-to-farm gate for production systems in Italy, Spain, or Cyprus.

4.2 Inventory Analysis

The inventory analysis results indicate that the material and energy flows involved in grape production differ notably both within and between production systems, though similarities within production locales have also emerged. The inventory inputs relative to one kg of grape output for each of the 27 case studies of interest are reported below in Table 1, organized by production locale. For interpretation purposes, the global warming potential of each system has also been included along with the inventory analysis, and the systems have been ranked from least to most impactful in terms of total GHG emissions per kg grape output.

Table 1. Life cycle inventory results communicated as material and energy inputs, reported for all sampled LCAs (n=27), and organized by production locale.

Material and energy inputs						**GWP (Rank)**
** Values more than one standard deviation above the total sample mean (n ≈ 27) ** Values more than one standard deviation below the total sample mean Note, yields have been interpreted in an inverse fashion because greater yields are generally thought to correlate to lower GWP						
Region Source (Case study ID)	Diesel (L)	Synthetic Fertilizer (g)	Organic Fertilizer (g)	Pesticides (g)	Yield (kg/ha)	CO2 eq (g)
Cyprus, where the regional mean GWP value (n=4) was 496						
Litskas et al., 2017c (C4)		**61.0			**11500	**812 **(24)**
Litskas et al., 2017b (C3)		**58.8			6800	543 **(23)**
Litskas et al., 2020 (C1)	0.01	2.83			6500	377 **(18)**
Litskas et al., 2017a (C2)		**58.9			**4240	252 **(13)**
Central Italy, (Tuscany and Umbria), where the regional mean GWP value (n=9) was 262						
Bonamente et al., 2016 (U1)		5.97	1.86		10000	**820 **(25)**
Rinaldi et al., 2016b (U3)		6.64	2.60	0.44	8000	282 **(15)**
Rinaldi et al., 2015a (U2)		6.00	1.84	0.32	10000	226 **(10)**
Bosco et al., 2011a (T3)	0.04	**60.0	265	3.64	**5000	241 **(12)**
Recchia et al., 2018 (T1)	0.06	0.76		6.78		210 **(9)**
Bosco et al., 2011b (T4)	0.05	**50.0	793	**83.4	6000	201 **(8)**
Bosco et al., 2011c (T5)	0.05	27.3	143	2.57	**11000	189 **(7)**
Bosco et al., 2011d (T6)	0.04	22.2	47.0	4.00	9000	96.5 **(4)**
Bosco et al., 2013 (T2)	0.004	3.21	11.7	0.28	9000	96.0 **(3)**
Sardinia, Italy, where the regional mean GWP value (n=3) was 325						
Bendetto, 2013 (S3)	0.06	1.25	14.1	3.52	12000	424 **(22)**
Marras et al., 2015 (S2)	0.04	2.25	0.50		10000	390 **(19)**
Fusi et al., 2014 (S1)	0.09	0.56	2.46	3.25		160 **(6)**
Other, Italy						
Falcone et al., 2017b (Cal2)	0.002	3.37	242			303 **(17)**
Falcone et al., 2016a (Cal1)	0.002	2.91	212			271 **(14)**
Cichelli et al., 2016 (A1)	0.02	26.3	0.00	9.16	9833	108 **(5)**
Ferrari et al., 2018 (E1)		19.8	60.1			60.1 **(1)**
Northern Spain (Galicia and Asturias) where the regional mean GWP value (n=4) was **971						
Vázquez-Rowe., 2013 (G3)	0.08		**3259	4.40	7617.5	**1742 **(27)**
Laca et al., 2020 (G1)		10.6			**3150	**1420 **(26)**
Vázquez-Rowe., 2012 (G4)	0.05	3.07	134		**14841	421 **(21)**
Villanueva-Rey., 2014 (G2)	0.07		246		9715	299 **(16)**
Other, Spain						
Gazulla et al., 2010 (R1)	0.01	**78.7	473			398 **(20)**
Meneses et al., 2016 (Cat1)	0.01		26.9		**4727	231 **(11)**
Sinisterra-Solís et al., 2020 (V1)		12.0	570	2.10	7000	93.0 **(2)**

