Sustainability of Beef Production: Farm Size, Inputs, and Impacts

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PREFACE

All four years of high school I took college classes for high school credit to earn an associate degree along with my high school diploma. As a result, upon my application and acceptance to CU Boulder, I was able to shorten the track to earning my bachelor's degree down to just two years. It has been challenging, though rewarding, learning to navigate an accelerated academic experience; I have always sought an academic challenge. Therefore, my decision to conduct an honors thesis came easily. I was excited at the thought of being able to pursue my research interests and gain experiences that will be critical in my professional life and as I prepare to earn a master's degree. I encountered many successes and challenges throughout this process. I learned the coding program R and developed proficient data analysis skills. Further, I learned to read, understand, and dissect research papers more proficiently, which will prove valuable for the rest of my academic career and beyond.

I have always struggled, like many people, with stepping out of my comfort zone. When initially considering the opportunity to conduct an honors thesis, I feared integrating into a group of people that I didn't know while I was already trying to overcome the fears and challenges associated with being a first-year junior. However, I decided that I shouldn't let my anxieties prevent me from seeking out exciting, new opportunities, so I continued with my thesis. I, therefore, had the opportunity to integrate with the GIRAFFES, the research group collectively advised by my lead advisor, Peter Newton. Such an experience was more rewarding than I ever could have imagined. I learned the value of sharing knowledge and having a solid support system from which to receive feedback and share resources. Overall, my honors thesis has been the highlight of my undergraduate experience and has taught me a plethora of knowledge that I will inevitably carry with me for the rest of my life.

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Thank you to my parents, you both have loved and supported me through every endeavor, no matter how ambitious, and I truly could not have done this without you both. And thank you to the rest of my family for your endless love and enthusiasm for all I do.

ABSTRACT

Global food systems have significant environmental impacts. This is especially true of beef production. The environmental sustainability of a beef production system can be measured in terms of its resource use (i.e., inputs) and its environmental externalities (i.e., impacts), which, according to previous studies, may also be associated with farm size. Farm size can be conceptualized in several ways including: as the number of animals, land area, or productive output. In this thesis, I explore the relationship between farm size, resource inputs, and environmental impacts for beef cattle production systems across five regions. I use data from Poore and Nemecek (2018) that contains production system-level data for beef to compare farm size – measured as number of cattle, area of permanent pasture, and productivity – to two resource inputs (water and land use) and three impacts (eutrophication, acidification, and greenhouse gas emissions). I analyzed these relationships in RStudio to identify relationships between the studied variables and developed a conceptual framework to interpret my results. The global trends from my analysis indicated that smaller farms (in terms of the number of cattle and productivity) were more sustainable when looking at environmental impacts. However, trends in environmental impacts varied significantly between and within regions, suggesting the global trend may not represent the entire complexity of these relationships. The relative best (defined as most efficient) farms were generally conventional dairy operations with high levels of management. The relative worst farms were generally extensive systems with little to no management. My results suggest that different measures of farm size reveal different relationships between inputs and impacts across beef production systems, which may be useful for other researchers conceptualizing and measuring farm-level sustainability. While further research is needed to understand regional variation in these trends, the trends identified in this research could help producers, decision-makers, and researchers to identify opportunities to improve the environmental efficiency of beef production.

INTRODUCTION

Global food systems have significant environmental impacts (Poore & Nemecek, 2018) including high water use, greenhouse gas emissions, and land use (Ritchie et al., 2022). Food systems are responsible for around one-third of all anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021), and food production (i.e., agriculture) accounts for around 26% of these GHG emissions and occupies approximately half of the world's habitable land surface (Ritchie et al., 2022). Further, agriculture uses 70% of globally available freshwater while simultaneously being responsible for 78% of ocean and freshwater eutrophication (Ritchie et al., 2022). The creation of new cropland and pastureland is the primary driver of land use change and deforestation (Nguyen et al., 2010). As such, food production is also a primary driver of habitat and biodiversity loss (Ritchie et al., 2022). Global food production is projected to increase anywhere from 35% to 56% by the year 2050 (van Dijk et al., 2021) due to population growth and increases in per capita food demand (Başer & Bozoğlu, 2023). The global population is expected to reach at least 9 billion by 2050 (Elferink & Schierhorn, 2016). Importantly, per capita demand for resource-intensive foods, like animal products, is rising as many people escape poverty, enter the middle class, and demand more animal products (Tichenor et al., 2017).

Given the intensity of their input use and environmental impacts, many current food production systems are widely critiqued as unsustainable (Nguyen et al., 2010; Poore & Nemecek, 2018). As such, there are doubts about whether current agricultural practices will be able to meet the food demands projected by 2050 (Elferink & Schierhorn, 2016). For example, replacing current beef consumption with purely grass-fed beef could require as much as 30% more cattle than are currently being produced for beef (Hayek & Garrett, 2018). Such shifts would have significant implications for additional land use and environmental costs (Hayek & Garrett, 2018). Thus, it is important to understand the environmental impacts of global food systems. It may also be useful to identify what practices used by farmers and ranchers that could produce food in ways that minimize environmental impacts, account for the challenges that climate change will impose on food production, and halt and/or reverse the environmental degradation caused by food production (Webb et al., 2020).

Within the global agricultural system, beef cattle production is among the most resource-intensive and environmentally impactful food products (Broom, 2019; Halpern et al., 2022; Koehn et al., 2022; Poore & Nemecek, 2018). For example, water use, land use, biomass appropriation, and GHG emissions are higher, on average, per unit of edible protein for beef than for most other animal or plant products (Gerber et al., 2015; Poore & Nemecek, 2018). On average, globally, the production of 100g protein of beef is associated with an average of 165 m^2/year in land use (Poore & Nemecek, 2018) making beef more land-intensive per unit output than any other food except for some lamb production systems (Poore & Nemecek, 2018; Tichenor et al., 2017). Beef cattle production is associated with, on average, 50 kg CO_2 eq per 100g protein, compared to 6 kg CO_2 eq per 100g protein for chicken (Poore & Nemecek 2018).

