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An Economic- and Environmental Assessment of Ground Beef in Response to the Introduction of Plant-Based Meat Alternatives in the United States

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An Economic- and Environmental Assessment of Ground Beef in Response to the Introduction of Plant-Based Meat Alternatives in the United States

By

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DISSERTATION

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Dedication

For Mom and Dad, who have never wavered in their faith in my abilities.

For Trixie and Boots, their unconditional love was the support system that kept me going.

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While the completion of this dissertation is the final milestone in my completion of my PhD, it and all of the steps along the way have by no means been a solitary effort. It truly takes a village, or in my case the city of Davis and beyond, to accomplish what has been achieved over the past six years.

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Table of Contents

List of Tables

List of Figures

Abstract

Cattle production and meat consumption have long been criticized for their environmental impacts and contribution to climate change. In the United States, this has led to increased research into way to mitigate environmental impacts from cattle production as well as alternative foods to replace beef and its associated impacts. The goal of the present dissertation was to review current literature related to the environmental impacts of cattle and meat alternatives and to present research related to mitigating emissions from cattle production as well as research into the comparative impacts of both beef and plant based meat alternatives.

Chapter one presents a review of current literature on the sustainability of beef in meat alternatives. This literature review covers three primary areas of environmental impacts that are most prevalent in the literature on environmental impacts of cattle: climate change, land use, and water use. Further discussed are the nuances that accompany evaluation of these impacts from cattle production. Environmental impacts of plant based meat alternatives (MA) are then discussed with a particular focus on Beyond Burger (BB) and Impossible Burger (IB), the two most prevalent MA in the US due to their similar taste and textural profiles compared to ground beef (GB).

Chapter two investigates a novel feed additive aimed at promoting environmental stewardship while maintaining or improving the efficiency of cattle production. Selective β modulator (lubabegron; **LUB**), recently approved by the United States Food and Drug Administration (**FDA**) to be fed to feedlot cattle during the last 14 to 91 d of the feeding period, was evaluated clinical efficacy for reductions in gaseous emissions/kg of final BW or HCW when different doses of LUB were fed to feedlot cattle over a 91-d duration. A 4 × 2 factorial arrangement design was utilized with the factors of dose (0.0, 1.25, 5.0 or 20.0 g/ton DM basis) and sex (steers or heifers). Three cycles were conducted (112 animals/cycle) with each dose × sex combination being represented

by a single cattle pen enclosure (**CPE**; 14 animals/CPE) resulting in a total of 168 steers and 168 heifers (BW = 453 ± 34.5 kg). Five gases were evaluated based on CPE concentrations relative to ambient air: NH_3, CH_4, N_2O, H_2S, and CO_2. Lubabegron was shown to reduce emissions of NH_3 while simultaneously increasing the pounds of beef produced, demonstrating that feed additives are a promising tool towards reducing environmental impacts of cattle production.

Chapters three and four aimed to gain a more complete picture of the sustainability of GB compared to BB or IB through two means: (1) first in chapter three, national and international economic impacts of decreasing GB consumption in the US in response to the introduction of BB and IB were investigated; and (2) in chapter four, the widespread US environmental impacts associated with a decrease in GB consumption and corresponding increase in BB and IB consumption in the US were evaluated. Contrary to previous work comparing these products, the present research utilized a methodology which accounts for the complicated national and international supply chains associated with the production of these products beyond their direct inputs.

In chapter three, the Global Trade Analysis Project (GTAP) Model was used to assess the effects of reducing GB consumption in the US on both US and global economies. A 15% reduction in US GB, resulted in rather significant impacts on the US economy. Most notably, national and international consumption behaviors changed which resulted in changes to the structure of world trade. In the US, the reduction in GB consumption resulted in loss of labor (up to 9.9% of labor for the US GB sector and 4.1% for the US cattle sector) as well as substantial reductions in land used for cattle production. Similarly, reductions in labor and land use were observed for the top four countries that the US imports of lean trimmings of GB from (Australia, Canada, Mexico, and New Zealand).

In chapter four, GTAP and the multi-regional input-output database, EXIOBASE, were utilized to perform a macro-life cycle assessment (M-LCA) of GB, BB, and IB. Compared to conventional LCA, this method makes it possible to account for the detailed production systems associated with GB, BB, and IB. When replacing 15% of GB consumption with either BB or IB, environmental impacts were variable. When considering impacts to the GB sector alone, replacement with BB resulted in overall reductions to climate change impacts (i.e., greenhouse gas emissions), land use, water use, and energy use. Meanwhile, replacement with IB resulted in reductions of climate change and land use impacts from the GB sector but had the potential to increase overall water and energy use. When considering the effects of changes in the GB sector on a national scale: Climate change impacts (i.e., greenhouse gas emissions) declined minimally (0.08%), with the new GB sector contributing to 0.66% of national emissions. Land use declined by up to 1.6%, nationally. Meanwhile, water use, and energy use had mixed effects at the national level for both BB and IB, each having the potential to increase national resource use, though by relatively small amounts

When considering the sustainability of these GB compared to BB or IBs, it remains difficult to draw clear conclusions on which product might be superior, but it is clear that BB and IB will not produce the profound positive impacts suggested by their respective companies.

Key words: cattle production, climate change, meat alternatives, sustainability

Chapter 1 Literature Review - Sustainability of beef and meat alternatives

INTRODUCTION

By the year 2030 the world population is projected to increase from 7.7 billion to 8.5 billion people, growing at an average rate of 0.9% per annum (p.a) and requiring the agricultural community to produce enough to feed nearly 70 million additional people every year (OECD/FAO, 2021). While population is expected to grow, natural resources such as land and water will not increase, presenting unprecedented challenges for the agricultural community (Gerber et al., 2013). Population growth is expected to occur primarily in urban areas and in low and middle income regions of the world, with two-thirds of growth occurring in Sub-Saharan Africa, India and the Near East and North Africa (OECD/FAO, 2021; ***Figure 1.1***). Food production will need to increase by 1.2% p.a. to meet the needs of a growing global population (OECD/FAO, 2021). Meat production, in particular, will need to increase by approximately 1.2% p.a. primarily due directly to increases in population, though continued income growth and urbanization in China will be responsible for approximately 33% of increased meat demand (OECD/FAO, 2021). Beef production, specifically, is only projected to increase by 4 Mt in the next decade, with per capital beef consumption in high-income countries declining slightly. This weakening demand for beef in high-income countries is primarily due to concerns about the impacts of cattle production on the environment and dietary recommendations by governments suggesting reduced red meat intake (OECD/FAO, 2021).

In recent years, the environmental impacts of food choices has become a topic of increasing importance among consumers in high-income countries. There has been an observed shift of consumers towards vegetarian and "flexitarian" diets in high-income regions; while small, this shift has resulted in an increase in consumer interest in plant-based meat alternatives (OECD/FAO, 2021). Cattle are criticized due to their perceived large environmental impacts – from belched methane (CH_4) emissions to land used to graze cattle, and the large water requirements associated with production (Eshel et al., 2014; Ripple et al., 2014; Kyriakopoulou et al., 2018; Eisen and Brown, 2021). For these reasons, a growing numbers of consumers believe that beef is not sustainable and that replacement with plant based meat alternatives (MA) will be necessary to combat the effects of meat consumption on the environment. More often than not, when discussing the sustainability of beef, the focus is on environmental impacts and does not take into account other factors of sustainability. Most often, sustainability is defined as including three main pillars: (1) the environment; (2) the economy; and (3) society (Dalampira and Nastis, 2020). For a food to be considered wholly sustainable it must be produced in an environmentally conscientious manner while being beneficial both for the economy and human health (Dalampira and Nastis, 2020). In essence, sustainable food production is a balance, lending itself to tradeoffs and compromise in order to obtain the best outcome. To gain a better understanding of the sustainability of beef compared to meat alternatives, the present review will discuss the current literature surrounding the environmental impacts of beef and MA, providing insight into the trade-offs associated with production of each, and alternate characterization methods, aimed at presenting a more complete picture of the sustainability of each product.

ENVIRONMENTAL IMPACTS AND TRADE-OFFS OF BEEF PRODUCTION

Environmental impacts from beef production can be characterized in a multitude of ways, including use of both direct and indirect measurements. Many governing bodies – such as the United States Department of Agriculture (USDA), the U.S. Environmental Protection Agency (EPA), or the United Nations Food and Agricultural Organization (FAO), to name a few – collect information on direct production and use of resources required to produce commodities like beef. With this data direct environmental impacts can be estimated at national and international scales, accounting for impacts such as greenhouse gas emissions (GHG) or land use associated with cattle production. However, these direct emission data do not account for indirect environmental impacts associated with production of beef – such as GHGs, land or water resources required to grow feed for cattle, or the energy required for transport and processing of both cattle feed and the cattle themselves – and thus do not provide a complete picture of the environmental impacts associated with beef production (Pitesky et al., 2009).

Life cycle assessment (LCA) is a tool commonly used to evaluate both the direct and indirect environmental impacts of beef production, along with other commodities, accounting for raw material acquisition, production and use, and waste management of the product life cycle (ISO, 2006; Finnveden et al., 2009; Pitesky et al., 2009; Muralikrishna and Manickam, 2017). There are two primary types of LCA: attributional and consequential. The attributional LCA accounts for flows of resources, materials, energy, and emissions involved in the life cycle (i.e., production) of a product, utilizing average data for each unit process within the product life cycle (Finnveden et al., 2009; Earles and Halog, 2011). By contrast, consequential LCA models how flows might change as a consequence of an increase or decrease in demand for a product system (Finnveden et al., 2009; Earles and Halog, 2011). Consequential LCA includes unit processes both within and outside of the immediate product system, accounting for of indirectly affected processes through the use of economic data (Earles and Halog, 2011).

Most LCAs surrounding beef production are attributional and characterize environmental impacts from cradle (i.e., raw material extraction) to gate (i.e., a cut-off point prior to waste management). The "gate" for beef LCA is variable across studies but will often end either at the point where cattle are ready for slaughter or at the point where cattle have been processed all the way to packaged cuts of meat ready for transport to retail. Variation in the "gate" for beef production along with variability in the functional unit assigned to the product, such as kg of boneless beef or kg of hot carcass weight (HCW) or live weight (LW), and data sources leads to inherent variability across LCAs. Additionally, trade-offs associated with different environmental impacts determined in LCA are not included in analyses. The following sections outlines the most frequently debated environmental impacts studied with LCA (climate change, land use, and water use) as well as the trade-offs associated with these environmental impacts.

Climate Change

To quantify and compare climate change impacts of various GHG emissions, global warming potential (GWP) values are used. Global warming potential is described as the time-integrated radiative forcing which results from a pulse emission of a given GHG relative to a pulse emission of an equal mass of CO_2 (Myhre et al., 2013). Characterization of GWP in LCA most commonly utilizes emission factors defined by the Intergovernmental Panel on Climate Change (IPCC). Climate change impacts are most commonly evaluated on a 100-year time horizon (GWP_{100}) and are characterized by three primary GHG emissions: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In the most recent Fifth Assessment Report of the IPCC (AR5), these three gasses are assigned GWP_{100} values of 1, 28 (biogenic) or 30 (fossil), and 265, respectively (Myhre et al., 2013), though a large portion of beef LCA utilize IPCC GWP_{100} values from previous reports which can contribute to some of the variation between beef LCA.

Cattles' contribution to climate change is arguably the most researched and most discussed environmental impact associated with beef production (de Vries and de Boer, 2010; de Vries et al., 2015; McClelland et al., 2018). Cattle are ruminant animals that ferment feed in the front chamber of their four-chambered stomach (i.e., the rumen), producing and eructating (i.e., belching) CH_4 as a by-product of their natural digestion process. Production of enteric CH_4 paired with N_2O emissions from cattle manure constitute the bulk of climate change impacts from cattle production (France and Dijkstra, 2005). Depending on how these emissions are quantified (i.e., based on system boundaries and direct vs. indirect emissions) and characterized (i.e., AR5 or earlier IPCC assessments) along with the location and type of production system under review, GHG emissions from cattle can be extremely variable leading to vast differences in the reported climate change impacts of cattle (de Vries et al., 2015).

When considering direct emissions from cattle, beef cattle contribute to 41% of global livestock GHG emissions and or approximately 5.9% of global total GHG emissions (Gerber et al., 2013). However, these values represent global cattle production and do not distinguish between location and production techniques, both of which have substantial effects on emissions. Mitigation of CH_4 emissions by means of improved genetics, feeding efficiency, and feed additives has proven helpful in reducing the climate change impacts from cattle in high-income countries, such as the United States and the European Union plus the United Kingdom, where cattle contribute to 3.4% (2.16% for beef cattle, specifically) and 4.99% of national GHG emissions, respectively (EEA, 2021; EPA, 2021). However, this is not the case in many developing countries around the world. The IPCC estimated emissions in developing countries make up 75% of global GHG emissions for this sector (Herrero et al., 2013). Cattle producers often lack access to these advanced technologies and cattle, as a result, require more resources, produce less beef per unit input (i.e., are less efficient), and emit more overall GHG emissions, rendering them less sustainable and more GHG intensive than their U.S. or EU counterparts (Gerber et al., 2013; Gerber et al., 2015).

When considering beef from the LCA perspective, there are notable differences in characterized GHG emissions. With growing concerns for the climate change impacts of beef production in the US, there have been several LCA assessing US beef, specifically. A cradle-to-grave assessment of a representative US beef production system found climate change impacts of US beef to be 48.4 kg CO_2eq/kg consumed, boneless beef (Asem-Hiablie et al., 2019). A follow-up study of national impacts for beef in the US assessed beef impacts with a regional approach (Rotz et al., 2019). Southwestern US cattle production was found to have the lowest average impacts (20.2 kg CO_2eq/kg CW) while Southeastern US was found to have the highest (28.9 kg CO_2eq/kg CW). Perhaps the most important finding from this regional analysis was that N_2O emissions were most significantly affected by soil type, precipitation, and N fertilizer use while CH_4 emissions were most affected by the lifetime of the animals (i.e., the longer an animal is alive the more CH_4 emitted).

In addition to factors affecting regional climate change impacts from cattle, an important consideration in US cattle production is the use of dairy animals. Calves from dairy production that do not enter the milking herd are placed into beef production, contributing to a notable portion US beef production. Stackhouse-Lawson et al. (2012) compared Angus-beef to Holstein-beef production in California and determined that the latter contributed to 50 to 63% less GHG emissions. Tichenor et al. (2017) reported similar effects when comparing grass-fed cattle to dairy beef production in Northeastern US. When incorporating dairy production into national emissions, dairy important regions in the US were the areas with lowest overall emissions (Rotz et al., 2019). Furthermore, cull cows from dairy production in the US lead to further reductions in emissions from beef production (Rotz et al., 2019). The addition of dairy steers and cull cows into beef production result in reduced impacts for two primary reasons: (1) dairy steers are commonly fed a diet higher in grains and reach slaughter weight faster than beef animals – less time in production directly correlates to reduced lifetime emissions and grain based diets lead to reduced CH_4

emissions during the digestion process; and (2) both dairy steers and cull cows reduce the numbers of beef animals needed, thus diverting a portion of emissions from total beef production.

While dairy animals provide a dual purpose that results in reduced emissions from beef production, another factor that effects emissions in production is that of carbon sequestration (C-seq). This is a component commonly left out of accounting for climate change impacts in beef LCA, but one that has important implications for beef production, and especially for the grass-based systems that have become popular with US consumers. Grass-based systems typically modeled with LCA refer to either grass-fed, characterizing impacts of cattle on grass for the entire production cycle, or grass-finished, which is specific to emissions from the finishing stage of production (Stanley et al., 2018). Depending on the management strategies applied to grass-based cattle production, GHG emissions along with land use and ecosystem biodiversity can be significantly impacted (Oates et al., 2011; de Vries et al., 2015; Rowntree et al., 2016). While mismanaged lands can result in increased GHG emissions from cattle production due to poor quality feeds and increased time to finish for animals, well managed lands can lead to improved C-seq and the potential for substantially reduced GHG for cattle (Rotz et al., 2015).

Utilizing adaptive multi-paddock (AMP) grazing, in which relatively high stocking densities and short grazing intervals are employed, and accounting for C-seq can result in GHG emissions as low as -6.65 kg CO_2eq/kg hot carcass weight (HCW; Stanley et al., 2018). Beyond the C-seq observed in beef finishing system, multispecies pasture rotation (MSPR) – in which cattle along with small ruminants, chickens, swine, and rabbits were moved in various herd combinations across grazing land – has been found to be successful at long term C-seq, with emissions from cattle produced in this system becoming a net sink at -4.4 kg CO_2eq/kg CW. While well managed grazing lands have the potential for C-seq, there is controversy over the sequestration potential in soils and how long benefits may be observed before the soil is C "saturated" (Godde et al., 2020). Under the MSPR system, C-seq increased annually over a 13 year period post-establishment and is expected to continue to do so (though at reduced rates) as long as the land continues to undergo MSPR (Rowntree et al., 2020). Meanwhile, Machmuller et al. (2015) found that after a decade of management-intensive grazing, C-seq occurred at a rate of 8.0 Mg/ha·yr and resulted in increased cation exchange and water holding capacity of soils, indicating that long-term C-seq of well managed lands is possible. Furthermore, Beauchemin et al. (2011) found that after reseeding long standing grazing lands resulting C-seq had the potential to offset emissions from cattle production, rendering a net C sink. While mismanaged lands can results in loss of soil (Xu and Jagadamma, 2018), these works showcase the potential to successfully offset C emissions from cattle production through well managed grazing systems.

A final consideration for emissions from cattle production is that CH_4 is a short lived climate pollutant (SLCP). This means that once emitted, CH_4 remains in the atmosphere approximately 12-years before being oxidized (Collins et al., 2002; Reay et al., 2007). Methane oxidation in the process by which hydroxyl radicals (OH^-) in the atmosphere remove hydrogen (H) from CH_4 until it is eventually converted into one CO_2 and two water (H_2O) molecules (Collins et al., 2002; Allen et al., 2016). This means that with a steady rate of CH_4 emissions, the concentration of CH_4 in the atmosphere also remains steady, neither adding nor reducing climate warming (Cain et al., 2019; Ridoutt, 2021). By contrast, carbon dioxide (CO_2) is a long-lived climate pollutant and remains in the atmosphere for 1,000 years (Cain et al., 2019; Lynch et al., 2020). This means that CO_2, and its warming impacts, accumulate in the atmosphere and any added emissions of CO_2 add to climate warming.

Recent work evaluating the variability between the lifetimes of SLCPs, such as CH_4, and CO_2, has highlighted that the standard metric for evaluating climate change impacts (GWP) may produce misleading results (Lynch et al., 2020; Cain et al., 2021; Smith et al., 2021). Through the use of CO_2-warming equivalents (CO_2we) to characterize CH_4, an alternative application of GWP, GWP-star (GWP*), has been proposed as a means of addressing these differences. The GWP* assesses the temperature response from a change in rate of CH_4 emissions to the response from a pulse emission of CO_2 (Allen et al., 2018; Lynch et al., 2020; Ridoutt, 2021).

When using GWP* to assess Australian beef production between 1990 and 2018, total emissions, though still positive, were 35% less than if characterized with GWP (Ridoutt, 2021). Between 1990 and 2018, total production increased, but due to advances in cattle production over this time, total emissions did not increase at a comparable rate. As a result, cattle's climate change impacts were 16.7 kg CO_2we/kg edible beef using GWP* compared to 25.5 CO_2e/kg edible beef using GWP. With appropriate characterization of emissions impacts from cattle production, any gains in animal or production efficiencies that result in the need for fewer animals or the production of less emissions will contribute to fewer emissions from cattle. It may also be possible that gains in efficiencies could result in net zero or even net negative climate change impacts from cattle, something that would be unthinkable for many other protein sources (e.g., poultry, swine, plant based meat alternatives, etc.).

Land Use

Along with climate change, land use is one of the largest environmental impacts associated with cattle production. More than one-third of global and is dedicated to agriculture, with 75% of this land being used for livestock (Foley et al., 2011; Tichenor et al., 2017b). Grazing systems in particular represent 34% of global cattle production and represents the largest livestock land area cover (Gerber et al., 2015). Furthermore, all of beef production utilizes the most land per unit of output (de Vries and de Boer, 2010). While there is no "one size fits all" style of cattle production, the majority of cattle produced in low to middle income regions are raised extensively, meaning that they spend their lives on range and pasture lands and obtain the majority of their nutrition from grazing and eating forages (Place and Myrdal Miller, 2020). In high income regions land use in cattle production is more variable: commonly in the US, cattle are raised extensively for the cow-calf and stocker phases of production and are then intensively (i.e. feedlot) finished for the final stage of production. Variations include intensive stocker and finish operations as well as extensive cow-calf through finish operations.

Land use from cattle production is much greater for the cow-calf stage of production compared to any other stage of production in part as a result of the time cow-calf pairs spend on pasture and rangeland but also due to the breeding cow, which spends her entire life on pasture and rangeland (Rotz et al., 2015; de Vries et al., 2015; Rotz et al., 2019). The impact of cow-calf operations on land use is further exemplified when comparing cow-calf reared cattle to those coming from dairy production into the beef supply chain. Comparing two extremes, grass-based beef results in land use impacts of 122 m^2/kg HCW while dairy produced beef results in land use of 17 m^2/kg HCW (Tichenor et al., 2017a). A review of seven LCAs on cattle production revealed that land use was reduced by up to 49% for animals sourced from dairy production (de Vries et al., 2015). This same review demonstrated that type of feed used for cattle had a direct impact of land use. Animals fed concentrates (e.g., corn, distillers grains, etc.) grow faster than those on pasture and thus reach the finishing stage faster (de Vries et al., 2015). However, if land is managed in a semi-intensive silvopastoral, such as that studied in Broom (2019), 25-32% less land is needed compared to feedlot finished animals. This highlights that even in a grass-finished system it is still possible to effectively utilize land.

A topic that is not covered in LCAs, but an important consideration of land use in cattle production is that of the "feed-food debate". Given that cattle require the greatest amount of land per unit output, there is rising concern that cattle are either utilizing land that could be used to grow human food on or that cattle are consuming food that is human edible. In either case, there is an aspect of competition for food with humans. Cropland used for cattle feed may otherwise be used for human crop production, and is thus viewed as competing the human food supply (de Vries et al., 2015). However, this is a common misconception and, globally, 86% of all feed used in livestock (cattle, small ruminants, swine, and chicken) production is not edible to humans (Mottet et al., 2017). In cattle production, specifically, the vast majority of land used to produce beef is marginal, meaning it is not suitable for crop production due to hilly terrain or lack of water resources and soil nutrients (Zanten et al., 2016). Cattle on marginal lands are therefore able to contribute to human food supply, through consumption of human inedible grasses. For example, Pelletier et al. (2010) found that grass finished beef returned nearly 70% of the human edible feed it consumed. However, this is highly dependent on the land being used.

As exemplified in Tichenor et al. (2017b), if land used for cattle were suitable for crop production, such as high protein soybean, then this land could actually produce more human edible protein when used for crops, suggesting that cattle are not the best use for that land. From a global perspective, however, over 60% of cattle feed is made of grasses and tree leaves while the remaining 40% is primarily crop residues, crop products, and crop by-products (Gerber et al., 2015). When considering global ruminant systems, including feedlot systems, animals require 0.6 human-edible protein per kg of protein product (Mottet et al., 2017). In the US, this value is slightly higher (1.43 kg of human edible protein per kg of protein from cattle) due to the larger portion grains used in US cattle diets, but regardless remains the lowest protein conversion ratio among US livestock production (Mekonnen et al., 2021). While cattle utilize large amounts of land for production, this ability to upcycle nutrients, turning low quality grasses on marginal lands and by-products into high quality protein, is perhaps one of the most important trade-offs to consider in cattle production. This is further supported by the work of van Kernebeek et al. (2016), who determined that largely populated regions of 40 million people or more could only meet their nutritional needs through consumption of animal protein. This is directly linked to limits of crop land and the need to utilize marginal lands for food production.

Well-managed grass-based systems, in addition to making use of marginal lands, have been found to provide a source of clean drinking water and preserve and enhance biodiversity (de Vries et al., 2015). Furthermore, improved land management can result in ecological co-benefits such as improvement of biodiversity, water quality, and soil health and well as minimizing the instance of soil erosion and improving productivity of livestock leading to reduced production costs as well as reduced total GHG emissions (Foley et al., 2011; Teague et al., 2016; Binder et al., 2018; Allen and Hof, 2019; Valentini and Vincenza, 2020). Maintenance of semi-natural grassland habitats with appropriate grazing management can result in areas of improved biodiversity where removal of cattle on these lands can results in loss of biodiversity and conversion of these lands to shrublands and forests, which typically have lower conservation ratios (Gerber et al., 2015). In some instances, limiting land use for cattle may lead to changes in land use and by extension have negative effects on biodiversity. Such a case was predicted for the Western US, where policies focused on limiting grazing of national rangelands lead to conversion of some of this land to cropland, thereby destroying native plant and animal populations (Runge et al., 2019).

Furthermore, there is evidence that use of livestock in silvopastoral systems can improve organic matter decomposition and nutrient mobilization while also reducing flammable biomass, thus adding a feature of fire mitigation through land use (Damianidis et al., 2020).

Water use

Agriculture accounts for 70% of global fresh-water use (IPCC, 2019a), and beef is among the highest food contributors to water use (Damerau et al., 2019). Water use is typically characterized as "green" or "blue", where green water is rainwater and blue water is groundwater and surface water resources (Pfister et al., 2011; Hoekstra, 2019). Given that cattle spend the majority of their lives on rain fed grazing land, the vast majority of water used for beef is green water (Damerau et al., 2019). Grass-based, extensive systems on dry grazing lands will therefore have a large green water footprint, as they occur on large acreages. Additionally, while crop production benefits from both blue and green water, it is difficult to account for the amount of green water used in production (Hoekstra, 2019). For these reasons, green water use is not typically characterized in LCA – it leads to overestimation of water use from production systems.

Richter et al. (2020) note that water is currently being used a rate faster than it is being replenished and find that, in the Western US, irrigation needed for cattle-feed crops is the greatest consumer of river water, and suggest a reduction in beef and dairy consumption as a solution. While many studies agree that cattle water use is relatively high and that crop production used for cattle feed is the greatest contributor to water use in beef production, Damerau et al. (2019) notes that the water use from beef is only in direct competition with other food sources (i.e., plants) when crops are included in cattle diets. Meaning that cattle under more extensive production systems, that do not require added crops during production, do not compete with other foods for water use and are not directly contributing to losses of water as a resource.

This is consistent with work comparing feedlot finished cattle to pasture-based cattle production, in which conserved water (blue water plus water conserved from rainfall) use was 87% lower in pasture-based production (Broom, 2019). Regardless of pasture or feedlot finishing of cattle, blue water use in the US is primarily attributed to irrigation needed for crops, totaling nearly 97% of blue water use (Asem-hiablie et al., 2019). In relation to total US livestock production (cattle, small ruminants, swine, and poultry), US cattle production accounts for 48% of blue water use (Mekonnen et al., 2021). Similar values and trends are reported for the Middle East and North Africa (Mourad et al., 2019) as well as for global blue water use (Mekonnen and Hoekstra, 2012). Rather than suggesting that the best way to reduce water use from livestock is to limit beef consumption, it would be more reasonable to work toward utilizing feeds that require minimal irrigation or shift towards grass-based systems that do not require further blue water inputs. Furthermore, these studies indicate that in the US and abroad, cattle provide the least water intensive source of protein. An important consideration for the low and middle income regions which are expected to increase livestock production in the coming decade.

PLANT BASED MEAT ALTERNATIVES

Regardless of the nuances surrounding the environmental impacts of beef production, the popular opinion is that beef production does more environmental harm than good (Heller et al., 2020; Lee et al., 2020). . In particular, there has been call for consumers to shift from beef consumption toward MAs as a means of reducing their individual carbon footprint (Reynolds et al., 2014; Westhoek et al., 2014; Hartmann and Siegrist, 2017; Poore and Nemecek, 2018; Springmann et al., 2018; Willett et al., 2019; Aiking and de Boer, 2020). Beyond this, health concerns have been used as a popular argument in favor of switching to MAs. While a heavily debated topic with conflicting data, increased meat consumption around the world has been thought to greatly increase the incidence of diseases such as type II diabetes and coronary heart disease, along with other chronic non-communicable diseases and may result in lower global life expectancies (Lock et al., 2010; Tilman and Clark, 2014). Recent work has investigated the potential for plant-based diets to meet human nutritional needs while benefitting the planet due, primarily, reduced GHG emissions and land use (Eshel et al., 2016). Beyond this, a "universal healthy reference diet" has recently been proposed by Willett et al., (2019) with the goal of meeting worldwide nutritional needs while addressing climate change among five other primary environmental concerns associated with food production. This is predominantly achieved through the reduction of meat consumption, beef in particular, and increases in plant-based eating.

As a result of compelling calls to reduce beef and other red meat consumption, there has been an increase in research and development of meat alternatives (MA) – products made from plants, insects, and even cell culture that aim to mimic the look, texture, and taste of conventional animal proteins (Bonny et al., 2017; Kyriakopoulou et al., 2018; Lee et al., 2020; Santo et al., 2020). The idea being that MA made from plants, insects, or cell culture will require fewer resources and result in less GHG emissions than conventional animal sourced proteins (Candy et al., 2019; Chen et al., 2019; Godfray et al., 2019; Aiking and de Boer, 2020; Santo et al., 2020; Smetana et al., 2020; Eisen and Brown, 2021). To this end, MAs, with their innovative manufacturing processes and perceived reduced environmental impacts, have been dubbed "techno-saviors" (Lonkila and Kaljonen, 2021). However, meat remains deeply ingrained in modern society and, at present, MA cater to a niche market (van der Weele et al., 2019). Nevertheless, MA have become increasingly popular in the US and other high income regions and consumers are expected to be willing to pay a premium for these products in the near future (Tziva et al., 2020). Investment into marketing and technological innovation surrounding MA have played, and will continue to play, an important role in improved consumer acceptance of these products.

Over the past decade, innovations in MA have focused on improvements in food processing, ingredient blends and flavorings, and biotechnology with the goal of developing PBMAs that mimic the taste, texture, and flavor of traditional meat and successfully satisfy consumer desire for meat (Hartmann and Siegrist, 2017; Godfray et al., 2019; Davis et al., 2021). In the case of MAs aimed at replacing beef, Beyond Meat™ and Impossible Foods® have been most successful in the production and sale of their ground beef-like products, the Beyond Burger (BB) and Impossible Burger (IB) (Heller and Keoleian, 2018; Khan et al., 2019). Due to their success in mimicking ground beef (GB), these produces have been marketed as more sustainable alternatives to beef and are the most commonly considered MA when discussing a shift toward plant-based diets. A quick media search of these two products renders an overwhelming host of articles and op-eds touting the environmental benefits of BB and IB compared to GB and presenting persuasive reasons for making such a switch. However, as with beef production, there are always trade-offs associated with these claims and it is important to understand the impacts of these products at a deeper level. As such, the remainder of this section reviews current research related to the sustainability of BB and IB.

Environmental impacts of MA compared to beef

As with beef production, the primary mode by which sustainability of MAs has been considered is through their environmental impacts. In the case of BB and IB, any assessment of environmental impacts has been coupled with comparisons to animal proteins, with a particular focus on GB. To date, four LCA have been performed for BB and IB: a report, commissioned by Beyond Meats™, comparing BB to GB (Heller and Keoleian, 2018); a peer-reviewed publication, comparing the original formula of IB to GB (Goldstein et al., 2017; Khan et al., 2019); a report, commissioned by Impossible Foods®, comparing the second formulation of IB to GB (Goldstein et al., 2017; Khan et al., 2019); and a report, commissioned by the National Pork Board, comparing BB, IB, and pork (Nair et al., 2019). Across all studies climate change impacts, land use, and water use impacts were evaluated. Energy use was evaluated for both BB and IB in Nair et al. (2019) and for BB in (Heller and Keoleian, 2018). ***Figure 1.2*** provides an "at-a-glance" comparison of environmental impacts evaluated across all studies standardized with the functional unit (FU) of kg product; however, this figure only serves to present a general idea of GHG emissions as these values were not standardized for system boundaries, LCA methods, etc. This variability across studies makes it impossible to provide an accurate direct comparison across studies, however general trends can be noted. To gain further insight, each study is evaluated in further detail below.

Heller and Keoleian (2018) assessed BB and GB with system boundaries including: patty ingredients and material supply, processing and packaging operations, cold storage, distribution to point of sale, and disposal of packaging materials. To compare BB to GB, environmental impacts of US beef production were drawn from Thoma et al. (2017) and characterization methods from the Thoma et al. (2017) work were used for the Heller and Keoleian (2018) study. Results highlight that for BB, ingredients were the primary contributors to GHG emissions, land use, and energy use, while processing was the greatest contributor to water use. Packaging also made notable contributions to overall environmental impacts. In comparison to GB, the study found that BB outperformed GB across all impacts, producing 90% less GHG emissions and utilizing 46% less energy, 99% less water, and 93% land per kg of product.

Goldstein et al. (2017) evaluated the effects of substituting GB with IB in the US diet, assessing the original formulation of IB (which was primarily a wheat protein-based patty compared to the current formulation which is a soy protein-based patty). System boundaries included patty ingredients and processing but did not include anything beyond manufacture-gate, citing that while impacts would be under-reported that the impacts from these stages were marginal and associated impacts would likely be relatively low. A hybrid-LCA methodology, by which process-based LCA were combined with input-output (IO) LCA, was employed in this study as a mean of assessing the impact of replacing GB with IB in the average US diet. However, results were also presented for GB compared to IB, apart from the average US diet and showed that that IB reduced GHG emissions by 77%, water consumption by 97%, and land use (characterized as land occupation) by 70%. In contrast to that reported for BB by Heller and Keoleian (2018), energy required in IB processing was the primary contributor to GHG emissions, with agricultural production (i.e., patty ingredients) the second largest contributor. When considering the effects of replacing beef with IB, Goldstein et al. (2017) noted that large-scale sourcing for fats used in IB could eventually pose a risk for land use change. For example, the use of coconut oil presents a risk given that the humid environments in which coconuts are grown may be susceptible to loss of habitat and biodiversity with increased production.

Khan et al. (2019) assessed the impacts of the updated formula of IB compared to GB with system boundaries including: patty ingredient production, processing, and packaging. To compare to GB, data for GB cattle feed production, rearing, and slaughter were sourced from previously published works and the assumption was made that GB manufacturing and packaging would be the same as IB processes. As reported for BB in Heller and Keoleian (2018), patty ingredients for IB production constituted the majority of GHG emissions, land use, and water use while processing contributed to approximately 40% of GHG emissions and 20% of water consumption. Leghemoglobin (i.e., the ingredient in IB, which gives it the characteristic meat flavor, color, and texture) was found to be the greatest ingredient contributor to GHG emissions, followed by potato protein and coconut oil, while potato protein was the greatest contributor to water consumption and coconut oil the greatest contributor to land occupation. These three products, which are essential to creating the GB-like taste and texture of IB, constitute 42-82% of all impacts across the product life cycle. Compared to GB, Khan et al. (2019) found that IB resulted in 89% less GHG emissions, 96% less land occupation, and 87% less water consumption compared to GB.

Nair et al. (2019) has been the only study, to date, to assess the impacts of BB and IB side by side; however, this was in comparison to pork rather than GB. While this study allows a first look into comparison of BB and IB it remains difficult to draw firm conclusions in comparison to GB. Nair et al. (2019) conducted a cradle-to-grave analysis of BB and IB with system boundaries including patty ingredients, processing, packaging, consumption, and disposal. In comparison to the other three LCAs discussed, this was the most comprehensive study on BB and IB. Similar to the above mentioned studies, ingredient processes constituted, for the most part, the greatest portion of life cycle impacts. In the case of BB GHG emissions and energy use, processing and packaging also played important roles in the overall impacts. Consistent with findings from of Goldstein et al. (2017), who noted that energy related emissions were major contributors to overall GHG emissions, IB was found to have elevated energy use and GHG emissions as a result of manufacturing. Of note from this analysis, in comparison to the other BB and IB studies, was that retail refrigeration and at home cooking proved to be significant contributors to environmental impacts, a result consistent with earlier work assessing full life cycle impacts of different protein sources (Smetana et al., 2015). This finding highlights that, while it can be assumed that these production stages are similar across different product LCAs, they still contribute to a meaningful portion of overall impacts, and slight variations may lead to notable differences in product impacts.