The inventories identified in Table 1 illustrate that the underlying material and energy flows involved in grape cultivation are highly variable across production systems, regardless of location. For some key inputs, such as fuel and organic fertilizer inputs, very few notable similarities were found within production locales. Generally, where sufficient data were present, each production locale encompassed production systems using fuel inventories well above the sample average, as well as systems using fuel inputs well-below the sample average. It is noteworthy, however, that these fuel inventories are much less variable than other inputs, ranging from 2 mL to 88 mL per kilogram of grapes produced (Table 1). Organic fertilizer inputs also showed very little indication of consistent patterns either within or between production locales, ranging dramatically in Central Italy and Northern Spain. In Sardinia, all three production systems were found to use low organic fertilizer inputs relative to the other case studies. In contrast to the lack of clear patterns in terms of fuel use and organic fertilizer inputs, synthetic fertilizer inventory values did provide a slight indication of regional patterns, where consistently and markedly higher inputs were more prevalent in Cyprus and Central Italy compared to Sardinia and Northern Spain (Table 1). Specifically comparing synthetic fertilizer inputs in Cyprus to those in Sardinia, average inputs ranged dramatically, from to 1.3 g - 45.4 g of synthetic fertilizer for one kg of grape output.

4.3 Impact assessment

The impact assessment phase of this review and comparison assesses percent contributions of fundamental system substages to the overall GWP values of the production systems from cradle-to-farm gate (Figure 6). The substages that were assessed included the following: Fuel use and field operations, fertilizers, pesticides, and an other/unknown source category. For the purpose of this study, the fuel use and field operations substage category refers to the combustion of fossil fuels for farm operations such as machinery use, and input transportation, as well as any other emission sources associated with field operations reported as separate substages in the original case studies. These emission sources were aggregated to resolve issues of methodological inconsistencies between studies, specifically differences in the subsystem boundaries of the activities and emission sources that were included in each substage. The fertilizer substage refers to both the direct and indirect GHG emissions associated with fertilizer production and use. Similarly, GHG emissions associated with pesticide production, application, and use are considered within the pesticide substage, though it should be noted that not all case studies were clear about what their reported substages considered. The other/unspecified stage reported in Figure 6 accounts for the remaining emissions sources of the systems. An important note is that some case studies did not provide contribution data for all of the above substages, and so it is possible that the other/unknown category may also represent contributions from the other three stages.