Even the least emissions-intensive beef cattle (at the 10th percentile) produce 20 kg CO_2 eq per 100g protein. As such, beef is more than twice the emissions intensity of the next-most emissions-intensive food (Poore & Nemecek, 2018; Ritchie et al., 2022). That said, the range of emissions for beef is large, in part because dairy cattle account for around half of the world's beef, and dairy cattle are associated with lower environmental impacts (Ritchie et al., 2022). Also, a wide diversity of beef production systems, management practices, and contexts under which beef cattle are raised may contribute to this variation in environmental impacts (Greenwood, 2021).

The environmental sustainability of a beef production system can be measured in terms of its resource use (i.e., inputs) and its environmental externalities (i.e., impacts). Resource use includes the amount of land, water, and energy used to produce a unit of food. Resource use intensity can contribute to sustainability because farms that operate more efficiently can produce more output using fewer inputs per unit output. In other words, farms using resources more efficiently leave more resources to either be used for others or not at all, contributing to sustainability goals. Since resources such as land and water are finite and are becoming increasingly scarce, it is increasingly important to be intentional about where and how they are used to meet growing food demand (Demircan & Koknaroglu, 2007). A more sustainable system might be characterized by high on-farm efficiency and productivity, which implies greater resource use efficiency (i.e., less input per unit output). Efficiency is a valuable lens through which to view the sustainability of beef production; it can be described as the balance between reducing inputs and environmental impacts (Gerber et al., 2015; Greenwood, 2021). Many researchers have viewed the sustainability of beef production systems from an inputs-impacts lens. For example, Hayek & Garrett (2018) model a hypothetical shift to the United States beef system based entirely on grass-fed beef. In doing so, they highlight the relative inefficiency of pasture-raised beef rather than more conventional, intensively-raised beef. Broom (2019) compares four different beef production systems representing four methods of global beef production with data mostly from North and South America and found that in terms of land use per unit of beef produced, the least efficient system used 13 times more land than the most efficient. As a final example, Nguyen et al. (2010) also studied four different beef production systems in France and compared climate warming, acidification, eutrophication, land use, and energy use across these systems. Broadly, they found lower environmental impacts from beef from dairy calves than from suckler calves.

Environmental sustainability may be associated with farm size (Ren et al., 2019). Many previous studies have identified links between farm size and environmental sustainability, whether implicitly or explicitly, but reported different trends. For example, a global meta-analysis found that smaller farms, on average, have higher yields and support more biodiversity than larger farms (Ricciardi et al., 2021). In contrast, a study of 120 maize farms in China revealed similar yields across farms of varying size, but lower environmental efficiency (i.e., lower agrochemical inputs, lower energy use, lower GHG emissions) on larger farms (Zhang et al., 2021). Specifically concerning beef production, a comparison of 155 beef cattle farms in Turkey revealed that larger farms were more economically and environmentally sustainable than smaller farms (Başer & Bozoğlu, 2023). A study using farm-level data and questionnaire responses found that the larger the farm, the lower the energy output ratio (the lower the energy-use efficiency) (Nguyen et al., 2010). Further, a review of global beef production systems (data mostly from North and South America) revealed that larger farms are associated with lower water use per unit of carcass weight, whereas smaller farms generally use greater amounts of water (Broom, 2019).

Farm size can be defined or conceptualized in several ways (Lund, 2009; Lund & Price, 1998; Stanton, 1978). Size can be conceived in terms of the physical land area of the farm, such as how many hectares (ha) of land the farm incorporates (e.g., Lowder et al., 2016). Alternatively, farm size can be measured in terms of the total production of the operation - either in terms of total crop productivity or, in the case of beef, the total tons of beef produced (e.g., Veysset et al., 2015). Finally, for a beef cattle operation, a farm can be characterized in terms of the number of cattle that are grazed on the property (Demircan & Koknaroglu, 2007). Different conceptions of farm size might intersect with sustainability in different ways.

The central research question that this thesis will address is: What is the relationship between farm size, resource inputs, and environmental externalities for beef cattle production systems on a global scale? By exploring this question, I aim to understand how resource inputs (e.g., land use) and negative environmental externalities (e.g., methane and other GHG emissions) change with the size of beef cattle operations. This research is interesting because it considers the sustainability implications for agriculture and the trade-offs for meeting the rising demand for food on a global scale, especially for animal products such as beef. Understanding the relationship between farm size, resource inputs, and environmental externalities for beef could be useful in helping to identify pathways toward more sustainable food production systems.

METHODS

Data collection

I used a dataset created by Poore and Nemecek (2018) that contains production system-level data for 40 food products globally. These data were sourced and compiled from life cycle analyses (LCA) from around 38,000 farms globally. I chose to use this dataset because LCA data provides unique farm-level data related to food's environmental footprint, and because it is currently the most comprehensive collection of LCA data publicly available. Additionally, the variables of interest (i.e., measurements of farm size, resource inputs, and environmental impacts) for this study were available in the Poore and Nemecek data for a variety of beef production systems. The dataset included 149 total observations of beef production systems, including non-dairy beef production (that is, cattle raised exclusively for beef) (n = 106) and beef from dairy (n = 43) across 19 countries at the farm level. Both conventional and organic beef production systems were included as well as systems that rely on exclusively grass-fed, grain-fed, and mixed forage systems. For all production system observations, I collated three measures of *farm size*, two measures of resource inputs, and three measures of *environmental impact*.

