AgImpacts

The Covariance of Environmental Impacts Across Agricultural Commodities

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Introduction

Today's society relies heavily on agricultural production to feed the growing human population. With the population of roughly 7.6 billion people estimated to rise to 9.2 billion by 2050, demand for food is expected to rise as well.[1] In fact, studies show that by 2050, global agriculture will need to increase its output by 60-70% to accommodate for the population size.[2] However, agriculture in its current state already poses a major threat to the environments we inhabit and consumes a vast amount of resources. Agriculture is responsible for 70% of all freshwater withdrawal, 50% of usage of habitable land, and around 20% of greenhouse gas emissions.[3,4,5]

As a result of these practices, globally, about 25% of the total land area has been degraded, meaning that the soil has lost much of its productive capacity.[6] As much as 95% of the Earth's land areas could become degraded by 2050.[7]

If the current trends persist, agricultural systems will decrease in productivity even as demand continues to increase, which could result in severe food insecurity worldwide. Keeping such risks in mind, it is critical to consider the environmental impacts of food production to build a more sustainable future for agriculture.

This research project analyzed the covariance of environmental impacts within agricultural systems. Currently, much environmental action is focused on reducing greenhouse gas (GHG) emissions, but oftentimes the reduction of GHGs has other trade-offs. Ultimately, this paper and our web tool will aid individuals within the industry as well as nonprofit organizations in determining which factors will have the most significant impact on the sustainability of an agricultural system.

This research encompassed 10 commodities, each of which fall within one of three categories: plants, livestock, and seafood. These three categories are based on commonalities in agricultural methods, as well as the types of emissions, land use, and freshwater withdrawal which occur in the production of the commodities. For example, while feed might be an important consideration for livestock, it is not relevant to plants. Looking at multiple types of food products is critical, as the source of environmental impacts and potential mitigation interventions vary dramatically.

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[1] Silva, George. 2018. "Feeding the world in 2050 and beyond – Part 1: Productivity challenges." Michigan State University Extension. https://www.canr.msu.edu/news/feeding-the-world-in-2050-and-beyond-part-1.

[2] Ibid.

[3] "Water in Agriculture," World Bank, 2017, https://www.worldbank.org/en/topic/water-in-agriculture.

[4] Hannah Ritchie and Max Roser, "Land Use," Our World in Data, September 2019, https://ourworldindata.org/land-use.

[5] "ESS Website ESS : Emission Shares," www.fao.org, n.d., http://www.fao.org/economic/ess/environment/data/emission-shares/en/.

[6] "Land Degradation," Global Environment Facility, March 24, 2016, https://www.thegef.org/topics/land-degradation#:~:text=Globally%2C%20about%2025%20percent%20of.

[7] Ibid.

Across all commodities, analysis will include five environmental indicators: GHG emissions (kg CO_2 eq. per kg product), freshwater withdrawal (L per kg product), eutrophication potential (kg PO_4^{3-} eq. per kg product), acidification potential (kg SO_2 eq. per kg product), and land use (m^2yr per kg product). We selected these indicators based on the planetary boundary framework proposed in Rockström et al. (2020), which uses these metrics to describe the basic conditions under which humanity can survive.[8] These five indicators are relevant to all of our commodities, and we have standardized data on them, which is used for the graphs throughout this paper. We used freshwater withdrawal instead of water scarcity because scarcity is weighted by region and varies geographically, so freshwater withdrawal was more consistent.

Our guiding question has precedent as covariance relationships between environmental indicators have been observed several times in the literature both in the context of environmental interactions and the context of agriculture. For example, Li et al. (2021) characterizes a feedback loop between freshwater eutrophication and GHG emissions and Sepulveda-Jauregui et al. (2018) concludes that freshwater eutrophication exacerbates lake methane emission.[9,10] Furthermore, an article by the Union of Concerned Scientists describes the complex relationship between ocean acidification and GHG emissions.[11] Specific to agriculture, Heck et al. (2018) developed a land use optimization model designed to mitigate observed trade-offs between land use, environmental carbon storage, and other indicators.[12] It is based on this growing body of research on environmental indicator covariance that we decided to investigate covariance in the production of specific commodities.

The majority of the data in this paper is from Poore and Nemecek (2018), which consolidated data on the environmental impacts of farms, processors, packaging types, and retailers to identify solutions to reduce food's environmental impact. However, for the commodities of roundwood, salmon, shrimp, and tuna, we compiled and standardized data from additional studies on the life cycle assessment (LCA) of each commodity. An LCA is an analysis method used to quantify the environmental impacts of a commodity at all stages in the supply chain, from the production of the raw materials to use or consumption.[13] Our main data source, Poore and Nemecek (2018), did not include any information on roundwood, so we collected all of the roundwood data points from various LCAs. For the seafood commodities, we incorporated LCAs into our dataset to supplement the existing points from Poore and Nemecek (2018).

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[8] Johan Rockström et al., "Planet-Proofing the Global Food System," *Nature Food* 1, no. 1 (January 2020): 3–5, https://doi.org/10.1038/s43016-019-0010-4.

[9] Yi Li et al., "The Role of Freshwater Eutrophication in Greenhouse Gas Emissions: A Review," *Science of the Total Environment* 768 (May 2021): 144582, https://doi.org/10.1016/j.scitotenv.2020.144582.

[10] Armando Sepulveda-Jauregui et al., "Eutrophication Exacerbates the Impact of Climate Warming on Lake Methane Emission," *Science of the Total Environment* 636 (September 2018): 411–19, https://doi.org/10.1016/j.scitotenv.2018.04.283.

[11] Union of concerned scientists, "CO2 and Ocean Acidification: Causes, Impacts, Solutions," Union of Concerned Scientists, 2019, https://www.ucsusa.org/resources/co2-and-ocean-acidification

[12] Vera Heck et al., "Land Use Options for Staying within the Planetary Boundaries – Synergies and Trade-Offs between Global and Local Sustainability Goals," *Global Environmental Change* 49 (March 2018): 73–84, https://doi.org/10.1016/j.gloenvcha.2018.02.004.

[13] Muralikrishna, Iyyanki V., and Valli Manickam. 2017. "Chapter Five - Life Cycle Assessment." In Environmental Management: Science and Engineering for Industry, 57-75. N.p.: Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-811989-1.00005-1.

Environmental Indicators

What Are Trade-Offs?

Within this project, five major environmental indicators (GHG emissions, freshwater withdrawal, eutrophication potential, acidification potential, and land use) were selected for study across all commodities. These indicators were specifically chosen with the intent of diversifying sustainable agriculture efforts beyond sole reduction of GHG emissions. The breadth covered by these indicators also contributes to this project's intent of encouraging agricultural producers and distributors to consider potential "trade-offs" as they make sustainable choices.

Trade-offs refer to the way that sustainability efforts might reduce emissions within one targeted category, but unintentionally cause harmful environmental impacts across a different category. For example, if an initiative focused solely on reducing GHG emissions, the choice might be made to switch to on-site solar production. In doing so, although the GHG emissions from fuel use would decrease, land use or freshwater withdrawal might increase, and remain unaccounted for. It is important to evaluate whether the unintended consequences of sustainability efforts create environmental harm beyond the intended benefit.

Evaluation of trade-offs is complex and requires awareness of trends across a wide variety of environmental indicators. This project assists producers and distributors by providing data, graphs, and analysis of the relationships between five major environmental indicators, alongside several commodity-specific indicators. By establishing the presence or lack of correlations between different environmental indicators, this project assists in optimization of sustainability efforts, and helps with decision making to best ameliorate environmental impact.

Our Analysis

Generally, our team found one of three relationships for each comparison. When our team observed a positive correlation between the given environmental indicator and GHG emissions, we considered it a co-beneficial relationship, in which decreasing GHG emissions has the same effect on the given environmental impact (Figure 0.1, top). When points are scattered with seemingly no coordination, and the resulting line of best fit is roughly horizontal, our team considered GHG emissions and the given environmental indicator to be independent of one another (Figure 0.1, center). The final commonly observed relationship was a negative correlation, which our team considered to be a "trade-off" (Figure 0.1, bottom). This implies that decreasing GHG emissions is somehow connected to increasing the magnitude of the given environmental impact.

Figure 0.1. This graphic gives examples of relationships between environmental indicator pairs.

GHG Emissions

Overview

Greenhouse gas emissions refer to the anthropogenic production of certain gases which are known to trap heat in the atmosphere.[14] Increased emissions result in higher concentrations of greenhouse gases present in the atmosphere, accelerating global warming. The global warming potential of GHGs is determined as a function of radiative forcing (the effect of each unit of gas on the level of energy remaining on the

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[14] US Environmental Protections Agency. n.d. "Overview of Greenhouse Gases." EPA. https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

Earth), mean lifetime, and emissions (total quantity of gas emitted).[15] Several GHGs (water vapor, carbon dioxide, ozone, methane, and nitrous oxide) occur naturally, but have increased in production due to human activity, while others do not occur naturally and were created entirely through anthropogenic means.[16] The effects of these GHGs are compared by using the global warming potential (GWP) of each gas, and standardizing in terms of carbon dioxide equivalents. Essentially, this means that a certain amount of one GHG can be converted into the amount of carbon dioxide with the same GWP.

Agricultural GHG Emissions

Globally, the food system contributes 21 to 37% of all human GHG emissions, surpassing both industry and transport.[17] Agriculture is a source of three main GHGs: carbon dioxide, methane, and nitrous oxide. Agricultural activities primarily contribute to carbon dioxide emissions through on-farm energy use, deforestation, burning, drainage of wetlands, and tillage.[18] Methane is released primarily through enteric fermentation and manure management, while nitrous oxide is emitted through nitrogenous fertilizers and cropping practices.[19] Soil and organic matter involved in agriculture can also serve as carbon sinks, slightly offsetting emissions.[20]

Impacts of GHG Emissions

GHG emissions directly lead to global warming by trapping heat in the atmosphere. The effects of global warming include more frequent and severe weather, including storms, heat waves, floods, and droughts.[21] Global warming results in both the melting of ice sheets and thermal expansion of water, both of which contribute to rising sea levels, which will threaten coastal populations.[22] Higher temperatures also cause an increase in ground-level ozone, creating more smog and directly harming human health.[23]

Global warming forces changes in the behavioral patterns of wildlife and is correlated to an increased rate of extinction.[24] GHG emissions also contribute to ocean acidification, as the ocean absorbs excess carbon dioxide in the atmosphere.[25] Acidification causes major losses in the populations of marine life and also accelerates the rate of extinction.

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[15] Johnson, Jane, Alan Franzluebbers, Sharon Weyers, and Donald Reicosky. 2007. "Agricultural opportunities to mitigate greenhouse gas emissions." *Environmental Pollution* 150, no. 1 (November): 107-124. https://doi.org/10.1016/j.envpol.2007.06.030.

[16] Ibid.

[17] IPCC. 2019. "Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems." https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf.

[18] Johnson, Jane, Alan Franzluebbers, Sharon Weyers, and Donald Reicosky. 2007. "Agricultural opportunities to mitigate greenhouse gas emissions." *Environmental Pollution* 150, no. 1 (November): 107-124. https://doi.org/10.1016/j.envpol.2007.06.030.

[19] Ibid.

[20] Ibid.

[21] Denchak, Melissa. 2016. "Are the Effects of Global Warming Really that Bad?" Natural Resources Defense Council. https://www.nrdc.org/stories/are-effects-global-warming-really-bad.

[22] Ibid.

[23] Ibid.

[24] Ibid.

[25] Ibid.

Freshwater Withdrawal

Overview

Freshwater withdrawal is the measure of how much water is used from a terrestrial source. This includes lakes, rivers, groundwater, and other forms of surface water, but excludes the water used in rain-fed systems.[26] It is essential that the resource is not being used carelessly as several countries are already subject to high water stress (high ratio of freshwater withdrawal to renewable freshwater sources). Furthermore, freshwater withdrawal is projected to grow with increased population and consumption of water intensive food products, such as beef.[27] This paper will be measuring freshwater withdrawal throughout a commodity's life cycle unless specifically stated otherwise, composed of the water used during farming and growth stages, as well as inputs from processing. We report freshwater withdrawal as liters of water per kilogram of edible product, with an exception to roundwood, which will be per cubic meter of underbark roundwood.

Agricultural Freshwater Withdrawal

Freshwater withdrawal comes from many different industries, but the agriculture industry makes up upwards of 80% of the surface water used in the United States and 70% of the world's supply.[28,29] This water is directed toward a variety of uses such as irrigation, agrochemical application, crop cooling, and frost control and positively affects yields if used properly. However, due to it being a finite resource, it is crucial that conservation practices are implemented to maximize the efficiency of water usage.[30]

Impacts of Freshwater Withdrawal

Water supplies are limited, so using excessive amounts before these sources are able to "recharge" leads to regions becoming "water-stressed."[31] Groundwater-dependent countries that experience little rainfall are threatened by potential water-stress as the lack of precipitation halts the recharge process.[32] As reported by the United Nations in a 2018 report, over 2 billion people live in highly water-stressed countries, many of which face the risk of displacement from a lack of water.[33] Water is important for human consumption and sanitation, as well as for agricultural production. For farms, it is important that practices are adjusted in order to preserve the longevity of farms as regions that are strained for water may suffer from destroyed produce, negatively impacted wildlife, worsened soil quality, and more.[34]

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[26] Hannah Ritchie and Max Roser, "Water Use and Stress," Our World in Data, November 13, 2013, https://ourworldindata.org/water-use-stress. Accessed 24 Jan. 2021.

[27] Ibid.

[28] Irrigation and Water Use. USDA. https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/. Accessed 24 Jan. 2021.

[29] "Water Scarcity." WWF. https://www.worldwildlife.org/threats/water-scarcity. Accessed 24 Jan. 2021.

[30] "Agricultural Water." CDC. https://www.cdc.gov/healthywater/other/agricultural/index.html. Accessed 30 Jan. 2021.

[31] "Freshwater Withdrawals." EPA. https://www.epa.gov/report-environment. Accessed 24 Jan. 2021.

[32] "Artificial Groundwater Recharge." USGS. https://www.usgs.gov/mission-areas/water-resources/science/artificial-groundwater-recharge?qt-science_center_objects=0#qt-science_center_objects. Accessed 27 Jan. 2021.

[33] "Water Scarcity." UN. https://www.unwater.org/water-facts/scarcity/. Accessed 30 Jan. 2021.

[34] "HOW DOES DROUGHT AFFECT OUR LIVES?" NDMC. https://drought.unl.edu/Education/DroughtforKids/DroughtEffects.aspx. Accessed 24 Jan. 2021.

Eutrophication Potential

Overview

Eutrophication is an overabundance of nutrients in a body of water. This over-fertilization can ultimately lead to an oxygen depleted or otherwise toxic environment[35]. In general, the limiting nutrient for algal plankton and blue-green algae is either phosphorus or nitrogen, depending on their environment[36]. However, the sudden introduction of nutrient rich compounds causes algae populations to swell to a size that cannot be maintained, leading to mass death and decomposition, a process that consumes the oxygen dissolved in the water[37]. In oxygen-depleted water, populations of anaerobic bacteria increase dramatically. These bacteria release toxic byproducts such as ammonia and hydrogen sulfide as they continue to decompose the biomass[38]. In tandem, oxygen depletion and toxic compounds can create "dead zones" where animal and plant species perish. Other effects of these algal blooms include blocking sunlight from reaching deeper water, and selection for a different profile of phytoplankton, which disrupts the food chain, destabilizes endemic species, and reduces biodiversity[39].

Agricultural Eutrophication Potential

Agricultural runoff is the largest source of phosphate and other eutrophying emissions, followed by industry and municipal sewage discharge.[40] The source of these emissions are soluble fertilizers and regular soil disturbances that make them more easily swept away in rain or snow.[41] A wide variety of compounds have a eutrophying effect, whether they are phosphate or nitrogen containing themselves or have a high oxygen demand that triggers compounds like iron phosphate to be reduced and release phosphate.[42] It is the net effect of nutrient availability that is quantified. Eutrophication potential is commonly expressed in terms of kilograms of phosphate equivalents (kg PO_4^{3-} eq) when dealing with freshwater, although kilograms of nitrogen equivalents (kg N eq) are often used to quantify marine eutrophication.[43] A variety of experimentally determined conversion factors are needed to arrive at common units.[44]

Impacts of Eutrophication

Globally, eutrophication is an increasingly frequent and severe phenomenon. It can be observed in the incidence of coastal hypoxia, which is the development of low oxygen regions in water near human

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[35] Mikhail Butusov and Arne Jernelöv, "Eutrophication," *SpringerBriefs in Environmental Science*, 2013, 57–68, https://doi.org/10.1007/978-1-4614-6803-5_7.

[36] Ibid.

[37] Santosh Kumar Sarkar, *Marine Algal Bloom: Characteristics, Causes and Climate Change Impacts* (Singapore: Springer Singapore, 2018), https://doi.org/10.1007/978-981-10-8261-0.

[38] Ibid.

[39] Ibid.

[40] Ibid.

[41] Mikhail Butusov and Arne Jernelöv, "Eutrophication," *SpringerBriefs in Environmental Science*, 2013, 57–68, https://doi.org/10.1007/978-1-4614-6803-5_7.

[42] Ibid.

[43] Annex 5 Environmental Impacts Analysed and Characterisation Factors Contents," (2006), https://ec.europa.eu/environment/waste/pdf/study/annex5.pdf.

[44] Ibid.

settlements. For the past three decades, the amount of regions like these has increased by 5.5%.[45] In certain regions such as the North Sea and Baltic Sea, analyses of the spatiotemporal distribution of oxygen between 2001 and 2003 revealed severe hypoxia to such an extent that researchers concluded a 30% reduction in nutrient concentrations would be required to prevent further oxygen depletion.[46] For these reasons, eutrophication poses a severe threat to biodiversity in aquatic environments.

Acidification Potential

Overview

Acidity describes the pH of a solution. By definition, pH is a measure of the concentration of hydrogen ions (H^+) on a scale of 1 to 14. Solutions with a pH between 1 and 6 have a higher concentration of H^+, making them acidic, while those with a pH between 8 and 14 have lower concentrations of H^+ and are basic. A pH of 7 is considered neutral. Measurements of pH are often useful in monitoring soil, plant, animal, and ecosystem health, as acidic environments harm or kill organisms.

Acidifying emissions are commonly caused by sulfur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), and carbon dioxide (CO_2). Each of these molecules contribute differently to acidification. It is worthwhile to recognize that any molecule can impact multiple environmental indicators. CO_2, for example, plays a significant role in global warming as described in the GHG emissions section above, but it is also responsible for certain types of acidification, mainly ocean acidification.[47]

Sulfur dioxide (SO_2) is also a contributor to ocean acidification, and, along with nitrogen oxides, is largely a consequence of burning fossil fuels. According to data collected by the NASA Ozone Monitoring Instrument Satellite, roughly two-thirds of global sulfur dioxide emissions are from oil and coal refineries and power plants.[48] Freshwater acidification is less widely-researched than ocean acidification, but studies suggest that CO_2 also decreases the pH levels of bodies of freshwater such as lakes, rivers, ponds, and streams.[49] All types of acidification—ocean acidification, freshwater acidification, and soil acidification, which is detailed below—contribute to the larger, global problem of acidification.

Agricultural Acidification Potential

Soil acidification is mainly caused by agricultural processes. Harvesting crops and cutting down trees naturally increase soil acidity, as plants absorb basic nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), and

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[45] Santosh Kumar Sarkar, *Marine Algal Bloom: Characteristics, Causes and Climate Change Impacts* (Singapore: Springer Singapore, 2018), https://doi.org/10.1007/978-981-10-8261-0.
[46] Ibid.
[47] National Oceanic and Atmospheric Administration. 2020. "Ocean acidification." National Oceanic and Atmospheric Administration. https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification.
[48] Dahiya, Sunil, and Lauri Myllyvirta. 2019. "Global SO2 emission hotspot database." Greenpeace International. https://www.greenpeace.org/static/planet4-africa-stateless/2019/08/5f139f4c-final-global-hotspot-and-emission-sources-for-so2_19th_august-2019.pdf.
[49] Weiss, Linda C., Leonie Pötter, Annika Steiger, Sebastian Kruppert, Uwe Frost, and Ralph Tollrian. 2018. "Rising pCO2 in Freshwater Ecosystems Has the Potential to Negatively Affect Predator-Induced Defenses in Daphnia." Current Biology 28, no. 2 (January): 327-332. https://doi.org/10.1016/j.cub.2017.12.022.

potassium (K^+) from the soil.[50,51] When crops are harvested, they take these compounds with them, leaving more-acidic soil behind. Additionally, ammonium-based fertilizers can impact soil and freshwater acidification, as soil converts ammonium nitrogen into nitrate (NO^{3-}) and hydrogen ions (H^+), which lower the soil's pH levels.[52] When applied in excess, these chemicals can leach through the soil and enter the water cycle.[53]

This paper defines acidification potential as the sum of the acidification potential of the feed, farm, processing, transportation, storage, and retail for each individual commodity. We measure acidification potential in kilograms of sulfur dioxide equivalents (SO_2 eq.) per kilogram of edible weight produced. A SO_2 equivalent is a molecule whose acidification potential, when multiplied by a conversion factor, is comparable to that of SO_2. For example, the acidification potential of 1 kilogram of NH_3 is equivalent to 1.88 kilograms of SO_2.[54]

Impacts of Acidification

For agriculture and aquaculture, the consequences of acidification are great. Acidic soil is less fertile and can lead to significant losses in production due to the lack of basic nutrients or excessive application of chemical fertilizers, as detailed above. Decreased crop production can negatively impact livestock farmers, too, as animals like beef cattle and poultry rely heavily on crops for feed.

Acidifying emissions can also enter the water cycle through run-off, erosion, or leaching into the water table.[55] This can decrease the pH levels of aquatic environments, disrupting the salinity of fish blood and increasing the risk of fish heart attack and suffocation.[56] Moreover, evaporation from acidified bodies of water can create acid rain, which kills crops and trees.[57]

Thus, acidification impacts commodity production, both for food and raw materials, and reducing emissions is ultimately in the best interest of producers, distributors, and consumers. The most widely-effective method for reducing the acidification of ecosystems is to eliminate acidifying emissions

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[50] Ball, Jeff. 1999. "Understanding and Correcting Soil Acidity." Noble Research Institute, January 1, 1999. https://www.noble.org/news/publications/ag-news-and-views/1999/january/understanding-and-correcting-soil-acidity/.

[51] "Chapter 3: Causes of Acidification." n.d. Agriculture Victoria: Victorian Resources Online. Accessed January 30, 2021. http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/0d08cd6930912d1e4a2567d2002579cb/2b4e9f0f68863059ca2574c8002b3e83/$FILE/Acid%20soil%20strategy-final%20June%20ch3.pdf.

[52] Ibid.

[53] "Soil Acidity." n.d. Soil Quality. Accessed January 30, 2021. http://soilquality.org.au/factsheets/soil-acidity#:~:text=The%20main%20cause%20of%20soil,hydrogen%20ions%20in%20the%20soil.

[54] "Acidification." n.d. Life Cycle Assessment. Accessed January 30, 2021. http://qpc.adm.slu.se/7_LCA/page_10.htm.

[55] Ibid.

[56] "Acidification Impacts." n.d. United States Department of Agriculture Forest Service. Accessed January 30, 2021. https://webcam.srs.fs.fed.us/pollutants/acidification/index.shtml#:~:text=Fossil%20fuel%20burning%20emits%20air,acids%2C%20and%20ammonium%20to%20ecosystems.

[57] United States Geological Survey. n.d. "Acid Rain and Water." United States Geological Survey. Accessed January 30, 2021. https://www.usgs.gov/special-topic/water-science-school/science/acid-rain-and-water?qt-science_center_objects=0#.

altogether.[58] In extreme cases, however, neutralizing the pH of soil through the process of liming may be necessary to restore basic nutrients.[59]

Land Use

Overview

Land use is the last of the five main indicators analyzed to assess the environmental impacts of our commodities. It is a measure of the amount of land that a farm uses per unit of product. A higher land use value for a specific farm means that the farm is using more land to produce the same amount of a crop than a farm that has lower land use. High land use effectively means that a producer is using the land more extensively. This is generally worse for the environment because land that could be used for other agriculture, urban space, or natural habitat is essentially being wasted.

Agricultural Land Use

The agricultural sector uses a lot of the Earth's land. Today, half of the world's inhabitable land is used for agriculture.[60] 77 percent of agricultural land is used for livestock (including grazing land and land used to grow animal feed), while the remaining 23 percent is used for crops.[61] Agricultural expansion within the last thousand years has been one of humanity's largest impacts on the world. There are many consequences of agricultural land use, such as affecting the water quality in the area. The crops being planted and agricultural practices can limit the amount of water available, and runoff from fertilizers, pesticides, and livestock can pollute water.[62] The expansion of land often results in the destruction of natural habitats for animals in the area.[63] Additionally, agricultural land use can also lead to the spread of invasive species that can disrupt the ecosystem and damage animal and human habitats.[64] For these reasons, decreasing land use and land expansion as well as improving agricultural land use practices are important steps towards improving ecosystems locally and in turn improving the global environment.

A Note on Units

At first glance, the units for land use might seem strange: m^2yr. This metric indicates the area occupied to produce 1kg of product. It is calculated using the inverse of yield and using total occupation time, which includes fallow time.[65]

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[58] "Acidification Impacts." n.d. United States Department of Agriculture Forest Service. Accessed January 30, 2021. https://webcam.srs.fs.fed.us/pollutants/acidification/index.shtml#:~:text=Fossil%20fuel%20burning%20emits%20air,acids%2C%20and%20ammonium%20to%20ecosystems.

[59] Ibid.

[60] Ritchie, Hannah, and Max Roser. "Land Use." Our World in Data. November 13, 2013. Accessed January 27, 2021. https://ourworldindata.org/land-use.

[61] Ibid.

[62] "Land Use." EPA. July 16, 2018. Accessed January 27, 2021. https://www.epa.gov/report-environment/land-use.

[63] Ibid.

[64] Ibid.

[65] J. Poore and T. Nemecek, "Reducing Food's Environmental Impacts through Producers and Consumers," Science 360, no. 6392 (June 1, 2018): 987–92, https://doi.org/10.1126/science.aaq0216.

Data Source

The data used in this analysis come from life-cycle assessments; these assessments may characterize a single farm or a set of farms characteristic to a region. In these assessments, a life-cycle inventory was conducted, wherein the processes and inputs necessary to produce a functional unit are quantified. The total outputs from these processes are then calculated using known relationships and emissions factors. Finally, the outputs are grouped into impact categories—like climate change or eutrophication.

We treat each of these data points as a sample of a production system—the impacts resulting from that system are a function of all the processes for that farm and cannot be varied independently. For example, we cannot pick the "best" water footprint and the "best" GHG footprint from two different points because the processes don't influence only one impact category or another.

Commodity Specific Methodology and Analysis

Plants

The plant commodities we analyzed encompass multiple facets of agriculture, with maize and soy representing annual staple crops, and palm oil, coffee, and roundwood representing longer term cultivation. Trade-off relationships were relatively rare in our datasets, as the majority of our data indicates no correlation, with some notable relationships between GHG emissions and other indicators.

Maize

We found no apparent trends between GHG emissions and the other four environmental indicators for maize. Given the diversity of climates, rotations, and seed types used for maize, further analysis is needed to ensure that this diversity did not obfuscate relationships within these types of production. However, geographic analysis reveals abnormally high levels of land use and GHG emissions in Sub-saharan Africa; this is most likely attributed to the "yield gap," a phenomenon resulting from a lack of fertilizer input and optimized production systems which is especially prevalent in developing countries. As a staple food crop, demand for maize in developing countries is expected to increase 200% while yield will drop a predicted 10% by 2050. ***Based on our geographic analysis, it is especially important to optimize maize production in developing parts of the world to decrease environmental impact and match this growth in demand.***

Overview

Along with rice and wheat, maize, also known as corn, provides at least 30% of the food calories for more than 4.5 billion people on the planet. Today, maize is the most important food crop in Sub-Saharan Africa and Latin America.[66] However, while consumption is expected to increase two-fold, yields are expected to decline 10% by 2050 due to climate change, leading to higher global prices and malnutrition.[67] Thus, it is especially important that producers find more land-, water-, and energy-efficient methods of farming maize while preserving livelihoods in the developing world.

Summary of Analysis and Limitation

To conduct our analysis of maize, we used 152 data points from the Poore and Nemecek (2018)[68] supplemental dataset. The raw data and code are available for use on GitHub.[69, 70] We compared four

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[66] "Why MAIZE – MAIZE - CGIAR Research Program on MAIZE." https://maize.org/why-maize/. Accessed 15 Jan. 2021.

[67] Michelle Tigchelaar et al., "Future Warming Increases Probability of Globally Synchronized Maize Production Shocks," Proceedings of the National Academy of Sciences 115, no. 26 (June 26, 2018): 6644–49, https://doi.org/10.1073/pnas.1718031115.

[68] J. Poore and T. Nemecek, "Reducing Food's Environmental Impacts through Producers and Consumers," Science 360, no. 6392 (June 1, 2018): 987–92, https://doi.org/10.1126/science.aaq0216.

[69] https://github.com/anushreechaudhuri/agimpacts.

[70] Using the Pandas library in Python, a script extracted commodity-specific data from the source spreadsheet and created scatter plots, map plots, bar graphs, and other relevant charts based on the type of relationship being analyzed. A total of 152 sample points were used.

environmental indicators to GHG emissions (Figure 1.1), further analyzed land use and freshwater withdrawal from each stage of the production process (Figure 1.2), and finally mapped each indicator to geographic location (Figure 1.3).

The data were not grouped by irrigation method or crop rotation system because of a lack of consistent reporting across the studies compiled in Poore and Nemecek (2018). Based on pre-labeled system types, we plotted data categorically by conventional and organic farming methods, but because of the small number of organic systems, this analysis produced insignificant results and is not included.

Aggregate Indicator Analysis

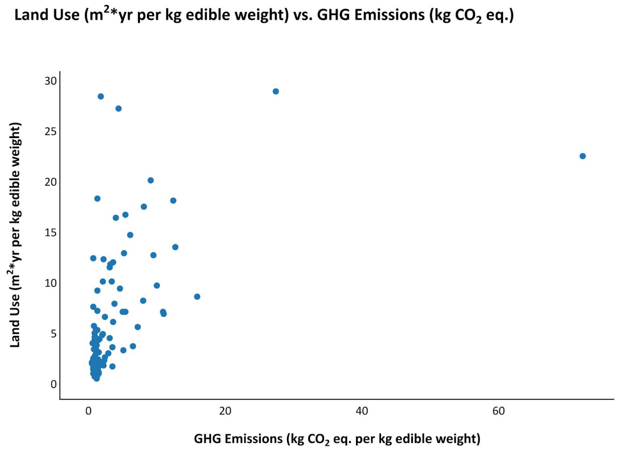

Figure 1.1a. Most data points are clustered at low land use and GHG emissions, but outliers spread with a loose positive correlation. A similar distribution of data points is observed in Figure 1.2a.

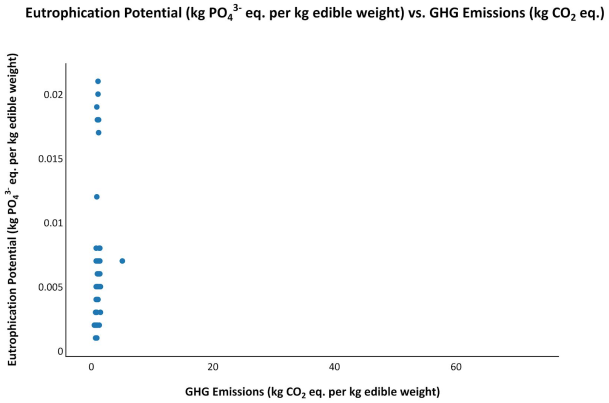

Figure 1.1b. There is no apparent trend observed between eutrophication potential and GHG emissions.

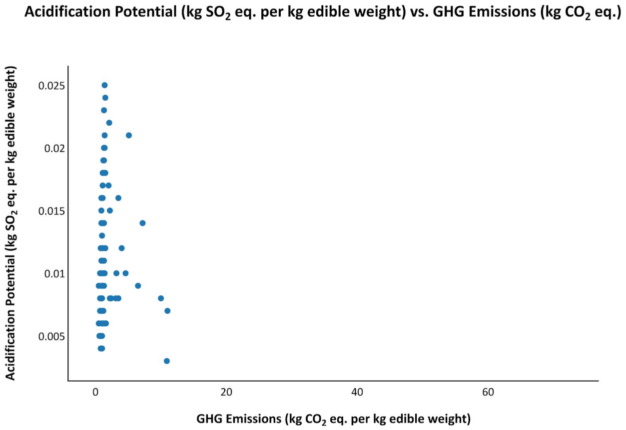

Figure 1.1c. There is no apparent trend observed between acidification potential and GHG emissions.

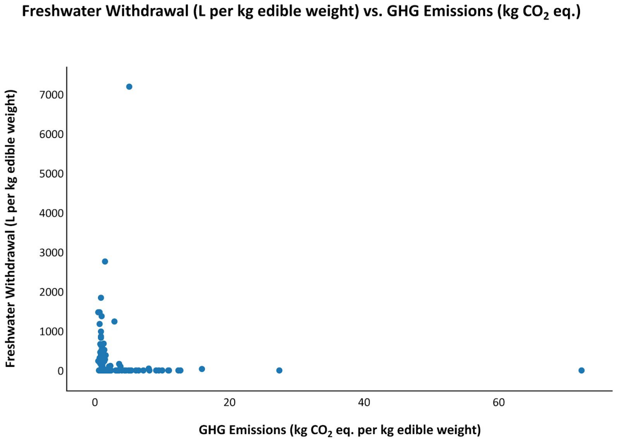

Figure 1.1D. With the exception of two outliers in Sub-saharan Africa (Angola and Zambia), there is no trend between non-zero values of freshwater withdrawal and GHG emissions. 44 of 86 data points that reported zero freshwater withdrawal are explicitly labeled as rainfed systems.

