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Thermodynamic Limitations to Agricultural Productivity and Food Security: Livestock in Sub-Saharan Africa

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THERMODYNAMIC LIMITATIONS TO AGRICULTURAL PRODUCTIVITY AND FOOD SECURITY: LIVESTOCK IN SUB-SAHARAN AFRICA

by

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THERMODYNAMIC LIMITATIONS TO AGRICULTURAL PRODUCTIVITY AND FOOD SECURITY: LIVESTOCK IN SUB-SAHARAN AFRICA

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By 2050, to feed a nearly tripling and more urbanized population in sub-Saharan Africa (SSA) will require significant increases in crop productivity throughout the region's agricultural systems, if a greater reliance on imports is to be avoided. Increases in crop yields to maximum potential productivity (closure of crop yield gaps) can produce more calories and protein, but may be insufficient to sustain the burgeoning human population according to recent analysis (van Ittersum et al., 2016). In this thesis, alternative management options (i.e. crop allocation and crop substitutions) are found to increase total energy productivity and the thermodynamic efficiency of food production systems, and provide theoretical potential to support population growth for four SSA countries. Using feeding efficiencies for US livestock systems and accounting for human caloric and protein requirements, the diversion of maize grown explicitly for livestock feed (subsequently referred to as "maize-for-feed") to direct consumption by humans was found to currently enable population growth by 6 – 11% in Ghana, 4 – 7.4% in Nigeria, 4.4 – 10.5% in Tanzania, and 24.8 – 40.9% in South Africa. By 2050, if crop yield gaps were closed to 80% of potential yields for rainfed maize (by

increasing irrigation and nitrogen application) and assuming no increase in harvest area, significantly larger fractions of projected populations were found to be sustained from direct consumption of maize-for-feed, where protein is limiting: 18.4 – 32.2% in Ghana, 11.7 – 21.1% in Nigeria, 6.6 – 15.6% in Tanzania, and 38.1 – 59.5% in South Africa. But when considering energy alone, these amounts are 35 – 42%, 20 – 25%, and 24 – 29% greater, respectively excluding South Africa, than recent projections that include substantial grain-fed livestock, meaning that previous yield gap assessments to identify 'biophysical limitations' on agricultural systems may be significant underestimations (van Ittersum et al., 2016). Alternatively, substitution of maize-for-feed with yams, cassava, sorghum, millet, and potatoes was found to also increase population significantly. Cultural practices and socioeconomic conditions affect food demand such as taste preferences and diet composition, but diversification away from grain-fed livestock products with substitution of alternative cropping systems could more efficiently feed people using fewer resources in sub-Saharan Africa.

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CHAPTER 1 – ENVIRONMENT AND DEVELOPMENT TO 2050

1.1 Population, Externalities and Climate Change

Global projected human population growth to 9 billion and associated economic growth by 2050 are expected to stress ecosystem services that support agriculture, society, and human well-being (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009; Sachs, 2015). Mankind's extraction of natural resources for ever-increasing human demand for food, water, and energy and the consequential environmental degradation have culminated in a transition from a 10,000-year period of relative climate stability – what geologists call the "Holocene" – to a new period characterized by climate volatility from warming – the "Anthropocene" (Crutzen, 2002). The effects of "unprecedented" atmospheric concentrations of three main greenhouse gases (GHG's) – carbon dioxide, methane, and nitrous oxide – directly tied to human activity are "extremely likely" to be the primary driver of climate change (IPCC, 2014a). Major "planetary boundaries" – Earth's biophysical thresholds defining a "safe operating space for humanity" – are either being approached rapidly or have already been surpassed due to anthropogenic, or human-associated, activity (Rockström et al., 2009).

The direct and indirect threats to human health posed by climate change are substantial, and are often compounded by feedback loops (Smith et al., 2014). Higher surface and atmospheric temperatures will likely intensify and increase the number of extreme heat, heavy precipitation, and drought events endangering vulnerable populations and straining the productivity of agricultural systems. Rising sea levels – from the melting of ice caps and glaciers, thermal expansion, and massive ice sheet loss in Greenland and Antarctica – will jeopardize populations living on low-elevation coasts and likely cause mass human migration; by 2050, one billion people could be forced from their homes, becoming refugees, due to sea level rise (Watts et al., 2015; Watts et al., 2017). Ocean acidification from carbon dioxide dissolution will likely threaten aquatic life and disrupt marine trophic webs integral to the food security of many (IPCC, 2014a). Violent conflict erupting over increasing competition for scarcer resources such as food, land, and water is projected to escalate. The national security implications of climate change (a "threat multiplier") elucidate why military forces of some of the richest and most powerful countries have recognized and been in preparation for increasing worldwide political destabilization even as some elected leaders have fully dismissed the legitimacy of the phenomenon (US Department of Defense, 2015; Matthews, 2017).

Having known about the potential repercussions of climate change for decades, progress by developed countries to minimize its effects has been dilatory. In October of 2017, an interdisciplinary team of scientists, economists, health experts and doctors followed up findings from the 2015 Lancet Commission on Health and Climate Change that the last 50 years of improvements to public health are under threat from anthropogenic climate change by reporting that worldwide inaction to mitigate and adapt during the last 25 years – since the United Nations Framework Convention on Climate Change (UNFCCC) initiated international, collaborative efforts to counter climate change in 1992 – has escalated the urgency for comprehensive, effectual measures. The negotiation of the Paris Agreement at the 21st Conference of Parties (COP) of the UNFCCC – which aims to keep warming below 2˚C from pre-industrial levels by curbing GHG emissions – and ratification (i.e. legally binding) by roughly 90% of nearly 200 participating countries, as of November 2017, represents a momentous step toward enhanced, collective action. Nationally-determined contributions of the participating countries, however, has been shown to be insufficient for meeting the 2˚C pathway by 2030 (UNEP, 2016). Combined with the intention of the United States, the world's second largest GHG emitter behind China, to pull out of the Paris Agreement by 2020, this underscores the need for even more drastic action if the worst of catastrophes is to be averted.

Worldwide, the poorest populations are suffering, and will continue to, disproportionately from accelerating environmental degradation exacerbated by climate change despite having little hand in its making (Smith et al., 2014). Currently, air particulate pollution – of which middle and high-income countries' burning of fossil fuels has been primarily responsible for though population-dense, developing countries such as China and India have ramped up production of coal-fired power in recent decades – contributes to approximately nine million premature deaths per year, 16% of all global deaths – the majority of which (92%) occur in low and middle-income countries (Landrigan et al., 2017).

While impacts of climate change are expected to be felt by all populations eventually (regardless of economic development), "social, economic, and demographic inequalities" prevalent in low and middle-income countries will likely worsen with climate change as social and environmental conditions conducive to good health continuously deteriorate or become fully compromised (Watts et al., 2017). Postponement of impactful and comprehensive responses to the global threat posed by climate change will likely augment the severity of its consequences, particularly for the most vulnerable populations (IPCC 2014a; Watts 2017).

1.2 Agricultural Productivity and Contribution to Climate Change

Increases in agricultural productivity have been coupled with immense environmental transformations (MEA 2005; Rockström et al., 2009; Sachs 2015). While technological advancement in agriculture over the past few centuries has produced largely positive outcomes in some places such as life expectancy gains via significant reductions in poverty, disease, and hunger – 85% of the world's population has adequate or excessive supplies of energy and protein although two-thirds lack essential micronutrients (Black, 2003) – initially-unforeseen consequences of this "revolution's" increasingly-industrialized and fossil fuel-dependent practices have likely debilitated the biosphere's coping capacity (McMichael, 2007).

The agriculture and food production sector contributes 19 – 35% of worldwide anthropogenic GHG emissions, mostly from expansion into tropical forests, emissions of methane – a far more potent GHG than carbon dioxide (CO_2) – from livestock rearing and rice cultivation, and nitrous oxide emissions from soil fertilization (Vermeulen et al., 2012; IPCC, 2014a; McMichael et al., 2007; Foley et al., 2011). Primarily from humans' domestication of livestock animals, global terrestrial animal mass has increased by three-fold since 1900, and now ~50% of nitrogen in the global human population has been transferred from the atmosphere via the Haber-Bosch process (Smil, 2012; 2013; Galloway 2008; Erisman, 2008). In the US, fertilizer runoff (e.g. nitrate and phosphorus runoff) into the Mississippi River from animal manure and the growing of crops – mostly soy and corn largely designated for animal feed and biofuel production – is believed to have been the main contributing factor to the formation of one of the largest-ever recorded ecological "dead zones" in the Gulf of Mexico where the mouth of the river is located (MEA, 2005; USGS, 2016; NOAA, 2017).

The global extent of agricultural intensification and expansion – aimed at increasing crop productivity and cultivation area, respectively, and as indicated by a 5-fold increase in fertilizer use (>8-fold for nitrogen, alone) and the clearing or conversion of 70% of grasslands, 50% of savanna, 45% of temperate deciduous forest, and 27% of tropical forests – is vast (Ramankutty et al., 2002; Foley et al., 2011; Tilman et al., 2001). Three "planetary thresholds" manifestly tied to agricultural practices are already believed to have been breached: biodiversity loss, nitrogen cycle, and climate change as indicated by species extinction rate, amount of nitrogen removed from the atmosphere for human use, and carbon dioxide concentration in the atmosphere, respectively (Rockström et al., 2009); there are also arguments that agriculture is ultimately responsible for pushing all of the world's planetary thresholds (Sachs, 2015).

1.3 Human Health and Environmental Externalities from Livestock

Livestock production is the largest land use sector on Earth and accordingly resource-intensive (Herrero & Thornton, 2013). The Food and Agriculture Organization of the United Nations (FAO) has estimated that the livestock sector contributes 18% of global GHG emissions, more than the transportation sector (Steinfeld et al., 2006); this includes 9% of anthropogenic carbon dioxide emissions, 37% of anthropogenic methane (with 23 times the global warming potential [GWP] of CO_2) and 65% of anthropogenic nitrous oxide (with 296 times the GWP of CO2 by mass). In the U.S., methods currently used by the U.S. Environmental Protection Agency associated with feedlot beef production have been found to be largely imperfect, accounting only for 3 – 20% of life cycle GHG emissions. Beef cattle feedlots in the U.S. alone have been estimated to contribute 26% of U.S. agricultural GHG emissions (Dudley, Liska, Watson, & Erickson, 2014).

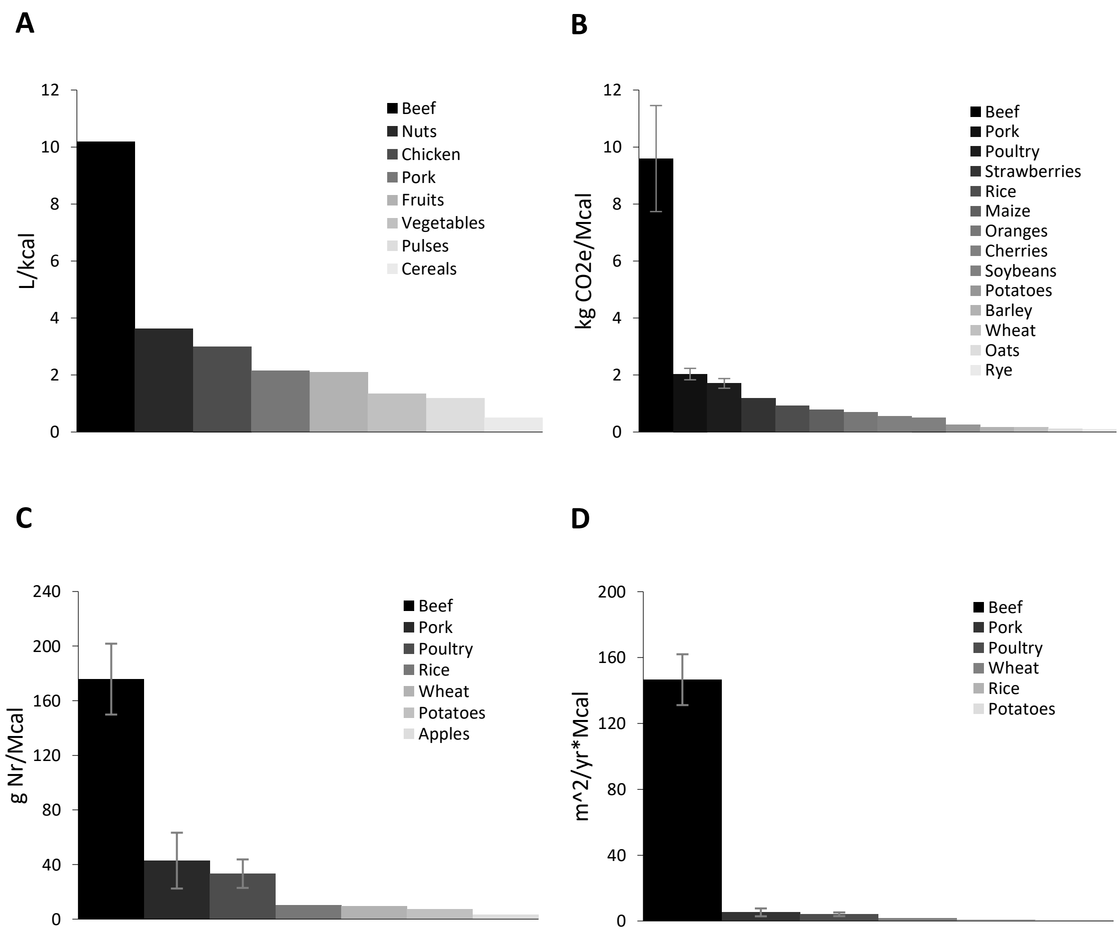
Using comprehensive methodology created by the FAO - an international non-profit – focused on supporting smallholder farmers primarily in Africa, Asia, and Latin America – found that the top 20 meat and dairy corporations emitted more cumulative GHG's than the entire country of Germany, Europe's largest emitter, in 2016 – nearly twice the individual, total emissions of France and the United Kingdom (GRAIN et al., 2017). If the top 20 meat and dairy corporations were considered their own country, they would be the seventh largest emitter in the world. The report also found that the top five meat and dairy corporations – JBS, Tyson, Cargill, Dairy Farmers of America, and Fonterra Group – emitted more GHG's combined in 2016 than the individual emissions of the three largest oil and gas companies – Exxon Mobil, Shell, and BP – in 2015. Released just ahead of the 23rd COP of the UNFCCC, the report stressed that "business-as-usual" projections of meat and dairy emissions, driven largely by industrial producers and consumer demand, alone will constitute 45% and 81% of the worldwide GHG emission thresholds needed to prevent warming of greater than 2 and 1.5˚C by 2050, respectively, as targeted by the Paris Agreement (GRAIN et al. 2017; Majot & Kuyek, 2017).