Resource inputs and environmental impacts

I defined resource inputs as any factor of beef production that would be considered an input for, or as a means of, production. The resource inputs I included in my analysis were *water use* (liters (L)/kg Live Weight (LW)) and *land use* (meters (m)^2/kg LW/year (yr)). Some studies included information about energy use, but too few (n = 12) to reasonably conduct a reliable analysis. I defined environmental impacts as any externality of beef production that disproportionately affects the environment. The environmental impacts I focused on were *eutrophication potential* (kg PO4 3-/kg LW), *acidification potential* (kg SO2/kg LW), and *greenhouse gas (GHG) emissions* (kg CO_2 eq/kg LW). Combined, these indicators of both resource inputs and environmental impacts allowed for a relatively holistic assessment of beef production systems. All five input and impact metrics had sufficient data points (n > 30) for beef to be able to correlate with measures of farm size.

Farm size

I defined farm size in three different ways to best examine the full scope of the relationship between each of the above inputs and impacts with farm size. These three measures of farm size were: 1) the *number of cattle (*measured as the number of animals), 2) the *productivity* (LW) (defined as the total amount of live weight (LW) among all cattle), and 3) the *total amount of permanent pasture* in hectares (ha). The variable *total herd size* was unavailable in the original dataset (Poore & Nemecek 2018). Therefore, I went back to the original research articles from which the Poore & Nemecek (2018) paper had sourced its data and I extracted the relevant information on herd size from each paper to create a new variable ('*number of cows*'). Note that for herd size, I assume that the herd size reported in the paper was the average size of the herd at any given time during the beef production life cycle. Both productivity and permanent pasture were included in the original dataset.

Farm size is best captured using the unstandardized values - that is, measurements that are not relative to any other given unit (such as LW). In the data, both productivity and permanent pasture were reported relative to the functional unit. Though the standardization of the dataset helped in making comparisons between different production systems, I needed total productivity and total permanent pasture use to adequately measure farm size. As such I calculated updated productivity and land use values.

First, I calculated *productivity* with the following equation:

$$\frac{\textbf{number of animals}}{\textbf{farm}} \times \frac{\textbf{kg liveweight}}{\textbf{animal}} = \frac{\textbf{yield}}{\textbf{farm}}$$

Next, I calculated the *total amount of permanent pasture* with this equation:

$$\frac{\textbf{hectares}}{\textbf{kg liveweight}} \times \frac{\textbf{kg liveweight}}{\textbf{animal}} \times \frac{\textbf{number of animals}}{\textbf{farm}} = \frac{\textbf{hectares}}{\textbf{farm}}$$

It is important to note that averages were used where ranges were given when making calculations.

Data Analysis

I used R Studio (See Appendix A) to analyze data and create the figures. I plotted my three measures of farm size against my two measures of resource inputs and three measures of environmental impact. I assumed there was no change over time and the year to be irrelevant. I plotted lines of best fit and confidence intervals. I filtered out any system larger than 1,000 cattle because these systems reported production-system-level data that captured national-level information but included no farm-level data. Because I was unable to retrieve or calculate farm-level data for these systems, as I did with the rest of the data, I was unable to include them in the analysis.

To develop a more nuanced understanding of how the relationship between farm size, resource inputs, and environmental impacts might vary between geographic regions, I categorized the country of origin of each farm into its United Nations (UN)-defined region. I hoped that by disaggregating the data by geographic regions, I would be better able to understand the production systems and would be able to identify trends and relationships. This geographic disaggregation also presented the opportunity to determine which world regions were most and least sustainable as I had defined it. Finally, I also distinguished between dairy beef and non-dairy beef to reflect the same distinction made by Poore and Nemecek (2018).

RESULTS

The goal of this research was to explore the relationship between farm size, resource inputs, and environmental impacts. I defined farm size in three different ways. First, as the total number of cattle on a farm. Second, as the total live weight produced (to capture farm size in terms of output productivity). Third, as the total amount of permanent pasture (to capture farm size in terms of direct land use, not including land for feed inputs). I compared these three metrics of farm size to farm resource inputs (land use, water use) and environmental impacts (greenhouse gas emissions, eutrophication, and acidification) in 149 beef production systems from across the globe.

This Results section is organized as follows. First, my analysis of the Poore & Nemecek (2018) dataset revealed several relationships and trends among two inputs, three impacts, and three measures of farm size variables (Fig. 1). Second, I developed a conceptual framework (Fig. 2) to identify the relative "best" and "worst" farms, in terms of efficiency (unit inputs and impacts per unit output). I define the relative best farms as those production systems that were most efficient and the relative worst farms as those that were least efficient. Third, I use this framework to characterize farms included in this study to understand what practices corresponded with better and worse efficiency for beef production systems at the farm level (Fig. 3).