Figure 1.1. Scatter plots of four environmental indicators compared to GHG emissions for maize production show no apparent trend. With the exception of outliers, ranges for GHG emissions, land use, eutrophication potential, acidification potential, and freshwater withdrawal are normal compared to other studies with the same standardizations.[71, 72, 73, 74, 75, 76] *Data from Poore and Nemecek (2018).*

With the exception of outliers, the ranges of GHG emissions and acidification potential from maize production is comparable to soy and palm oil, and lower than coffee and roundwood. The range of eutrophication potential is slightly lower than soy, and much lower than coffee, roundwood, and palm oil. The range of land use is comparable to soy, lower than coffee, and higher than palm oil. The range of freshwater withdrawal is comparable to soy and much higher than roundwood. All indicator ranges for maize are comparable to soy, suggesting possible similarities in production scale and impact.

No apparent trends were found when comparing GHG emissions to the four other indicators (Figure 1.1). We also looked for trends after filtering by country and tested whether extreme cases were hiding a true trend by removing outliers with an interquartile method (not shown); these additional analyses did not yield any correlations. The lack of a clear relationship between GHG emissions and the other indicators across all analysis methods indicates that because maize production is so variable in different parts of the world[77] and across such a large dataset, it is difficult to identify patterns with comparisons between broadly calculated indicators.

Impact of Specific Production Stages

We sought to quantify the impact of specific production stages, which may be more consistent around the world and show trends that are isolated to on-farm or post-farm processes. We isolated the emissions

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[71] Titaporn Supasri et al., "Life Cycle Assessment of Maize Cultivation and Biomass Utilization in Northern Thailand," Scientific Reports 10 (February 26, 2020), https://doi.org/10.1038/s41598-020-60532-2.

[72] Seungdo Kim, Bruce E. Dale, and Robin Jenkins, "Life Cycle Assessment of Corn Grain and Corn Stover in the United States," The International Journal of Life Cycle Assessment 14, no. 2 (March 1, 2009): 160–74, https://doi.org/10.1007/s11367-008-0054-4.

[73] Chong Wang et al., "Life Cycle Assessment of Wheat-Maize Rotation System Emphasizing High Crop Yield and High Resource Use Efficiency in Quzhou County," Journal of Cleaner Production 68 (April 1, 2014): 56–63, https://doi.org/10.1016/j.jclepro.2014.01.018.

[74] Valentina Fantin et al., "Environmental Assessment of Wheat and Maize Production in an Italian Farmers' Cooperative," Journal of Cleaner Production, Towards eco-efficient agriculture and food systems: selected papers addressing the global challenges for food systems, including those presented at the Conference "LCA for Feeding the planet and energy for life" (6-8 October 2015, Stresa and Milan Expo, Italy), 140 (January 1, 2017): 631–43, https://doi.org/10.1016/j.jclepro.2016.06.136.

[75] Lieselot Boone et al., "Environmental Life Cycle Assessment of Grain Maize Production: An Analysis of Factors Causing Variability," Science of The Total Environment 553 (May 15, 2016): 551–64, https://doi.org/10.1016/j.scitotenv.2016.02.089.

[76] M. Holka et al., "Life Cycle Assessment of Grain Maize in Intensive, Conventional Crop Production System," 2017, https://doi.org//paper/LIFE-CYCLE-ASSESSMENT-OF-GRAIN-MAIZE-IN-INTENSIVE-%2C-Holka-Bie%C5%84kowski/d60944ec562db8a9bff5fbd98770f2cb486275ec.

[77] Nadiezhda Y. Z. Ramirez-Cabral, Lalit Kumar, and Farzin Shabani, "Global Alterations in Areas of Suitability for Maize Production from Climate Change and Using a Mechanistic Species Distribution Model (CLIMEX)," Scientific Reports 7, no. 1 (July 19, 2017): 5910, https://doi.org/10.1038/s41598-017-05804-0.

created during each production stage for the five indicators. **There are no apparent correlations between indicator values for production stages and GHG emissions (Figure 1.2).**

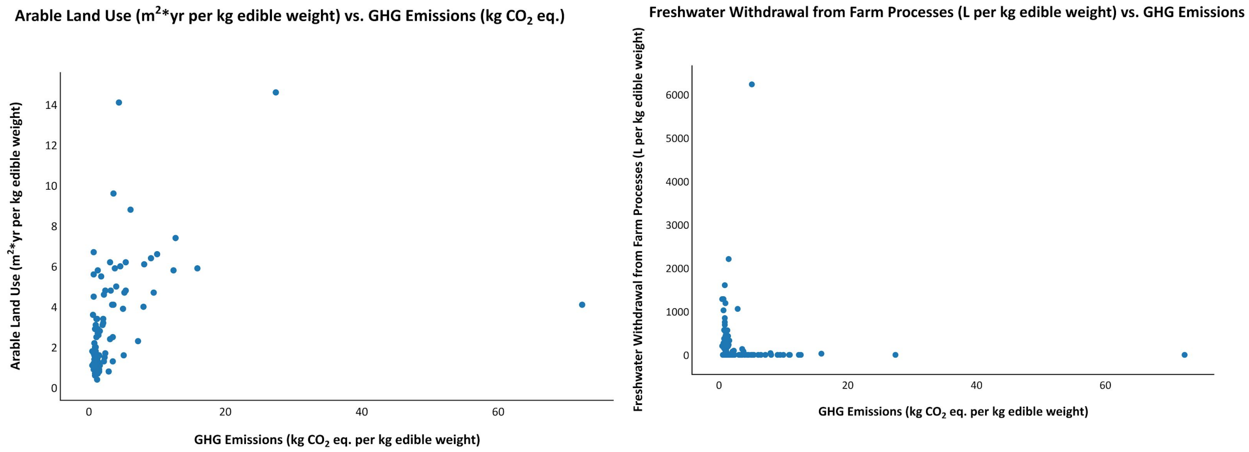


Figure 1.2a. Most data points are clustered at low land use and GHG emissions, but outliers spread with a loose positive correlation. These outliers include Angola, Namibia, and Zambia. There is a similar distribution to Figure 1.1A.

Figure 1.2b. There is no apparent trend in non-zero freshwater withdrawal values. As in Figure 1.1D, 44 of 86 data points that reported zero freshwater withdrawal from farm processes are explicitly labeled as rainfed systems.

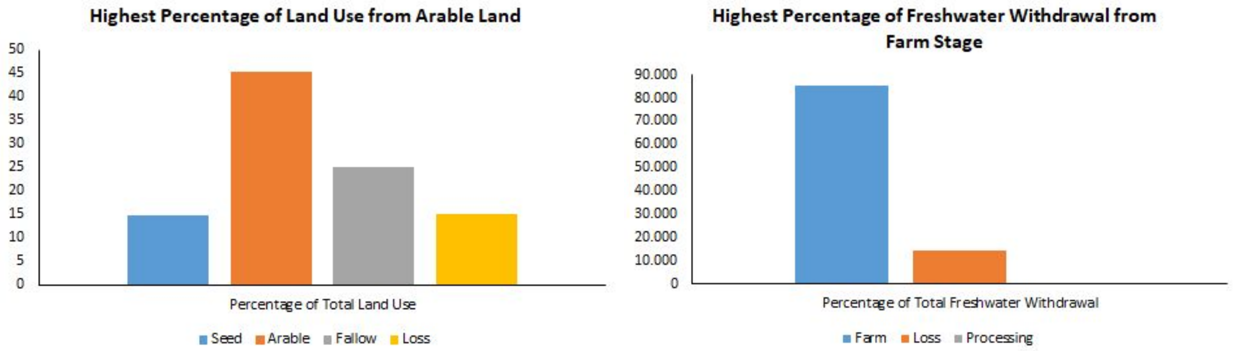


Figure 1.2c. Arable land use contributes the highest percentage to total land use for maize production.

Figure 1.2d. Freshwater withdrawal from the farm stage contributes the highest percentage to total freshwater withdrawal for maize production. No freshwater withdrawal is used for processing.

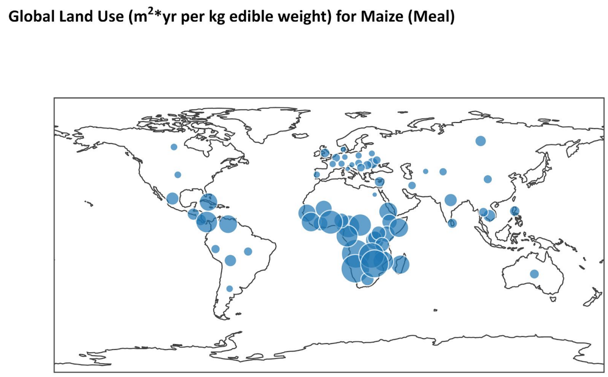
Figure 1.2. Plots of arable land use and freshwater withdrawal from the farm stage, with arable land use and freshwater withdrawal from the farm stage contributing the greatest to total land use and freshwater withdrawal, respectively. Data from Poore and Nemecek (2018).

Isolating the farm production phase yielded similar results to the aggregate production data for land use and freshwater withdrawal because on-farm processes are the main contributors to those indicators (Figure 1.2c and 1.2d). The Food and Agriculture Organization (FAO) defines arable land as "land under temporary agricultural crops (multiple-cropped areas are counted only once)."[78] The majority of arable land is used for cereal production, including maize; land use in other production stages are minimal because seed and fallow stages are shorter in duration of use when growing maize.[79, 80] Therefore, **increasing the efficiency of on-farm arable land use and freshwater withdrawal will most likely have the greatest impact on decreasing land use and freshwater withdrawal overall.**

Although there are no significant correlations between GHG emissions and the indicators (Figures 1.1 and 1.2), this lack of trends may be because of covariance between indicators or inconsistent reporting: for example, some studies exclusively reported irrigation methods, while others exclusively reported farm size or crop rotation system, so comparing between these data points is difficult. **This lack of trends does not necessarily indicate a lack of trade-offs and is valuable because it incentivizes further research and data analysis on maize production, specifically by system type, climate, species, and seed.**

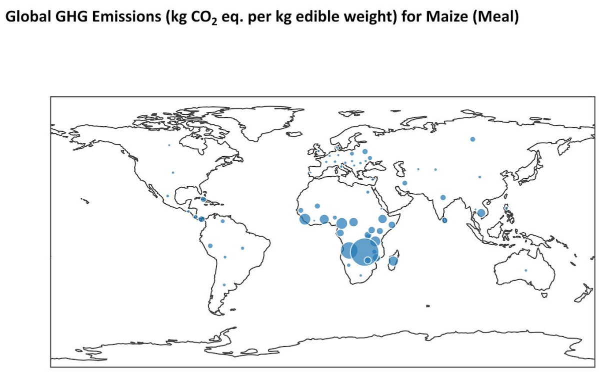
Geographic Analysis of Land Use and GHG Emissions

We noted that the range of impact intensities are largely driven by geography and further explored these trends.



Global Land Use (m^2*yr per kg edible weight) for Maize (Meal)

Figure 1.3a. Sub-saharan Africa (SSA) shows a higher land use per kg of retail weight maize produced compared to the Americas, Europe, and Asia. A larger circle size indicates larger values of land use, and each circle represents the average land use of one country.



Global GHG Emissions (kg CO_2 eq. per kg edible weight) for Maize (Meal)

Figure 1.3b. Like land use, SSA also shows higher GHG emissions per kg of retail weight maize produced compared to the Americas, Europe, and Asias. A larger circle size indicates more emissions, and each circle represents the average GHG emissions of one country.

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[78] "Arable and Permanent Crop Land Area. - the United Nations." https://www.un.org/esa/sustdev/natlinfo/indicators/methodology_sheets/land/arable_cropland_area.pdf. Accessed 26 Jan. 2021.

[79] "USDA ERS - Data Feature: How Is Land Used," accessed January 26, 2021, https://www.ers.usda.gov/amber-waves/2012/march/data-feature-how-is-land-used/.

[80] Hannah Ritchie and Max Roser, "Land Use," Our World in Data, November 13, 2013, https://ourworldindata.org/land-use.

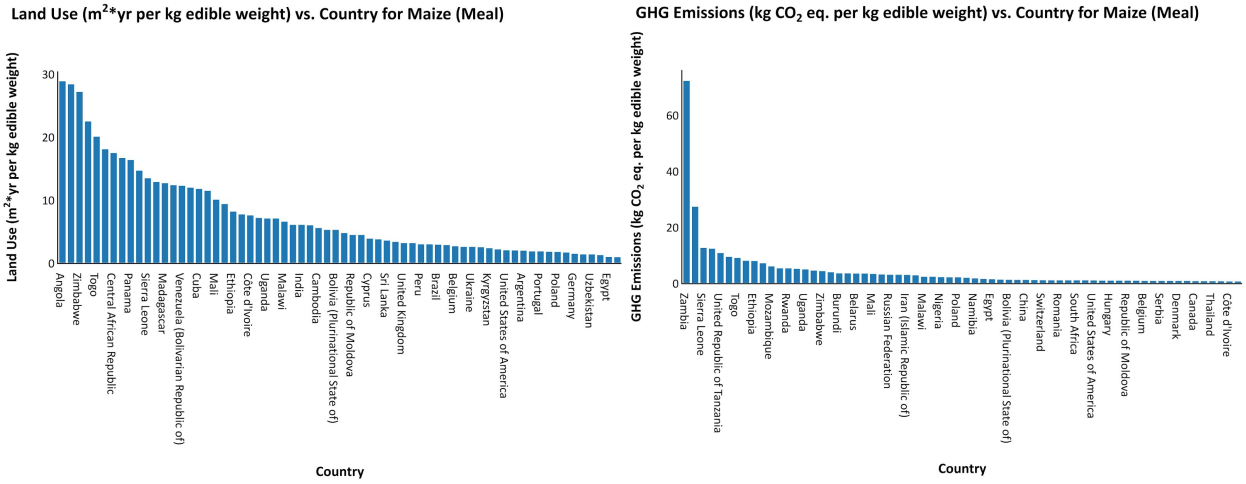

Figure 1.3c. Angola, Namibia, and Zimbabwe have unusually high land use.

Figure 1.3d. Zambia, Angola, and Sierra Leone have unusually GHG emissions.

Figure 1.3. Geographic analyses of land use and GHG emissions by country. Data from Poore and Nemecek (2018).

Figure 1.3 maps the relative magnitudes of land use and GHG emissions by country. The distributions for both map plots in Figure 1.3a and 1.3b show a similar concentration of values by country. In general, countries with high emissions have high land use values as well. This similarity in distribution may suggest that GHG emissions and land use are correlated for countries with emissions higher than 10 kg CO_2 eq. per kg edible weight, which is also seen in the loose positive correlation in Figures 1.1a and 1.2a. **This slight positive correlation between emissions and land use is strongest for countries that are outliers, such as Angola, Namibia, Sierra Leone, Zambia, and Zimbabwe.** Unfavorable rainfall, limited fertile land, and limitations in technology may all contribute to the high land use and emissions per kg of edible weight of maize produced in these three outlier countries.[81] Specifically, Angola and Zimbabwe are two of four countries that are tied to the consistent agricultural trade deficit—having more imports than exports, and therefore causing a fiscal loss—in SSA.[82]

Figure 1.3c and 1.3d shows relatively high land use and emissions for countries in SSA; these areas contribute 21.4% of the total land use in the Poore and Nemecek (2018) data (which accounts for >75% of global maize production), even though SSA only produces 7.5%[83] of the world's total maize product. **Because of lower fertilizer input, drought, and other climate factors, the well-known yield gap phenomenon in SSA may account for these higher land use and emissions values.[84]**

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[81] M. van Djik, "Mapping Maize Yield Gaps in Africa; Can a Leopard Change Its Spots?," WUR, September 19, 2012, https://www.wur.nl/de/Publicatie-details.htm?publicationId=publication-way-343233353535.

[82] Louise Fox and Thomas Jayne, "Unpacking the Misconceptions about Africa's Food Imports," Brookings (blog), December 14, 2020, https://www.brookings.edu/blog/africa-in-focus/2020/12/14/unpacking-the-misconceptions-about-africas-food-imports/

[83] Gatien N. Falconnier et al., "Modelling Climate Change Impacts on Maize Yields under Low Nitrogen Input Conditions in Sub-Saharan Africa," Global Change Biology 26, no. 10 (2020): 5942–64, https://doi.org/10.1111/gcb.15261.

[84] R.J. Hillocks, "Addressing the Yield Gap in Sub-Saharan Africa," Outlook on Agriculture 43, no. 2 (June 1, 2014): 85–90, https://doi.org/10.5367/oa.2014.0163.

In comparison to countries in SSA, the share of global production from the U.S. accounts for 37.6% of worldwide total annual product[85] and contributes 25.8% of the total land use in the Poore and Nemecek (2018) data, only slightly more than SSA. Maize is the largest crop in the US: in 2019, U.S. farmers planted 91.7 million acres, according to the National Agricultural Statistics Service. The crop is protected from climate and economic risk with farm subsidies, which are government financial benefits paid to primarily large producers to offset price changes. Thus, the U.S. rarely experiences maize shortages; its problems stem from maize surplus. Although farm subsidies for maize are not directly linked to obesity and cardiovascular disease, advocating for comprehensive commodity policy reform that reduces overproduction and stabilizes price and supply can help improve public health related to maize and maize derivative consumption.[86] **From an environmental standpoint, improving maize production in the U.S. would result in relatively small impact.**

On the other hand, from an equity viewpoint, a significant yield gap in maize production for developing countries is concerning, considering that population growth in areas like SSA necessitates importing food to meet nutritional needs. This reduces the quality of produce, increases the occurrence of food deserts, makes countries dependent on foreign imports to address hunger[87], and increases emissions from processing, packaging, and transportation.[88] **Thus, bringing more efficient maize production methods to developing parts of the world can make a far higher impact on environmental indicators, quality of life, and the economy than focusing on countries like the U.S.**

Palm Oil

Our study on palm oil supports the effort to prevent carbon-rich land from being converted and to limit fire use in land clearing. Our data also suggests that it is important to minimize emissions for established plantations. Trade-offs among environmental impacts for palm oil were minimal. Instead, GHG emissions are strongly related to acidification potential and eutrophication potential. Targeting one source of emissions would likely decrease other emissions as well. Land use has no correlation with GHG emissions, so land could be used more intensely to increase output and conserve land.

Overview

Palm oil is a form of vegetable oil that is produced from the fruit of oil palm trees. These trees are grown predominantly in Southeast Asia, but they are also grown in Africa and South America. Palm oil is an important global commodity as it is found in many packaged goods around the world and is used as fuel

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[85] Jim Barrett, "Corn Planted Acreage Up 3 Percent from 2018," accessed January 26, 2021, https://www.nass.usda.gov/Newsroom/2019/06-28-2019.php.

[86] "Do Farm Subsidies Cause Obesity?," Food and Water Watch, September 24, 2015, https://www.foodandwaterwatch.org/insight/do-farm-subsidies-cause-obesity.

[87] "Sub-Saharan Africa Food Products Imports by Country 2018 | WITS Data," accessed January 26, 2021, https://wits.worldbank.org/CountryProfile/en/Country/SSF/Year/LTST/TradeFlow/Import/Partner/by-country/Product/16-24_FoodProd.

[88] "Why Has Africa Become a Net Food Importer? Explaining Africa Agricultural and Food Trade Deficits | African Growth and Development Policy Modeling Consortium (AGRODEP)," accessed January 26, 2021, http://www.agrodep.org/fr/resource/why-has-africa-become-net-food-importer-explaining-africa-agricultural-and-food-trade-defic.

in some countries. The main problem with palm oil production is that in order to grow the palm trees to harvest the oil, natural forests are being destroyed to create space for the trees. The destruction of these forests releases carbon from both above- and below-ground biomass and destroys animals' homes. About 44 million acres of land worldwide have been used to produce palm oil, and around 60% of that land has been converted directly from natural forests.[89] As demand for palm oil increases, more forests are being cleared around the world. After converting the land, farming the palm trees leads to continued emissions. A leading question for our palm oil analysis is whether there are trade-offs between land conversion and other emissions, and another question is whether there are trade-offs between land use (on a plantation) and emissions.

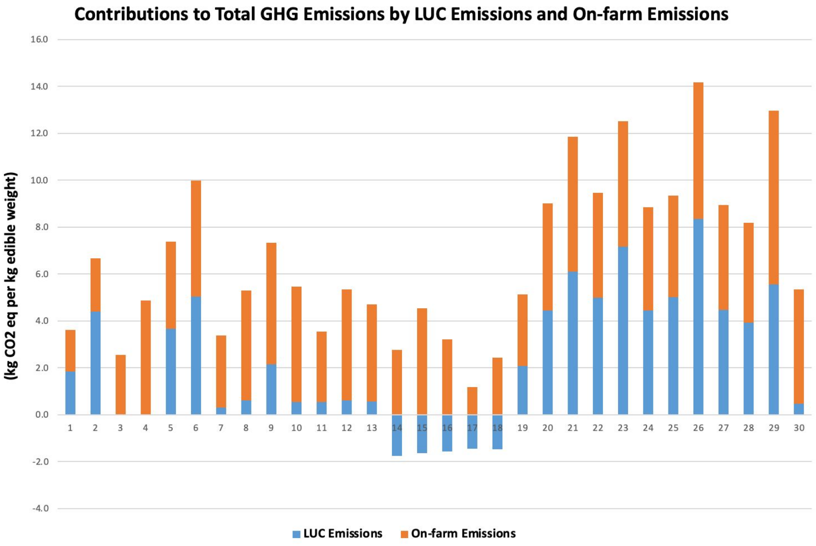
Methodology

To conduct our analysis of palm oil, we used the dataset from Poore and Nemecek (2018).[90] The data collection process was similar to that of maize.[91] A total of 30 sample points were used. The production system type for palm oil was not standardized by intensity, so extensive vs. intensive system types were not compared. Additionally, most of the data was recorded from producers in Southeast Asia, so there was an insufficient sample size to compare plantations across Asia, Africa, and South America.

Our analysis focuses on the impacts of palm oil within two major categories: land-clearing and on-farm operations. We looked for trade-offs in both categories.

Analyzing GHG Emissions

We began our analysis by looking at our GHG data to understand which part of the life cycle contributes the most to GHG emissions.



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[89] Bergen, Molly. "What You Need to Know about Palm Oil - in 5 Charts." Conservation International. October 04, 2016. Accessed January 11, 2021. https://www.conservation.org/blog/what-you-need-to-know-about-palm-oil-in-5-charts.

[90] Ibid.

[91] Data processing using Pandas, Numpy, Matplotlib Python libraries and using Excel graphing system

Figure 2.1. The make-up of total GHG emissions by land use change (LUC) emissions and on-farm emissions for all thirty sample points. Data from Poore and Nemecek (2018).

Total GHG emissions come from emissions released from land use change (LUC) and emissions released from the established plantations (on-farm). LUC measures GHG emitted from land conversion and is split into LUC emissions from burning (LUC Burn) and LUC emissions from the carbon stock before conversion (LUC C Stock). On-farm measures GHG emitted from production processes after the land has been converted and the farm has been created. Note that LUC measures GHG emissions caused directly from converting land and is distinct from land use, which measures land occupied to produce palm oil.

In Figure 2.1, we can see that the overall GHG emitted by producers are influenced both by LUC Emissions (sum of LUC Burn and LUC C Stock) and on-farm Emissions. So even though a lot of emissions are caused from land conversion, there is still much progress for palm oil producers to make in minimizing GHG emissions during the production process. Note that negative LUC percentages mean that the land is sequestering more GHG after conversion than prior.

Comparing Environmental Indicators

After analyzing the sources of GHG emissions, we then searched for relationships between the other environmental impacts: land-use, acidification potential, and eutrophication potential.

We first investigated acidifying and eutrophying emissions (Figure 2.2).

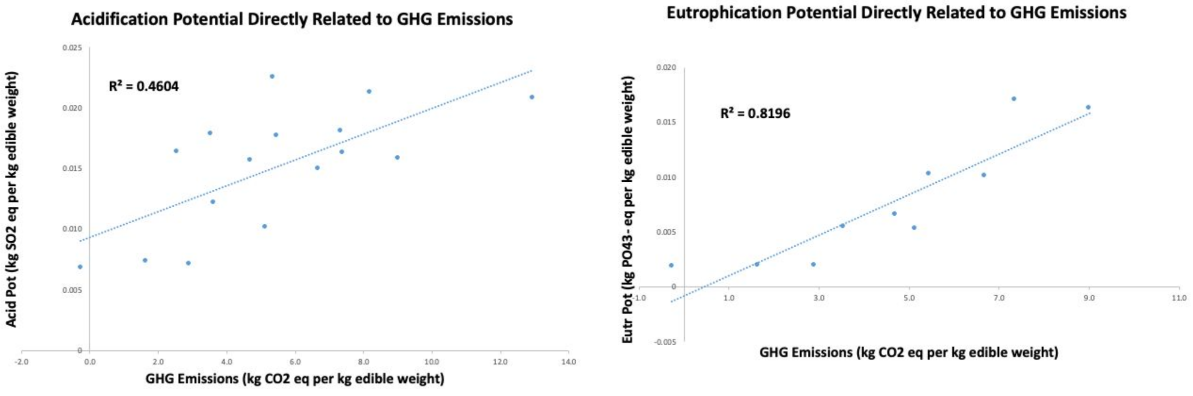

Fig 2.2a *Fig 2.2b*

Figure 2.2. Acidification emissions and eutrophying emissions plotted against GHG emissions. Data from Poore and Nemecek (2018).

Here there is a direct relationship: producers who have higher GHG emissions also have higher acidification potentials and higher eutrophication potentials (Figure 2.2). The relationships indicate that the various emissions indicators may be linked. This is somewhat expected; palm oil mill effluent (POME) that comes as a by-product of palm oil milling is often treated in open lagoons.[92] This releases

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[92] Saswattecha, Kanokwan, Melissa C. Romero, Lars Hein, Warit Jawjit, and Carolien Kroeze. "Non-CO2 Greenhouse Gas Emissions from Palm Oil Production in Thailand." Taylor and Francis. December 02, 2015. Accessed January 25, 2021. https://www.tandfonline.com/doi/full/10.1080/1943815X.2015.1110184.

methane and carbon, which contribute to GHG emissions, as well as emitting acidifying and eutrophying compounds. There is also waste from harvested palm fruit, which comes in fresh fruit bunches (FFB). FFB that are old cannot be used and are usually burned. Empty fruit bunches (EFB), which are leftover fibers after the palm fruit has been removed from the FFB, are often dumped in landfills or burned. Poor treatment of FFB and EFB leads to increased GHG emissions, eutrophying emissions, and acidifying emissions.[93,94] Additionally, overuse of fertilizers leads to higher eutrophication potential and also more GHG emissions.[95]

The positive relationships between GHG emissions and other emissions (Figure 2.2) appear to be a good sign, as decreasing GHG emissions seems to decrease the other emission types. At the very least, there is not a consequence for lowering GHG emissions. This is likely because decreasing GHG emissions implies better waste management, in turn translating to lower acidifying emissions and eutrophying emissions. However, it is worth noting that for acidification potential versus GHG emissions, only 16 points had corresponding data, and for eutrophication potential versus GHG emissions, only 10 data points were available.

We next analyzed the correlation between land use and greenhouse gas emissions emissions for palm oil.

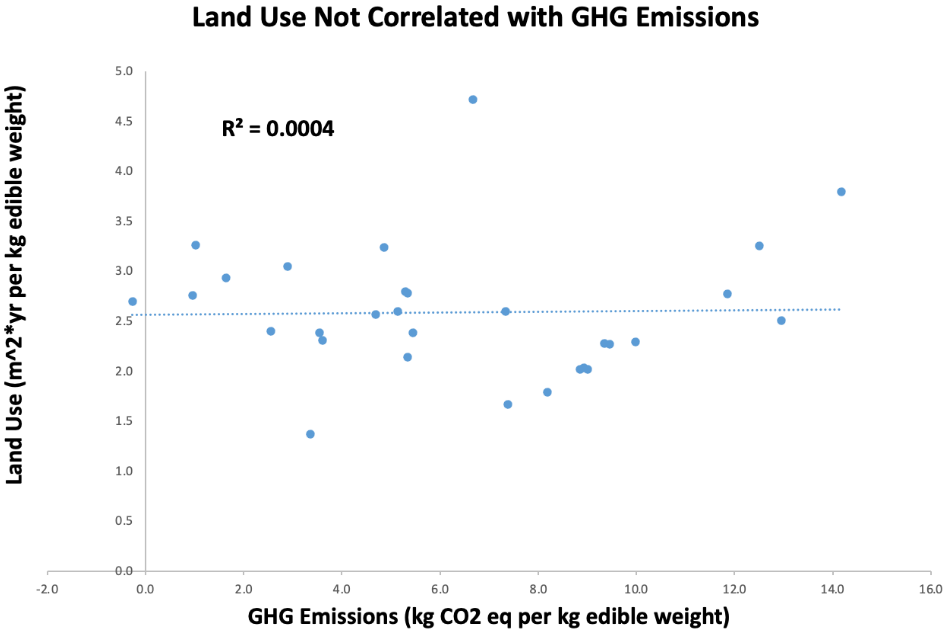

Figure 2.3. GHG against Land Use. Data from Poore and Nemecek (2018).

The outlier point with high land use is a producer located in Cameroon (Figure 2.3). Along with using land extensively, this producer also disposes POME to rivers.[96] Discharging POME to waterways leads to

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[93] Patel, Seeta S. *Environmental Impacts of Palm Oil*. Accessed January 23, 2021.

[94] Ibid.

[95] Ibid.

[96] Wouter M. J. Achten et al. “Life Cycle Assessment of a Palm Oil System with Simultaneous Production of Biodiesel and Cooking Oil in Cameroon.” May 24, 2010. Accessed January 18, 2021.

massive pollution and thus higher emissions. Disregarding the outlier, Figure 2.3 shows that there is no trend between GHG and land use, and it appears as though land use has no impact on total GHG emitted. Here, the trend seems to show that decreasing land use does not consistently increase or decrease GHG emissions.

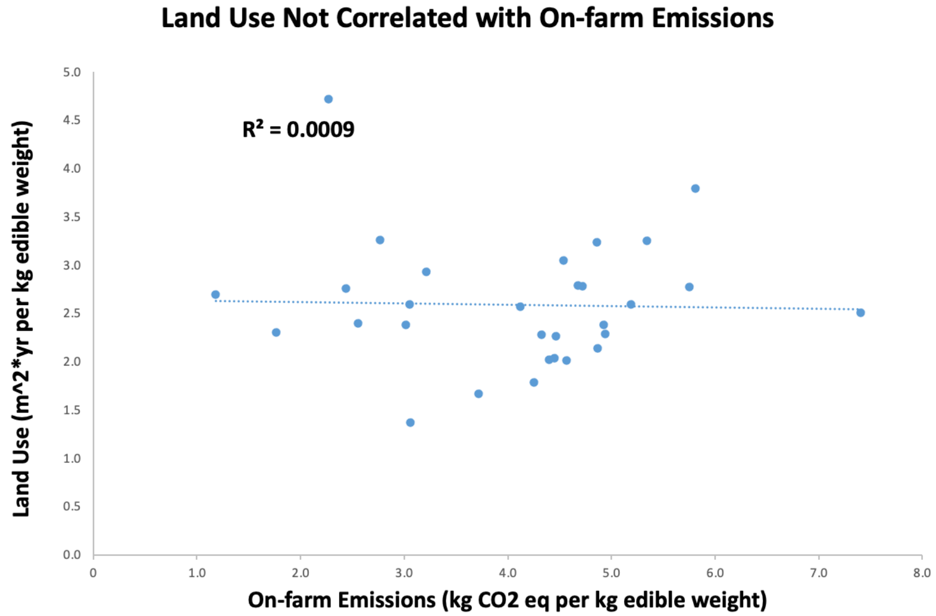

Figure 2.4. On-farm emissions against land use. Data from Poore and Nemecek (2018).

Because LUC was often a large component of total GHG emissions, and land-use reflects the ongoing operations, we investigated this relationship for only on-farm emissions. Figure 2.4 reveals that land use is also uncorrelated with on-farm emissions. Though decreasing land use is not correlated with decreasing on-farm emissions, this is still a good sign, as using land intensely to farm palm oil does not result in heightened GHG emissions. Therefore, palm oil plantations should aim to decrease their overall land use. Since land use is inversely correlated with yields, the producers can therefore increase their output without expanding the plantations. This is a great sign: producers do not have to clear new land to produce more palm oil. Ongoing work at the yield gap for palm oil suggests that there is significant scope for improvement.

To answer our primary question, we have found no trade-offs between land conversion and other emissions. In fact, by minimizing the conversion of peatlands and the use of burning to clear, farms can decrease GHG emissions, eutrophying emissions, and acidifying emissions. For established farms, land use and GHG emissions are uncorrelated, and since GHG is directly related to eutrophication potential and acidification potential, efforts to reduce GHG emissions or increase yields seem unlikely to have unintended negative impacts in these other areas.

Moving Forward

There is much room for improvement in the palm oil industry. The Roundtable on Sustainable Palm Oil

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(RSPO), a nonprofit that is dedicated to implementing standards for producing sustainable palm oil, has outlined steps that producers should follow.[97] Relating to LUC, a main objective is that primary forestry (land that has not been altered by humans) and forests containing endangered species cannot be cleared. Another important goal is to reduce fire use in land clearing. Producers who abide by these criteria can receive certifications from RSPO, and companies can source their palm oil from these certified producers. Consumers can also purchase RSPO-approved products to further support the effort towards the global production of sustainable palm oil. Additionally, maps that highlight suitable lands could be used to allocate land for plantations more effectively. For established plantations, there is more opportunity to decrease emissions. Using correct amounts and types of fertilizer can increase yield while also decreasing waste and emissions.[98] Biogas capture systems can convert POME emissions to useful gasses and produce electricity, reducing emissions while also providing an energy source.[99] EFB that is normally wasted can return to the palm tree plantations and be placed around palm trees to provide necessary nutrients to the trees.[100]

There are important next steps in our study of palm oil. As noted earlier, there was no apparent trend between land use and GHG emissions. Currently, our studies show that farms should increase yield as there is no consequence for optimizing for land use. We believe that more specific data on land conversion could help reveal even more benefits of avoiding land clearing to produce palm oil. The methods by which the land was converted to create space for palm oil trees along with the type of land that was converted both directly contribute to emissions. For example, many of the palm oil plantations come from carbon-rich peatlands, and conversion of this type of land releases massive amounts of greenhouse gases, especially if fire is used in clearing. However, we currently only have data on LUC fire and LUC carbon stock. Data on aboveground versus belowground carbon reserves as well as soil content before land conversion would give us further insight into the effects of LUC.