Cattle diets in extensive systems (more typical of livestock sectors in developing regions) are primarily, if not entirely, composed of pasture or natural grasses, forage, and crop residues. Life-cycle assessments – "cradle-to-grave" analyses – have shown that GHG emission intensities of ruminants (e.g. cattle, sheep) raised intensively (i.e. on commercial feedlots) are lower than ruminants raised primarily on grasslands (Peters et al., 2010; Dudley et al., 2014; González et al., 2011). In general, concentrate grains – high-energy feeds like maize, wheat, oats, barley, soy, meals and mill by-products – are easier for ruminants to digest than grasses and forage due to their low fiber content so pasture-raised animals produce more GHG's through enteric fermentation – a microbial, digestive process that releases methane – than feedlot animals of the same weight (IPCC, 2006). This suggests that extensive livestock production systems in developing countries have greater GHG reduction potential if strategies for improving emission intensities can be complemented with "local resources and contexts" (IPCC, 2014b; Herrero & Thornton, 2013).

Animal products from grazing production systems have been shown to have larger total water footprints also – an aggregate measure of blue (surface and groundwater), green (rainwater excluding runoff), and grey water (freshwater required to assimilate pollutants for quality standards) – than products from industrial systems (Hoekstra, Chapagain, Aldaya, & Mekonnen 2009; Mekonnen & Hoekstra, 2012). Even with higher blue and grey water footprints (due to more grain-based diets), industrial animal products' have a substantially lower green water footprint. Livestock produced in grazing systems depend more heavily on grasses and roughages for feed which are not commonly under irrigation (i.e. rainfed) nor fertilized. Chickens are an exception as they typically rely on concentrate feed regardless of production system. Since issues of freshwater availability revolve primarily around competition for surface and groundwater, not rainwater, this indicates that grazing systems may be preferable to industrial systems concerning water use (Mekonnen & Hoekstra, 2012).

When lifecycles of livestock feed constituents are accounted for, environmental burdens characterized by water use, reactive nitrogen use (from fertilizer), GHG emissions, and arable land use from grain-fed animal-based food production have been found to be orders of magnitude higher than the growing of staple food crops per unit of both energy and protein produced (Figure 1.1; Tilman & Clark, 2014). Meat is generally most resource-intensive than other food crops; beef, particularly, requires significantly more resources to produce than poultry and pig meat.

Figure 1.1. Environmental impacts of livestock and common food crops in the U.S. (B, C, and D) and globally (A). **A)** Total water use (Mekonnen & Hoekstra, 2012); **B)** Greenhouse gas emissions (González et al., 2011; Eshel, Shepon, Makov, & Milo, 2014); **C)** Reactive nitrogen use; **D)** Arable land use (Eshel et al., 2014).



Note: Environmental impacts of beef, pork, and poultry include results from other life-cycle-assessments compiled by Eshel et al. (2014) including: de Vries and de Boer (2010); Phetteplace, Johnson, & Seidl (2001); Pelletier et al. (2008; 2010a, 2010b). Thus, they are plotted as averages with standard deviations here.

High intake of red and processed meat in developed countries has been linked to an increase in risk of cardiovascular disease, obesity, colon cancer, rectal cancer, and type II diabetes (Pan et al., 2012; Wang & Beydoun, 2009; Larsson & Wolk, 2006; Chao et al., 2005; Norat et al., 2001; Aune, Ursin, & Veierød, 2009). Diet composition of livestock also may affect human consumer health. Beef produced from cattle with primarily grass-based diets has been found to contain higher levels of beneficial omega-3 polyunsaturated fatty acids, conjugated linoleic acid as well as less saturated fatty acids than primarily grain-fed cattle (Daley et al., 2010; French et al., 2000). However, animal-derived products provide essential nutrients; a recent study that simulated the nutritional and environmental effects of phasing out animal agriculture entirely in the United States via plants-only diets found that while total food production increased substantially and total agricultural GHG emissions fell 28%, the prevalence of nutritional deficiencies in diets grew significantly (White & Hall, 2017).

Analysis of historical diet changes and income increases of developing countries shows the two are closely related, the latter being associated with urbanization and industrial food production (Tilman & Clark, 2014; Kearney 2010). From these trends, it is estimated that average global, "income-independent" diets to 2050 could undergo significant, largely unhealthy shifts in composition: 61% more calories, 18% fewer servings of fruits and vegetables, 2.7% less plant protein, 23% more pork and poultry, 31% more ruminant meat, 58% more dairy and egg, and 82% more fish and seafood (Tilman & Clark, 2014). This kind of dietary shift would likely result in further increases in incidence of type II diabetes, coronary heart disease, and other non-communicable diseases as well as increased GHG emissions from land clearing for agricultural use, threatening species. Additional human and environmental health threats arise from the widespread use of antibiotics in animals, which may lead to the evolution of increasingly-resilient microbes, and the transmission of zoonotic diseases and pathogens from livestock-rearing (McDermott, Enahoro, & Herrero, 2013; Kummerer, 2003; Kemper, 2008). The coupling of human and environmental well-being through dietary preferences and composition presents a "trilemma" of utmost public and global health importance (Tilman & Clark, 2014).

In developed countries, meat and dairy consumption have begun to plateau, but a substantial reduction of both consumption and production may be needed if deleterious environmental impacts are to be minimized (Gerber et al., 2013). Relying on advancing technology, alone, to reduce environmental externalities could be precarious as technological improvements may only reduce livestock GHG emissions by 30 percent.

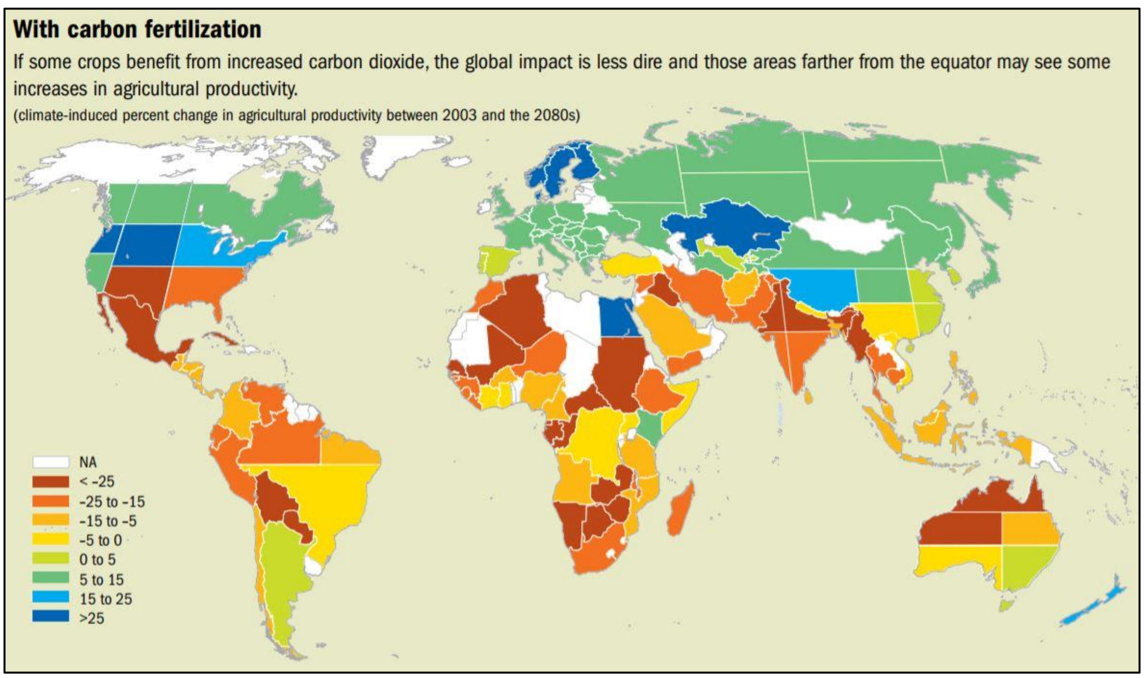
1.4 Sub-Saharan Africa and Climate Change

While some evidence suggests agricultural systems in temperate and polar climates may see marginal economic gains from warming air temperatures, effects of anthropogenic climate change are expected to affect already-vulnerable tropical and subtropical regions of the world negatively; higher temperatures are projected to destabilize water balances further making precipitation events highly variable and drought more frequent and intense (IPCC, 2014a). Damage to these regions' agricultural sectors, which low-income domestic economies depend most heavily on, is subsequently expected. A recent study found that even when the generally-assumed net beneficial phenomenon of "carbon fertilization" – where higher atmospheric carbon dioxide concentration contributes to increased crop productivity – is accounted for, agricultural productivity at lower latitudes, with a few exceptions, will be diminished to the 2080s from climate-induced effects (Figure 1.2; Cline, 2008).

One of the most vulnerable places, sub-Saharan Africa (encapsulation of all African countries geographically located partially or fully south of the Sahara Desert [United Nations, 2017]; subsequently referred to as "SSA"), is characterized by infrastructural, financial, and technological development incapable of adequate adaptation to increasing climate variability (Hassan, 2010;

Dinar et al., 2015). Adverse consequences exacerbated by climate change – including, but not limited to, widespread famine and disease – are expected to be particularly prevalent here (Hassan, 2010).

Figure 1.2. Climate-induced percent change in agricultural productivity to the 2080s with carbon fertilization. Source: Cline (2008).



Even in the absence of future challenges from climate change, malnutrition rates throughout Africa have been historically high, especially in the sub-Saharan region (FAOSTAT). Furthermore, growing evidence of an increasing "double-burden" of malnutrition – the simultaneous occurrence of under and over-nutrition within a population – in low and middle-income countries presents a critical challenge that if unchecked, may intensify a "vicious cycle" of poverty and disease (Kolčić, 2012). To minimize human suffering, already-stressed agricultural sectors will need to increase production drastically while contributing to the welfare of society and the environment (Tilman, Balzer, Hill, & Befort, 2011).

1.5 Thesis Goals

The overall goal of this research is to develop a more explicit theoretical understanding of agricultural productivity gaps (total energy productivity and thermodynamic energy efficiency) from crop production to final human consumption, which can help inform alternative management options to increase food security in SSA by closing productivity gaps (total energy [i.e. calories] and protein productivity from crop production to human consumption). Thermodynamic models were developed to evaluate the efficiency of theoretical agricultural productivity gaps and then applied to animal-based food systems in four SSA countries: Ghana, Nigeria, Tanzania, and South Africa.

Ghana, Nigeria, and Tanzania were chosen, in part, due to recent crop yield gap simulations suggesting these three countries cannot achieve cereal self-sufficiency (supply equal to demand of five main cereal crops: maize, rice, wheat, sorghum and millet) to 2050 even with yield gap closure to 80% of water-limited (rainfed) potential yields and will, thus, become more reliant on imports than currently (van Ittersum et al., 2016). This study was the first prominent analysis anywhere globally to combine yield gap closure, livestock, supported population, and trade in a closed system; the authors stressed the "biophysical limitations" to these systems. Compared to 2015, these countries are also projected to see the largest percentage increases in demand of cereals for animal feed in SSA to 2050: 16.8%, 6.3%, and 6.7% for Ghana, Nigeria, and Tanzania, respectively (van Ittersum et al., 2016; Sulser et al., 2015).

Furthermore, most of SSA will likely undergo exponential population growth throughout the century, and Nigeria is forecasted to surge from the seventh to the third most populous country in the world by 2050 (United Nations, 2017). Such a rapid population growth, with pronounced rural-urban migration expected, underscores the need for urgent increases in agricultural productivity. South Africa, having one of most developed agricultural and productive systems in SSA, is an outlier in this analysis and was included as a means of comparison because its model of development may be achieved by lesser-developed SSA countries in the decades to come (Mcunu, N., personal communication, July 12, 2017).