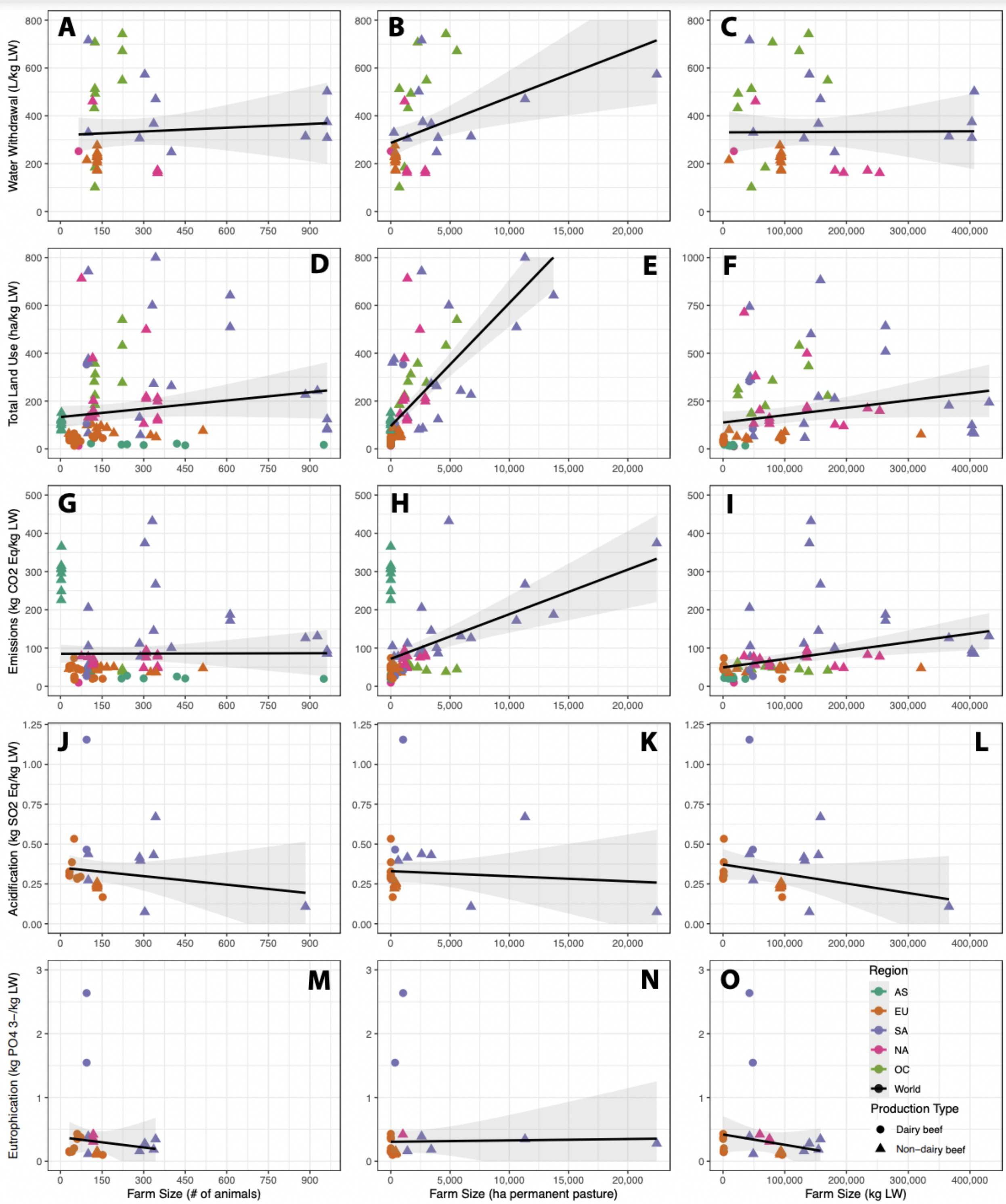


Figure 1. The results of an analysis of the relationship between farm size, inputs, and impacts among 149 beef-producing farms globally. The three measures of farm size are plotted against each of two inputs and three impacts. The data points are color-coded by their UN-defined region (data from countries in Asia (AS), Europe (EUR), South

and Central America (SA), North America (NA), and Oceania (OC) were available). Additionally, a black trend line (and gray confidence interval) shows the overall (global) trend for the relationship depicted in each graph. When the confidence interval of the trend line went beyond the bounds of possibility (e.g., farm size cannot be less than zero hectares), I did not extend the trend line. The shape of the data point is used to distinguish between beef from dairy cattle (circle) and beef from non-dairy cattle (triangle).

Correlations between farm size, resource inputs, and environmental impacts

Global analysis

When measuring farm size in terms of the number of animals, farm size ranged from 2 to 962 cattle (mean = 211). The very largest farms (with >800 head of cattle) were mainly beef cattle (non-dairy) farms in South America (e.g., Fig. 1A, D, G). I found a weak positive correlation between farm size and water use and land use. That is, larger farms tended to use more resources per unit of live weight of cattle. I found no significant correlation between farm size and greenhouse gas emissions (Fig. 1G). In contrast, my analysis revealed weak negative correlations between the number of animals and acidification and eutrophication. That is, larger farms tended to have similar or lower environmental impacts than smaller farms.

When measuring farm size in terms of hectares of permanent pasture, farm size ranged from 0 to 22,444 ha of permanent pasture (mean = 1,645). I found a strong positive correlation between farm size and water use, land use, and greenhouse gas emissions (Fig. 1B, E, H). That is, larger farms (measured in terms of ha of pasture) used many more resources and had a much higher emissions footprint per unit of beef than did smaller farms. In contrast, I found a weak negative correlation between farm size and acidification (Fig. 1K) and no significant correlation between farm size and eutrophication (Fig. 1N).

When measuring farm size in terms of productivity, farm size ranged from 896 to 431,055 kg LW of productivity (mean = 108,328). I found no significant correlation between farm size and water use (Fig. 1 C). I found a weak positive correlation between farm size and land use (Fig. 1 F), and between farm size and greenhouse gas emissions (Fig. 1 I). In contrast, I found a weak negative correlation between farm size and acidification and eutrophication (Fig. 1 L, O).

Regional analysis

The relationships between farm size, inputs, and impacts varied significantly between the five different UN regions (Fig. 1; regions represented by data points of different colors). In most regions, there were few clear discernible trends between independent (farm size) and dependent (inputs, impacts) variables. That said, my analysis revealed a few notable cases of clear relationships. For example, there was a clear trend between emissions and land use compared to farm size measured in hectares of permanent pasture for farms in South and Central America (Fig. 1 E, H). The number of data points for some regions and for some variables (e.g., eutrophication and acidification) was low, which made it difficult to assess regional trends with a high level of confidence.

Conceptual framework for thinking about the efficiency of beef production

I developed a conceptual framework through which to assess which production systems were the most and least efficient (Fig. 2). This framework is based on the directional relationships between inputs, impacts, and measures of farm size. The relative best (most efficient) farms vary between the three measures of farm size but are consistently those that minimize either their use of inputs or their production of negative environmental impacts while maximizing their productivity. The relative worst (least efficient) farms are consistently those that maximize their use of inputs or production of outputs while minimizing their productivity.