We also lack sufficient data on the eutrophication potential and the acidification potential of palm oil plantations. Of the 30 total palm oil sample points, only 16 of them included numbers for acidification potential, and only 10 of the points included numbers for eutrophication potential. More sample points in total would also be helpful to further support some relationships found in the section.

Soybeans

Soybean oil and soybean production does not display strong relationships between the environmental indicators and GHG emissions, but farms within a certain country tend to demonstrate similar patterns. Further research into identifying characteristics of regional farms that drive trade-offs—such as in South African farms with a low acidification potential but high land usage or Iranian farms that maintain low land use values but much greater acidifying emissions—will allow for strategic intervention. Finally,

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[97] "About." RSPO. Accessed January 25, 2021. https://rspo.org/about.

[98] Ibid.

[99] Khatun, Rahima, Mohammad Imam Hasan Reza, M. Moniruzzaman, and Zahira Yaakob. "Sustainable Oil Palm Industry: The Possibilities." Renewable and Sustainable Energy Reviews. March 27, 2017. Accessed January 23, 2021. https://www.sciencedirect.com/science/article/pii/S1364032117304203.

[100] Ibid.

greenhouse gas emissions in Latin America are predominantly from land use change, making proper regulation of the practice critical for reducing emissions.

Overview

Soybeans have become a staple crop due the crop's diverse range of uses, including for human and livestock consumption. Of the millions of metric tonnes of soybeans produced annually, upwards of 85% goes to livestock feed while the remainder consists of soybean oil and products specific for human consumption (tofu, soymilk, etc.).[101,102] The demand for the crop is only projected to grow in the coming decades as animal protein consumption increases. If current trends continue, the growth of soybean production will come at the cost of increased land and agrochemical usage. Increased land usage is a particularly threatening issue as local ecosystems are often destroyed; this also dramatically increases global greenhouse gas emissions. Soy is a major driver of agricultural expansion in various regions, seen especially in the Amazon.[103] For the last two decades, the Amazonian Basin has seen the fastest growth of arable land and also has the most available area to be converted to farmland.[104] Given that soy is one of the most commonly grown crops, it is critical that the coming years feature improved systems by which soybeans can be grown, processed, and transported.[105]

Methodology

We investigate the environmental effects of the soybean life cycle ranging from the inputs (fertilizers, soil, etc.) to the start of product processing, analyzing specifically farms producing raw soybeans or soybean oil as a retail product.[106] All emissions released and land or water used to process and transport raw soybeans were not included in the values for this paper's analysis, to appropriately capture soybeans destined for animal feed. The data used for this commodity has also been derived from the Poore and Nemecek (2018) data set and consists of 8 soybean oil and 41 soybean data points from the following 10 countries: Argentina, Brazil, Canada, China, India, (the Islamic Republic of) Iran, South Africa, Switzerland, Thailand, and the United States of America. The species of soybean, *Glycine max* (L.) Merr., is consistent across all farms. Analysis of certain indicators included fewer data points as the farms were not documented equally—acidification potential and eutrophication potential have 44 and 28 data points respectively.

Poore and Nemecek's data measured the effects of soybean oil emissions per liter of soybean oil. However, in order to standardize all of the data points, the values for soybean oil farms were adjusted to a kilogram of unprocessed soybeans. We used the generic density of soybean oil—0.93 kg/L, found in the Poore and Nemecek data sheet—to convert the indicators to be in terms of kg soybean oil, and then

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[101] Voora, Vivek, et al. "Global Market Report: Soybeans." IISD. https://www.iisd.org/system/files/2020-10/ssi-global-market-report-soybean.pdf. Accessed 17 Jan. 2021.
[102] Fraanje, Walter and Garnett, Tara. "Soy: food, feed, and land use change." FCRN. https://tabledebates.org/building-blocks/soy-food-feed-and-land-use-change#SOYBB2. Accessed 17 Jan. 2021.
[103] "Soy Agriculture in the Amazon Basin." Yale. Accessed 26 Jan. 2021.
[104] Rocha, Jaun C., et al. "Toward understanding the dynamics of land change in Latin America: potential utility of a resilience approach for building archetypes of landsystems change." Resilience Alliance, 2019. Accessed 26 Jan. 2021.
[105] "The Growth of Soy Impacts and Solutions." WWF. http://awsassets.panda.org/downloads/wwf_soy_report_final_feb_4_2014_1.pdf. Accessed 29 Nov. 2021.
[106] Poore, J. and Nemecek, T. "Reducing food's environmental impacts through producers and consumers." Science. https://science.sciencemag.org/content/360/6392/987 Accessed 17 Jan. 2021.

multiplied by 0.18 to convert from kg soybean oil to kg soybean (Figure 3.1). 18% is a commonly accepted value for the fraction of soybean oil able to be extracted from soybeans by weight, and is consistent with the paper's methodology.[107,108,109]

$$\frac{Indicator}{Liter\ Soybean\ Oil} \cdot \frac{Liter\ Soybean\ Oil}{.93\ kg\ Soybean\ Oil} \cdot \frac{.18\ kg\ Soybean\ Oil}{kg\ Soybean\ (Raw)} = \frac{.18\ Indicator}{.93\ kg\ Soybean\ (Raw)}$$

Figure 3.1. The equation used to convert values from soybean oil data points from per liter soybean oil to per kg soybean.

Environmental Indicators and GHG Comparison

There is a level of disparity across the graphs due to the aforementioned lack of equal documentation. All 49 samples include data for land use, freshwater withdrawal, and GHG emissions, but graphs including acidification or eutrophication potential contain fewer plot points (Figure 3.2b, c). Note that for freshwater withdrawal, dramatically different systems of water provisioning account for the split between zero and non-zero water use; China, Iran, and parts of the USA use flood application irrigation, while the other data points are rainfed.[110,111]

We saw no correlations between the four environmental indicators against GHG emissions; this was also true for country-specific data, although some clustering by country does appear, likely driven by similar production methods and/or climate. The strongest trend present between land use and GHG emissions in Brazil (Figure 3.2a); the wide range of emissions from Brazil are driven by land-use change. This trend suggests that the farms on recently converted forest are relatively low-yielding.

The other country clusters may merit further study to identify common drivers or mitigation opportunities. For example, Iran (Figures 3.2a and 3.2c) has high acidification potential, while Switzerland has high eutrophication potential (Figure 3.2a, c). By studying all of these clusters and selectively choosing aspects of the most optimized countries, we may be able to create a system that minimizes all five environmental indicators for all countries without any technological advances. Analyzing the clusters of data points, further research into Iran for minimizing land use, South Africa and the USA for acidification potential, the countries aside from Brazil, India, and Switzerland for eutrophication potential, and South Africa, Thailand, Canada, and the USA for freshwater withdrawal will offer glimpses into the conditions that allow for their low values (Figure 3.2).

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[107] "Conversion Table." USSEC. 6 Oct. 2015. https://ussec.org/resources/conversion-table/. Accessed 21 Jan 2021.

[108] "Soybeans." University of Nebraska-Lincoln. https://cropwatch.unl.edu/bioenergy/soybeans. Accessed 21 Jan. 2021.

[109] Sadaka, Sammy. "Biodiesel." UAEX. https://www.uaex.edu/publications/pdf/FSA-1050.pdf. Accessed 21 Jan. 2021.

[110] Poore, J. and Nemecek, T. "Reducing food's environmental impacts through producers and consumers." Science. https://science.sciencemag.org/content/360/6392/987 Accessed 17 Jan. 2021.

[111] "Irrigation Methods: Furrow or Flood Irrigation." USGS. https://www.usgs.gov/special-topic/water-science-school/science/irrigation-methods-furrow-or-flood-irrigation?qt-science_center_objects=0#qt-science_center_objects. Accessed 21 Jan. 2021.

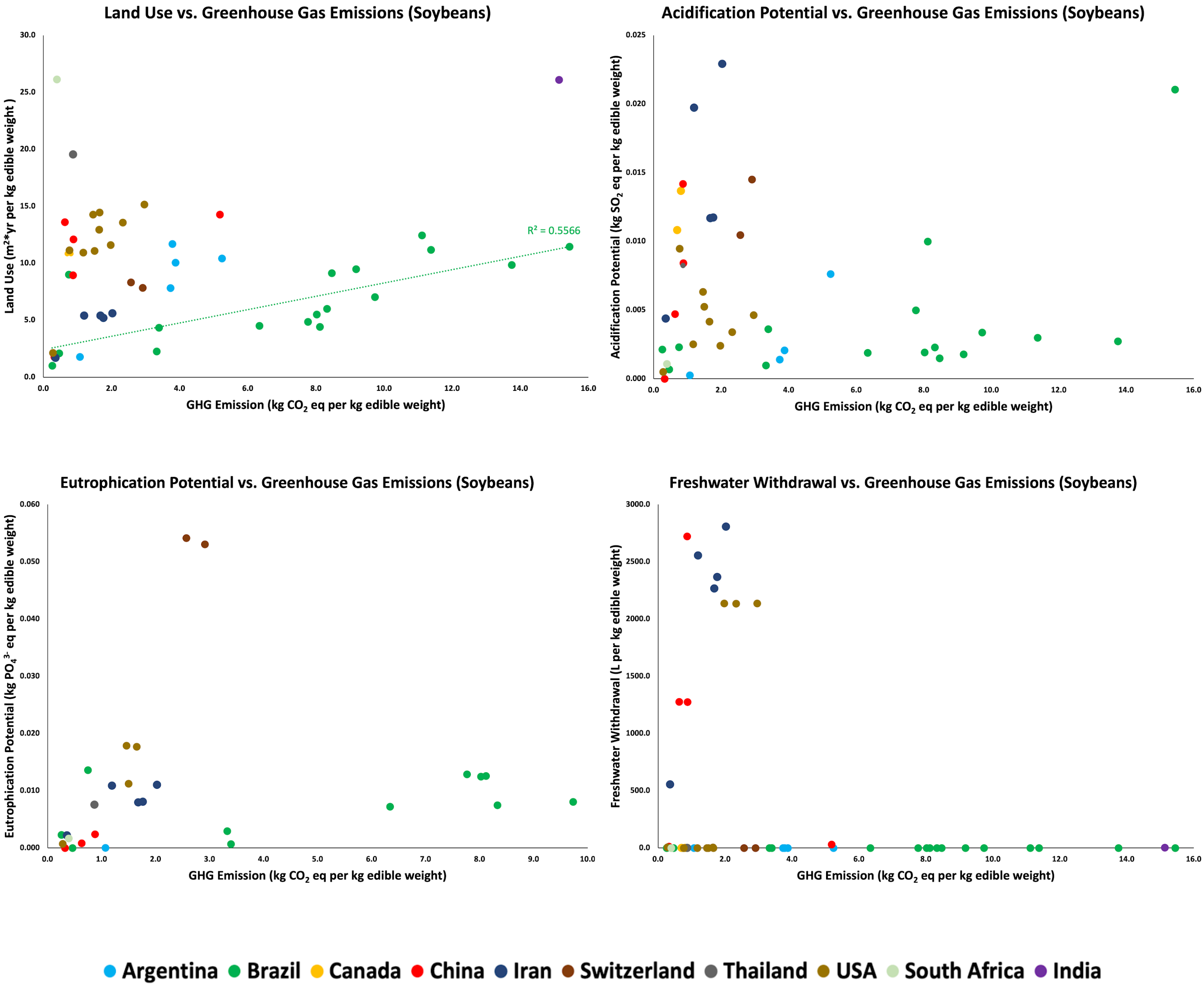

Figure 3.2a, b, c, d. Land use, acidification potential, eutrophication potential, and freshwater withdrawal have no strong correlation to GHG emissions, the strongest being Land Use vs GHG emissions in Brazil. Colors indicate country. Data from Poore and Nemecek (2018).

Land Use Change

As mentioned previously, land use change poses a major consequence for the future of soybean production. The conversion of forests into farmland is especially damaging to the environment because the process not only releases greenhouse gases into the atmosphere from the tree biomass but also from the soil; habitat for many rare species is also lost.

Figure 3.3a showcases the greenhouse gas emissions from Argentina (columns 1-5) and Brazil (6-22). In nearly every point, land use change is overwhelmingly the main source of greenhouse gases, with the only other country from the dataset to somewhat rival this pattern being India (Column 8 of Figure 3.3b). This is extremely significant because not only has the bulk of Latin America's GHG emissions been identified, it is a feature that can be reduced through legislation and improved practices without disrupting existing soybean farms. In comparison to Figure 3.3b, the average greenhouse gas emissions from farming in Argentina and Brazil are about a kilogram of CO_2 eq less than the average of all of the other countries. This is another possible region to study for potential ways to reduce GHG emissions during the farming stage of a soybean's life cycle.

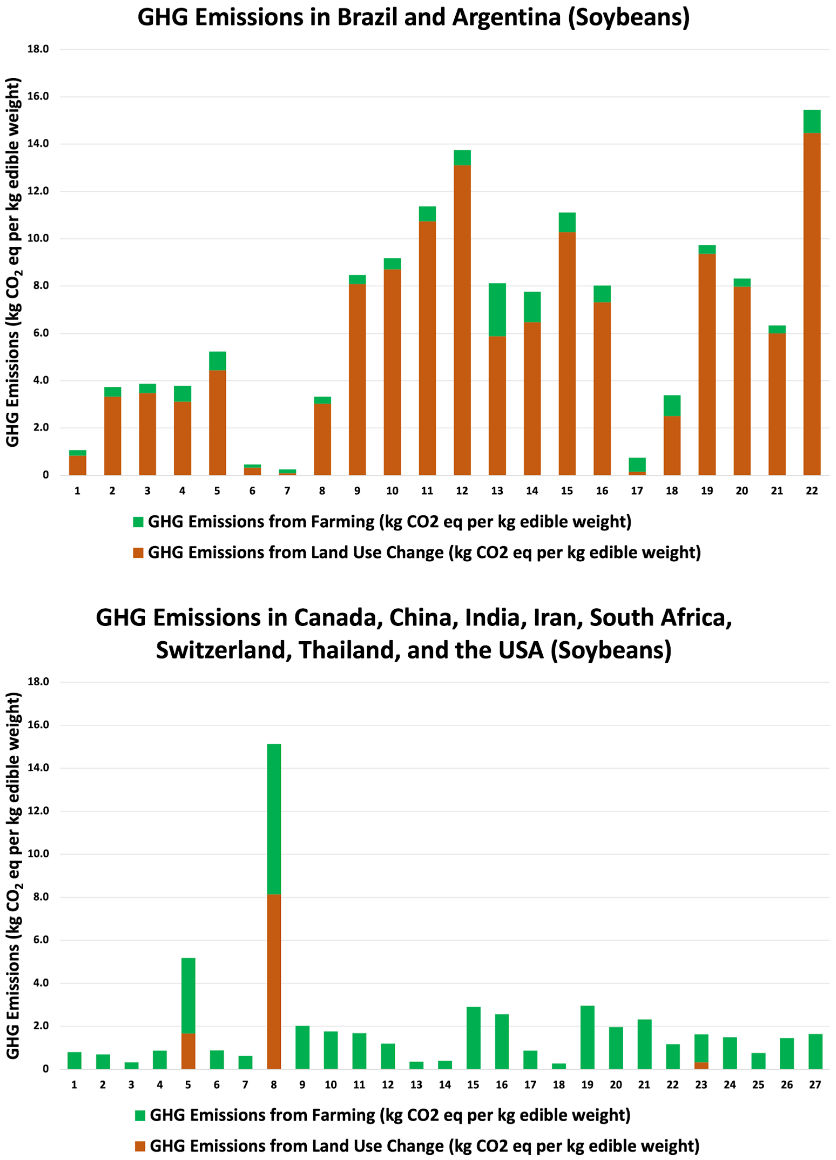

Figure 3.3a, b. Greenhouse Gas Emissions are separated into emissions from land use change and the farming process. Data from Poore and Nemecek (2018).

The Amazon, where land use change is a prominent issue, acts as a major carbon sink for the planet.[112] It becomes increasingly vital to improve the practices or legislature governing it to protect against the dual consequences of deforestation.

Patterns in Acidification and Eutrophication Potential

Further analysis of impacts at different production stages may be a promising avenue for future research. For example, We noted that eutrophying and acidifying emissions were loosely correlated overall (Fig 3.4) but tightly correlated in the inputs (fertilizers, pesticides) (Fig. 3.5); because this relationship was not present with land-use, better nutrient management may be a win-win for both the environment and input budgets.

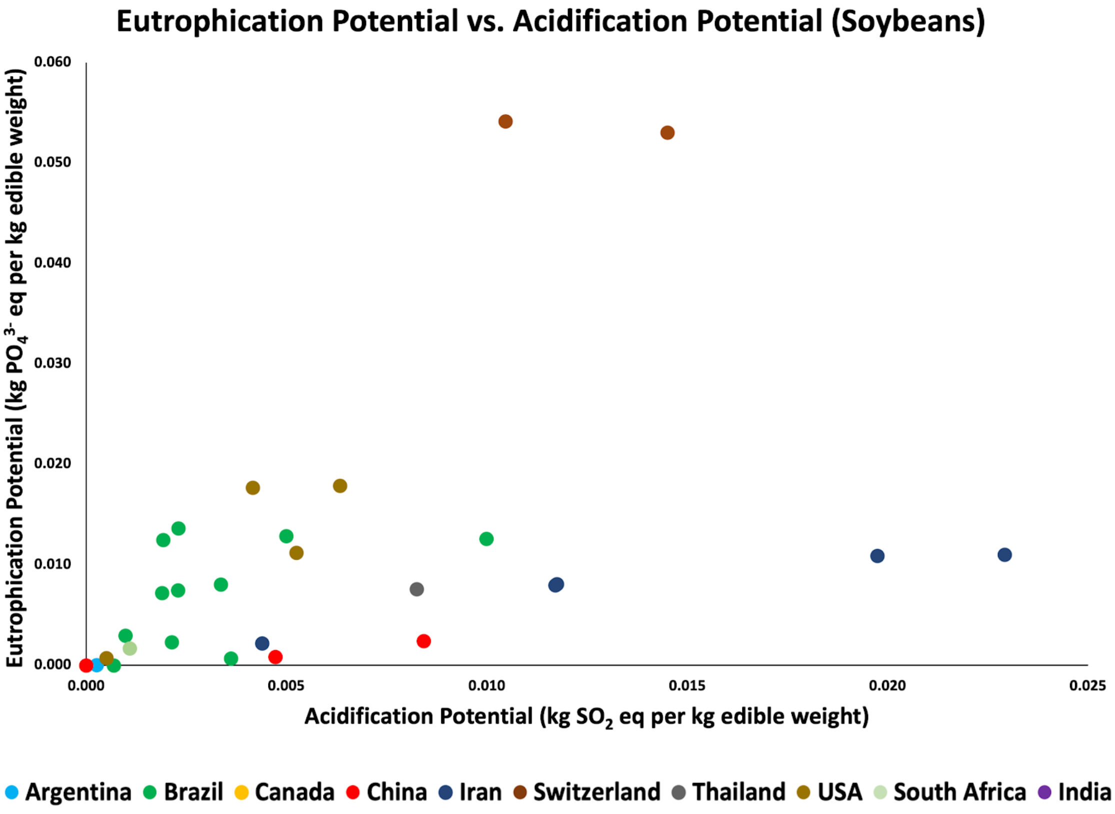

Figure 3.4. Eutrophication Potential plotted against Acidification Potential with varying degrees of correlation. China and Iran demonstrate a low maximum threshold for eutrophication potential across a wide range of acidification potential values while Brazil and the US cluster for lower acidifying emissions but greater eutrophying emissions. Data from Poore and Nemecek (2018).

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[112] "Why is the Amazon Rainforest Important?" WWF. https://wwf.panda.org/discover/knowledge_hub/where_we_work/amazon/about_the_amazon/why_amazon_important/?. Accessed 27 Jan. 2021.

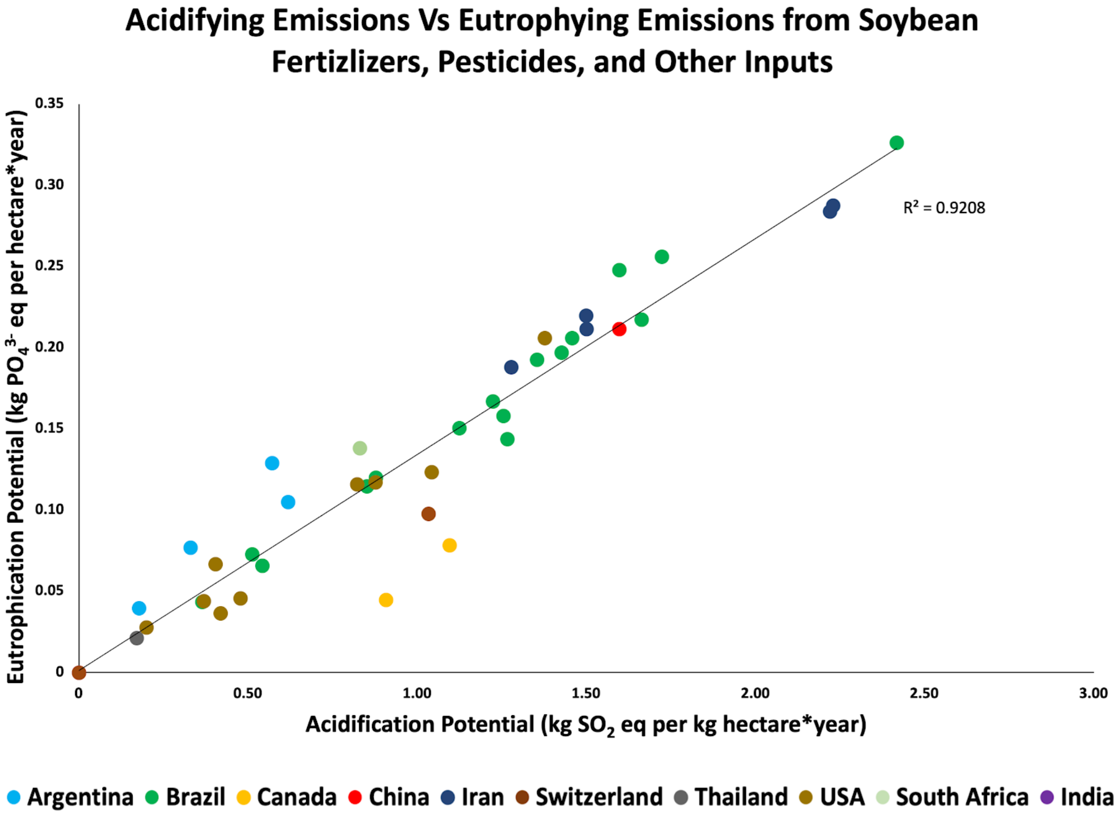

Figure 3.5. Acidifying emissions and eutrophying emissions from soybean inputs have a direct linear correlation. Data from Poore and Nemecek (2018).

Moving Forward

Determining the drivers between any pattern requires further assessment of individual farming systems, but in order to understand the acidifying and eutrophying emissions released, future research could target agrochemicals. One of the core components of soybean production in many farms is the necessity of fertilizers, pesticides, and herbicides to help farmers improve crop yields, but often impacts the neighboring environment.[113,114,115] Because the emissions were not directly proportional, the data suggests that different agrochemicals, or ratios of, may have led to different ratios of emissions from each country. Research may be able to identify if these distinctions are the result of unnecessary chemical usage or farm conditions that demand such use.

Seeing that not all of the countries follow the same trend and many countries do not show any trends reveals differences in the conditions of farms both regionally and individually within a country. Moving forward, this information could be used to analyze regions or individual farms to better understand the conditions and system that soybeans are grown in there. Other farmers or policy makers may selectively

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[113] Poore, J. and Nemecek, T. "Reducing food’s environmental impacts through producers and consumers." Science. https://science.sciencemag.org/content/360/6392/987 Accessed 17 Jan. 2021.

[114] “Pollutants.” https://www.emep.int/mscw/pollutants.html. Accessed 18 Jan. 2021.

[115] Tzanetou, Evagelia and Karasali, Helen. "Glyphosate Residues in Soil and Air: An Integrated Review." https://www.intechopen.com/books/pests-weeds-and-diseases-in-agricultural-crop-and-animal-husbandry-production/glyphosate-residues-in-soil-and-air-an-integrated-review Accessed 18 Jan. 2021.

choose for the systems or features of such that allow for the most environmentally sustainable soybean production. Many of the patterns identified in the figures above demonstrated a balance of low values for multiple environmental indicators. Being able to recognize the reasons for these offers the prospect of being able to apply those principles to other farms and improve their ecological viability. Furthermore, having found no inversely proportional relationships is evidence that efforts to mitigate one of environmental indicators does not tend to come at a commensurate increase of another. Future investigation may include the regional or individual conditions of each farm such as latitude, system type (tillage or no tillage), type of agrochemicals involved, etc.

Other potential improvements for global soybean production, as highlighted in the 2014 World Wildlife Fund for Nature's report, consists of improved policies and legislation (prevention of deforestation) and better use of land, agrochemicals, and water to reduce negative environmental effects.[116] Land use change is the primary contributor of greenhouse gas emissions in Latin America while agrochemicals add to acidifying and eutrophying emissions globally. Furthermore, a large contributor of emissions in the life cycle of soybeans is transportation; faulty or poor infrastructure to move soy may increase emissions from loss as well as from transport.[117] Improvements in transportation networks will help reduce the effects of multiple farms.[118]

Compared to another commonly grown crop, most maize farms paralleled the values found in soybean farms (with a few outliers, such as soybeans grown in Switzerland releasing much more eutrophying emissions). No significant trends for either crop across the environmental indicators and GHG emissions were found. Similar to maize, high land-use values were found in Africa (the one soybean data point documenting South Africa, reports highland usage in comparison to all other countries).

The presented information is not enough to derive any significant conclusions from yet but offers insight into where research may be conducted. This analysis suggests where better and worse practices may be found and points towards interventions that have minimal negative environmental impact.

Coffee

The data indicates that the focus of conservation efforts should be tailored to individual countries, as different countries appear to exhibit different trends and trade-offs. Negative correlations appeared most frequently between GHG emissions and eutrophication potential, which indicates that these factors must be balanced in sustainability efforts. Additionally, more research is needed to determine why some countries' coffee farms have higher negative effects than others. The relationship between emissions and wet processing of coffee should also be explored and mitigated where possible.

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[116] "The Growth of Soy Impacts and Solutions." WWF. http://awsassets.panda.org/downloads/wwf_soy_report_final_feb_4_2014_1.pdf Accessed 29 Nov. 2021.

[117] Knudsen, Marie Trydeman, et al. "Transport is important in the carbon footprint of imported organic plant products." ICROFS. https://core.ac.uk/download/pdf/45495317.pdf. Accessed 27 Jan. 2021.

[118] "Global trade in soy has major implications for climate" https://www.sciencedaily.com/releases/2020/05/200507104446.htm Accessed 18 Jan. 2021.

Overview

Coffee is one of the most popular beverages in the world, likely because it contains the stimulant caffeine.[119] Global coffee consumption has recently decreased due to the COVID-19 pandemic, as the effort to combat the spread of the virus caused many patrons of coffee shops to stay at home.[120] While coffee production, like other commodities, may contribute to negative environmental effects, coffee crops are also sensitive to climate change, and if climate change continues on its current path, coffee production may be forced to move to a more temperate climate.[121]

Summary of Methods and Limitations

Our data visualization for coffee used 28 entries from the Poore and Nemecek (2018) dataset [122]. The main five environmental factors were analyzed in conjunction with other data, such as country, species of coffee grown, mono- and polyculture, wet and dry processing, and whether the coffee was organic. Acidification potential and eutrophication potential data was only available for 12 of the 28 entries, meaning that it is more difficult to establish reliable correlations between acidification/eutrophication potential and other factors. Data on mono- and polyculture, as well as dry vs. wet processing, was also very limited. Additionally, while we intended to use data on freshwater use, energy use, soil nitrates, and soil phosphates, this data appears to consist mainly of placeholder values, so these categories were not analyzed.

Analysis

We initially compared the range of environmental impacts across the producing countries. From this analysis, we can see that the country with the highest impact intensity differs across impacts.

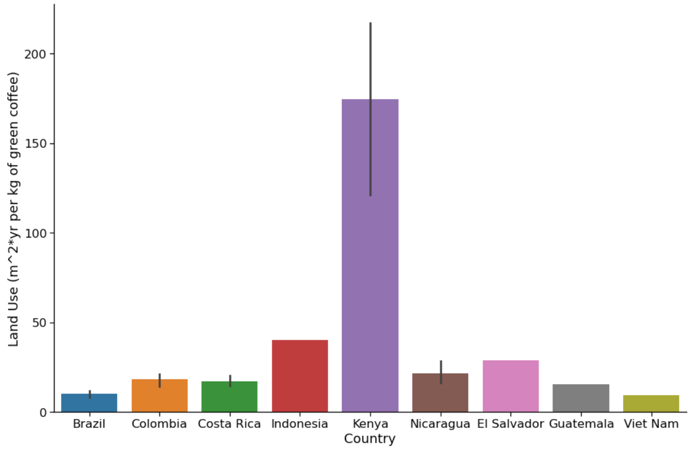

Figure 4.1. A bar graph of average land use by country. Data from Poore and Nemecek (2018). Error bars depict a 95% confidence interval and are not present where there is only one data point.

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[119] Myhrvold, N. 2020. "Coffee." *Encyclopedia Britannica*, June 1, 2020. https://www.britannica.com/topic/coffee.

[120] International Coffee Organization. 2020. "Impact of Covid-19 on the global coffee sector: the demand side." *ICO Coffee Break Series*, no. 1, April 2020. http://www.ico.org/documents/cy2019-20/coffee-break-series-1e.pdf

[121] Bunn, C., Läderach, P., Ovalle Rivera, O. et al. 2015. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change* 129, 89–101 (2015). https://doi.org/10.1007/s10584-014-1306-x.

[122] The *pandas* and Seaborn packages in Python were used to generate graphs of the data.

In Kenya, land use appears to be higher than all other countries included in the data (Figure 4.1). Because land use captures yield, this would indicate that Kenya would use more land to produce the same amount of coffee as other countries.

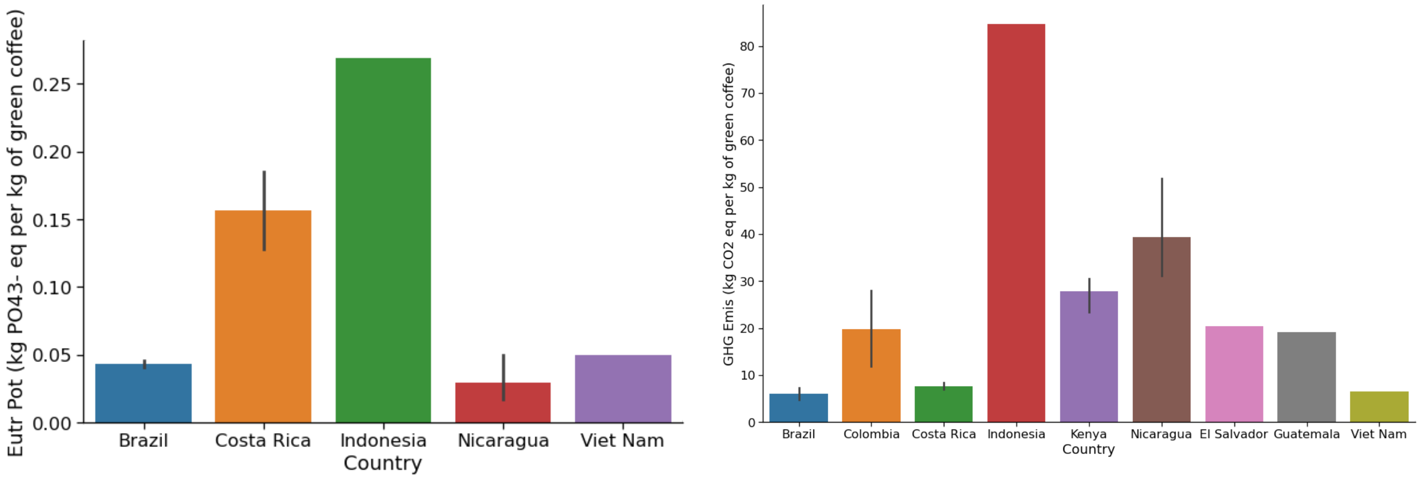

Figure 4.2a *Figure 4.2b*

Figure 4.2. Bar graphs of average eutrophication potential and GHG emissions by country. Data from Poore and Nemecek (2018). Error bars depict a 95% confidence interval and are not present where there is only one data point.

Farms in Nicaragua and Brazil appear to have low eutrophication potential; Brazil has low GHG emissions intensity, while Nicaragua's is higher. Furthermore, while Costa Rica has low GHG emissions, the eutrophication potential is relatively high (Figure 4.2a, 4.2b). Note that only one data point in Vietnam and Indonesia had a value for eutrophication potential. Additionally, there is only one data point available for Vietnam, El Salvador, Guatemala, and Indonesia. While there is only one data point in Indonesia, it appears that some of the high emissions there stem from land-use change.

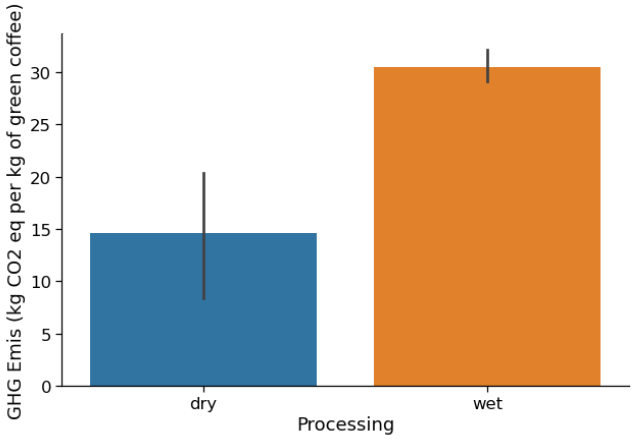

Figure 4.3. A bar graph of average emissions by processing method. Data from Poore and Nemecek (2018). Error bars depict a 95% confidence interval and are not present where there is only one data point.