Approximately 35% of global crop production is used for animal feed currently (Foley et al., 2011). Where land is used to grow crops for animal feed that are otherwise fit for human ingestion, direct consumption or the substitution and prioritization of indigenous or other high-yielding food crops could be more productive in terms of energy and protein produced allowing for greater population increases, and more efficient per unit of water and fertilizer used, which might strengthen food security and improve human welfare.

These population increases depend on dietary preferences and composition, but this analysis approximates the biophysical boundaries of the productivity of these agricultural systems, based on similar assessments of agricultural systems and other thermodynamic systems (e.g. growing wheat alone in the absence of livestock systems could theoretically support up to 20 billion people in the future [Cohen, 1995, p. 360]). Similar assessments have suggested that a 50 – 70% greater population could be attained by limiting meat consumption, but these analyses have not coupled estimates with more explicit and rigorous thermodynamic analyses of the systems associated with crop yield gaps, where the latter are essentially climatic-thermodynamic-efficiency analyses of cropping systems (Foley et al., 2011).

Throughout the world's developing countries, how to feed larger and more affluent populations while eliminating hunger amongst the poorest in ways that are economically, environmentally and socially sustainable is the principle food security crisis facing the planet (Godfray et al., 2010). To identify the true "biophysical limitations" of agricultural and food production systems, analysis of the physical constraints due to thermodynamic laws is needed.

CHAPTER 2 – THERMODYNAMICS AND DEVELOPMENT OF FOOD SYSTEMS

2.1 Thermodynamic Laws and Biophysical Order

Thermodynamics quantifies the efficiency of energy conversions in all physical systems, which includes agricultural systems. The first law of thermodynamics, commonly known as the "law of conservation of energy," states that the amount of energy in the universe is constant (Atkins, 2007); consequently, energy cannot be created or destroyed in any process, only converted to different forms (electromagnetic, chemical, kinetic, thermal, etc.; in this case, associated with sunlight, crops, and animals, respectively). The second law of thermodynamics then constrains all energy conversions to be less than 100% efficient (Atkins, 1984). In any energetic conversion, irreversible physical processes (diffusion, chemical reactions, etc.) degrade a fraction of the ordered energy available to do work – "free energy" or "exergy" – to low-temperature heat, thermal energy, or entropy (Bakshi, 2014).

On a universal scale, the second law states there is natural tendency toward increasing disorder (or "randomness"), but inputs of exergy counteract this process and allow for local order to occur and be sustained as evidenced by the emergence of complex life forms and all physical complexity from the evolution of energy and matter over billions of years (Atkins, 1984; Prigogine & Stengers, 1984; Liska & Heier, 2013). Although maximum levels of biological complexity have generally increased over time (Chaisson, 2001), the previous widespread belief that evolution inherently eliminates biotic simplicity is seemingly unsubstantiated by the persistence and abundance of microscopic bacteria that have undergone relatively little genomic change over the course of millennia (Ayala, 2007).

Life on earth, consisting of trillions of ordered atoms in complex macromolecules, relies on autotrophic photosynthesis in plants and cyanobacteria to transform the limited exergy in solar radiation into biochemical polymers such as cellulose, nucleic acids, and proteins (Kauffman, 1995). This process, called primary production, provides the "energetic basis" for all heterotrophic food webs (Haberl, 2001). When plants, or primary producers, are consumed by animals, the second law of thermodynamics constrains the conversion of energy and ensures that a majority of stored free energy (in chemical form) in plants converted from solar radiation (the source of nearly all free energy on Earth) is emitted as thermal energy or "heat" through locomotive or metabolic processes (Blaxter, 1989). This disorganized heat (i.e. energy inherently of low quality) is consequently lost through atmospheric dissipation as the second law holds that heat always flows from high to low temperatures and not conversely (Atkins, 1984; Liska & Heier, 2013). This loss of free energy explains why large predators at the top of the food chain are so rare in nature; with each successive energy transfer, smaller and smaller fractions of available energy are converted and therefore, available to do work. Though some organisms have tended to evolve by increasing body size (Cope's rule) and by diversifying into specialized forms to acquire limited exergy from external niches, there is simply not enough energy to support an abundance of the most complex living organisms, i.e. "big and fierce" animals (Colinvaux, 1988; Liska & Heier, 2013).

Through the development of agricultural systems, humans have been cultivating energy from our environments for thousands of years. In opposition to patterns found in the natural world, modern agricultural systems can now maintain massive populations of various animal species (i.e. livestock) through enormous inputs of free energy arising from the cultivation of biomass mostly in the form of grain and grass. Although these systems require and yield thousands of times more energy on an area basis, the energy efficiencies of these agricultural systems remain relatively low (Table 2.1).

Table 2.1. Approximate energy efficiency and supported population density of agricultural production systems. Source: Adapted from Christian (2004).

Agricultural Production System	**Energy Input (GJ_{in}/ha)**	**Food Harvest, Energy Output (GJ_{out}/ha)**	**Agricultural Efficiency (GJ_{out}/GJ_{in})**	**Population Density Supported (person/km^2)**
Foraging	0.001 (1x)	0.003 – 0.006 (1x)	~3 – 6	0.01 – 0.9
Pastoralism	0.01 (10x)	0.03 – 0.05 (10x)	~3 – 5	0.8 – 2.7
Slash-and-burn Agriculture	0.04 – 1.5 (~800x)	10 – 25 (~3000x)	~7 – 250	10 – 60
Traditional Farming	0.5 – 2 (~1200x)	10 – 35 (~4000x)	~18 – 70	100 – 950
Modern Agriculture	5 – 60 (~30,000x)	29 – 100 (~15,000x)	~<2 – 20	800 – 2,000

Note: GJ = gigajoules; ha = hectares.

Recent studies analyzing efficiencies and sustainability of agricultural systems have employed various accounting methods of free energy or exergy – "the maximum quantity of work that the system can execute in its environment" (Wall, 1977; Hoang & Alauddin, 2011). As a metric, the physical universality of exergy simplifies quantitative comparison of natural resource extraction needed for sustainability assessment (Wall, 1977). "Energy balances," a common method for accounting flows or conversions of exergy (and losses), have been employed in concert with material balances to generate more complete quantification of societal "metabolism" – that is, the "physical exchange processes between human societies and their natural environments" and those within human societies (Haberl, 2001).

Assessments quantifying human appropriation of net primary productivity (HANPP) – the total harvest of biomass for human use as measured by amount of carbon assimilated by vegetation – reveal the extent of humanity's energetic extraction from ecosystems; one-third of global terrestrial (i.e. above ground) NPP and 38% of total annual NPP has been appropriated by humans, mostly via agriculture. With estimates that 53% of remaining global NPP is not harvestable, future increases in HANPP – as projected from population increase and rising consumption trends – may push us closer to our environment's thermodynamic capacity (Haberl & Erb, 2007; Running, 2012). The efficiencies of energy conversions ubiquitous in food crop and livestock production systems merit analysis as they are no exception to thermodynamic laws.

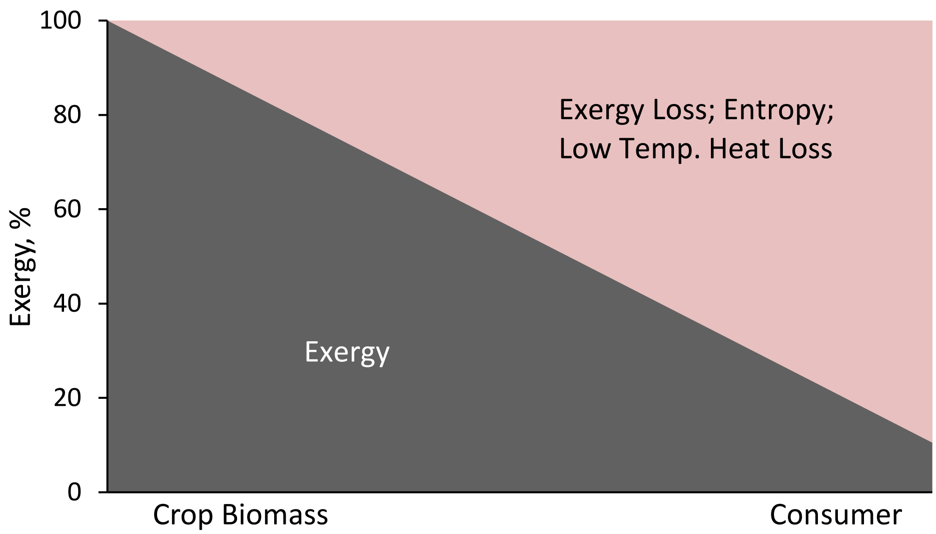
2.2 Livestock Feeding Efficiencies

In animal husbandry, feed conversion ratios (FCRs) are an important economic metric for assessing efficiency by quantifying how much animal feed is required to produce a certain amount of meat. Analysis of global, major livestock systems' feeding efficiencies – the inverse of FCR, calculated as gross energy content of product output (i.e. human food) divided by gross energy content of feed eaten (i.e. livestock food) – found that livestock animals transfer 1 – 15% of exergy from plants to humans via meat, dairy products, and eggs (Wirsenius, 2000; 2003a,b). This range varies spatially and temporally based on system conditions such as rearing/feeding practice, animal type/breed, animal diet composition, and feed quality; also, it encompasses the complete diet of livestock, which in addition to cereal grains (~10% of global livestock diet on a dry mass basis), consists of grasses from permanent pastureland (~43%), forage crops like hay and silage (~11%), crop residues (~20%), non-agricultural biomass (~8%), industrial food waste/byproducts (~5%), cropland pasture (< 2%) and other edible crops including soybeans (< 2%) (Wirsenius, Azar, & Berndes, 2010). Globally, accounting for the main livestock production systems and complete diets, about 10.5% of exergy from livestock feed is transferred to humans via meat in the form of beef, chicken, and pork (Wirsenius et al., 2010; Figure 2.1A). Poultry is the largest consumer of grain-based animal feed consuming 46% of the world's production (DAFF, 2015a). Pigs and ruminants (dairy cows, beef cattle, and small ruminants) follow, receiving 25% and 21% of animal feed, respectively. Of all crops grown for concentrate feed utilization globally, over half (57%) are cereals on a fresh weight basis (Mekonnen & Hoekstra, 2012).

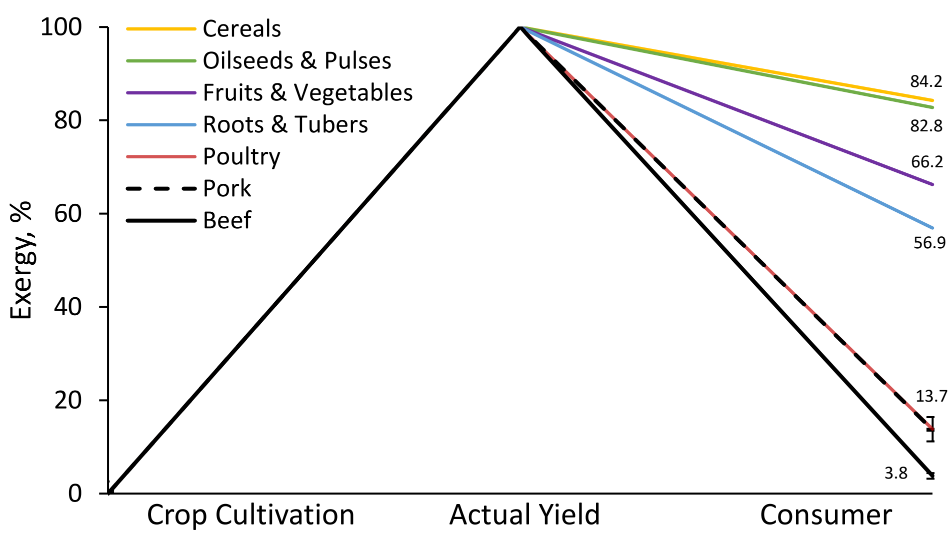
In more intensive systems where higher grain composition characterizes livestock diets, livestock has been found to be slightly more efficient at transferring exergy, converting 3 – 17% of exergy from feed, depending on animal species and food product type (Smil, 2013; Eshel et al., 2014). Isolating the energy transfer efficiency of livestock via grain exclusively, rather than accounting complete dietary feed composition, has only been assessed with reasonable certainty for more developed agricultural systems where data throughout food production (e.g. allocation of various feed types to different livestock classes, live/slaughter/edible weights of animals, nutritional composition of feed and resulting animal product types/quantity) are more completely recorded and readily available, typically, from governmental agencies and industry reports (Shepon, Eshel, Noor, & Milo, 2016; Figure A.1).

Figure 2.1. Exergy loss from crops to livestock to humans. **A)** Global exergy loss from feed to livestock to humans via meat (beef, chicken, and pork). Adapted from Wirsenius et al. (2010) and weighted by 2013 production (FAOSTAT). **B)** Exergy loss from U.S. livestock (avg. ± SD; Smil, 2013; Eshel et al., 2014) and food crops using average harvest/postharvest losses up to consumption (FAO, 2011).