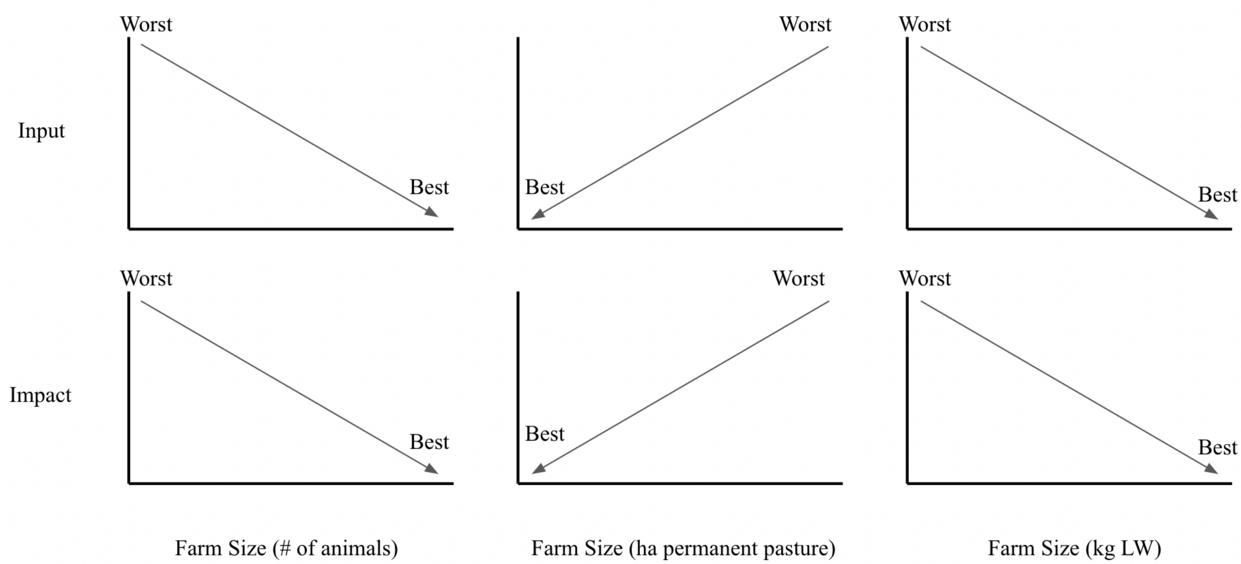


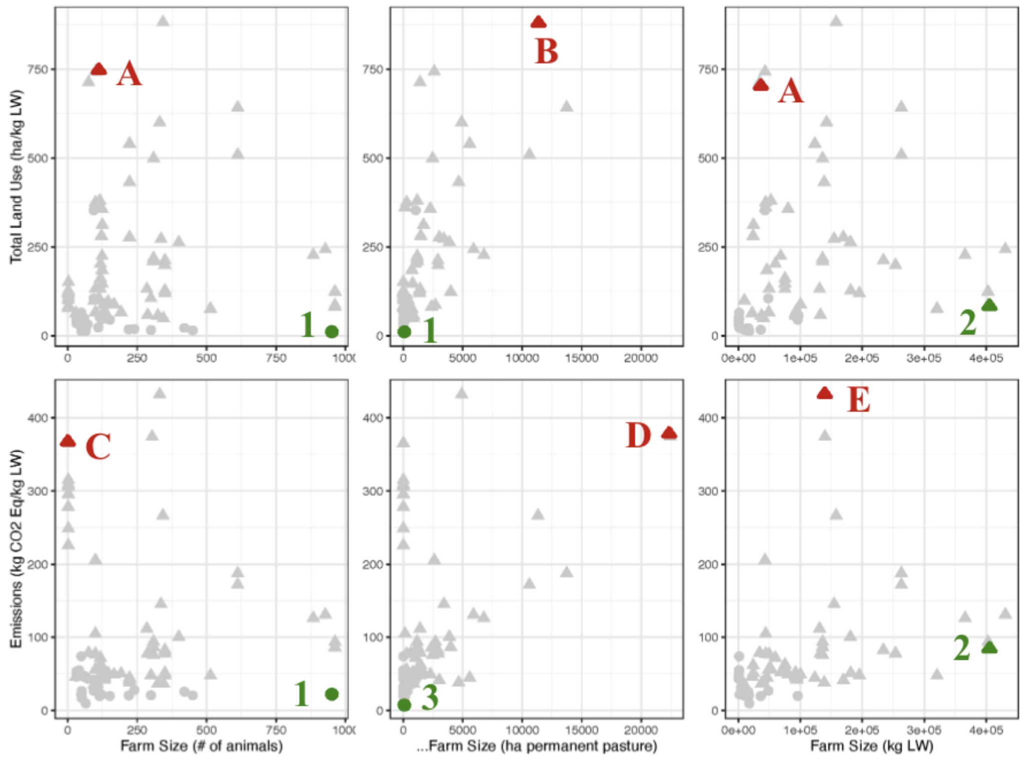
Figure 2. From the results presented in Figure 1, I developed a conceptual framework to examine the efficiency of the included beef production systems and to be able to determine the general practices that constitute the "best" (most efficient) and "worst" (least efficient) systems. In this conceptual figure, I plotted inputs and impacts against each measure of farm size and used arrows to indicate which areas of the graphs house the relative "best" and "worst" systems.