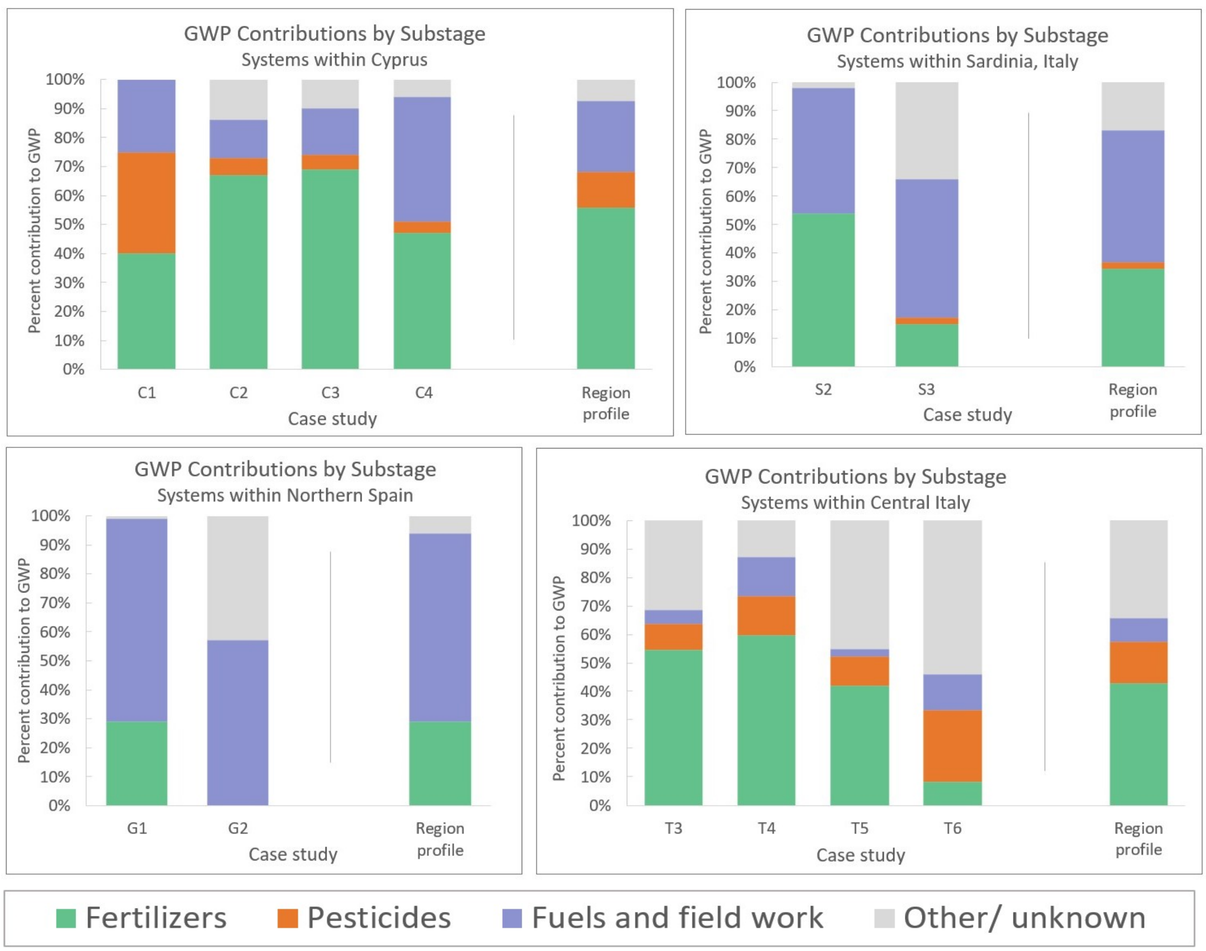

Figure 6. Global warming potential contributions by major substages for each case study that falls within one of four identified wine growing regions, Cyprus, Sardinia, Northern Spain (Galicia and Asturias), and Central Italy (Umbria and Tuscany), along with each region's 'typical' emission profile. Region profiles were estimated using a combination of arithmetic averaging and assumptions. Where data were provided from all studies within a given region, contributions by substage were averaged (arithmetic) to represent the region. In some cases, such as case study S2, substage contribution values could not be determined from the data provided in the study, in which case the study was omitted from the regional profile, and the contributions of that substage were calculated as an average (arithmetic) of the remaining studies.

4.3.1 Patterns within production locales

The review of impact assessments by studied wine growing region does indicate some regional patterns for major substage contributions to total GHG emissions. In Central Italy, the emissions attributed to fuel and field operations are notably lower than other regions, making up a very low percentage of GWP in all of the assessed studies (Figure 6). Meanwhile, fuel and field operation impact value similarities were present in Northern Spain case studies, as well as studies in Cyprus and Sardinia, while varying dramatically between these regions. Though these fuel and field use contribution patterns are notable, there are also many instances where there is no indication of patterns or similarities. Greenhouse gas emissions from pesticide inputs, for example, range widely within regions such as Cyprus and Central Italy (Figure 5), while emission contributions from fertilizer inputs also display a high level of variability both within and between regions. Though fertilizer contributions appear similar when presented as regional means, the underlying systems informing these values vary greatly within the regions as well as between (Figure 5). These underlying values are important to note when assessing Figure 7, below, where regional mean GHG contributions by substage are compared to assess differences across production locales.