A



B



However, the implication that because livestock is inefficient at transferring energy from plant biomass, all meat consumption is inherently wasteful is susceptible to scrutiny. Although a significant portion of livestock are fed grains that are suitable for direct consumption by humans (maize, soy, sorghum, etc.), a substantial portion of livestock are almost primarily "grass-fed", grazing on natural grassland – which otherwise would not be able to support cultivation of food crops without extensive conversion efforts that carry risks of detrimental environmental outcomes – and consuming processed roughage (e.g. hay, silage) or industry byproducts that are indigestible by non-ruminant humans (Godfray et al., 2010; Eshel et al., 2014). A U.S.-based study found that livestock convert more than four million tons of human-inedible food and fiber processing byproducts to human-edible food, pet food, industrial products, and fertilizer (White & Hall, 2017).

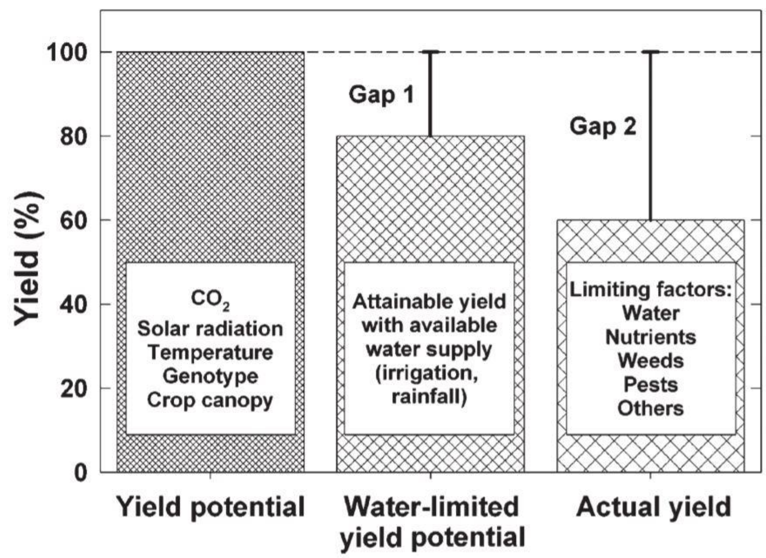
Currently, animal agriculture in SSA is dominated by livestock grazed on grasslands. In this region, energy derived from animals is mostly in dairy form, which is a more efficient conversion of energy and protein from crop production than from meat consumption (Shepon et al., 2016). Grass-fed cattle are more typical of developing economies where financial and infrastructural resources needed to produce, import, or store animal feed are lacking, and pastoralism is more commonly practiced, such as the case throughout most of SSA. Pasture-raised livestock is not uncommon in developed countries such as the United States, however, where recent consumer trends toward grass-fed animal products reflect a growing consumer awareness of food production requirements. Although notable ecosystem services and biodiversity may be affected, livestock grazed on grasslands are still the most efficient way to extract energy from these ecosystems (Eshel et al., 2014; McDermott et al., 2013).

CHAPTER 3 – AGRICULTRAL PRODUCTIVITY POTENTIAL IN SUB-SAHARAN AFRICA

3.1 Crop Yield Gap Analyses

Global crop production will need to double by 2050 to meet the rising demands from population growth, dietary changes, and biofuel production (Chapter 1). An analysis of four key global crops – rice, maize, wheat, and soybeans – which account for nearly two-thirds of agricultural calories has shown that current yield trends will fall drastically short of what is required to meet food demand in 2050 (Ray et al., 2013). One commonly-proposed method to maximize crop production is to optimize crop yields by closing yield gaps, especially in developing economies where crop productivity is currently low compared to potential yield. Closing the yield gap, the difference between maximum potential yield (theoretical) and average yields achieved (actual), has been shown to modestly increase crop productivity in developed systems where yields have begun to plateau (Lobell, Cassman, & Field, 2009). Optimizing yields relies on a multitude of factors including, but not limited to, water and nutrient (i.e. fertilizer) availability, herbicide/pesticide use in the presence of weeds/pests, crop genotype, and many climate-related influences (Figure 3.1).

Figure 3.1. Conceptual framework and constraining production factors associated with attaining yield potential, water-limited yield potential, and actual farm yields. Source: Cassman et al., 2003.



In agricultural research, yield gap analyses have become the dominant theoretical framework for understanding productivity (van Ittersum et al., 2013; Mueller et al., 2012; Lobell et al., 2009; Cassman, 1999). A recent analysis of ten SSA countries found that crop yield gap closure alone (increasing actual crop yields to potential yields determined by climate and agronomic management) is unlikely to meet a nearly three-fold increase in cereal demand by 2050, making the region more dependent on imports than currently. This analysis stressed the quantification of "biophysical opportunities and limitations" to yield optimization in these agricultural systems yet little attention has been paid to the thermodynamic efficiency of grain-fed livestock systems and how assessment of these systems greatly underestimates the amount of energy potentially transferred from cropping systems to humans (van Ittersum et al., 2016). Thus, the proposed "biophysical limitations" may be substantial underestimates of the potential productivity of these agricultural systems and the number of people who could be fed.

As a relatively new method employed for aiding sustainable intensification, yield gap analyses also suffer from a lack of standardization and a shortage of data as to accurately model developing countries' crop systems (van Ittersum et al., 2013). Models of rainfed crop systems, where yields are 50% or less of yield potential, are inherently prone to more errors than those of irrigated systems generally found in more developed systems (Lobell et al., 2009). Moreover, projected climate change impacts are rarely accounted for when quantifying gains from yield gap closure even though the productivity of developing countries' agricultural sectors, typically in lower latitudes and where yield gaps are largest, stand to be most negatively impacted (Chapter 1), and may be overly optimistic as a result. Specifically, yield projections to 2050 for SSA in van Ittersum et al. (2016) assumed no climate change.

Novel methods for increasing crop productivity such as improving nutrient management based on a "modern understanding of crop ecophysiology and soil biogeochemistry" using soil-crop system management practices have been shown to increase cereal yields significantly with no fertilizer use increase in developing countries (Chen et al., 2014). Yet, the substantial reduction of environmental benefits when cereal grains are "allocated to inefficient animal production systems" was emphasized and more attention paid to the environmental and human health burdens of livestock systems was called for.

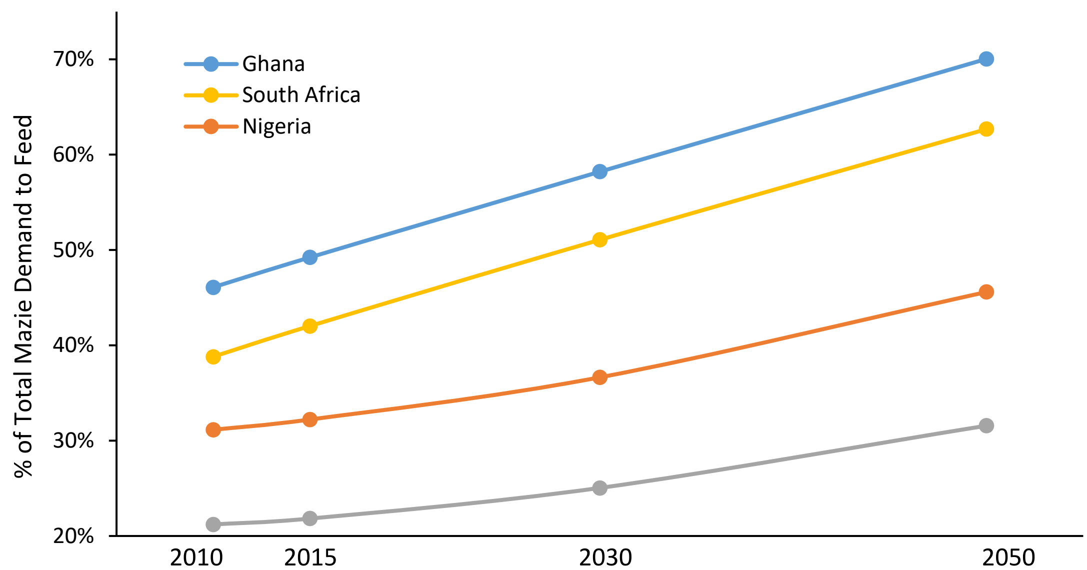
A recent analysis explored many theoretical "biophysical" options for feeding the world to 2050 that do not require expansion of agricultural land through deforestation nor near closure of yield gaps (Erb et al., 2016). The researchers concluded that high yields are "no biophysical necessity" and that little yield increase and cropland expansion could feed the world if diets with a reduced intake of animal products were adopted. Compared to meat-based diets, plant-based diets – vegan and vegetarian – were found to require half the cropland demand, grazing intensity, and total biomass harvest. Still, the authors stressed the many important services, other than food, that livestock provide, particularly in developing countries.

In developing regions, such as SSA, achieving closure through increases in irrigation water use, fertilizer use, genotypic changes, herbicide, and pesticide use theoretically improves crop productivity and provides greater local cereal production. Although cropland expansion and intensification (i.e. increased irrigation water use and fertilizer use) could provide greater local cereal production, this strategy would also result in increased environmental burdens and resource depletion where coupled with relatively inefficient livestock production (Chapter 1).

3.2 Maize Use for Animal Feed

From 2010 to 2050, maize demand (i.e. consumption) for animal feed production, as percentage of total demand, is projected to increase from 46% to 70%, 31% to 46%, 21% to 32%, and 39% to 63% in Ghana, Nigeria, Tanzania, and South Africa, respectively (Figure 3.2; van Ittersum et al., 2016; Sulser et al., 2015). Maize is also the predominant cereal component of animal feed in these countries, making up nearly all of cereals used for animal feed in Ghana, Tanzania, and South Africa and just less than half in Nigeria, where sorghum and millet also contribute significant fractions.

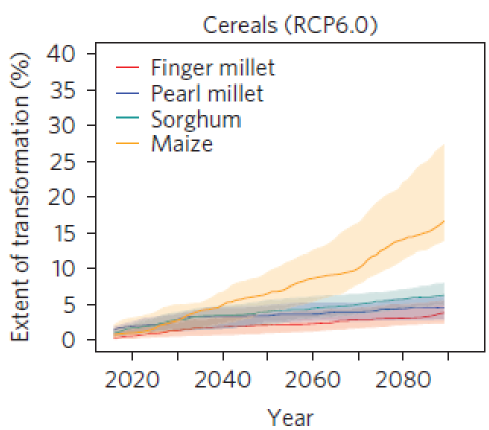
Figure 3.2. Projected percentage of total maize demand (consumption) allocated for animal feed production for Ghana, Tanzania, Nigeria, and South Africa to 2050. Assumes ~70% increase in dietary meat/dairy intake to 2050. Source: IFPRI's IMPACT model (van Ittersum et al., 2016; Sulser et al., 2015).



A recent study that simulated potential timescales of transformational adaptation to climate change (defined by the IPCC as a "response to the effects of climate change that changes the 'fundamental attributes of a system'") for SSA agriculture found – by combining a crop suitability modelling approach with climate model data of likely radiative forcing scenarios – that approximately 30 to 50% of current SSA maize harvest area will likely need to undergo transformation (i.e. supplanted by other crops) by the end of the century due to increasing unsuitability and shifts in climate (Rippke et al., 2016). Of the staple cereals analyzed, maize was the clear outlier (Figure 3.3).

Figure 3.3. Means (lines) and interquartile ranges (shading) of cumulative percentage of suitable maize area in SSA projected to undergo "transformational change" to 2100 for **A)** RCP6.0 and **B)** RCP8.5. Source: Rippke et al. (2016).