In all cases, a higher value on the y-axis for both inputs and impacts indicates a worse environmental outcome (i.e., more inputs needed, or more negative environmental impacts created, per unit of beef production). The trends across the three measures of farm size vary since more animals per unit input or impact represents greater efficiency, but more pasture per unit input or impact represents less efficiency (Fig. 2). The best farms maximize productivity (e.g., number of animals, productivity) while minimizing inputs (e.g., land use, water use) and impacts (e.g., GHG emissions, eutrophication, acidification). Thus, when comparing inputs and impacts to farm size measured as the number of cattle, the systems in the top left are the worst because they had the fewest number of cattle while having the highest impact or resource use. These farms are less efficient compared to farms in the bottom right corner, which had the lowest inputs and impacts with the greatest number of animals. In contrast, when comparing inputs and impacts to the second measure of farm size (amount of permanent pasture), the worst systems were those in the top right corner as they used the most land and either required the most input or produced the most impact. The best systems were those in the bottom left because these systems used the least land and used either the fewest resources or produced the least environmental impact. Finally, the trend for the best and worst systems when comparing inputs and impacts to the third farm size measure, productivity, was the same trend present with the first measure of farm size (number of cattle). The worst systems were those in the top left because they were the least productive (produced the least amount of liveweight) and used the most resources or produced the most impact.

I then used this conceptual framework to identify specific examples of individual farms that represent the best (most efficient) and worst (least efficient) systems across each farm size measure. I used one example of input (land use) and one example of impact (greenhouse gas emissions). I chose these two variables as those with the most data points and the strongest correlations, to better examine the commonalities, differences, and notable characteristics of these beef production systems.

The practices that characterize more-efficient and less-efficient beef production

I used the conceptual framework (Fig. 2) to identify one of the best and one of the worst production systems (i.e., farms) from each panel in Figure 1 that explored the relationship between land use and greenhouse gas emissions and each of the three measures of farm size. I defined the best systems as those systems that were most efficient (i.e., that maximized productive output while minimizing resource inputs and environmental impacts) and I defined the worst systems as those that were the least efficient.



	Farm Size (# of animals)	Farms Size (ha permanent pasture)	Farm Size (kg LW)
Land use	**A:** Extensive native pasture; Brazil	**B:** Semi-extensive, nominal pasture quality, continuous grazing, low pasture management; Brazil	**A:** Extensive native pasture; Brazil
	1: Confinement dairy operation; China	**1:** Confinement dairy operation; China	**2:** Fertilized Guinea grass; Brazil
Emissions	**C:** Wet upland, Ongole cattle, stall feeding; Indonesia	**D:** Extensive, with degraded pasture and continuous grazing, no pasture management; Brazil	**E:** Fed on crop residue and natural pasture; Brazil
	1: Confinement dairy operation; China	**3:** Intensive; 70% veal, 30% spent dairy cow; Canada	**2:** Fertilized Guinea grass; Brazil

Figure 3. Total land use and greenhouse gas emissions were each plotted against the three measures of farm size (a replication of a subset of Fig. 1). Then, using the conceptual framework expressed in Fig. 2, I identified one example of a high-efficiency system (highlighted in green) and one example of a low-efficiency system (highlighted in red). I assigned each point either a letter (low-efficiency systems) or a number (high-efficiency systems). In the table below, I described the specific production systems (i.e., farms) and the overall characteristics of these systems. In instances in which points on different panels reference the same production system, I use the same point label (e.g., the farm labeled "1" which appears three times above).

Overall, the worst farms were located in South America (Brazil: Fig. 3 farms A, B) and Asia (Indonesia: Fig. 3 farm C). The best farms were found in a variety of regions (e.g., South America (Brazil: Fig. 3 farm 2), Asia (China: Fig. 3 farm 1), and North America (Canada, Fig. 3 farm 3)).

When farm size was measured in terms of the number of animals, the best production system was a confinement dairy operation in China for both total land use and greenhouse gas emissions. This production system has the highest productivity among those included in the original study (in terms of kg of output) as well (Wang et al., 2016). This system also ranks as one of the lowest land use per kg LW values among all farms included in this study (Fig. 3 Farm 1). The worst farm for total land use was an extensive native pasture system in Brazil (Fig. 3 Farm A). This system involved cattle being raised exclusively on native pasture, large tracts of land with little to no management allowing the cattle to graze all year, which has generally proved to produce less feed than a managed pasture system (Dick et al., 2015). This system also was less productive than the intensive system to which it was compared (Dick et al., 2015). The worst system for greenhouse gas emissions was a stall-feeding system in the wet uplands of Indonesia. This system is characterized by the production of Ongole cattle specifically, which have lower weights than other, crossbred breeds of cattle (Widi et al., 2015).

When farm size was measured in terms of total land use, the best farm for land use (input) was the same Chinese dairy confinement operation as with the previous measure of farm size (Fig. 3 Farm 1). The best farm for greenhouse gas emissions was an intensive system in Canada (Fig. 3 Farm 3). This system is characterized by "typical conditions in Quebec," including that feed was produced on-farm and manure from the cattle was all directly used as fertilizer (Mc Geough et al., 2012). Further, this system is a dairy system in which beef is produced as a coproduct, so input and impact allocation is much lower, considering allocation often favors milk (Mc Geough et al., 2012). The worst farm for land use was a semi-extensive system in Brazil (Fig. 3 Farm B). This system is characterized by low manure management, nominal pastureland, and continuous grazing practices (Mazzetto et al., 2015). The worst farm for greenhouse gas emissions was another extensive system in Brazil (Fig. 3 Farm D). This system is characterized by no pasture management, degraded pastureland, and continuous grazing (Mazzetto et al., 2015).

When farm size was measured in terms of productivity, the best farm for both land use and greenhouse gas emissions was a pasture-based system in Brazil (Fig. 3 Farm 2). This system was characterized by high land and animal management and the use of fertilized Guinea grass in the pasture (Cardoso et al., 2016). This farm, counterintuitively with one of the highest productivity, could have been able to be so productive because of the cattle's diet of regularly fertilized grass with mineral and protein supplementation that helped produce higher carcass weights (Cardoso et al., 2016) The worst farm for land use was the same extensive native pasture system in Brazil as when looking at the number of cows as a measure of farm size and land use

(Fig. 3 Farm A). The worst farm for greenhouse gas emissions was a natural pasture system in Brazil (Fig. 3 Farm E). This farm is characterized primarily by the integration of cattle and crop production in which the cattle are fed crop residue during the times they are not being pasture-fed (Pashaei Kamali et al., 2016).