4.3.2 Comparisons across production locales

Drawing data from Figure 6, Figure 7 (below) reports the typical emission contribution profile for each of the four regions studied. From Figure 6, it is evident that emissions from fuel use and field operations vary greatly between regions, from less that 10% of GWP in Central Italy to roughly 65% in Northern Spain (Figure 6). Alternatively, as briefly discussed above, the GHG emission contributions arising from fertilizer use are relatively stable between production locales, although the underlying production systems vary greatly. Regional mean values also show variation for pesticide contributions, though the data informing this observation is sparse. In making these comparisons, it is important to consider that these case studies were undertaken with different objectives in mind and different methodological approaches, though methodology was generally controlled for during case study selection.

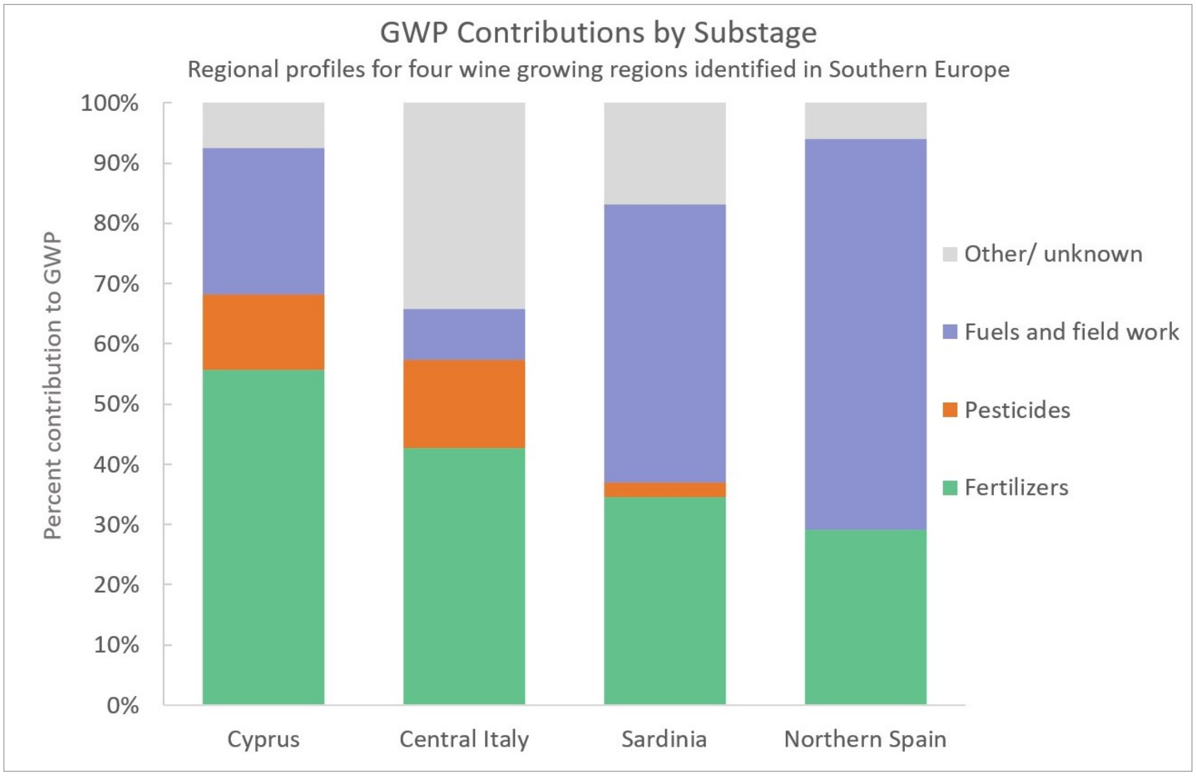

Figure 7. Comparing patterns of GWP contributions by substage between 4 wine growing regions, Cyprus (n=4), Sardinia (n=2), Northern Spain (Galicia and Asturias) (n=2), and Central Italy (Umbria and Tuscany) (n=4). Regional profiles were created using a combination of arithmetic averaging and estimations, as described above (Figure 6).