A



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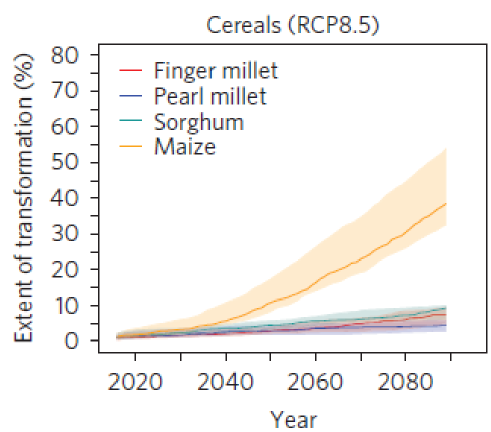
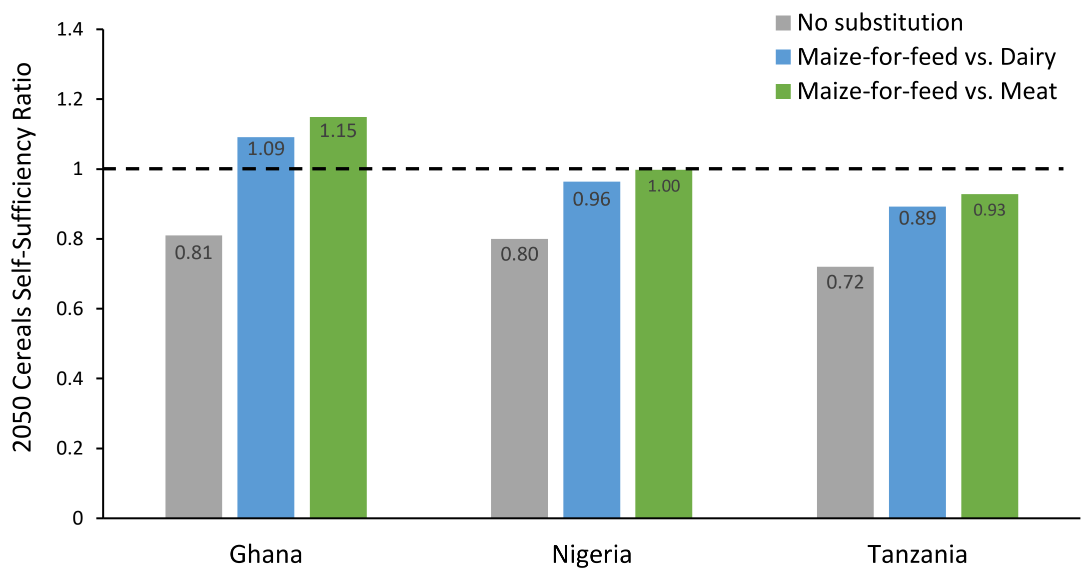


3.3 Direct Consumption of "Maize-for-feed"

Applying feeding efficiencies from U.S. livestock systems (Table 3.1) and accounting for daily caloric and protein requirements for humans, the analysis presented here found that diversion of maize grown explicitly for livestock feed (subsequently referred to as "maize-for-feed") to direct consumption by humans would enable current population growth by 6 – 11% in Ghana, 4 – 7.4% in Nigeria, 4.4 – 10.5% in Tanzania, and 24.8 – 40.9% in South Africa in 2015 (Tables 3.2 & 3.3). By 2050, if crop yield gaps were closed to 80% of potential yields for rainfed maize (by increasing irrigation and nitrogen application, but not considering the probable effects of anthropogenic climate change) and assuming no increase in harvest area, significantly larger fractions of projected populations could be sustained from direct consumption of maize-for-feed, where protein is limiting: 18.4 – 32.2% in Ghana, 11.7 – 21.1% in Nigeria, 6.6 – 15.6% in Tanzania, and 38.1 – 59.5% in South Africa (Tables 3.4 & 3.5). But when considering energy alone, compared with results from van Ittersum et al. (2016), projected populations supported in 2050 increase by 35 – 42%, 20 – 25%, and 24 – 29%, respectively excluding South Africa (Figure 3.4). The above results follow directly from an understanding of the energy losses (i.e. entropy increase) via livestock thermodynamics (Figure 3.5), which are not directly observable (Chapter 2), and suggest that previous yield gap assessments to identify "biophysical limitations" on SSA agricultural systems may be significant underestimations (van Ittersum et al., 2016). Throughout SSA, maize is primarily consumed by humans in meal, or porridge, form accompanied with sides of vegetables, nuts, or meat; this dish is known as "kenkey" or tuozafi" in Ghana, “sakora” in Nigeria, “meliepap” in South Africa, and “ugali” or “nguna” in Tanzania (McCann, 2009). The analysis here does not account for macronutrient alterations (i.e. energy and protein losses) that likely occur during culinary preparation of maize for human consumption.

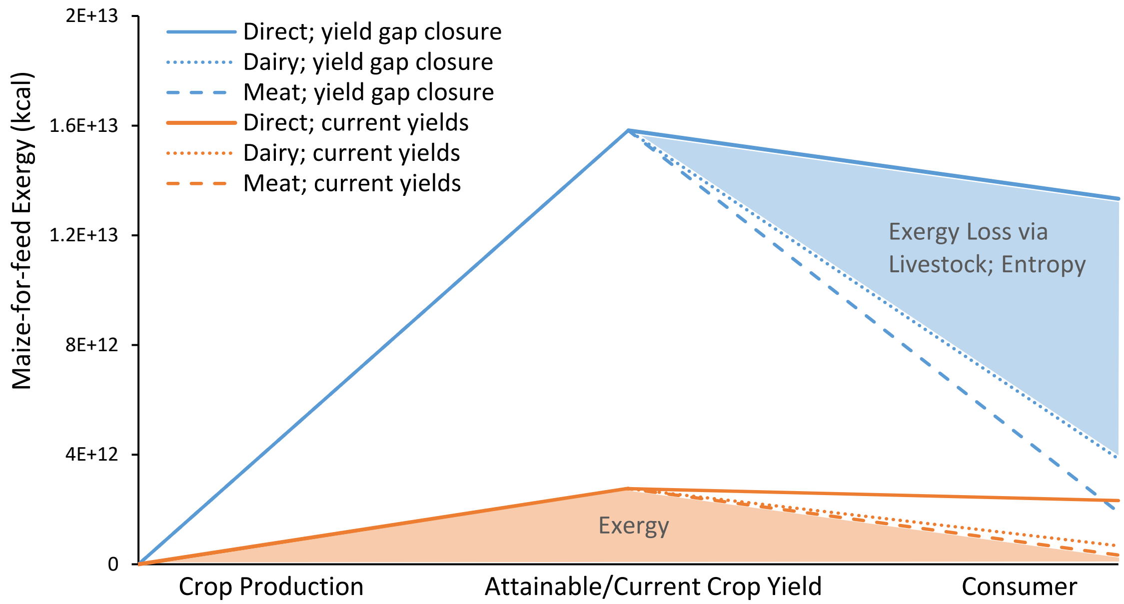
Figure 3.4. Cereal self-sufficiency ratios[a] in 2050, on an energetic basis, from substitution of meat and dairy via maize-for-feed with direct consumption for Ghana, Nigeria, and Tanzania.



[a] “No substitution” cereal SSR’s for 2050 reported as ratio of national cereal production and cereal demand per country by van Ittersum et al. (2016) after 80% yield gap closure achieved for five main cereals. Gains made in cereal SSR’s from substitution of direct consumption of maize-for-feed shown here equivalent to those shown in Table 3.4.

Figure 3.5. Maize-for-feed exergy loss via direct consumption and animal products, using concentrate feeding efficiencies for livestock (Shepon et al., 2016), with current yields and yield gaps closed to 80% of yield potential (van Ittersum et al., 2016) for **A)** Ghana; **B)** Nigeria; and **C)** Tanzania.

A



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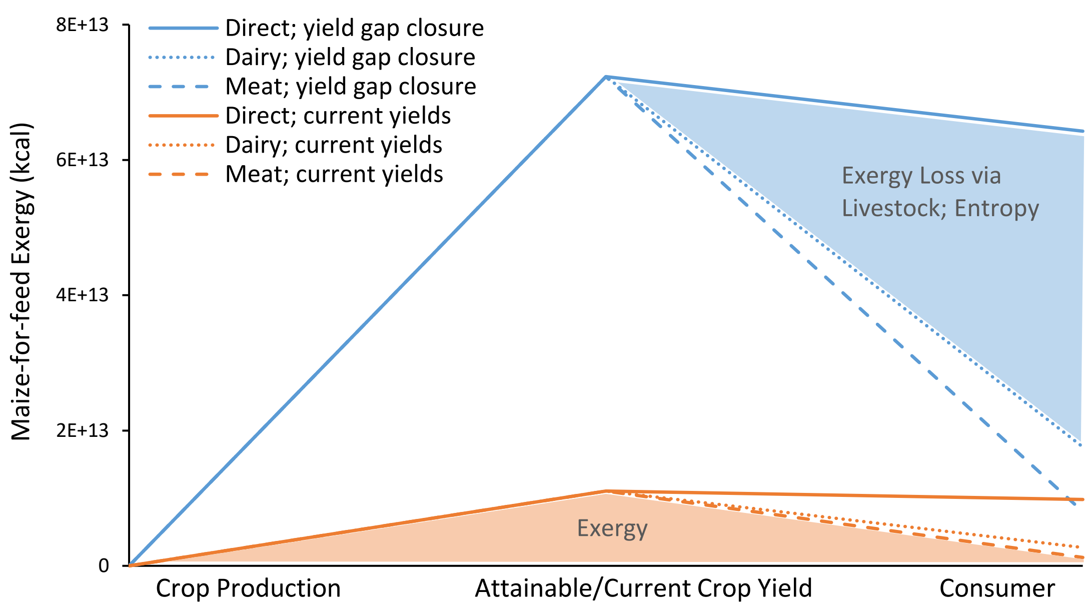


C

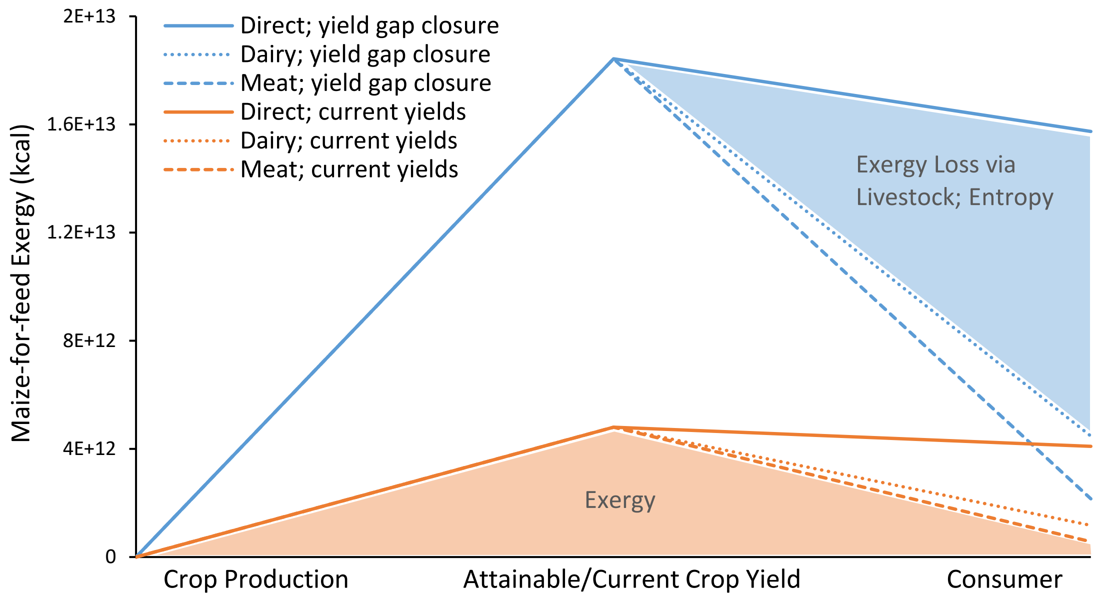


Table 3.1. Weighted energy and protein transfer efficiencies of grain-fed meat (beef, poultry, and pork) and dairy in Ghana, Nigeria, Tanzania, and S. Africa.

	Ghana	Nigeria	Tanzania	South Africa
Energy – Meat[a] [meat kcal/grain feed kcal]	12.0%	11.1%	11.7%	12.0%
Protein – Meat[b] [meat g Pr/grain feed g Pr]	36.0%	24.0%	27.7%	25.7%
Protein – Dairy[c] [dairy g Pr/grain feed g Pr]	42.0%	42.0%	46.7%	43.3%

Note: kcal = kilocalories; g Pr = grams of protein.

[a] Energy transfer efficiencies (E out/E in; E meat/E grain) of 11.6%, 12.5%, and 9.0% for beef, poultry and pork, respectively, as reported by Shepon et al. for US livestock (2016); Weighted per country by current meat type consumption from FAOSTAT.

[b] Concentrate feed protein efficiencies (meat-g Pr/grain-Mcal) of 5.37, 10.94, and 4.47 for beef, poultry, and pork, respectively, for US livestock (Shepon et al. 2016). Weighted per country by meat type consumption from FAOSTAT.

[c] Concentrate feed protein transfer efficiency (dairy product-g Pr/grain-Mcal) of 11.05. Energy transfer efficiency (E food out/E feed in) of dairy is 24.29% (Shepon et al., 2016) for all four SSA countries.

Table 3.2. Current net available energy (kcal) and additional population supported through substitution of 1) direct consumption of maize-for-feed, for 2) meat and dairy via maize-for-feed in SSA countries.

	Direct vs. meat			**Direct vs. dairy**		
Country	Additional energy[a] (kcal)	Energy requirements met[b] (# of people)	% of 2015 population[c]	Additional energy[a] (kcal)	Energy requirements met[b] (# of people)	% of 2015 population[c]
Ghana	1.99E+12	3.02E+06	11.0%	1.65E+12	2.50E+06	9.1%
Nigeria	8.60E+12	1.35E+07	7.4%	7.14E+12	1.12E+07	6.2%
Tanzania	3.54E+12	5.60E+06	10.5%	2.93E+12	4.65E+06	8.7%
S. Africa	1.58E+13	2.25E+07	40.9%	1.35E+13	1.92E+07	34.9%

[a] Maize losses of 15.8%, 11.1%, 14.6% and 3.7% for Ghana, Nigeria, Tanzania, and South Africa, respectively, from FAOSTAT (3-year average, 2011-2013). Caloric contents of maize derived for each country from FAO Food Supply-Crops Primary Equivalent Data.

[b] Based on Minimum Dietary Energy Requirements by country interpolated to 2015 (FAOSTAT, 2008).