Coffee farms that employ wet processing methods tend to have higher GHG emissions (Figure 4.3). The majority of emissions from wet processing come from the wastewater generated.[123] While we did not utilize freshwater data in our analysis, it has been established that the processing stage of coffee production also heavily contributes to water use.[124]

We then compared the GHG emissions with the associated eutrophication potential and land use to see if there were trade-offs across these impacts.

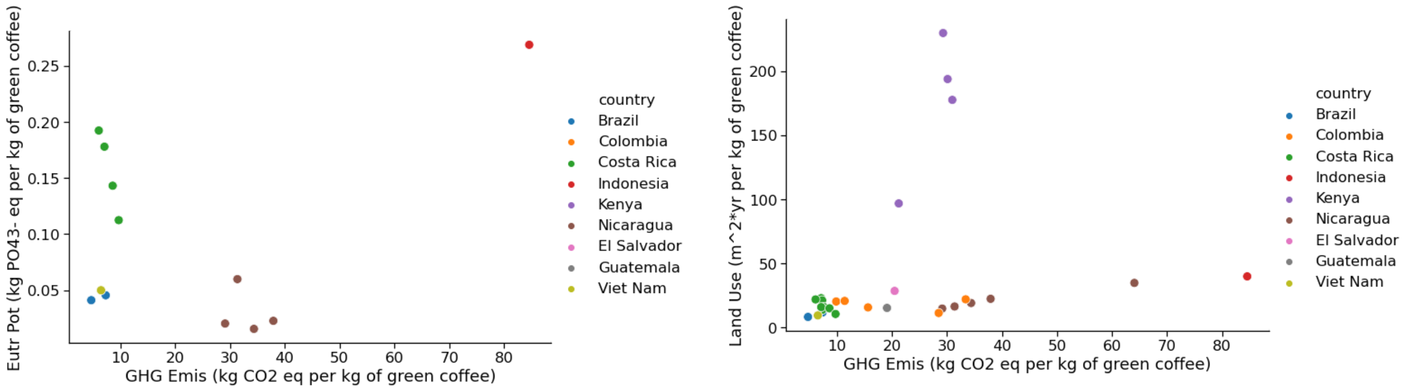

Figure 4.4a

Figure 4.4b

Figure 4.4. Scatterplots of eutrophication potential and land use vs. GHG emissions by country.

When looking at these various environmental impact factors plotted onto these graphs, there appeared to be no clear trends. However, when examining these factors based on country, coffee species, and organic vs conventional systems, clearer trends did emerge.

Country trends: The impacts by country appear to be clustered, and often appear weakly related. For example, GHG emissions and eutrophication potential appear to be negatively correlated in Costa Rica (Figure 4.4a, green dots) specifically, and GHG emissions and land use appear to be positively correlated in Nicaragua and negatively correlated in Costa Rica (Figure 4.4b, brown and green dots respectively). In Nicaragua, the majority of GHG emissions appear to come from land-use change, which explains the upwards trend: as more land is converted to farmland, GHG emissions from the conversion increase. No correlations appeared between GHG emissions vs acidification potential between countries.

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[123] Maina, Joan J., Urbanus. N. Mutwiwa1, Gareth. M. Kituu1, and M. Githiru. 2015. "Evaluation of Greenhouse Gas Emissions along the Small-Holder Coffee Supply Chain in Kenya." Journal of Sustainable Research in Engineering vol. 2 (4): 111-120 (2015). http://ir.jkuat.ac.ke/handle/123456789/2171.

[124] Giraldi-Díaz, Mario R., Lorena De Medina-Salas, Eduardo Castillo-González, Rosario León-Lira. 2018. "Environmental Impact Associated with the Supply Chain and Production of Grounding and Roasting Coffee through Life Cycle Analysis." *Sustainability* 10, no. 12: 4598. https://doi.org/10.3390/su10124598.

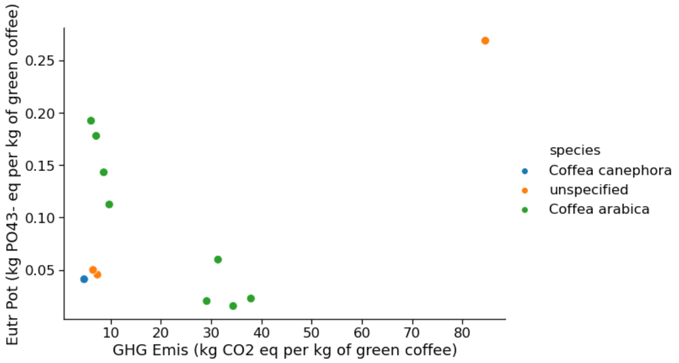

Figure 4.5. A scatterplot of eutrophication potential vs. GHG emissions by species.

Coffee species: When examining the environmental factors based on coffee species, a negative correlation between GHG emissions and eutrophication potential was found for arabica coffee (Figure 4.5). However, some studies did not state which coffee species was used, and if some of the unspecified data was *Coffea arabica*, that could impact the strength of the linear correlation. No correlations between emissions and land use or acidification potential were found between species.

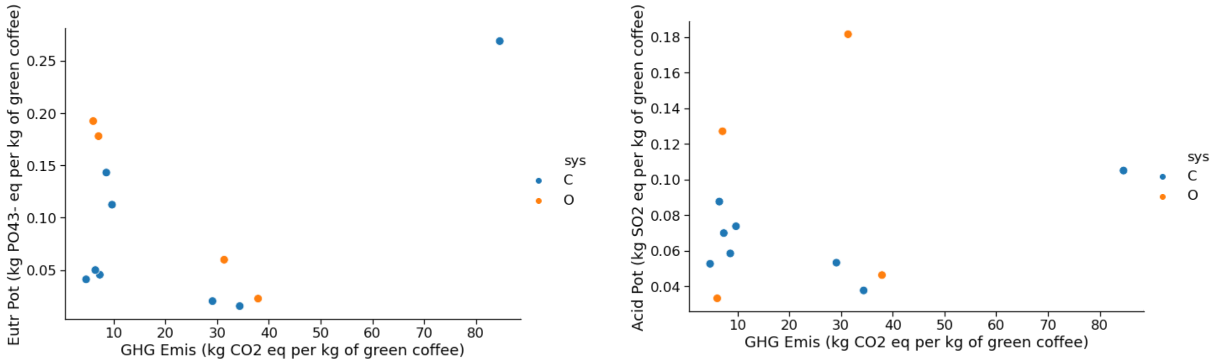

Figure 4.6a

Figure 4.6b

Figure 4.6. Scatterplots of eutrophication potential and acidification potential vs. emissions by organic (O, orange dots) or conventional (C, blue dots) farming.

Organic and conventional farming: A potential negative correlation between emissions and eutrophication potential was found for organic farming (Figure 4.6a). However, there are only four data points that are organic and have eutrophication potential data, so there is not strong evidence for this correlation. There also appears to be a negative correlation between emissions and acidification potential in conventional farming (Figure 4.6b). No significant correlations were found between emissions and land use within these systems.

Processing: No strong correlations were found between emissions and any of the environmental factors between dry and wet processing systems. However, data on whether wet or dry processing was employed is absent from many of the data points. Additionally, no correlations were found between emissions and any of the environmental factors between poly- and monoculture. However, as with processing, data on whether polyculture or monoculture was used is absent from the majority of data points.

Moving Forward

Despite organic coffee production being lauded as a more sustainable way to produce coffee, the data did not show any significant decrease in environmental factors with organic coffee. While there are not as many data points from organic coffee farms, the organic coffee trend has been criticized as not having a significant positive impact.[125] Furthermore, although demand for organic coffee may be growing, it appears that farmers who grow organic coffee will not receive much of a benefit from it in the long term.[126] [127] Organic certifications require that coffee farmers use agricultural practices that may produce less yield. If they are not as effective as previously thought, then the focus needs to turn to practices that are effective, and better economic incentives should be offered for growing coffee with these practices.

Because of the presence of what appears to be placeholder values for freshwater use, energy use, soil phosphates, and soil nitrates, we decided not to use these factors in our analysis. Further research should use reliable values for these categories and compare them to the factors analyzed above.

Roundwood

Our data suggests that sustainability efforts in roundwood production should focus on the logging and hauling phase and that eutrophication potential does not require as much individual focus as it varies little in the industry. Trade-off relationships were minimal, but included an association between higher land use and lower GHG emissions, and a weak connection between longer rotation length and better indicator metrics. Overall, lower GHG emissions were associated with lower impact in other indicators, with a relatively strong connection between GHG emissions and acidification potential.

Overview

Roundwood is a raw material critical to the availability of paper products, manufactured products such as furniture, and construction materials like particleboard and strandboard, all of which underlie modern quality of life. Around 85% of roundwood is produced for industrial purposes like these.[128] In 2010,

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[125] Van Der Vossen, H. A. M. 2005. “A critical analysis of the agronomic and economic sustainability of organic coffee production.” Expl Agric., vol. 41: 449–473 (2005). https://pdfs.semanticscholar.org/0c0b/0ba8e7513b443930b7f60cdd8b4472f7214d.pdf.

[126] Lewis, Jessa, and David Runsten. 2008. “Is Fair Trade-Organic Coffee Sustainable in the Face of Migration? Evidence from a Oaxacan Community.” Globalizations, 5:2: 275-290, https://www.tandfonline.com/doi/full/10.1080/14747730802057738.

[127] Bernard Kilian, Connie Jones, Lawrence Pratt, Andrés Villalobos. 2006. “Is sustainable agriculture a viable strategy to improve farm income in Central America? A case study on coffee.” Journal of Business Research, Volume 59, Issue 3: 322-330 (2006). https://doi.org/10.1016/j.jbusres.2005.09.015.

[128] C Jurgensen, Walter Kollert, and A Lebedys, “Assessment of Industrial Roundwood Production from Planted Forests,” 2014, http://www.fao.org/3/a-i3384e.pdf.

global per capita consumption of forestry products had been increasing by one percent each year for the past three decades.[129] In order to support the demand for these commodities, as of 2015, planted forests cover 277.9 million hectares globally, a number that is only increasing.[130] Due to the ubiquity and magnitude of this demand, improving industry sustainability is critical. In 2012 the FAO (Food and Agriculture Organization of the United Nations) found that the top ten producers were Brazil, the USA, China, India, Chile, New Zealand, Australia, South Africa, Thailand, and Indonesia.[131] More recently in 2016, the FAO found that the top five producers of industrial roundwood were the USA, the Russian Federation, China, Canada and Brazil, together accounting for 55% of global production.[132] Due to availability, our dataset currently represents only Europe, South America, and the USA.

Methodology

Due to lack of data on roundwood in the aforementioned Poore and Nemecek (2018) paper, we sourced life cycle analysis data on roundwood from 18 independent peer reviewed sources, yielding 31 data points.[133] We harmonized this data to a functional unit of cubic meters of under bark (ub) roundwood. In several sources, the functional units differed. We converted between volumes and weights of roundwood using the United Kingdom Forestry Commission's conversion factors and converted units of manufactured wood products to cubic meters of solid wood equivalent using the 2020 FAO Forest Product Conversion Factors manual.[134, 135] If multiple GHGs were reported without a collective GWP100 value, this value was calculated using the EPA GHG equivalencies calculator.[136] Acidification potential was standardized to kg SO_2 eq using the equivalencies provided in a 1992 Centre Of Environmental Science report.[137]

We then categorized the harmonized data by production system descriptors. Guided by an FAO review of silvicultural definitions, we defined natural systems as using natural regeneration and having no site preparation, stand establishment or maintenance.[138] We defined extensive systems as having artificial regeneration through minimal methods such as seed sowing, no fertilization, and otherwise minimal initial

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[129] "State of the World's Forests," www.fao.org, n.d., http://www.fao.org/3/X6953E/X6953E02.htm.

[130] Tim Payn et al., "Changes in Planted Forests and Future Global Implications," *Forest Ecology and Management* 352 (September 2015): 57–67, https://doi.org/10.1016/j.foreco.2015.06.021.

[131] C Jurgensen, Walter Kollert, and A Lebedys, "Assessment of Industrial Roundwood Production from Planted Forests," 2014, http://www.fao.org/3/a-i3384e.pdf.

[132] "Global Forest Products Facts and Figures," *Fao.org* (Food and Agriculture Organization of the United Nations, 2016), http://www.fao.org/3/I7034EN/i7034en.pdf.

[133] J. Poore and T. Nemecek, "Reducing Food's Environmental Impacts through Producers and Consumers," *Science* 360, no. 6392 (May 31, 2018): 987–92, https://doi.org/10.1126/science.aaq0216.

[134] "Conversion Factors," Forest Research, May 29, 2018, https://www.forestresearch.gov.uk/tools-and-resources/statistics/forestry-statistics/forestry-statistics-2016-introduction/sources/timber/conversion-factors/.

[135] United Nations Economic Food And Agriculture Organization Of The United Nations Europe, *Forest Product Conversion Factors.* (S.L.: Food and Agriculture Org, 2020).

[136] US EPA,OAR,OAP,CPPD, "Greenhouse Gas Equivalencies Calculator | US EPA," US EPA, February 19, 2019, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

[137] Reinout Heijungs et al., *Environmental Life Cycle Assessment of Products* (Leiden: Centre Of Environmental Science, 1992).

[138] Neil Stocker, "An Argument for Intensive Forest Management," www.fao.org, accessed January 18, 2021, http://www.fao.org/3/XII/0750-B1.htm.

site clearing and pruning. We defined intensive systems as those using artificial regeneration through seedling cultivation and planting, and fertilizer application for site preparation and stand maintenance. Most papers also reported data in the following production stages: site preparation, stand establishment and maintenance, logging and hauling, infrastructure establishment and maintenance. Some papers used different production stage groupings. Where possible, we regrouped the impacts to fit the former format.

We analyzed the harmonized data points along the five indicators as well as rotation length, which is the time between stand establishment and final harvest. Our dataset can be found here and our sources can be found here.

Comparing Environmental Indicators

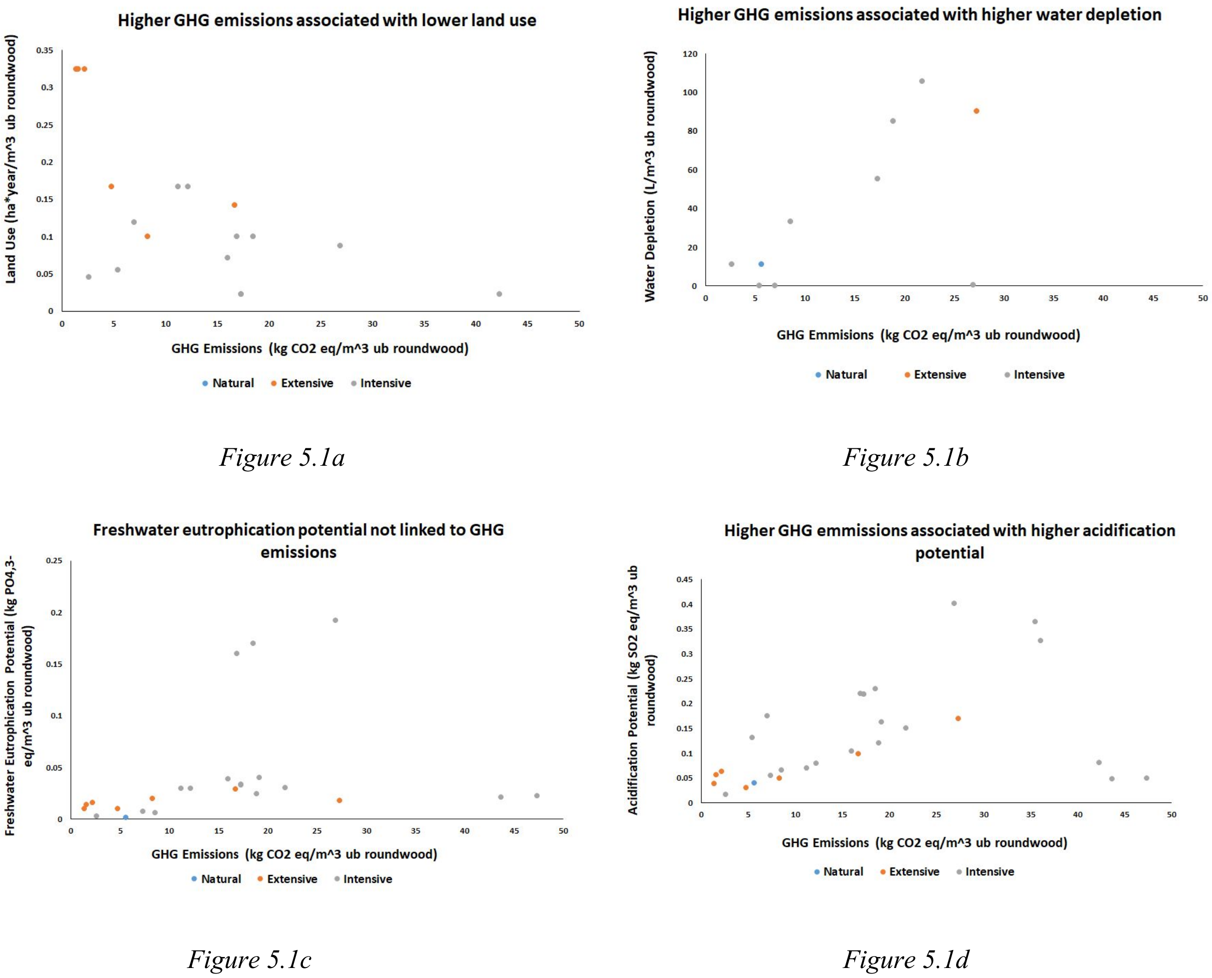

Figure 5.1a

Figure 5.1b

Figure 5.1c

Figure 5.1d

Figure 5.1. GHG emissions plotted against four other environmental indicators, color coded by the production system. Data from here.

In Figure 5.1a, while there is significant spread in the data, overall, higher GHG emissions were associated with lower land use. The trend is only visually apparent collectively, and isn't pronounced in any individual production system (natural, extensive, etc.), suggesting either that more data would result in no correlation or that the driver of the association transcends production system.

Data on water depletion was relatively scarce, making conclusions based on Figure 5.1b necessarily weak. For the available points, however, higher GHG emissions were consistently associated with higher water depletion, particularly in intensive systems. One notable outlier suggests that other life cycle assessments may have also involved zero water depletion and therefore didn’t report a measurement. If this is the case, then it is particularly difficult to make conclusions. Datasets that do not report water depletion likely do so because the plantation is rainfed and not irrigated.

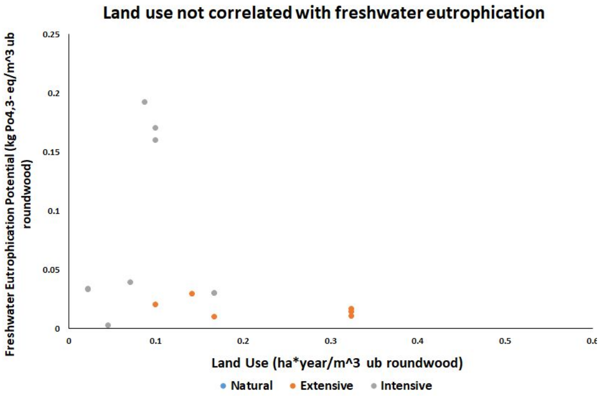

Figure 5.2a

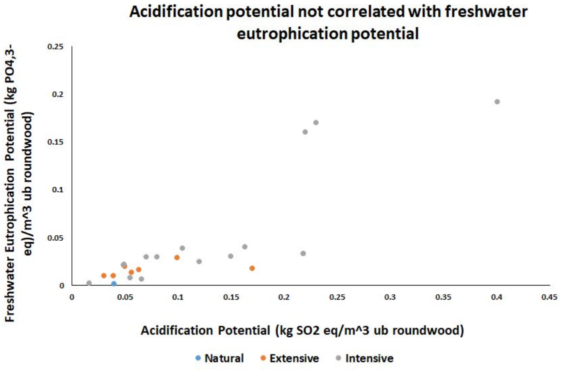

Figure 5.2b

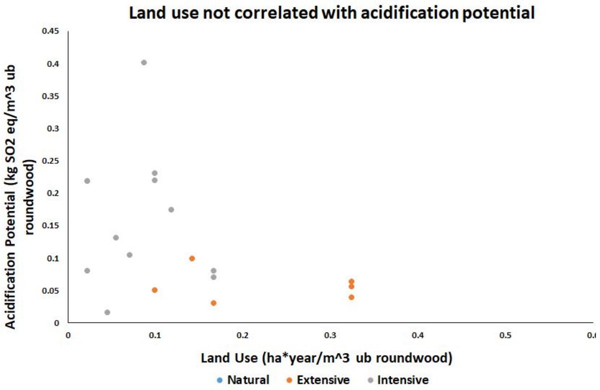

Figure 5.2c

Figure 5.2. Land use, acidification potential, and freshwater eutrophication potential plotted against one another, color coded by production system. Data from here.

As seen in Figure 5.1c, with the exception of three outliers, freshwater eutrophication potential in our dataset was remarkably consistent—below .05 kg PO_4^{3-} eq regardless of production system and regardless of increasing GHG emissions. This suggests that the drivers of freshwater eutrophication potential transcend system type and are separate from the drivers of GHG emissions. If this is the case, efforts to reduce GHG emissions do not have a predictable effect on freshwater eutrophication.

As seen in Figure 5.1d, the relationship between GHG emissions and acidification potential is the strongest of any relationship between environmental indicators in roundwood production. In both intensive and extensive production systems, higher GHG emissions were associated with higher acidification potential with relatively low spread and only a few outliers. This suggests that efforts to lower GHG emissions may not have a negative impact on acidification and that GHG emissions and acidification may share many drivers.

We also compared indicators other than GHG and water depletion to each other, finding across these comparisons that if two or three outliers are excluded, no correlation exists (Figure 5.2).

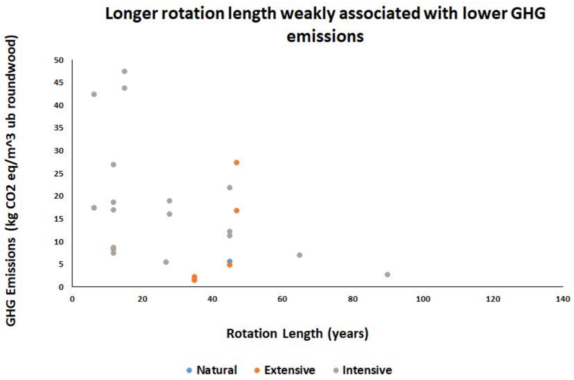

Figure 5.3a

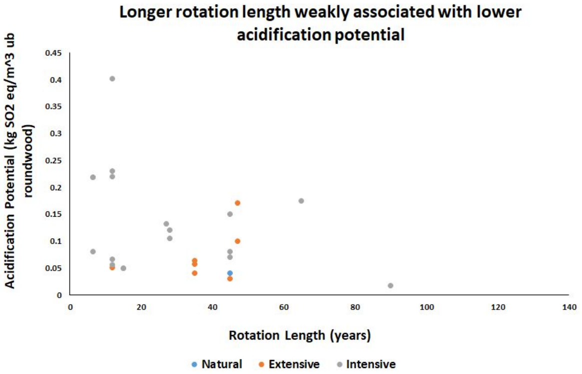

Figure 5.3b

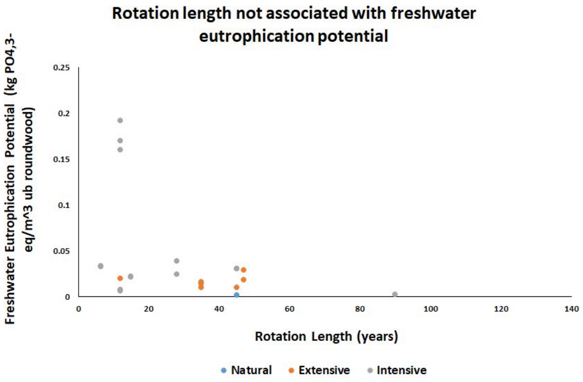

Figure 5.3c

Figure 5.3. Rotation length plotted against GHG emissions, acidification potential, and freshwater eutrophication potential, color coded by production system. Data from here.

Rotation length is a major variable across production systems, making it potentially useful for understanding drivers of impact. In our data, longer rotation length was weakly associated with lower GHG emissions (Figure 5.3A). However, variability in emissions is extreme between data points representing shorter rotation lengths. This indicates that rotation length is not particularly predictive as a driver. Fortunately for producers, this also indicates that there is major room for improvement even within systems with very short rotations.

The situation is very similar for acidification potential, displayed in Figure 5.3B. Overall, longer rotation lengths seemed to be weakly associated with lower acidification potential, but high variability indicates that across extensive and intensive systems, vast improvements can be made despite very short rotation lengths.

By contrast, in Figure 5.3c rotation length appears to be entirely unconnected to freshwater eutrophication potential. Once again the consistent clustering beneath .05 kg PO_4^{3-} eq makes it difficult to draw conclusions about potential improvement.

Investigating Impact Drivers

Having analyzed the relationship between environmental indicators, we then searched for potential drivers of these impacts. We did this by isolating the absolute and relative contributions of the four production stages to total impact of GHG emissions, acidification potential, and freshwater eutrophication potential.

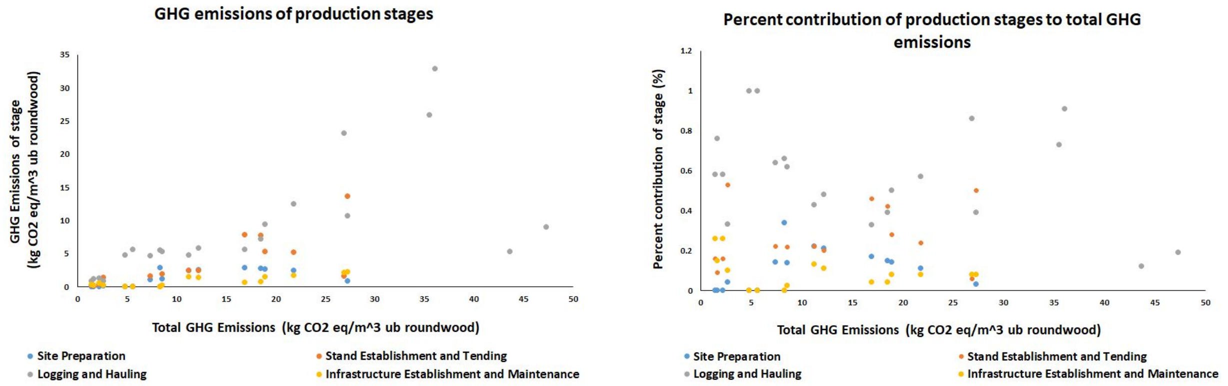

Figure 5.4a *Figure 5.4b*

Figure 5.4. Absolute and relative contributions of production stages to GHG emissions plotted against total GHG emissions, color coded by production stage. Data from here.

GHG emissions associated with the logging and hauling stage in Figures 5.4a and 5.4b varied dramatically, indicating significant room for industry improvement. This variability exists not only in raw numbers (5.4A) but also in percent contributions (5.4B). Additionally, the variability persists independently of increasing or decreasing total GHG emissions, further indicating the flexibility of this stage.

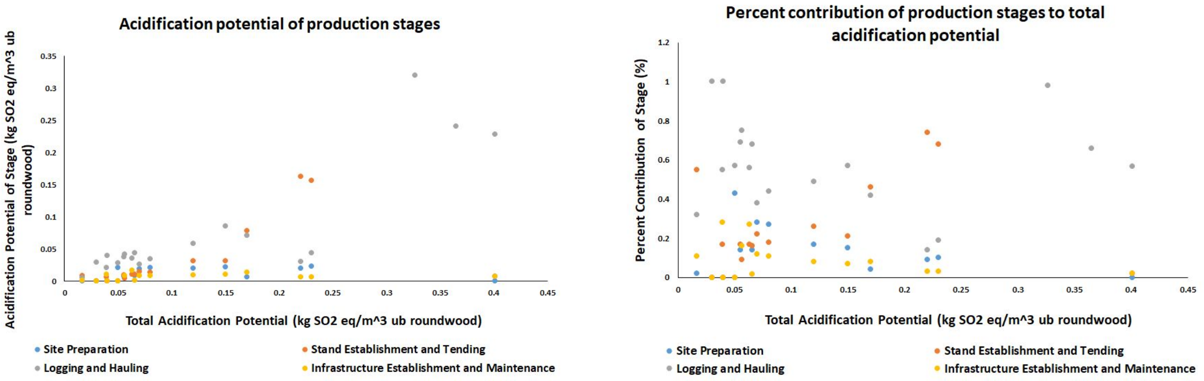

Figure 5.5a

Figure 5.5b

Figure 5.5. Absolute and relative contributions of production stages to acidification potential plotted against total acidification potential. Data from here.

Similar to GHG emissions, acidification potential, shown in Figure 5.5, also shows the most potential for improvement in the logging and hauling stage as indicated by high variability of impact within production stages. This is also the case with the stand establishment and tending stage. Percent contributions for both of these stages vary independently of total acidification potential, making it a promising target.

Because the infrastructure establishment and maintenance and site preparation stages have a relatively consistent contribution to GHG emission and acidification potential in this dataset, it appears that the stand establishment and tending stage and the logging and hauling stage are more strategic targets for improved sustainability.

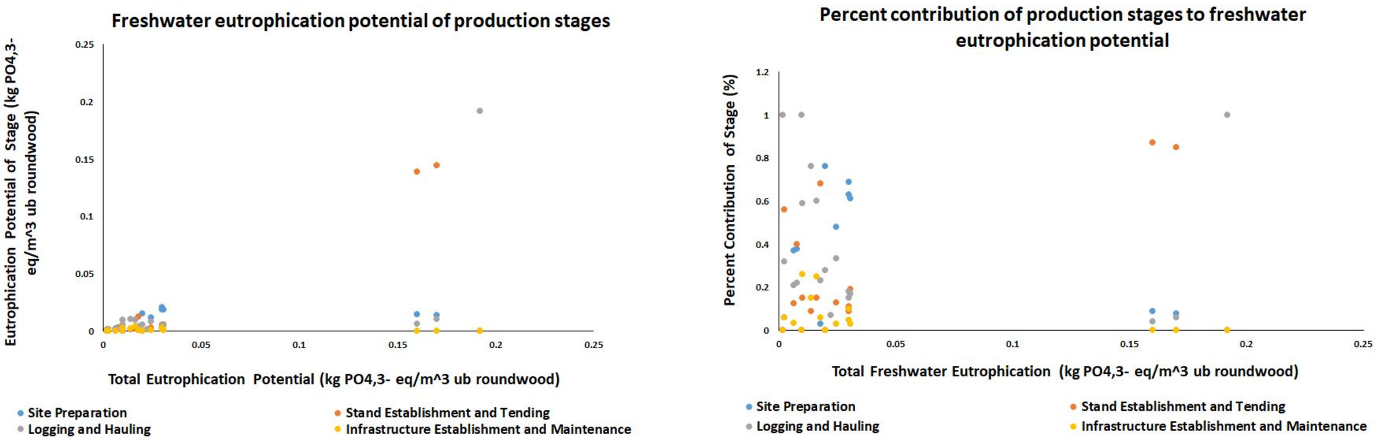

Figure 5.6A

Figure 5.6b

Figure 5.6. Absolute and relative contributions of production stages to freshwater eutrophication potential plotted against total freshwater eutrophication potential. Data from here.

In Figure 5.6a and 5.6b, the eutrophication potentials associated with each production stage vary dramatically, with site preparation having a relatively large and varied contribution to eutrophication as opposed to GHG emissions and acidification.

Finally, in the search for leads on potential impact drivers, we graphed GHG emissions by country and tree type.

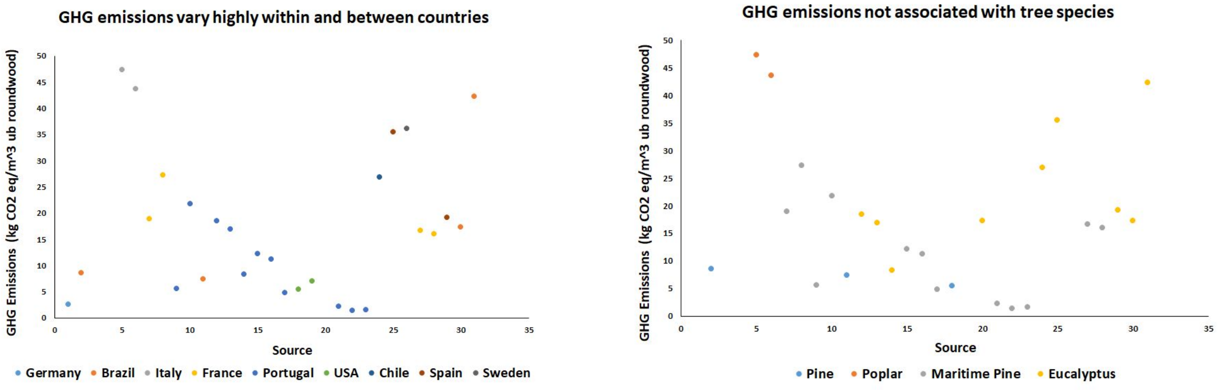

Figure 5.7a

Figure 5.7b

Figure 5.7. GHG emissions color coded by country and tree species. Data from here.

Because emissions vary drastically within and between countries (Figure 5.7a) as well as within and between tree species (Figure 5.7b), it appears that neither is a good lead for potential drivers of environmental impact.