These earlier publications showed that GB versus BB and IB has a considerably higher environmental impact but they also highlight opportunities for each product to improve their respective production systems to further reduce resultant impacts. However, when considering these studies together, a few important conclusions can be formed. Due to the energy demands of manufacturing, potential gains in sustainability of MA become less certain when high levels of processing are required to convert plant products into patty products (van der Weele et al., 2019). Also noted across studies was that nutrient profiles of BB and IB were comparable to that of GB; however, this only accounted for macronutrients (e.g., protein, fat, and carbohydrates) and leaves out information on micronutrients (e.g., B vitamins, iron, etc.). Beef not only provides micronutrients but also provides essential micronutrients, which are not naturally present in MAs. Furthermore, comparisons are made for BB and IB with an 80:20 blend of GB because the product has been made to mimic this lean:fat profile; however, GB is available in varying degrees of lean:fat with 80:20 at the extreme high end. Thus, to replace GB with BB, consumers lose the option of a lower fat protein source and end up consuming more of their calories from fat than from protein.

Additionally, these studies do not consider the actual consumer behavior surrounding ASF and MA consumption. They investigate how one product compares to another, but do not provide insight into the widespread effects that a shift from GB to BB or IB consumption might have on the US economy and how that then may alter US emissions. Additionally, the methods of characterizing emissions and resource use often leave out fundamental details (i.e., lifetime of GHG emissions or types of land and water used), which results in misleading, and sometimes erroneous, interpretations of results. Furthermore, these studies comparing BB and IB to GB lack detail on the complicated interrelationships between production and consumption of each product.

Consumption of BB, IB, and GB in the US results in environmental impacts in other countries, which a US focused, attributional LCA approach cannot accurately capture beyond a small degree of change.

ALTERNATIVE MODELLING STRATEGIES

Given the nuanced discussion surrounding environmental impacts from beef and MAs, it is hard to gather a complete picture of sustainability of these products compared to one another. As a result alternative modelling strategies may prove valuable in the assessment and comparison of these products. Input-output (IO) models, pioneered by Professor Wassily Leiontief in the late 1930s, present an analytical framework that can be used to determine the interdependence of industries in an economy (Miller and Blair, 2009). At the most basic level, IO consists of a set of linear equations that describe the distribution of an industry's product throughout the economy (Miller and Blair, 2009). This includes accounts the flows of products from each industrial sector (i.e., producers) to each sector, itself, and others (i.e. consumers) in addition to final demand accounts (i.e., sales of each sector to final government and household purchasers) and value added accounts (i.e., non-industrial inputs such as labor, capital, imports, etc.). These accounts create a social accounting matrix (SAM) that can then be utilized for analysis of current economies, future changes to economies, as well as a practical planning tool for developing economies (Rose and Miernyk, 1989; Miller and Blair, 2009).

While IO has long been utilized to describe the complicated interworkings of economies and technological shifts, it can also be utilized to evaluate environmental impacts of economies and technologies. Leontief (1970) described how IO can be a useful tool in describing environmental consequences of economic and technological growth, which has since evolved into various national and international level environmentally extended IO (EEIO) models. EEIO are especially useful in providing a reliable top-down approach attributing pollution and resource use to final consumption from end users, such as consumers, in a consistent manner (Wiedmann, 2009; Steen-Olsen et al., 2014). Beyond EEIO, multi-regional EEIO (MRIO) provides a means by which to quantify environmental and economic impacts imbedded in trade and varying regional technologies (Wiedmann, 2009; Marques et al., 2017). Two such models, the Global Trade Analysis Project (GTAP) and EXIOBASE, are becoming more frequently used to provide a comprehensive understanding of economic and environmental implications of technology shifts, changes to national and international policy, etc.

Global Trade Analysis Project

GTAP is a computational general equilibrium (CGE) model, which utilizes an IO framework, providing sectoral detail and the consideration of intermediate production in an economy, but with the added advantage of demand side detail, non-linear relationships, and responsiveness to changes in prices (Rose and Miernyk, 1989; Burfisher, 2016). The tenth version of accounts for annual flows of 65 products and services (i.e., sectors) and 6 factors of production in 121 countries and 20 aggregate regions for the reference year 2014 (Aguiar et al., 2019). GTAP is comprised of country-based Input Output Tables (IOT) and describes global bilateral trade patterns which links individual countries and regions. Several studies of the years demonstrated that GTAP is a powerful tool for macroeconomic analysis (Wesenbeeck and Herok, 2002). While GTAP is primarily an economic tool, in recent years it has incorporated energy, land use, and CO_2 emission extensions which have made it easier to pair environmental aspects of analysis to modeled changes in the economy.

Golub et al. (2009) utilized GTAP to evaluate the role of global land management alternatives in mitigation of GHG emissions form land-based activities in agriculture and forestry.

This work highlighted the efficacy of using GTAP to test changes in tax structures and their resultant impacts on emissions at a global scale. Additionally, this work highlighted that the predominant source of GHG emissions from agricultural land-based activities was due to CH_4 emissions from livestock, thus indicating the potential of this model to provide reasonable and necessary estimates from the impacts of cattle production at national and global scales. Further related to livestock, Taheripour et al. (2011) was able to utilize GTAP to provide detailed insight into the trade-offs related to livestock production with their analysis of the impacts of biofuels on global livestock production. In this case productivity of livestock was evaluated and it was found that the countries increasing biofuel production experienced increases in livestock production, ruminants in particular, due to the increased need to utilize the by-products of biofuel production; meanwhile, livestock production in other region of the world experienced declines in livestock due to increased prices for grain which resulted from increased biofuel production. GTAP primarily shows strength in its ability to assess complicated macroeconomic impacts nationally and globally, representing the interrelationships of global trade and so on, but also has demonstrated strength in providing a means of connecting the economy with the environment. As beef production is a major contributor to the global market, GTAP may provide a reliable means to understand how future shifts in production might affect national and international production, consumption, and trade.

EXIOBASE

EXIOBASE is an environmentally extended MRIO database with environmental and resource use focus, containing high levels of primary production (Wood et al., 2015). EXIOBASE contains detailed SUTs for multiple regions based off of internationally available data and integrates detailed environmental accounts which cover resource inputs, such as energy, materials, water, and land, along with outputs of waste and emissions to land and water (Wood et al., 2015).

Supply use tables in EXIOBASE are trade-linked for ease of environmental footprinting. In addition, EXIOBASE aims to address sectoral truncation errors inherent in IO with the focus of increasing product and industry detail within the model (Wood et al., 2015). Modeling is taken even further with EXIOBASE in the use of rectangular SUTs, unique among MRIO, which enable detailed assessment of a single technology along with its co-products (Wood et al., 2015). Detailed information on the initial formation of EXIOBASE and its applications can be found in Wood et al. (2015). In its most recent version, EXIOBASE 3 contains 44 countries, 5 world regions, 163 industries, and 200 products (Stadler et al., 2018). Initial SUTs were expanded upon to incorporate more detailed data on energy, agricultural production, resource extraction, and bilateral trade rendering EXOBASE 3 one of the more promising MRIO for use in assessment of products such as beef or MAs.

EXIOBASE 3 application was exemplified by Wood et al. (2017) in which changes to consumption patterns and overall reductions in consumption as well as changes to product material sources were modeled. Results suggest that EXIOBASE 3 is well suited to expand upon traditional LCA, providing detailed information on economy-wide impacts of modeled scenarios with the added bonus that results can be more easily compared across different scenarios and more meaningful conclusions drawn from the work. The effects of changing consumption patterns were further explored and demonstrated the efficiency with which EXIOBASE 3 can be used to assess regional variations and how repercussions of difference changes might be experienced on a global scale (Bjelle et al., 2021b). Furthermore, Wood et al. (2018), demonstrated the use of EXIOBASE 3 to evaluate changes in the rate of resource use efficiency and how international trade contributes to displacement of pressures on the environment which arise from changing consumption patterns of a population. Such applications of EXIOBASE 3 provide insight into how changes in production or demand of one product might lead to resultant changes not only in economic output but global environmental impacts. EXIOBASE 3 has been further used to demonstrate the potential to accurately account for income effects on production and demand result in land use and biodiversity impacts (Bjelle et al., 2021a). This is a tool that would prove valuable for analysis of beef production and MAs, providing a means of not only assessing potential environmental and economic implications from future shifts of consumption patterns for these products but also potential displacement effects through international trade.

Macro-LCA

The GTAP model can be useful in collecting information on how changes in consumer behaviors might impact economic activity in the U.S. and abroad. It considers price variations as well as direct and indirect effects on economic sectors, but has limited detail on related environmental impacts. To overcome this lack of detail and further improve upon the idea of utilizing MRIO to quantify environmental impacts, Dandres et al. (2012) proposed a new approach to LCA, macro-LCA (M-LCA), which utilizes GTAP to generate a life cycle inventory (LCI). In early works with M-LCA, the GTAP generate LCI was paired with the ecoinvent database (Frischknecht et al., 2005), which models bottom-up environmental flows for various technologies, to estimate environmental impacts. While effective at providing greater insight into the economic links to environmental outputs than GTAP alone, the ecoinvent database is not as robust as GTAP and necessitates truncation of economic sectors resulting in a loss of detail in reported results (Steen-Olsen et al., 2014).

This method was further updated and the truncation issue overcome by Somé et al. (2018), through coupling GTAP with EXIOBASE. As previously indicated, EXIOBASE provides extensive detail on environmental impacts of various sectors through the use of detailed input-output tables. Through this M-LCA approach, economic responses modeled with GTAP can be linked to EXIOBASE enabling environmental impacts to be more accurately and completely characterized. Through a case study assessing the effects of biofuel policies over time, Somé et al. (2018) demonstrated the potential of this method to enable a more robust analysis of environmental impacts resulting from global policy change than typical LCA. This work still requires further uncertainty analysis, but it is the first work of its kind, providing a means of more completely evaluating implications of shifts in policy. These results can be further extended to analysis of consumption behaviors nationally and internationally, and would be of considerable use in the assessment of environmental impacts from beef production, MAs, and possible shifts in global production that could result from changes in consumption patterns related to these products.

CONCLUSIONS

The production livestock and sale of animal sourced foods is responsible for the livelihoods of 1 billion people worldwide, a number that will continue to increase as the global population continues to rise (Godfray et al., 2019). Those in low to middle income regions of the world are most reliant on livestock not only for their livelihoods, but also for a source of manure and draught power and essential micro nutrients (Mottet et al., 2017). Thus it is important when considering beef versus MA to be cognizant of the need in low to middle income regions as well as disadvantaged communities that are reliant on meat for livelihood and basic nutrition needs (Godfray et al., 2019). If the overarching goal of substituting beef with MA is to reduce environmental impacts and improve overall sustainability of the food system: (1) these highly processed forms of MA may not actually produce strong reductions in environmental impacts; (2) meat is deeply ingrained in western society, supporting livelihoods and rural economies; and (3) MA provide an economically less viable product, as they are a niche market from which a premium is owed. To obtain a more complete picture of the sustainability of GB compared to BB or IB, it is essential that economic impacts of these products be considered. Furthermore, it will be necessary to consider how changes in production and consumption will impact the environment. While conventional LCA is useful in determining impacts directly associated with these products, it does not provide a means of determining broader impacts. Alternative modelling tools, such as the use of GTAP and EXIOBASE, would be valuable in further determination of impacts of beef compared to MAs. Furthermore, a reasonable consideration is that both LCA and alternative modeling methods should be taken into account when evaluating the environmental impacts of different production systems or products as a means of more complete assessment (Yang et al., 2017). M-LCA provides a reliable means by which to do exactly that and future research considering the full impacts of beef compared to MA would be remiss not to take advantage of this methodology.

A. **B.**

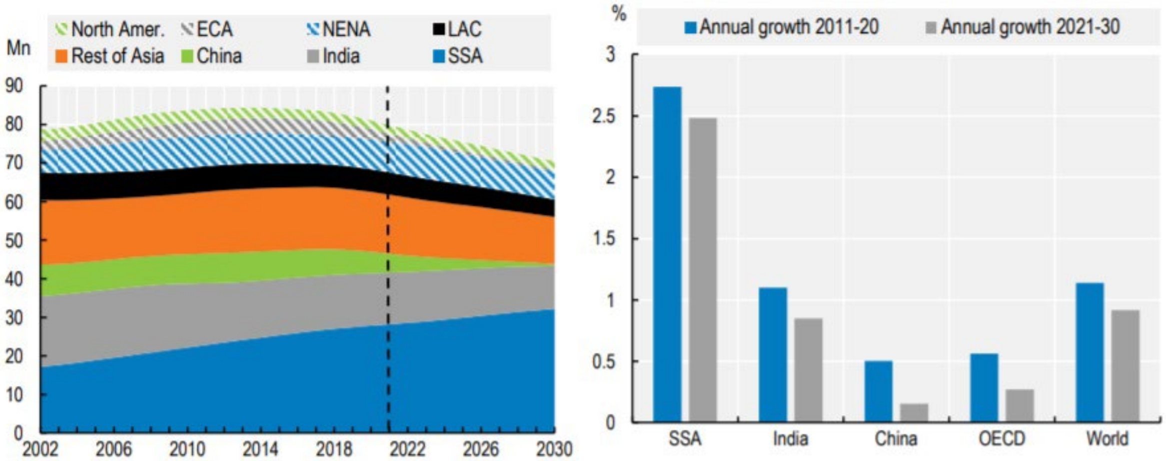


Figure 1.1. (A) Year-on-year human population changes (Mn) by region[1] and (B) annual population growth (%) by region from 2011-20 compared to projected annual population growth from 2021-30. Figures from OECD/FAO (2021).

[1] SSA = Sub-Saharan Africa; LAC = Latin America and Caribbean; ECA = Europe and Central Asia; NENA = Near East and North Africa; Rest of Asia = Asia Pacific excluding China and India.

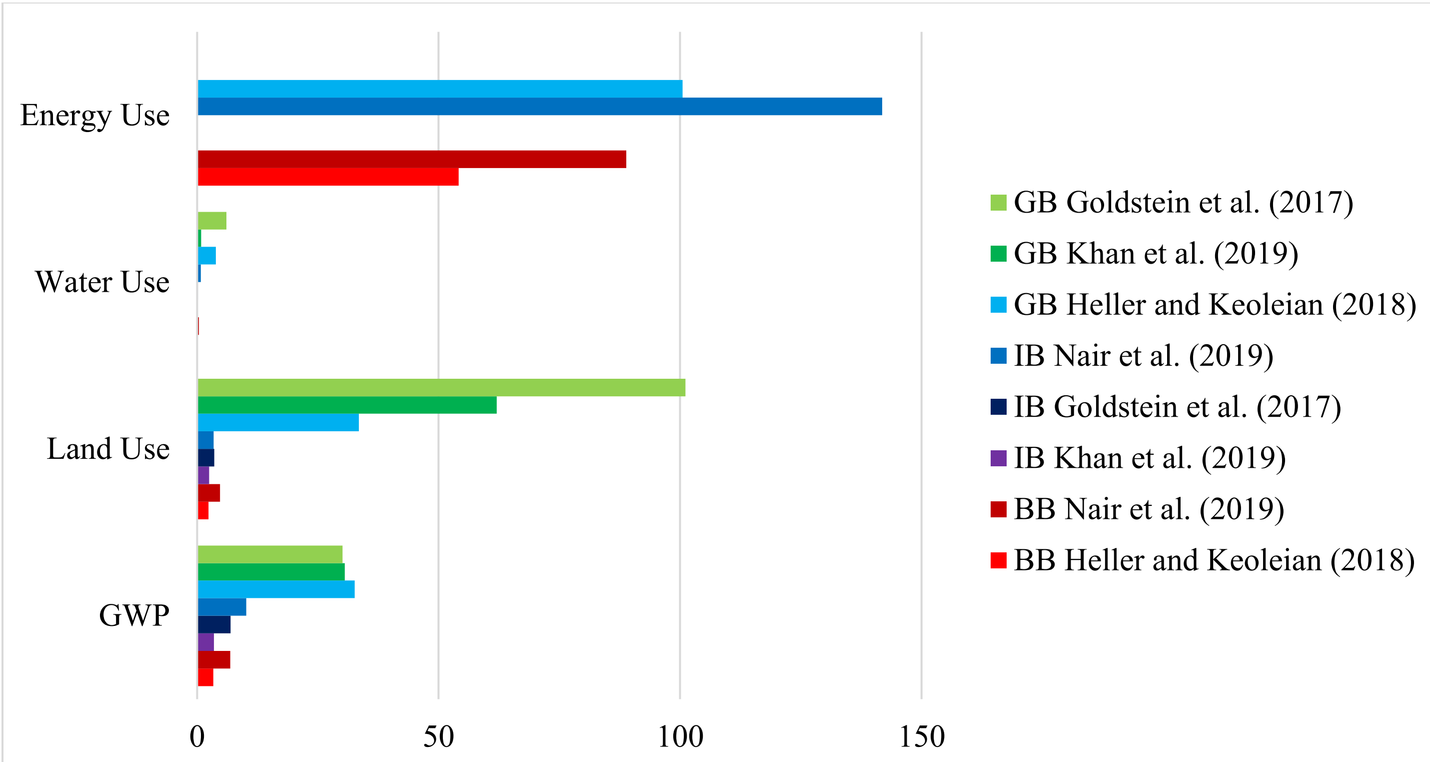


Figure 1.2. Environmental impacts of ground beef (GB), Impossible Burger (IB), and Beyond Burger (BB). Energy use is reported in MJ, water use in m^3, land use as m^2 or m^2a, and global warming potential (GWP) as kg CO_2eq. All impacts are reported per kg of product, but have not been normalized across studies to account for differences in life cycle methodology.

Chapter 2 Effects of lubabegron on gaseous emissions, growth performance, and carcass characteristics of beef cattle during the last 91 days of the feeding period

ABSTRACT

The development of technologies that promote environmental stewardship while maintaining or improving the efficiency of food animal production is essential to the sustainability of producing a safe, wholesome food supply that is capable of meeting the demands of a growing population. As such, Elanco Animal Health (Greenfield, IN) was compelled to pursue an environmental indication for a selective β modulator (lubabegron; **LUB**) that was recently approved by the United States Food and Drug Administration (**FDA**) to be fed to feedlot cattle during the last 14 to 91 d of the feeding period. The study described herein was submitted in partial fulfillment of the FDA drug approval process to provide evidence of clinical efficacy for reductions in gaseous emissions/kg of final BW or HCW when different doses of LUB were fed to feedlot cattle over a 91-d duration. A 4 × 2 factorial arrangement design was utilized with the factors of dose (0.0, 1.25, 5.0 or 20.0 g/ton DM basis) and sex (steers or heifers). Three cycles were conducted (112 animals/cycle) with each dose × sex combination being represented by a single cattle pen enclosure (**CPE**; 14 animals/CPE) resulting in a total of 168 steers and 168 heifers (BW = 453 ± 34.5 kg). Five gases were evaluated based on CPE concentrations relative to ambient air: NH_3, CH_4, N_2O, H_2S, and CO_2. Cumulative NH_3 emissions were reduced by feeding 5.0 and 20.0 g/ton LUB ($P \leq 0.023$), and tended ($P = 0.076$) to be lower for the cattle fed 1.25 g/ton LUB compared to the negative controls. These emission reductions, coupled with HCW increases of at least 15 kg for each LUB inclusion rate ($P \leq 0.019$), led to reductions in NH_3 emissions/kg HCW for all 3 LUB treatments ($P \leq 0.004$). Final BW was not altered by dose ($P = 0.257$), although a similar trend was observed whereby it was increased no less than 15 kg by each LUB treatment, and similar to HCW, reductions in NH_3 emissions/kg of BW were observed for all non-zero LUB doses ($P \leq 0.009$). No reductions in cumulative emissions or emissions standardized by BW or

HCW were noted for the other 4 gases ($P \geq 0.268$). Given the data provided herein, lubabegron is a novel tool to reduce emissions of NH_3 while simultaneously increasing the pounds of beef produced.

Key words: ammonia emissions, environment, feedlot cattle, hot carcass weight, lubabegron, shear force

Introduction

According to a 2015 report by the United Nations Department of Economic and Social Affairs, the global population is projected to increase to 9.7 billion people by 2050. Within the same timeframe, the global demand for animal protein is predicted to grow by as much as 70% (Capper and Hayes, 2012). Food animal agriculture continues to be challenged by urban development and perceptions of potentially negative impacts on the environment, and because of this, the development of new technologies that reduce agriculture's emission footprint while simultaneously maintaining or improving the efficiency of food animals is appealing to both meat producers and consumers.

Traditionally, life cycle assessments have primarily been used to evaluate the impact of livestock production management practices on the environment (Clark and Tilman, 2017). Lesser work has been conducted measuring direct changes to the environment when tested in controlled experimental settings; furthermore, no clinical registration programs for products approved by the United State Food and Drug Administration (**FDA**) have targeted reductions in specific gas analytes of environmental concern. Consumer attention to emissions from modern food production systems has intensified, and compelled Elanco Animal Health (Greenfield, IN) to pursue a label indication for the reduction of emissions for a new feed additive containing the active pharmaceutical ingredient lubabegron (**LUB;** Experior™; Elanco Animal Health, Greenfield, IN).

Lubabegron is a selective beta-adrenergic modulator (SβM) with agonistic properties at the β_3 receptor subtype and antagonistic properties at β_1 and β_2 receptor subtypes in cattle, and as such is classified by the Center of Veterinary Medicine (**CVM**) as a 'beta-adrenergic agonist/antagonist' (Dilger et al., 2021). This pharmacodynamic profile differentiates LUB from the β ligands historically used in livestock species, as their apparent mode of action is predominately through agonistic behavior at either the β_1 or the β_2 receptor subtype. Lubabegron's affinity for the β_3 receptor and the ability to antagonistically bind the β_1 and β_2 receptors distinguish it as a novel technology and warranted evaluation for reducing the environmental impact of meat production. The 91-d study described herein was 1 of 2 studies conducted (the other being the 14-d study described by Teeter et al., in press) to provide evidence of clinical effectiveness. These studies were submitted to the FDA to support an indication for a reduction in gaseous ammonia emissions per unit of BW and HCW when lubabegron is fed to finishing cattle for a duration of 14 to 91 d.

MATERIALS AND METHODS

This study was conducted in accordance with the Good Clinical Practice standards (FDA, 2015), and the procedures outlined were approved by the University of California Davis Animal Care and Use Committee (Protocol #17063).

Experimental Design and Treatments

A randomized complete block design was used to evaluate the effect of LUB on gaseous emissions over a 91-d period using 336 beef cattle (BW = 453 ± 34.5 kg) housed in cattle pen enclosures (**CPE**). Four LUB treatments were included in the study based on dose: 0.0 (**control**), 1.25, 5.0, and 20.0 (g/ton of DM). Because there was a limited number of CPE's (n = 8), 3 sequential cycles (blocks) were required to generate 6 replicates of each dose × sex combination. As such, 112 cattle (56 steers and 56 heifers) were housed concurrently within each cycle across the 8 CPEs (14 cattle/CPE) with each dose × sex combination being represented by a single CPE/cycle. To assure different biological types of cattle were represented, cattle in cycles 1 and 3 were large-frame Continental crossbreds, and cattle in cycle 2 were medium-frame British crossbreds. Based on details provided in the 2003 National Research Council report on air emissions (NRC, 2003), 4 gases were chosen to be measured based on their importance to animal feeding operations: ammonia (**NH_3**), nitrous oxide (**N_2O**), methane (**CH_4**), and hydrogen sulfide (**H_2S**). A fifth gas, carbon dioxide (**CO_2**), was also measured because of its importance as a greenhouse gas. Response variables of primary interest were the ratios of cumulative emissions to final BW and HCW (g/kg of BW or HCW) for each of these 5 gases.

Study Timeline and Treatment Allocation

Treatment administration for the 3 cycles occurred from April through July, August through November, and December through March of 2014 and 2015, respectively. Four weeks before beginning treatments for each cycle (d -28), up to 145 cattle were sourced from a common origin and transported to the Beef Cattle Feedlot Facility (**BCFF**) at the University of California Davis to be group-housed in single-sexed outdoor pens. The presence of growth-promoting implants was assessed and any implants present were excised before shipment to the BCFF to ensure they had been implant-free for at least 28 d before treatments began on d 0.

On d -8, cattle were screened for abnormal health conditions by a veterinarian and ranked by body weight to identify the 56 eligible cattle within each sex that provided the narrowest weight range. The following day (d -7), the 56 cattle selected for study enrollment within each sex were stratified by sequentially grouping sets of 4 consecutively weight-ranked animals. Cattle were then randomly allocated to treatment within each weight group and transferred into the CPEs. The CPEs were randomly assigned to sex and dose treatment before each cycle, and all personnel were blinded to treatments throughout the duration of the study. All cattle were fed the negative control basal finishing diet (***Table 2.1***) for 1 wk (d -7 to -1) after being placed into the CPEs to allow for acclimation before beginning treatments.

Treatments began on d 0 and ended when cattle were shipped to the abattoir on d 91, which permitted each CPE to receive their respective LUB treatments for 91 d. Emission measurements began at 0800 h on d 0 and ended at 0500 h on d 91, immediately preceding cattle removal from the CPE for final BW measurements and transport to the commercial slaughter facility.

Cattle Pen Enclosures (CPE)

The CPE were dome-shaped, 22.0 × 11.3 m structures oriented east to west, standing 6 m tall at the highest point and constructed with a steel frame, welded truss arches with parallel steel tubes, and continuous structural webbing (11 m Legend Series Cover-All Building, Saskatoon, Saskatchewan, Canada; **Figure *1.1***) which was covered with a double stacked Dura-Weave cover (Intertape Polymer Group, Montreal, Quebec, Canada). Each CPE contained 185 m^2 of soil surface, 9.1 m linear bunk space, 3% slope from the bunk towards the west of the pen, and a float-activated waterer. Two hinged bunk flaps were used to facilitate feed delivery, and each CPE had 2 doors. There was 1 large roll-up door to move cattle in and out of the CPE, and 1 small door to allow study personnel access to the CPE. Both doors and the bunk flaps remained closed when not in use to prevent disruption of CPE gas equilibrium.

Each CPE floor was cleaned before the first cycle and between each subsequent cycle by allowing the manure to air dry for 24 to 48 h, and then removing manure with a skid-loader and a power washer. The pen floor was leveled and thoroughly saturated with water to allow volatilization of pre-existing NH_3 from the soil. Fresh soil was applied following a 24-h volatilization period and then compacted with a weighted roller to create a solid pen surface. Accumulation of excreta began on d -7 when cattle were allocated to the CPE and remained uninterrupted for the entirety of the 91-d gas emission measurement period for each cycle.

CPE Airflow and Emissions Measurements

Each CPE was equipped with a 4.9 × 1.2 m cooling pad on the east side for evaporative cooling of incoming ambient air, plus 2 ventilation fans on the west side to create directional airflow and generate negative pressure inside the CPE. Flow rates were independently determined for all 16 ventilation fans using a customized purpose built anemometer before and after each cycle, and the sum of the 2 fans within a CPE determined total outflow for each respective CPE. Fan efficiency decay curves were created for the determination of airflow at any given time using the 2 flow rates obtained at the beginning and end of a cycle. Fan speed was monitored continuously using 2 sensors (Monarch Instruments, Amherst, NH), and the static differential pressure between internal and external air was monitored to ensure proper ventilation. The temperature and relative humidity within CPEs were monitored every 15 s during emission sampling periods (**Table 2.2**) using RH/T sensors (Dwyer Instruments, Inc., Michigan City, IN), and the same measurements were obtained continuously from ambient air using an on-site weather station (Novalynx, Model 110-WS-16, Auburn, CA).

Emissions were monitored using calibrated analyzers (Thermo Environmental Instruments (**TEI**), Waltham, MA) for 5 gases: NH_3 (TEI 17i), CH_4 (TEI 55c), CO_2 (TEI 410i), H_2S (TEI 450i), and N_2O (TEI 46i). The analyzers were located in a temperature-controlled building adjacent to the northernmost CPE, and the inlet to the analyzers was independently connected to each of the 8 CPE outlets using 103 m of Teflon tubing (9.53 mm OD, 6.35 mm ID) so that emissions flowed through the same length of tubing for each CPE being sampled. Analyzer outputs were recorded every 15 s using automatic data capture with LabVIEW software (Version 2011, National Instruments, Austin, TX). Emissions were measured from an individual source over 15-min periods in sequential order, starting with ambient air and followed by the 8 individual CPE units. This procedure was continuous, resulting in a maximum of 11 sampling periods/day for the determination of daily emission rates from a single CPE. Daily emissions were defined as those spanning from 0800 h to 0759 h the next morning, as this time corresponded with disruptions to gas equilibrium associated with daily feeding and health observations.

Daily calibration checks were performed to confirm the gas analyzers were functioning properly. A “zero check” was performed to ensure the analyzers read 0 when compressed air containing no detectable traces of the gases of interest were introduced. “Span checks” consisted of introducing compressed air with known concentrations of analyte gases and measuring against the analyzer’s calibration specifications. An analyzer was re-calibrated in any instance where either check fell outside specification limits (2% for methane; 10% for all other gases) by introducing a known concentration of analyte gas to the analyzer and adjusting the instrument parameters until the measured value was within the acceptable range.

Emission Data Validity

Because emissions monitoring was a continuous process, intermittent disruptions to steady-state equilibrium could not be entirely avoided. To account for this, the time and duration of instances where the large door or bunk flaps had to be opened were noted so that the emissions measurements during, 5 min before and 15 min after could be identified and removed from the dataset. Entry and exit through the small door did not necessitate the removal of emissions data since the airflow disruption during these events was deemed negligible. Emissions data compromised because of a gas analyzer failure was handled according to predefined scenarios outlining how replacement data would be substituted, and a minimum of 4 min of emissions data needed to be available after removal of any required exclusions during a 15 min sampling period to be considered valid. Data representing a minimum of 4 valid emission periods were required for calculation of daily emissions. Only 1 analyzer malfunction occurred throughout the entire study resulting in less than 4 valid observations for an analyte gas (methane, cycle 1, d 7), for which the mean emissions of 2 d before and 2 d after (d 5, 6, 8 and 9) the malfunction were substituted to permit the determination of cumulative emissions

Emissions Calculations

Emissions were measured as the ratio of analyte gas volume to total air volume, and were reported in parts per million (**ppm**) for CH_4, CO_2, and N_2O, and parts per billion (**ppb**) for NH_3 and H_2S. To calculate emission rates for each 15-min sampling period, the concentration of analyte gas in the sample was converted to g/min using the molar gas volume in the following equation (Eq. 1):

$$\text{Total Flux}\left(\frac{\text{g}}{\text{min}}\right) = \frac{\dfrac{(\text{Gas ppm} - \text{Incoming ppm}) \times \text{Air Flow}\,\frac{\text{m}^3}{\text{min}} \times 1{,}000\,\frac{\text{L}}{\text{m}^3}}{\dfrac{\text{V}_\text{s}\,\frac{\text{L}}{\text{mol}} \times (\text{Temp}\,°\text{C} + 273.15)}{273.15\ \text{K}}} \times \text{MW}\,\frac{\text{g}}{\text{mol}}}{1{,}000{,}000}$$

where: Gas ppm (or ppb) = gas concentration in the CPE air sample; Incoming ppm (or ppb) = gas concentration in ambient air; Airflow ($\frac{m^3}{min}$) = airflow rate through the CPE corresponding to the point in time of sampling, calculated as the sum of the individual fan unit airflow rates according to fan efficiency decay curves; $V_s(\frac{L}{mol})$ = molar volume of a gas at constant temperature and pressure (both temperature and pressure were held constant in the analyzers, therefore $V_s(\frac{L}{mol})$ = 22.4 for all calculations); MW ($\frac{g}{mol}$) = molecular weight (MW = 16.04 g for CH_4, 44.01 g for N_2O, 44.01 g for CO_2, 34.08 g for H_2S, and 17.03 g for NH_3); and temperature (°C) converted to kelvin (K). In order to standardize calculated values to g, the denominator was 1,000 times greater for variables measured in ppb compared to variables measured in ppm (1 million for ppm, 1 billion for ppb).

The concentration of analyte gas in ambient air was subtracted from the concentration of analyte gas in samples from each CPE to adjust for baseline values and supply the net amount contributed by the CPE (Eq. 1). The net concentration was multiplied by the CPE airflow rate and divided by the number of minutes in the sampling period to yield the net emission rate (g/min). The emission rates were then averaged over all sampling periods occurring within defined 24-h periods to produce the daily emission rate (g/min) for individual gases from a CPE. Finally, daily emissions/animal were determined by multiplying the CPE average g/min emission rate by 1,440 min to convert to cumulative daily emissions. Cumulative daily emissions/CPE were then divided by the number of cattle present in the CPE on that day in order to account for any removals during the treatment phase. The resulting daily emission rates (g/animal) were summed over each interim BW measurement period (d 0 to 7, 0 to 14, 0 to 28, 0 to 56) and over the entire 91-d period to provide cumulative gas emissions, cumulative gas emissions/kg BW, and cumulative gas emissions/kg HCW on a per animal basis.

Health Observations

Cattle were observed daily by trained personnel and abnormal health observations were noted by exception. Health conditions observed at the BCFF that would deem an animal ineligible or potentially require removal later in the study were documented to prevent affected animals from being considered for study enrollment. Additional observations were performed by a licensed veterinarian as cattle progressed through the marketing channel, including during loading onto the semi-trailers, during unloading at the abattoir, and finally as ante-mortem observations after a minimum lairage time of 5 h.

Diet Formulation and Feed Assays

Cattle had been fed a concentrate-based diet before arrival to the BCFF on d -28, at which point they were provided *ad libitum* access to water and re-acclimated to a concentrate-based diet using a step-up program involving 2 intermediate diets based on increasing concentrate levels (approximately 60 and 70%, respectively) and varying proportions of alfalfa and wheat hay. On d -14, cattle were transitioned onto a finishing diet (***Table 2.1***) formulated to meet or exceed the minimum nutrient requirements for growing beef cattle (NRC, 2000) that would be fed for the remainder of the study. A non-medicated Type B feed (i.e., ground corn carrier) was included as 2.5% of the diet DM for all cattle from d -14 until the beginning of test article administration on d 0, at which point 1 of 4 Type B feeds were added to the basal diet to provide either 0.0, 1.25, 5.0, or 20.0 g of LUB/ton (DM basis) in a type C medicated feed. Basal rations containing all feed ingredients except the Type B feed were prepared at the study site, and Type C feeds containing the appropriate concentrations of LUB were prepared by adding the same proportions of Type B feed, water, and basal ration in a rotary mixer wagon (Roto-Mix® Forage Express, Dodge City, KS). No concomitant feed additives (ionophores, antibiotics, estrous suppressors, β-agonists) were permitted for use in this study, and the mixer wagon flush procedures were implemented between each load. The digital scale on the mixer wagon measured feed deliveries with a 1.0 lb resolution.