DISCUSSION

Summary of the key results

From my analysis of global beef production systems from the Poore and Nemecek (2018) dataset, I was able to plot each input (water and land use) and each impact (greenhouse gas emissions, acidification, and eutrophication) against each of three measures of farm size (number of cattle, total land use, and productivity). This revealed several correlations between farm size, inputs, and impacts. When observing farm size measured as the number of cattle, I observed a weak positive correlation between farm size and land and water use, no correlation between farm size and greenhouse gas emissions, and a weak negative correlation between farm size and acidification and eutrophication (Fig. 1). When observing farm size measured as the area of permanent pasture, I observed a strong positive correlation between farm size and land use, water use, and greenhouse gas emissions, a weak negative correlation between farm size and acidification, and no correlation between farm size and eutrophication (Fig. 1). Finally, when observing farm size measured as productivity, I observed a weak positive correlation between farm size and land use and greenhouse gas emissions, no correlation between farm size and water use, and a weak negative correlation between farm size and acidification and eutrophication (Fig. 1). Trends in correlations between farm size, inputs, and impacts varied significantly between geographic regions.

I used this analysis to develop a conceptual framework through which to determine the best and worst farms depending on the measure of farm size. I established that high-efficiency farms would be characterized by low inputs and low impacts per animal and per unit production and that low-efficiency farms would be characterized by high land area per unit input or impact (Fig. 2). I applied the conceptual framework (Fig. 2) to the empirical data (Fig. 1) to identify examples of best and worst farms for land use and greenhouse gas emissions across all three measures of farm size. I identified examples of farms from around the world that exemplified production systems and practices that resulted in lower- and higher-efficiency beef production. The worst farms across inputs and impacts tended to be extensive beef farms in South America while the best farms were predominantly high-efficiency dairy farms located in various regions.

Interpretation of my findings

Making sustainable choices

Given the severity of many environmental problems including biodiversity loss, land degradation, and water and air pollution, many consumers are motivated to make environmentally conscientious decisions and many consumers strive to be aware of how their choices as buyers affect the environment (Hayek & Garrett, 2018). It is a common perception that beef, and indeed many agricultural products, sourced from smaller farms is better for the environment than beef produced on larger farms (Berlin et al., 2009). My study suggests that there may be poor alignment between perceptions of, or assumptions about, the relative sustainability of different forms of beef production and the actual observed impacts of those systems. That is, I found that, globally, smaller beef production systems may be more sustainable than larger systems on all measures of farm size. However, it is important to consider that these global trends may be oversimplifying and that it may be more important to consider regional or local trends. Beef production systems that many people perceive to be more sustainable (e.g., smaller in terms of farm size, with a lower stocking density), such as grass-fed beef, are often more resource-intensive per unit of output (Hayek & Garrett, 2018).

In my study, the global trends suggest there was a weak, positive correlation between farm size (measured as the total pastureland) and water use, land use, and greenhouse gas emissions. This means that the smaller farms (i.e., farms with a smaller area of permanent pasture) used the least land while also requiring the least land and water and producing the least emissions. Several different factors could explain this relationship. First, total land use is inherently a function of permanent pasture. Thus, the two variables will always have a positive relationship. Additionally, it could be the case that land use is simply a greater driver of resource use and the production of environmental impacts. The weak positive correlation between land and water use and farm size (measured as the number of cattle) indicated that farms that supported smaller herd sizes used fewer resources. The weak negative correlation between acidification and eutrophication and the number of cattle and productivity measures of farm size indicated that smaller farms by these two measures of farm size were more productive while producing less of an environmental impact. These global trends would indicate that smaller farms (in terms of the number of cattle and productivity) were generally more sustainable when looking at environmental impacts, which supports the current literature (Nguyen et al., 2010; Torres Jara de García et al., 2023). Nguyen et al. (2010) found that smaller farms (often dairy farms) are less environmentally impactful and therefore may be more environmentally sustainable. The findings of Torres Jara de García et al. (2023) further solidify that smaller farms are often less environmentally degrading than larger farms. These trends also suggest that smaller farms (in terms of number of cattle and total land use) may require fewer resource inputs. The results of my analysis suggest that globally and on average, larger farms had a higher input and impact per unit product. However, the trends were highly variable at the regional level and the small number of data points may have biased the global trends.

Choosing sustainable practices

Figure 3 identified the best and worst farms from those included in this study. From these farms, several characteristics and practices were revealed as being potentially correlated with greater sustainability in beef production. First, however, it is useful to examine the worst farms to determine what practices may be worth shifting away from to better promote large-scale sustainability. Four of the five different worst farms were extensive or semi-extensive, pasture-based systems (Fig. 3). This trend fits within the existing literature, which suggests that pasture-based systems are generally less productive and can be more land-intensive per unit output, therefore pointing to greater inefficiency (Hayek & Garrett, 2018; Tichenor et al., 2017). Therefore, transitioning away from extensive, pasture-based systems towards more intensive production systems may be in the best interest of farmers in terms of improving efficiency. Additionally, three of the five worst systems received little to no management (Fig. 3). Research has suggested that farms better able to manage their operations are more economically successful and less environmentally impactful. In one study, it was found that farms better able to manage their pesticide use contributed less to environmental degradation (Başer & Bozoğlu, 2023). Farmers may want to consider the economic and environmental advantages of adopting more active management practices.

Now, two of the three different production systems constituting the best farms were dairy operations. This is likely because beef from dairy systems is produced as a coproduct, so when resource inputs and environmental impacts are allocated, beef receives a proportional share and the remainder of the environmental impacts are assigned to the dairy products produced from the same cow (Nguyen et al., 2010). Therefore, this trend, as my analysis has identified it, does not have significant implications as to what more sustainable practices could be worth consideration by beef producers. Additionally, two of the three best farms utilized high farm management, which further establishes that active management practices can be key to being more sustainable, both in terms of resource use and environmental impact (Başer & Bozoğlu, 2023). Overall, farmers may want to consider the practices of other farms that perform better on measures of sustainability to identify what practices are worth adopting.