In summary, Figures 6 and 7 illustrate that the different production regions of a given area, in this case Southern Europe, can host systems with vastly different underlying processed resulting in very different scales of GHG emissions. For some major production substages, such as emissions from pesticides, contributions to total emissions were found to be as variable within locales as they were between. This is not to say, however, that similarities and patterns did not present themselves within some production regions. The emissions attributed to fuel use and field operations, for example, appeared to be relatively consistent within production locales, while still varying greatly between regions. In conclusion, these results show that patterns do not always exist within geographic regions, but can certainly appear for some stages and areas. The similarities and differences observed in my sample of LCAs has implications for both public and private decision-making surrounding emission reduction strategies, as well as implications for data aggregation efforts and impact assessment research drawing from LCA results, further discussed in chapter 6.

Chapter 5: Results II - Systematic literature inventory

For the second component of this project, 63 wine and grape LCA publications were identified, taking place in 13 countries around the world. Figure 1 displays a tornado chart comparing the national wine production volumes of these countries (Figure 8, right column) relative to the number of wine or grape LCA studies conducted on vineyards in these regions (Figure 8, left column). This process aims to assess whether individual LCA studies, while undertaken for a wide range of reasons, might in aggregate more systematically represent large-scale production patterns, where the identified studies below are meant to represent a comprehensive inventory of wine and grape LCAs. In combination with the above results, these findings are intended to determine whether global scale representativeness should be more closely considered by LCA practitioners in the future.

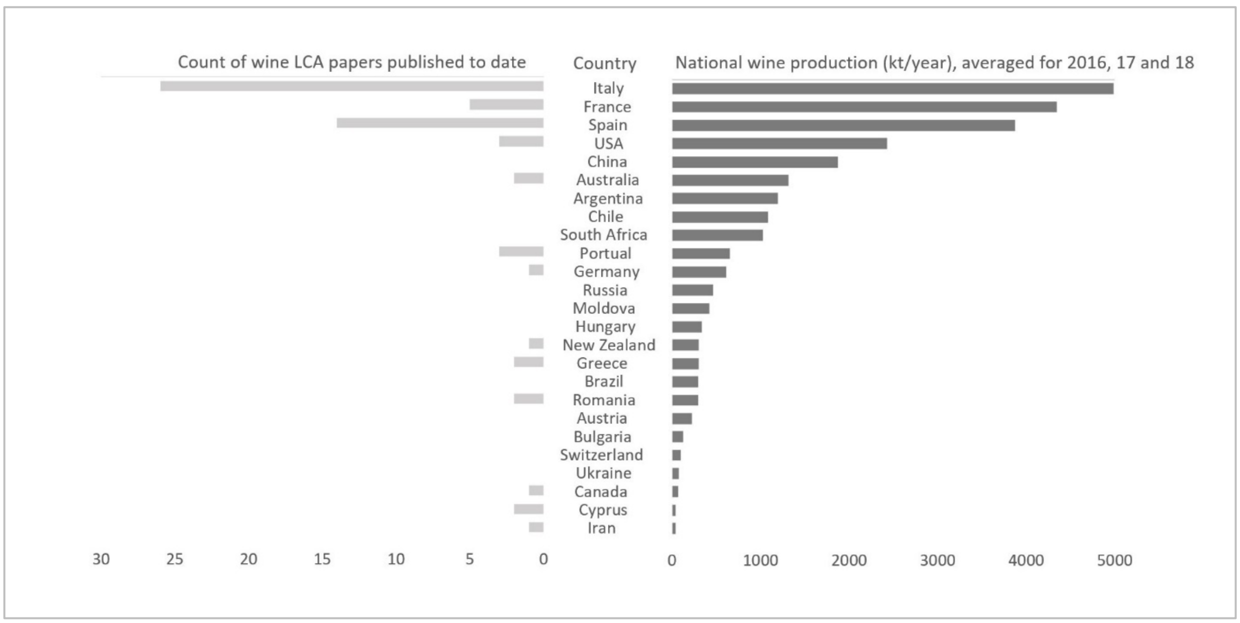

Figure 8. A tornado chart comparing national wine production volumes to the number of wine or grape LCA studies that have been conducted by country. This assessment included all countries that produced more than 1 million hectoliters of wine in 2018, or where a vineyard has been assessed by at least one identified LCA. National wine production volumes were calculated as an average of annual gross production in 2016, 2017, and 2018. The number of studies conducted in each country was determined by an advanced search and inventory of published LCA literature.