Target nutrient densities (% of DM) for CP (13.5%), Ca (0.7%), and P (0.3%) were set based on the recommendations of consulting feedlot nutritionists reported in a survey by Vasconcelos and Galyean (2007). Triplicate samples were collected daily during delivery from the mixer wagon into the bunk for each batch of complete feed and frozen until analysis. Three of the 7 composite samples representing a week were randomly selected for each treatment and combined and subsampled for weekly analyses of nutrient content (AOAC methods #985.01 and 990.03, Minnesota Valley Testing Laboratories, New Ulm, MN) and LUB concentration (Covance Laboratories, Inc., Greenfield, IN). The minimum acceptable assay value for Ca (0.3%) and P (0.2%) was set to the National Research Council's minimum nutrient requirement for growing beef cattle (NRC, 2000), whereas the minimum acceptable value for CP was set at 12.5%. The threshold for CP was chosen as this was the minimum level recommended by feedlot nutritionists (Vasconcelos and Galyean, 2007), and CP concentration can have a profound effect on NH_3 emissions. Lubabegron concentrations were required to be within +/- 25% of the target for the 1.25 g/ton and 5 g/ton samples, and +/- 20% for 20 g/ton samples in accordance with FDA guidance (FDA, 2012). No samples fell below the assay thresholds for any nutrient, and the mean LUB potency values for each weekly composite sample over all 3 study cycles were within the acceptable assay concentration range for each dose level (data not shown). Lastly, feed samples from the control group were assayed for LUB to confirm the flush procedure prevented feeding of LUB, and levels were below the level of quantification in each sample assayed.

Feeding and Growth Performance

Body weight measurements were obtained using a certified scale with a 1 lb resolution before feeding on d -8 (randomization), 0 (initial BW), 7, 14, 28, 56 and 91 (final BW). Trained personnel assessed each CPE feed bunk daily for orts from the previous day. From this estimate, trained personnel determined the amount of feed to be provided in a single delivery to ensure animals had *ad libitum* access to feed. Orts remaining on d 91 were weighed to adjust for actual DMI, and average daily DMI for an individual animal was calculated by dividing the daily feed delivery by the number of cattle in the CPE to determine as-fed consumption, and then multiplying by diet DM. The CPE mean for unshrunk initial and final BWs were used for calculating ADG over the 91 d period, and G:F was calculated as a quotient of ADG divided by daily DMI.

Slaughter

On d 91, cattle were loaded onto 2-floor aluminum semi-trailers and transported approximately 1,000 km to a commercial abattoir where they were harvested following approximately 5 to 9 h in lairage. Carcass identification was maintained throughout the slaughter process by recording ear tag sequence at stunning and then cross matching to sequentially numbered carcass tags. Hot carcass weights and KPH were measured after a dressing procedure standard for industry, and the following measurements were obtained from the left side of each carcass after a 22-h chill period: LM area, 12^{th} rib adjusted fat thickness, marbling score, lean maturity, skeletal maturity, overall maturity, USDA yield grade, and USDA quality grade. Statistical analyses for yield grade were performed on both continuous and discrete (YG 1 = 1.00 to 1.99, YG 2 = 2.00 to 2.99, and so on) forms of data, and quality grades were further sorted into the 5 categories routinely used for determining premium or discount adjustments when cattle are marketed on a grid-based system (Prime, Upper 2/3 Choice, Low Choice, Select, and Standard and below).

Warner-Bratzler Shear Force Measurements

Following chill, striploins (longissimus dorsi m.) were collected from 3 cattle/CPE and shipped to the University of Illinois Meat Sciences Laboratory for Warner-Bratzler shear force (**WBSF**) determination. At the laboratory, the anterior end of the striploin was fabricated into 2.54-cm steaks, vacuum packaged, and aged (4°C) until 14 d postmortem. Steaks were frozen after aging, and then thawed at 4°C for 24 h before being cooked using a Farberware Open Hearth electric broiler (Farberware, Bronx, NY). Copper-constantan Type T thermocouples (Omega Engineering, Stanford, CT) connected to a digital scanning thermometer (Barnant Co., Barington, IL) were used to monitor internal temperature, and each steak was flipped a single time when the internal temperature reached 35°C. The steaks were removed from the grill when a temperature of 70°C was achieved, and cooled to approximately 25°C before 6 cores (1.25 cm diameter) were removed parallel to muscle fiber orientation. Cores were sheared perpendicular to the muscle fibers using a Texture Analyzer TA.HD Plus (Stable Microsystems, Godalming, UK) equipped with a WBSF attachment, and the peak WBSF measurement was averaged over all 6 cores to obtain a single shear force measurement (kg of force) for each steak.

Statistical Analysis

Data were analyzed using version 9.2 of SAS® (SAS Institute, Cary, NC), and CPE was the experimental unit. Continuous variables were analyzed using a linear mixed model (PROC MIXED) with LUB dose, sex and the dose × sex interaction included as fixed effects; cycle was included as a random effect. If the dose × sex interaction was not significant ($P > 0.05$), the interaction term was sequentially removed and the reduced model was used to analyze the main effects of dose. When the main effect of dose was significant ($P \leq 0.05$) or tended to be significant ($0.05 \leq P \leq 0.10$), orthogonal contrast comparing each individual non-zero LUB dose to the controls was performed in a pairwise fashion. The objective of the study was to evaluate different doses of LUB to a negative control; therefore, pairwise comparisons evaluating non-zero LUB doses against each other (i.e., 1.25 vs 5.0 g/ton, etc.) were not performed. Treatment means were estimated using the LSMEANS statement.

The minimum effective dose for standardized (BW and HCW adjusted) emission response variables was determined to be the smallest dose used in the study that differed from the control following the protected ($P < 0.05$). F-test. In order to determine the lowest maximum effective dose, a dose response curve fit to the least squares means of the doses was performed. If the dose response curve was determined to be a linear plateau model (Anderson and Nelson, 1975) and the slope or slopes were different ($P \leq 0.05$) from 0, then the maximum effective dosage was the "join point" where the plateau began. Five competing linear and linear plateau models were evaluated based on the smallest P-value indicating best fit: 1) Linear from 0 to 20 g of LUB/ton of DM; 2) Linear from 0 to 1.25 g of LUB/ton of DM, plateau from 1.25 to 20 g of LUB/ton of DM; 3) Linear from 0 to 5 g of LUB/ton of DM, plateau from 5 to 20 g of LUB/ton of DM; 4) No response from 0 to 1.25 g of LUB/ton of DM, linear from 1.25 g LY488756 / ton to 5 g LY488756 / ton, plateau from 5 to 20 g of LUB/ton of DM; and 5) No response from 0 to 1.25 g of LUB/ton, linear from 1.25 to 20 g of LUB/ton of DM.

Discrete variables were analyzed with a generalized linear mixed model using a binomial distribution and logit link function in PROC GLIMMIX. The classification of fixed and random effects and the handling of interactions and pairwise comparisons were performed in a similar manner as the continuous variables. Because the model did not converge due to sparseness of data for mortality, yield grade 4, and Select and Prime quality grades, Fisher's exact test was performed using the FREQ procedure to evaluate the frequency distribution of the control cattle compared to each LUB treatment group. Statistical significance for the main effects of dose was determined by $P \leq 0.05$ and tendencies were declared when $0.05 \leq P \leq 0.10$.

RESULTS

There were no interactions observed between dose and sex for any variable measured in the study ($P \geq 0.063$). Therefore, the results and discussion will focus on the effects of dose (***Tables 2.3, 2.4, and 2.6***), whereas the main effect of sex is reported over the entire 91-d period for reference (**Tables 2.7** and **2.8**).

Animal Health

Incidence of mortality during the treatment phase was 3, 1, 0, and 2 animals for the control, 1.25, 5.0, and 20.0 g of LUB/ton cattle, respectively, and did not differ between any LUB inclusion rate and the negative controls ($P \geq 0.246$; data not shown). Necropsy findings suggested ruminal acidosis was the likely cause of death in 4 of the 6 mortalities, and these cases were spread across treatments (1, 1, 0, and 2 animals for control, 1.25, 5.0, and 20.0 g/ton, respectively). The remaining 2 mortalities were both control cattle, with the etiologies being unknown for 1 animal and interstitial pneumonia for the other. An additional 4 cattle (2 control cattle and 2 from the 20.0 g/ton group) were removed from the study during the treatment phase: 3 due to various degrees of musculoskeletal injury and 1 due to bloat complications. No cattle were withdrawn at any point during shipment for slaughter, and all cattle passed USDA ante-mortem inspection following lairage at the abattoir.

Emissions

Lubabegron dose had no effect on cumulative emissions or cumulative emissions standardized by BW or HCW for CH_4, CO_2, H_2S, or N_2O during any interim time-period (data not shown) or for the entire 91-d LUB treatment period ($P \geq 0.268$; ***Table 2.3***). However, each dose of LUB reduced NH_3 emissions/kg BW and HCW ($P \leq 0.009$), with the magnitude of reduction in NH_3 emissions produced by feeding 1.25, 5.0 and 20 g/ton LUB over the 91-d period being 11.0, 14.0, and 14.7%/kg BW, and 12.6, 16.1 and 17.0%/kg HCW, respectively. There also tended (P = 0.052) to be an effect of dose on non-standardized NH_3 emissions, with the magnitude of reduction appearing to be somewhat dose-dependent as the emissions from cattle fed 20.0 g/ton LUB were 13.3% lower than those of the controls compared to a reduction of only 8.9% for 1.25 g/ton, and the 5.0 g/ton group being intermediate ($P \leq 0.076$).

There was an effect of dose on cumulative NH_3 emissions ($P \leq 0.022$) and NH_3 emissions/kg BW ($P \leq 0.003$) in each of the 4 time-periods corresponding to interim BW measurements (***Table 2.4***). The effect was dose-dependent from d 0 to 7, as cumulative NH_3 emissions and NH_3 emissions/kg BW were 21.4 and 21.7% lower ($P \leq 0.004$) for cattle fed 20.0 g/ton LUB compared to the controls, respectively, but neither the standardized nor non-standardized cumulative NH_3 emissions for cattle fed 1.25 or 5.0 g/ton LUB differed from the control group ($P \geq 0.139$). However, NH_3 emissions/kg BW were lower ($P \leq 0.010$) than controls for cattle fed LUB during d 0 to 14, 0 to 28 and 0 to 56, regardless of dose ($P \leq 0.010$). Cumulative NH_3 emissions from d 0 to 14 were 15.9 and 26.7% lower for the cattle fed 5.0 and 20.0 g/ton LUB ($P \leq 0.020$), respectively, while the emissions from cattle fed 1.25 g/ton only tended ($P = 0.062$) to be reduced during this period. From d 0 to 28 and d 0 to 56, LUB produced ≥ 11.5% reductions in NH_3 emissions regardless of dose ($P \leq 0.050$).

The model assuming a linear response from 0 to 5 g of LUB/ton of DM and then a plateau from 5 to 20 g of LUB/ton of DM had the best fit of the 5 models evaluated for both NH_3 emissions/kg of BW and NH_3 emissions/kg of HCW (***Table 2.5***). Therefore, the minimum effective dose and lowest maximum effective dosage were determined to be 1.25 and 5.0 g of LUB/ton of DM, respectively.

Growth Performance and Carcass Characteristics

Initial BW did not differ by dose ($P = 0.937$; ***Table 2.6***). Similarly, there was no effect of dose on DMI ($P = 0.585$). However, G:F was improved by 8.3, 9.7 and 13.2% ($P \leq 0.065$) and ADG was improved by 11.8, 9.4 and 12.6% ($P \leq 0.067$) for cattle fed 1.25, 5.0 and 20.0 g/ton LUB compared to the controls. Final BW was not altered by dose ($P = 0.257$), although final BW was at least 15 kg numerically greater for each LUB dose compared to the controls.

There was an effect of dose on HCW, dressing percentage, LM area, and KPH ($P \leq 0.035$; ***Table 2.6***), and tended ($P = 0.058$) to be an effect on marbling scores. Orthogonal contrasts revealed that each LUB dose increased HCW, dressing percentage and LM area compared to the controls ($P \leq 0.019$); however, KPH was only reduced by feeding 20.0 g/ton LUB ($P = 0.001$) and did not differ between the control cattle and the 1.25 and 5.0 g/ton LUB treatments ($P \geq 0.742$). Dose did not affect adjusted fat thickness, calculated yield grade, or skeletal, lean, and overall maturity ($P \geq 0.155$). When yield grade was analyzed as a discrete variable, the probability of cattle producing a yield grade 3 carcass was greater for control cattle compared to cattle administered LUB ($P = 0.030$; ***Figure 2.2***). However, there was no impact of treatment on the remaining yield grades ($P \geq 0.233$).

Feeding LUB shifted the quality grade distribution lower, where cattle fed LUB had a lower probability of grading high Choice ($P = 0.004$; ***Figure 2.3***) and a greater probability of grading low Choice ($P = 0.021$). Carcasses from control cattle had a greater probability of grading Prime compared to carcasses from cattle fed the 5.0 g/ton LUB ($P = 0.012$); however, the number of Prime carcasses in the 1.25 and 20.0 g/ton LUB treatments did not differ from the controls ($P \geq 0.117$). Furthermore, there was no effect of LUB on the probability of cattle grading Select or Standard ($P \geq 0.459$). Dark-cutter incidence was not influenced by LUB, as only a single carcass fell into this category over the entire study. Striploin WBSF was greater in LUB cattle compared to the controls ($P = 0.017$; ***Table 2.6***), and the increase over control ranged from 0.27 to 0.44 kg ($P \leq 0.039$).

DISCUSSION

The 2003 report on air emissions from animal feeding operations published by the National Research Council identified NH_3 as having the greatest relative importance of pollutants on a global and national to regional scale (NRC, 2003). Since then, the relative importance of NH_3 emissions has likely increased due to the expansion of the ethanol industry and increased availability of high-protein co-products for use as a low-cost feedstuff. Feeding greater proportions of these feedstuffs increases the quantity of N excreted which subsequently becomes susceptible to volatilization as NH_3 (Hales et al., 2012; Hünerberg et al., 2013). Because of the importance of NH_3 to livestock operations, in conjunction with the fact that LUB did not affect any other gas measured, NH_3 is the only gas that will discussed for the remainder of the report herein.

Air Quality Regulations

In addition to the NRC, the National Oceanic and Atmospheric Administration (**NOAA**) and the Environmental Protection Agency (**EPA**) recognize ammonia (**NH_3**) as an important pollutant involved with the deterioration of ecosystems, reduced visibility, and reductions in air quality due to formation of fine particulate matter created by reactions with nitric and sulfuric acid (Pinder et al., 2007; Hristov, 2011a; NOAA, 2014). Fine particulate matter, which refers to particles with a diameter less than 2.5 µm (**$PM_{2.5}$**), affects more humans than any other pollutant monitored and can be lethal due to the ability of particles to infiltrate pulmonary bronchioles and impair alveolar gas exchange (Hristov, 2011). To date, regulations intended to reduce inorganic $PM_{2.5}$ have focused primarily on the sulfur dioxide (SO_2) and nitrogen oxides (NO_x) rather than NH_3, not only because of their relative potencies, but also because an estimated 80% of worldwide NH_3 emissions are linked to agriculture and therefore the ability implement control strategies is considerably more challenging (Pinder et al., 2007; Hristov, 2011a; NOAA, 2014).

Pinder et al. (2007) predicted further reductions in SO_2 and NO_x will become costlier and less efficacious, and therefore called for the exploration of methods to reduce NH_3 emissions as a tool for managing $PM_{2.5}$. In the same report, Pinder et al. (2007) modeled 250 different scenarios of $PM_{2.5}$ concentrations under present-day emission rates compared to $PM_{2.5}$ concentrations if NH_3 emissions were reduced by 10 to 50%, and concluded that technologies to control NH_3 would be more cost effective compared to the current methods being used for SO_2 and NO_x. Livestock have been recognized as a major contributor to NH_3 emissions in the United States (Cole et al., 2005), and these emissions have been estimated to contribute an average of 5 to 10% of the total $PM_{2.5}$ (Hristov, 2011). Thus, it is logical to expect a tool such as LUB that reduces NH_3 emissions while improving growth performance of beef cattle would be of significant interest to the scientific community, beef producers, and the public sector.

The Comprehensive Environmental Response, Compensation, and Liability Act (**CERCLA**) and the Emergency Planning and Community Right-To-Know Act (**EPCRA**) have provided the basis for which NH_3 emissions from all industries, including agriculture, are regulated by the EPA (Waldrip et al., 2015). While livestock operations have been exempt from these regulations historically, recent activity within governing bodies in response to growing societal concerns related to the environmental footprint of livestock production may be a signal of more stringent regulations for protein producers in the near future. In 2008, the EPA ruled confined animal feeding operations (**CAFO**) were exempt from having to report NH_3 emissions under CERCLA, but feedlots with permitted capacities greater than 1,000 animals or daily NH_3 emissions surpassing 45 kg are required to report under EPCRA (Waldrip et al., 2015). As such, feedlots are required to calculate upper and lower bounds of NH_3 emissions annually using good-faith estimates of cattle inventory and emission rates set forth by the EPA, and must report those estimates to the EPA when either of these 2 criteria are exceeded.

More than a decade before the 2008 ruling by the EPA, $PM_{2.5}$ had been added as a criteria pollutant to the Clean Air Act (**CAA**), which triggered conversations regarding the potential for indirect NH_3 regulations under the CAA because NH_3 is an acknowledged precursor to $PM_{2.5}$. Clarification was not provided until a January 2013 ruling by the U.S. Court of Appeals for the District of Columbia Circuit, which deemed the precursory role of NH_3 allows it to be presumptively regulated under the CAA. In essence, this established the basis for state-level regulation of NH_3 emissions from feedlots that are located in nonattainment areas failing to fulfill the National Ambient Air Quality Standards (EPA, 2016). Not long after, heavy opposition by environmentalists claiming the 2008 CERCLA and EPCRA rulings inappropriately favor emissions from farms compared to other sources led to the CAFO exemptions being vacated during April of 2017 (Waterkeeper Alliance v. Environmental Protection Agency, 2017). As a result, livestock operations of any size may be subject to the reporting requirements outlined in CERCLA and ERPCA in the near future.

Alternative Strategies for Mitigating NH_3 Emissions

Pre-excretion strategies. Ammonia emissions from confined animal feeding operations are the result of microbial hydrolysis of urinary urea nitrogen (**UUN**) by fecal bacteria containing a urease enzyme which produces carbon dioxide and ammonium, which can then volatize to NH_3 as excreta pH alkalizes (Cole et al., 2005; Archibeque et al., 2007; Vasconcelos et al., 2007). Previous research suggests feedlot cattle only retain a small portion (10 to 30%) of the N consumed, whereas the majority is excreted as UUN (Cole et al., 2006; Koenig and Beauchemin, 2013; Waldrip et al., 2015) and dependent on factors such as protein degradability of the diet consumed and the nutrient requirements of the animal (Cole et al., 2005; Archibeque et al., 2007; Vasconcelos et al., 2007).

Although CP concentrations of the finishing diet fed in this study were based on the recommendations reported in a 2007 survey of feedlot nutritionists, it should be noted these recommendations remain relatively unchanged according to the respondents of a more recent version of the same survey (Samuelson et al., 2016). It is generally understood that the CP requirements of feedlot cattle are not static throughout a feeding period; but rather, CP requirements generally decrease as cattle mature and the composition of gain shifts from predominately protein deposition early in the feeding period to primarily fat closer to harvest (NRC, 1996). When a static CP concentration is fed, the efficiency of nitrogen utilization as a function of intake is inherently reduced and more nitrogen is excreted late in the feeding period, thereby increasing potential NH_3 losses (Cole et al., 2005; Vasconcelos et al., 2007; Vasconcelos et al., 2009). Numerous accounts exist in the literature to confirm this, such as McBride et al. (2003) who reported that the proportion of N retained in the body decreased as CP concentration and length of the feeding period increased for crossbred steers, and a trial reported by Vasconcelos et al. (2009) describing linear increases in fecal and urinary N excretion as dietary CP concentration and length of the feeding period increase. As such, it is rational that the exploration of methods aimed to improve nitrogen efficiency and mitigate N excretion as cattle mature has served as the cornerstone for research designed to alleviate NH_3 emissions from feedlots.

As potential pre-excretion strategies to reduce NH_3 emissions, precision and phase-feeding programs geared towards feeding lowered CP concentrations that still satisfy the requirement needed for optimal performance during different phases of the growth curve have been evaluated. Vasconcelos et al. (2009) reported that excretion of UUN was increased when greater percentages (14.5 vs 13.0 vs 11.5%) of dietary CP were fed to crossbred steers. Using data from the same study, Cole et al. (2005) noted *in vitro* NH_3 emissions were increased 60 to 200% after 30, 75 and 120 days from cattle fed diets targeted to contain 13.0 vs. cattle fed 11.5% CP. As a second treatment level, Cole et al. (2005) also evaluated 3 different urea inclusion rates to determine the effect of N degradability on in vitro NH_3 emissions. Although N degradability did not interact with dietary

CP, greater urea concentrations did increase NH_3 emitted over a 7-d span. More recently, Koenig et al. (2013) used a passive horizontal flux sampling technique to measure NH_3 emissions from pens of crossbred steers fed barley diets containing 12.6 or 14.0% CP, and observed a numeric reduction of nearly 50% in NH_3 in each of 5 different periods when emissions were collected over 4 d. When expressed as a fraction of N intake, NH_3 emissions were 40% less for cattle fed the lower level of CP, although the fraction emitted from either treatment (7.8 vs 12.7%) was considerably lower than what has been reported in previous work by others (Hristov, 2011; Waldrip et al., 2015). Although we cannot say definitively, the authors of the current study speculate this can likely be explained by the challenges associated with quantifying NH_3 emissions in open feedlots vs. laboratory or closed-chamber settings.

While an opportunity exists to reduce NH_3 emissions from feedlot cattle through the use of phase and precision-feeding programs, the adoption of these practices remains minimal because of logistical challenges and the potential for inadvertent reductions in growth performance that accompany their use under commercial conditions. In practical terms, reducing NH_3 by lowering dietary CP is difficult because most of the supplemental CP fed is urea, and urea is needed as a source of degradable intake N to optimize organic matter fermentation by bacteria in the rumen (Shain et al., 1998). Milton et al. (1997) and Shain et al. (1998) reported 4 to 8% increases in daily gain of crossbred steers when urea was added to a diet predominately comprised of dry-rolled corn. Likewise, Cole et al. (2006) evaluated phase-feeding programs with steam-flaked corn diets and reported the overall daily gain for cattle whose dietary CP was reduced from 13.0 to 10.0% by removing the urea fraction of the diet during the last 56 d on feed was approximately 7% lower than cattle fed 13.0% CP for the entire feeding period. When looking solely at the final 56 d of the same study, which corresponded to the timing of changes in CP inclusion for the phase-feeding treatment, the ADG of the cattle that continued to receive 13.0% CP was 8.5 and 16.3% superior compared to cattle whose urea concentrations were reduced so that their total dietary CP was 11.5 and 10.0% CP, respectively. However, cattle switched to the lower levels of CP also had lower DMI over that same time-period, which is noteworthy as this also contributed to differences in weight gain, and underlines the need to consider unintended consequences when altering diet composition in feedlots. Albeit a different source of supplemental N, Archibeque et al. (2007) described a roughly 25% reduction in feed conversion along with HCW that were 20 kg lighter in cattle fed diets formulated to contain 9.1% CP vs. diets containing soybean meal that were formulated to contain 11.8 or 13.9% CP. Collectively, these findings are especially relevant if trying to reduce NH_3 emissions, as inadvertent shortcomings in meeting protein requirements or hindering the extent of ruminal organic matter fermentation would have a detrimental effect because reductions in growth performance and longer feeding periods required to achieve a desired endpoint would inevitably increase NH_3 emissions.

Post-excretion strategies: Post-excretion modes of reducing NH_3 emissions from feedlots have also been explored, but producer adoption remains limited because of the inability to practically implement them into commercial settings (Shi et al., 2001; Todd et al., 2006; Ndegwa et al., 2008). For instance, multiple reports summarizing laboratory research designed to assess the ability of the urease inhibitor N-(n-butyl) thiophosphoric triamide (**NBPT**) for reducing NH_3 emissions from feedlot surfaces have been published in the literature. Parker et al. (2005) evaluated both NBPT application rate (0, 1, and 2 kg/ha) and frequency (8, 16 and 32 d intervals), and found that NH_3 emissions were only reduced when NBPT was applied every 8 days, and that applications greater than 1 kg/ha provided no additional benefit. The authors performed an economic analysis which concluded cost of applying the NBPT every 8 d outweighed the value of the N retained as fertilizer, and realized this monetary imbalance restricts the integration of NBPT into a production system. Shi et al. (2001b) evaluated the ability of an array of urease inhibiting or manure acidifying agents as chemical amendments to decrease NH_3 emissions over 21 d, and also reported no additional reductions in NH_3 when doubling the NBPT application rate from 1 to 2 kg/ha. However, the 65% reduction in NH_3 emissions using 1 kg/ha NBPT in this study was substantially greater than the 49% reduction in the study by Parker et al. (2005a), and resulted in a favorable benefit-to-cost analysis, although the cost of labor was not accounted for in their analysis. Expanding on the same study by Shi et al. (2001b), aluminum sulfate produced 98.3% reductions in NH_3; yet, even with such substantial reductions in NH_3 emissions, the authors conceded that the cost of application (projected to cost $21.72/animal in 2005 for a 120-d feeding period if applied every 21 d) relative to the benefit derived by the producer would likely prohibit adoption in the field.

Contrary to the *in vitro* research previously described, peer-reviewed reports of large-scale field studies supporting the efficacy of urease inhibitors as a post-excretion strategy to reduce NH_3 emissions from feedlot surfaces do not exist to our knowledge. Parker et al. (2005b) measured NH_3 from feedlot pens using flux chambers and a chemiluminescence gas analyzer similar to the one used in this study, and reported no difference after 6 d between a negative control pen and a pen treated with 40 kg/ha NBPT. Varel et al (1999) described 2 studies where manure samples were collected serially from the area adjacent to the concrete feed apron in feedlot pens that had been treated with either NBPT, another urease inhibitor (cyclohexylphosphoric triamide; **CHPT**), or no urease inhibitor. The first study compared both urease inhibitors to a negative control over 14 d and reported transient urea accumulation, although the ability to prevent volatilization appeared to taper as no urea was found in samples obtained beginning on d 11 and 14 for pens treated with

CHPT and NBPT, respectively. The second study involved 2 phases: phase I evaluated weekly applications of NBPT over 6 wk, and phase II spanned the 30 d following the last application of NBPT. Similar to the first study, urea accumulation in the manure was greater in pens where NBPT was applied; however, urea levels rapidly declined during the 30 d period after the last application. Although actual NH_3 volatilization was not measured in these studies, the ability of NBPT and CHPT to increase urea in manure from open-aired feedlot pens is encouraging, as UUN has been established as the predominant driver of NH_3 emissions. Still, these results simultaneously shine a light on the shortcomings of these chemical amendments for use as long-term tools, as the frequency and cost of application required to have a meaningful impact on NH_3 emissions are not practical.

Other post-excretion strategies to enhance manure N retention and minimize volatilization losses have been examined. Lorey et al. (2002) documented nearly 80% improvements in manure N retention following a 132-d feeding period from pens that were bedded with sawdust twice/wk compared to open-dirt pens, although the labor and time associated with this practice is certainly prohibitive in commercial settings. In the same study, acidification (pH < 5.5) of the pen floor surface using sulfuric acid did not reduce N losses compared to the control group, which is surprising as NH_3 volatilization is greatest in alkaline conditions and lower pH favors the formation of non-volatile NH_4 (McCrory and Hobbs, 2001; Shi et al., 2001). Adams et al. (2004) studied different diet compositions and pen cleaning frequencies, and reported interesting results whereby feeding 30% corn bran reduced calculated N loss compared to cattle fed greater proportions of dry-rolled corn when pens were cleaned monthly, but actually increased N loss when pens weren't cleaned until the end of the feeding period. Cole et al. (2007) described up to 67% reductions in NH_3 emissions when potassium zeolite was added as an amendment to simulated feedlot surfaces *in vitro*, but provided data in the same report suggesting it loses efficacy when applied through the feed. Sherwood et al. (2005) produced similar results where feeding a zeolite did not reduce calculated N volatilization losses in an open feedlot environment, further suggesting *in vivo* transformations render the zeolite ineffective as a post-excretion tool. Collectively, the cost and labor, in addition to the lack of field efficacy or alternative routes of application while maintaining efficacy, limit the feasibility of the afore mentioned post-excretion strategies being implemented into commercial feedlot settings for NH_3 indications.

A Modern Approach

Research geared towards improving the environmental stewardship of meat production will be vital in the future as the world population and consumption of meat-based diets both continue to surge. To date, life cycle assessments have been the primary means for evaluating the effect of growth promoting technologies on the environmental impact of livestock production systems, and typically focus on reducing resources (e.g. feedstuffs, water, land) or maximizing productivity (e.g. growth rate, slaughter weight) while holding the other constant (Pelletier et al., 2010b; Capper, 2011; Capper and Hayes, 2012). For example, a recent meta-analysis of life cycle assessments encompassing 742 food production systems by Clark and Tilman (2017) suggest increasing resource efficiency in conventional systems would be more advantageous for the environment than switching to non-conventional systems. On the other hand, previous researchers have employed an approach similar to our study and outlined the environmental benefit of various growth-enhancing technologies by collecting an array of emissions measurements (Cooprider et al., 2011; Stackhouse-Lawson et al., 2013a). However, the clinical effectiveness program designed for LUB (Experior™; Elanco Animal Health, Greenfield, IN) is unique as it is the first technology approved based on a quantifiable reduction in emissions measured for a specific analyte.

The results of the current study show LUB reduces NH_3 emissions/kg of BW and HCW when fed at a dose as low as 1.25 g/ton of DM; no additional reduction in NH_3 emissions were observed when LUB was fed at doses greater than 5.0 g/ton of DM over the 91 d feeding period [the inclusion rate range approved by the FDA is 1.4 to 5.0 g of LUB/ton DM; full information regarding the label can be referenced in the FOI (FDA, 2018)]. There are 3 avenues which can result in reductions in NH_3/kg of BW and HCW: 1) reduced NH_3 emissions, 2) increased BW and/or HCW, or 3) a combination of both. The reductions in NH_3 emissions/kg of BW or HCW for cattle fed LUB are driven not only by decreases in NH_3 emissions, but also by increased weight. The quantitative reduction of 8.9 to 13.3% in NH_3 emissions relative to control cattle observed in concert with a 4.6%-increase in HCW provides evidence that LUB works on both sides of the ratio. From this, some general modes of action of LUB can be hypothesized. First, it is unlikely that the reduction in NH_3 by cattle fed LUB was a function of reduced N intake. Dietary CP was constant across treatments due to the common diet being fed, and feed intake was either equivalent or numerically greater for cattle fed LUB. The most likely explanation to describe how LUB reduces NH_3 emissions while concurrently improving growth performance is to consider a greater retention of nutrients within the body. Because protein comprises 16.5% of a beef carcass (Benedict, 1987; Heinz and Hautingzer, 2007) and protein is 16% N, it is reasonable to hypothesize that a greater magnitude of protein accretion in the carcass would result in more N being captured and thus not available to be excreted as UUN with subsequent volatilization as NH_3. A major source of the additional N deposited into beef carcass can be derived from reduced NH_3 emissions since ammonia is 82.2% N.

Recent research supports the hypothesis that β-ligands elicit their effects by retaining more nutrients in the body to be preferentially deposited in the carcass as lean tissue, rather than by an *in vivo* N shift from abdominal viscera to skeletal muscle. Walter et al. (Walter et al., 2016) reported that cattle fed a β_2 agonist (zilpaterol hydrochloride) had greater skeletal muscle protein and improved N retention as a percent of digested N, and Holland et al. (2010) observed increases in HCW without reductions in offal mass in cattle fed zilpaterol. Still, while the authors hypothesize LUB conserves nitrogen from being emitted as NH_3, studies conducted as part of the drug development process suggest LUB also directs nutrients into tissue cells by improving responsiveness to insulin (Elanco Animal Health, unpublished data). Insulin area under the curve was 33% less in steers fed LUB (after 21 days of being on treatment diets) compared to control after intravenous infusion with 0.5 mL of a 50% glucose solution/kg of BW. Additionally, significant reductions in circulating glucose concentrations have also been observed in cattle fed LUB, which could be an indication that insulin is more effective in driving glucose into the cell in LUB treated cattle. It is also known that insulin stimulates the uptake of amino acids into cells. These data highlight the need for additional research to gain a better understanding of how LUB may elicit its effects.

Recent research pertaining to the sustainability of livestock production has focused on 3 major pillars: society, economics, and the environment (Cooprider et al., 2011; White et al., 2014). As the first feed additive approved by the FDA to reduce NH_3 emissions, lubabegron is a novel technology that addresses these 3 pillars of sustainability by providing beef producers with a flexible tool to more efficiently produce beef in an environmentally responsible manner.

Tables and Figures

Table 2.1. Ingredient composition (DM basis) and analyzed nutrient content of the finishing diet fed during the 91-d treatment phase.[1]

Ingredient	% of DM
Ground corn[2]	2.5
Dried distiller's grains with solubles	10.0
Steam-flaked corn	63.5
Tallow	3.0
Cane molasses	6.0
Alfalfa	6.0
Wheat straw	6.0
Limestone	1.4
Urea	1.1
Salt	0.3
Trace minerals[3]	0.2
Total	100.0
Analyzed nutrient content, DM basis[3]	
DM	76.5
CP, % of DM	14.2
Ca, % of DM	0.66
P, % of DM	0.31
Calculated DIP[4]	9.34
Calculated UIP[4]	4.86
Calculated NE_m, $Mcal \cdot kg^{-1}$	2.21
Calculated NE_g, $Mcal \cdot kg^{-1}$	1.54

[1]Water was included at 7.5% of as-fed feed in order to reduce likelihood of segregation of ingredients within the Type C feed.

[2]Ground corn was fed without LUB in the negative control treatment group and served as the carrier for LUB in the 1.25, 5.0, and 20.0 g/ton treatment groups.

[3]Formulated to contain: 90.60% MgO, 5.05% $MnSO_4$, 2.31% $CuSO_4$, 1.98% ZnO, 0.03% KI, 0.02% Na_2SeO_3, and 0.01% $CoSO_4$.

[4]DIP = Degradable intake protein, UIP = Undegradable intake protein. The sum of DIP and UIP = CP. The DIP, UIP, NEm, and NEg were calculated based on the NRC (2000).

Table 2.2. Maximum, minimum and mean daily ambient temperature (TA), relative humidity (RH) and temperature humidity index

	TA, ºC			RH, %			THI[2]		
Source/Cycle	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
Ambient air									
Cycle 1	42.5	10.1	23.9	70.4	12.9	47.7	86.2	48.6	67.8
Cycle 2	40.0	7.7	21.5	71.3	13.4	52.1	85.9	44.0	65.0
Cycle 3	25.6	0.8	12.2	64.8	18.4	43.2	72.5	31.5	52.7
Cattle pen enclosures									
Cycle 1	40.4	9.0	21.2	94.4	19.5	72.7	85.5	51.9	69.1
Cycle 2	40.0	6.4	19.1	98.7	23.1	79.2	83.3	48.3	66.5
Cycle 3	26.6	-0.8	11.5	99.9	27.5	86.8	70.2	38.7	55.2

[1]The temperature (TA) and relative humidity (RH) within CPEs were monitored every 15 s during the 15 min emissions sampling periods using RH/T sensors (Dwyer Instruments, Inc., Michigan City, IN), and the same measurements were obtained for outside ambient air continuously using an on-site weather station (Novalynx, Model 110-WS-16, Auburn, CA).

[2]THI was calculated using the same equation as Mader et al. (2006) where THI = (0.8 × TA) + [(RH × 0.01) × (TA – 14.4)] + 46.4; TA = Ambient Temperature; RH = Relative Humidity.