Analysis and Future Steps

These analyses have resulted in many directions for future research, particularly when it comes to impact drivers. The common drivers behind GHG emissions and acidification potential are likely located at the logging and hauling stage of production. This inquiry could be further investigated in several ways. For example, it may be useful to compare types of machinery used in the logging and hauling stage and even within other stages. A 2015 literature review of forest product life cycle assessments introduces mechanization level as a categorization.[139] However, their system does not encompass the full range of listed machinery in the LCAs in our dataset and does not address mechanization in stages other than logging and hauling. We therefore suggest the development of a more comprehensive metric for mechanization level based on the one found in the review.

Further research related to fuel types could help investigate the possibility of fuel type being a driver for the correlation between acidification potential and GHG emissions. While diesel was the most commonly used fuel, sources varied between natural gas, petrol, electricity generated onsite by biomass, and others.

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[139] Daniel Klein et al., "20 Years of Life Cycle Assessment (LCA) in the Forestry Sector: State of the Art and a Methodical Proposal for the LCA of Forest Production," *The International Journal of Life Cycle Assessment* 20, no. 4 (January 20, 2015): 556–75, https://doi.org/10.1007/s11367-015-0847-1.

According to a 2002 review of terrestrial acidification, fuel burning is a major source of acidifying nitrogen and sulfur compounds in forestry emissions, further implicating fuel type.[140]

A similar analysis could be performed between types of fertilizers, herbicides, and pesticides. Finally, future research could distinguish between biogenic and non biogenic CO_2 emissions and investigate their tradeoffs with acidification potential separately. This would require more data because our sources overall did not distinguish biogenic and non-biogenic CO_2.

Alternatively, future inquiries could focus on deepening our analysis of land use since land conversion is one of the main drivers of environmental degradation caused by the forestry industry in Southeast Asia, where much of the world's roundwood is sourced.[141] Data on land conversion and soil carbon was not readily available in the sources for our dataset, but other sources could be procured. Abiotic depletion measurements, however, are present in some of the life cycle assessments and may warrant investigation.

Finally, future work could involve building on our dataset. Due to the lack of life cycle analyses in conventional public databases, there is a discrepancy between the regions represented in our dataset and the regions that produce the most of the world's roundwood supply. In particular, China, India, and Indonesia warrant greater representation. Efforts towards this endeavor could involve contacting field experts for data.

Livestock

In the past 50 years, global annual meat consumption has risen from an average of 10 kilograms per person in 1960, to 26 kilograms in 2000, and to 41.3 kilograms in 2015.[142,143] *This average is expected to continue to increase as the global middle class grows over the next century.*[144] *Meat also contributes 14.5% of global human-caused GHG emissions.*[145] *The subcategory of livestock contains beef and poultry meats, which the team chose because cattle are representative of ruminants (meaning they have multiple stomachs), and poultry broadly covers both farmed bird meat, and other monogastrics (which only have one stomach). In general, there seem to be few trade-offs between GHG emissions and other environmental indicators for livestock. Correlations are generally either positive, implying that decreased GHG emissions are also connected to a decrease in other environmental impacts, or neutral, which indicates a lack of relationship between GHG emissions and the given environmental indicator. This*

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[140] A. F. Bouwman et al., "A Global Analysis of Acidification and Eutrophication of Terrestrial Ecosystems," *Water, Air, and Soil Pollution* 141, no. 1/4 (2002): 349–82, https://doi.org/10.1023/a:1021398008726.

[141] David P. Edwards et al., "Degraded Lands Worth Protecting: The Biological Importance of Southeast Asia's Repeatedly Logged Forests," *Proceedings of the Royal Society B: Biological Sciences* 278, no. 1702 (August 4, 2010): 82–90, https://doi.org/10.1098/rspb.2010.1062.

[142] Vranken, L., Avermaete, T., Petalios, D., and Mathijs, E. (2014). Curbing global meat consumption: Emerging evidence of a second nutrition transition. Environmental Science and Policy, 39, 95–106.

[143] United States of America. Food and Agricultural Organization. (2003). *World Agriculture: towards 2015/2030.*

[144] Katare, B., Wang, H. H., Lawing, J., Hao, N., Park, T., and Wetzstein, M. (2020). Toward Optimal Meat Consumption. American Journal of Agricultural Economics. doi:10.1002/ajae.12016

[145] "Key Facts and Findings," FAO (Food and Agriculture Organization), accessed January 27, 2021, http://www.fao.org/news/story/en/item/197623/icode/.

suggests that pursuing systems which minimize GHG emissions in livestock production systems does not come with a consistent cost of increased environmental impacts.

Beef

In farms with high GHG efficiency, beef herd cattle generally produce lower eutrophying emissions and use smaller amounts of land than in farms with worse GHG efficiency. Acidification potential and freshwater withdrawal seem to have no correlation with GHG efficiency, meaning that for beef herd cattle there does not seem to be trade-offs to prioritizing low GHG emissions among the other four environmental indicators. Dairy herd cattle used for beef production have somewhat different environmental relationships. For dairy herd, we found positive correlations between land use and GHG emissions, acidification potential and GHG emissions, and eutrophication potential and GHG emissions. There was no observed correlation between freshwater withdrawal and GHG emissions. The surveyed upper-middle income countries had far higher GHG emissions than high income countries, resulting in a clear disparity. The source of this seems to be a far higher destruction of ground cover carbon sinks to clear land for beef production, and poor feed quality, resulting in far higher levels of enteric methane production.

Overview

Beef represents 22% of meat production globally, but also is responsible for approximately 37% of GHG emissions produced by the agricultural sector.[146,147] Additionally, the protein input to energy output for beef cattle is 40:1, which is extremely inefficient in comparison to other sources of food.[148] So it is critical that we find ways to make beef production more efficient in terms of greenhouse gas emissions, without significantly increasing other environmental impacts.

In order to determine the trade-offs associated with decreasing the GHG emissions of the beef industry, the AgImpacts team used data from Poore and Nemecek (2018) to create visualizations of the relationship between GHG emissions and other environmental indicators. Beef is generally produced from either beef herd cattle, or dairy herd cattle. Beef herd cattle are bred specifically for beef production, meaning that they are more massive and muscular than dairy herd cattle, which are bred primarily for their milk. In this section, we separately analyze these production systems in order to find any similarities and differences between them. For beef from beef herd cattle, this dataset included 105 points of data. For beef from dairy herd cattle, the set included 40 points of data. The data for dairy herd cattle excluded two data points from beef production in Mexico because the environmental impacts were extreme outliers compared to the rest of the data.

Environmental Impact Comparisons

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[146] Hannah Ritchie (2017) - "Meat and Dairy Production". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/meat-production' [Online Resource]

[147] Asem-Hiablie, S., Battagliese, T., Stackhouse-Lawson, K. R., and Alan Rotz, C. (2018). A life cycle assessment of the environmental impacts of a beef system in the USA. The International Journal of Life Cycle Assessment. doi:10.1007/s11367-018-1464-6

[148] Pimentel, D., and Pimentel, M. (2003). Sustainability of meat-based and plant-based diets and the environment. The American Journal of Clinical Nutrition, 78(3), 660S–663S. doi:10.1093/ajcn/78.3.660s

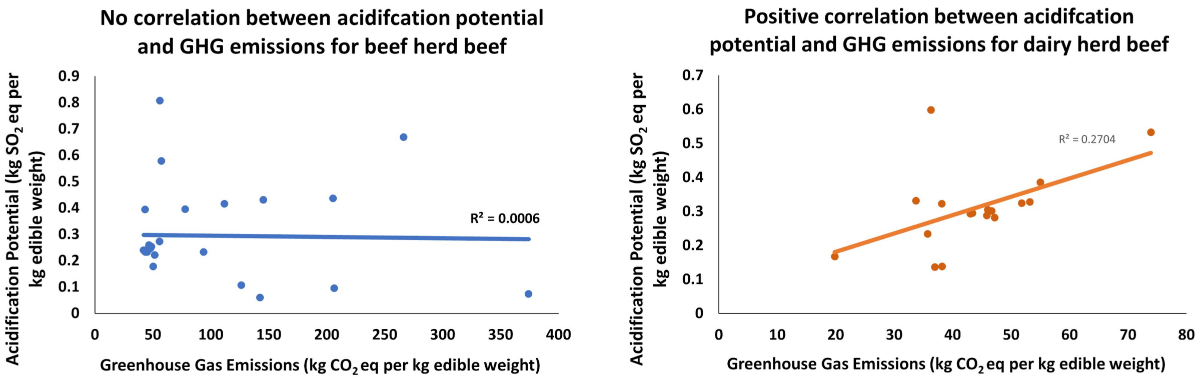

Figure 6.1. Charts of acidification potential plotted against greenhouse gas emissions for beef from beef herd cattle (left) and dairy herd cattle (right). Data from Poore and Nemecek (2018).

Acidification potential seems to have little correlation with GHG emissions for beef herd cattle (Figure 6.1, left), but notably, beef produced from dairy herd cattle shows a positive correlation (Figure 6.1, right). This implies that for both types of beef production, there is not a detrimental increase in the release of acidifying compounds when GHG emissions are reduced. For dairy herd cattle, it even seems that methods which reduce GHG emissions also result in reduced release of acidifying compounds.

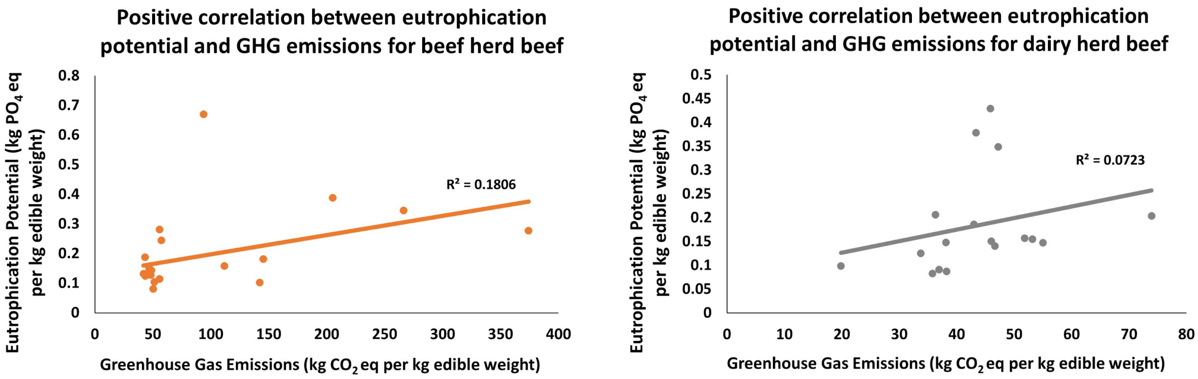

Figure 6.2. Charts of eutrophication potential plotted against greenhouse gas emissions for beef from beef herd cattle (left) and dairy herd cattle (right). Data from Poore and Nemecek (2018).

Eutrophication potential shows a somewhat different relationship, for both beef herd cattle and dairy herd cattle there is a positive correlation between GHG emissions and the release of eutrophying compounds (Figure 6.2). This implies that methods which decrease GHG emissions also result in lower eutrophication potential.

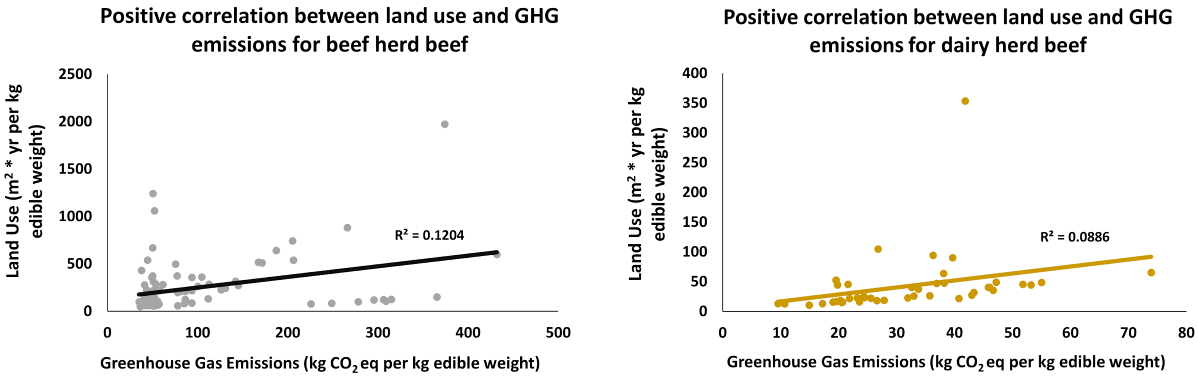

Figure 6.3. Charts of land use plotted against greenhouse gas emissions for beef from beef herd cattle (left) and dairy herd cattle (right). Note the different scales between the dairy herd cattle and beef herd cattle. Data from Poore and Nemecek (2018).

Land use shows a similar relationship between beef herd and dairy herd cattle. Both production systems indicate a positive correlation between land use and GHG emissions (Figure 6.3), suggesting that farms more efficient in terms of GHG emissions are also more efficient in their use of land.

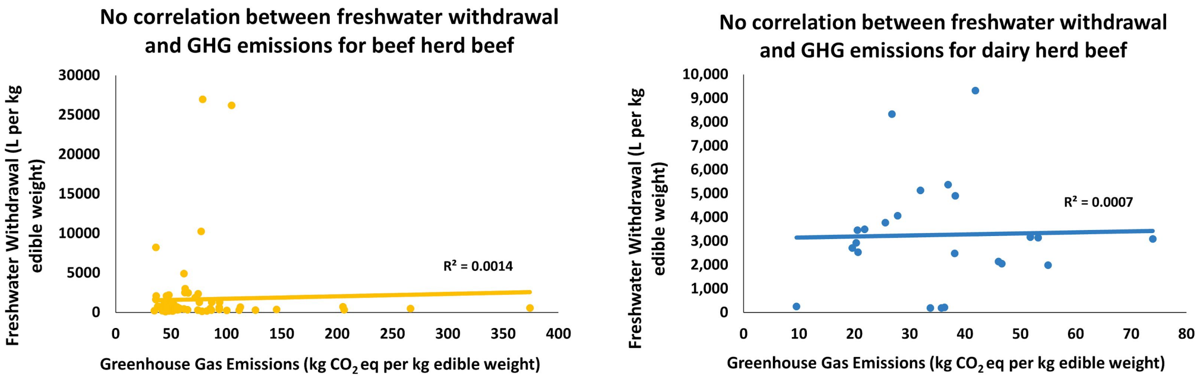

Figure 6.4: Charts of freshwater withdrawal plotted against greenhouse gas emissions for beef from beef herd cattle (left) and dairy herd cattle (right). Note the difference in scales between the beef herd and dairy herd data. Data from Poore and Nemecek (2018).

For both beef herd and dairy herd cattle, there seems to be no correlation between GHG emissions and freshwater withdrawal (Figure 6.4). This implies that freshwater withdrawal is unaffected by strategies which reduce GHG emissions in beef production. The majority of freshwater used in beef production is due to water consumed for crop growth, which is processed into feed for cattle.

In all examples except the relationship between dairy herd eutrophication potential and GHG emissions, it seems that environmental consequences of beef production systems are either reduced or unaffected by the use of techniques which result in lower GHG emissions. But there is still a significant difference between the lowest and highest levels of GHG emissions. Based on the apparent connection between GHG emissions and other environmental indicators (Figures 6.1, 6.2, 6.3), the difference implies that there is also a disparity among local environmental impacts of beef production. If there exists a disparity, then it could be possible to target beef production systems associated with greater environmental consequences, and potentially find a way to improve their efficiency. This would result in a more significant environmental improvement than spending resources to improve systems which are already comparably quite efficient.

The Unequal Intensity of GHG Emissions by Income Level

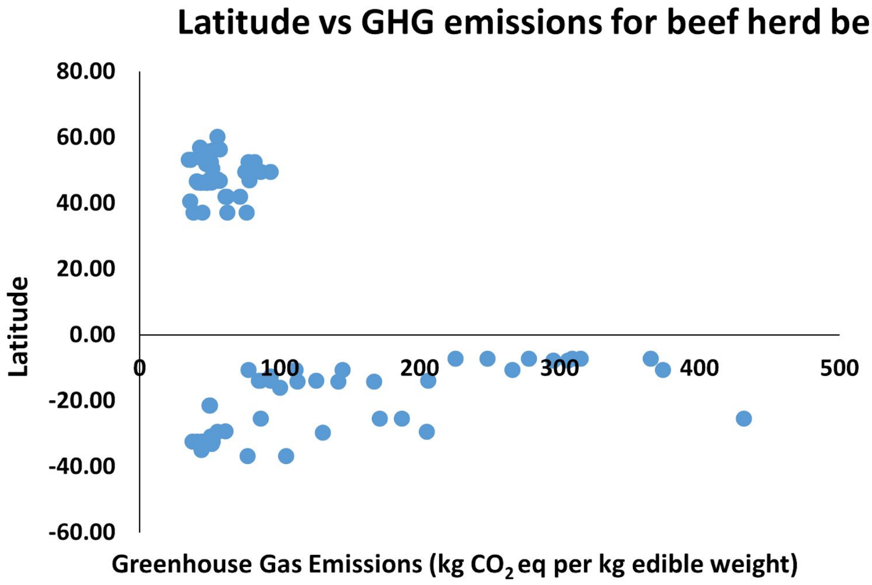

Figure 6.5. Latitude plotted against GHG emissions for beef herd beef. Data from Poore and Nemecek (2018).

To work towards identifying the source of this disparity in GHG emissions, the AgImpacts team chose to compare latitude and GHG emissions, based on a hypothesis that climate could affect GHG emissions of cattle. Although latitude is not the only indicator of climate, this comparison was intended to be a first step in the investigation. Note that for some data points, latitude was not listed by Poore and Nemecek (2018), so the AgImpacts team assumed an average latitude of the region, if given, or the average latitude of the country, if region was not available. The hypothesis was not supported; instead, an interesting trend emerged. There appear to be distinct clusters of data points with relatively low greenhouse gas emissions (Figure 6.5). These clusters seem to be contrasted with a significant number of data points which are scattered along the x-axis, possessing much higher emissions than those in the cluster.

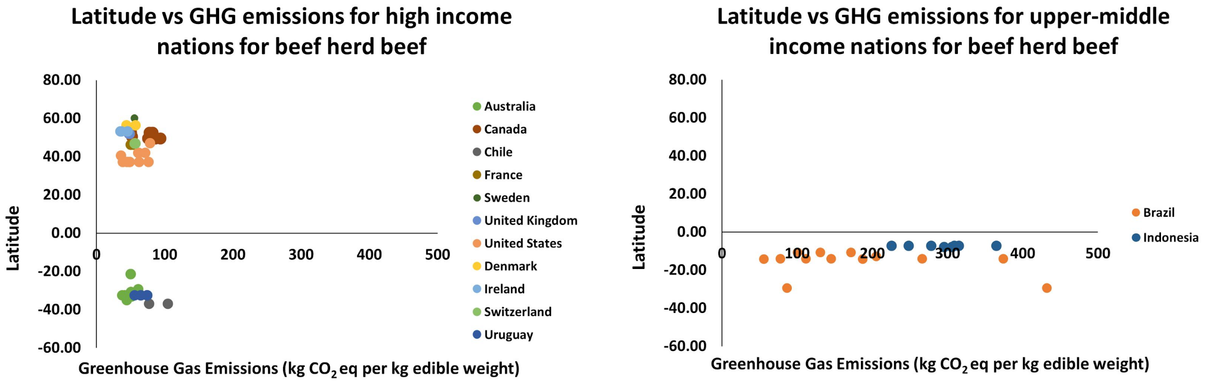

Figure 6.6. Latitude plotted against GHG emissions, divided by income and color-coded by country, for beef from beef herd cattle. Data from Poore and Nemecek (2018). Country income levels from the World Bank (2020).

There doesn’t seem to be a discernible relationship between latitude and emissions, but when these data points are filtered by country, far clearer trends emerge. The surveyed European nations, the United States, Canada, and Australia seem to be the source of the aforementioned “clusters” of countries with similar latitudes, but relatively low emissions (Figure 6.6, left).

Brazil and Indonesia seem to be responsible for the erratic data points with relatively high emissions (Figure 6.6, right). Based on this data, beef produced in Brazil and Indonesia produce significantly more greenhouse gas emissions per kilogram than beef produced in other countries. Perhaps production systems in less-efficient nations could be improved by using techniques from more-efficient nations. Not just to mitigate their impact on the global climate, but also to reduce the local environmental impacts tied to heightened greenhouse gas emissions. Notably, Brazil and Indonesia are the only two surveyed upper-middle income countries, contrasted with the clustered and lower-emitting nations, which are all considered high income by the World Bank.

The higher amount of greenhouse gas emissions for beef cattle in Indonesia is likely due to the extremely extensive nature of their beef agriculture. In Indonesia, generally one to two heads of cattle are kept per small farm.[149] We hypothesised that this, combined with the longer lifespans of cattle in Indonesia, are part of the significantly increased GHG emissions per kilogram of beef product. But our team doubted that this was the only explanation for the nearly quadrupled GHG emissions per kilogram of beef (Figure 6.6), so we investigated other sources.

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[149] Mazzetto, A. M., Bishop, G., Styles, D., Arndt, C., Brook, R., and Chadwick, D. (2020). Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. Journal of Cleaner Production, 124108. doi:10.1016/j.jclepro.2020.124108.

Extreme Difference in Change in Land Use Change by Income Level

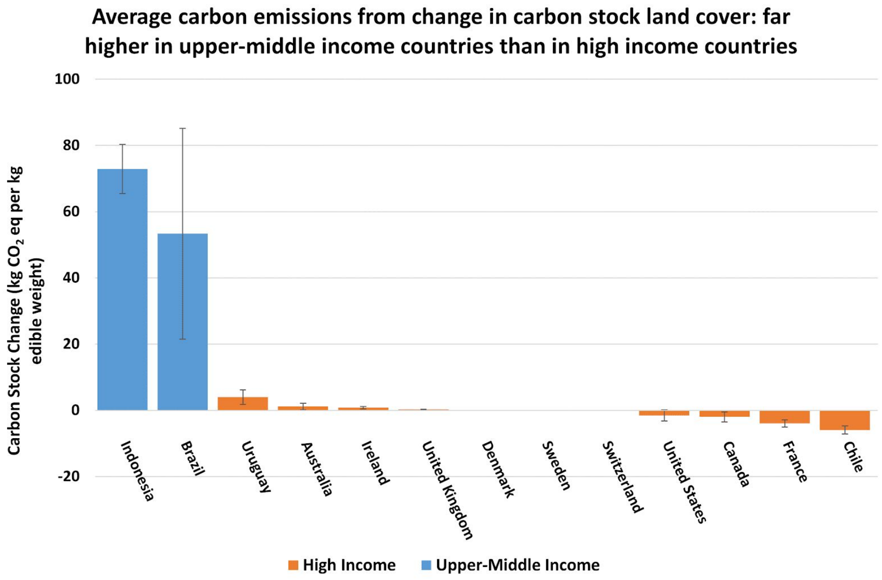

Figure 6.7. Change in carbon stock land cover for beef herd cattle. Each bar represents an average of available data points for the given country, where the error bars indicate one standard deviation of each set of country data. Data from Poore and Nemecek (2018). Country income levels from the World Bank (2020).

To further investigate this disparity in GHG emissions, the AgImpacts team examined differences among the carbon emissions from land use change in the surveyed nations (Figure 6.7). This metric represents the loss in stored carbon, which consists of above ground, leaf litter, and below ground carbon sinks. The metric is negative for many data points, because the planting of fields can result in an increase in carbon storage. A high level of stored carbon loss implies that land which was formerly covered in carbon-capturing vegetation was replaced by an empty pasture or facility for beef production, releasing the formerly stored carbon. Beef produced in Brazil and Indonesia is connected to extremely high loss in stored carbon compared to beef from high income nations (Figure 6.7). This reveals a greater cost to Brazil and Indonesia’s beef production, there is not just emission of polluting compounds, but also active replacement of vegetated areas. However, the difference in GHG emissions from land-use change alone does not entirely explain the disparity between upper-middle income and high income countries, so more investigation was warranted.

Trade-offs Between Enteric Methane Emissions and Cattle Feed GHG Emissions

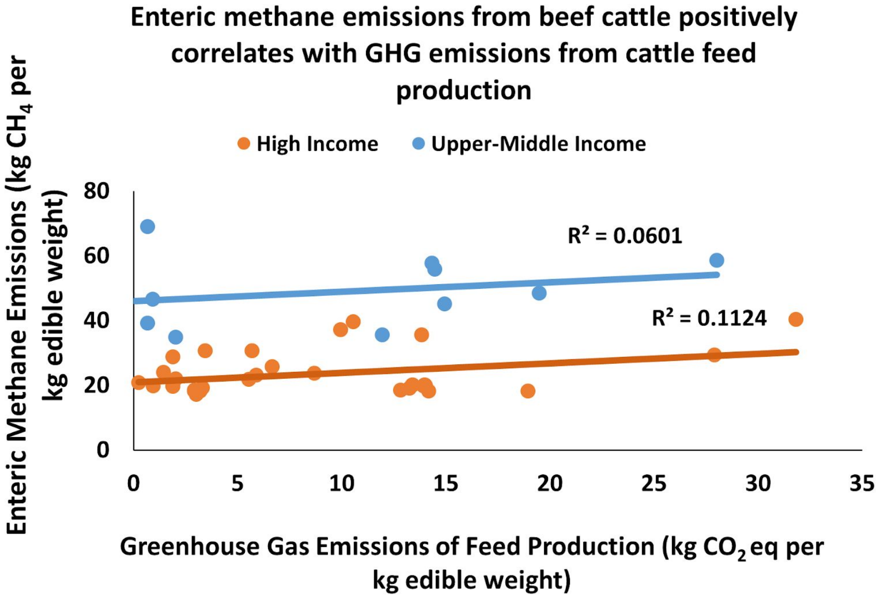

Figure 6.8. Enteric methane emissions plotted against GHG emissions of feed quality, divided by income and color-coded by country, for beef from beef herd cattle. Data from Poore and Nemecek (2018). Country income levels from the World Bank (2020).

Our team was curious to investigate any potential trade-offs between the GHG emissions produced by the feed for non-grass fed cattle and the resulting methane produced by the cattle through enteric fermentation. When we examined the data, a very similar, slightly positive trend emerged for both high income and upper-middle income nations (Figure 6.8). This implies that more efficient feeds, which reduce the methane produced by cattle through enteric fermentation, are not associated with increased carbon costs in their production. This analysis also provides more explanation for the vast difference in carbon emissions from beef production among the surveyed high and upper-middle income countries (Figure 6.6). It seems that a significant portion of this disparity is enteric methane emissions, which are connected to poor feed quality and feeding from pasture.[150]

Summary

Poor feed quality, extensive systems, and release of land cover carbon stock seem to be the primary difference between systems in more and less efficient beef-producing countries. In order to minimize the environmental impacts of beef production, it would be best to help farmers in these less-efficient countries gain access to better feed, and potentially encouraging intensive farming practices *without* threatening the livelihoods of farmers who depend on their cattle.

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[150] Mazzetto, A. M., Bishop, G., Styles, D., Arndt, C., Brook, R., and Chadwick, D. 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. Journal of Cleaner Production, 124108. https://doi.org/10.1016/j.jclepro.2020.124108

Poultry Meat

Within the poultry commodity, GHG emissions seem to be most closely tied with acidification potential, with our data showing a distinct, direct relationship between these indicators regardless of system intensity. This is related to the feed and farm stages in production, since the highest acidifying emissions occur during those stages. GHG emissions are also related to country of origin, with Vietnam and Finland having the highest at ~20 kg CO_2 *eq per kg edible weight. There seem to be no other notable correlations between GHG emissions and the other environmental indicators, suggesting that there may not be any other covariances. However, trends among these indicators, without GHG emissions, were found. Land use and eutrophication potential show a slight positive relationship with each other, which is also likely related to the feed stage in production. With only 45 data points to work with, more research is needed to investigate the possible trends found in this analysis.*

Overview

Poultry meat, which includes chickens, ducks, turkey, and geese, is the second most widely eaten meat in the world. It accounts for about 28% of meat production worldwide,[151] and it is projected that by 2050, 2.3 times as much poultry meat will be consumed than in 2010.[152] In order to keep up with increasing demand, farms must become more efficient and increase yield. As this push to meet demand spikes, it is crucial that farms follow practices that reduce waste and mitigate environmental harm.

Analysis Methods

This section will cover the trends found among the five environmental indicators and investigate whether the intensity or specifications earned by a farm have an effect on such trends. In this section, there are two defined farm specifications: *organic* means the animals were given feed without synthetic pesticides, antibiotics, hormones, and mammalian byproducts, and were given access to the outdoors;[153] *Label Rouge* is a French quality assurance seal, which prioritizes animal welfare and the quality of the product and requires the animals to have been raised free-range.[154] Farm systems are also classified as extensive or intensive. The key difference between these two types is the animal's access to the outdoors. Extensive systems allow for animals to graze, while intensive systems contain the animals and bring feed to them.[155] Generally, extensive systems are found in small to medium sized farms, while intensive systems are large, automated farms.

The entries for poultry meat were taken from the Poore and Nemecek (2018) dataset, which consisted of 46 entries from 13 countries. Because this spreadsheet is a compilation of other data, not all of the entries have a value for each environmental indicator investigated. When this occurred, the entry was omitted

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[151] Food and Agriculture Organization. 2003. World Agriculture: towards 2015/2030. United States of America: FAO. http://www.fao.org/3/y4252e/y4252e00.htm.

[152] FAO. 2011. World Livestock 2011. Livestock in food security. http://www.fao.org/3/i2373e/i2373e.pdf

[153] University of Georgia Extension. (2018). Organic poultry production vs. other systems. https://extension.uga.edu/publications/detail.html?number=C1139&title=Organic%20Poultry%20Production%20vs.%20Other%20Systems

[154] Volaille Label Rouge. (2020). What is Label Rouge poultry? http://www.volaillelabelrouge.com/en/what-is-label-rouge-poultry/

[155] Pitesky, M. E., Stackhouse, K. R., and Mitloehner, F. M. (2009). Clearing the Air. Advances in Agronomy, 1–40. https://doi.org/10.1016/S0065-2113(09)03001-6

from that specific analysis. Additionally, one outlier present in the Poore and Nemecek dataset was omitted from this analysis. The data point represents foie gras, a type of poultry meat that requires excessive feed and resources due to how it is typically farmed. Foie gras depends on fattening up the liver of geese and ducks; the animals are force fed,[156] causing the notable increase in each environmental indicator, and skewing the intervals on each graph. As this outlier is constant throughout all graphs, it was removed to allow for easier data visualization.

Relationships Between GHG and Key Indicators

We first analyze GHG emissions against the other four environmental indicators: freshwater withdrawal (Figure 7.1), land use (Figure 7.2), acidification potential (Figure 7.3), and eutrophication potential (Figure 7.5).

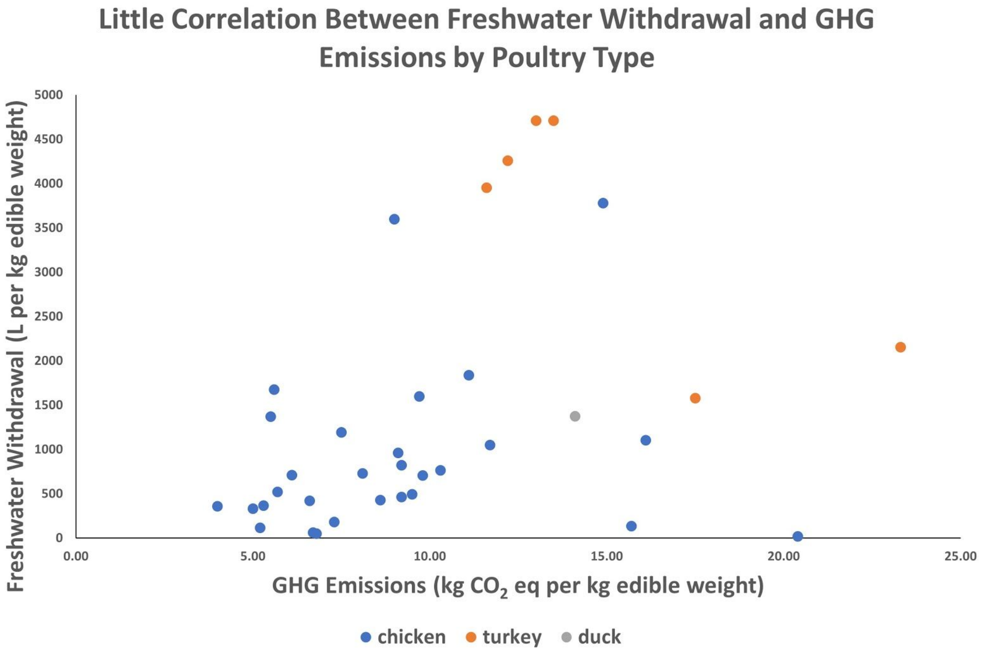

Figure 7.1. GHG emissions and freshwater withdrawal seem to have little relationship, with significant spread. Data from Poore and Nemecek (2018).

We found little correlation between freshwater withdrawal and GHG emissions intensity, although the lowest emitters tended to be among the lowest users of freshwater (Figure 7.1). In addition, it appears that chickens and ducks are less impactful in terms of both indicators, while turkeys seem to require more freshwater per the same amount of emissions as chicken.

There are a few concerning points with near-average GHG emissions, but very high freshwater withdrawal (>3,500 L). When the data is sorted by the type of poultry being farmed, as Figure 7.1 is, it becomes apparent that this cluster of concerning points are mostly turkey. The four turkey data points come from the same study within the United Kingdom, which is based on structural models of the

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[156] Scientific Committee on Animal Health and Animal Welfare. (1998). Welfare aspects of the production of foie gras in ducks and geese. FAO. https://ec.europa.eu/food/sites/food/files/safety/docs/sci-com_scah_out17_en.pdf

industry, process models, and simulation models to provide the data.[157]

From that study's methodology, it is not entirely clear why there is such high freshwater withdrawal for these points; it could just be due to the mathematical models used by the authors. The two chicken data points with unusually high freshwater withdrawal have similar reasoning; the right-most data point comes from a sister study of the one responsible for the turkey data points, and therefore has the same underlying model for such high freshwater withdrawal.[158] The left-most chicken data point with high withdrawal comes from a French farm that took into account water used as both drinking water for the animals, and water for cleaning the equipment and buildings and cooling systems.[159] This is atypical for the other LCA's used in this analysis; most accounted for irrigation and drinking, but not the water associated with cleaning equipment. This suggests that the other studies may have underestimated the freshwater withdrawal associated with their systems.