The results, shown in Figure 8, indicate that published LCA literature is not representative of global wine production patterns. Rather, these results reinforce the idea that there are many underlying motivations behind LCA research that have little to do with representing production patterns. China, Argentinian, Chile, and South Africa were among the top ten wine producing countries between the years 2016 and 2018, yet no LCAs were identified that have been conducted in these regions and published to academic journals. Meanwhile, countries such as Iran, Cyprus, and Canada have received significantly more research focus than would be predicted based on the volume of wine that they produce. Even for the top producers that have received research attention, the amount of LCA research that has been undertaken is often not proportional to production volumes. This is the case for Spain and France, where France produced more wine than Spain, but has received roughly one third the amount of published research focus.

Chapter 6: Discussion

6.1 System contributions to global warming

As previously suggested by Poore and Nemecek (2018), and by Clune et al., (2017), food system contributions to environmental concerns can be highly variable. Clune et al. (2017) attribute the variable outcomes of LCA research to a number of factors, including LCA practitioner choices, method differences, varying geography, and system boundaries. Based on these suggestions, it is likely that the variability observed within and across regions in this research is the result of two types of factors: Differences within the systems assessed (e.g. agronomic practices) and differences in assessment methods (e.g. system boundaries).

Differences within the systems are typically easier to identify, as they are more likely to show up in the inventory analysis phase of the LCA, and would ideally be defined within the goal and scope phase of the assessment. The most impactful system sampled for this review was studied by Vazquez-Rowe et al. (2012) in Galicia, Northern Spain. Based on data presented in Table 1, above, their high impact value is likely the result of the organic fertilizer inputs to the system, which are significantly higher than other case studies. The second most impactful system sampled in this review was studied by Laca et al., (2020), also in Galicia, Northern Spain. This system incinerates their pruning waste, making their agronomic practices the most likely source of excessive emissions.

Based on these observations, I conclude that the variability observed across systems can, in part, but attributed to substantial differences in the agronomic practices of the farmers. The underlying influences that could dictate these practices include climatic influences, the socio-economic status of the farmer, resource accessibility, and differences in the characteristics of the farmer (e.g. experience, education). Some of these variables could be dependant on production locales, such as climate and resources availability, among others. Other influences, however, could vary more-or-less randomly from system to system, such as framer characteristics and socio-economic status. It is also important to note that some system variables are not always captured by the inventory analysis stage of the LCA, such as differences in soil quality. There could therefore be other differences between these systems that have not been captured by inventory values or substage contributions to emissions, but that indirectly influence the systems productivity. In order to fully understand the variability of contributions to environmental concerns across and within systems, all of these variables must be considered.

In combination with these systemic variables, it is also necessary to consider the influence of differences in methodology and practitioner choices, as mentioned above. These variables refer to choices such as LCA database and software decisions, characterization factors, and substage boundaries, among other things. In synthesizing the results of LCAs from various practitioners, it is essential to consider the influence of LCA methods, regardless of whether methodology has been controlled for. According to Clune et al. (2018), as well as many other works (Röös et al., 2011; McAuliffe et al., 2016), LCAs are not suitable for comparisons due to the influence of methodological variation. Despite these suggestions, researchers continue to attempt LCA comparisons, syntheses, and aggregations because they are an important component of sustainability research (Clark & Tilman, 2017; Poore & Nemecek, 2018; Clune et al., 2018; Richie et al., 2018). In conclusion there are a variety of underlying influences dictating food system contributions to environmental concerns, and it is thus unsurprising that impacts have been found to be highly variable both within and across production locales. This is in line with the conclusions of Scrucca et al. (2020), who have demonstrated that practitioner choices may significantly affect LCA results.

The purpose of this review was to help inform future directions for developments in aggregate food system impact assessments, such as those at the diet level. As suggested by Clune et al., (2018) very few reviews have adequately assessed food system contributions to environmental concerns at the regional, national, diet, or global level. One of the prominent challenges of performing these aggregate analyses is the challenge of obtaining a representative sample of LCAs to draw from. Poore and Nemecek addressed this issue in their meta-analysis by weighting observations based on output as a share of national production, and each country by a share of global production. My findings, which illustrate that impacts are highly variable across geographies as well as across neighbouring systems, underline the importance of representative sampling and weighting practices for food system meta-analyses.