(THI).[1]

Table 2.3. Least squares means for the effect of lubabegron (LUB) dose on cumulative emissions and cumulative emissions standardized by final BW and HCW for 5 gases measured from cattle pen enclosures (CPE) over 91 d.[1]

Variable	LUB (g/ton DM) 0.0	1.25	5.0	20.0	SEM	Dose × Sex *P*-value[2]	Dose *P*-value[2]	Significance of contrast: Control vs. 1.25 g/ton	Control vs. 5.0 g/ton	Control vs. 20.0 g/ton
Final BW, kg[3]	567	583	582	582	19.4	0.916	0.257			
HCW, kg	349	364	365	365	11.7	0.865	0.035	0.019	0.014	0.014
NH_3										
Total emissions, g/animal	7,783	7,093	6,860	6,751	855	0.281	0.052	0.076	0.023	0.013
Standardized by BW, g/kg	13.6	12.1	11.7	11.6	1.19	0.161	0.004	0.009	0.002	< 0.001
Standardized by HCW, g/kg	22.3	19.5	18.7	18.5	1.97	0.147	0.001	0.004	< 0.001	< 0.001
CH_4										
Total emissions, g/animal	10,466	10,692	10,763	10,476	638	0.712	0.895			
Standardized by BW, g/kg	18.4	18.3	18.5	18.0	1.06	0.439	0.858			
Standardized by HCW, g/kg	30.0	29.3	29.5	28.7	1.81	0.376	0.601			
CO_2										
Total emissions, g/animal	720,485	757,740	734,295	755,048	47,338	0.616	0.302			
Standardized by BW, g/kg	1,268	1,299	1,261	1,299	61.3	0.322	0.268			
Standardized by HCW, g/kg	2,061	2,081	2,013	2,070	107.8	0.269	0.331			

[1]Emissions were measured from an individual CPE (n = 8) over 15-min sampling periods using calibrated, gas-specific analyzers (Thermo Environmental Instruments (TEI), Waltham, MA). This procedure was continuous so that a maximum of 11 sampling periods were available for determination of daily emission rates/animal for each CPE. Emissions were measured from 0800 h on d 1 until 0500 h on d 91.

[2]Insignificant interactions ($P \geq 0.05$) were sequentially removed and the reduced model was used to evaluate the main effects of LUB dose. Statistical significance for dose was declared when $P \leq 0.05$ and tendencies were declared when $0.06 \leq P \leq 0.10$.

[3]Unshrunk; initial BW did not differ by dose ($P = 0.937$; ***Table 2.6***).

[4]Measured values from CPE's were less than the values reported from ambient air, resulting in negative values.

Table 2.3. Continued.

Variable	LUB (g/ton DM) 0.0	1.25	5.0	20.0	SEM	Dose × Sex *P*-value[2]	Dose *P*-value[2]	Significance of contrast: Control vs. 1.25 g/ton	Control vs. 5.0 g/ton	Control vs. 20.0 g/ton
H_2S										
Total emissions, g/animal	20.6	19.9	20.3	20.0	6.04	0.581	0.975			
Standardized by BW, g/kg	0.035	0.033	0.035	0.033	0.0110	0.417	0.905			
Standardized by HCW, g/kg	0.057	0.055	0.055	0.055	0.0176	0.379	0.776			
N_2O[4]										
Total emissions, g/animal	-27.4	-36.8	-36.4	-34.7	10.2	0.279	0.627			
Standardized by BW, g/kg	-0.046	-0.062	-0.060	-0.060	0.0154	0.306	0.693			
Standardized by HCW, g/kg	-0.075	-0.097	-0.095	0.095	0.0264	0.311	0.742			

[1]Emissions were measured from an individual CPE (n = 8) over 15-min sampling periods using calibrated, gas-specific analyzers (Thermo Environmental Instruments (TEI), Waltham, MA). This procedure was continuous so that a maximum of 11 sampling periods were available for determination of daily emission rates/animal for each CPE. Emissions were measured from 0800 h on d 1 until 0500 h on d 91.

[2]Insignificant interactions ($P \geq 0.05$) were sequentially removed and the reduced model was used to evaluate the main effects of LUB dose. Statistical significance for dose was declared when $P \leq 0.05$ and tendencies were declared when $0.06 \leq P \leq 0.10$.

[3]Unshrunk; initial BW did not differ by dose ($P = 0.937$; ***Table 2.6***).

[4]Measured values from CPE's were less than the values reported from ambient air, resulting in negative values.

Table 2.4. Least squares means for the effect of lubabegron (LUB) on cumulative NH_3 emissions and standardized cumulative NH_3 emissions corresponding to each BW measurement.[1]

	LUB (g/ton DM)							Significance of contrast		
Variable	**0.0**	**1.25**	**5.0**	**20.0**	**SEM**	**Dose × Sex *P*-value[2]**	**Dose *P*-value[2]**	**Control vs. 1.25 g/ton**	**Control vs. 5.0 g/ton**	**Control vs. 20.0 g/ton**
BW, kg										
Initial	451	454	455	452	10.0	0.996	0.937			
d 7	464	469	470	469	10.4	0.968	0.935			
d 14	474	484	484	478	12.3	0.962	0.655			
d 28	496	508	506	501	12.2	0.990	0.627			
d 56	529	545	542	539	15.2	0.974	0.411			
Final	567	583	582	582	19.4	0.916	0.257			
NH_3, g										
d 0 to 7	415	394	387	326	49.1	0.746	0.022	0.439	0.300	0.004
d 0 to 14	953	835	801	699	106	0.802	0.006	0.062	0.020	< 0.001
d 0 to 28	2,097	1,783	1,686	1,563	265	0.573	0.006	0.027	0.006	< 0.001
d 0 to 56	4,619	4,089	3,888	3,763	540	0.420	0.019	0.050	0.011	0.004
d 0 to 91	7,783	7,093	6,860	6,751	855	0.281	0.052	0.076	0.023	0.013
NH_3, g/kg BW										
d 0 to 7	0.89	0.84	0.82	0.70	0.106	0.619	0.003	0.278	0.139	< 0.001
d 0 to 14	2.01	1.73	1.66	1.47	0.223	0.698	< 0.001	0.010	0.002	< 0.001
d 0 to 28	4.21	3.53	3.33	3.13	0.509	0.463	< 0.001	0.004	< 0.001	< 0.001
d 0 to 56	8.66	7.50	7.14	6.99	0.871	0.258	< 0.001	0.004	< 0.001	< 0.001
d 0 to 91	13.6	12.2	11.7	11.6	1.19	0.161	0.004	0.009	0.002	< 0.001

[1]Emissions were measured from an individual CPE (n = 8) over 15-min sampling periods using calibrated, gas-specific analyzers (Thermo Environmental Instruments (TEI), Waltham, MA). This procedure was continuous so that a maximum of 11 sampling periods were available for determination of daily emission rates/animal for each CPE. Daily gas emissions were defined as those within the span beginning at 0800 h and ending at 0759 h the next morning. Cumulative emissions were standardized by the BW measured on the day corresponding to the emissions time-period for reporting.

[2]Insignificant interactions ($P \geq 0.05$) were sequentially removed and the reduced model was used to evaluate the main effects of dose. Statistical significance for dose was declared when $P \leq 0.05$ and tendencies were declared when $0.06 \leq P \leq 0.10$.

Table 2.5. Comparison of 5 linear and linear plateau models used to determine the minimum effective and lowest maximum effective lubabegron (LUB) doses for reducing ammonia (NH_3) emissions per kilogram of body weight and hot carcass weight over the entire 91-d period.[1]

	Model[2]				
Variable	1	2	3	4	5
NH_3/kg BW, *P*-values	0.0107	0.0005	0.0004	0.0033	0.0052
NH_3/kg HCW, *P*-values	0.0056	0.0002	0.0001	0.0015	0.0025

[1]The minimum effective dose for standardized (BW and HCW adjusted) emission response variables was determined to be the smallest dose used in the study that differed from the control following the protected ($P < 0.05$). *F*-test. In order to determine the lowest maximum effective dose, a dose response curve fit to the least squares means of the doses was performed. If the dose response curve was determined to be a linear plateau model (Anderson and Nelson, 1975) and the slope or slopes were different ($P \leq 0.05$) from 0, then the maximum effective dosage was the "join point" where the plateau began.

[2]Five competing linear and linear plateau models were evaluated based on the smallest *P*-value indicating best fit: 1) Linear from 0 to 20 g of LUB/ton of DM; 2) Linear from 0 to 1.25 g of LUB/ton of DM, plateau from 1.25 to 20 g of LUB/ton of DM; 3) Linear from 0 to 5 g of LUB/ton of DM, plateau from 5 to 20 g of LUB/ton of DM; 4) No response from 0 to 1.25 g of LUB/ton of DM, linear from 1.25 g LY488756 / ton to 5 g LY488756 / ton, plateau from 5 to 20 g of LUB/ton of DM; and 5) No response from 0 to 1.25 g of LUB/ton, linear from 1.25 to 20 g of LUB/ton of DM.

Table 2.6. Least squares means for the effect of lubabegron (LUB) on growth performance traits and carcass characteristics of beef cattle over a 91-d treatment period.

Variable	LUB (g/ton DM)				SEM	Dose × Sex *P*-value[1]	Dose *P*-value[1]	Significance of contrast		
	0.0	1.25	5.0	20.0				Control vs. 1.25 g/ton	Control vs. 5.0 g/ton	Control vs. 20.0 g/ton
Growth performance[2]										
Initial BW, kg	451	454	455	452	10.0	0.996	0.937			
Final BW, kg	567	583	582	582	19.4	0.916	0.257			
DMI, kg	8.8	9.2	8.8	8.8	0.56	0.980	0.585			
ADG, kg	1.27	1.42	1.39	1.43	0.126	0.724	0.075	0.027	0.067	0.023
G:F, kg:kg	0.144	0.156	0.158	0.163	0.0071	0.856	0.031	0.065	0.033	0.005
Carcass characteristics										
HCW, kg	349	364	365	365	11.7	0.865	0.035	0.019	0.014	0.014
Dressing percentage[2]	61.5	62.4	62.7	62.8	0.34	0.738	0.002	0.006	< 0.001	< 0.001
Adjusted fat thickness, cm	1.28	1.15	1.24	1.19	0.119	0.994	0.579			
LM area, cm^2	88.4	94.8	96.1	96.8	1.78	0.063	< 0.001	< 0.001	< 0.001	< 0.001
Marbling score[3]	623	573	560	562	16.7	0.979	0.058	0.051	0.018	0.022
Calculated yield grade[4]	2.68	2.37	2.41	2.25	0.164	0.816	0.155			
KPH, %	1.96	1.99	1.96	1.61	0.066	0.802	0.002	0.742	0.981	0.001
Lean maturity[5]	162	163	167	163	3.5	0.731	0.262			
Skeletal maturity[5]	172	170	170	172	1.9	0.585	0.592			
Overall maturity[5]	169	168	169	168	2.5	0.639	0.805			
14-d WBSF[6], kg	2.48	2.79	2.92	2.75	0.117	0.620	0.017	0.022	0.003	0.039

[1]Insignificant interactions ($P \geq 0.05$) were sequentially removed and the reduced model was used to evaluate the main effects of dose. Statistical significance for dose was declared when $P \leq 0.05$ and tendencies were declared when $0.06 \leq P \leq 0.10$.
[2]Growth performance and dressing percentage were based on unshrunk initial and final BW.
[3]Marbling was evaluated in the longissimus dorsi m. between the 12th and 13th ribs and expressed as a combination of a marbling category and degree (e.g. Sm30), and then converted to a numerical score for analysis: Small = 500 to 599, Modest = 600 to 699, etc.
[4]Yield Grade = 2.50 + (2.50 × adj. fat thickness, in) + (0.2 × KPH) + (0.0038 × HCW, lb) – (0.32 × LM, in^2) (USDA, 1997)
[5]100 = A maturity; 200 = B maturity
[6]WBSF = Warner-Bratzler shear force, measured after a 14-d aging period

Table 2.7. Least squares means for the effect of sex on growth performance, carcass characteristics and NH_3 emissions in beef cattle over a 91-d period.

	Sex				
Variable	**Steers**	**Heifers**	**SEM**	**Dose × Sex *P*-value**[1]	**Sex *P*-value**[1]
Growth performance[2]					
Initial BW, kg	475	432	9.2	0.996	< 0.001
Final BW, kg	601	556	18.9	0.916	< 0.001
DMI, kg	9.1	8.6	0.53	0.980	0.038
ADG, kg	1.38	1.38	0.12	0.724	0.875
G:F, kg:kg	0.151	0.159	0.0065	0.856	0.064
Carcass characteristics					
HCW, kg	376	346	11.3	0.865	< 0.001
Dressing percentage[2]	62.5	62.2	0.30	0.738	0.078
Adjusted fat thickness, cm	1.13	1.30	0.110	0.994	0.024
LM area, cm^2	14.7	14.5	0.26	0.063	0.216
Marbling score[3]	567	592	11.8	0.979	0.156
Calculated yield grade[4]	2.39	2.46	0.137	0.816	0.582
KPH, %	1.65	2.10	0.049	0.802	< 0.001
Lean maturity[5]	164	164	3.3	0.731	0.854
Skeletal maturity[5]	167	175	1.7	0.585	< 0.001
Overall maturity[5]	166	171	2.4	0.639	< 0.001
14-d WBSF[6], kg	2.80	2.67	0.100	0.620	0.142

[1]Insignificant interactions ($P \geq 0.05$) were sequentially removed and the reduced model was used to evaluate the main effects of sex. Statistical significance for sex was declared when $P \leq 0.05$ and tendencies were declared when $0.06 \leq P \leq 0.10$.
[2]Growth performance and dressing percentage were based on unshrunk initial and final BW.
[3]Marbling was evaluated in the longissimus dorsi m. between the 12th and 13th ribs and expressed as a combination of a marbling category and degree (e.g. Sm30), and then converted to a numerical score for analysis: Small = 500 to 599, Modest = 600 to 699, etc.
[4]Yield Grade = 2.50 + (2.50 × adj. fat thickness, in) + (0.2 × KPH) + (0.0038 × HCW, lb) – (0.32 × LM, in^2) (USDA, 1997)
[5]100 = A maturity; 200 = B maturity
[6]WBSF = Warner-Bratzler shear force, measured after a 14-d aging period

Table 2.8. Least squares means for the effect of sex on cumulative emissions and cumulative emissions standardized by final BW and HCW for 5 gases from cattle measured over 91 d.[1]

	Sex				
Variable	**Steers**	**Heifers**	**SEM**	**Dose × Sex *P*-value[1]**	**Sex *P*-value[1]**
Final BW, kg	601	556	18.9	0.916	< 0.001
HCW, kg	376	346	11.3	0.865	< 0.001
NH_3					
Total emissions, g/animal	7,264	6,979	835.3	0.281	0.283
Standardized by BW, g/kg	12.0	12.5	1.16	0.161	0.198
Standardized by HCW, g/kg	19.3	20.1	1.75	0.147	0.153
CH_4					
Total emissions, g/animal	11,169	10,029	591.3	0.712	0.005
Standardized by BW, g/kg	18.6	18.1	1.02	0.439	0.200
Standardized by HCW, g/kg	29.7	29.1	1.75	0.376	0.298
CO_2					
Total emissions, g/animal	764,608	719,176	46,084.4	0.616	0.010
Standardized by BW, g/kg	1,271	1,293	60.2	0.322	0.216
Standardized by HCW, g/kg	2,033	2,080	106.0	0.269	0.109
H_2S					
Total emissions, g/animal	21.5	18.9	5.96	0.581	0.066
Standardized by BW, g/kg	0.035	0.034	0.0101	0.417	0.385
Standardized by HCW, g/kg	0.057	0.054	0.0164	0.379	0.430
N_2O					
Total emissions, g/animal	-42.5	-25.1	9.35	0.279	0.008
Standardized by BW, g/kg	-0.070	-0.044	0.0146	0.306	0.017
Standardized by HCW, g/kg	-0.112	-0.070	0.0235	0.311	0.018

[1]Insignificant interactions ($P \geq 0.05$) were sequentially removed and the reduced model was used to evaluate the main effects of sex. Statistical significance for sex was declared when $P \leq 0.05$ and tendencies were declared when $0.06 \leq P \leq 0.10$.

[3]Marbling was evaluated in the longissimus dorsi m. between the 12th and 13th ribs and expressed as a combination of a marbling category and degree (e.g. Sm30), and then converted to a numerical score for analysis: Small = 500 to 599, Modest = 600 to 699, etc.

[4]Yield Grade = 2.50 + (2.50 × adj. fat thickness, in) + (0.2 × KPH) + (0.0038 × HCW, lb) – (0.32 × LM, in^2) (USDA, 1997)

[5]100 = A maturity; 200 = B maturity

[6]WBSF = Warner-Bratzler shear force, measured after a 14-d aging period

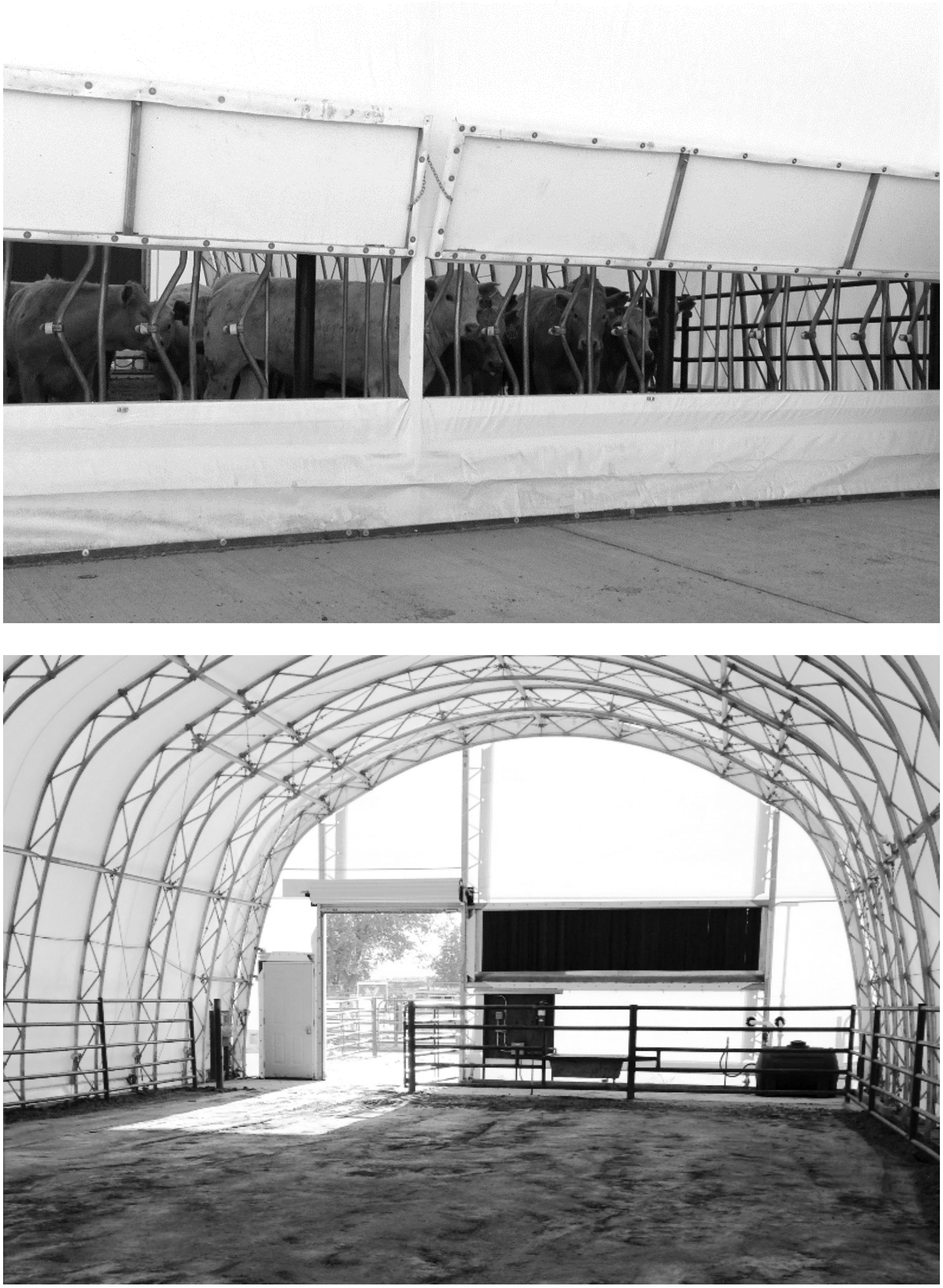


Figure 2.1. Cattle pen enclosures (CPE).

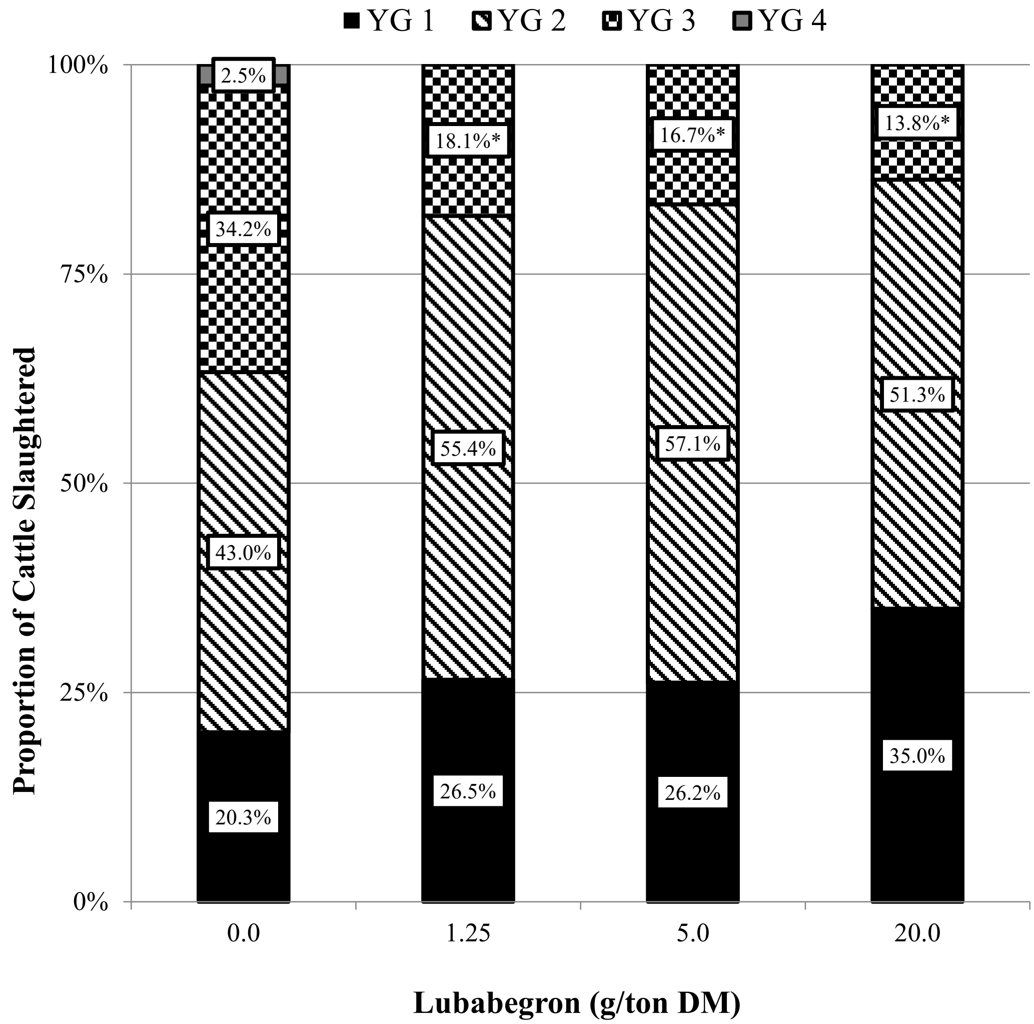


Figure 2.2. Discrete yield grade expressed as a proportion of the cattle slaughtered within each treatment. Within a yield grade category, means for the non-zero LUB treatment groups marked with an "*" differ from the control ($P \leq 0.05$). Values represented in this figure are arithmetic means, whereas the denoted differences are between the least squares means calculated using PROC GLIMMIX and represent the probability of cattle in a pen displaying a given response.

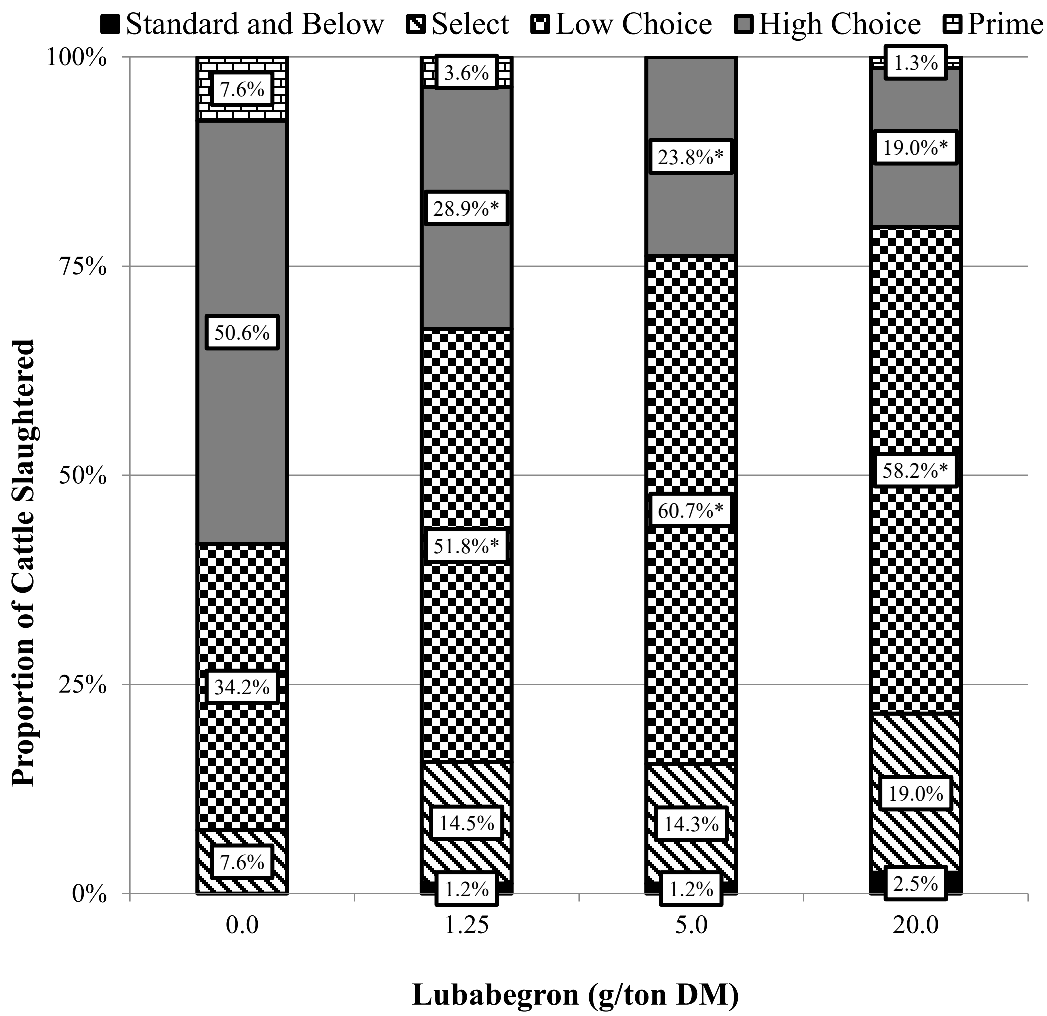


Figure 2.3. Quality grade expressed as a proportion of the cattle slaughtered within each treatment. Within a quality grade, means for the non-zero LUB treatment groups marked with an "*" differ from the control ($P \leq 0.05$). Values represented in this figure are arithmetic means, whereas the denoted differences are between the least squares means calculated using PROC GLIMMIX and represent the probability of cattle in a pen displaying a given response.

Chapter 3 An economic assessment of United States ground beef in response to the introduction of plant-based meat alternatives

ABSTRACT

Red-meat has been criticized as detrimental to both the environment and human health, leading to a push in the US for consumers to reduce red-meat consumption, beef in particular. Plant-based meat alternatives (MA) may provide viable replacements for ground beef (GB) due to their reportedly lower environmental impacts; however, they do not replace the actual source of GB, cattle. Cattle production is a vital part of the U.S. food supply chain and plays an important role in the economy. As such, the goal of the present research was to perform a comprehensive assessment of the economic impacts associated with a reduction in GB consumption in response to increased MA consumption in the U.S. The Global Trade Analysis Project (GTAP) was used to model GB production in the U.S. While there was a cattle meat sector in GTAP, there was not a unique sector for GB. SplitCom was used to disaggregate the cattle meat sector into two sectors: (1) GB and (2) other beef products (OB). GTAP then was aggregated into 19 sectors, 3 regions (the U.S., primary U.S. beef import countries, and rest of world), and 6 factors of production. As the private household budget share for GB was 0.31%, the investigated reductions in consumer purchase and consumption (1, 5, 10, and 15%) did not greatly impact overall economic output. Even at 15% reduction in GB, most sectors experienced minor changes in terms of price or quantity demanded. Most notably, land use and price for cattle (CTL) was reduced by 2.89% and 4.78%, respectively. Agricultural labor and capital were reduced by nearly 10% each for GB and 4% each for CTL. While these results do not account for the economic effects of a corresponding increase in consumer demand for MA, it is unlikely that more significant changes would be observed. Further analysis on this topic is needed to understand the economic impacts of a reduction in GB paired with a corresponding increase in MA.

Key words: GTAP, multi-regional input-output, cattle, sustainability, protein

INTRODUCTION

Climate change is one of the greatest issues facing humanity today. Average global temperatures have increased by 1°C and the sea level has risen 0.19 m above pre-industrial levels (IPCC, 2014; IPCC, 2019b). Anthropogenic greenhouse gas (GHG) emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have been the primary drivers of climate change (IPCC, 2014). More than half of anthropogenic GHG emissions have been produced in the past 40 years and despite policies and efforts to mitigate emissions from countries around the world, the largest absolute increases have been observed between 2000 and 2010 (IPCC, 2014). Climate change impacts have been observed across the globe, from the melting of polar ice caps to the changing of migration patterns, ranges, and seasonal activities of terrestrial and aquatic species (IPCC, 2014). Economic and population growth have been the greatest drivers of increased emissions, due to increases in CO_2 emissions from fossil fuel combustion; meanwhile, human food production, livelihoods, and health have been directly impacted by the resulting climate change (IPCC, 2014; IPCC, 2019b). The United Nations Paris Agreement aims to address climate change by holding increases in global temperatures to below 2 °C above pre-industrial levels and to pursue efforts to limit temperature increase to 1.5 °C above pre-industrial levels (UN, 2015). If sizeable and sustained reductions in GHG emissions are not achieved, further warming will result in long-lasting and irreversible impacts on both people and ecosystems (IPCC, 2014; IPCC, 2019b).

One strategy proposed to help address the climate crisis is for consumers to change their eating habits. In particular, there has been call for consumers to minimize beef consumption as a means of reducing their individual carbon footprints (Reynolds et al., 2014; Westhoek et al., 2014; Hartmann and Siegrist, 2017; Poore and Nemecek, 2018; Springmann et al., 2018; Willett et al., 2019; Aiking and de Boer, 2020). Globally, livestock production contributes to 14.5% of humaninduced GHG emissions, with beef cattle contributing to 41% of these emissions (Gerber et al., 2013). The short-lived climate pollutant, CH_4, emitted as a result of the digestion process of cattle is the primary source of GHG from cattle production (France and Dijkstra, 2005). Mitigation of CH_4 emissions by means of improved genetics, feeding efficiency, and feed additives have proven helpful in reducing the climate change impacts from cattle in the United States and the European Union plus the United Kingdom, where cattle contribute to 3.4% (2.16% for beef cattle, specifically) and 4.99% of national GHG emissions, respectively (EEA, 2021; EPA, 2021). However, this is not the case in many developing countries around the world where cattle producers often lack access to these advanced technologies. Cattle, as a result, require more resources, produce less beef per unit input, and emit more overall GHG, rendering them less sustainable and more GHG intensive than their U.S. or EU counterparts (Gerber et al., 2013; Gerber et al., 2015). Given these inconsistences, a growing global population and the rising demand for meat has called into question whether beef can remain a sustainable part of the human diet. Recently, Willett et al., (2019) proposed a universal healthy reference diet with the goal of meeting worldwide nutritional needs while addressing climate change among five other primary environmental concerns associated with food production. Included in this universal diet is the recommendation to "limit red meat, by at least 50%, with a recommended daily combined intake of 14 g (in a range that suggests total meat consumption of no more than 28 g/day)."

As a result of calls to reduce beef and other red meat consumption, there has been an increase in research and development of meat alternatives (MA) – products made from plants, insects, and even cell culture that aim to mimic the look, texture, and taste of conventional animal proteins (Bonny et al., 2017; Kyriakopoulou et al., 2018; Lee et al., 2020; Santo et al., 2020). The idea being that MA made from plants, insects, or cell culture will require fewer resources and result in less GHG emissions than conventional animal sourced proteins (Candy et al., 2019; Chen et al., 2019; Godfray et al., 2019; Aiking and de Boer, 2020; Santo et al., 2020; Smetana et al., 2020; Eisen and Brown, 2021). Meat alternatives made to substitute ground meat products, such as burger patties and sausages, have been the most successful in mimicking the look and texture of their conventional counterparts; however, there has been limited success in replicating the taste of animal proteins or the satisfaction consumers experience when eating meat (Hartmann and Siegrist, 2017; Davis et al., 2021). Impossible Foods and Beyond Burger are the first companies who claim to have successfully created a plant-based meat patty that not only successfully mimics the look and texture of a traditional ground beef (GB) patty, but also the taste and satisfaction of eating a GB burger. Both alternative patties contain technology that even allows these patties to "bleed" like a traditional beef patty. With the creation of the Impossible Burger (IB) and Beyond Burger (BB), these companies suggest that there is no longer a need for consumers to eat conventional beef and promote their products as the more sustainable food choice.

To demonstrate the sustainability of IB and BB, both Impossible Foods and Beyond Meat have commissioned life cycle assessments of their products compared to GB (Goldstein et al., 2017; Heller and Keoleian, 2018; Khan et al., 2019). According to these works, on a per kg product basis, both IB and BB use 96% and 93% less land, 87-97% and 99% less water, and produce 77-89% and 89% less GHG emissions, respectively, than U.S. produced GB (Goldstein et al., 2017; Heller and Keoleian, 2018; Khan et al., 2019). While both IB and BB are thought to be more sustainable than GB, this is based solely on environmental impacts and does not incorporate a full picture of sustainability. Sustainability can be defined with three key pillars: (1) the environment; (2) the economy; and (3) society (Dalampira and Nastis, 2020). With this definition in mind, for a food to be considered wholly sustainable it must be produced in an environmentally conscientious manner while being beneficial both for the economy and for human health (Dalampira and Nastis, 2020). In essence, sustainable food production is a balance, lending itself to tradeoffs and compromise in order to obtain the best outcome. Previous studies have assessed the environmental impacts of GB compared to IB or BB; however, these studies have not incorporated economic or health impacts, thus failing to provide a complete picture of the sustainability of these products.

To obtain a more complete picture of the sustainability of GB compared to IB or BB, it is essential that economic impacts of these products be considered. While replacing GB has been the target of IB and BB, GB is just one component of cattle production. Whole muscle cuts (e.g., ribeye steaks, briskets, etc.), hides, tallow, edible and inedible offal, pharmaceuticals and many other by-products are also obtained from processed cattle (Marti et al., 2012). In total, cattle production is a $66 billion dollar industry, consistently ranking first in total cash receipts for agricultural commodities in the U.S. (USDA, 2021). Additionally, cattle production is an intricate process that supports a large segment of U.S. labor at each stage in the supply chain and is directly linked to several other U.S. sectors. Furthermore, the U.S. is the third largest exporter of beef, playing a large role in international markets. Previous analyses have not considered the role that GB plays in the broader economy and have thus only considered the sustainability of GB compared to IB and BB from one of the three pillars of sustainability. The objective of the present research is to gain a more complete picture of the sustainability of GB compared to IB and BB by assessing the national and international economic impacts of decreasing GB consumption in the U.S.