[c] Equivalent to population sustained from direct consumption in addition to population supported by meat and dairy. Country populations for 2015 obtained from World Bank Group (2017).

Table 3.3. Current net available protein (g Pr) and additional population supported through substitution of 1) direct consumption of maize-for-feed, for 2) meat and dairy via maize-for-feed in SSA countries.

	Direct vs. meat			**Direct vs. dairy**		
Country	Additional protein[a] (g Pr)	Protein requirements met[b] (# of people)	% of 2015 population[c]	Additional protein[a] (g Pr)	Protein requirements met[b] (# of people)	% of 2015 population[c]
Ghana	3.49E+10	1.88E+06	6.8%	3.07E+10	1.65E+06	6.0%
Nigeria	1.89E+11	1.01E+07	5.6%	1.36E+11	7.33E+06	4.0%
Tanzania	6.55E+10	3.52E+06	6.6%	4.39E+10	2.36E+06	4.4%
S. Africa	3.38E+11	1.81E+07	33.0%	2.54E+11	1.36E+07	24.8%

[a] Maize losses of 15.8%, 11.1%, 14.6% and 3.7% for Ghana, Nigeria, Tanzania, and South Africa, respectively, from FAOSTAT (3-year average, 2011-2013). Protein contents of maize derived for each country from FAO Food Supply-Crops Primary Equivalent Data.

[b] Based on average adult protein requirement of 51 g/day/person (46 g/day for adult females; 56 g/day for adult males) suggested by the Institute of Medicine (2005).

[c] Equivalent to population sustained from direct consumption in addition to population supported by meat and dairy. Country populations for 2015 obtained from World Bank Group (2017).

Table 3.4. Future net available energy (kcal) and additional population supported through substitution of 1) direct consumption of maize-for-feed, for 2) meat and dairy via maize-for-feed in SSA countries.

	Direct vs. meat			**Direct vs. dairy**		
Country	Additional energy[a] (kcal)	Energy requirements met[b] (# of people)	% of 2050 population[c]	Additional energy[a] (kcal)	Energy requirements met[b] (# of people)	% of 2050 population[c]
Ghana	1.14E+13	1.65E+07	32.2%	9.49E+12	1.37E+07	26.7%
Nigeria	5.63E+13	8.64E+07	21.1%	4.67E+13	7.17E+07	17.5%
Tanzania	1.36E+13	2.15E+07	15.6%	1.13E+13	1.78E+07	12.9%
S. Africa	3.30E+13	4.44E+07	59.5%	2.81E+13	3.79E+07	50.8%

[a] Maize losses of 15.8%, 11.1%, 14.6% and 3.7% for Ghana, Nigeria, Tanzania, and South Africa, respectively, from FAOSTAT (3-year average, 2011-2013); yield gaps closed to 80% of water-limited yield potential (van Ittersum et al., 2016). Caloric contents derived for each country from FAO Food Supply-Crops Primary Equivalent Data.

[b] Based on Minimum Dietary Energy Requirements by country extrapolated to 2050 (FAOSTAT, 2008).

[c] Equivalent to population sustained from direct consumption in addition to population supported by meat and dairy. Projected country populations for 2050 obtained from World Bank Group (2017).

Table 3.5. Future net available protein (g Pr) and additional population supported through substitution of 1) direct consumption of maize-for-feed, for 2) meat and dairy via maize-for-feed in SSA countries.

	Direct vs. meat			**Direct vs. dairy**		
Country	Additional protein[a] (g Pr)	Protein requirements met[b] (# of people)	% of 2015 population[c]	Additional protein[a] (g Pr)	Protein requirement s met[b] (# of people)	% of 2015 populatio n[c]
Ghana	2.00E+11	1.08E+07	21.0%	1.76E+11	9.45E+06	18.4%
Nigeria	1.24E+12	6.64E+07	16.2%	8.93E+11	4.79E+07	11.7%
Tanzania	2.51E+11	1.35E+07	9.8%	1.69E+11	9.06E+06	6.6%
S. Africa	7.05E+11	3.79E+07	50.8%	5.29E+11	2.84E+07	38.1%

[a] Maize losses of 15.8%, 11.1%, 14.6% and 3.7% for Ghana, Nigeria, Tanzania, and South Africa, respectively, after yield gaps closed to 80% of water-limited yield potential. Protein contents of maize calculated for each country from Food Supply-Crops Primary Equivalent Data.

[b] Based on average adult protein requirement of 51 g/day/person (46 g/day for adult females; 56 g/day for adult males) suggested by the Institute of Medicine (2005).

[c] Equivalent to population sustained from direct consumption in addition to population supported by meat and dairy. Projected country populations for 2050 obtained from World Bank Group (2017).

3.4 Alternative Food Crop Substitutions

In general, indigenous plants are adapted better and more acclimated to thrive in a given environment than non-native crop plants without additional resource inputs (Mooney, 1972). Globally, the net primary productivity (NPP) of cropland is 35% less than that of its supplanted native vegetation on average (Haberl, 2007) and land-use change has resulted in some areas of Africa and Asia possessing less than 10% NPP of the original, native vegetation (DeFries, 1999). Often, calculated yield potentials of crop plants are based on the productivity of native plants, which also contributes to less sensitive crop yield models (Lobell et al., 2009). Native crops to SSA have increasingly been supplanted by nonnative staples such as maize and soy and have all but disappeared consequently (NRC, 1996). Crop biodiversity has been diminished as monocultures of high-yielding cereals have become more prevalent. Emphasis on diversification of food crops in agricultural systems may increase their resilience to climate volatility and plant diseases while contributing to nutrition. While probably less productive, substitution of maize-for-feed with yams, cassava, sorghum, millet, and potatoes could also increase population carrying capacity significantly (Table 3.6). But in some cases (e.g. substitution of millet for dairy via maize-for-feed), protein production limits population growth.

Table 3.6. Additional projected population[e] supported in 2050 through substitution of alternative food crops for dairy/meat via maize-for-feed accounting for daily caloric[c] (top percentage) and protein[d] requirements (bottom percentage) with 80% yield gap closure achieved[a].

	Direct consumption vs. meat via maize-for-feed[b]					**Direct consumption vs. dairy via maize-for-feed[b]**				
Country	Cassava	Sorghum	Millet	Potatoes	Yams	Cassava	Sorghum	Millet	Potatoes	Yams
Ghana	81.8% 10.6%	24.3% 18.2%	10.9% -0.3%	-	68.1% 28.0%	76.3% 8.0%	18.8% 15.6%	5.4% -2.9%	-	62.6% 25.4%
Nigeria	15.4% -3.0%	9.8% 7.9%	1.8% -1.6%	-	19.7% 6.7%	11.8% -7.5%	6.2% 3.4%	-1.8% -6.1%	-	16.1% 2.2%
Tanzania	8.3% -0.9%	6.9% 5.1%	3.3% 0.6%	13.4% 6.6%	13.6% 4.3%	5.7% -4.1%	4.2% 1.9%	0.6% -2.7%	10.7% 3.3%	10.9% 1.1%
S. Africa	-	24.8% 20.1%	-	60.1% 39.0%	-	-	16.1% 7.4%	-	51.4% 26.3%	-

[a] Assumes alternative food crops are grown on maize land allocated for animal feed calculated by: No expansion of maize harvest area to 2050 from current (3-year avg., 2012-2014; FAOSTAT) and projected maize demand for animal feed (% of total demand) of 70%, 46%, 32%, and 63% for Ghana, Nigeria, Tanzania, and South Africa, respectively, for 2050 (van Ittersum et al., 2016; Sulser et al., 2015). Alternative food crop yields were closed to 80% of potential yields from current yields (3-year avg., 2012-2014; FAOSTAT), calculated proportionately to water-limited (rainfed) maize yield gap closure as reported by GYGA for each SSA country (van Ittersum et al., 2016).

[b] Average crop losses by crop type for SSA up to the point of consumption used (FAO, 2011)

[c] Based on Minimum Dietary Energy Requirements by country extrapolated to 2050 (FAOSTAT, 2008).

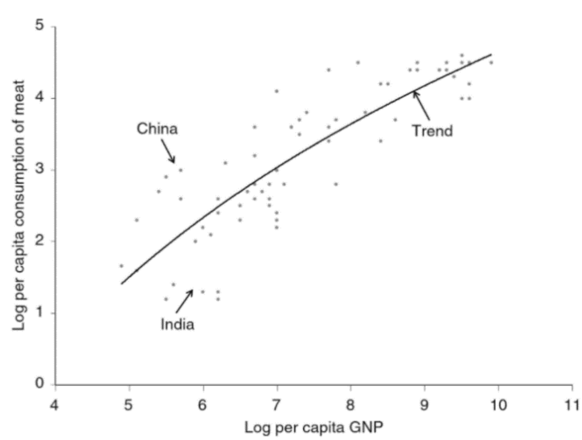
[d] Based on average adult protein requirement of 51 g/day/person (46 g/day for adult females; 56 g/day for adult males) suggested by the Institute of Medicine (2005). Caloric and protein contents for alternative food crops derived for each country from FAO Food Supply-Crops Primary Equivalent Data (FAOSTAT).

[e] Country projected populations for 2050 obtained from World Bank Group (2017).

3.5 Livestock Projections in SSA

Throughout the developing world, income gains, rapid population growth, and urbanization have contributed to increases in livestock product consumption; this trend is well documented (Figure 3.6). While Africa has been slow to catch up in recent decades, the continent will likely experience considerable increases in meat and dairy consumption and production relative to other regions in the world due to demographic and socioeconomic changes (Table 3.7; FAO, 2013). Africa's population is expected to grow to 1.5 billion by 2050, an approximate 50% increase from 2010; GDP is projected to be four times its 2010 level and nearly half of the population will be living in urban areas, up from 39% in 2010.

Figure 3.6. Relationship between per capita meat consumption and per capita gross national product (GNP) in recent decades. Source: McDermott et al. (2013).



Compared to other regions, African meat and milk markets will not be exceptionally large by 2050. However, they are projected to increase in size more rapidly than most regions beyond 2025. Estimated meat consumption is projected to more than triple from 2007 levels when 10.5 million tons were consumed, with poultry and pork consumption increasing by the largest annual rates of 3.3%. Africa will be consuming as much meat per year – 34.8 million tons – by 2050 as Latin America does currently. Milk consumption is expected to nearly triple, from 32.4 million tons in 2007 to 82.6 million tons by 2050.

Table 3.7. Historical and projected global and regional annual livestock production growth in percent. Source: Adapted from Bruinsma (2003).

	1997-2007	**2005/2007-2030**	**2030-2050**
World	2.0	1.4	0.9
Developing countries	3.4	2.0	1.3
idem, excl. China & India	3.5	2.1	1.5
Sub-Saharan Africa	**3.3**	**2.7**	**2.6**
Latin America & Caribbean	3.8	1.6	0.9
Near East/North Africa	3.0	2.2	1.7
South Asia	3.2	2.7	2.2
East Asia	3.4	1.8	0.8

With large consumption increases projected, the meat and dairy sector has substantial economic potential for Africa. To meet consumer demands domestically, animal feed production will likely exponentially increase. In most low and middle-income countries, industrial pig and poultry production is the fastest growing sector (McDermott et al., 2013) and international agri-businesses are currently capitalizing on emergent meat and dairy markets. Sub-Saharan African countries are no exception. In Nigeria, Olam Group recently invested $150 million to construct two "state-of-the-art" animal feed mills/hatcheries in Nigeria which, at full capacity, will produce more than 600,000 metric tons of poultry and fish feed per year (Olam Group International, 2016).

While animal product markets in Africa are expected to see some of the largest increases worldwide, local producers are not expected to fully meet demand (Herrero et al., 2013). To 2050, it is projected that Africa will increasingly become a net importer of livestock products with meat and milk imports set to increase from 0.9 and 5.7 to 5 and 10.2 million metric tons, respectively (FAO, 2013). Between 12 – 15% of all dairy and meat consumed in Africa is expected to come from outside the continent, including peaks of 21% of poultry imports in 2030 and 16% of beef imports in 2050.

3.6 South African Beef Sector and Feed Allocation

In the past decades, South Africa's middle class has gained more affluence and has begun to consume a more "Westernized" diet characterized by an increased demand for meat (Meissner et al., 2014). South Africa, the most developed agricultural system in the sub-Saharan region, retains an increasingly commercialized beef industry consisting of approximately 50,000 established commercial beef cattle farmers and nearly 100 commercial feedlots (DAFF, 2015b; Figure A.4). Compared to the 3.24 million emerging smallholder and communal beef farmers that process 5.7 million cattle, the commercial beef sector processes 13.8 million cattle (nearly triple the amount by smallholders) accounting for most of the total beef production in South Africa.