6.2 LCA sampling patterns and observations

As suggested by Figure 8, above, wine LCA research has not been undertaken systematically to geographically represent global wine production patterns, which is likely the case for other agricultural products and potentially other classes of foods as well. Rather, LCA practitioners are motivated to assess food systems for a variety of reasons, including institutional funding opportunities, personal interest, proximity, and local economic relevance, among other things. In Cyprus, for example, the local culture and economy is dependant on the wine sector, representing a potential motivation for the number of LCA case studies conducted to date. Meanwhile, other wine case studies have been undertaken in marginal wine production regions, such as Nova Scotia, Canada, due to proximity and interest. The idea that wine LCA research is driven by a variety of motivations, and not systematically undertaken to represent geographic production patterns, is extremely relevant to past and future aggregate food system impact assessments, synthesizing LCA databases, and systematic LCA reviews. These works all draw from LCA literature to inform their conclusions, and must thus be considerate of geographic overrepresentation and underrepresentation when sampling form the literature.

Though relevant on their own, the importance of these discussion topics is emphasised by the high variability of contributions to environmental concerns observed across and within production locales, as well as the emission similarities observed within locales. These findings suggest that case studies cannot be assumed to represent production without appropriate geographic weighting, making strategic case study sampling and weighting techniques necessary for any research that seeks to draw from LCA case studies.

6.3 Next steps for the LCA framework

To better understand how farm-level LCAs can inform aggregate food system assessments, and how researchers can draw from these LCAs more efficiently, it is important to identify current challenges and areas of uncertainty within these fields that must be addressed by future research. In this section, I draw from the result of this work as well as the conclusions of well-cited systematic LCA reviews to identify three key recommendations for food system impact assessment practitioners.

First, it is important to determine who is responsible for ensuring that, when relevant, LCA case study samples are geographically representative of the food systems being assessed. This involves recognizing that LCA research is not undertaken systematically to represent geographic production patterns, emphasizing the need for research methods that address overrepresentation and underrepresentation when drawing from LCAs. Between LCA practitioners, database developers, and the researchers running meta-analyses and systematic reviews, the responsibility of geographically representative sampling should be made clear to all involved though interdisciplinary collaboration. If not, all should proceed with extreme caution when sampling, understanding that systems can be highly variable both within and across production locales.

Second, the accessibility of LCA case study data is currently also a challenge for those looking to perform aggregate assessments and meta-analysis at regional, national, global, and diet-level scales. Heller et al. (2013) discuss this point as part of their recommendations for next steps in LCA developments as well, where they suggest that data availability remains a primary obstacle for diet level assessments. This is further acknowledged by Clune et al. (2018), who state that there is a lack of publicly accessible synthesised open access LCA data. The finding that contributions to environmental concerns are highly variable both within and across locales further stresses the need for accessible LCA data that covers all products and geographies. In this case, the geographic underrepresentation observed by this project is an excellent example of the gaps that exist in accessible LCA data, ultimately creating major challenges for meta-analyses and systematic reviews.

Last, LCA practitioners are currently limited in their ability to systematically utilise the current breadth of published LCA literature when selecting future directions for research. Although LCAs are undertaken for a variety of reasons, as discussed above, it is important that LCA practitioners address the current gaps in LCA literature by seeking to undertake research in underrepresented regions and for understudied food groups. In order to achieve this, a better mechanism is needed for identifying these novel or underrepresented LCA case study topics. This highlights the importance of global scale LCA synthesizing databases, and emphasizes the importance of their development. For LCA practitioners, these statements also highlight the importance of utilising LCA synthesizing databases when selecting future projects and allocating funding.