MATERIALS AND METHODS

GTAP model

The Global Trade Analysis Project (GTAP) Model, a widely-used computational general equilibrium model, was used to assess the impact of reducing GB consumption in the US on both

US and global economies (Aguiar et al., 2019). The tenth version of the GTAP Data Base used herein accounted for annual flows of 65 products and services (i.e., sectors) and 6 factors of production in 121 countries and 20 aggregate regions for the reference year 2014. The GTAP Data Base is comprised of country-based Input Output Tables (IOT) and describes global bilateral trade patterns which links individual countries and regions. As US GB production is directly linked to US cattle production, an internationally important sector of food production, the GTAP Data Base provides a unique opportunity to assess the impacts of reduced GB consumption in the US not only on the US economy but also on international trade for products and services associated either directly or indirectly with GB production in the US.

GTAP Data Base Aggregation

The 65 unique economic sectors from GTAP 10 were first aggregated into 18 sectors, with cattle meat and other relevant sectors isolated for more detailed analysis. In total, a 19-sector model was created for the present analysis, aggregated to represent GB production and sectors associated with other by-products from cattle production (***Table 3.1***). Sectors of particular interest included: ground beef (GB); other bovine meet (OB); cattle (CTL); animal fats and vegetable oils (F_O); vegetables and pulses (VEG); oil seeds (OIS); leather (LTH); and pharmaceuticals (PHA). The 141 countries/regions from GTAP 10 were aggregated into three regions: (1) the US (USA); (2) Australia, Canada, Mexico, and New Zealand, import countries important to USA beef production (IMP); and (3) rest of world (ROW). Finally, six factors of production were classified, including: (1) agricultural labor, (2) skilled labor, (3) unskilled labor, (4) capital, (5) land, and (6) natural resources.

Creating a Ground Beef Sector in GTAP

While the GTAP Data Base contained a unique sector for cattle meat, this sector included data on all meat products from cattle, including GB, along with meat production from other ruminant animals. As such, the cattle meat sector in GTAP was disaggregated into two sectors: (1) GB and (2) OB. SplitCom software was used to perform this disaggregation as it accepted comprehensive data on splitting GTAP flows while it maintained the integrity of the Data Base IOT (Horridge, 2008). Within the SplitCom software there were four key equations which were modified to successfully split GB from the USA cattle meat sector: (1) trade weight for exports (TEXT); (2) national cross weight (XWGC); (3) national row weights (ROWC); and (4) national column weights (COLC).

The TEXP equation factored in both imports and exports of the original commodity (cattle meat) into the new commodities (GB and OB) in the USA as well as other regions. According to USA beef trade data, 72% of all USA beef imports in 2020 were lean trimmings, which were used directly for GB production in the USA (National Cattlemen's Beef Association Member Newsletter, 1 May 2020). Of these lean trimmings, 83% were sourced from IMP (Australia, Canada, Mexico, and New Zealand) while the remaining 17% were from ROW. To determine the time relevant input for TEXP, these data were cross-referenced with the United Nations Comtrade Database for the year 2014 (UN, 2020). These values ensured that the splitting data remained consistent with the 2014 GTAP 10 Data Base used in the present work. From this data it was determined that 91% of lean trimmings were from IMP countries and 9% from ROW. This information was then used to populate TEXP with values that would most accurately reflect USA trade for GB.

The XWGC equation functioned to describe the interactions of the new commodities, which resulted from the split. XWGC combined the new commodities (GB and OB) with their new industries to create a national matrix. For this equation, the new commodities were set to have minimal cross interaction, as GB would not move back into the OB sector once it was designated GB.

For the ROWC and COLC splitting equations, total USA GB production was first estimated. National survey data was used to determine the total number of cattle slaughtered in the year 2014 and average dressing percentages for each type of animal (i.e., heifer, steer, bull, or cow) were used to determine total kg of beef production (NASS, 2020). It was assumed that 100% of meat from slaughtered bulls and cull beef and dairy cows were used for GB while 30.9% of feed steer and heifer meat was used for GB (Bowling and Gwartney, 2015). Based on this information, 41.9% of USA produced beef was allocated to GB and 58.1% to OB, and the ROWC and COLC equations were populated accordingly.

With all four splitting equations populated, the GB sector was created in GTAP. To validate this split, several test runs of the GTAP model were performed to ensure that baseline trade data within the model was in line with the national and international trade databases. Additionally, analysis of sectors connected to GB and OB, such as cattle production, were evaluated to ensure that USA production values were accurate in the model.

Scenario Descriptions

The GTAP Data Base accounts for private household (i.e., consumer), government, and firm (i.e., intermediate) spending. With these designated spending accounts, it was possible to model specific changes to private household consumption of GB. To determine the economic impacts of a decline in GB consumption in the USA, private household demand for GB was reduced in four set intervals. Reduction rates (i.e., scenarios) included: 1%, 5%, 10%, and 15%. The maximum reduction rate of 15% was selected based on market behavior related to USA dairy milk consumption in response to the introduction of alternative milks. According to Dairy Management Inc., retail sales of milk alternatives were 8.7% of the combined volume (gallons) of milk and milk alternatives in 2019 (Stewart et al., 2020). Meanwhile, The Good Food Institute (GFI) reported that milk alternatives were 15% of retail milk sales in 2020 (Gaan, 2021). However, if national milk production data is used with GFI milk alternative production data this value drops to 6% of combined milk and milk alternative sales in 2020 (NASS, 2020). Given that reported replacement rates of milk alternatives for milk are conflicting, the 15% maximum replacement rate for meat alternatives was chosen to encompass all possible options.

To achieve the desired consumer reduction of GB in GTAP, private household demand (*qpd*) for GB in the USA was swapped for consumption tax (*tpd*) in the model closure and the shock, *qpd*("GB","USA"), was applied at -1%, -5%, -10%, and -15%. In utilizing this method, consumer demand specifically in the USA was targeted. To avoid possible effects from a tax distortion, the endogenous variable, *del_ttaxr* (change in the ratio of taxes to income), was made exogenous by swapping with the variable *tp* (tax on private consumption). This provides redistribution of the tax revenues from spending on GB back to consumers so that they have the same income but choose to spend it on items other than GB. To ensure total USA consumer demand for GB was reduced by the intended rate in each scenario, substitution between imported and domestic products was eliminated by setting the substitution parameter, ESUBD, for GB to 0. Each of the four reduction scenarios (1%, 5%, 10%, and 15%) were compared against the GTAP baseline scenario (i.e., the unaltered USA, IMP, and ROW economies).

RESULTS

Economic Effects in USA

When considering the quantity output (*qo*) of each USA sector in response to reduced consumer demand for GB, the sectors most affected were GB and CTL, while other sectors of interest were minimally affected (**Table *3.2***). As the budget share for GB in USA private household domestic consumption was determined to be 0.31%, a shift in consumer demand for GB was not expected to greatly impact the output from other sectors. Outside of GB, CTL was the only sector that observed any noted changes, with *qo* reduced by a maximum of 3.76% when consumer demand for GB was reduced by 15%. Other sectors of interest (OB, F_O, VEG, OIS, and LTH) had slight increases in *qo*; however, even at the 15% GB reduction rate, no sector experienced more than 0.38% increase in *qo*. Pharmaceuticals was the only sector of interest, which experienced a decline in *qo*, with a maximum reduction of 0.02% when consumer demand for GB was reduced by 15%.

While *qo* of GB decreased substantially with reduced consumer demand, USA *qo* of GB did not change at an equivalent rate to that of the consumer demand. Quantity output is a function of three entities: government, private household (i.e., consumer), and firm. When consumer demand was reduced, only private household demand was reduced by the set rate. Meanwhile, firm demand for GB was only slightly reduced and government demand increased slightly in each reduction scenario.

Overall, changes in response to reduced USA consumer demand for GB were most pronounced at the 15% reduction rate. As such, further discussion of results will focus on this scenario. **Table *3.3*** presents results for factors related to consumer demand in USA. Overall, the cost of GB increased substantially, which resulted in the intended reduced demand (15%) and a similar reduction in the total budget share[1] of GB (15.19%). While total demand was reduced, total expenditure for GB increased by 3.59% because of the increased price. Across all other sectors of interest, minor changes were observed in terms of price, quantity demanded, expenditure, or budget share.

Regional Analysis

The model predicts a very small positive impact on USA real gross domestic product (GDP), increasing by 0.009%; while the IMP and ROW regions face slight reductions in GDP, declining by 0.016% and 0.001%, respectively. When reviewing the GDP expenditure differences between the updated GTAP output (15% reduction in GB) and the original GTAP output (baseline), the changes to GDP become clearer (**Table *3.4***).

In USA, consumption, investment, and government expenditures grew, while export and import expenditures declined. The domestic decline in GB consumption was overcome by increases in consumption of SER, O_I, MFG, and OTF. Additionally, the higher domestic private household consumption tax of GB led to greater government earning which in turn led to the observed increase in government spending. These increases in consumption and government spending are the primary drivers for GDP growth in USA. The inverse is true for IMP and ROW - consumption, investment, and government expenditures decreased. There was a pronounced decline in IMP exports of GB, CTL, and GRA to USA which was partially compensated by slight increases in IMP exports of OTM, GB, LIV, CTL, F_O, GRA and VEG to ROW. These changes in exports resulted in the slight decline in GDP observed in IMP. In addition, IMP spending on imports decreased as a result of a reduction in the regional private consumption expenditure, which affected overall domestic consumption. While ROW exports grew as a result of the slight increase

[1] Budget share is the portion of the consumers' total spending budget allotted to the product in question.

in its biggest exported commodity, MFG, to both USA and IMP, there were overall declines in consumption, investment, and government expenditures. In addition, the import of meat and agricultural commodities to ROW increased along with most other sectors, contributing to the overall decline in ROW GDP.

Equivalent variation (EV) is used to measure consumer welfare as the difference between consumer spending required to obtain the new level of utility (from the experiment) at baseline prices and spending prior to the experimental change (Huff and Hertel, 2000). Equivalent variation was analyzed as a means of determining the effect on consumer welfare of the change in consumer spending as a result of the decline in GB consumption. A positive value suggests a benefit to the consumer, while a negative value suggests a disadvantage to the consumer. The GTAP welfare decomposition feature facilitates the analysis of changes to EV, which are presented in **Table *3.5***. It was estimated that USA and ROW would experience overall welfare gains (positive EV value), while IMP an overall welfare loss (negative EV value) as a result of the 15% reduction in USA consumer demand for GB. Three components contributed to the observed EV effects: allocative efficiency, goods and services terms of trade, and savings-investment terms of trade.

Gains in allocative efficiency are the result of improved allocation of resources to more productive sectors. In the present work, all three regions experienced allocative efficiency gains.' For USA, even though the increased tax on GB resulted in a negative allocative efficiency gain of -220 million USD, this loss was absorbed by gains in other sectors, mainly SER, MFG, OTF, and O_I. While IMP experienced slight changes in allocative efficiency across all sectors, negative allocative efficiencies were most pronounced in O_I, GB, and SER and these losses were absorbed primarily with gains in O_G. In ROW, all sectors except O_I experienced gains in allocative efficiency. Most notably, GRA had a gain of 353 million USD while GB had a gain of 5.99 million USD.

Terms of trade for goods and services impact EV as a result of changes in export and import prices for a country. If a country's exports' prices increase relative to imports' prices then that country has the ability to buy greater quantity of imports while keeping the quantity of exports constant, resulting in greater welfare for that country. Small gains in terms of trade for goods and services were found for USA and ROW at the expense of IMP – both USA and ROW gained on their exports while IMP substantially lost as a result of reduced exports. Most of USA goods and services welfare gain was from the MFG and SER sectors, in addition to small gain from the GB sector. For IMP, the reduced demand for GB in USA had an impact on exports of lean trimmings (i.e., GB) from IMP. Additionally, CTL, GRA, VEG, MFG, O_I, and SER were reduced as a result of the reduced demand for GB in USA. Welfare gains in goods and services for ROW were predominantly due to gains in the agricultural sectors, most notably OTM, GRA, VEG, OIS and OAG. While there were losses to industrial related sectors, these were not large enough to affect the overall gain in terms of trade for goods and services for ROW. Finally, positive savings-investment terms of trade in USA indicates an increase in USA purchasing power for capital goods (a proxy for future consumption), while both IMP and ROW experienced a loss of savings-investment.

Although the USA experienced an overall welfare gain, it still experienced a 546 million trade balance deficit (**Table *3.5***). Despite a positive trade balance of 591 million USD from GB, the result of the decline in domestic consumption, an overall trade deficit could not be avoided. This was primarily the result of a 1222 million USD trade balance deficit from MFG. Conversely, both IMP and ROW experienced positive trade balances in the new economy. For IMP, the trade balance deficit of 465 million USD caused by the reduction in GB exports was overcome by the positive trade balance of 479 million USD from MFG along positive balances from most other sectors. While ROW experienced 112, 160 and 108 million USD trade deficits from GB, GRA, and OAG, respectively, this was overcome by the positive trade balances of 726 and 209 million from MFG and SER, among most other sectors.

Factors of Production

In GTAP, factors of production (land, labor, capital, and natural resources) are in a fixed supply, falling under the resource constraints assumption. Capital and labor are assumed to be imperfectly mobile, or sector-specific, as the transformation of existing machinery and equipment for use in different industries is rarely possible and labor requires time and training in order to move between industries. Results suggest that the 15% reduction to GB may lead to large declines in labor (i.e., increased unemployment) in both USA and IMP regions for GB and sectors closely linked to GB (**Table *3.6***). In USA, labor in GB and CTL sectors were most impacted, with employment dropping by 9.98% and 4.10%, respectively. While not as large of reductions, IMP regions also experienced declines in labor for GB and CLT sectors, with employment decreasing by 2.22% and 1.19%, respectively. Most other sectors linked to GB experienced minimal changes in both USA and IMP regions while labor in ROW remained virtually unaffected.

Land is specific to agricultural sectors in GTAP and is assumed to be fully mobile, which allows for it to be rented by another industry within the agricultural sectors until its rent differential disappears. Natural resources are specific to limited GTAP sectors, which are aggregated in O_G and OTL sectors in the present analysis. Percent changes to the quantity of land used (i.e., land use) and prices of land (i.e., land rent) for livestock and other agricultural sectors in USA and IMP are presented in **Table *3.7***. Changes to ROW were negligible and thus not reported. In USA, land use for CTL was reduced by 2.89%, while land use for OAG, OIS, VEG, and LIV increased. In addition, the price of land declined for all sectors, with the largest decline or 4.78% observed in CTL. In IMP, there was a slight increase in land use for all sectors, except CTL in which there was a 0.800% reduction. Moreover, the price of land declines slightly for all sectors, with the largest decline of 1.57% observed in CTL.

Systematic Sensitivity Analysis

While the present research has assumed a maximum of a 15% reduction in USA consumer demand for GB as a response to the introduction to plant based meat alternatives, it is not possible to predict the true effect the introduction of meat alternatives will have on consumer demand for GB. As such, a sensitivity analysis was performed, using the GTAP systematic sensitivity analysis (SSA) tool to test a range of replacement rates for GB. Ground beef accounts for just 0.31% of private household spending and 0.20% of total domestic spending. With GB contributing minimally total USA economic output, performing the SSA with 100% variation (±15% shock to *qpd*), will provide the opportunity to gain more insight into the impacts of replacing GB with meat alternatives. Additionally, it provides a means of testing what might happen if MAs end up replacing GB at a greater share than currently anticipated. With the GTAP SSA tool, the mean and standard deviation of the model results for each variable were estimated for reduction rates ranging from 0 to 30% for GB. A 95% confidence interval was constructed using Chebyshev's theorem, which describes the minimum proportion of results that exist within a range of one standard deviation around the mean, for a variety of model results. Results of the SSA are presented below with the mean (μ), and the 95% confidence interval (CI) represented as the lower confidence limit (LCL) and upper confidence limit (UCL) in brackets.

When assessing *qo* of goods, most changes were observed in the meat and agricultural sectors, though most changes were minimal (***Figure 3.1***). The *qo* (% change from baseline) for GB experienced the most variability, with a mean of -9.98 [-28.2, 8.23]. The cattle sector was similarly variable, with the mean *qo* of -3.76 [-10.2, 3.10]. The greater CIs for GB and CTL indicate that their reported changes to *qo* are most affected by a shock to consumer demand for GB, which further highlights the strong connection between the two sectors. Conversely, all other agricultural sectors display relatively small confidence intervals, indicating that changes in *qo* of these sectors are least likely to be impacted by changes to GB *qpd*.

The effect of the SSA on EV indicates that welfare changes in all three regions are likely to be robust in response to changes in GB *qpd* (**Figure *3.2***). The USA *qpd* (million USD) averaged 230 [-190, 651]. Meanwhile, IMP and ROW regions averaged -161[-453, 132] and 260 [-214, 734], respectively. These results indicate that, when consumer demand for GB is reduced at a greater rate (30%), an overall welfare gain can be expected across all three regions. This change in EV can be attributed to the increased tax on GB, meaning that if the cost of GB had remained the same after the reduction in consumer demand, then consumers would have been able to spend less money overall to achieve the same utility of GB.

Results from the SSA indicate that changes to GDP (% change from baseline) for USA and IMP as a result of reduced consumer demand for GB are strong with the average change to GDP of 0.053 [-0.05, 0.15] for USA and -0.016 [-0.04, 0.01] for IMP (**Figure *3.3***). Meanwhile, the standard deviation for ROW region was zero, indicating that the GDP for this region was not affected by the modeled range of change to GB demand.

For the USA, the mean trade balance (million USD) was -303 [-856, 250] (**Figure *3.4***). For IMP and ROW regions, average trade balances were 122 [-101, 345] and 181 [-149, 511], respectively. These results suggest that the trade effects resulting from a greater range of demand for GB are less certain, in some instances it may be possible that each region experiences a surplus and in other instances each region may experience a deficit. However, when running the model at a 30% reduction in GB, we find that the trends in terms of trade remains consistent with our maximum reduction scenario of 15%: the USA experiences an overall deficit while IMP and ROW experience trade surpluses.

DISCUSSION

While GB represents a relatively small percent of total USA economic output, reducing consumer demand for GB did result in changes both nationally and internationally; impacting welfare across regions and altering trade between regions. While many of these changes were relatively small, they highlight that GB consumption in USA does play a role in both national and international economies. Although the present research was not able to assess the introduction and substitution of MAs for GB within the GTAP framework, these results suggest that replacement of GB with MA may not provide comparable economic benefits to USA or global economies. As such, further discussion will focus on the possible economic effects that may arise from the introduction of MA in USA based on the reported economic effects of reducing GB in USA.

Total economic output for USA was reduced by 0.014% when GB was reduced by 15%. Mukhopadhyay and Thomassin (2012) found that reducing meat by 20% in Canadian diets lead to a 0.2% reduction in total economic output. Furthermore, when a 50% increase in vegetables and fruits in Canadian diets was added to this meat reduction, the authors still found a 0.12% reduction in total economic output. These results support the conclusion that while a replacement of GB with MA may add to economic output, it is not likely to replace the loss observed from reducing GB. Mukhopadhyay and Thomassin (2012) also found that reducing meat by 20% in Canadian diets led to a 0.12% reduction in GDP and when a 50% increase in vegetables and fruits in Canadian diets was added to this meat there was a 0.05% reduction in GDP. This suggests that, as with GB in the USA, meat plays an important role in the Canadian economy.

When reducing GB by the maximum of 15%, the quantity output of most goods was minimally affected, though GB and CTL sectors in both USA and IMP regions experienced reductions. In line with the present work, Mukhopadhyay and Thomassin (2012) found that reducing meat by 20% in Canadian diets led to 2.3% and 9.5% reductions in cattle and meat products sector outputs, respectively. When a 50% increase in vegetables and fruits in Canadian diets was added to this meat reduction, the authors report mixed results, but indicate that the increase in fruits and vegetables is not enough to offset the negative economic effects of meat reduction.

Observed reductions in sector outputs resulted in rather large declines in labor for USA and smaller declines in labor for IMP. Mukhopadhyay and Thomassin (2012) found that reducing meat by 20% in Canadian diets led to a 0.13% reduction in employment and when a 50% increase in vegetables and fruits was added to meat reduction, the authors still found a 0.05% reduction in employment. As labor is not easily mobile across industries, this suggests that when new labor is needed for MA production (from growing crops for patties to the factory work to manufacture the patties) it will not be automatically sourced from the lost labor in the CTL and GB sectors. More resources and training will be necessary if such a shift is to be accomplished.

Land use is a topic that is often brought up when discussing environmental impacts of GB compared to MA, but it has yet to be considered from an economic perspective. The present work found that both land use and the price of land were reduced for the USA CTL sector in response to GB reduction. Because GTAP allows for land to be mobile across agricultural sectors, a corresponding increase in land use is observed or other agricultural sectors. Even with this replacement of land use, there is an overall 0.8% reduction in land use in the USA. However, it is important to note that this assumes that the land no longer used for CTL could be used for other agricultural purposes. While ideally this would be the case, it is very unlikely that all of the land no longer used for cattle would be able to directly transfer into any other type of agricultural use. The majority of land used for cattle production (35% of total USA land area) in USA is marginal land, land that is too hilly, rocky, has minimal access to water, or has poor soil quality and thus cannot be used to produce crops (USDA, 2016; Bigelow and Borchers, 2017). For land that is converted from range or grasslands to croplands, land productivity must also be considered. While the reduced land used for CTL may be used to grow crops for MA on, it is likely that yields on these converted lands will be lower than established crop lands, thus resulting in less value gained from the land (Lark et al., 2020).

A final consideration is how replacing GB with MA in USA will impact the consumer. While the present study resulted in a reduction of consumer spending on GB, the current costs of MA are not equivalent to replace GB – IB and BB are 3.8 and 2.7 times the cost of GB, respectively. This means that consumers would need to choose either: (1) to maintain the same level of spending and thus reduce their overall food intake; or (2) to maintain the same level of consumption and thus increase their food budget share to maintain the same level of food intake. If consumers chose option 1, they would be consuming about 11% or 9.5% less food to eat IB or BB instead of GB, respectively. While with this option consumers are not affected financially, they are nutritionally, a consideration that is not addressed herein but is nonetheless important to note. Alternately, if consumers chose option 2, they would be spending about 41.6% or 25.7% more to eat IB or BB instead of GB, respectively. This means that consumers now have to reallocate funds to afford the

MAs and give up spending in some other area of their budget. In this sense, MAs become a luxury product that consumers have to decide whether they are willing to spend money on or not. For many Americans, this may not be a pressing concern, but this does become a bigger issue in lower income households and lower income countries.

Further analysis on this topic is needed to more completely understand the economic impacts of a reduction in GB consumption paired with a corresponding increase in MA. However, the present work provides a first look into the sustainability of MA compared to GB from the economic standpoint. Paired with current work comparing the environmental impacts of MA and GB the decision to choose one product over the other becomes more challenging. With a growing global population, it may prove to be more essential for future research to investigate how to produce both GB and MAs sustainably. Furthermore, there exists an untapped opportunity for the two products to develop a more symbiotic relationship – the pea and soy pulp which results from formation of MAs is a feasible feedstuff for beef and dairy cattle. This means that the by-products of MA production have the potential to support cattle production, helping to mitigate some of the competition for feeds/food between the two industries while simultaneously increasing the global protein supply.

TABLES AND FIGURES

Table 3.1. GTAP sectors.

Number	Sector	Description	Comprising
1	OTM	Other Meat	Meat products n.e.c.[1]; dairy products
2	GB	Ground Beef	Ground beef
3	OB	Other Bovine Meat	Bovine meat products (excl. ground beef)
4	LIV	Livestock and Raw Milk, Non-Bovine	Animal products n.e.c.; raw milk
5	CTL	Cattle	Bovine cattle, sheep and goats
6	F_O	Animal Fats and Vegetable Oils	Vegetable oils and fats
7	GRA	Grains	Paddy rice; wheat; cereal grains n.e.c.
8	VEG	Vegetables and Pulses	Vegetables, pulses, and fruits
9	OIS	Oil Seeds	Oil seeds
10	OAG	Other Agricultural Products	Sugar cane, sugar beet; plant-based fibers; crops n.e.c.; wool, silk-worm cocoons
11	OTF	Other Processed Foods	Processed rice; sugar; food products n.e.c.; beverages and tobacco products
12	LTH	Leather	Leather products
13	PHA	Pharmaceuticals	Basic pharmaceutical products
14	RUB	Rubber	Rubber and plastic products
15	O_G	Fuels	Coal; oil; gas; petroleum, coal products; gas manufacture, distribution
16	OTL	Other Land Use Industries	Forestry; fishing; minerals n.e.c.
17	MFG	Manufacturing	Textiles; wearing apparel; wood products; paper products, publishing; chemical products; mineral products n.e.c.; ferrous metals; metals n.e.c.; metal products; computer, electronic and optic; electrical equipment; machinery and equipment n.e.c.; manufactures n.e.c.; electricity
18	O_I	Other Industries	Water; construction; trade; accommodation, food and service activities; transport n.e.c.; water transport; air transport; warehousing and support activities
19	SER	Services	Communication; financial services n.e.c.; insurance; real estate activities; business services n.e.c.; recreational and other service; public administration and defense; education; human health and social work; dwellings

[1]Not elsewhere classified.

Table 3.2. Changes is quantity output from selected sectors when US consumer demand for ground beef was reduced by 1%, 5%, 10%, and 15%. Values reported as percent change from baseline.

	Reduction Scenario			
Sector	1%	5%	10%	15%
Ground Beef (GB)	-0.665	-3.33	-6.65	-9.98
Other Beef (OB)	0.014	0.068	0.137	0.205
Cattle (CTL)	-0.251	-1.25	-2.51	-3.76
Fats and Oils (F_O)	0.002	0.009	0.017	0.026
Vegetables (VEG)	0.011	0.053	0.107	0.160
Oil Seeds (OIS)	0.025	0.126	0.252	0.378
Leather (LTH)	0.004	0.022	0.044	0.065
Pharmaceuticals (PHA)	-0.002	-0.008	-0.015	-0.023
19 Sector Total	-0.853	-4.26	-8.51	-12.8

Table 3.3. Changes to factors of consumer demand for selected sectors when US consumer demand for ground beef was reduced by 15%. Values reported as percent change from baseline.

	Factors of Consumer Demand			
Sector	Price	Quantity Demanded	Expenditure	Budget Share
Ground Beef (GB)	18.6	-15.0	3.59	-15.2
Other Beef (OB)	-0.26	0.21	-0.05	0.01
Cattle (CTL)	-0.50	0.41	-0.09	-0.04
Fats and Oils (F_O)	-0.12	0.09	-0.03	0.03
Vegetables (VEG)	-0.24	0.00	-0.24	-0.19
Oil Seeds (OIS)	-0.25	0.00	-0.25	-0.20
Leather (LTH)	-0.07	0.06	-0.01	0.04
Pharmaceuticals (PHA)	-0.06	0.06	0.00	0.05

Table 3.4. Gross domestic product (GDP) expenditure differences between updated GTAP output (15% reduction in ground beef) and original GTAP output (baseline). Results displayed in units of million USD.

Region	Consumption	Investment	Government	Export	Import	Total
USA	1175	800	158	-428	-118	1587
IMP	-480	-267	-133	3.60	137	-740
ROW	-450	-459	-39.0	470	-66.0	-544

Table 3.5. Equivalent variation (EV) and trade balance in each GTAP region as a result of a 15% reduction in USA consumer demand for ground beef. Results reported in million USD.

Region	Allocative Efficiency	Terms of Trade: Goods and Services	Terms of Trade: Savings-Investment	EV	Trade balance
USA	143	76.7	66.0	285	-546
IMP	3.53	-156	-7.38	-160	140
ROW	205	79.7	-58.6	226	405

Table 3.6. Changes to labor for selected sectors in USA and IMP regions when USA consumer demand for ground beef was reduced by 15%. Values reported as percent change from baseline.

	Labor	
Sector	USA	IMP
Ground Beef (GB)	-9.98	-2.22
Other Beef (OB)	0.202	-0.001
Cattle (CTL)	-4.10	-1.19
Fats and Oils (F_O)	0.024	0.090
Grains (GRA)	-0.552	-0.096
Vegetables (VEG)	0.057	0.002
Oil Seeds (OIS)	0.288	-0.073
Other Agricultural Products (OAG)	0.417	0.047
Leather (LTH)	0.062	0.093
Pharmaceuticals (PHA)	-0.024	0.036

Table 3.7. Changes to the quantity used and price of land for livestock (LIV) and other agricultural sectors in USA and IMP regions as a result of a 15% reduction in consumer demand for ground beef in the USA. Values reported as percent change from baseline.

	Land Quantity		Land Price	
Sector	USA	IMP	USA	IMP
Livestock (LIV)	0.32	0.13	-1.57	-0.64
Cattle (CTL)	-2.89	-0.80	-4.78	-1.57
Grains (GRA)	-0.06	0.07	-1.95	-0.69
Vegetables (VEG)	0.43	0.15	-1.46	-0.61
Oil Seeds (OIS)	0.61	0.09	-1.27	-0.67
Other Agricultural Products (OAG)	0.71	0.19	-1.17	-0.58

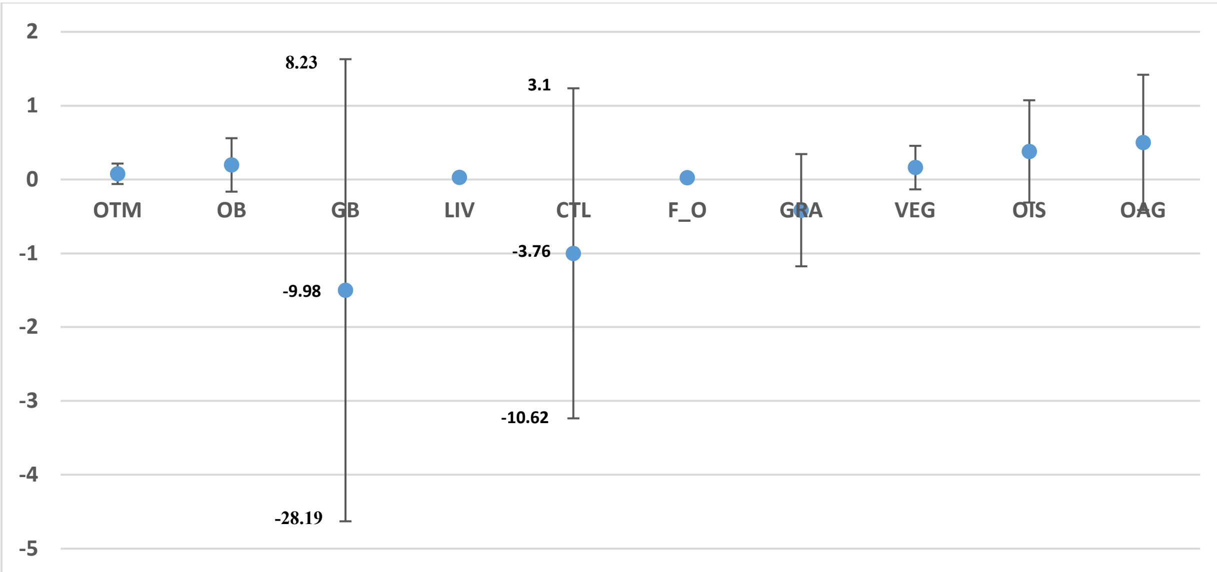


Figure 3.1. 95% confidence intervals[1] for the quantity output of select sectors[2] as a result of performing a systematic sensitivity analysis on consumer demand for GB.

[1] Note: values for GB and CTL fall outside of the range presented in this chart. In order to see the much smaller changes in the other sectors, these error bars have been modified to fit within the range of the current chart.

[2] OTM = other meat; OB = other beef; GB = ground beef; LIV = livestock; CTL = cattle; F_O = fats and oils; GRA = grains; VEG = vegetables; OIS = oil seeds; OAG = other agricultural products.

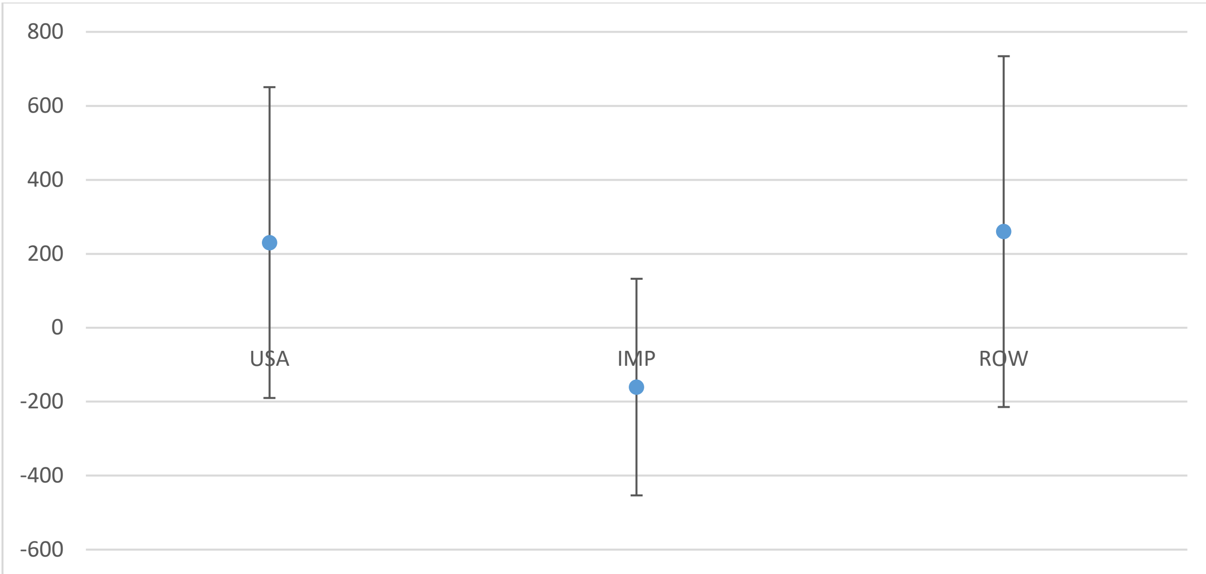


Figure 3.2. 95% confidence intervals for equivalent variation (EV; in million USD) in USA, IMP, and ROW regions[1] as a result of performing a systematic sensitivity analysis on consumer demand for ground beef (GB).

[1] USA =United States; IMP = import countries important to USA GB (Australia, Canada, Mexico, New Zealand); ROW = rest of world.

Figure 3.3. 95% confidence intervals for percent changes (%) in gross domestic product (GDP) for USA, IMP, and ROW regions[1] as a result of performing a systematic sensitivity analysis on consumer demand for ground beef (GB).

[1] USA =United States; IMP = import countries important to USA GB (Australia, Canada, Mexico, New Zealand); ROW = rest of world.

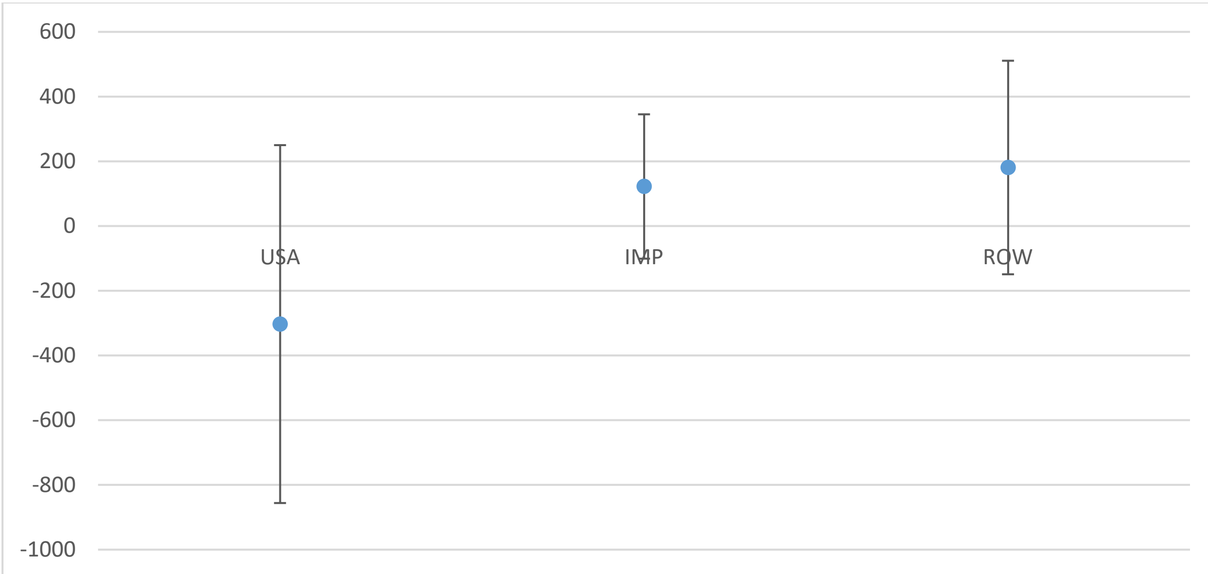


Figure 3.4. 95% confidence intervals for trade balance (million USD) in USA, IMP, and ROW regions[1] as a result of performing a systematic sensitivity analysis on consumer demand for ground beef (GB).