Of South Africa's roughly 1.9 million head of cattle slaughtered each year for beef, roughly 1.4 million are raised on commercial feedlots, and the remaining ~26% is grass-fed (Grant, Vink & Murray, 2004). Here, animal feed is produced on a larger scale domestically than the rest of SSA. Approximately 10.5 million tons of yellow maize are harvested per year, of which 60% is used by the starch industry (37%) and for direct human consumption and seed production (23%) (DAFF, 2015a; Figure A.3). About 4.5 million tons, 40% of total yellow maize grown, is used in the production of animal feed. Members of the Animal

Feed Manufacturers Association (AFMA) dominate South African animal feed production, producing 65% of all animal feed in South Africa, of which yellow maize constitutes about 55%. Throughout SSA, the use of grain for animal feed is on the rise, suggesting increasing commercialization similar to that of South Africa's livestock sector (Mcunu, N., personal communication, July 12, 2017).

CHAPTER 4 – FOOD SYSTEM EVOLUTION AND DEVELOPMENT

4.1 Livestock as Essential for Well-being and Development in SSA

Though thermodynamically inefficient and potentially environmentally destructive, livestock still are one of the best sources of essential nutrients and high-quality protein and remain the most efficient means of extracting energy from grasslands (Smith et al., 2012). But in developing countries, livestock provide much more than macro and essential micronutrients in the form of meat, dairy and eggs (Randolph et al., 2007). The livelihoods of nearly one billion smallholder farmers and pastoralists throughout SSA and South Asia depend on livestock (McDermott et al., 2013). For many, livestock are the principal source of income and act as a financial buffer during emergency or unexpected economic turmoil. Smallholder dairy production particularly can provide employment opportunities and regular, reliable income (Kaitibie et al., 2008). Animal manure provides the main source of fertilizer, and large livestock animals are used for draft power and transporting goods (McDermott et al., 2013). The multi-faceted benefits of "livestock as capital" in rural, agro-pastoral systems was demonstrated in a recent statistical analysis which found that Kenyan households that kept livestock could till more land and produce higher grain yields during the wet season (Nyariki, 1999). During the dry season, they were then able to exchange livestock as commodities. Transitioning from cropping to livestock-rearing may also serve as an important, adaptive livelihood strategy in SSA if currently arable land becomes increasingly unsuitable for agriculture due to climate change (Jones & Thornton, 2009).

In South Sudan, famine resulting from inter-tribal conflicts and drought have pushed many families to "sell" their daughters into arranged marriages in exchange for cattle (Chamberlain, 2017). "Cattle-raiding" (i.e. cattle theft) has been prevalent for centuries but has become deadlier as guns have permeated violent disputes. Since South Sudan gained independence in 2011, an estimated 5,000 civilians have been killed in cattle raids (Morgan, 2017). Throughout SSA, particularly in the Sahel, similar tensions have arisen between pastoralists and farmers, who lack resources for sufficient fencing, when herders drive their cattle cross-country (usually following wet season precipitation patterns) and damage or destroy farmers' crop plots – generally, inadvertently. Increasingly, a more illicit "neo-pastoralism" is becoming more pervasive where pastoralists and their herds are being purchased or overtaken by more powerful urban elites as a means to store wealth and illegally smuggle and trade goods like precious minerals, ivory, and bush meat (The Economist, 2017). Infrastructural improvements (e.g. access to resources and tools to construct fencing) throughout SSA combined with simple and relatively inexpensive technologies such as the use of radio-frequency identification (RFID) tags to track and monitor cattle herd movement – as herd ownership becomes less transparent – could help to reduce tensions (Mohammed-Raji, A.R., personal communication, July 7, 2017). More sophisticated technology ubiquitous in developed countries is being innovatively employed in some SSA countries.

In the past decade, the prevalence of mobile phones has surged in Africa as it has globally; it is estimated that as much 85% of the world now owns a mobile phone (UNESCO, 2014). In SSA countries like Kenya and Uganda, mobile banking services have gained traction allowing millions of citizens – who otherwise might not be able to afford the expenses of setting up accounts with established banks – to effortlessly pay utilities bills or wire money (Fox, 2011). Smallholder farmers can lease smartphones from these "microfinance" programs giving them access to vital information like seasonal weather reports, crop disease diagnostics, market prices, and planting tips. Making data-informed decisions on production-side practices could be instrumental in increasing farmers' resilience to climate change. Similarly, African consumers, armed with information, could influence demand-side dynamics. Access to credit, financing and the considerable literacy gains also being made from cellular internet access could help to lift many out of poverty (UNESCO, 2014).

4.2 Uncertainties and Future Work in Transitions from Grain-Fed Livestock

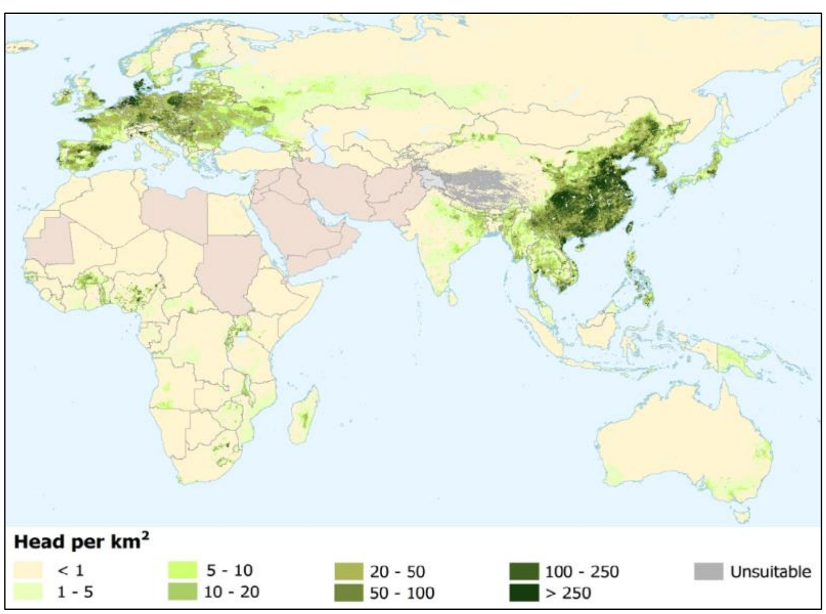
In this thesis, thermodynamic models were used to quantify gains made by diverting domestic production of the main animal feed component, maize, from livestock production to direct human consumption. Applying grain-fed livestock feeding efficiencies of developed to developing livestock systems increases the uncertainty of the resulting gains found here. Detailed, producer-side data for extensive analysis of the livestock sectors (e.g. how animal feed is allocated between meat, dairy, and egg production and feeding regimens for grain-fed livestock) in the SSA countries analyzed here is not widely available but this information may be obtained through communication with contacts working on the ground in this region. Thus, in determining gains from substitution of direct consumption, the assumption that maize-for-feed either contributed 100% to dairy production or 100% to meat production was made, again, because allocation data of maize-for-feed between meat and dairy sectors is lacking, with the exception of South Africa (Table A.3). Therefore, realized cereal self-sufficiency ratios (SSR's) resulting from direct consumption of maize-for-feed for Ghana, Nigeria, and Tanzania are likely between the two values for meat and dairy substitution in Figure 3.4.

Additionally, without accounting for climatic, agronomic and genomic factors such as rainfall patterns, soil type/fertility, and plant/animal breeds, the models may be overly simplistic in their current form (Guilpart et al., 2017). Substitution scenarios involving alternative food crops also require further refinement. Yield gap closure for these crops was assumed proportionate to that of rainfed maize measured by GYGA and used by van Ittersum et al. (2016); see Table 3.6 above. Consequently, energetic and protein gains from these yields may be over- or under-estimations. More realistic yield potentials for these crops need to be incorporated from the scientific literature. Micronutrient and macronutrient profile alterations that may occur during food preparation were also not considered. Further development of the models will aim to increase sensitivity along with quantifications of resource-related externalities (e.g. water use, nitrogen use, soil erosion, GHG emissions).

Trade is also of great importance. Sub-Saharan Africa is currently about 80% cereal self-sufficient (van Ittersum et al., 2016). Although domestic production of animal feed and animal products is increasing, many SSA countries depend on imports currently and will likely continue to do so (Herrero, Thornton, Gerber, & Reid, 2009). Recognizing that food security and food self-sufficiency are not necessarily mutually dependent, the latter can still contribute to achieving the former. In low-income developing countries, adequate foreign exchange reserves and infrastructure are usually lacking to effectively purchase and store imports (van Ittersum et al., 2016). Furthermore, achieving food self-sufficiency throughout Africa is recognized as a key priority for development; increased local agricultural productivity and regional trade combined with policy reforms could help to reduce food prices for rural and urban populations, reduce unemployment and reduce domestic currency depreciation by minimizing reliance on foreign food imports which costs the continent $35 billion annually (ADBG, 2015, 2016). For these reasons, the results presented in this analysis assume that maize-for-feed, animal products produced from maize-for-feed, and alternative food crops are produced domestically currently and will be in 2050. Where self-sufficiency is not obtained in SSA, global trade can provide agricultural commodities at perhaps even lower costs. But without quantifying environmental and health externalities and including them in prices, underpriced commodities largely do not account for environmental degradation, and thus, these agricultural practices may be essentially borrowing natural capital and ecosystem services from future generations (Stiglitz, 2010; Daily, 1997; Costanza, 1997).

Dietary preferences and culture are also dominant factors for determining types of food consumption (Bourdieu, 1984). The trend toward more animal-based diets with increasing incomes is widespread (Figure 3.6), but with notable exceptions. Religious beliefs, tradition, and cultural taste preferences greatly vary among populations. In majority-Muslim countries, for instance, pork consumption is taboo due to scriptural prohibition (Figure 4.1).

Figure 4.1. Distribution of pigs in Africa, Europe, Asia, and Australia, and the distribution of Muslim-majority countries. Source: Adapted from Robinson, et al. (2014).



In India, similarly but with much greater variability, cow veneration or practiced nonviolence towards animals and vegetarianism are integral customs of religion (including Hinduism, Jainism, Buddhism, and Sikhism) (Michaels, 2003); calls for nationwide bans on cow slaughter are currently being debated, though buffalo meat is still widely produced and consumed (Mangaldas, 2017). Muslims and Hindus are the second and third largest religious groups in the world with – 1.8 and 1.2 billion followers, respectively – and in the case of Islam, trends indicate it will surpass Christianity within forty years to become the most widely-practiced religion on the planet (Pew Research Center, 2017). Socioeconomic factors driving trends toward animal-based diets are powerful, but religious and cultural beliefs can be more influential on dietary preferences, as demonstrated by these two significant cases.

4.3 Conclusions

In this thesis, direct consumption, by humans, of maize grown for animal feed ("maize-for-feed") was shown to theoretically support significantly larger populations, accounting for energy and protein requirements, than from maize-fed livestock (i.e. meat and dairy products) in four SSA countries. Direct consumption of maize-for-feed by humans was found to currently enable population growth by 6 – 11% in Ghana, 4 – 7.4% in Nigeria, 4.4 – 10.5% in Tanzania, and 24.8 – 40.9% in South Africa. By 2050, if crop yield gaps were closed to 80% of potential yields for rainfed maize (by increasing irrigation and nitrogen application) and assuming no increase in harvest area, significantly larger fractions of projected populations were found to be sustained from direct consumption of maize-for-feed versus livestock production, where protein is limiting: 18.4 – 32.2% in Ghana, 11.7 – 21.1% in Nigeria, 6.6 – 15.6% in Tanzania, and 38.1 – 59.5% in South Africa. Considering the relative thermodynamic inefficiency of grain-fed livestock, previous yield gap assessments that include livestock may significantly underestimate the "biophysical limitations" to these agricultural systems.

Feeding more people is not simply a matter of eating more crops, however. There are complex trade-offs involved and powerful cultural, political, social, economic, and business forces at work. Improvements to infrastructure and resource allocation would go a long way to bolstering food security by minimizing waste and increasing access to markets in SSA countries (ADBG, 2016). Closure of yield gaps should be pursued but with caution as effects of intensification practices (e.g. increases in water use and fertilizer application) are likely to harm ecosystem services conducive to human health if regulated poorly and if externalities remain unaccounted for in food prices.

Agricultural markets have been highly regulated, and government policies have distorted prices, via subsidies, tariffs, and crop insurance. Underpriced commodities do not account for the complete costs of a broad range of negative externalities from agriculture, such as air and water pollution, and health hazards that will be paid by others, usually in other sectors (Pretty et al., 2000). If external costs become recognized in prices, markets could correct for inefficiencies by raising the price of inputs to grain production such as water, land, and fertilizer. Agricultural commodity prices would probably be much higher than they are currently which would provide greater incentives to stimulate the development of more efficient agricultural systems. With increasingly costly crop production, meat prices would increase to represent a larger fraction of related environmental costs. To create new agricultural innovations to meet food security and environmental challenges, agricultural markets should make the most efficient use of resources, and prices should be adequate incentives to push inefficient producers out of the market in a continuous process of “creative destruction” (McCraw 2007).

Sustainable intensification of SSA livestock production systems (Herrero et al., 2009) and changes to animal diets where the use of feed crops suitable for human consumption (e.g. maize) is lessened could help feed more people while minimizing environmental degradation. Prioritization of nutritionally-adequate and energy-equivalent food crops (e.g. potatoes, yams, cassava, sorghum, millet) over human-edible grains grown primarily for animal feed production could also feed greater populations. As regional populations increase exponentially to 2050, convergence by SSA countries to "Westernized" diets replete with grain-fed animal products will likely stress total agricultural productivity and food security (Herrero et al., 2009). Decisions concerning the evolution of livestock systems in SSA, as well as other developing regions, require an understanding of the complex trade-offs involved, particularly from the expansion of grain-dominated livestock production practices as evidenced by livestock systems in developed countries.