6.4 Implications for practice

These conclusions have many important implications for food system LCA practice, relevant to the practitioners assessing farm-level production systems as well as the researchers aggregating food LCAs and/or synthesizing the assessments in databases. First, these conclusions indicate that somewhere within the field of food system sustainability research, responsibility must be established for ensuring geographically representative sampling whenever relevant. Second, the breadth of openly available and accessible LCA case studies must be able to support representative aggregate food system assessments. As suggested by Heller et al. (2013), data availability and accessibility remain an obstacle for food system impact assessment research, and must thus be improved. Last, a better mechanism is needed for utilising the current breadth of LCA literature to inform future directions for farm-level LCAs. Perhaps if it were easier to identify the systems, products, and regions that have, and have not yet, been assessed by LCA practitioners, future LCA research could be undertaken more systematically to geographically represent production patterns, thus facilitating representative sampling. This is not to say that the other underlying motives behind LCA research will not influence sampling patterns, but that geographic over-representation and under-representation may be mitigated by better transparency.

6.5 Recommendations for future research

This research addressed some of the uncertainty surrounding farm-level LCA sampling patterns as well as the relationship between geography and system contributions to GHG emissions. From here, there are many directions that future research can take to help characterize the relationship between LCA sampling patterns, how systems vary across geographies, and how both factors can be applied to form recommendations for future LCA aggregations and meta-analyses. For example, the research conducted in this study can and should be undertaken for other food products and regions of the world. LCA literature inventories for other products would progress research towards truly understanding LCA sampling patterns and thus addressing sampling biases, and comparisons of available food product LCA data between geographies is an integral step in estimating aggregate food system contributions to environmental concerns. As well, these assessments could be conducted on system contributions to other environmental concerns, such as eutrophication and acidification, which may yield very different results than the above assessments relating to global warming.

The results of this research regarding the geographic sampling patterns of LCA literature indicate that there are underlying sampling motivations that are not yet fully understood, and which may have significant influences on the breadth of existing LCA literature. Future research is needed to assess the degree to which some regions have been studied more than others, and why. I recommend, for example, assessing whether industrialized countries have disproportionately been addressed by LCA case studies in comparison to less-industrialized countries. Understanding the specific underlying motivations behind farm-level LCA research is an important next step in aggregate LCA research.

As suggested by Hallström et al. (2015), comparing life cycle assessments from various practitioners is associated with substantial research challenges such as high uncertainty and potential for error, ultimately affecting the quality of the results. My research is one of many studies to have reviewed and compared available LCA results, such as the meta-analysis of Poore and Nemechek (2018), among others (Hallström et al., 2015; Aleksandrowicz et al., 2016; Martin & Brandão, 2017). Though these works are generally undertaken to better understand the environmental impacts of food systems, many also discuss the substantial challenges that are typically encountered when comparing LCAs, such as variation in functional units, system boundaries, and uncertainty surrounding practitioner choices (Scrucca et al., 2020). This work was no exception to these challenges, and thus emphasizes the need for more research focus on the development and standardization of a more systematic, or at least transparent, LCA approach.

6.6 Summary

This research was conducted to help improve our understanding of how individual farm-level life cycle assessments may influence aggregate food system impact meta-analyses, thus contributing to the development of food LCA aggregation methods, and highlighting the relevance of geographic representativeness for all food LCA research. Based on an examination of broadly methodologically consistent LCAs of commercial scale wine-grape production systems, I have concluded that production system emissions and their underlying emission sources are highly variable within production locales, and even more so between them. Furthermore, based on a thorough inventory of published wine LCA literature, which I have compared to global wine production patterns, I conclude that wine LCA research has not been undertaken systematically to represent geographic production patterns, and has rather been influenced by alternative underlying motivations, such as interests, funding, and convenience, among other factors. Put very broadly, I thus conclude that geographic representativeness is an imperative consideration for any food system sustainability research drawing from food LCAs, and that there is much more to be understood with regard to food LCA research sampling patterns at the farm-level, the emission patterns that exist for production systems located across different geographies, and the associated implications for food LCA aggregations estimating cumulative emissions. This is primarily due to the high variability that has been observed between systems in different regions and even systems in the same region, as well as the variability of practitioner decisions and associated repercussions within the field of food LCA research.

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