[1] USA =United States; IMP = import countries important to USA GB (Australia, Canada, Mexico, New Zealand); ROW = rest of world.

Chapter 4 An environmental assessment of replacing ground beef with plant-based meat alternatives in the United States utilizing EXIOBASE

ABSTRACT

In recent years, the environmental impacts of food choices has become a topic of increasing importance among US consumers and many believe meat alternatives (MA) are more environmentally friendly replacements based on conventional life cycle assessment (LCA). The goal of the present study was to utilize macro-LCA (M-LCA) to determine the widespread environmental impacts associated with a reduction in ground beef (GB) consumption and a replacement with two popular MAs, Beyond Burger (BB) and Impossible Burger (IB), consumption in the US. Through the use of the Global Trade and Analysis Project (GTAP) model, life cycle inventory data for GB was determined and coupled with EXIOBASE to determine environmental impacts associated with GB production in the US. EXIOBASE was used to model ingredient production, manufacturing and processing of both BB and IB. ReCiPe 2016 was used to characterize climate change, land use, and water consumption impacts while built-in EXIOBASE energy accounts were used to determine total energy use impacts. Combined results for GB reduction and replacement with BB or IB were determined at rates of 1, 5, 10 and 15%. When considering impacts to the GB sector, impacts to climate change and land use were the most pronounced, rendering reductions for both BB and IB replacements. While GB proved to be more GHG and land intensive, further evaluation and consideration of these results indicates that these reductions have a more nuanced interpretation. Sectoral impacts were less substantial for water and energy use, leading to increases in each depending on the replacement scenario. When considering impacts at the national scale, results proved to be much less impactful with climate change and land use minimally reduced (0.08% and 1.6%, respectively), energy use virtually unchanged (0.001% decrease or 0.004% increase), and water use actually increased by as much as 0.4% (in the case of IB). When considering the sustainability of these two products, it remains difficult to draw clear conclusions on which product might be more sustainable, but it is clear that BB and IB will not produce the profound positive impacts suggested by their respective companies.

Key words: MRIO, Life Cycle Assessment, Meat Alternatives

INTRODUCTION

Plant-based meat alternatives (MA) have become an increasingly popular commodity in the United States for vegans and flexitarians alike, offering consumers a "guilt-free" food experience (Gaan, 2021). Eliminating the need to consume animal sourced foods (ASF), choosing what is considered a "healthier" alternative to ASF, and helping to minimize ones contribution to climate change are among the chief reasons these products have been deemed "guilt-free" by those who consume them (Aiking and de Boer, 2020; Gaan, 2021). Two companies in particular, Beyond Meat® and Impossible Foods™, have been most successful with the production and sale of their plant-based burgers, the Beyond Burger (BB) and Impossible Burger (IB), which look, cook, taste, and even bleed like their traditional ground beef (GB) counterpart (Heller and Keoleian, 2018; Khan et al., 2019). While these companies have taken different routes to create their beef-like patties – BB using all natural, non-genetically modified organism (GMO) plant-sourced ingredients, IB developing and utilizing the GMO, leghemoglobin, as the key to their "bleeding" plant-based burgers – their overarching goals have been very similar: reduce humanity's impact on the environment by eliminating the need for consumption of ASF (***Figure 4.1***). Both companies intend to achieve this goal with the creation of plant-based products that successfully mimic ASF.

Ground beef, specifically, has been the primary target ASF for BB and IB to replace for a few key reasons. First, a ground product is much easier to mimic from a food science standpoint – it is easier to create a comparable texture and, to an extent, flavor when the product is ground (Saerens et al., 2021). Second, a ground beef burger is a longstanding American tradition – thereby allowing for a larger possible consumer base. Finally, the cattle from which GB is procured are one of the most criticized ASF consumed in the US due to their perceived large environmental impacts – from methane (CH_4) emissions belched by cattle, to the expanses of land used to graze cattle, to the large water requirements associated with production (Eshel et al., 2014; Ripple et al., 2014; Kyriakopoulou et al., 2018; Eisen and Brown, 2021).

Life cycle assessment (LCA) is a common method employed to gain insight into the environmental impacts of a product and is often used to systematically compare different products or production systems. Through compiling a detailed inventory of inputs and outputs associated with production of each item, LCA practitioners are able to evaluate environmental impacts associated with each product and compare their respective results. To date, four LCA have been performed for BB and IB: one comparing BB to GB (Heller and Keoleian, 2018), two comparing IB to GB (Goldstein et al., 2017; Khan et al., 2019), and one comparing BB and IB side by side with pork (Nair et al., 2019). Although there are inconsistences in results between studies (in part due to the inherent variability which results from the designated system boundaries, data sources, and impact characterization methods) these studies have made it clear that BB and IB emit less greenhouse gas (GHG) emissions and require less land, water, and, except for possibly IB, energy than GB on a "per kg of product" basis (***Table 4.1***).

These studies provide valuable insight into not only how environmental impacts of BB, IB, and GB compare to one another but also different opportunities for each product to improve their respective production systems and possibly reduce resultant emissions. However, these studies do not take into account the actual consumer behavior surrounding ASF and MA consumption. They investigate how one product compares to another, but do not provide insight into the widespread effects that a shift from GB to BB or IB consumption might have on the US economy and how that then may alter US emissions. Additionally, the methods of characterizing emissions and resource use often leave out fundamental details (i.e. lifetime of GHG emissions or types of land and water used) which results in misleading, and sometimes erroneous, interpretations of results.

Furthermore, the studies comparing BB and IB to GB lack detail on the complicated interrelationships between production and consumption of each product. Consumption of BB, IB, and GB in the US results in environmental impacts in other countries which a US focused, attributional comparative LCA approach cannot begin to accurately capture.

The computational general equilibrium (CGE) model, Global Trade and Analysis Project (GTAP; Aguiar et al., 2019), can be useful in collecting information on how changes in consumer behaviors might impact economic activity in the US and abroad. The GTAP model considers price variations as well as direct and indirect effects on economic sectors, but has limited detail on related environmental impacts. Dandres et al. (2012) proposed a new approach to LCA, macro-LCA (M-LCA), which utilizes GTAP to generate a life cycle inventory (LCI). This LCI can then be paired with the ecoinvent database (Frischknecht et al., 2005), which models bottom-up environmental flows for various technologies, to estimate environmental impacts. While effective at providing greater insight into the economic links to environmental outputs, the ecoinvent database is not as robust as GTAP and necessitates truncation of economic sectors resulting in a loss of detail in reported results.

This method was further updated and the truncation issue overcome by Somé et al. (2018), through coupling GTAP with the environmentally extended multi-regional input-output (EE MRIO) database, EXIOBASE (Stadler et al., 2018). EXIOBASE provides extensive detail on environmental impacts of various sectors through the use of detailed input-output tables. Through this M-LCA approach, economic responses modeled with GTAP can be linked to EXIOBASE enabling environmental impacts to be more accurately and completely characterized. Thus, the objective of the present research was to utilize M-LCA to determine the environmental impacts associated with a shift from GB to BB and IB consumption in the US, taking into consideration national and international economies and resource use.

MATERIALS AND METHODS

General System Overview

A gradual replacement of GB with BB and IB was analyzed, comparing the baseline US economic activity for GB to four replacement scenarios: 1%, 5%, 10%, and 15%. The maximum reduction rate of 15% was selected based on market behavior related to US dairy milk consumption in response to the introduction of alternative milks. While reported replacement rates of milk alternatives for milk are conflicting, the 15% maximum encompasses all current numbers thereby providing a conservative high end replacement estimate (Stewart et al., 2020). The LCIs for GB at baseline and each of the four replacement rates were generated using GTAP 10 and coupled with EXOBASE 3 (Stadler et al., 2018). Both BB an IB were modeled utilizing EXIOBASE 3. OpenLCA (GreenDelta, 2020) was utilized to perform the environmental assessment for each product and replacement scenario.

The GTAP 10 database for the year 2014 was used to generate GB LCI data and outputs were provided in units of 'million USD'. The EXOBASE 3 database for the year 2011 was utilized to determine the emissions inventory and units of output were provided in 'million EUR'. To couple GTAP with EXIOBASE, all GTAP outputs were converted to 2011 EUR values and the primary functional unit reported herein is 'million EUR'. Final emissions were characterized with ReCiPe 2016 (Huijbregts et al., 2017) by mapping ReCiPe characterization factors onto EXIOBASE emissions flows in OpenLCA (the modified impact assessment method for use in OpenLCA available upon request).

Mapping GTAP to EXIOBASE

In order to utilize the LCI generated by GTAP with EXIOBASE, the aggregated 19 sector GTAP model had to be recreated with EXIOBASE and mapped into an OpenLCA process that could then be evaluated. Steps taken to accomplish this are outlined herein.

The original GTAP model consists of 65 individual sectors. These sectors were aggregated into 19 sectors, with one GTAP sector, 'cattle meat', split into two unique sectors, 'ground beef' and 'other cattle meat'. EXIOBASE contains 163 sectors and 200 products. Based on GTAP and EXIOBASE documentation, a total of 163 EXIOBASE sectors were aggregated into the GTAP 65 model and finally mapped into the 19 sector GTAP model. Each of the 19 sectors were recreated as EXIOBASE processes within OpenLCA. While both GTAP and EXIOBASE contain information on multiple countries and regions, the USA was the only country of focus for the present work.

Total output (million USD) from each of the GTAP 65 sectors was used to determine the relative percent contribution of each sector aggregated into the final GTAP 19 sector model. Where the GTAP 65 and EXIOBASE sectors mapped directly to one another, the GTAP total output value was utilized to populate that sector (e.g., GTAP 65 'cattle' and EXIOBASE 'cattle' sectors were directly linked and the GTAP 65 value was used in the final EXIOBASE model). For GTAP 65 sectors in which more than one EXIOBASE sector mapped to it (e.g., GTAP 65 'electricity' corresponded to 14 different EXIOBASE electricity related sectors), national and international data were used to populate the relative contributions of each EXIOBASE sector into GTAP 65. Through this method, the 19 sector GTAP model was recreated with EXIOBASE as an OpenLCA process.

Coupling GTAP with EXIOBASE

Within GTAP, US consumer demand for GB was reduced by 1, 5, 10, and 15% and results from each reduction scenario served as LCI data to be utilized in EXIOBASE. To determine each scenario input for EXIOBASE, GTAP output was coupled with EXIOBASE following Somé et al. (2018). A total production vector (x) was calculated as follows:

$$x = [(I - A)^{-1}y]$$

Where I was the identity matrix, A was the technology matrix presenting monetary transactions between each economic sector (in USD/USD), and y was the final demand vector (in USD). Final demand (y) from GTAP was calculated as the sum of private household purchases at market prices (VDPM), government purchases at market prices (VDGM), bilateral exports at market prices (VXMD) and capital goods (CGDS) for the US The sum of FD and domestic purchased at market prices (VDFM) was utilized to calculated total output (TO). The technology matrix (A) was calculated as the proportion of each VDFM column value per TO of the column sector. To determine the final LCI inputs for each scenario (baseline, 1%, 5%, 10%, and 15%) the VDPM value for GB was input in y and remaining sectors were set to zero. With this, total production values for each of the 19 sectors were isolated to GB spending by consumers in the US.

Total production values for each sector in each scenario were converted from 2014 USD to 2011 EUR and input into their respective EXIOBASE processes. Final characterized environmental impacts (Q) were determined (in kg characterized emissions) within OpenLCA using the following:

$$Q = CBx$$

Where C was the EXIOBASE characterization matrix (kg characterized emissions/kg emissions) and B was the environmental matrix linking emissions and resources to economic sector (in kg emissions/EUR).

Meat Alternatives Modelling

While it was possible to split GB off the existing 'cattle meat' sector in GTAP to characterize economic activity specific to GB and generate an LCI for use with EXIOBASE, this was not possible to do for BB or IB. Both BB and IB contain several ingredients that exist as small portions of various existing GTAP sectors. As such, it was not possible to split off these ingredients and then aggregate them to recreate BB or IB sectors within GTAP, characterize their economic activity, or generate corresponding LCI data for use with EXIOBASE. As a result, BB and IB were modeled as individual processes directly using EXIOBASE. To do this, first each burger ingredient was recreated as a process with EXIOBASE and combined to create a patty product. Next, all manufacturing needs were characterized as processes with EXIOBASE. Finally, the patty product and manufacturing processes were combined with remaining items necessary to create the final BB and IB processes (***Figure 4.2***). The following sections outline methods for creation of each stage of BB and IB production.

Meat Alternative Ingredient Processes

Ingredients for BB and IB were obtained directly from their respective product websites (accessed June 2021), individual unit processes were created for each ingredient, and each ingredient was mapped to EXIOBASE sectors based on their corresponding NAICS codes (available from the EXIOBASE 3 Zenodo community website). National production data and international trade data (value of imports to US) from the Food and Agricultural Organization Statistical Database (FAO, 2020) was used to determine primary crop production data for pea protein concentrate, soy protein concentrate, coconut oil, sunflower oil, and cocoa butter. Relative proportions of domestic US production versus US imports were determined. The countries which contributed to the top 90% of crop imports for each respective primary ingredient were used to characterize the contribution of imported goods necessary to produce the US manufactured BB and IB. Canola oil was assumed to be a 70:30 mix of production from Canada and the US (Heller and Keoleian, 2018). It was assumed that rice for rice protein and potatoes for potato protein were both sourced directly from the US Water used in BB and IB was characterized as 'collected and purified water' for the US.

Several BB and IB ingredients could not be attributed to specific EXIOBASE sectors and were grouped into one of two sectors: (1) Other Food n.e.c. (not elsewhere classified) which corresponded to the EXIOBASE sector 'Food products n.e.c.'; and (2) Methylcellulose which corresponded to the EXIOBASE sector 'Chemicals n.e.c.'. For BB, natural flavors, potato starch, apple extract, pomegranate extract, vinegar, lemon juice concentrate, sunflower lecithin, and beet juice extract were included in the Other Food n.e.c. process and methylcellulose, salt, and potassium chloride were included in the Methylcellulose process. For IB, natural flavors, yeast extract, food starch modified, and soy leghemoglobin were included in the Other Food n.e.c. process and methylcellulose, cultured dextrose, salt, mixed tocopherols, zinc gluconate, thiamin hydrochloride, niacin, pyridoxine hydrochloride, riboflavin, and vitamin B12 were included in the Methylcellulose process.

For those EXIOBASE inputs that represented raw ingredients, manufacturing was added to the process with the sector 'Food products n.e.c.' as this EXIOBASE sector includes milling of raw food materials. Transportation via either land, railway, or sea and coastal waters was included in each ingredient process as well. For ingredients sourced outside of the US, transportation was assumed to be 11% of the value of imported goods and manufacturing was assumed to be 15% of the ingredient production costs (World Bank, 2020). For ingredients sourced in the US, transportation was assumed to be 8.7% of ingredient production costs (BTS, 2018) and manufacturing was assumed to be 15% of ingredient production costs (World Bank, 2020).

Meat Alternative Patty Processes

Ingredient processes were combined to form individual processes for BB and IB patties. The patty processes included only primary patty ingredients and did not include the final steps of manufacturing necessary to manufacture the final product. Inputs for each respective ingredient were determined as the total cost (EUR/kg) of each ingredient costs. The calculated portion of each patty ingredient (g/kg) was used to determine relative inclusion rates (%) of each ingredient and these rates were multiplied by the cost of each ingredient (EUR/kg) to determine final process inputs in EUR (***Tables 4.2 and 4.3***). As ingredient composition is proprietary information for both BB and IB, a linear program (LP) was developed to determine the physical proportions of each BB and IB ingredient necessary to create the patties (g ingredient/kg patty; see below for more detail on the LP). Costs of each individual ingredient was obtained via personal communication (P.M. Hart, Elm Lea Partners Ltd.).

The LP constraints were assigned based on nutrition facts and ingredient information listed on each respective products nutrition label. Calculated inclusion rates followed FDA guidance (FDA, 2010), assuming that ingredients are listed in order of predominance and that certain ingredients are included at rates below 1% for BB and 2% for IB. Both BB and IB include "vitamins and minerals" at the end of their ingredients lists. Impossible Burger specifies the amount of each vitamin and mineral present in each patty and these were calculated to be the exact inclusion rate within the LP. As specific percentages or volumes of vitamins and minerals for BB were not provided on the nutrient label, inclusion rates were estimated based on IB. Each patty LP was formulated to ensure that grams of protein and fat were equal to those reported on the respective product labels, as these are the two nutrients that would be most likely to impact LCA results. Finally, leghemoglobin inclusion in IB was determined from the FDA documentation of the compound, in which it was specified that each patty would contain no more than 0.8% (FDA, 2017). Individual ingredient nutrient profiles were obtained from the USDA Food Statistics Database (USDA, 2019). Mineral ingredient profiles were not available the USDA and were sourced online from a bulk food supplement company (bulksupplements.com). Ingredient lists and BB and IB LPs are available upon request.

Three different LPs were tested for each patty to determine ingredient inclusion rates that resulted in BB and IB nutrient profiles that most closely reflected official nutrient labels: the Solver add-in from Microsoft Excel; the OpenSolver add-in for Microsoft Excel; and LP results adapted from Nair et al. (unpublished data). Outputs from all three LPs were input into EXIOBASE and resultant environmental impacts compared as a sensitivity analysis. Results from each LP varied minimally and the LP Solver results for both BB and IB were selected as the final input values for the present work (***Tables 4.4*** and ***4.5***).

Meat Alternative Manufacturing Processes

Manufacturing of MA raw ingredients required mixing, forming, and cooling of products as well as packaging and transportation of final product to retailers. Five key components were accounted for in manufacturing of BB and IB: electricity, transport, water for processing, steam for forming patties, and packaging materials. Three individual Electricity processes were created to represent the specific mix of electricity for each BB and IB manufacturing plant. Beyond Burger has two manufacturing sites in the US, one in California and another in Missouri. Impossible

Burger also has two primary manufacturing sites, one in California and another in Illinois. Net generation of electricity by source was determined for each state based on US EIA data (EIA, 2020) and converted to costs (EUR/per kWh) based on data from both US EIA and OpenEI ((EIA, 2020; OpenEI, 2020). Transportation was represented by a single EXIOBASE sector, 'Other land transportation services' for the US. Water for processing was represented with 'Collected and purified water, distribution services of water' for the US. Steam for forming patties was represented with 'Steam and hot water supply services' for the US. A process for packaging materials was created which included a 70:30 mix of papers to plastics, represented by the US processes 'Paper and paper products' and 'Plastics, basic', respectively. The mix of paper and plastic packaging was determined based on LCI data for BB and IB from Nair et al. (2019). This estimate was based on mass rather than cost due to unavailability of more detailed data on relative costs.

Final Meat Alternative Production

To create the final manufactured BB and IB processes, respective manufacturing processes were combined with respective patties and final input costs (EUR/kg product) were determined for BB and IB. The BB and IB patties were calculated as the total cost of ingredients, 1.92 EUR/kg for BB and 1.32 EUR/kg for IB. Goldstein et al. (2017) has been the only LCA that has modeled IB using proprietary information and provided corresponding LCI data for production. Nair et al. (2019) utilized this information to develop manufacturing LCIs for IB and BB. As such, manufacturing LCI data for both IB and BB was adapted from Nair et al. (2019) for the present work. Electricity generation (kWh/kg product) was converted to final cost using EIA average retail price (USD/kWh) of electricity for CA, MO, and IL (EIA, 2020). Transportation (tkm/kg product) was converted to the final cost using average freight revenue (USD/tkm) from the US Bureau of

Transportation Services (BTS, 2019). Water (L/kg product) was converted to final process input costs using data on local industrial water prices for each respective city in which BB and IB were manufactured. Heat (MJ/kg product) was converted to final process input costs with data on cost (USD/MJ) of steam production from USA Department of Energy (EERE, 2003). Packaging was assumed to be 2.5% of production costs (Canning, 2011). Details on the LCI for final manufactured BB and IB can be found in ***Table 4.6***.

Life Cycle Impact Assessment

Impact assessment of climate change, land use, and water consumption was performed using ReCiPe 2016 (Huijbregts et al., 2017), adapted from OpenLCA assessment methods (available at https://nexus.openlca.org; Acero et al., 2015) for use with EXIOBASE specific elementary emission flows. EXIOBASE energy extensions provide data on the supply of natural inputs (i.e., primary energy supply), which served as the primary energy supply extension to calculate energy use[2] (Stadler et al., 2018). In addition, value added (VA) was characterized to provide some insight into the potential economic implications of a shift from GB to MA consumption as it represents the contribution of GB and MAs to the US gross domestic product (GDP). Final impacts were first determined for the five GTAP LCIs (baseline, 1%, 5%, 10%, and 15%) and next determined for BB and IB. These impacts were combined to determine total impacts of the shift from GB to BB, IB, or a 50/50 substitution of the two MA at 1%, 5%, 10%, and 15% compared to baseline.

RESULTS

In contrast to conventional LCA, M-LCA provides the ability to determine impacts beyond the direct production of GB, BB, and IB, taking into consideration how other sectors and other

[2] Detailed methodology on energy use accounts in EXIOBASE can be found in the "Supporting information for energy accounts" from Stadler et al. (2018).

countries contribute to total impacts and are impacted by large shifts in GB production[3]. Because M-LCA accounts for a more expansive system (that is without truncation effects typical of conventional LCA), results reported herein are generally larger than might be expected from conventional process-based LCA. Additionally, results are reported as impacts for total production in the GB sector rather than per kg of production, as is typically reported.

Given that the reduction of GB in each GTAP scenario was simulated as a reduction in consumer spending, replacement with MAs have been evaluated in two ways: (1) expenditure based substitution (EBS) - the expenditure (EUR) of decreased consumer spending on GB was allocated to MA spending; or (2) quantity based substitution (QBS) - the physical quantity (kg) of decreased consumer intake of GB was allocated to MA purchases. With the former, consumers spending budget was not affected – they spend the same total amount on ground meat products (GB plus MAs) – but their intake was impacted. As BB and IB cost 2.7 and 3.6 times more than GB, respectively, replacing GB with these products for the same total expenditure results in an overall reduction in amount of food purchased by consumers. Alternatively, for consumers to ensure they are purchasing the same total amount of food, their expenditure must increase. With these two methods in mind, results are presented to reflect both options. Additionally, the bulk of results below are focused specifically on changes that occur within the GB sector, comparing the baseline GB sector to the new GB sector, which accounts for new levels of GB and MA consumption combined. The section "National Inventories" presents how impacts in the GB sector effect national environmental impacts, reporting the new GB sector as a portion of national impacts.

[3] While conventional LCA can do this to an extent, underlying assumptions in conventional LCA would be violated at the larger reduction rates investigated in the present study (i.e., beyond the 1% scenario).

Results for EBS of GB with BB are presented in ***Table 4.7*** and results for QBS of GB with BB are presented in ***Table 4.8***. Results for EBS of GB with IB are presented in ***Table 4.9*** and results for QBS of GB with IB are presented in ***Table 4.10***. For each of the four replacement scenarios, the percent difference from baseline is also presented, with a negative value indicating an overall decline and a positive value an overall rise in the respective impact categories. In all comparison scenarios, GB declined in both final demand and VA, as is expected as the result of reducing consumer demand for GB. Similarly, both BB and IB increased in final demand and VA as a result in increasing consumer demand for either MA. However, when combining the new GB consumption with MA consumption, total VA changed depending on the substitution method.

When GB was replaced by EBS of either BB or IB, final demand (million EUR) of combined GB and MA did not change (***Tables 4.7*** and ***4.9***), which was intended given the goal was to not increase consumer spending in the GB sector. However, total VA (i.e., the GB contribution to USA GDP, in million EUR) was reduced by 6.8% when replacing 15% of GB with BB or IB; meaning that overall spending in the new GB sector declined in the USA. Similarly, when this 15% replacement occurred, total consumption declined by 9.5% for BB and 11% for IB. When GB was replaced by QBS of either BB or IB, final demand of combined GB and MA increased by 25.7% for BB and 41.6% for IB, at the 15% replacement (***Tables 4.8 and 4.10***). In addition, VA increased by 7.7% for BB and 15.9% for IB. While these increases may be interpreted as benefits to the sector, they are the result of consumer spending increasing by 25.7% with BB replacement and 41.6% with IB replacement, when replacing GB with 15% MA.

Trends in environmental impacts were variable depending on the MA and the substitution method under analysis. The following sections provide more detailed analysis of climate change, land use, water use, and energy use impacts, evaluating not only total emissions but also sectoral impacts associated with observed changes. While changes were found in the lower replacement scenarios (1, 5, and 10%), further analysis focuses on the maximum replacement (15%) of GB with MA.

Climate Change

Global warming potential (GWP) was used as the midpoint characterization factor for climate change (Huijbregts et al., 2017). ReCiPe 2016 utilizes IPCC 2013 GWP 100a characterization factors with climate-carbon feedback for non-CO_2 GHG emissions. Thus, GWP characterization factors for carbon dioxide (CO_2), biogenic CH_4, fossil CH_4, and nitrous oxide (N_2O) were 1, 34, 36, and 298 equivalents of CO_2 (CO_2eq), respectively. While including climate-carbon feedback introduces a level of uncertainty, this method also provides more consistent midpoint characterization (Huijbregts et al., 2017).

When GB consumption was reduced by 15%, GHG emissions for the sector were reduced by 15%, from 234 MMT CO_2eq to 199 MMT CO_2eq. When BB was used to replace GB, total emissions were reduced by 14.2% (201 MMT CO_2eq total; ***Table 4.7***) for EBS or 12.9% for QBS (204 MMT CO_2eq total; ***Table 4.8***). When IB was used to replace GB, total emissions for the sector were reduced by 14.4% (201 MMT CO_2eq total; ***Table 4.9***) or 12.6% (205 MMT CO_2eq total; ***Table 4.10***) with EBS or QBS, respectively. When considering the sector contributions of GHG emissions, GB and cattle (CTL) sectors, together, contributed to over 80% of emissions across all scenarios (**Figure *4.3***a).

Comparing across scenarios, EBS of IB for GB showed the largest GHG reduction potential; however, QBS of IB for GB showed the least GHG reduction potential (**Figure *4.3***b). With EBS, less IB was needed to meet baseline spending than BB due to the higher cost of IB, thus the GHG impacts were reduced simply as the result of price differential between IB and BB.

However, when using QBS to replace GB with IB, the increased cost of IB resulted in greater emissions produced than BB. When considering the major production processes of both BB and IB, the patty ingredients contributed most significantly to GHG emission production (**Figure *4.3***b). Methane emissions from cattle production were by far the greatest contributor to GWP across all scenarios, regardless of MA replacement, contributing to 63% of GWP emissions at baseline, and approximately 62% when replacing GB with BB or IB. Across all replacement scenarios, CH_4 was reduced by nearly 15%. However, both BB and IB proved to be CO_2 intensive, offsetting some of these observed CH_4 reductions (**Figures *4.3***a and ***4.4***).

Characterizing climate change utilizing GWP compared to traditional GWP_{100}*

An important consideration when comparing emissions from cattle production, or any related activity, is that methane (CH_4), the primary source of greenhouse gas (GHG) emissions from cattle, is a short-lived climate pollutant (SLCP). This means that once emitted, CH_4 remains in the atmosphere approximately 12-years before being oxidized[4] (Collins et al., 2002; Reay et al., 2007; Allen et al., 2016). By contrast, carbon dioxide (CO_2), the primary source of GHG emissions from industrial processes, remains in the atmosphere for 1,000's of years. Recent work evaluating this variability between the lifetimes of short-term and long-term climate pollutants, such as CH_4, and CO_2, has highlighted that the standard metric for evaluating climate change impacts (GWP) may produce misleading results (Lynch et al., 2020; Cain et al., 2021; Smith et al., 2021). Through the use of 'warming-equivalents' to characterize CH_4, an alternative application of GWP, GWP-star (GWP*), provides a means of addressing these differences. GWP* provides an answer for question of why did we not observe increasing temperatures in the 17 and 1800s when the population of bison was approximately equivalent to the population of cattle today. Briefly, the

[4] Methane (CH_4) oxidation in the process by which hydroxyl radicals (OH^-) in the atmosphere remove hydrogen (H) from CH_4 until CH_4 is converted to CO_2 and two water (H_2O) molecules.

answer is that the warming effect of methane from biological sources achieves and approximate steady-state when the animal number is essentially constant. This occurs because the emission rate and atmospheric degradation rate become equal and the total amount of heat trapping greenhouse gases in the atmosphere becomes constant, causing milk for the warming. Thus the GWP* metric appears to be a more suitable one for evaluating the climate change contribution of ruminants.

As mentioned above, when considering a constant rate of emissions, such as CH_4 from a relatively stable cattle herd in the USA, this method accounts for the fact that the concentration of CH_4 in the atmosphere attributable to cattle remains constant, that is, CH_4 is destroyed at the same rate of its creation. If the GWP* metric was applied to the current work, the total emissions from a 15% reduction in GB would result in dramatically lower emissions than presently reported, negative CO_2eq* emissions from reduced CH_4 (resulting from a decrease in herd size driven by the reduction in ground beef demand) would offset a substantial amount of CO_2 and N_2O emissions. When applied to 15% increases in BB or IB, the GWP* impacts of the increase in these individual products would actually be greater than presently reported due primarily to an increase in CH_4 emissions associated with production of these products. Expenditure-based substitution of BB would result in an increase of 0.40 MMT CO_2eq* from BB and 0.33 MMT CO_2eq* from IB while quantity-based substitution (QBS) would result in a 1.1 MMT CO_2eq* increase form BB and a 1.3 MMT CO_2eq* increase from IB. Though it is important to note that the source of CH_4 leading to the associate observed with either products is related to cattle production related to background economic processes in BB and IB. One could then argue that these emissions are not in fact new CH_4 emissions, rather just emissions relocated to BB and IB, and thus would not actually contribute to new warming. Regardless of interpretation of emissions from BB or IB, total emissions would still remain relatively low and total emissions for the new GB sector (i.e., the lower level of GB production plus the increased MA production) would be substantially reduced compared to baseline.

Table 4.11 provides an example of what these emissions might look like by applying GWP* following work done in Cain et al. (2021). These values assume that the emissions from baseline GB production have been stable for the past 20 years. This is done for ease of calculation and to provide an example of what GWP* means in the context of this research, but it is recognized that more than likely emissions from GB have reduced substantially over the past 20 years due to improved technology, efficiencies, etc. Additionally, these calculations do not reflect changes in the total production of either GB or MA that would possibly be needed to accommodate a growing population. The United Nations does not predict significant changes to the US population between now and 2050, as most of the global population growth is expected to occur in low to middle income regions, and thus this decision (to exclude population growth) is unlikely to cause any noteworthy changes to the results presented herein.

Baseline annual emissions from the GB sector under GWP* would total 130 MMT CO_2eq* rather than 234 MMT CO_2eq with GWP_{100}, highlighting how the current GWP_{100} metric likely overestimates emissions from GB by as much as 44.4%. When GWP* is then used to assess the effects of a 15% reduction in GB and corresponding replacement with BB or IB emissions for the GB sector are substantially reduced compared to the main report results. Specifically, the 15% reduction in GB results in 75.6% reduction when using the GWP* metric, in contrast to only a 15.0% reduction when using the GWP_{100} metric. When BB is used to replace GB, total emissions for the GB sector are reduced by 73.8% with EBS or 70.1% with QBS. When IB is used to replace GB, total emissions are reduced by 74.2% with EBS and 70.2% with QBS. While the increase in BB or IB production does result in higher emissions for those specific products when using GWP* compared to GWP_{100}, this is more than offset by the substantial reductions which result in the GB sector as a whole due to the reduction in GB (i.e., reduced number of cattle meeting to provide the smaller demand). While it is important to note that substantial reductions will occur with a reduction in GB consumption regardless of what has caused the reduction, the use of GWP* further fuels and strengthens the argument of BB and IB for reduced GB consumption.

The results presented in ***Table 4.11*** are broken-down into two main sections. The first are the annual emissions that would be observed in the new GB sector (i.e., GB plus the 15% replacement of MA) over a 20-year period if BB and IB replacement of GB held constant at 15% during this time period. The second are the predicted annual emissions for the new GB sector after this 20-year period if the replacement rate remained at 15%. To this point in our discussion, the results in the former scenario have been addressed. What is notable about the latter scenario is that emissions from CH_4 will no longer be negative 20 years after the initial reduction but will increase back to a positive value that is approximately 14.8% of the baseline emissions regardless of EBS or QBS – meaning that these emissions after the 20-year period align with the original GWP_{100} estimates. This is because the period over which the emission rate is relevant for GWP* is typically taken as 20-years and after that time, the rate is considered stabilized and an approximate steady-state is achieved were further effects of changing methane emissions no longer affect the result. Similarly, total GWP* for the GB sector becomes 10.8 (QBS) to 13.8% (EBS) less than baseline emissions.

Land Use

EXIOBASE provides detailed land use accounts for six major land use categories[5]: cropland, permanent pasture, forest area, settlement area, other land (assumed to be used for wood

[5] Detailed methodology for land use accounts can be found in the supplementary material "Supporting information for land accounts) in Stadler et al. (2018)

fuel extraction and occasional livestock grazing), and wilderness (Stadler et al., 2018). ReCiPe (2016) midpoint land occupation characterization factors were applied to EXIOBASE land use flows and land occupation (m^2a) associated with GB, BB, and IB was determined. Reduction in GB alone resulted in a 15% reduction in land use for the GB sector compared to baseline. As with GHG emissions, land use for the GB sector was dominated by GB and CTL production, accounting for up to 96% of the land use footprint depending on the MA replacement scenario (**Figure *4.5***a). When replacing GB with 15% BB or IB total land use was reduced regardless of substitution scenario. However, EBS produced the greatest overall land use reduction potential, with 14.5% and 13.3% reductions for BB and IB, respectively (***Tables 4.7 and 4.9***). For QBS, BB still led to large reductions in land use (13.7%) while replacement with IB did not maintain quite as high a reduction (8.53%) (***Tables 4.8*** and ***4.10***). Both BB and IB land use were predominantly attributed to crop production for patties, with IB being more land use intensive than BB, explaining why IB land use effects were not quite as pronounced with QBS (**Figure *4.5***b).

While total land use apparently declined when replacing GB with either BB or IB, the type of land use is an important factor of consideration. EXIOBASE characterizes land use with three categories: permanent pasture, cropland, and other land use[6]. Land use associated with GB was dominated using permanent pastures for grazing cattle, accounting for nearly 63% of total land use in both the baseline and 15% reduction scenarios. Meanwhile, cropland (dominated by crops for cattle fodder) accounted for approximately 8% of land use in both baseline and 15% GB reduction scenarios. With the addition of either BB or IB, total reduction in permanent pastureland use for grazing cattle remained unchanged. As BB is not land use intensive, even when BB replaced GB

[6] More detail on EXIOBASE land use accounts can be found in “Supporting information for land accounts” from Stadler et al. (2018).

by EBS or QBS, total cropland use declined. However, when IB replaced GB by EBS or QBS, cropland use was increased by 4.37% and 57.9%, respectively.