Farm size as a measure of sustainability

Farm size, by many different measures, has often been identified in the literature surrounding the sustainability of beef production, either implicitly or explicitly. However, in many instances, the link between farm size and sustainability is only explained insofar as land use and the associated environmental impacts of land use change (Broom, 2019; Hayek & Garrett, 2018; Tichenor et al., 2017). Farm size is also frequently measured by the number of cattle (Başer & Bozoğlu, 2023; Demircan & Koknaroglu, 2007; Tichenor et al., 2017; Torres Jara de García et al., 2023). Occasionally, farm size will be measured more economically (i.e., in terms of productivity) (Torres Jara de García et al., 2023).

However, there has been little attention paid to the implications of the choice of measure of farm size used on environmental outcomes when observing sustainability. My research addresses that gap. The variability in my data indicates that it could be very important to consider the implications of using alternative measures of farm size when studying the sustainability of beef production. When observing the total pastureland use metric of farm size, the positive correlation between farm size and land use, water use, and greenhouse gas emissions, negative correlation between farm size and acidification, and no correlation between farm size and eutrophication (Fig. 1, B, E, H, K, N) suggest that smaller farms were more sustainable for all the studied factors except for eutrophication. However, when observing the number of cattle measure of farm size, the positive correlation between farm size and land use and water use, negative correlation between farm size and acidification and eutrophication, and no correlation between farm size and greenhouse gas emission (Fig. 1, E, D, G, J, M) suggest that smaller farms were more sustainable regarding water use, land use, acidification, and eutrophication, but that there was no relationship between farm size and emissions. Therefore, the measure of farm size may affect the interpretation of the sustainability outcome of the system in question, so it is important to consider this implication when observing the sustainability of beef production systems.

Limitations

Though the results from this analysis may have important implications for how researchers and decision-makers view and measure the sustainability of beef production, there were limitations to my approach. First, I note that there was a concentration of data points in the bottom left corner of most graphs in Fig. 1. This indicates that many production systems included in this study were smaller in size. As such, the small number of significantly larger farms may have dramatically skewed the data. Second, the global trends also presented limitations due to the presence of outliers, such as the observations in South America and variability in the regional trends. Given this, the global trends could have been skewed and also may have oversimplified the underlying regional trends. That could have led to misleading conclusions about the applicability of these trends. For example, it may be incorrect to assume that these global trends would apply to any one region.

Third, I encountered several challenges associated with data sourcing. The dataset I used was incomplete and did not contain all the variables I hoped to study. This meant I had to generate the variables I needed (i.e., productivity, total permanent pasture) with the data available to me. Additionally, many production systems lacked data on some variables, which may have limited the precision of my results. Further, there was more data available in some regions than others: there was an abundance of data for South America and Europe, but other regions (e.g., Asia, North America, Oceania) lacked sufficient data, especially on acidification and eutrophication.

Caveats

There is an important distinction to be made between systems producing beef from dairy cattle and those producing beef from non-dairy cattle. The two systems have different allocation methods for inputs and impacts. Most dairy farms across all graphs were found primarily in the bottom right corner. This is likely because dairy beef is a coproduct of dairy production, and therefore inputs and impacts are allocated proportionally (usually using an economic weighting).

Further, there are certain caveats to the measures of sustainability I chose to measure (i.e., water use, land use, greenhouse gas emissions, acidification, and eutrophication). These inputs and impacts are relevant and important, but my analysis excluded many other, equally important, measures of sustainability including economic sustainability and social sustainability (e.g., interest in continuing the farming profession in a specific region and using particular production practices). I also did not account for other measures of environmental sustainability including energy use or effects on biodiversity. My analyses also did not account for animal welfare in any way, and there may be significant trade-offs between animal welfare and environmental efficiency (e.g., Herrero et al., 2009). Therefore, when identifying the best and worst farms (Fig. 3), I did not take into account any of these factors, among many others, that may affect the sustainability of the farm depending on how sustainability is being defined.

Future research

My analysis presents many avenues for future research. In Figure 1 or an entirely separate graph, it would be interesting to differentiate between pasture vs grain-finished cattle, as the trend has been that the worst farms are pasture-based systems. Additionally, it could be interesting to consider, instead of the two best and worst points identified in Figure 3, to produce a similar graph but with a red-to-green, or best-to-worst gradient to better visualize the directionality of the relationships in Figure 2. Finally, it is important to note that there was a concentration of data points in the bottom left corner of most graphs in Figure 1. This likely indicates that many production systems included in this study were smaller in size and therefore significantly larger farms may skew the data. A useful future study might analyze these trends using different farm size thresholds.

Conclusions

In this paper, I analyzed the relationship between three measures of farm size, two measures of resource inputs, and three measures of environmental impact to observe the overall environmental efficiency of beef production systems located in various global regions. The global trends weakly indicated that smaller-scale farms are generally more sustainable than larger-scale farms across all measures of farm size. However, the regional trends and data reveal that the correlations between farm size, inputs, and impacts vary significantly and can be much more complex than the global trends would suggest. Therefore, while I cannot prescribe either smaller or larger farms as being more sustainable than the other for any size metric due to the uncertainty surrounding the global trend, my research indicates that observing and comparing trends at a variety of scales and comparing a variety of factors to determine a relatively optimal farm size for a specific location would be ideal. Best and worst farms for each farm size correlation also reveal implications of the common characteristics identified of these farms on how beef producers should adapt to the need for greater environmental efficiency. In a world facing a growing population and a subsequent rise in food demand, understanding the importance of farm size in measuring the sustainability of beef production systems and empowering the consumer and the producer to make more informed choices will be critical.

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