No significant relationship was found between GHG emissions and land use (Figure 7.2), but a handful of points can provide insight.

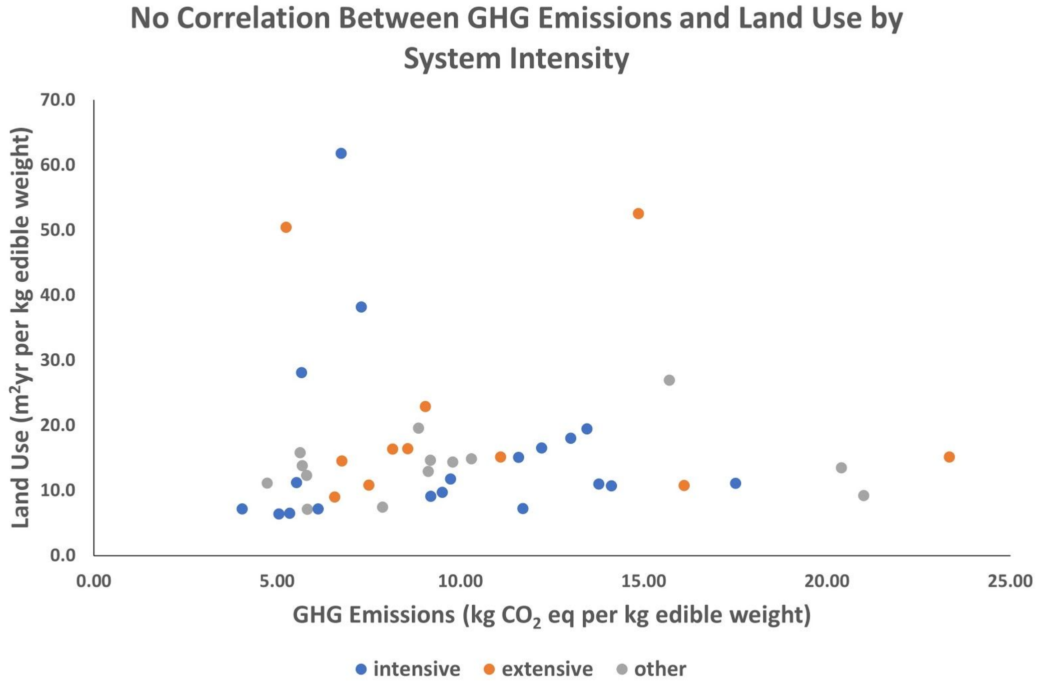

Figure 7.2. There is no apparent correlation between GHG emissions and land use. Data from Poore and Nemecek (2018).

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[157] Leinonen, I., Williams, A. G., and Kyriazakis, I. (2016). Comparing the environmental impacts of UK turkey production systems using analytical error propagation in uncertainty analysis. Journal of Cleaner Production, 112, 141–148. https://doi.org/10.1016/j.jclepro.2015.06.024

[158] Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I. (2012a). Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Broiler production systems. Poultry Science 91, 8-25. https://doi.org/10.3382/ps.2011-01634

[159] Koch P. and Salou T. 2015. AGRIBALYSE® : Rapport Méthodologique – Version 1.2. March 2015. Ed ADEME. Angers. France. 385 p.

This figure, unlike Figure 7.1, is coded by the intensity of the system. It should be noted that the intensity of the system does not seem to be a predictor of higher GHG emissions or higher land use. A few points stick out as having unusually high land use (>50 m^2yr). The two left-most points (one is extensive, the other is intensive) come from the same study. Focusing on South Australia, it assessed land use by aggregating impacts throughout the supply chain, which meant that both total land occupation and arable land occupation were reported.[160] Within South Australia, crop yields are lower, which means arable land use increases and thus the total land use reported is consequently higher.[161] The right-most data point with land use >50 m^2yr summarizes the organic system from a UK study; this organic system had higher feed consumption and a higher land area requirement for the production of organic crops when compared with conventional systems, increasing the relative land use.[162]

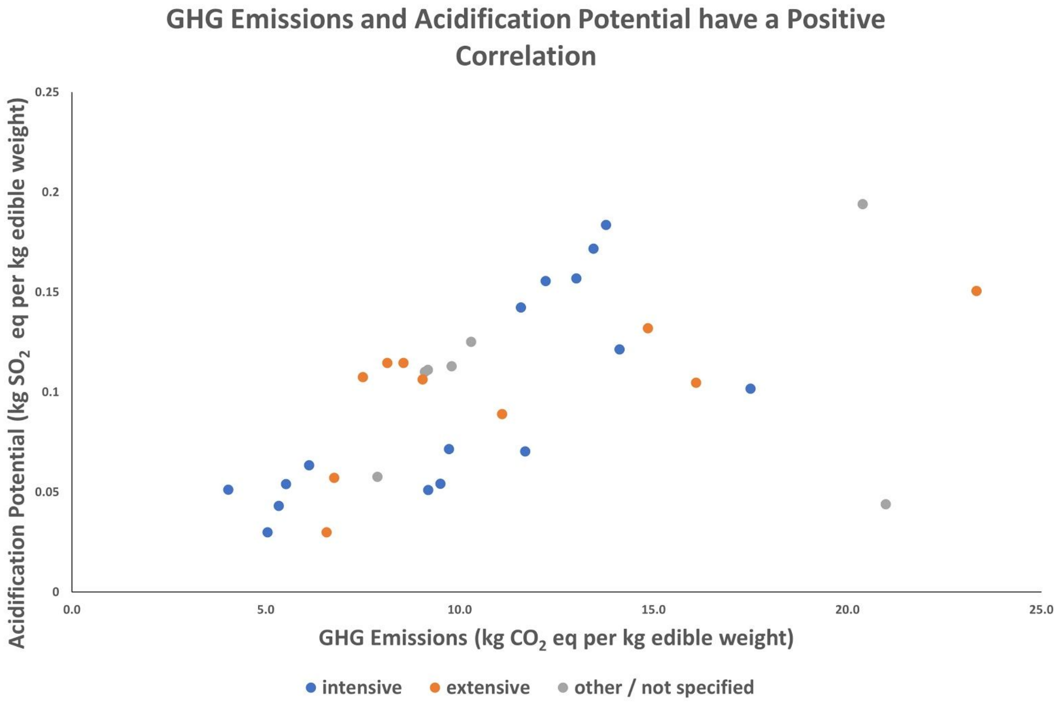

Figure 7.3. GHG emissions plotted against acidification potential, color coded by the intensity of the system. Data from Poore and Nemecek (2018).

The relationship between GHG emissions and acidification potential is direct. It is also independent of the intensity of the system, suggesting that this correlation is not just due to the farm, and may have causes in other production steps. Reviewing the data broken down into each production step, the most consequential outside of the farm is the feed (Figure 7.4).

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[160] Wiedemann, S. G., McGahan, E. J., and Murphy, C. M. (2017). Resource use and environmental impacts from Australian chicken meat production. Journal of Cleaner Production, 140, 675-684. https://doi.org/10.1016/j.jclepro.2016.06.086

[161] Ibid.

[162] Leinonen, I., Williams, A. G., Wiseman, J., Guy, J., and Kyriazakis, I. (2012). Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Broiler production systems. Poultry Science, 91(1), 8–25. https://doi.org/10.3382/ps.2011-01634

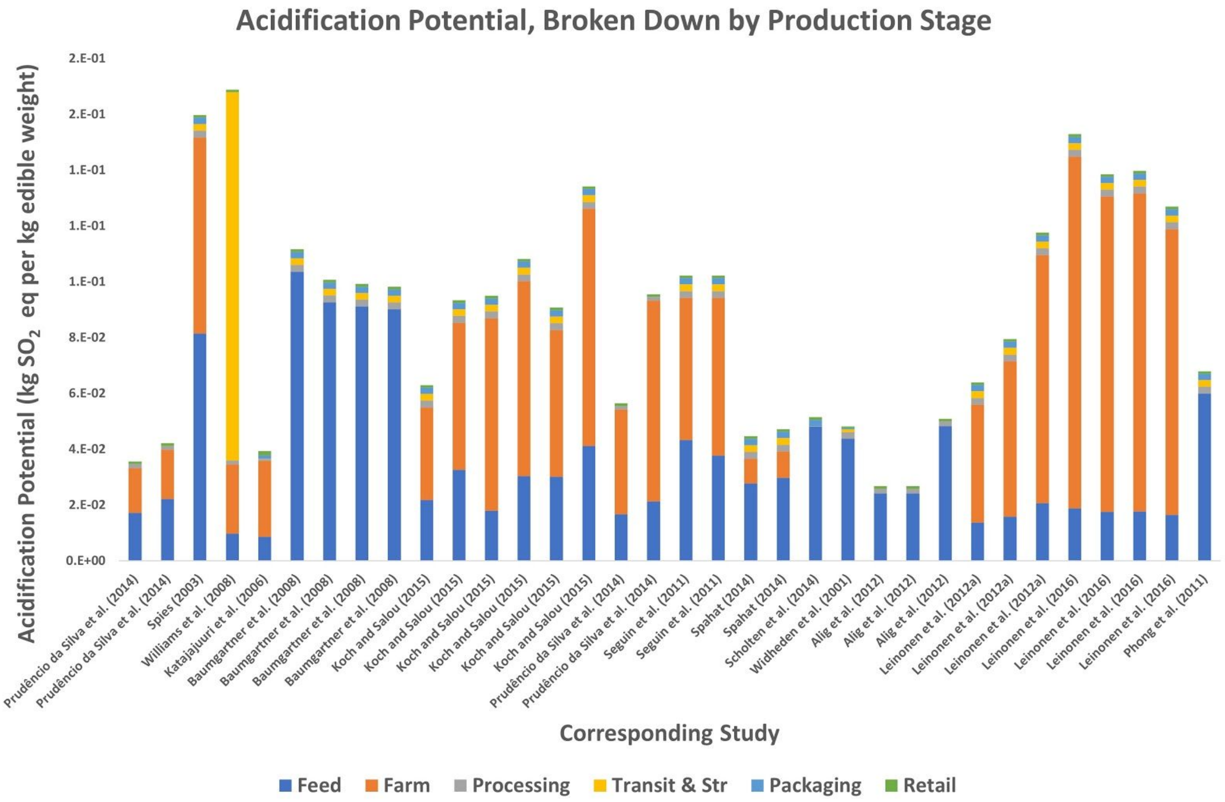

Figure 7.4. Acidification potential, broken down into different stages of production. The farm stage contributes the greatest, closely followed by the feed stage. Data from Poore and Nemecek (2018).

The other stages of production, like processing, transit, packaging, and retail, do not have as pronounced of an effect on acidification potential as the feed and the farm.

The acidification potential from the farm stage is likely due to waste produced by the animals. For example, spreading manure on fields can cause volatilization of ammonia and nitrous oxide, leading to soil and water acidification.[163] Additionally, ammonia emissions can result from manure storage and animal housing, causing the increased acidification potential.[164] In the feed stage of production, the high acidification potential is likely due to the usage of nitrogen-based fertilizers to cultivate the crops.[165]

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[163] Provolo, Giorgio and Mattachini, Gabriele and Finzi, A. and Cattaneo, Martina and Guido, Viviana and Riva, Elisabetta. (2018). Global Warming and Acidification Potential Assessment of a Collective Manure Management System for Bioenergy Production and Nitrogen Removal in Northern Italy. Sustainability. https://doi.org/10.3390/su10103653.

[164] Ibid.

[165] Li, Li and Wu, Wenliang and Giller, Paul and O'Halloran, John and Liang, Long and Peng, Peng and Zhao, Guishen. (2018). Life Cycle Assessment of a Highly Diverse Vegetable Multi-Cropping System in Fengqiu County, China. Sustainability. 10. 983. https://doi.org/10.3390/su10040983.

The outlier with transport contributing an abnormal amount to the acidification potential had its product transported from Brazil to the UK, explaining the skewed data.[166]

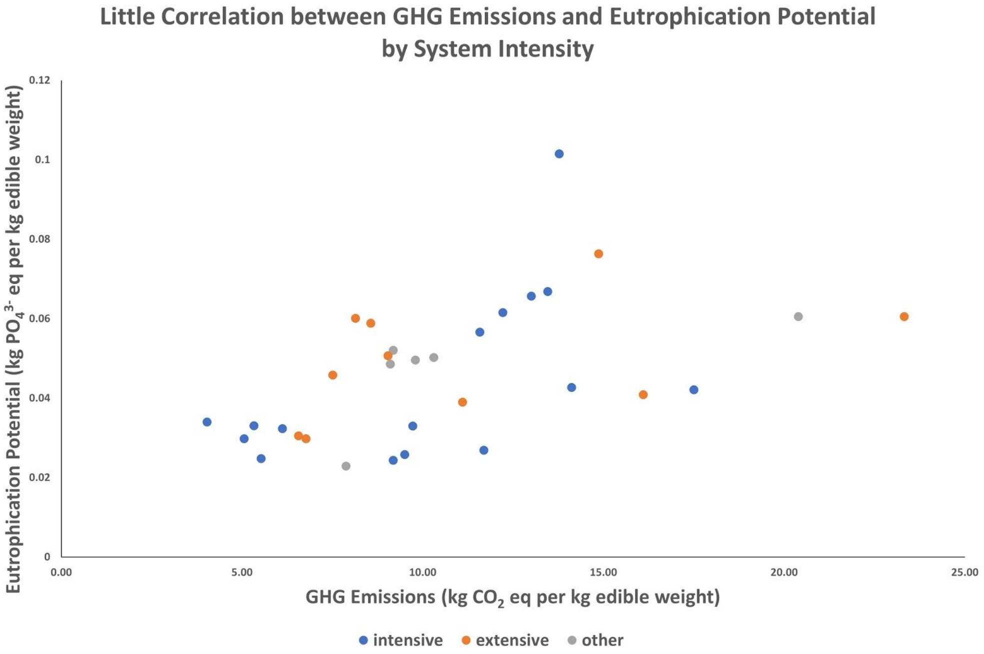

Figure 7.5. GHG Emissions plotted against eutrophication potential, coded by system intensity. Data from Poore and Nemecek (2018).

Having high GHG emissions does not correlate with high or low eutrophication potential (Figure 7.5), and no trends emerge when this data is coded by farm specifications or poultry type. The outlier data point, with eutrophication potential >0.08 kg PO_4^{3-}, comes from Brazil. Within the LCA in the study, it is evaluated that 99% of the eutrophication potential comes from "transport to the UK," explaining the high value.[167]

From this analysis, it appears that of the four key indicators, GHG emissions are only correlated with acidification potential. There also seem to be no trade-offs within the poultry commodity, only the co-benefit that as GHG emissions are reduced, so is acidification potential.

Other Trends

Solely comparing GHG emissions with the other four indicators does not provide an entire picture of the relationships among the poultry commodity. The environmental indicators have relationships amongst each other, outside of GHG emissions. As shown in Figure 7.6 below, there is a clear, positive relationship between eutrophication potential and land use in both intensive and extensive systems.

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[166] Williams, A. G., Pell, E., Webb, J., Tribe, E., Evans, D., Moorhouse, E., Watkiss, P. (2008). Final Report for Defra Project FO0103, Comparative Life Cycle Assessment of Food Commodities Procured for UK Consumption through a Diversity of Supply Chains. UK.

[167] Ibid.

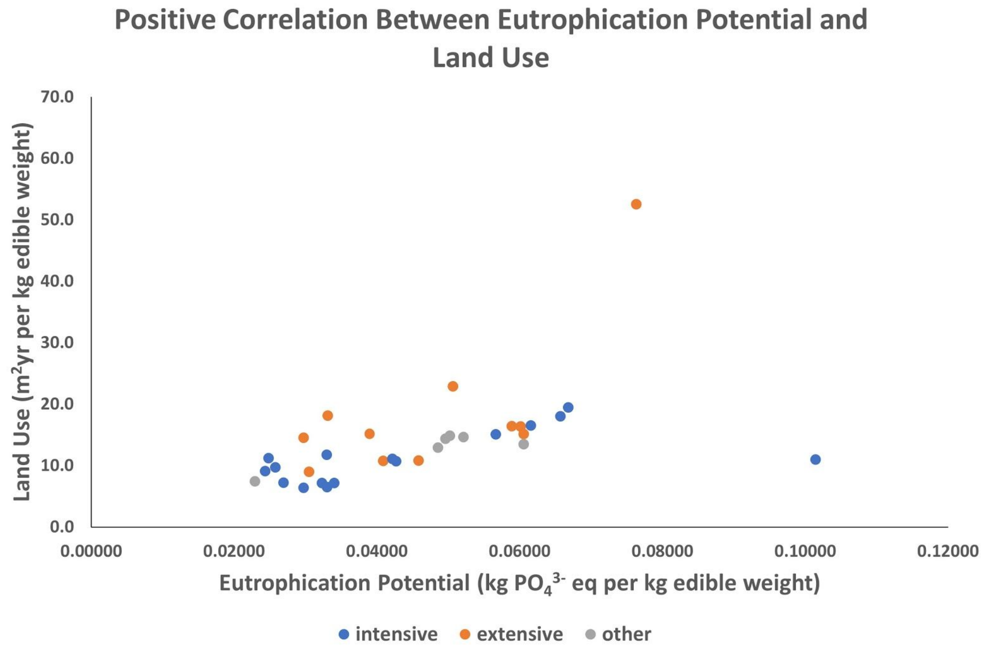

Figure 7.6. Eutrophication potential plotted against land use, coded by the intensity of the system. Data from Poore and Nemecek (2018).

This direct relationship is likely due to the fact that LCA's include the feed stage in production. Land use includes arable land used to produce the feed for poultry, and eutrophication potential can come from artificial fertilizers used to increase yields. It follows that as the arable land used to make feed increases, so would the amount of artificial fertilizer used on that land, contributing to this direct relationship.[168]

Additionally, it should be noted that GHG emissions seem to be closely related to the country of origin. Both Vietnam and Finland have abnormally high emissions when compared with other countries (Figure 7.7).

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[168] EPA. (2020). The sources and solutions: Agriculture. https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture

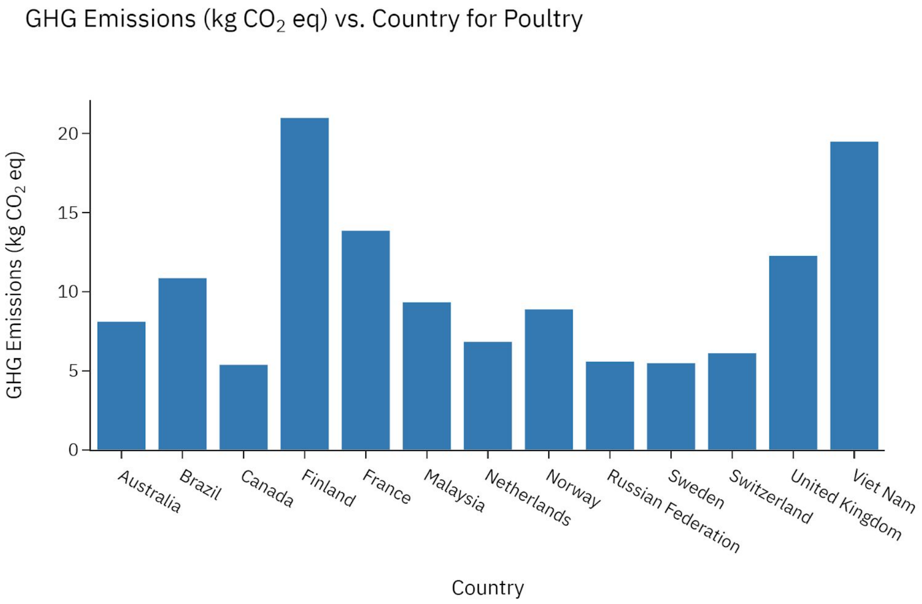

Figure 7.7. GHG emissions, sorted by country of origin. Notably, only Finland and Vietnam break a threshold of 15 kg CO_2 eq. Data from Poore and Nemecek (2018).

The issue of GHG emissions from Vietnam is highly documented, as Vietnam ranks among the 20 countries with the highest GHG emissions in the UNFCCC and FAOSTAT databases.[169] Half of all livestock emissions are due to manure management, and the other half is due to emissions from enteric digestion.[170]

The high GHG emissions from Finland are not as easily explained. The outlying number is reported from one data point.[171] It is likely that this study is an anomaly, since comparable farms in the Nordic countries have much lower GHG emissions, but more research is needed to determine why the emissions were reported to be so high.

Summary and Next Steps

Within the poultry commodity, there seem to be no trade-offs between GHG emissions and the four key environmental indicators: land use, freshwater withdrawal, eutrophication potential, and acidification potential. No correlation was found between GHG emissions and land use, freshwater withdrawal, or eutrophication potential. However, there is a direct relationship between acidification potential and GHG emissions, which likely comes from the feed stage in production. As this is a direct relationship, there is a co-benefit between GHG emissions and acidification potential: if one of these indicators is decreased, the other follows.

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[169] Truong, A. H., Kim, M. T., Nguyen, T. T., Nguyen, N. T., and Nguyen Q. T. (2018). Methane, Nitrous Oxide and Ammonia Emissions from Livestock Farming in the Red River Delta, Vietnam: An Inventory and Projection for 2000–2030. Sustainability 10(10):3826. https://doi.org/10.3390/su10103826

[170] Ibid.

[171] Katajajuuri, J-M., Grönroos, J., Usva, K., Virtanen, Y., Sipilä, I., Venäläinen, E., Kurppa, S., Tanskanen, R., Mattila, T., & Virtanen. H. (2006). Broilerin fileesuikaleiden tuotannon ympäristövaikutukset ja kehittämismahdollisuudet. Maa-ja elintarviketalous. 90, 1-118.

No notable trends were found when this data was organized by the specifications earned by a farm, which is why those corresponding graphs weren't shown. This is in large part due to the fact that there were not enough data points of each type to be able to draw reasonable conclusions. Expanding this data set to include these farm types would allow an exploration of the trade-offs between different specifications earned by a farm. It could even reveal trade-offs between animal welfare, or the quality of product, with environmental factors.

Room for expansion within this project includes expanding the dataset to include more non-chicken entries to provide crucial insight. In Southeast Asia, the traditional rice-fish/rice-duck (RF/RD) farming systems use less chemical fertilizers and pesticides[172] and promote sustainable use of the limited arable land available.[173, 174,175] Inclusion of this data would provide interesting comparisons with the current dataset. Analyzing different systems to understand their unique trade-offs is especially important because the poultry industry must become more efficient to meet demand by 2050,[176] and such an investigation would look into polyculture as a potential way to increase yield and land efficiency.

Seafood

The subcategory of seafood contains three commodities — shrimp, salmon, and tuna — representing very distinct aspects of the seafood industry. The three were chosen for the team's analysis as salmon are representative of farmed fish, shrimp are representative of farmed crustaceans, and wild-caught tuna are representative of wild-caught seafood.

Within this subcategory, common overarching points of interest are centered around the different parts of the supply chain. Special interest is concentrated in the transportation stage, as seafood is often produced in a few geographical regions and exported to consumers worldwide through various methods, including emissions-heavy air-lifting. Trends vary between the specific commodities, but strong direct correlations between GHG emissions and acidification potential exist for all three.

Seafood is often treated separately from other agricultural products, so data availability was often limiting. Unfortunately, comprehensive data on seafood commodities remains comparatively scarce, especially for wild-caught tuna. However, given the huge growth of fisheries and aquaculture— with a 48% increase in capture fishery production and a staggering 1160% increase in aquaculture production

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[172] Zheng, H., Huang, H., Chen, C. et al. (2017). Traditional symbiotic farming technology in China promotes the sustainability of a flooded rice production system. Sustain Sci 12, 155–161. https://doi.org/10.1007/s11625-016-0399-8

[173] Edwards, P., Pullin, R. S. V., and Gartner, J. A. (1988). Research and education for the development of integrated crop-livestock-fish farming systems in the Tropics. International Center for Living Aquatic Resources Management. https://core.ac.uk/download/pdf/6515188.pdf

[174] National Research Council. (1993). Sustainable Agriculture and the Environment in the Humid Tropics. https://www.nap.edu/read/1985/chapter/5

[175] Hughes, A. C. (2017). Understanding the drivers of Southeast Asian biodiversity loss. https://esajournals.onlinelibrary.wiley.com/doi/10.1002/ecs2.1624

[176] FAO. (2011). World Livestock 2011. Livestock in food security. http://www.fao.org/3/i2373e/i2373e.pdf.

worldwide in the past three decades[177]—it is imperative to ensure environmentally safe practices are utilized in this expansion.

Salmon

Outstanding points of concern for salmon aquaculture include an overwhelming amount of emissions generated at the feed stage and inverse cofactor relationships between GHG emissions versus land use and freshwater withdrawal. Such relationships, as well as the lack of relationship between GHG emissions and eutrophication potential, suggests that lowering GHG emissions may come at the cost of other environmental effects.

Overview

Salmon aquaculture, the fastest-growing food production system worldwide[178], is at a crucial stage where understanding its environmental effects is key. As salmon moves onto more and more people's plates, a careful eye on responsible production methods is needed in order to curb its environmental footprint. Despite its importance, however, there is a lack of available data on aquaculture systems outside of GHG emissions, which impacts our ability to make conclusions with solid statistical significance.

Analysis Methods

The AgImpacts team sourced salmon data from Poore and Nemecek (2018), Ayer (2009), Parker (2017), and Pelletier (2009). All data was standardized to the functional unit of 1 kilogram of retail weight, with the conversion factor of 60% from live weight to retail.[179] Life cycle assessment methods were also cross-checked for consistency among sources and adjusted accordingly, using the method outlined within Pelletier (2009). Scope was left untouched, but units were converted in one instance from kilograms of nitrogen equivalents to kilograms of phosphate equivalents by a factor of 0.42.[180] In total, 34 data points were utilized, with only 15 points containing data other than GHG emissions. The data spans six countries (Australia, Canada, Chile, France, Norway, and the United Kingdom) and six broad system types (floating bag, flow-through, net pen, recirculating, sea cages, and solid wall aquaculture systems).

Environmental Impacts of Salmon

A starting area of interest for us was the eutrophying emissions released by the specific fish farms. At a glance, we hypothesized that there would be a strong correlation between GHG emissions and eutrophication potential, inferring that recirculating systems take more energy but release less organic material freely in the environment compared to open-water cages. However, the two seem to not be

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[177] Food and Agriculture Organization of the United Nations. 2020. "Fisheries and Aquaculture - Statistics." Food and Agriculture Organization of the United Nations. http://www.fao.org/fishery/statistics/en.

[178] McNevin, Aaron. n.d. "Farmed Salmon." World Wildlife Fund. Accessed January, 2021. https://www.worldwildlife.org/industries/farmed-salmon#:~:text=Salmon%20aquaculture%20is%20the%20fastest,US%2C%20Europe%2C%20and%20Japan.

[179] Marine Harvest. 2015. Salmon Farming Industry Handbook 2015. Bergen, Norway: n.p. http://www.aquacase.org/other_information/docs/2015-salmon-industry-handbook.pdf.

[180] GHK and BIO Intelligence Services. 2006. "Annex 5 Environmental Impacts Analysed And Characterisation Factors." In A Study to Examine the Costs and Benefits of the ELV Directive – Final Report. Brussels: European Commission.

correlated at all (Figure 8.1a), yet it is true that recirculating systems produce lower eutrophying emissions than net pen or cage systems (Figure 8.1b).

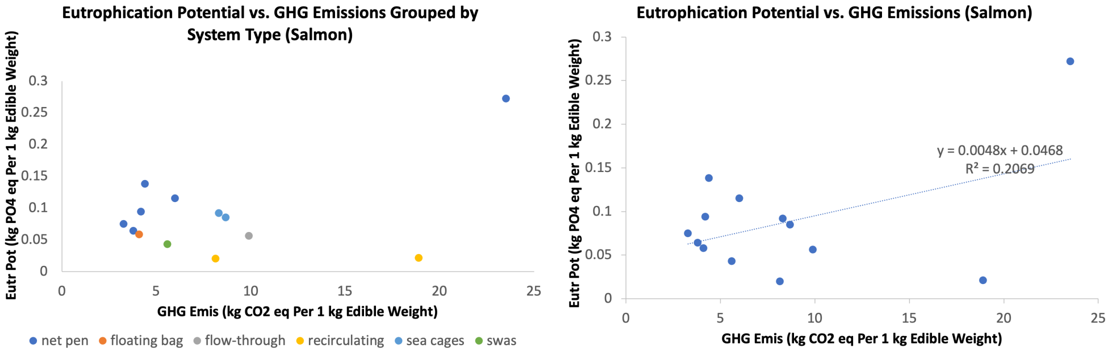
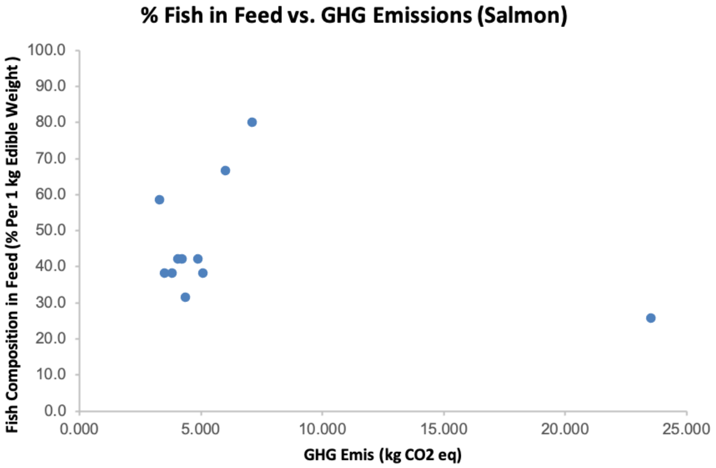


Figure 8.1. GHG emissions vs eutrophication potential , first clustered by farm type (left) and second with a linear regression on the full dataset (right). Data from Poore and Nemecek (2018), Ayer (2009), Parker (2017), and Pelletier (2009).

A possible reason for the lack of correlation lies in the overwhelmingly large amounts of GHG emissions at the feed stage — dwarfing the variations of the different production systems.[181] Unfortunately, tracing feed impacts is difficult as inputs vary and arrive from a plethora of sources, often by-products of other commodity processing. Emissions factors for minor ingredients are often lacking, and the composition of feed changes rapidly. Note that when different allocation methods are applied, the importance of animal source foods to the total impact may change.



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[181] Parker, R. Implications of high animal by-product feed inputs in life cycle assessments of farmed Atlantic salmon. Int J Life Cycle Assess 23, 982–994 (2018). https://doi.org/10.1007/s11367-017-1340-9

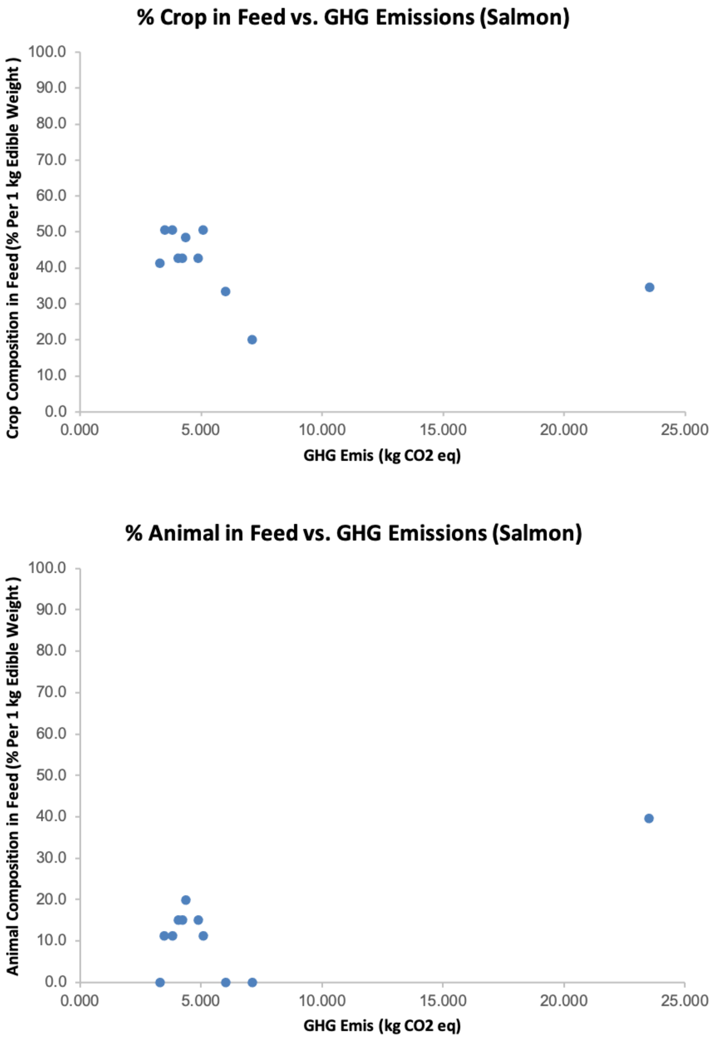

Figure 8.2. GHG Emissions vs various feed composition ratios. Emissions allocated by energy. Data from Parker (2017).

When analyzing feed composition ratios of crop, fish, and (non-fish) animal products against GHG emissions, we find that while total GHG emissions have little correlation with the feed composition (Figure 8.2). While animal source components may have high embedded GHG emissions, other non-animal source components of feed, like soy, may also have relatively high emissions intensity.

Less data exists on land use and freshwater withdrawal, but with existing points we see a potential inverse relationship (Figure 8.3). However, the points displayed actually fall in an extremely small range of GHG emissions, so further data would be needed before any conclusions can be made.