Methodology

For both current (2015) and future (2050) scenarios, the product of maize harvest area (three-year average for 2012-2014 [FAOSTAT]), maize yield, and percentage of total maize demand (consumption) allocated for animal feed, as reported by Sulser et al. (2015) from IFPRI's IMPACT model (International Food Policy Research Institute; International Model for Policy Analysis of Agricultural Commodities and Trade), gives total maize-for-feed production (i.e. production of maize grown explicitly for animal feed). Current yields, calculated as three-year averages for 2012-2014 (FAOSTAT), were used for the "current" scenario. For the "future" scenario, maize yield gaps for Ghana, Nigeria, and Tanzania were closed to 80% of water-limited yield potentials as reported by the Global Yield Gap Atlas (GYGA). For South Africa, no maize rainfed yield potential was available through GYGA, so it was calculated proportionately to 80% of yield potential for rainfed sugarcane and checked against calculated yield potentials for Ghana, Nigeria, and Tanzania for reasonable consistency. Water-limited (rainfed) yield potentials were used due to the rarity of irrigated cereals in these countries and marginality of total irrigated land; less than five percent of cropland in Tanzania and less than one percent of cropland in Nigeria and Ghana is irrigated (FAO AQUASTAT, 2016; You et al., 2011). Future projections of potential areas suitable for irrigation also vary widely and are typically based solely on water availability, not accounting for sustainability, rechargeability, and other associated economic and environmental costs and thus, are likely overly optimistic (van Ittersum et al., 2016).

Total energy (in kilocalories) and total protein (in grams) from maize-for-feed were calculated by multiplying maize-for-feed production by caloric and protein contents of maize derived from FAO Food Supply data (FAOSTAT). These values represent the total energy and protein of maize-for-feed available per year *before losses*. FAO standards for cereal yield, production, and supply data require reporting in terms of clean, dry weight (12 – 14% moisture) which is the form usually marketed (FAO, 2017). Losses were obtained from maize production data, as percentages of total production, and then subtracted to give aggregate energy and protein i.e. total energy (caloric basis) and total protein (mass basis) of maize-for-feed available for direct human consumption.

For transformation of maize-for-feed to meat and dairy products in terms of energy and protein, feeding efficiencies outside SSA were then applied. “Meat” was aggregated and weighted by consumption per country for beef, chicken, and pork (Table 3.1). These feeding efficiencies were derived using an “energy balance” approach for U.S. livestock systems, using farm and animal product production/consumption data (Table A.2; Eshel et al., 2014; Shepon et al., 2016). Analyzed and calculated separately from the feeding efficiencies of pasture and forage, the average feeding efficiency of grain or "concentrates" – which includes maize, sorghum, barley, oats, soybeans, and wheat – for livestock was used in this analysis due to maize being the sole input of interest. These efficiencies are uncoupled from their source data and consequently, imperfect when applied to lesser-developed livestock and crop systems such as those in SSA. Feed allocation data (i.e. what amounts of what feed constituents are fed to which classes of livestock) is more readily accessible for more regulated, developed agricultural sector agencies such as the United States Department of Agriculture and National Research Council yet, reported feed efficiencies are subject to many variables, and wide ranges have been measured by various sources (Shepon et al., 2016). Calculating individual feeding efficiencies for different livestock classes in the individual SSA countries under analysis was considered but available data was insufficient, and broad assumptions would likely have produced imprecise and tenuous results – though, this may be pursued in further research. The application of feeding efficiencies characteristic of an intensive and more "optimized" livestock sector (i.e. the U.S.'s) to SSA livestock systems represents a significant assumption. Regarding uncertainty, though, this means the results of this analysis (e.g. additional population supported) could be pessimistic because SSA countries are likely many developmental stages from attaining the kind of feeding efficiencies found in the U.S. (McDermott et al., 2013). In determining gains from substitution by direct consumption, the assumption that maize-for-feed either contributed 100% to dairy production or 100% to meat production was made.

Additional (net) populations supported from direct consumption of maize-for-feed versus those supported by maize-for-feed via meat and dairy were calculated based on the average Minimum Dietary Energy Requirements (MDER) as reported by FAOSTAT for each SSA country interpolated to 2015 for the "current" scenario and extrapolated to 2050 for the "future" scenario. These values represent average caloric intake required to maintain sedentary – moderately active lifestyles and vary demographically (FAOSTAT, 2008). An average daily protein requirement of 51 grams per person was used to calculate protein gains from substitution based on the average requirements for adult males and females of 56 and 46 grams, respectively (Institute of Medicine, 2005).

Gains in cereal self-sufficiency ratios (ratio of domestic cereal production and cereal demand) for Figure 3.4 were calculated from original results of van Ittersum et al.'s (2016) of 0.81, 0.80, and 0.72 for Ghana, Nigeria, and Tanzania, respectively. These results are based on a no climate change, medium-fertility population scenario modeled by IFPRI's IMPACT. From projected cereal demand (Sulser et al., 2015) and using the projected cereal deficiency (i.e. the difference between projected production and demand), approximate cereal supply was determined, assuming equivalent deficiencies for all five main cereals (maize, rice, wheat, sorghum, and millet). For example, in Ghana, the approximate supply of the five cereals was calculated, on a mass basis, as 81% of the projected demand for each cereal. The cereal deficiencies were then converted into energetic terms (i.e. calories) using caloric contents derived from FAO Food Supply data (FAOSTAT) for each of the five cereals. The sum of these gives total deficiency of the five cereals in calories. Energetic gains made through direct consumption of maize-for-feed (columns 2 and 5 of Table 3.4) were then divided by the calculated total cereal deficiency to give percentage of deficiency filled and subsequent, "new" cereal SSR's from substitution of a) direct consumption of maize-for-feed, for b) meat and dairy via maize-for-feed in Ghana, Nigeria, and Tanzania (Figure 3.4).

Energy and protein gains from substitutions of alternative food crops for meat and dairy via maize-for-feed were calculated using an estimation of land area required to grow maize-for-feed based on demand and current maize harvest area (Table 3.6). These crops were selected based on general climate suitability, current prevalence in the selected SSA countries, and – in the case of millet, sorghum, and yams – probable African origin (NRC, 1996).

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Appendix

Figure A.1. Simplified schematic representation of methodology used by Shepon, et al. to determine environmental burdens of animal products in United States. Procedural derivations of concentrate feed energy and protein transfer efficiencies (Table 3.1) are imperfectly representative of those of a "developed" livestock food system. Source: Reproduced from Eshel, Shepon, Makov, & Milo (2014).

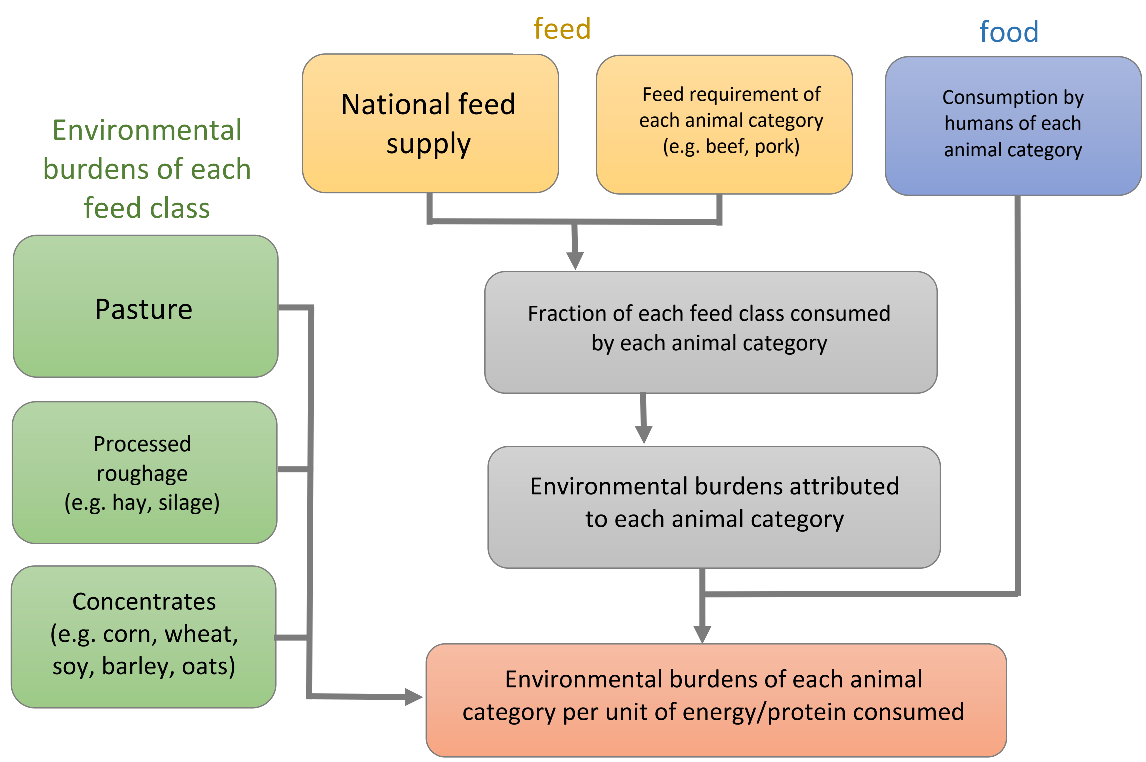

Table A.2. Key parameters used in evaluating US feed allocation and energy and protein transfer efficiencies. Source: Adapted from Shepon et al. (2016).

Parameter	**Units**	**Beef**	**Poultry**	**Pork**	**Dairy**	**Eggs**
Feed intake per LW	kg/kg LW	14 ± 4	1.9 ± 0.4	3.1 ± 1.3	NA	NA
Feed intake per EW	kg/kg EW	36 ± 13	4.2 ±0.8	6 ± 2.5	NA	NA
Feed intake per CW	kg/kg CW	49 ± 9	5.4 ± 1.4	9 ± 4	2.6 ± 0.6	2.4 ± 1.2
Feed caloric content	kcal/g	3.2 ± 0.3	2.3 ± 0.1	2.8 ± 0.2	1.2 ± 0.1	1.4 ± 0.1
Caloric conversion efficiency	%	2.9 ± 0.7	13 ± 4	9 ± 4	17 ± 4	17 ± 9
Feed protein content	%	12 ± 3	17 ± 7	17 ± 11	15 ± 5	17 ± 12
Food protein content	%	15 ± 2	20 ± 2	14 ± 1.4	6 ± 0.6	13 ± 1.3
Protein conversion efficiency	%	2.5 ± 0.6	21 ± 7	9 ± 4.5	14 ± 4	31 ± 16

Note: LW = live weight (USDA reported slaughter live weight); EW = edible weight (USDA reported retail boneless edible weight); CW = consumed weight (USDA reported loss-adjusted weight). NA = ‘not applicable’. Feed caloric content refers to metabolizable energy and feed protein content refers to crude protein.

Figure A.3. Maize production and allocation in South Africa. Adapted from DAFF (2015a).

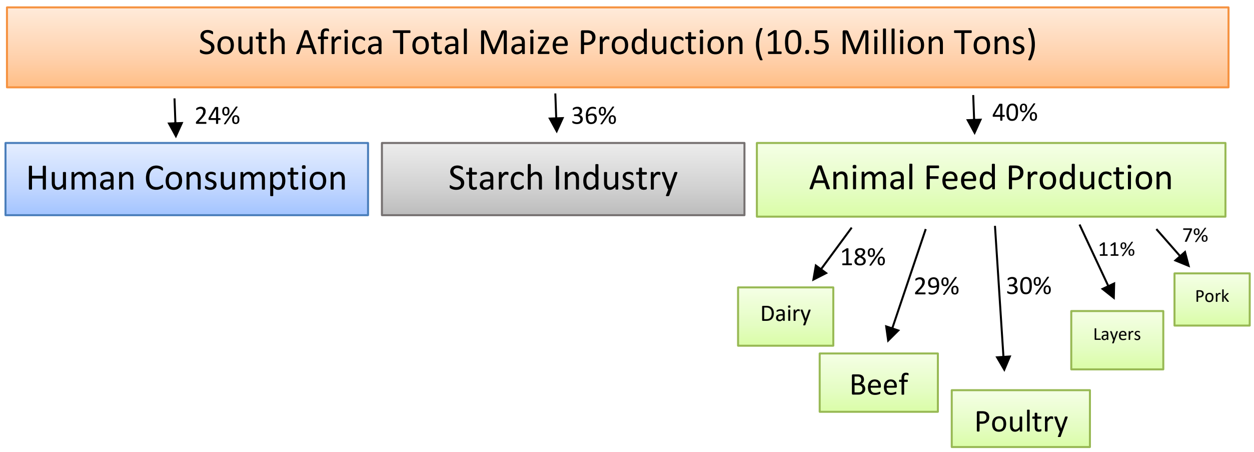

Figure A.4. South African beef value chain. Adapted from DAFF (2015b).