Water Use

Water use in EXIOBASE is classified as either 'consumption' or 'withdrawal'[7]. Water consumption accounts for the amount of water (m^3) not released back to the watershed from which it was removed, either as a result of evapotranspiration or plant uptake (Pfister et al., 2011). Water consumption in EXIOBASE is divided into four categories: agriculture, livestock, manufacturing, and electricity (Stadler et al., 2018). These are further divided into 'blue' (i.e., ground and surface water) and 'green' (i.e., water available for precipitation and soil moisture) water. Water withdrawal is the volume of water removed from either surface water or groundwater (Flörke et al., 2013) and is accounted for with manufacturing and electricity in EXIOBASE. Water use results presented herein describe only blue water consumption, following ReCiPe 2016 characterization (Huijbregts et al., 2017). Green water use is not typically characterized in LCA due to overestimation of water use from production systems and therefore was not evaluated in the present work. Water withdrawal was also not analyzed due to inconsistencies in data for this metric.

From baseline to a 15% reduction in GB, water use was reduced by 850.3 million m^3 and, when replacing GB with MA, total water use for the sector was reduced by 12.2% (EBS) and 7.3% (QBS) with BB and by 8.8% (EBS) with IB (***Tables 4.7***, ***4.8***, and ***4.9***); however, water use increased by 8.5% when IB replaced GB via QBS (***Table 4.10***). Ground beef, CTL, and crop sectors contributed most significantly to water use from the GB sector (**Figure *4.6***). Of these, the primary sources of water use from GB and CTL were the crops necessary for CTL production. As

[7] For information on the EXIOBASE water accounts methodology see "Supporting information for water accounts" in Stadler et al. (2018)

with climate change and land use, ingredients for patty production were the greatest contributors to water use from BB and IB (**Figure *4.6***). When considering the new GB sector, IB contributed to 21.7% of water use with QBS. Oil seed production (i.e., soybeans) was the primary source of water use for IB, contributing 16.4% (1010 million m^3) of total water use for the combined QBS replacement of GB.

Energy Use

A 15% reduction in GB resulted in the reduction of energy use for GB by 164586 million MJ. Manufacturing and industry sectors were the greatest contributors to energy use from GB both at baseline and with a 15% reduction (**Figure *4.7***a). When replacing either the EBS or QBS of GB with BB, total energy use in the new GB sector was reduced by 12.5% and 8.1%, respectively (***Tables 4.7 and 4.8***). The EBS of IB for GB resulted in a 10.9% reduction in total energy use, while the QBS of IB for GB resulted in a 0.45% increase in total energy use (***Tables 4.9 and 4.10***). The ingredients for the BB patty contributed most significantly to energy use (**Figure *4.7***b). In particular, BB ingredients characterized as 'Other Food n.e.c.'[8] accounted for nearly 25% of the energy used to produce BB. For IB, electricity required for manufacturing was the greatest contributor to energy use (**Figure *4.7***b).

National Inventories

Data presented thus far has focused on how the introduction of MAs impacts the GB sector specifically but does not consider national impacts. Without consideration how changes in the GB sector effect the national inventory, the consequences of these shifting markets have not been fully accounted for. Thus, the present section addresses how the reported changes in the GB sector impact national emission inventories. National impacts were determined for the total US output

[8] n.e.c = not elsewhere classified.

from all 19 sectors in the GTAP model (in contrast to the results reported in the sections above, which focused on the GB sector specifically) for both baseline emissions and for a 15% reduction in consumption of GB. In this manner, a consequential LCA approach was taken to determine how environmental impacts change in the entire USE economy in response to reduced GB consumption.

When considering the national impacts of baseline GB production, the GB sector accounted for 0.20% of USA gross domestic product (GDP), 0.76% of GWP, 12.19% of land use, 2.37% of water use, and 0.12% of energy use. ***Table 4.12*** presents the effects of EBS and QBS on national impacts. New national (NN) impacts are determined as the combination of the 15% reduction in GB and replacement with either BB or IB. From this, relative impacts of the new GB sector (GB plus MA replacement) are determined as well as overall changes in NN impacts compared to baseline.

While climate change and land use impacts were the most pronounced within the GB sector, the scale of these impacts were significantly reduced when applied to national inventories. Regardless of EBS or QBS, both national climate change and land use impacts were reduced when GB was replaced with BB or IB. However, national climate change impacts were minimally reduced, with a maximum national reduction of 0.08% for both BB and IB, using EBS. On the other hand, reductions in national land use were relatively substantial. Regardless of EBS or QBS national land use declined, with maximum reductions of 1.60% for BB and 1.45% for IB using EBS.

National water use and energy use impacts were least effected by the replacement of GB with BB or IB, and variability was observed with BB impacts on national inventories. When replacing GB with BB, national water use was reduced by 0.09% with EBS but increased by 0.02%

with QBS. In contrast, replacement of GB with IB resulted in increases to national water use, regardless of EBS (0.02%) or QBS (0.40%). Similar results were observed for national energy use, with BB leading to a slight decline under EBS (0.001%) but a slight increase under QBS (0.004%), and IB leading to declines under both EBS (0.001%) and QBS (0.015%).

Unit Comparisons

The use of M-LCA provided a unique means by which to investigate a shift from GB to MA consumption in the US, incorporating both direct and indirect impacts of GB and MA production. While this method allows for a more complete idea of total product impacts across the USA, it does not allow for direct comparison to results from conventional LCA. To overcome this barrier results for GB, BB, and IB were converted to a per EUR basis from which they were then converted to a per kg basis (***Table 4.13***). For GB, conversion from EUR to kg was achieved using the national average price per kg GB (BLS, 2020). For BB and IB, the average price per kg was determined based off the bulk product purchase price, found on both respective products websites.

For ease of interpretation, data entries in ***Table 4.13*** are highlighted in varying shades of red, darkest (the product with the greatest impact per unit production) to lightest (the product with the smallest impact per unit production). When comparing GB, BB, and IB per EUR production, GB was found to have the greatest overall impacts, while BB had the least overall impact. The trends observed per EUR production were similar to those outlined when comparing baseline GB to EBS of BB or IB. When converted to per kg product, BB proved to have the lowest environmental impacts of all three productions. However, it was more challenging to assign GB or BB as having an overall greater impact compared to all other products. In this case, GB had the highest GWP and land use impacts, which is consistent with the literature, and not surprising given the fundamental differences between GB and MAs. However, IB was found to be most impactful in regards to energy use and water use. These results were consistent with QBS of GB with BB or IB.

Discussion

Two crucial insights may be gained from the present work. First, with the consideration of the complex interconnectedness of the US economy, life cycle impacts of GB, BB, and IB are likely greater than commonly reported; this is a common result of using input-output modeling for LCA as opposed to process-based modeling, as is commonly reported. Second, unlike what is suggested in previous work comparing GB to IB and BB, a simple replacement of GB with either product is not a clear-cut strategy to uniformly reduce environmental impacts of the US food system.

Climate change impacts in the present study were dominated by CH_4 emissions from CTL related to GB production. This was consistent regardless of MA replacement scenario. These results coincide with literature both on beef production, in general (Pelletier et al., 2010a; Capper, 2011; Rotz et al., 2012; Stackhouse-Lawson et al., 2012; Rotz et al., 2013; Stackhouse-Lawson et al., 2013a; Stackhouse-Lawson et al., 2013b; Gerber et al., 2015; Rotz et al., 2015; Asem-hiablie et al., 2019; Rotz et al., 2019; Kamilaris et al., 2020; Place and Myrdal Miller, 2020; Thompson and Rowntree, 2020), as well as with current LCA of BB and IB compared to GB (Goldstein et al., 2017; Heller and Keoleian, 2018; Khan et al., 2019). However, an important consideration is that of GWP compared to GWP*. While GWP* ensures that cumulative emissions over this 20-year period have not been grossly overestimated, the use of GWP* also highlights that any reduction in GB will have immediate and profound reductions on emissions from the GB sector for a prolonged period. Furthermore, these emission reductions would be substantial enough that they would likely show similar trends when considering the effects of the replacement of GB with

MA on the national GHG emission inventory. These calculations should be considered with care when considering implications for the GB sector, and by extension US cattle production. Any advances made to reduce emissions from the GB sector are necessary to achieve as the cattle sector works to become carbon neutral, and perhaps these results can help to elucidate the possibility for the GB and MA sectors to work together to achieve carbon neutrality in the food sector while meeting the dietary needs and taste preferences of all consumers.

Land use was also found to be dominated by CTL, as is consistent with the literature (Zanten et al., 2016; Bigelow and Borchers, 2017; Broom, 2019; IPCC, 2019a). However, land use associated with GB was dominated by permanent pasture. Meanwhile land needed to replace GB with BB and IB was predominantly cropland. In the case of IB replacing GB, land use for cropland, specifically, increased by 45,801 m^2a, 3.3% of total USA cropland (ERS, 2020). While not a substantial portion of total land use, the change in cropland necessary to accommodate increased BB production in the USA is an important consideration. Impossible Burgers primary ingredient is soy protein. If it is assumed that soy protein is being produced in the USA (from the crops through to manufacturing), then likely the majority of that increased land use is attributed to soy production. This would represent a 13% increase in land used for soy production in the USA (NASS, 2020). Furthermore, the decline in grazing land used by cattle has possible implications. In well managed grazing lands, cattle have the potential to sequester carbon, which in turn improves water holding capacity in the lands and promotes improved soil quality (Machmuller et al., 2015; Ricard and Viglizzo, 2020). Additionally, on grazing lands, cattle are able to utilize human inedible feeds (i.e., the grasses) to produce a high quality protein (i.e., the cattle meat) for humans to then consume (Mottet et al., 2017; Karlsson and Röös, 2019), thereby upcycling resources. With grazing lands left unused by cattle, such benefits are either lost or the lands are converted for use by other ruminant animals (e.g., sheep or goats). In the case of repurposing land for other ruminant animals, then a large portion of the environmental concerns which lead to desired replacement of GB with BB and IB are not actually remediated, they are simply transferred to another species.

Water use was dominated by cattle production for GB and by crop production, manufacturing, and electricity, which was consistent with the literature for BB and IB (Avelino and Dall'erba, 2020). In connection with land use, whether the land is grazing land for cattle or arable land for crops has a direct impact on water use and how it can be assessed. The water used on rangeland is not water that can simply be applied in MA production as these lands, for the most part, cannot be converted into land for MAs (Damerau et al., 2019). Thus, when the land is not used due to reduced need for cattle, that water cannot be put to use for MA, and the water then required for MAs remains an additional source of water use.

Water use and energy use were two areas in which the replacement of GB with either BB or IB resulted in the possibility of increased resource use. Previous LCA comparing GB and to BB or IB found significant reductions to water use and mixed results for energy use (***Table 4.1***). However, these studies assessed products side by side on a per kg basis. Through this form of analysis connecting industries and scaled-up impacts of BB and IB were not considered and present work highlights that this was a shortcoming of previous works.

When considering the implications of a shift from GB to MA consumption on total US impacts, results were mixed. Land use was most notably minimized, though the consideration of type of land reduced is still warranted. Meanwhile, for both BB and IB, national GHG emissions were minimally reduced and mixed results (though still numerically minimal) were observed for national water use and energy use depending on substitution method. Overall, national impacts reported were greater than those reported by national inventories, in particular those of GWP and energy. However, this is expected to some degree when utilizing MRIO models and has been observed by other studies investigating national level impacts (Caron et al., 2014; Kucukvar et al., 2014; Yang and Heijungs, 2018; Bjelle et al., 2021a). Sectoral aggregation may play a role in the greater inventories as it may lead to changes in CO_2 multipliers that have the potential to inflate emissions (Steen-Olsen et al., 2014; Bjelle et al., 2020); however, in general, inventories across MRIO models are consistent (Wood et al., 2019). Furthermore, the relative trends observed in the proportion of sectoral impacts compared to national are, for the most part, consistent with nationally reported impacts. For example, in the baseline model output, CTL represent 2.81% of national emissions, slightly higher than the nationally reported 2.2%, but reasonable considering the methods used to determine these emissions (EPA, 2021). Meanwhile, characterized land use reported herein for both baseline and updated national inventories is much smaller than land use reported by the US Economic Research Service (ERS, 2020). In both instances, characterization methods and factors used for the present work are different than those used in national inventories, which contributes to the variability to a degree. However, future research investigating the variability of MRIO to national inventories would be beneficial for a more complete assessment.

Finally, in contrast to conventional process-based LCA, in which impacts are typically evaluated on a per kg basis, the present work focused on impacts of the entire GB sector as well as what these impacts mean when accounting for market mediated external effects on a national scale. In assessing impacts in this manner, it is possible to present a more complete picture of the impacts associated with GB compared to BB and IB. However, there remain other methods by which impacts of these products can be assessed that may help provide improved insight into some of the trade-offs found with a shift from GB to BB or IB. For example, consideration of protein and macronutrient quantities and qualities in GB, BB, and IB or the analysis of carbon sequestration potential and the use of human inedible feeds in CTL production may prove to be important factors to consider when determining impacts of these products.

Opportunities for the Future

In total, environmental impacts of replacing GB with BB or IB produced mixed results, highlighting that a simple ‘either-or’ choice may not be possible when considering which item to consume. While GB proved to be more GHG and land intensive, further evaluation and consideration of these results indicates that these reductions have a more nuanced interpretation. Emissions attributed to GB are likely over-estimated due to the emerging understanding of how CH_4 effects radiative forcing. Beyond this, the cattle from which GB is sourced primarily utilize land that cannot be used for other food production purposes. Replacement of GB with BB or IB has the potential to elevate national water use and energy use. While these increases are minimal, they present areas that have potential to be mitigated in future production through improved technologies and changes to primary sources of electricity (e.g., solar). Based on the work presented herein and contrary to that suggested in previous LCA of these products, when considering a realistic reduction in GB, there is not a uniformly positive effect from the reduction of GB and replacement of BB or IB. Furthermore, with a growing global population, determining a mode in which these products can coexist rather than compete will prove to be much more successful all around.

TABLES AND FIGURES

Table 4.1. Life cycle impacts from plant-based meat alternatives compared to ground beef reported per kg product.

Burger Patty	System Boundaries	GWP[1] (kg CO_2eq)	Land Use[2]	Water Use (m^3)	Energy Use (MJ)
Beyond Burger®					
Heller and Keoleian (2018)[3]	Cradle-to-distribution[4]	3.35	2.38	0.03	54.15
Nair et al. (2019)[5]	Cradle-to-grave[6]	6.88	4.71	0.34	88.83
Impossible Burger™					
Nair et al. (2019)	Cradle-to-grave	10.16	3.42	0.79	141.83
Goldstein et al. (2017)[7]	Cradle-to-processing[8]	6.94	3.53	0.18	NA
Khan et al. (2019)[9]	Cradle-to-manufacturers gate[10]	3.50	2.50	0.11	NA
Ground Beef					
Heller and Keoleian (2018)[11]	Cradle-to-distribution	32.63	33.51	3.86	100.53
Goldstein et al. (2017)[12]	Cradle-to-processing	30.10	101.10	6.07	NA
Khan et al. (2019)[13]	Cradle-to-manufacturers gate	30.60	62.00	0.85	NA

[1] GWP = global warming potential

[2] Each study characterized Land Use differently. Units for each result are as follows: Heller and Keoleian (2018) characterized as 'ecosystem damage potential' with units in m^2a-eq; Nair et al. (2019) characterized as strictly an inventory with units in m^2a; Goldstein et al. (2017) characterized as 'physical area of arable land occupied' with units in m^2; and Khan et al. (2018) characterized as 'land occupation' with units in m^2y.

[3] GWP characterized with IPCC (2007); Land Use follows Koellner and Scholz (2008); Energy Use (cumulative energy demand) followed Frischknecht et al. (2007); Water Use follows Pfister et al. (2009).

[4] Distribution includes refrigerated transport of packaged, finished product to retailer or distributor and packaging disposal.

[5] GWP characterized with IPCC (2013); Water Use characterized with ReCiPe (2016); and Land Use (land occupation) and Energy Use (cumulative energy demand) followed IMPACT World+ (2017).

[6] Cradle-to-grave included disposal of packaging waste and recycling of packaging materials.

[7] GWP characterized with IPCC (2013); Water Use calculated as "blue water"; Land Use followed IMPACT 2002+ (2003).

[8] Processing included formation of the patty final product at manufacturer, but excluded distribution (transport and packaging) of the final product.

[9] Environmental impacts characterized with IMPACT 2002+ (2003).

[10] Included packaged, finished product at manufacturing gate.

[11] Ground beef adapted from Thoma et al. (2017).

[12] Life cycle inventory data for beef was modeled after Pelletier (2010) and further calculations performed to determine ground beef footprint.

[13] Ground beef production determined from a variety of input sources with the assumption that there was no distinction between life cycle needs for ground beef compared to other beef cuts.

Table 4.2. Beyond Burger® (BB) list of ingredients, corresponding EXIOBASE processes, amount of ingredients, and estimated costs of ingredients.

Ingredients	**EXIOBASE Process**	**Amount (g)**	**BB Cost (EUR/kg)**
Water	Water	553	0.0129
Pea Protein	Pea Protein Concentrate	187	0.522
Expeller-pressed Canola Oil	Canola Oil	52.7	0.0521
Refined Coconut Oil	Coconut Oil	32.2	0.0413
Rice Protein	Rice Protein	24.0	0.0837
Natural Flavors	Other Food n.e.c.	24.0	0.418
Dried Yeast	Other Food n.e.c.	24.0	0.0126
Cocoa Butter	Cocoa Butter	24.0	0.282
Methylcellulose	Methylcellulose	24.0	0.335
Contains 1% or Less			
Potato Starch	Other Food n.e.c.	10.0	0.0047
Salt	Methylcellulose	5.00	0.0012
Potassium Chloride	Methylcellulose	5.00	0.0012
Beet Juice Extract	Other Food n.e.c.	5.00	0.0362
Apple Extract	Other Food n.e.c.	5.00	0.0274
Pomegranate Extract	Other Food n.e.c.	5.00	0.0291
Sunflower Lecithin	Other Food n.e.c.	5.00	0.0233
Vinegar	Other Food n.e.c.	5.00	0.0048
Lemon Juice Concentrate	Other Food n.e.c.	5.00	0.0116
Vitamins and Minerals			
Zinc sulfate	Methylcellulose	0.035	0.0012
Niacinamide [vitamin B3]	Methylcellulose	0.236	0.0008
Pyridoxine hydrochloride [vitamin B6]	Methylcellulose	0.410	0.0001
Cyanocobalamin [vitamin B12]	Methylcellulose	0.236	0.0011
Calcium pantothenate	Methylcellulose	2.37	0.0159

[1] n.e.c. = not elsewhere classified

Table 4.3. Impossible Burger™ (IB) list of ingredients, corresponding EXIOBASE processes, amount of ingredients, and estimated costs of ingredients.

Ingredients	EXIOBASE Process	Amount (g)	IB Cost (EUR/kg)
Water	Water	590	0.0137
Soy Protein Concentrate	Soy Protein Concentrate	258	0.720
Coconut Oil	Coconut Oil	103	0.132
Sunflower Oil	Sunflower Oil	20.0	0.026
Natural Flavors	Other Food n.e.c.[1]	20.0	0.349
Contains 2% or Less			
Potato Protein	Potato Protein	0.880	0.0031
Methylcellulose	Methylcellulose	0.880	0.0123
Yeast Extract	Methylcellulose	0.880	0.0005
Cultured Dextrose	Other Food n.e.c.	0.880	0.0123
Food Starch Modified	Other Food n.e.c.	0.880	0.0004
Soy Leghemoglobin	Methylcellulose	0.880	0.0154
Salt	Methylcellulose	0.880	0.0002
Mixed Tocopherols (Antioxidant)	Other Food n.e.c.	0.880	0.0248
Soy Protein Isolate	Soy Protein Concentrate	0.880	0.0031
Vitamins and Minerals			
Zinc Gluconate	Methylcellulose	0.254	0.0009
Thiamine Hydrochloride (Vitamin B1)	Methylcellulose	0.263	0.0069
Niacin	Methylcellulose	0.077	0.0008
Pyridoxine Hydrochloride (Vitamin B6)	Methylcellulose	0.003	0.0001
Riboflavin (Vitamin B2)	Methylcellulose	0.002	0.0001
Vitamin B12	Methylcellulose	0.027	0.0011

[1]n.e.c. = not elsewhere classified

Table 4.4A. Results compared to baseline of 15% reduction of ground beef (GB) replaced with Beyond Burger (BB). Three LPs are compared, high low difference determined, and percent (%) difference between high-low. Values below are reported for expenditure based substitution (EBS).

Name	Unit	Baseline	Nair LP	LP Solver	Open Solver	High - Low	% Difference
GB Final Demand	million EUR	2.41E+04	2.05E+04	2.05E+04	2.05E+04		
MA Final Demand	million EUR	0.00E+00	3.62E+03	3.62E+03	3.62E+03		
Total Final Demand	million EUR	2.41E+04	2.41E+04	2.41E+04	2.41E+04		
GB Value Added	million EUR	4.41E+04	3.75E+04	3.75E+04	3.75E+04		
MA Value Added	million EUR	0.00E+00	3.62E+03	3.62E+03	3.62E+03		
Total Value Added	million EUR	4.41E+04	4.11E+04	4.11E+04	4.11E+04		
Land Use	million m2a crop eq.	9.52E+05	8.14E+05	8.14E+05	8.14E+05	7.10E+02	0.04
Climate Change	million kg CO2 eq.	2.34E+05	2.01E+05	2.01E+05	2.01E+05	8.19E+01	0.02
	MMT CO2 eq.	2.34E+02	2.01E+02	2.01E+02	2.01E+02	8.19E-02	0.02
Energy	million MJ	1.10E+06	9.59E+05	9.60E+05	9.59E+05	7.24E+02	0.04
Water Use	million m3	5.66E+03	4.98E+03	4.97E+03	4.98E+03	4.42E+00	0.04

Table 4.4B. Results compared to baseline of 15% reduction of ground beef (GB) replaced with Impossible Burger (IB). Three LPs are compared, high low difference determined, and percent (%) difference between high-low. Values below are reported for expenditure based substitution (EBS).

Name	**Unit**	**Baseline**	**Nair LP**	**LP Solver**	**Open Solver**	**High - Low**	**% Difference**
GB Final Demand	million EUR	2.41E+04	2.05E+04	2.05E+04	2.05E+04		
MA Final Demand	million EUR	0.00E+00	3.62E+03	3.62E+03	3.62E+03		
Total Final Demand	million EUR	2.41E+04	2.41E+04	2.41E+04	2.41E+04		
GB Value Added	million EUR	4.41E+04	3.75E+04	3.75E+04	3.75E+04		
MA Value Added	million EUR	0.00E+00	3.62E+03	3.62E+03	3.62E+03		
Total Value Added	million EUR	4.41E+04	4.11E+04	4.11E+04	4.11E+04		
Land Use	million m2a crop eq.	9.52E+05	8.23E+05	8.25E+05	8.25E+05	2.88E+03	0.17
Climate Change	million kg CO2 eq.	2.34E+05	2.01E+05	2.01E+05	2.01E+05	3.31E+02	0.08
	MMT CO2 eq.	2.34E+02	2.01E+02	2.01E+02	2.01E+02	3.31E-01	0.08
Energy	million MJ	1.10E+06	9.75E+05	9.77E+05	9.76E+05	-9.77E+02	-0.05
Water Use	million m3	5.66E+03	5.12E+03	5.17E+03	5.16E+03	4.05E+01	0.39

Table 4.5A. Results compared to baseline of 15% reduction of ground beef (GB) replaced with Beyond Burger (BB). Three LPs are compared, high low difference determined, and percent (%) difference between high-low. Values below are reported for quantity based substitution (QBS).

Name	Unit	Baseline	Nair LP	LP Solver	Open Solver	High - Low	% Difference
GB Final Demand	million EUR	2.41E+04	2.05E+04	2.05E+04	2.05E+04		
MA Final Demand	million EUR	0.00E+00	9.81E+03	9.81E+03	9.81E+03		
Total Final Demand	million EUR	2.41E+04	3.03E+04	3.03E+04	3.03E+04		
GB Value Added	million EUR	4.41E+04	3.75E+04	3.75E+04	3.75E+04		
MA Value Added	million EUR	0.00E+00	9.81E+03	9.81E+03	9.81E+03		
Total Value Added	million EUR	4.41E+04	4.73E+04	4.73E+04	4.73E+04		
Land Use	million m2a crop eq.	9.52E+05	8.23E+05	8.22E+05	8.23E+05	1.93E+03	0.12
Climate Change	million kg CO2 eq.	2.34E+05	2.04E+05	2.04E+05	2.04E+05	2.22E+02	0.05
		2.34E+02	2.04E+02	2.04E+02	2.04E+02	2.22E-01	0.05
Energy	million MJ	1.10E+06	1.01E+06	1.01E+06	1.01E+06	1.96E+03	0.10
Water Use	million m3	5.66E+03	5.26E+03	5.25E+03	5.26E+03	1.20E+01	0.11

***Table 4.5*B.** Results compared to baseline of 15% reduction of ground beef (GB) replaced with Impossible Burger (IB). Three LPs are compared, high low difference determined, and percent (%) difference between high-low. Values below are reported for quantity based substitution (QBS).

Name	Unit	Baseline	Nair LP	LP Solver	Open Solver	High - Low	% Difference
GB Final Demand	million EUR	24080	20461	20461	20461		
MA Final Demand	million EUR	0.00E+00	1.36E+04	1.36E+04	1.36E+04		
Total Final Demand	million EUR	2.41E+04	3.41E+04	3.41E+04	3.41E+04		
GB Value Added	million EUR	4.41E+04	3.75E+04	3.75E+04	3.75E+04		
MA Value Added	million EUR	0.00E+00	1.36E+04	1.36E+04	1.36E+04		
Total Value Added	million EUR	4.41E+04	5.11E+04	5.11E+04	5.11E+04		
Land Use	million m2a crop eq.	9.52E+05	8.60E+05	8.71E+05	8.68E+05	1.09E+04	0.63
Climate Change	million kg CO2 eq.	2.34E+05	2.06E+05	2.05E+05	2.05E+05	1.24E+03	0.30
		2.34E+02	2.06E+02	2.05E+02	2.05E+02	1.24E+00	0.30
Energy	million MJ	1.10E+06	1.10E+06	1.10E+06	1.10E+06	-3.68E+03	-0.17
Water Use	million m3	5.66E+03	5.99E+03	6.14E+03	6.12E+03	1.52E+02	**1.26**

Table 4.6. Life cycle inventory of final Beyond Burger (BB) and Impossible Burger (IB) processes.

	Beyond Burger		Impossible Burger	
Manufacturing Component	**Mass[1] (component/kg BB)**	**Input Cost (EUR/kg BB)**	**Mass[1] (component/kg IB)**	**Input Cost (EUR/kg IB)**
Patty Ingredients (kg)	1	1.92	1	1.32
Electricity (kWh)	0.95	-	3.89	-
CA	-	0.03	-	0.33
MO	-	0.04	-	-
IL	-	-	-	0.05
Water (L)	10.1	-	14.0	-
CA	-	0.05	-	0.26
MO	-	0.11	-	-
IL	-	-	-	0.04
Heat (MJ)	0.58	3.53×10^{-14}	0.44	2.65×10^{-14}
Packaging (kg)	0.38	0.06	0.17	0.06
Transportation (tkm)	1.35	0.30	1.33	0.30

[1]Mass was adapted from Nair et al. (2019), reported LCI values converted from 113g patty to kg of BB and IB.

Table 4.7. Final demand, value added, and environmental impacts of reducing consumer demand for USA Ground Beef (GB) by 1, 5, 10, and 15% and replacing GB by expenditure-based substitution (EBS; i.e., the EUR amount of BB needed to replace the EUR amount reduced of GB) of Beyond Burger (BB) compared to Baseline (no BB). Global warming potential (GWP), land use, water use, and energy use are reported as output per total final demand (million EUR) of GB and BB.

		Reduction Scenario			
Impact	**Baseline**	**1%**	**5%**	**10%**	**15%**
Final Demand (million EUR)					
GB	24080	23839	22875	21669	20461
BB	0	241	1205	2411	3619
Total	24080	24080	24080	24080	24080
Difference from Baseline (%)[1]	-	*0*	*0*	*0*	*0*
Value Added (million EUR)					
GB	44110	43901	41905	39697	37485
Difference from Baseline (%)	-	*-0.47*	*-5.00*	*-10.00*	*-15.02*
BB	0	241	1205	2411	3619
Total	44110	44142	43110	42108	41104
Difference from Baseline (%)	-	*0.07*	*-2.27*	*-4.54*	*-6.81*
GWP[1] (MMT CO_2 eq.)	234	233	223	212	201
Difference from Baseline (%)	-	*-0.50*	*-4.74*	*-9.48*	*-14.23*
Land Use (million m^2a crop eq.)	952112	946937	906054	859903	813665
Difference from Baseline (%)	-	*-0.54*	*-4.84*	*-9.68*	*-14.54*
Water Use (million m^3)	5662	5645	5433	5203	4973
Difference from Baseline (%)	-	*-0.31*	*-4.05*	*-8.11*	*-12.18*
Energy Use (million MJ)	1096150	1094103	1050731	1005254	959713
Difference from Baseline (%)	-	*-0.19*	*-4.14*	*-8.29*	*-12.45*

[1] Difference from baseline is calculated as the difference between the new impact and the baseline impact divided by baseline the baseline impact. A positive value indicates an increase in the new impact compared to baseline and a negative value indicates a decrease in the new impact compared to baseline.

Table 4.8. Final demand, value added, and environmental impacts of reducing consumer demand for USA Ground Beef (GB) by 1, 5, 10, and 15% and replacing GB by quantity based substitution (QBS; i.e., the kg needed of BB to replace kg reduced of GB) of Beyond Burger (BB) compared to Baseline (no BB). Global warming potential (GWP), land use, water use, and energy use are reported as output per total final demand (million EUR) of GB and BB.

		Reduction Scenario			
Impact	**Baseline**	**1%**	**5%**	**10%**	**15%**
Final Demand (million EUR)					
GB	24080	23839	22875	21669	20461
BB	0	653	3266	6537	9812
Total	24080	24492	26142	28206	30273
Difference from Baseline (%)[1]	-	*1.71*	*8.56*	*17.13*	*25.72*
Value Added (million EUR)					
GB	44110	43901	41905	39697	37485
Difference from Baseline (%)	-	*-0.47*	*-5.00*	*-10.00*	*-15.02*
BB	0	653	3266	6537	9812
Total	44110	44554	45171	46234	47297
Difference from Baseline (%)	-	*1.01*	*2.41*	*4.82*	*7.70*
GWP[1] (MMT CO_2 eq.)	234	233	224	214	204
Difference from Baseline (%)	-	*-0.41*	*-4.29*	*-8.58*	*-12.88*
Land Use (million m^2a crop eq.)	952112	947462	908677	865153	821544
Difference from Baseline (%)	-	*-0.49*	*-4.56*	*-9.13*	*-13.71*
Water Use (million m^3)	5662	5663	5524	5386	5248
Difference from Baseline (%)	-	*0.01*	*-2.43*	*-4.88*	*-7.32*
Energy Use (million MJ)	1096150	1097309	1066767	1037347	1007882
Difference from Baseline (%)	-	*0.11*	*-2.68*	*-5.36*	*-8.05*

[1] Difference from baseline is calculated as the difference between the new impact and the baseline impact divided by baseline the baseline impact. A positive value indicates an increase in the new impact compared to baseline and a negative value indicates a decrease in the new impact compared to baseline.

Table 4.9. Final demand, value added, and environmental impacts of reducing consumer demand for USA Ground Beef (GB) by 1, 5, 10, and 15% and replacing GB by expenditure-based substitution (EBS; i.e., the EUR amount of IB needed to replace the EUR amount reduced of GB) of Impossible Burger (IB) compared to Baseline (no IB). Global warming potential (GWP), land use, water use, and energy use are reported as output per total final demand (million EUR) of GB and IB.

		Reduction Scenario			
Impact	**Baseline**	**1%**	**5%**	**10%**	**15%**
Final Demand (million EUR)					
GB	24080	23839	22875	21669	20461
IB	0	241	1205	2411	3619
Total	24080	24080	24080	24080	24080
Difference from Baseline (%)[1]	-	*0*	*0*	*0*	*0*
Value Added (million EUR)					
GB	44110	43901	41905	39697	37485
Difference from Baseline (%)	-	*-0.47*	*-5.00*	*-10.00*	*-15.02*
IB	0	241	1205	2411	3619
Total	44110	44142	43110	42108	41104
Difference from Baseline (%)	-	*0.07*	*-2.27*	*-4.54*	*-6.81*
GWP (MMT CO_2 eq.)	234	233	223	212	201
Difference from Baseline (%)	-	*-0.51*	*-4.78*	*-9.57*	*-14.38*
Land Use (million m^2a crop eq.)	952112	947724	909991	867783	825492
Difference from Baseline (%)	-	*-0.46*	*-4.42*	*-8.86*	*-13.30*
Water Use (million m^3)	5662	5658	5497	5331	5165
Difference from Baseline (%)	-	*-0.08*	*-2.92*	*-5.85*	*-8.78*
Energy Use (million MJ)	1096150	1095226	1056349	1016497	976588
Difference from Baseline (%)	-	*-0.08*	*-3.63*	*-7.27*	*-10.91*

[1] Difference from baseline is calculated as the difference between the new impact and the baseline impact divided by baseline the baseline impact. A positive value indicates an increase in the new impact compared to baseline and a negative value indicates a decrease in the new impact compared to baseline.

Table 4.10. Final demand, value added, and environmental impacts of reducing consumer demand for USA Ground Beef (GB) by 1, 5, 10, and 15% and replacing GB by quantity based substitution (QBS; i.e., the kg needed of IB to replace kg reduced of GB) of Impossible Burger (IB) compared to Baseline (no IB). Global warming potential (GWP), land use, energy use, and water use are reported as output per total final demand (million EUR) of GB and IB.

		Reduction Scenario			
Impact	**Baseline**	**1%**	**5%**	**10%**	**15%**
Final Demand (million EUR)					
GB	24080	23839	22875	21669	20461
IB	0	907	4536	9079	13627
Total	24080	24746	27412	30748	34088
Difference from Baseline (%)[1]	-	*2.77*	*13.84*	*27.69*	*41.56*
Value Added (million EUR)					
GB	44110	43901	41905	39697	37485
Difference from Baseline (%)	-	*-0.47*	*-5.00*	*-10.00*	*-15.02*
IB	0	907	4536	9079	13627
Total	44110	44808	46441	48775	51112
Difference from Baseline (%)	-	*1.58*	*5.29*	*10.58*	*15.88*
GWP (MMT CO_2 eq.)	234	233	224	215	205
Difference from Baseline (%)	-	*-0.39*	*-4.19*	*-8.38*	*-12.58*
Land Use (million m^2a crop eq.)	952112	950748	925118	898057	870932
Difference from Baseline (%)	-	*-0.14*	*-2.84*	*-5.68*	*-8.53*
Water Use (million m^3)	5662	5723	5822	5982	6142
Difference from Baseline (%)	-	*1.06*	*2.82*	*5.64*	*8.47*
Energy Use (million MJ)	1096150	1103512	1097799	1099451	1101098
Difference from Baseline (%)	-	*0.67*	*0.15*	*0.30*	*0.45*

[1] Difference from baseline is calculated as the difference between the new impact and the baseline impact divided by baseline the baseline impact. A positive value indicates an increase in the new impact compared to baseline and a negative value indicates a decrease in the new impact compared to baseline.