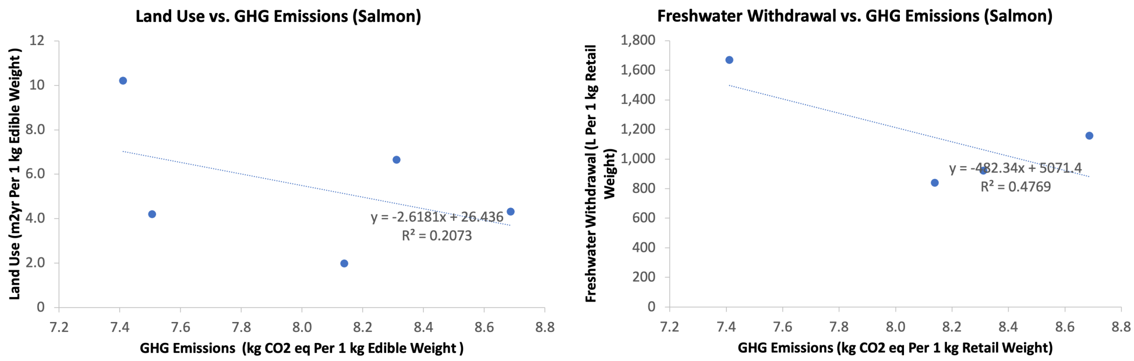

Figure 8.3. GHG emissions vs land use and freshwater withdrawal. Data from Poore and Nemecek (2018).

Perhaps a more interesting comparison is that of median salmon land use (4.3 m^2yr per kg edible weight) against median land use of primary feed ingredients soy (3.6 m^2yr per kg edible weight) and maize (2.3 m^2yr per kg edible weight). Given the context of the plant commodities' large land use range, it can be assumed a significantly large amount of the land use in salmon aquaculture is simply inherited through the feed stage; given that salmon have a relatively efficient feed conversion ratio, it makes sense these numbers are similar. In contrast, we find a large difference in values when comparing median salmon freshwater withdrawal (1038 L per kg edible weight) against median freshwater withdrawal of soy (6.1 L per kg edible weight) and maize (0.0 L per kg edible weight), suggesting that freshwater withdrawal arises mostly at the farm stage and is not passed on from feed.

It is also important to note that the above observations on land use and freshwater withdrawal may vary based on farm type— the systems represented in Figure 8.3 include only sea cage and recirculating for freshwater withdrawal, with one additional floating bag system in land use. More data is needed to confirm these deductions and move forward with assessing impacts at each part of the salmon life cycle.

In terms of acidification potential, there is a quite strong direct correlation between acidification potential and GHG emissions while no visual clustering of system types are seen (8.4). Such a relationship is a good indicator that lowering GHG emissions works in tandem with lowering acidification potential.

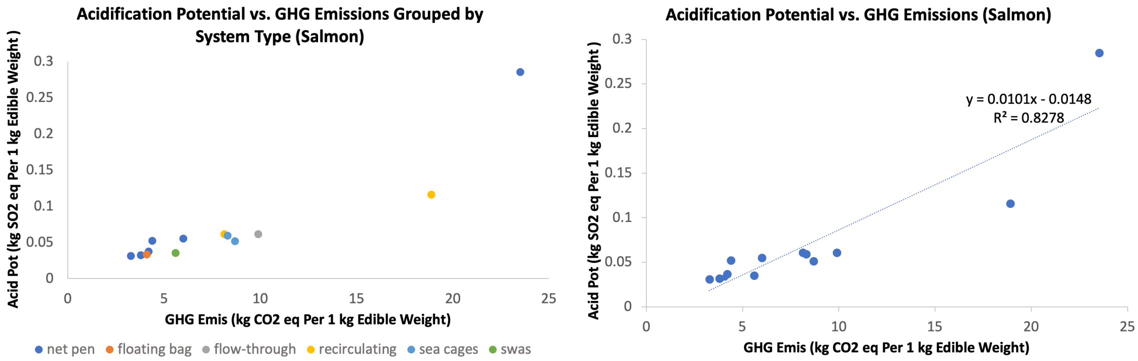

Figure 8.4. GHG Emis. vs Acid Pot, first clustered by farm type and second with a linear regression on the full dataset. Data from Poore and Nemecek (2018), Ayer (2009), Parker (2017), and Pelletier (2009).

Conclusion and Moving Forward

Overall, points for improvement surface overwhelmingly in the feed stage, especially in the inclusion of animal by-products. However, concerns about waste arise in the efficiency of shifting these compositions as much of salmon feed is made of by-products of other commodities — in the case of animal byproducts, poultry by-product, blood, and hydrolyzed feather meals are commonly used — and thus are already "produced" and ratios often are adjusted based on by-product availability.[182] Further concerns arise as shifting towards a crop-based diet may increase the amount of feed needed, possibly inflating impacts.

Thus, our next steps include looking further into the feasibility of changing feed compositions and more research on salmon feed, as well as further research into the more concerning initial data that suggests a potential inverse relationship of GHG emissions versus land use and freshwater withdrawal. Aggregation of more data points outside of solely GHG emission levels is also high priority in order to allow us to further explore and confirm trends observed.

Shrimp

For shrimp aquaculture, there appear to be direct linear relationships between all environmental indicator pairs excluding GHG emissions and land use. Thus, decreasing GHG emissions is unlikely to have trade-offs, and is likely to have environmental co-benefits. Variations in the performance of farms with certain system and water types suggest that cultivating less freshwater shrimp species and increasing intensity of production could lead to lower overall emissions.

Overview

Over 70% of global shrimp consumption is attributed to developed countries. Japan, the United States, and Europe lead with the highest rates of per capita consumption.[183] However, according to a 2019 report, China and Thailand are the leading producers worldwide, accounting for nearly 3/4 of production.[184] As the demand for these crustaceans is centered in countries with less shrimp production, the product is often exported before reaching consumers.

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[182] Food and Agriculture Organization of the United Nations. 2021. "Atlantic salmon - Feed Production." Aquaculture Feed and Fertilizer Resources Information System. http://www.fao.org/fishery/affris/species-profiles/atlantic-salmon/feed-production/en/.

[183] "World Shrimp Market Situation and Outlook." n.d. Food and Agriculture Organization of the United Nations. Accessed January 30, 2021. http://www.fao.org/3/ac058e/AC058E04.htm#:~:text=While%20almost%20three%2Dquarters%20of,EEC%20countries%20(0.5%20kg).

[184] Mordor Intelligence. 2021. *Shrimp Market - Growth, Trends, COVID-19 Impact, and Forecasts (2021 - 2026).* https://www.researchandmarkets.com/reports/5238781/shrimp-market-growth-trends-covid-19-impact?utm_source=GNOM&utm_medium=PressRelease&utm_code=6znzbh&utm_campaign=1264547+-+Shrimp%3a+The+Future+of+the+%2445%2b+Billion+Market%2c+2019+to+2024&utm_exec=joca2.

In fact, as the second-most popular seafood in the United States, shrimp tops the list of the nation's seafood imports along with salmon and tuna, according to a 2018 NOAA report.[185,186] In 2019 alone, the United States imported 698,358 metric tonnes, or approximately 1 billion pounds, of shrimp.[187]

This paper analyzes the environmental impacts of shrimp aquaculture, taking into consideration that over the past three decades, shrimp production has shifted almost entirely from wild-caught to farmed, or aquaculture, systems.[188] The analysis encompasses aquaculture farms across Bangladesh, Brazil, China, the Philippines, Thailand, and Vietnam. It includes five species, two freshwater and three marine: *Macrobrachium rosenbergii*, *Macrobrachium amazonicum*, *Penaeus monodon*, *Litopenaeus vannamei*, and *Fenneropenaeus chinensis*.

Analysis Methods

The AgImpacts team compiled a total of 22 sample points, each of which represents either a single farm or a group of farms in the same geographical region with similar methods. All data sources are available in the AgImpacts Web Tool. For further analysis, we classified each farm by system type—polyculture, extensive, semi-intensive, or intensive. We defined polyculture systems as farms that produce two or more seafood commodities within the same aquaculture system, then categorized the remaining farms as either extensive, semi-intensive, or intensive depending on their inputs, treatments, and outputs, as defined in the Aquaculture Production Intensity Scale (APIS).[189]

Mangrove ponds are not considered polyculture systems in this analysis. The team chose to exclude data from shrimp ponds built in mangrove forests because the data from such systems were extreme in comparison to that of the polyculture, extensive, semi-intensive, and intensive systems due to the negative environmental impacts of mangrove deforestation and inconsistent estimates of pond methane emissions.

For shrimp specifically, we color-coded the graphs by country, system type, water type, and species. The graphs color-coded by country are displayed below. The functional unit for this data is 1 kilogram of edible weight or retail weight.

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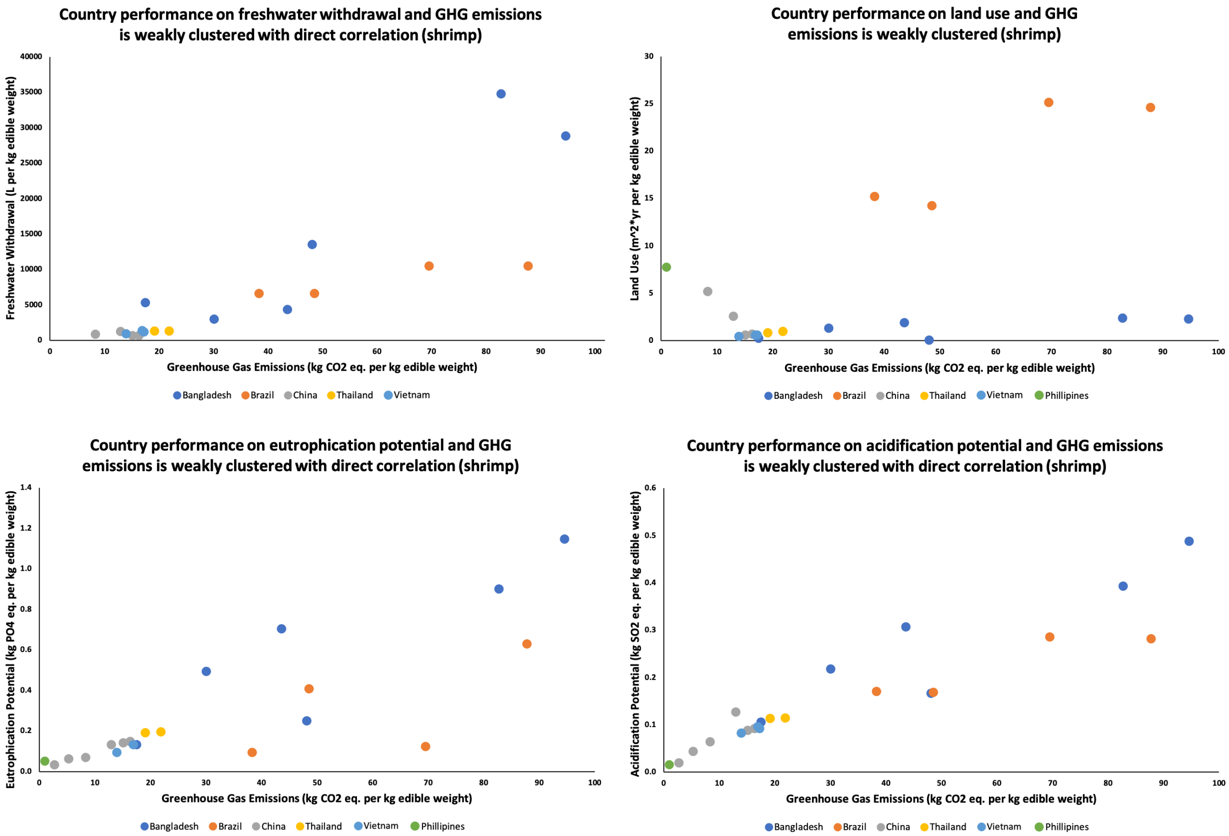
[185] Love, David C., Frank Asche, Zach Conrad, Ruth Young, Jamie Harding, Elizabeth M. Nussbaumer, Andrew L. Thorne-Lyman, and Roni Neff. 2020. "Food Sources and Expenditures for Seafood in the United States." Nutrients 12, no. 6 (June): 1810. https://doi.org/10.3390/nu12061810.

[186] National Oceanic and Atmospheric Administration. 2018. "American seafood industry steadily increases its footprint: New report also shows consistently high landings, value for U.S. fisheries." National Oceanic and Atmospheric Administration. https://www.noaa.gov/media-release/american-seafood-industry-steadily-increases-its-footprint.

[187] National Oceanic and Atmospheric Administration Fisheries. n.d. "U.S. Imports of Shrimp (All Types) by Country With Comparisons." National Oceanic and Atmospheric Administration Fisheries. Accessed January 30, 2021. https://www.st.nmfs.noaa.gov/apex/f?p=169:2.

[188] Shamshak, Gina L., James L. Anderson, Frank Asche, Taryn Garlock, and David C. Love. 2019. "U.S. seafood consumption." Journal of the World Aquaculture Society, (May). https://doi.org/10.1111/jwas.12619.

[189] Oddsson, Guðmundur V. 2020. "A Definition of Aquaculture Intensity Based on Production Functions—The Aquaculture Production Intensity Scale (APIS)." *Water* 12, no. 3 (March): 765. https://doi.org/10.3390/w12030765.


Country performance on freshwater withdrawal and GHG emissions is weakly clustered with direct correlation (shrimp)

Country performance on land use and GHG emissions is weakly clustered (shrimp)

Country performance on eutrophication potential and GHG emissions is weakly clustered with direct correlation (shrimp)

Country performance on acidification potential and GHG emissions is weakly clustered with direct correlation (shrimp)

Figure 9.1. GHG emissions compared to freshwater withdrawal, land use, acidification potential, and eutrophication potential, for shrimp aquaculture, color-coded by country. Data from Poore and Nemecek (2018), Cao et al. (2011), and Aubin et al. (2014)

Despite the commodity's popularity, there is significantly less available data on its environmental impacts in comparison to the other nine commodities in this study. Although there is insufficient data to make any statistically significant conclusions, visualizations seem to suggest relationships among the indicators, as well as clear differences in environmental impacts among countries, system types, and species (Figures 9.1, 9.2, 9.3).

Data Analysis

Our analysis suggests direct positive relationships between all indicator pairs aside from GHG emissions and land use (Figure 9.1). In fact, after further analysis, it became clear that all indicators except for land use vary directly with each other. Interestingly, the points that do not lie in a direct linear relationship in the GHG emissions versus land use graph are all from aquaculture farms in Bangladesh. Although the farms in Bangladesh represent the highest GHG emissions, freshwater withdrawal, eutrophication potential, and acidification potential within this dataset, it seems that land use stays relatively low, regardless of the magnitude of other environmental impacts.

However, it is possible that the trend described above is influenced by the system types represented by the farms in Bangladesh: extensive and polyculture. For every pair of impacts, the extensive systems are on the more extreme end of the spectrum, the intensive systems are clumped near the origin, and the semi-intensive and polyculture systems are spread out throughout the range (Figure 9.2). As the data from Bangladesh represents extensive and polyculture farms, it is possible that the independence of land use only stands true for certain system types.

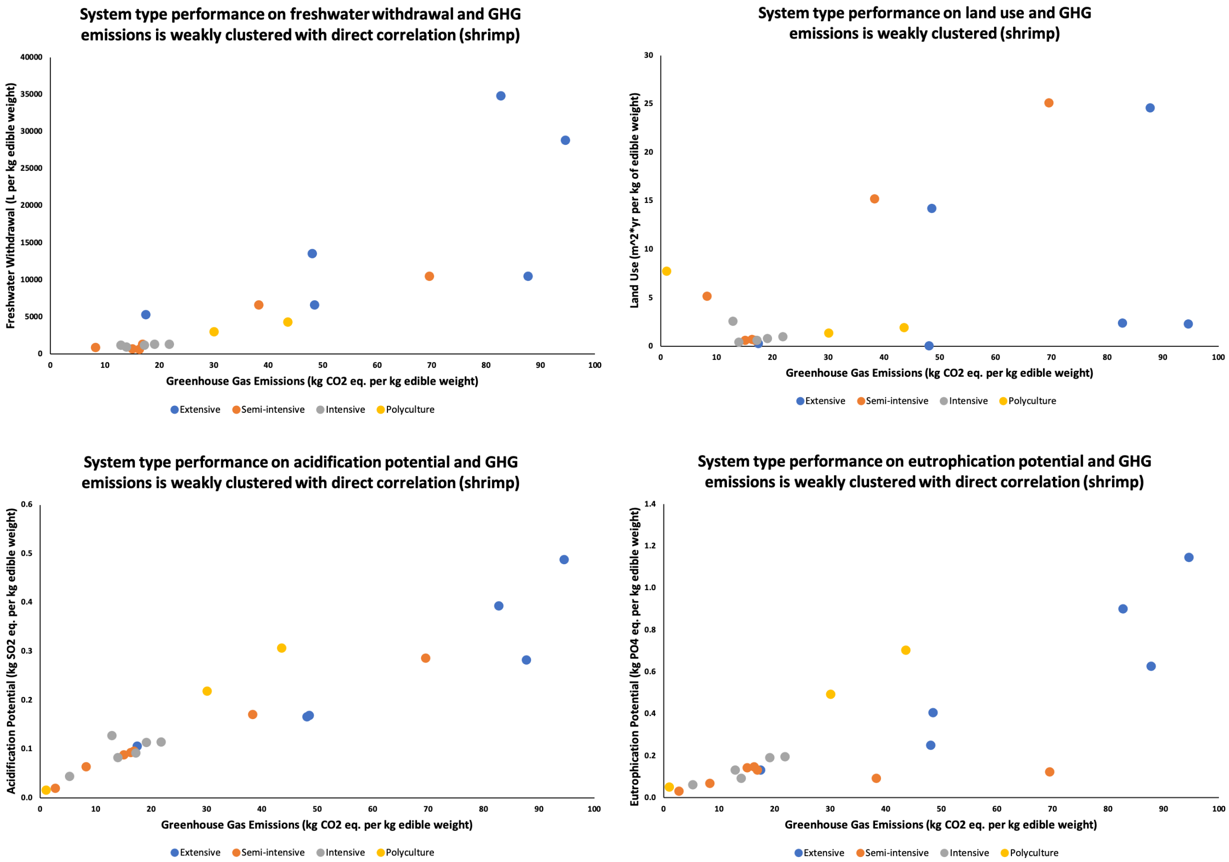


Figure 9.2. GHG emissions compared to freshwater withdrawal, land use, acidification potential, and eutrophication potential for shrimp aquaculture, color-coded by system type. Data from Poore and Nemecek (2018), Cao et al. (2011), and Aubin et al. (2014)

In discussing the relationship of land use to the other four indicators, it is also worthwhile to observe the data from China. The land use data for farms in China appears to be inversely, rather than directly, correlated with the other environmental indicators. Further investigation and data collection would be necessary to determine whether land use is actually independent of the other four key environmental impacts.

Lastly, we analyzed the data based on water type to search for relationships between freshwater and marine systems. The water type of an aquaculture system is typically determined by shrimp species. Of the species included in this project, two are freshwater species (*Macrobrachium rosenbergii* and *Macrobrachium amazonicum*) and three are marine species (*Penaeus monodon*, *Litopenaeus vannamei*, and *Fenneropenaeus chinensis*). The freshwater systems consistently showed the most extreme values in all five indicators (Figure 9.3). However, it is necessary to note that the team was unable to find any data on intensive freshwater farms. Therefore, it is unclear whether this trend is related to system types, lower water salinity, available farming technologies in various countries, or a difference in necessary maintenance between freshwater and marine species.

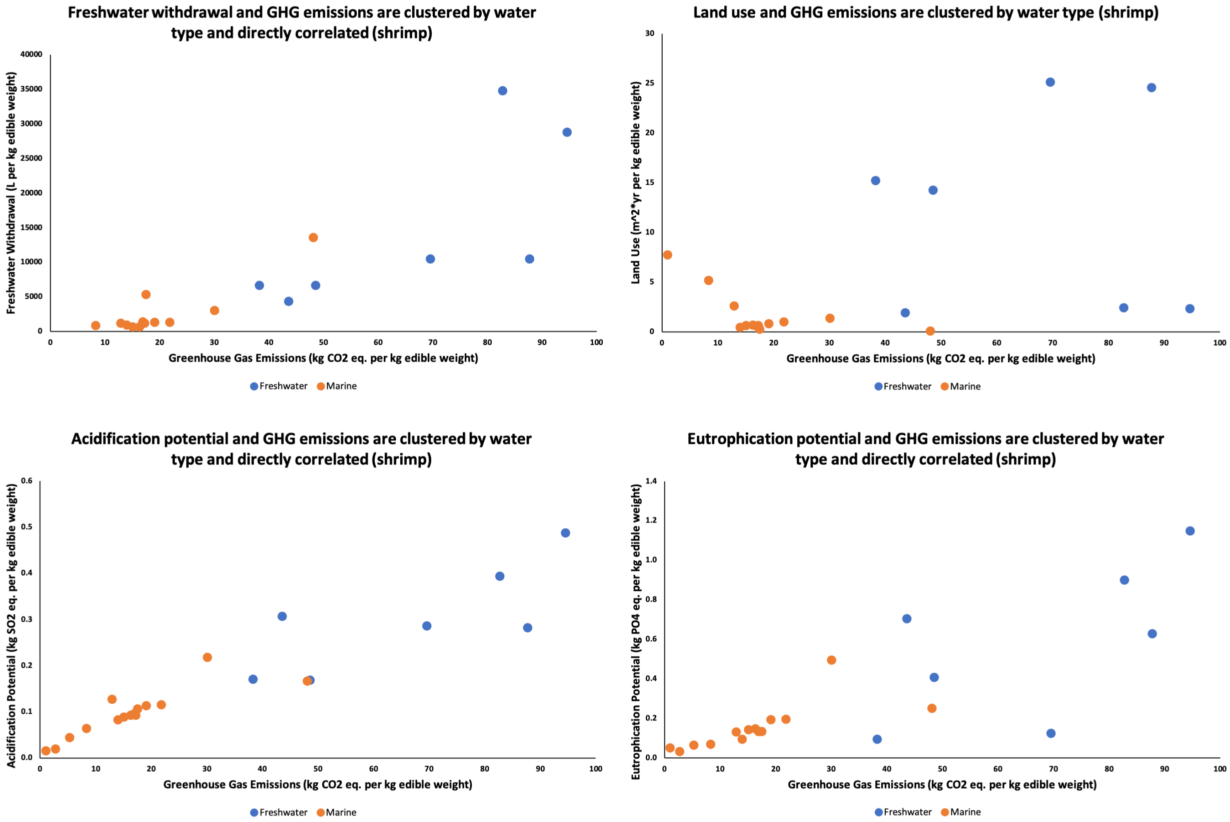


Figure 9.3. GHG emissions compared to freshwater withdrawal, land use, acidification potential, and eutrophication potential, for shrimp aquaculture, color-coded by freshwater versus marine species. Data from Poore and Nemecek (2018), Cao et al. (2011), and Aubin et al. (2014)

Environmental Impacts in Perspective

In comparison to the other nine commodities analyzed in this paper, shrimp aquaculture has high, if not the highest, environmental impacts for freshwater withdrawal, eutrophication potential, and acidification potential. In addition, while the land use required for shrimp production is relatively low, levels of GHG emissions are the second highest of all the commodities, second only to beef. We also saw the strongest relationships among environmental impacts, suggesting that for shrimp, intensification tends to improve environmental performance.

Indeed, there are physical explanations for these environmental indicators. The disparity between freshwater withdrawal and land use is perhaps the most intuitive, as shrimp aquaculture, by nature, requires less land and more water than crops or livestock. As for GHGs, a significant source of emissions could be due to transportation. However, data from Poore and Nemecek (2018) suggests the farm stage contributes most significantly to overall GHG emissions. This is most likely due to maintenance of the shrimp ponds, which, as detailed in the APIS, could entail lighting, temperature control, effluent processing, or solid waste processing, all of which require energy use.[190] In extensive systems, emissions

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[190] Ibid.

can come both from land-use change or from emissions of N_2O and methane from ponds. Higher levels of eutrophication potential could be due to the aforementioned effluents and solid waste produced by the shrimp. Additional research would be necessary to identify key sources of acidification.

Unlike the commodity analysis for salmon, there was little to no available data on emissions at the feed stage for shrimp aquaculture. Only 6 of the 22 compiled data points include itemized information on feed; by definition, the extensive systems were unfed, creating a large degree of heterogeneity. Considering the APIS criteria for system classification, higher environmental impacts due to feed would be expected for intensive and semi-intensive farms. However, of the 6 data points in question, only 1 represented an intensive system, 3 represented semi-intensive systems, and 2 represented extensive systems. From this distribution, we assumed that the feed stage had negligible impact on our shrimp aquaculture analysis.

Conclusion

Further research is needed before any concrete suggestions can be made regarding methods for improving the negative environmental impacts of the shrimp aquaculture industry as a whole. However, decreasing the cultivation of freshwater shrimp species and increasing the intensity of farms could reduce the environmental impacts of production. Considering the large volume of shrimp imported into Japan, the United States, and Europe annually, future research with more detailed data could involve inspection of environmental impacts from each stage in the supply chain. Moreover, analyses could conduct deeper investigation into the relationship of land use with the remaining indicators, as explained above.

In searching for methods to decrease the environmental impacts of shrimp aquaculture and the broader seafood industry, it is also critical to look beyond the four farming systems analyzed in this project. For example, producing shrimp in innovative polycultural systems such as aquaponics or regenerative ocean agriculture could not only decrease necessary inputs and treatments, but also reduce emissions related to importation. A multifaceted approach of improving existing farming systems while increasing the availability of new methods could significantly lower the negative environmental impacts of shrimp production.

Tuna

The emissions associated with wild-caught tuna vary based on fishing, transportation, and processing methods, as well as by fishery size and location. Across all methods, greenhouse gas emissions appear directly correlated to acidification and eutrophication potential, as all three emissions arise largely from fuel use during processing and transport. Purse seining is the most widely used fishing method, and has the lowest emissions and fuel use intensity; these fleets are, however, unable to catch large, higher quality tuna. This shortcoming allows longline fisheries and other fishing methods to persist, despite causing greater environmental impacts. Within the tuna industry, markets like canned tuna versus sushi-grade fish should be evaluated distinctly.

Overview

Within this project, the study of tuna was restricted to wild catch, causing it to differ greatly from each of the other commodities. Emissions and land use associated with the growing stage are not relevant to wild-caught tuna, and instead, the processing and distribution stages became the primary areas of focus.

Tuna Market and Fishery Characteristics

Tuna fisheries are concentrated in Asia and the Americas, with catches in Asia exceeding one million tonnes in 2010, but consumption does not occur in the same locations where tuna are caught.[191] Tuna represented 8% of global fish exports in 2010, and transportation between distant fisheries, processing plants, and consumer markets accounts for a large portion of the emissions attributed to the tuna industry.[192] One study reports that fuel use by industrial fishing vessels typically accounts for 60 to 90% of life cycle GHG emissions of seafood supply chains, and tuna fisheries are particularly notable for high fuel use intensity.[193,194]

Information from the United Nations Food and Agriculture Organization (FAO)'s database, FishStatJ, provides total quantities of tuna products exported, imported, processed, or re-exported within various geographic classifications. This data demonstrates that in 2018, about 51% of global tuna products were transported through Asia, while only 17% occurred in Europe and another 16% in the Americas.[195] This provides insight into the uneven distribution of tuna fisheries, processing plants, and consumers across the globe.

The same dataset also shows that in 2018, about 58% of global tuna products were transported frozen, about 40% were preserved and the remaining 2% were chilled or live.[196] Processing methods and the usage of refrigeration in transport of tuna products should be further studied to evaluate their contribution to emissions and fuel use intensity. This is particularly important because the majority of tuna exports and imports occur frozen, and the use of refrigeration can significantly contribute to higher emissions.

Data Collection Methods

Current ecolabelling systems for tuna focus primarily on sustainability of tuna stock and on the direct impacts of fisheries on their surrounding ecosystems, as seen through bycatch and dolphin-safe labels. This project examines a different set of environmental impacts: the indirect emissions that fall further

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[191] FAO Fisheries and Aquaculture. n.d. "Online Query Panels." Food and Agriculture Organization of the United Nations. http://www.fao.org/fishery/topic/16140/en.

[192] Parker, Robert W., Ian Vázquez-Rowe, and Peter H. Tyedmers. 2014. "Fuel performance and carbon footprint of the global purse seine tuna fleet." *Journal of Cleaner Production*, (May), 1-8. https://www.sciencedirect.com/science/article/pii/S0959652614004776?via%3Dihub.

[193] Parker, Robert W., Ian Vázquez-Rowe, and Peter H. Tyedmers. 2014. "Fuel performance and carbon footprint of the global purse seine tuna fleet." *Journal of Cleaner Production*, (May), 1-8. https://www.sciencedirect.com/science/article/pii/S0959652614004776?via%3Dihub.

[194] Tyedmers, Peter, and Robert Parker. 2012. "Fuel Consumption and Greenhouse Gas Emissions from Global Tuna Fisheries: A preliminary assessment." *ISSF Technical Report*, (March). https://iss-foundation.org/download-monitor-demo/download-info/issf-technical-report-2012-03-fuel-consumption-and-greenhouse-gas-emissions-from-global-tuna-fisheries-a-preliminary-assessment/.

[195] FAO. 2020. "Global Fisheries commodities production and trade 1976-2018 (FishstatJ)." Fishery and Aquaculture Statistics. http://www.fao.org/fishery/statistics/software/fishstatj/en

[196] Ibid.

along the supply chain, and are rarely tracked. The lack of life cycle assessments (LCAs) of wild-caught tuna became apparent throughout the process of data collection, as the vast majority of extant research looks solely at GHG emissions. This meant that trends for environmental indicators like acidification and eutrophication potential had to be determined from a small set of data, producing potential room for error.

We compiled data from ten individual LCA studies of the tuna industry, with each study taking into account similar stages of fishing, processing, packaging, and distribution. All data was standardized using a functional unit of one kilogram of edible weight. The environmental impacts studied for wild-caught tuna were GHG emissions (kg CO_2 eq), acidification potential (kg SO_2 eq), eutrophication potential (kg PO_4 eq), freshwater withdrawal (L), human toxicity and marine ecotoxicity potential (kg 1,4-DCB eq), and photochemical oxidant formation (kg NMVOC). Of these, GHG emissions, acidification potential, and eutrophication potential had the most available information and data, while freshwater withdrawal was covered in only one of the studies.

In studying the environmental impact factors, data points were categorized based on ocean of capture, country, species, gear type, and product type. The vast majority of data studied purse seine fisheries, but various other gear types, including longline, troll, and fish aggregating device fisheries were also analyzed. This data availability appears to correspond to the tuna industry's capture trends in 2010, in which purse seine fisheries represented the vast majority of tuna catch.[197] For this project, "gear type" is synonymous with "fishing method." Both industrial and small scale fisheries are represented in the dataset, and fishery locations include Europe, Asia, the Americas, and Oceania.

GHG Emissions

A first set of anomaly graphs was produced to examine the GHG emissions value calculated by various LCAs (Figures 10.1 and 10.2). To create these graphs, the average GHG emissions value was calculated for the entire dataset, then the difference between each point and the average was taken. A negative value indicates that the GHG emissions were lower than the average, while a positive value indicates GHG emissions greater than the average. Figure 10.2 displays the same set of data, but all of the values within each fishing method were averaged to produce one bar per fishing method.

The majority of purse seine fisheries produced lower GHG emissions than the average (Figure 10.1). Longline fisheries appear to have the highest GHG emissions, but among the 15 longline fishery data points, there is one high outlier point. Pole and line, large pump, and small pump fisheries also all fall above the average, while fish aggregating device and spear fisheries tend to produce lower GHG emissions. The averages within each fishing method demonstrate clearly that purse seine, fish aggregating device, and spear fisheries appear to be the best performers (Figure 10.2).

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[197] FAO Fisheries and Aquaculture. n.d. "Online Query Panels." Food and Agriculture Organization of the United Nations. http://www.fao.org/fishery/topic/16140/en.

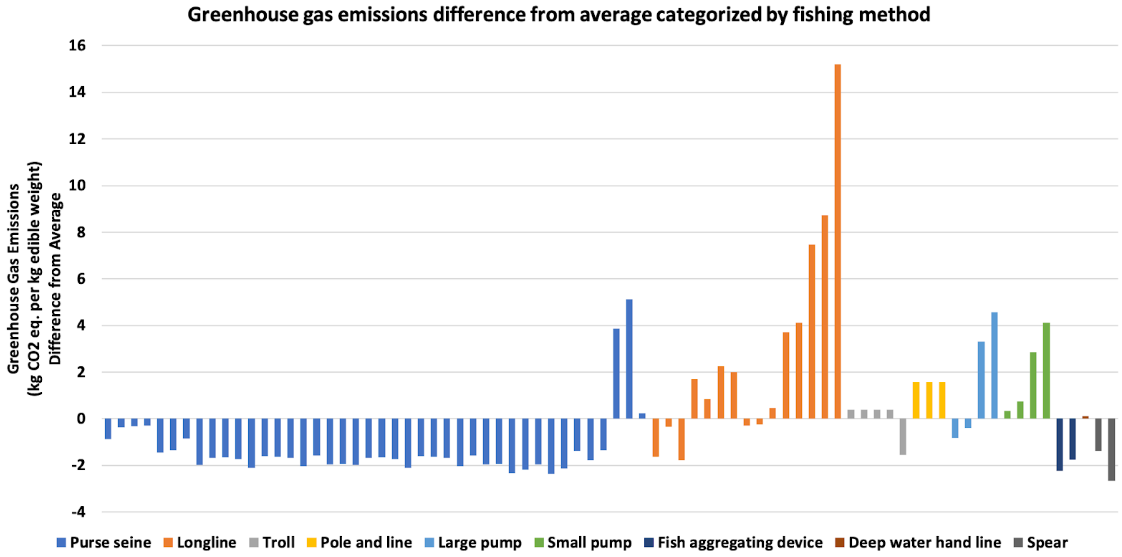

Figure 10.1. Distribution of GHG emissions difference from average, color coded by fishing method. Data from Avadí et al. (2015), Hillborn et al. (2006), Hospido et al. (2006), Hospido and Tyedmers (2005), Minami et al. (2004), Parker et al. (2014), Poovarodom et al. (2011), Tan and Culaba (2009), Tyedmers and Parker (2012), Wilson and McCoy (2009).