Table 4.11. Annual greenhouse gas emissions from a 15% reduction in ground beef (GB) production and a corresponding increase in Beyond Burger (BB) or Impossible Burger (IB) utilizing global warming potential-star (GWP*) compared to conventional GWP (GWP_{100}). Two replacement scenarios are investigate for BB and IB: (1) expenditure based substitution (EBS) - the expenditure (EUR) of decreased consumer spending on GB was allocated to MA spending; or (2) quantity based substitution (QBS) - the physical quantity (kg) of decreased consumer intake of GB was allocated to MA purchases. Are presented in three stages: (1) baseline emissions – no changes to GB production have occurred; (2) first 20 years – the time period when initial reductions to GB will have the most notable effect on GWP*; and (3) after year 20 – when emissions stabilize and GWP* treats emissions more similarly to GWP_{100}.

Reduction Scenario	**Biogenic CH_4** (MMT CO_2eq*)	**Fossil CH_4** (MMT CO_2eq*)	**N_2O** (MMT CO_2eq)	**CO_2** (MMT CO_2e)	**GWP*** (MMT CO_2eq*)	**GWP_{100}** (MMT CO_2eq)
Baseline	33.1	1.73	46.1	48.8	130	234
			Annual emissions: First 20 years			
GB 15% reduction	-46.5	-2.42	39.2	41.5	31.7	199
EBS						
GB + BB total	-46.1	-2.27	39.4	43.0	34.0	201
GB + IB total	-46.3	-2.20	39.4	42.6	33.6	201
QBS						
GB + BB total	-45.5	-2.00	39.7	45.6	37.8	204
GB + IB total	-45.7	-1.58	40.1	45.8	38.7	205
			Annual emissions: After 20 years			
GB 15% reduction	28.1	1.39	39.2	41.5	110	199
EBS						
GB + BB total	28.2	1.40	39.4	43.0	112	201
GB + IB total	28.2	1.40	39.4	42.6	112	201
QBS						
GB + BB total	28.2	1.41	39.7	45.6	115	204
GB + IB total	28.2	1.44	40.1	45.8	116	205

Table 4.12. Comparison of USA national inventories to ground beef (GB) baseline life cycle impacts and a 15% reduction and replacement of GB with Beyond Burger (BB) or Impossible Burger (IB). Impacts are reported as either expenditure based substitution (EBS) or quantity based substitution (QBS).

	Value Added		**GWP**		**Land Use**		**Water Use**		**Energy**	
	million EUR		MMT		million m^{2}a		million m^3		TJ	
National Baseline (NB)	2.17E+07		3.09E+04		7.81E+06		2.38E+05		8.78E+08	
GB Baseline	4.41E+04		2.34E+02		9.52E+05		5.66E+03		1.10E+06	
Percent NB (%)	*0.20%*		*0.76%*		*12.19%*		*2.37%*		*0.12%*	
GB 15% Reduction	3.75E+04		1.99E+02		8.09E+05		4.81E+03		9.32E+05	
MA Replacement	***EBS***	***QBS***	***EBS***	***QBS***	***EBS***	***QBS***	***EBS***	***QBS***	***EBS***	***QBS***
BB 15% Replacement	3.62E+03	9.81E+03	1.85E+00	5.02E+00	4.60E+03	1.25E+04	1.61E+02	4.36E+02	2.81E+04	7.63E+04
GB+BB	4.11E+04	4.73E+04	2.01E+02	2.04E+02	8.14E+05	8.22E+05	4.97E+03	5.25E+03	9.60E+05	1.01E+06
New National (NN)[1]	2.17E+07	2.17E+07	3.09E+04	3.09E+04	7.68E+06	7.69E+06	2.38E+05	2.39E+05	8.78E+08	8.78E+08
Percent NN (%)[2]	*0.19%*	*0.22%*	*0.65%*	*0.66%*	*10.59%*	*10.68%*	*2.09%*	*2.20%*	*0.11%*	*0.11%*
Change from NB (%)[3]	*0.01%*	*0.04%*	*-0.08%*	*-0.07%*	*-1.60%*	*-1.50%*	*-0.09%*	*0.02%*	*-0.001%*	*0.004%*
IB 15% Replacement	3.62E+03	1.36E+04	1.52E+00	5.71E+00	1.64E+04	6.19E+04	3.53E+02	1.33E+03	4.50E+04	1.70E+05
GB+IB	4.11E+04	5.11E+04	2.01E+02	2.05E+02	8.25E+05	8.71E+05	5.17E+03	6.14E+03	9.77E+05	1.10E+06
New National (NN)	2.17E+07	2.17E+07	3.09E+04	3.09E+04	7.70E+06	7.74E+06	2.38E+05	2.39E+05	8.78E+08	8.78E+08
Percent NN (%)	*0.19%*	*0.24%*	*0.65%*	*0.66%*	*10.73%*	*11.25%*	*2.17%*	*2.57%*	*0.11%*	*0.13%*
Change from NB (%)	*0.01%*	*0.06%*	*-0.08%*	*-0.07%*	*-1.45%*	*-0.87%*	*-0.01%*	*0.40%*	*0.001%*	*0.015%*

[1] New National incorporates changes to total outputs as a result of replacing 15% GB with either BB or IB.
[2]EPA (2021) Percent NN is the contribution of the new GB sector (GB plus either BB or IB) to the NN inventory.
[3]ERS (2020) Change from NB is calculated as the difference of NN and NB divided by NB. For Value Added, a positive value indicates a gain while a negative value indicates a loss. The inverse is true for the environmental impacts. To facilitate ease of interpretation, cells have been highlighted green (for positive impact) and red (for negative impact).

Dieter et al. (2018)EIA (2020b)

Table 4.13. Life cycle impacts of ground beef (GB), Beyond Burger (BB), and Impossible Burger (IB) on a per EUR product or per kg product basis. Darker shaded cells highlight the product with the greatest impact while lighter shaded cells highlight the product with the least impact.

	Expenditure Based Substitution			**Quantity Based Substitution**		
	GB	**BB**	**IB**	**GB**	**BB**	**IB**
Value Added (EUR)	1.83	1	1	13.82	20.46	28.41
Global Warming Potential (kg CO_2eq)	9.73	0.51	0.42	73.41	10.46	11.92
Land Use (m^2a)	39.54	1.27	4.54	298.35	26.03	129.00
Water Use (m^3)	0.24	0.04	0.10	1.77	0.91	2.77
Energy (MJ)	45.53	7.78	12.44	343.53	159.12	353.47

A.

B.

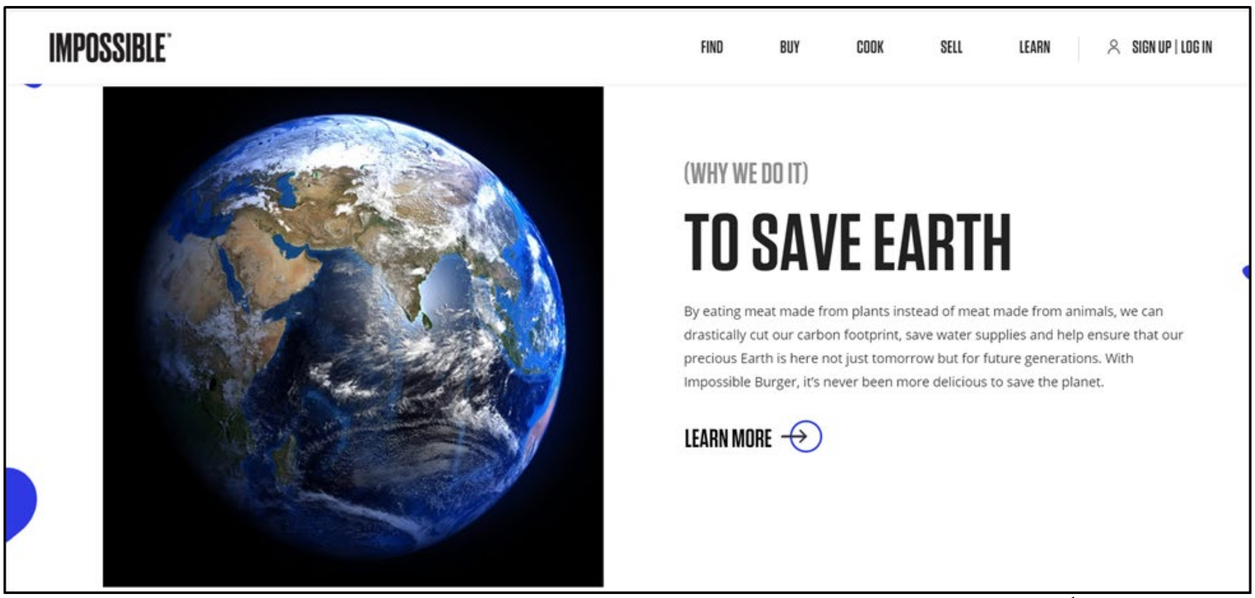


Figure 4.1. Mission statements of Beyond Meat® (A) and Impossible Foods™ (B)[1].

[1]https://www.beyondmeat.com/about/ (Accessed 25 May 2021); https://impossiblefoods.com/ (Accessed 25 May 2021).

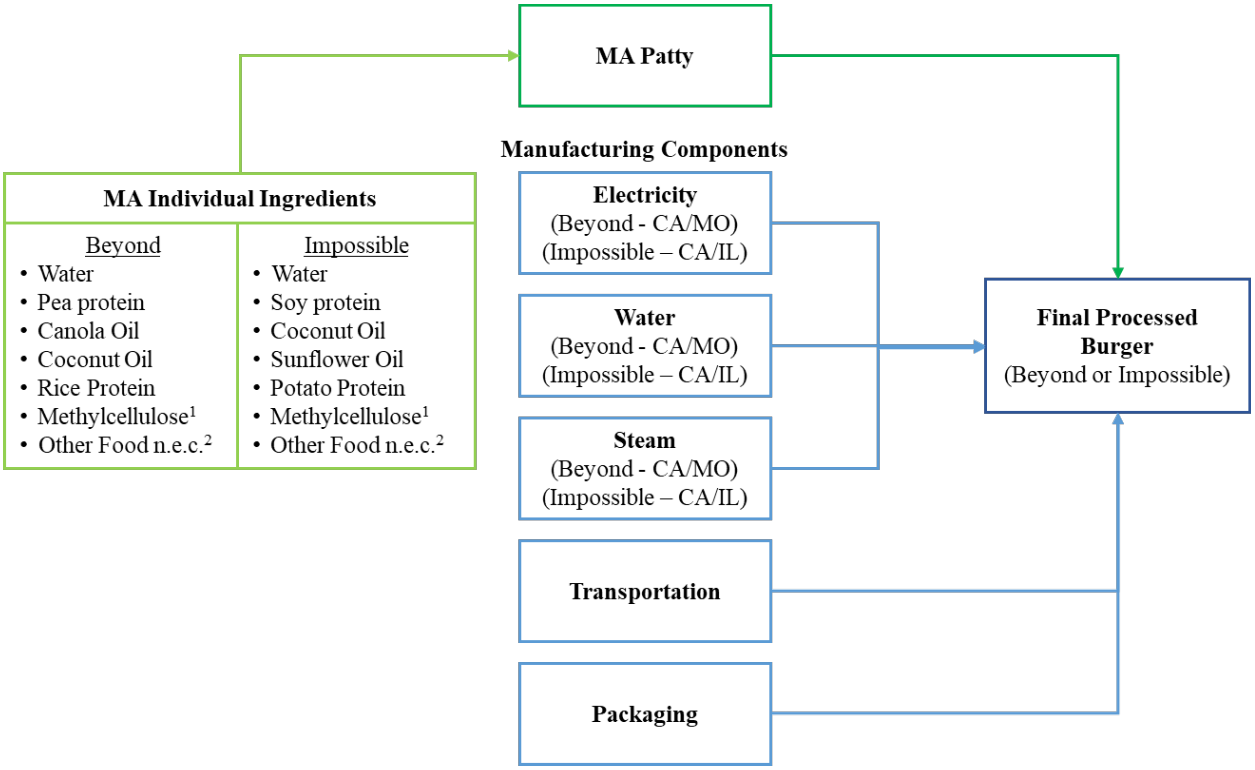
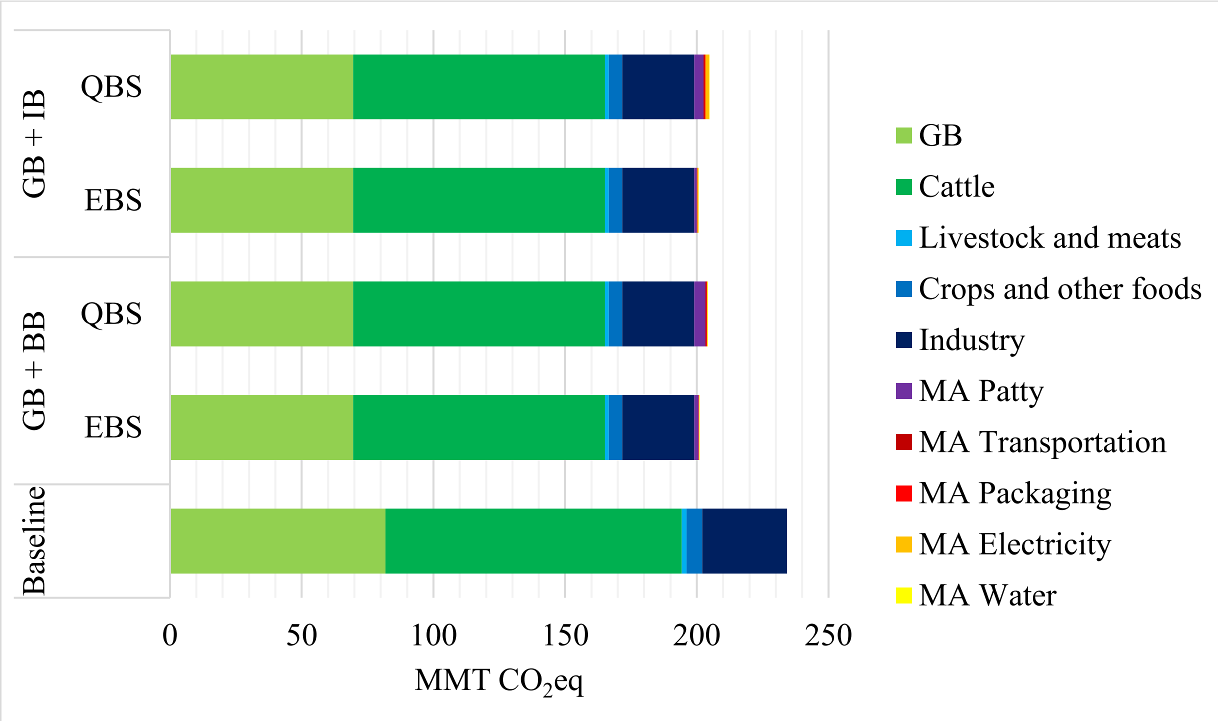


Figure 4.2. Beyond and Impossible Burger production processes as modeled within EXIOBASE.

[1] Methylcellulose grouped chemical ingredients that could not individually be represented with EXIOBASE into one category which corresponded to the EXIOBASE sector 'Chemicals n.e.c.'. For Beyond this included: methylcellulose, salt, and potassium chloride. For Impossible this included: methylcellulose, cultured dextrose, salt, mixed tocopherols, zinc gluconate, thiamin hydrochloride, niacin, pyridoxine hydrochloride, riboflavin, and vitamin B12.

[2] Other Food n.e.c. (not elsewhere classified) grouped food ingredients that could not be individually represented with EXIOBASE and corresponded to the EXIOBASE sector "Food products n.e.c.". For Beyond, this included: natural flavors, potato starch, apple extract, pomegranate extract, vinegar, lemon juice concentrate, sunflower lecithin, and beet juice extract. For Impossible, this included: natural flavors, yeast extract, food starch modified, and soy leghemoglobin.

A.



B.

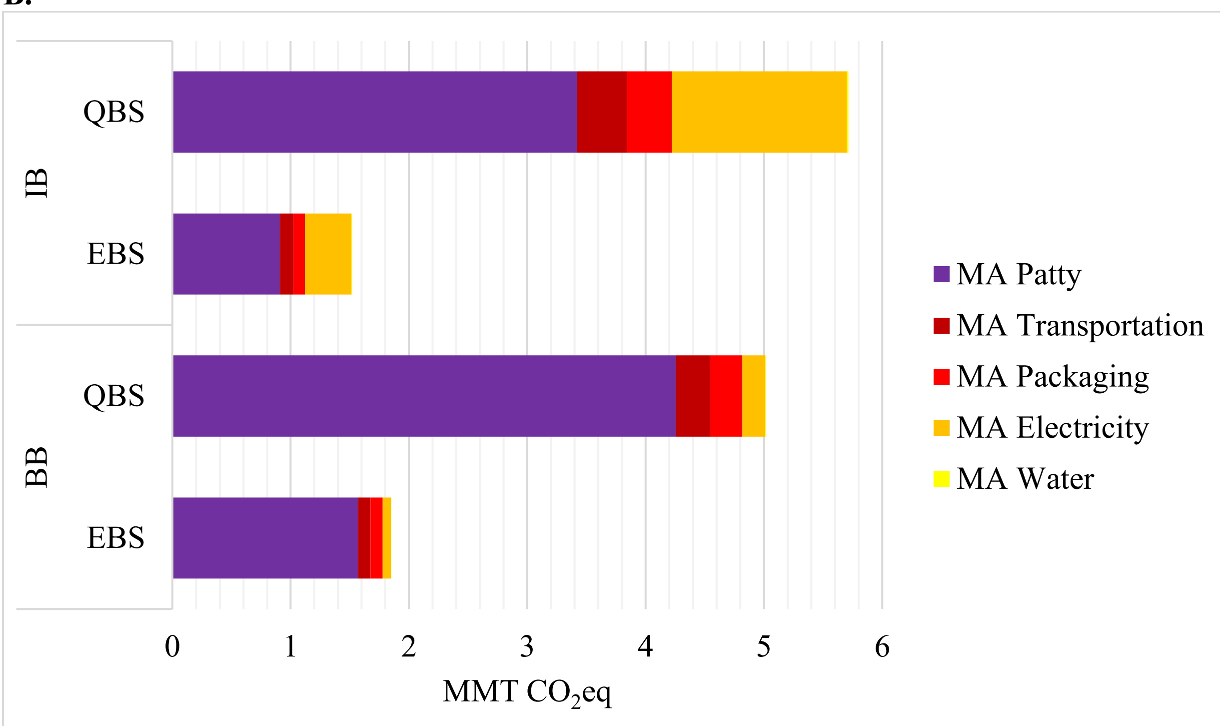
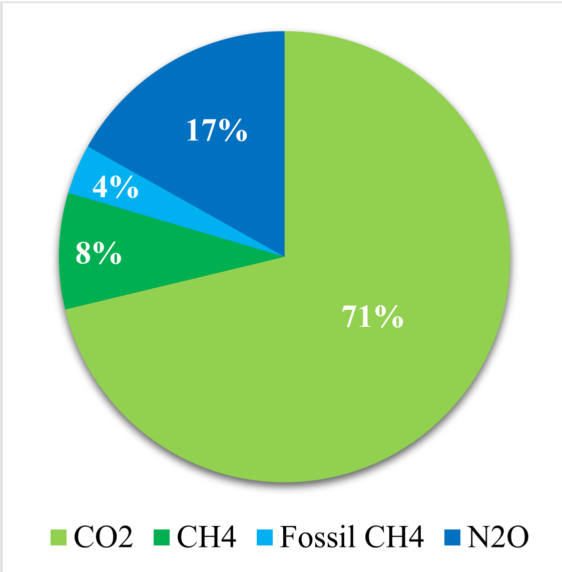


Figure 4.3. Greenhouse gas emissions (MMT CO_2eq) of: (A) baseline ground beef (GB) compared to a 15% replacement of GB with either Beyond Burger (BB) or Impossible Burger (IB) by expenditure based substitution (EBS) or quantity based substitution (QBS); and (B) individual production processes involved in formation of BB and IB by EBS or QBS.

A.



B.

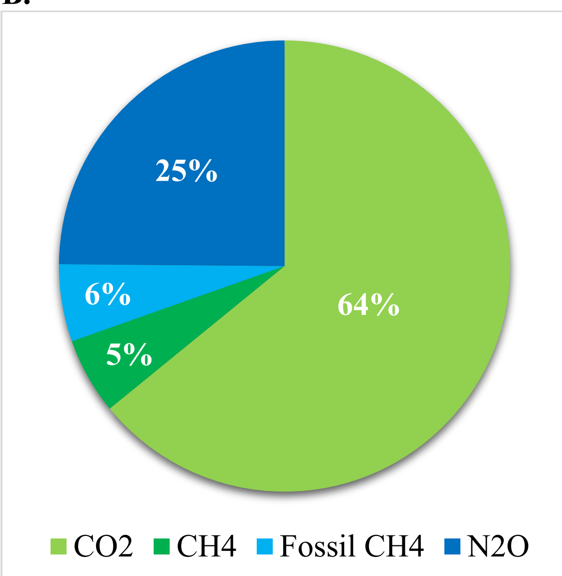
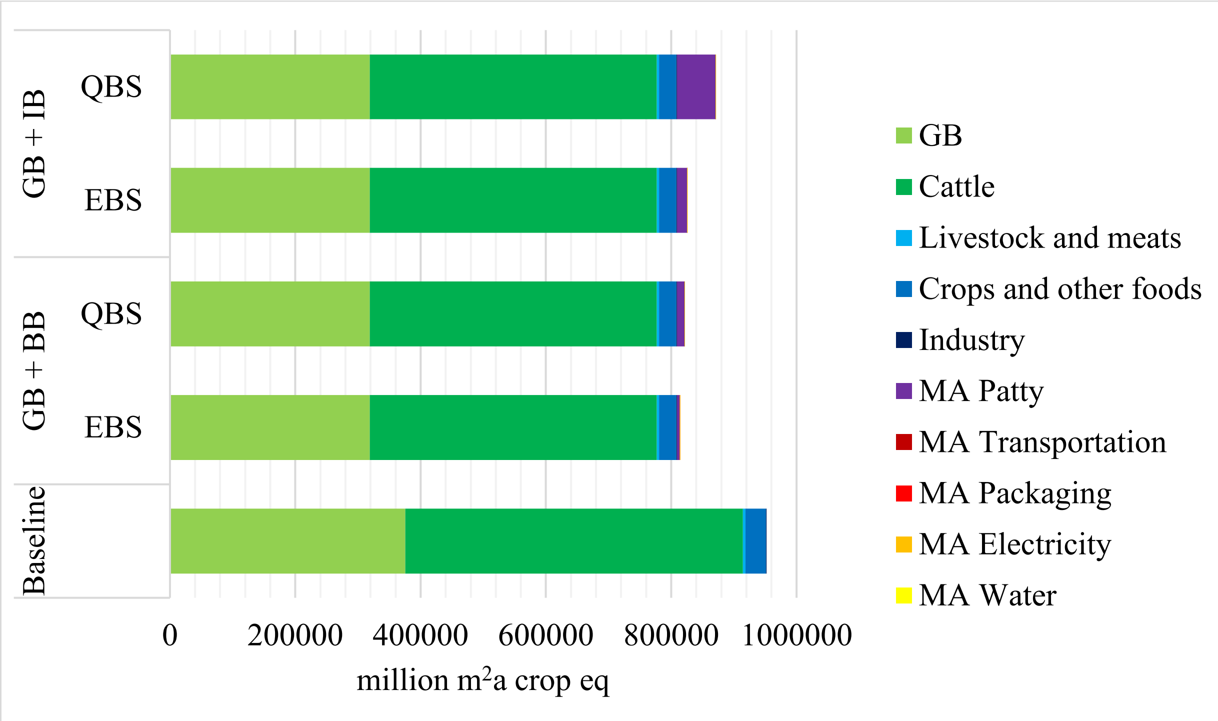


Figure 4.4. Proportion in equivalents of carbon dioxide (CO_2eq) of CO_2, biogenic methane (CH_4), fossil CH_4, and nitrous oxide (N_2O) contributing to the global warming potential of (A) Beyond Burger and (B) Impossible Burger.

A.



B.

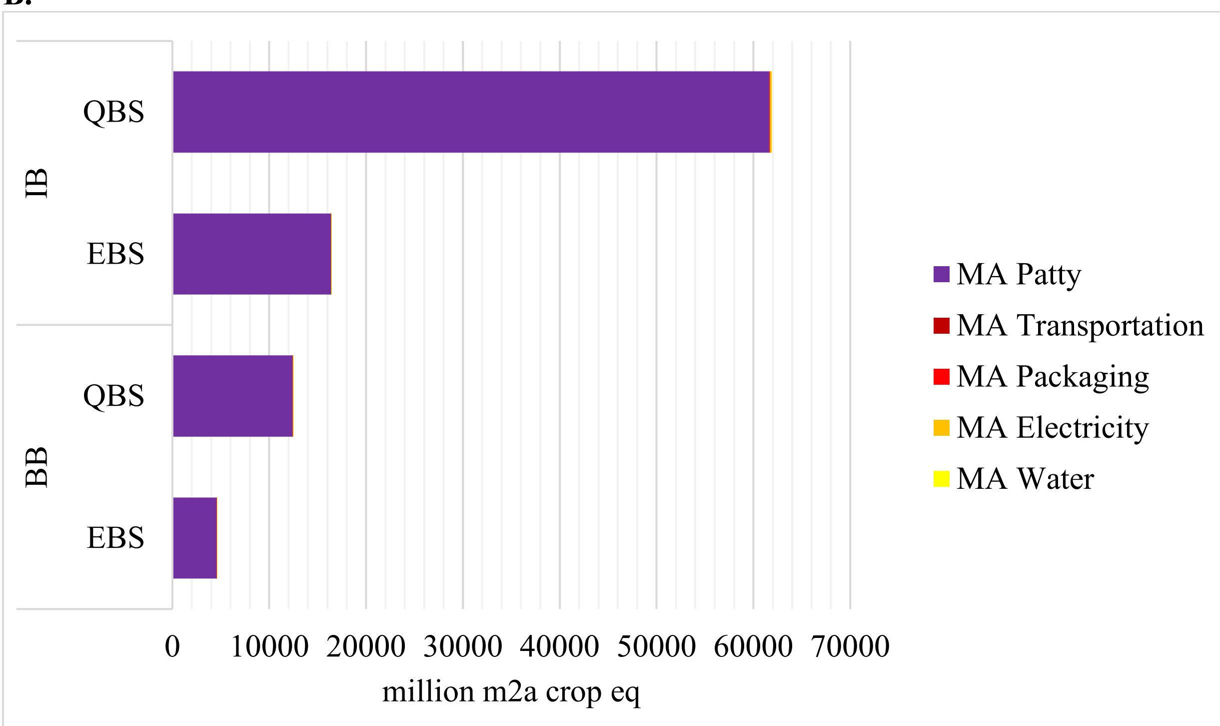


Figure 4.5. Land use (million m^2a crop eq) of: (A) baseline ground beef (GB) compared to a 15% replacement of GB with either Beyond Burger (BB) or Impossible Burger (IB) by expenditure based substitution (EBS) or quantity based substitution (QBS); and (B) individual production processes involved in formation of BB and IB by EBS or QBS.

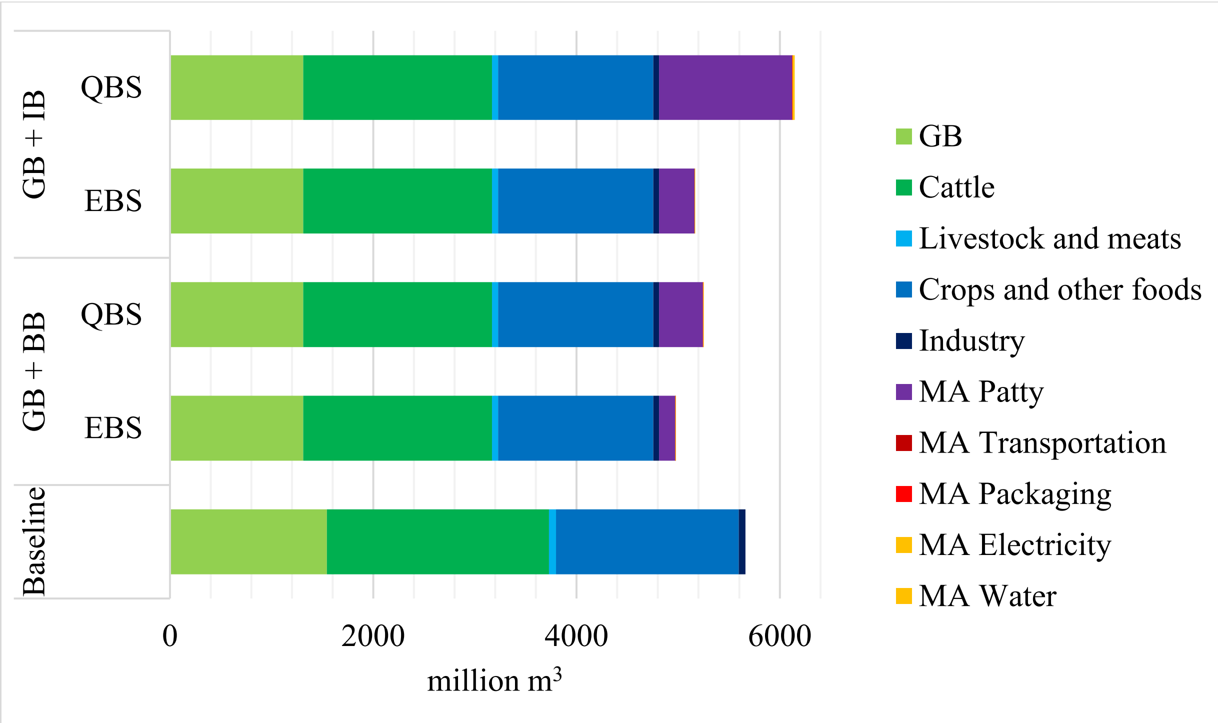
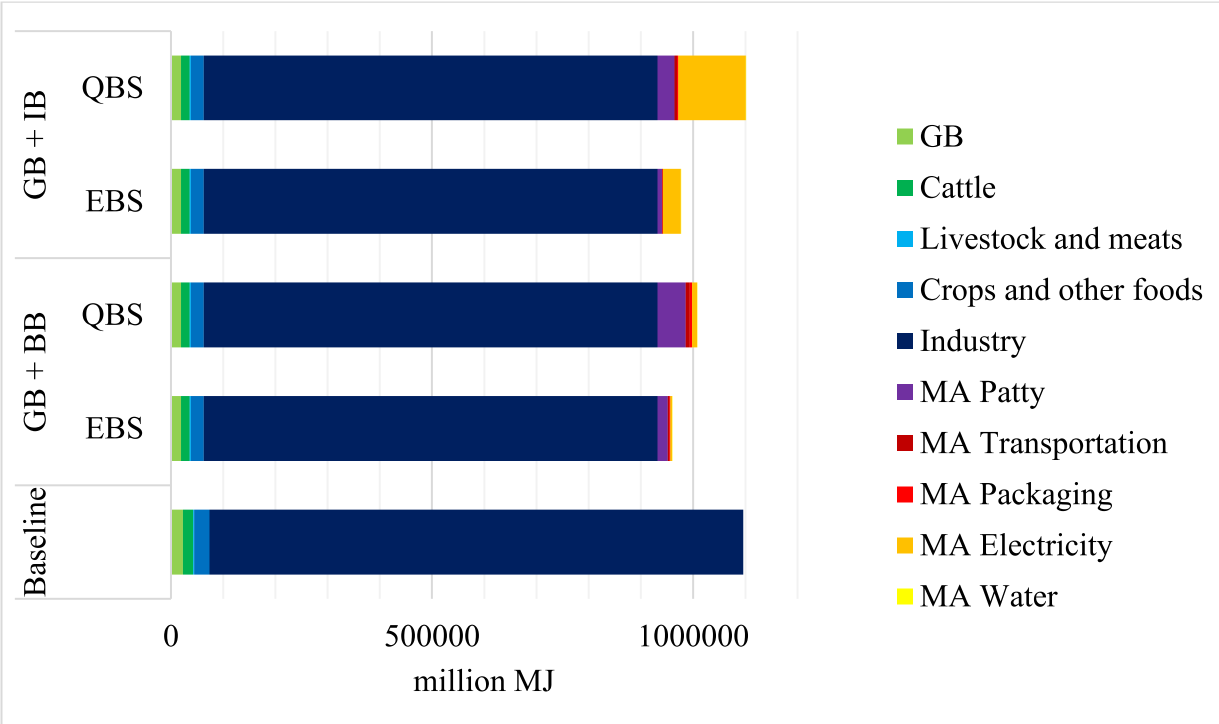


Figure 4.6. Water use (million m^3) of baseline ground beef (GB) compared to a 15% replacement of GB with either Beyond Burger (BB) or Impossible Burger (IB) by expenditure based substitution (EBS) or quantity based substitution.

A.



B.

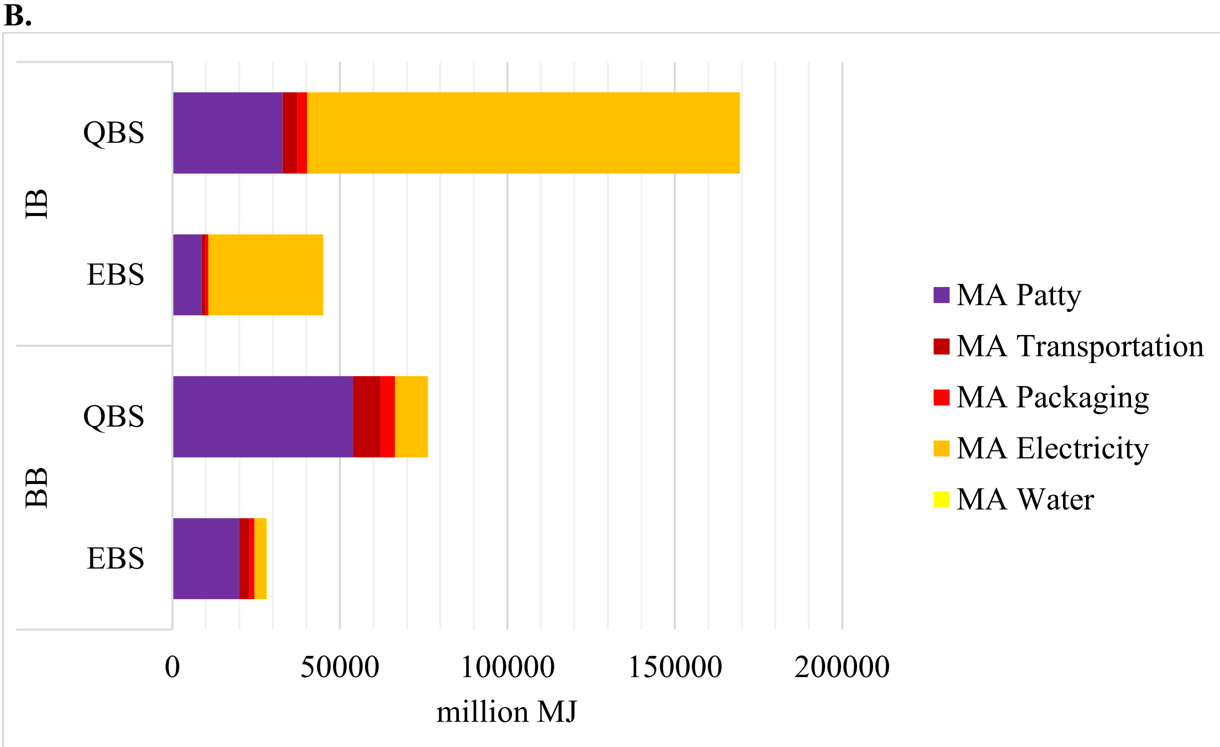


Figure 4.7. Energy use (million MJ) of: (A) baseline ground beef (GB) compared to a 15% replacement of GB with either Beyond Burger (BB) or Impossible Burger (IB) by expenditure based substitution (EBS) or quantity based substitution (QBS); and (B) individual production processes involved in formation of BB and IB by EBS or QBS.

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