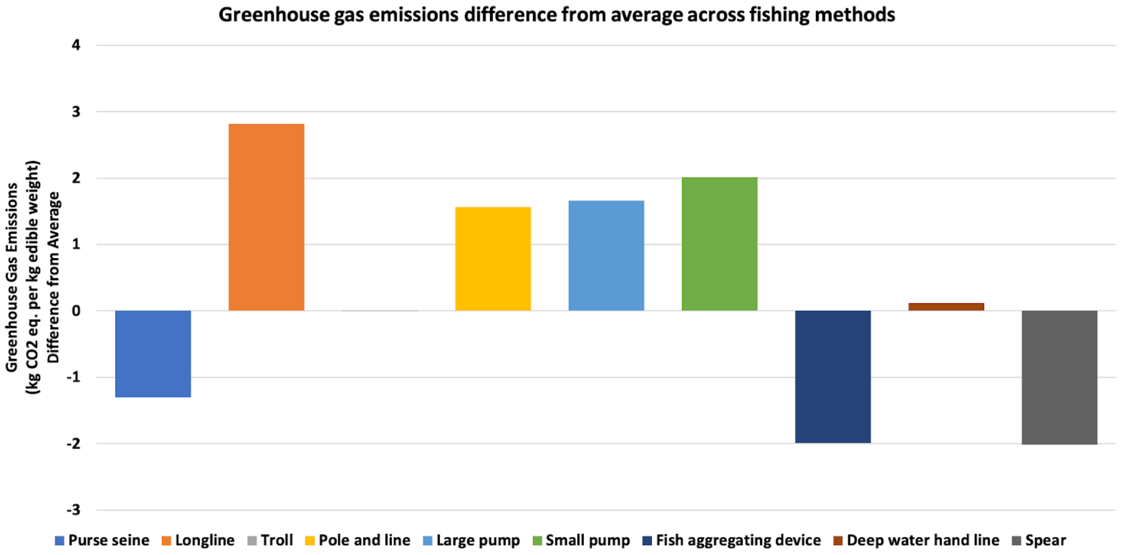

Figure 10.2. GHG emissions difference from average by fishing method for tuna. Data from Avadí et al. (2015), Hillborn et al. (2006), Hospido et al. (2006), Hospido and Tyedmers (2005), Minami et al. (2004), Parker et al. (2014), Poovarodom et al. (2011), Tan and Culaba (2009), Tyedmers and Parker (2012), Wilson and McCoy (2009).

This information is particularly fascinating because of the prominence of purse seine fisheries in the tuna industry. The FAO reports that in recent years, there has been an increase in the proportion of tuna caught by purse seine fleets relative to longline or pole and line fleets.[198] The International Seafood Sustainability Foundation (ISSF) explains that purse seine fisheries account for about 66% of annual global tuna catch, and that purse seine vessels typically consume about 368 liters of fuel per tonne of tuna landings.[199] In contrast, longline fisheries are responsible for roughly 10% of global tuna catch and consume approximately 1,070 liters of fuel per tonne of landings, while pole and line fisheries consume 1,485 liters and troll fisheries consume 1,107 liters.[200] These numbers do not directly correspond to the GHG emissions values found from compiling LCAs, but they do clearly relay that increased fuel consumption corresponds to increased GHG emissions.

With such high fuel efficiency for purse seine fisheries in comparison to other gear types, the question arises regarding why other methods of fishing are still used. The Organization for the Promotion of Responsible Tuna Fisheries (OPRT) explains that purse seine fleets catch relatively inexpensive, young, smaller tuna, which can be used in canned tuna products, whereas longline fisheries are responsible for higher quality, larger fish.[201] Although an approach which solely values GHG emissions reduction might favor a complete transition to purse seiners, longline fleets are important due to their higher quality of catch, as well as their lower rate of capture.[202] Longline fisheries also catch tuna at critical size, where fish can most sustainably be captured, whereas purse seine fisheries tend to catch tuna that are younger and smaller.[203] The case study of purse seine versus longline fisheries provides insight into the complex factors that must be taken into account when seeking sustainable forms of agriculture. Evaluating and making decisions based on only one indicator, such as GHG emissions, appears straightforward but can result in drastic consequences.

Covariance of Environmental Indicators

A second set of graphs demonstrates the relationships between GHG emissions, acidification potential, and eutrophication potential (Figures 10.3, 10.4, 10.5). These three graphs include acidification potential versus GHG emissions, eutrophication potential versus GHG emissions, and eutrophication versus acidification potential.

Within each of the three graphs, there is one significant outlier, which represents data from smaller longline fisheries in Japan. This point includes higher emission values for each of the three environmental impacts, but does follow the same linear trendline demonstrated by the other points, and is therefore included on the graphs. The reasons for this outlier should be further investigated, but might simply arise from a lack of data, which could have otherwise filled in the gap between the lower and higher values.

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[198] Gillett, Robert. 2007. "A SHORT HISTORY OF INDUSTRIAL FISHING IN THE PACIFIC ISLANDS." *FAO: The Asia and Pacific Plant Protection Commission (APPPC)*. http://www.fao.org/3/ai001e/ai001e00.htm#Contents.

[199] International Seafood Sustainability Foundation. n.d. "Fishing Methods: An Overview." ISSF. https://iss-foundation.org/about-tuna/fishing-methods/.

[200] Ibid.

[201] Organization for the Promotion of Responsible Tuna Fisheries. 2004. "Longline or Purse seine?" OPRT. http://oprt.or.jp/eng/dr-miyakes-tuna-chat/longline-or-purse-seine/.

[202] Ibid.

[203] Organization for the Promotion of Responsible Tuna Fisheries. 2004. "Longline or Purse seine?" OPRT. http://oprt.or.jp/eng/dr-miyakes-tuna-chat/longline-or-purse-seine/.

Each of the graphs demonstrates direct or linear correlation, with r^2 values greater than 0.9; note that these datasets comprise only a few data points, but these relationships also make sense based on our physical understanding of the system. This means that higher acidification potential generally corresponded to higher GHG emissions, higher eutrophication potential corresponded to higher GHG emissions, and higher acidification potential corresponded to higher eutrophication potential for the LCA studies included. Fishing and processing methods which seek to decrease one environmental impact would thus be capable of simultaneously decreasing various other emissions.

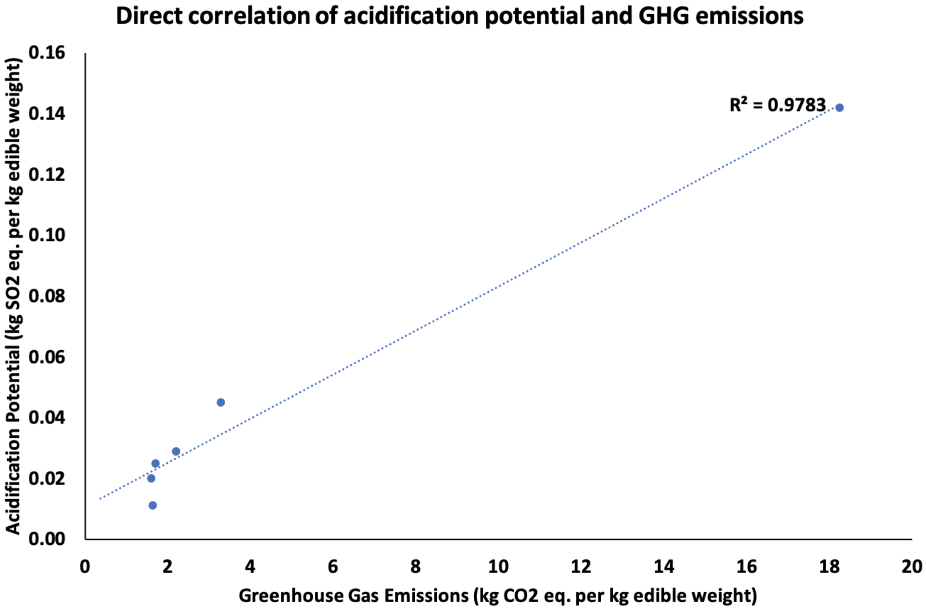

Figure 10.3. Correlation between acidification potential and GHG emissions of tuna fisheries. Data from Avadí et al. (2015), Hillborn et al. (2018), Hospido et al. (2006), Hospido and Tyedmers (2005), Minami et al. (2004).

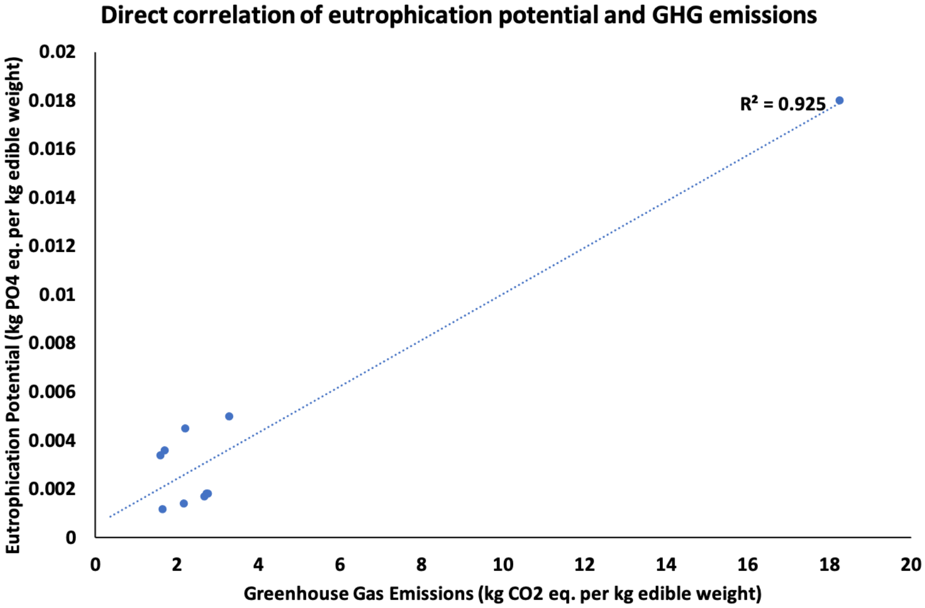

Figure 10.4. Correlation between eutrophication potential and GHG emissions of tuna fisheries. Data from Avadí et al. (2015), Hillborn et al. (2018), Hospido et al. (2006), Hospido and Tyedmers (2005), Minami et al. (2004).

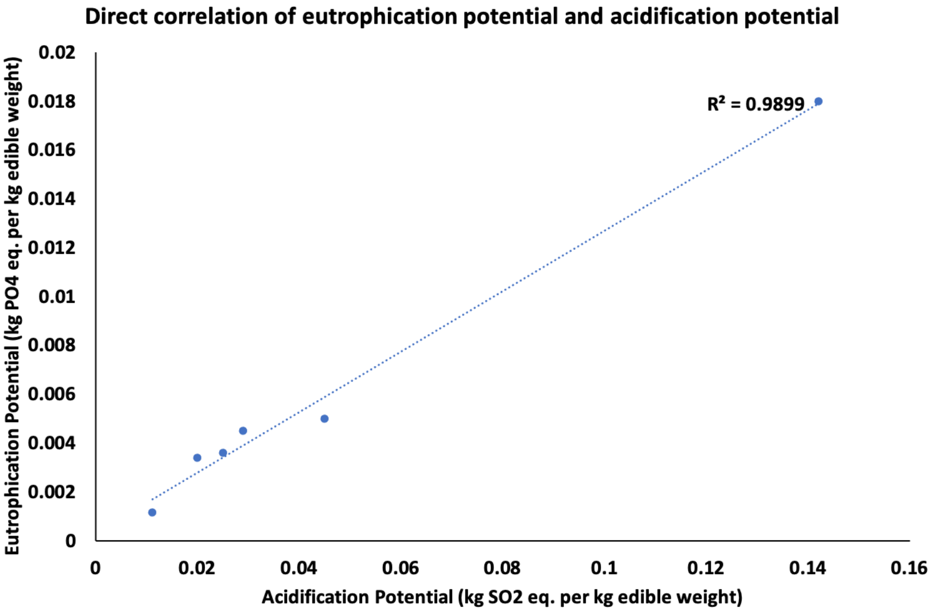

Figure 10.5. Correlation between eutrophication potential and acidification potential of tuna fisheries. Data from Avadí et al. (2015), Hillborn et al. (2018), Hospido et al. (2006), Hospido and Tyedmers (2005), Minami et al. (2004).

The linear relationship between the three environmental impacts is logical because GHG emissions, acidification potential, and eutrophication potential all generally arise from similar stages in the tuna supply chain. The study of Japanese longline fisheries demonstrates that all three emissions arise from "fishing" and "processing and sale," as opposed to "transportation" or "consumption."[204] It is important to distinguish here that "transportation" refers only to transport of the fully processed goods, whereas all transportation involved in the fishing process falls under the "fishing" category. Within the context of this study, it can be concluded that fishing vessels are responsible for a vast majority of the fuel use, and also are responsible for the majority of emissions. Another study explains that all three emissions categories are driven primarily by marine transport and diesel use, while a third LCA similarly shows that emissions primarily occur during processing and distribution.[205,206]

Within the wild-caught tuna industry, the bulk of emissions are created due to fishing vessels and their fuel use. The transportation of catch towards processing sites, as well as the outputs from processing plants contribute greatly towards emissions, and efforts to ameliorate environmental impacts should focus on the pursuit of greater fuel efficiency or renewable energy usage.

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[204] Minami, Wataru, Kunihiro Yasui, Katsuyuki Nakano, and Hee-Joon Kim. 2004. "Life Cycle Inventory of Air Pollutants for Consumption of Tuna." *Nippon Suisan Gakkaishi* 70, no. 4 (January): 548-554. https://www.jstage.jst.go.jp/article/suisan/70/4/70_4_548/_article.

[205] Hospido, Almudena, and Peter Tyedmers. 2005. "Life cycle environmental impacts of Spanish tuna fisheries." *Fisheries Research*, no. 76 (May), 174-186. https://www.sciencedirect.com/science/article/abs/pii/S016578360500175X.

[206] Hospido, A., M.E. Vazquez, A. Cuevas, G. Feijoo, and M.T. Moreira. 2006. "Environmental assessment of canned tuna manufacture with a life-cycle perspective." *Resources, Conservation and Recycling*, no. 47 (January), 56-72. https://www.sciencedirect.com/science/article/pii/S0921344905001515.

Finally, future research in the field should be done to evaluate whether emissions patterns are consistent across various fishing methods, locations, and product types. The tuna industry is large in magnitude and extremely diverse, and efforts to reduce the environmental impacts of tuna fisheries must embrace this innate diversity, seeking to adopt sustainable practices and make changes based on local needs and abilities.

Conclusion

In conclusion, no particular trends stand out as a commonality between all commodities—rather, trend groupings are more apparent at the commodity subgroup level. Notably, rather than inverse relationships suggesting direct trade-offs, we find that for many commodities, there exists a lack of a relationship at all between environmental indicators. This suggests that although optimization towards GHG emissions may not come at the expense of most indicators (in a broad sense), it likewise does not account for all necessary cofactor reductions. Generalizations are difficult to make as each commodity has different inputs, processes, and outputs, but the consensus is that a multifaceted approach to environmental indicator optimization is key.

A broader trend commonly found during our research, however, was the better performance of intensive systems in terms of environmental impact compared to extensive. For animal production, this raises perhaps not a research question but an ethical question of animal welfare—how does one go about defining animal welfare, much less decide the point at which this moral trade-off should occur?

Generally, an important plan of action moving forward is simply gathering more data, as some commodities lack the data points to have strong statistical significance. In particular, the seafood subcategory had a distinct lack of data to analyze, possibly due to its non-terrestrial nature. In addition, data and further analysis in specific parts of the supply chain rather than simply overall is critical, especially for the stages of feed and transportation. With such insight, efforts to streamline the life cycle of all commodities to have the least environmental impact can be utilized in a targeted and efficient way.

Most importantly, we must recognize that environmental action is permeated with nuance—as clearly seen here, a GHG reduction-only approach fails to account for many other crucial factors. In navigating each unique route to preserving the environment, we must keep our eyes on the larger picture of the entire biosphere and its complicated and codependent machinations. **We rarely found that reducing GHG emissions resulted in a consistent increase in another impact, but also rarely did it come with a corresponding improvement, suggesting that management moving forward must explicitly consider multiple environmental impacts.**

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Appendix

Personal Reflections

Max J. Burns

Prior to working on this ELO, I had no experience with any project of this scale, or with data examination in general. When we began working in the fall, it was the first time that I had even opened an Excel spreadsheet! This has been an *excellent* way to learn more about environmental science through hands-on work, I now feel that I have a far better grasp of what exactly work in this field entails; both in terms of how to find trends in data, and how to effectively present those trends to a reader. This project has also significantly improved my understanding of agricultural production systems in general, especially for beef, my commodity. I was peripherally aware of the wasteful nature of cattle from courses in high school, but I now feel that I have a far better understanding of the problems associated with beef production. I've gained more than just an insight into the global impacts of cattle farming, I have also learned details about the local consequences of beef production that directly impact communities. In future discussions about agriculture and the associated pollution, I feel prepared to explain *why* cattle are wasteful, supported by what I have learned and worked on in the past months.

But I've learned about far more than just data visualization and agriculture, this project has also been a great way to gain experience working with a team. We've found how to best utilize our individual strengths and experience, by dividing tasks properly and helping each other however we can. Our team has also grown into more than just a group of students working on a project, over the past few months we developed strong friendships, and a great sense of community. And all the while, we have been supported by our two incredible mentors, Emily and Gabi. This project seemed daunting and even overwhelming at times, but our mentors have always been there to guide us, and to help us develop our work into a final product. Anytime that we needed help with something, or were confused by a strange trend, they were both just a message away, which really helped this ELO become the fantastic learning experience that it was. Overall, I'm incredibly thankful that I had the opportunity to work on this project, and feel prepared (and excited!) to pursue similar work in the future.

Anushree Chaudhuri

Since I hadn't done much sustainability-related research in high school, I was excited to gain a set of like-minded peers at MIT and insight from experts in the field going into this project. This project was a valuable way to test my abilities in independent learning, time management, and prioritization.

I've never thought of myself as a "coder," so initially I was intimidated by the prospect of creating a feature-rich, interactive web app to visualize our data. I remember feeling overwhelmed after the first twenty-or-so hours reading through extensive Python and Streamlit documentation, understanding the basics of HTML and CSS, and taking a few command line courses. Initially, every time I would run into a bug, I became frustrated that even after looking through dozens of Stack Overflow threads, I wasn't able to figure out how to fix the issue. After recruiting the help of a more experienced friend and developing a systematic, logical, and patient approach to debugging, I started feeling more confident and calm in catching errors. It took me an embarrassingly long time—more than 100 hours—to finally create a working version of the tool. I recognize that this is much longer than it would have taken any “real” coder, but the experience taught me the importance of persistence, even when persisting is the most frustrating thing to do, and ultimately made me realize that I am capable of starting out from scratch and continuing to an end product in an area that I have no background in.

I’ve always regretted not spending more time on learning programming, because it is so useful regardless of what field you’re in. At the same time, I’ve always avoided taking on programming classes and projects because I fear failure in an environment where everyone else is more experienced than I am. This experience made me realize the importance of data visualization in environmental and policy work, which is what I hope to pursue in the future. Thanks to this project, I’m planning to take 6.859 (Interactive Data Visualization) next semester, and aspiring to change my tendency of shying away from data science classes within my potential considerations for technical majors: environmental engineering, materials science and engineering, and economics.

I’m so grateful to have gained a wonderful network of friends through this project and the Terrascope learning community. As I’ve gotten to know my peers better, I am constantly so impressed and inspired by their compassion, curiosity, genuineness, dedication, and supportiveness. They’re truly some of the best people I’ve met at MIT so far. I’m excited for road trips to corn fields in a post-COVID future and to see many familiar faces in sustainability-related classes and clubs in the next three years.

Yeji Cho

Last summer, this project team and I met online, through channels created for our Terrascope first-year learning community. We were all incredibly excited to enter the world of opportunities at MIT, and when we received an email about the chance to design our own ELO, this group coalesced through countless Zoom calls. At the beginning of this project, I think that we were somehow both under- and over-ambitious, creating grandiose proposals, but still a little doubtful that any of this would come to fruition. One of the most rewarding aspects of this project has been watching it grow into something very tangible and impactful, alongside the experience of producing work we did not even know we were capable of.

Prior to entering MIT, my research experience focused on very small-scale projects, both literally and figuratively. I studied individual species of microalgae, and carried out projects where I was responsible for every stage of the research. Participating in a larger project like this one was an entirely new experience for me. The scope of our research, covering global agricultural systems across ten different commodities, was already beyond any work I could have done alone, and the data collection, analysis, and writing that followed was just as intensive. Similarly, I also had to adapt to working with data that I had not collected. Producing cohesive outputs from the research of dozens of scientists across the world involved a whole new set of challenges, and I deeply enjoyed the learning that accompanied it. The design of this project allowed me to gain an overarching understanding of agricultural supply chains, then to dig deeper into the specific characteristics of the wild-caught tuna industry, where I could draw more unique and interesting conclusions.

Beyond the understanding of agricultural systems gained through this project, I feel that I have learned an incredible amount about the diversity of sustainability efforts. Environmental issues are a truly global problem, and as someone deeply passionate about this field, I think it can be easy to get stuck in one way of thinking. This project drastically opened my eyes to the interconnectedness of global systems—a fisherman in Japan might catch tuna that is shipped miles inland, then transported across the world to Europe or the Americas, and so on and so forth. I learned that sustainability also looks different in different places. The most fuel efficient fishing vessel in the Americas might not compare to the methods of local, small-scale fishers elsewhere, and this sort of diversity needs to be embraced in order to have a successful global push for sustainability. I hope to use what I have learned in this project as I continue my study of environmental and earth science, and to continue to keep an open mind about new ideas and innovation.

Finally, I would like to thank Emily, Gabi, and each of my teammates, for all of their incredible contributions to this project. It has been amazing to be a part of such a smart and capable group of people, and I look forward to continuing my work with them in the future.

Nicole E. Harris

Prior to this project, had I been told that I would spend the better part of late 2020/early 2021 doing data analysis, and *enjoying* it, I would have become fearful at how bad the pandemic would get. To me, data analysis always represented a boring necessity that people who liked tweaking algorithms or organizing Excel spreadsheets revelled in. It just wasn't my cup of tea.

I have no background in applied statistics, and barely any knowledge on the agriculture industry. In fact, my prior experience with farming was limited to watching my uncle rotate his cows through different pastures, walking next to them and occasionally using a cattle prod. I had no knowledge of the extent of large-scale farms, what made them efficient, or that they affected the environment outside of GHG emissions and water usage. Oh, how that has changed. I can now confidently talk about intensive poultry farms, the details of Label Rouge certifications, and the inter-relatedness of all of the environmental indicators we covered.

This ELO has been an amazing experience. I learned the obvious skills one would expect from a data analysis job: understanding what an R^2 value means, looking for meaningful trends, and delving into the studies for relevant context and data. I've also gained unexpected skills. I now know how to condense information into varying lengths, since we wrote up a scientific paper (long and detailed), a website (short but informative), gave a presentation (time sensitive but very detailed), and typed up a paragraph summary of our findings. I've also learned how to work on a team, virtually. The collaboration needed for a project this size is immense, and I was able to appreciate team dynamics like leaning on each other for help, or ramping up the work in the event that someone couldn't contribute for a specific week.

In addition to my wonderful teammates, I want to thank Dr. Emily Moberg and Dr. Gabriela Serrato-Marks for being our mentors on this project. They provided amazing support, both moral and technical. I have no idea where we'd be without Emily's feedback, which helped direct us to start looking at specific commodities, or Gabi's workshop on Excel. Their patience was unmatched as they continued to meet with us and push our work to exceed our own expectations, and they even used their networks to bring in colleagues for feedback. Thank you both, so much. You've helped me grow as a junior analyst, and as a team member. You both are wonderful mentors and I'm so glad I had the opportunity to work with you.

Remi O. Harrison

Being able to work on a project like this has been a dream come true for me; I've been interested in sustainability—or "saving the earth," as I put it back then—since I was a child, but I never got the chance to do much beyond, say, recycling and reducing water use. Unlike many of my teammates, I did have a bit of experience with data visualization and statistics before joining this project; however, I didn't know very much about how and why agriculture could have a negative impact on the environment, and I was excited to learn. In figuring out what the different environmental factors meant and how they translated to actual consequences, I learned a lot about the delicate balance of our environment. We hear a lot about "greenhouse gases," "climate change," and occasionally "deforestation," but rarely do things like "eutrophication" make the news. It was also striking to me that coffee production in certain regions was also in danger due to climate change. While it makes sense, it was interesting to see that even though economic reasons and practicality are touted as reasons not to switch to sustainable practices en masse, these arguments break down in the long run.

In addition to learning about agriculture sustainability, I also learned a lot about working on a team; gone are the days of group projects where only one person does all the work—we all needed to do our part here. Even though working on this project together virtually was difficult, we overcame the pitfalls of Zoom calls together, and I imagine that the connections we formed will only strengthen when we get on campus.

Of course, I could never end this without giving a big thank you to Dr. Emily Moberg for giving us a sense of direction and being willing to take us under her wing for this project, and Dr. Gabi Serrato-Marks for her masterclass on Excel; while I conducted most of my analysis in Python, I still needed to consult the spreadsheet regularly, and that Zoom meeting where she taught us all the ins-and-outs of the software helped immensely.

Sydney Paige Kim

Last week, I opened my freezer and picked up a bag of shrimp. I scanned the packaging for production information—were the shrimp extensively or intensively farmed? Were they from China or Brazil? Then, I thought about how manufacturing the plastic packaging involved burning fossil fuels, and how it was likely destined to be dumped into the ocean and harm marine organisms.

When our team first started this project, I would not have thought to consider the environmental impacts of food. Actually, I never paid enough attention to the climate crisis itself to feel more than mildly concerned. I was raised to be conscious of my energy and water use, but this project, in combination with a class I took about the biodiversity crisis this semester, forced me to open my eyes and see just how much we abuse our planet. For years, I dreamed of working in the aerospace industry, but after just one semester studying agricultural acidification, reading IPCC reports, and scrolling through NASA heat maps, my worldview has completely changed. Really, I can no longer justify using my education to launch people and objects off the surface of the Earth when the planet itself is burning.

I started this project with no prior research experience, but with Emily and Gabi's support and patience, I learned how to use Excel, analyze data, and communicate my findings. I am also incredibly grateful for my teammates. As a group, we are scattered across the country, but we have managed to collaborate, support each other, have fun together, and build friendships despite the distance. Through this project, I feel that I have grown so much, as a researcher, person, scientist, and global citizen and am so grateful to have had this experience.

Katherine LiYue Pan

Much like my fellow peers, I came into this project as a blank slate in terms of research — my only experience with data analysis was a rusty recollection of tenth grade AP Statistics. Excel was a foreign concept to me, as was the intricate methodologies of the agricultural sector. Though I felt I knew more than the average person about environmental efforts given my past interests and involvement in conservation, I quickly learned in the first stages of my research that there was even more to the difficult balance of environmentalism than meets the eye.

Throughout the process of this project, I've not only explored and mastered the above skills, but also learned the ropes of working in a group environment despite being physically thousands of miles apart. Our research project's journey was a bit unlike most traditional first-time research experiences, I'd say, as it was mostly student-led and self-designed from the beginning. Such a hands-on approach really opened my eyes to the interconnectivity of global agriculture — as I chased down different data points to understand the process better, I learned how almost everything in this world affects each other, be it individual cofactors within a commodity's production, or how different commodity impacts trickle into other commodities through vehicles like feed.

As well as gaining insight on educational topics, I've found myself a wonderful community to both work and play together with as well. I extend my eternal thanks to Yeji for sending the first message looking for ELO teammates when I was too shy to do it myself — on that day she catalyzed the formation of a team that spends contentful nights both poring over data and papers together as well as planning a cross-country cornfield expedition during much-needed breaks. They all are the best people I could have ever asked to meet (perhaps not yet in person, but after spending so much time together on Zoom, I'd argue that it's the same experience).

Of course, we couldn't have done this without our amazing mentors Dr. Moberg and Dr. Serrato-Marks — they've done a spectacular job of letting us grow under our own leadership but guiding us in creating a product we could all be proud of. After all, I'd probably still be floundering about in the abundance of new technologies and skills if it weren't for Dr. Serrato-Marks teaching me to "excel at Excel" or Dr. Moberg answering every question I emailed her at 2AM asking about strange points in my data clearly and promptly. For this, I'd like to thank them immensely. I've grown so much as not only an analyst, but as a writer, environmentalist, and scientist under their care — and I firmly believe all of our teammates will say the same.

Evan Seeyave

Before joining the team to work on this ELO, I had worked on some projects in the past, but they were all much smaller in scope. I had used Excel before, but I only knew the very basics. For this project, I processed data using Pandas, Numpy, and Matplotlib, Python libraries that I was unfamiliar with before. I have learned a lot about manipulating data and data visualization. I did not and still do not have a very strong environmental science background, so this project has been a fantastic way for me to learn more about environmental indicators and the impacts of agriculture on the environment. In particular, I have learned a lot about palm oil. I have always heard from time to time about palm oil contributing to GHG emissions and in some way impacting the environment, but I never understood how. After researching previous findings and creating some of my own work, I feel much more knowledgeable about the impacts of palm oil on the Earth's environment. Presenting the information that I have found has helped me to further reinforce what I have learned. I also have learned a lot about all the other commodities from my fantastic peers.

I am really thankful for all my teammates who have all supported me and have supported each other. I am glad to have worked with this team, and I think we have been able to work well with our different skill sets and strengths. In addition, I have been able to create great friendships with all my groupmates. I am also extremely grateful for our mentors, Emily and Gabi. They have helped us through this entire project and have dedicated so much time meeting with us, providing advice and guidance always. Our project would not have been the way it is now without them.

One thing I didn't realize was how difficult writing a research paper actually is, especially in teams. Before MIT, I had written papers before, but they were all guided and had a clear goal and direction to take. This was much more open-ended, so there were different approaches we could take. It was a great experience conducting real-world research, and I am excited to work on more projects like this in the future. This project has been a lot of fun, and it has also been fulfilling. Doing research for the WWF, an organization I have always looked up to, has really been an honor.

Daniel L. Tong

Stepping into the project was definitely very daunting; from the first day on the Discord channel, hearing all of the people talk about possible ideas, my imposter syndrome kicked into overdrive. But fast forward

7 months, 46 custom Discord emotes, and probably way too many “Cattle are wasteful” jokes later, the project is still daunting but at least I had some friends to tackle it with.

The project was definitely a memorable experience. I have always tried to involve myself with environmental activities, but the extent of it was either participating in or organizing community service events with friends (or convincing them to go vegan with me as a competition). It was exhilarating to be in a researching position for the first time but again, I have low self esteem so I was also anxious for the first few months until the team got more comfortable with each other (greatly in part to 12.000). I could talk about the satisfaction of finally learning how to use Excel or finally having the puzzle pieces in my head click when trying to interpret the data sheet, but those experiences don’t even begin to compare to the teamwork aspect of the project. The post-meeting zoom calls where we decompress from whatever practical project-related discussions we had were filled with some of my favorite moments of the whole semester and spawned some of the best inside jokes we have together. Listening to rants about how difficult research on a certain commodity is transforming into a completely unrelated topic, followed by everyone else jumping in with their own tangents was just one of the many lovely moments.

But truly, I am extremely grateful that I got to have this experience to understand the environmental impacts of the agriculture industry more. It fueled my desire to pursue a career like this even more and helped me get a taste of what that career would be like. I cannot stress enough how thankful I am to Emily and Gabi for bearing through the semester (and a little extra time) with us, and making this project something worthwhile. It absolutely was not possible for us to make something even comparable to this without their help, and I will always attribute my start in the field to their help. Also, my fight-or-flight response triggers when I pass by edamame in the supermarket.

Daniela L. Vallejo

The opportunity to work on this project has truly changed my perception of the commodities in my life. I had some prior knowledge of the impacts of agriculture on the planet, but particularly in the case of roundwood, because it is inedible I hadn’t quite thought of it as an agricultural product. Now as I look around my room, I realize that everything from books, to the desk, to the framing of the house itself is a product of roundwood silviculture. Similarly, I had no prior awareness of the significance of the eutrophication or acidification potential footprint of any of the commodities in my life. In this manner, exploring the relationship between our five environmental indicators has helped me to develop a more well rounded understanding of sustainability. I am now more skeptical of oversimplification in environmentalism and feel better equipped to advocate for sustainability in the future.

The process of searching the literature for data has also been a very illuminating experience. The lack of certain data in particular led me to realize just how many areas across scientific disciplines are in need of further research. This was particularly surprising when considering how the impact of particular subject matters may not always relate to the availability of research on the topic. I will keep these things in mind as my career develops.

On a more personal note, this project has facilitated the formation of friendships during a time when interpersonal connections are difficult to create and maintain. The passion and commitment of my teammates has been a great source of inspiration. I am particularly grateful for the guidance and mentorship of Emily and Gabi, without whom this project would not have been possible. The amount of time they have devoted to meeting with us and reviewing our work has enabled us all to thrive.

Emily Moberg (Mentor)

The students who produced this work self-organized the summer before their freshman year at MIT — virtually because of the Covid pandemic. They knew they wanted to contribute to a problem that mattered, and identified the environmental impacts of agriculture as a critical area for the future of both food security and ecosystem health.

They co-developed the scope of this project with me over the course of several months and then they dived into their research. They researched what palm oil, shrimp, roundwood production systems were, what the supply-chains looked like. They researched what the environmental impacts from agriculture are, asking questions like "are CO2 emissions *really* comparable to methane emissions?" that the scientific community is grappling with as well. They worked to extract data, standardize it, and make graphs in programming languages they were learning alongside this project. They wrote pages of text explaining what they did and, more critically, what it means for conservation action.

And they did all of this as they tackled their first semester in college.

The work they did is impressive in its breadth and thoroughness. It is fascinating and insightful, and I have learned so much from this team and their work. I am proud to have worked with every single one of this talented, creative team.

And I believe that if these students are the future for our planet, it is a bright future indeed.