GLOBAL FOOD SYSTEMS:
DIET, PRODUCTION, AND CLIMATE CHANGE TOWARD 2050

BY

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ABSTRACT

To address food security in a food abundant world requires a new paradigm that walks away from a strict production perspective. While research on agriculture and food security has increased significantly in the past decades, it has mostly focused on agriculture and food production rather than on the entire food system, from production to nutrition intake. It has also typically employed economic equilibrium approaches to make future predictions. This study proposes a paradigm shift by, first, using a material flow approach to construct an integrated model to analyze global food systems and estimate food surpluses and deficiencies toward 2050 under climate change and, second, by including the range of the food security systems (production, access and utilization). It does so by considering production, demographics and diet scenarios across a number of commodities/crops important to guarantee future food security among developed and developing regions. In contrast to the economic equilibrium approach, the material flow approach takes into consideration populations without conventional market-driven economic access for better addressing the food security and equity issues. The results show that, while there will be a surplus in overall food production by 2050, mainly from cereal and starchy roots, there will be also critical shortages to other staples such as meat, milk, and sugar & sweeteners, important to utilization and nutrition. These findings suggest a need for significant modifications to current global agriculture production systems to meet actual demand and to enhance understanding about diet and its implications to global food systems.

1. INTRODUCTION

Although global food production (measured by global average per-capita calorie consumption[1]), has never been higher (FAOSTAT.2014; Alexandratos, 1999), around the world more than 800 million people remain food insecure (FAO, 2012). In spite of the collective effort to combat famine through continuous progress in production since 1990, reducing undernourishment and, more importantly, improving healthy nutrition remains challenging (FAO, 2012). Increasing population, modernized diet, and climate change will continue to pressure global food systems – from agricultural production to nutrition consumption – for the next decades (Godfray et al., 2010). On the one hand, global food consumption has almost tripled between 1961 and 2009, and, if such trend continues, the global demand for food will require increased production. On the other hand, climate change, together with other environmental constraints, may have already affected production and potentially will likely undermine food systems' ability to meet those demands. By 2050, a year in which global population is projected to reach 9 billion people, the dynamics between population, diet, and climate change will amplify their effects on global food systems more directly.

Despite these daunting projections, the current scholarship focusing on global food systems remains relatively limited in its ability to provide an integrated analysis of the whole system--from production to consumption to food utilization. Literature focusing on climate change effects on food systems mainly explores different types of impacts on agricultural production and the technologies that help mitigate those adverse effects. Studies in this area have two main foci. Firstly, from a production perspective, a large body of research explores a spectrum of physical and biological properties that limit or control

[1] Measured in 2009.

agricultural production, including land degradation and limitation, water scarcity, precipitation and temperature, crop selection techniques, and production intensification. A major goal of this literature is to better understand future agriculture and food availability. Secondly, research focusing on Development and Food Security aims at generating policy-oriented knowledge about the determining factors and processes associated with global and/or regional undernourishment. A significant portion of this literature explores the socio-economic factors and processes associated with undernourishment in less developed regions, while others explore food consumption and nutrition intake under flawed food systems in the developing world.

Noting the necessity of bridging economic, technical, biophysical, and legal aspects of global agriculture, integrated assessment studies of global agriculture emerged in the beginning of new millennium. Often studies in this area employ economic equilibrium models focusing primarily on the production side of the food system (Mendelsohn & Nordhaus, 1999; Schneider et al., 2011; Stehfest, Berg, Woltjer, Msangi, & Westhoek, 2013). Especially at the global level, while making the assumption that global demand for food is equal to production, these studies examine price patterns and measure values of elasticity for various food commodities. However, the demand function, a curve that illustrates consumer's willingness to pay, implies that people who do not have money are not a part of that demand (Mankiw, 2014). This means that a whole group of people, especially the poor who are not part of formal markets, might be outside the purview of economic equilibrium models. What is critical here is that these models leave out precisely the people that might be the most food insecure and likely to be the most affected by climate change.

Hence, prevailing research approaches to date provide important yet incomplete views on the anthropogenic processes that affect food security and wellbeing, especially in less developed regions. While the globe gets warmer and more crowded, many human systems have moved to a state where food supply is more sufficient and people are richer, leaving the problem of large undernourished populations a modern puzzle. In the quest for food security, it is necessary to examine the food system beyond production and to integrate important attributes - demographic, climatic, and macro-behavioral changes.

To advance knowledge in this area and to facilitate possible policy considerations in food security, this study has three main objectives. First, it seeks to factor in changes in macro diet behaviors to the understanding of global food systems. To our knowledge, effects of diet shift regionally and globally have not been fully understood in most integrated assessment studies of global food systems, and such understanding is important to suggest the adjustments of agricultural production. Second, it examines estimates of future yield gaps between physically possible production and preference-based diet demand, incorporating four exogenous drivers- population growth, diet scenarios, climate change, and agriculture-nutrition conversion coefficients. Third, it proposes a new analytical framework to inform the need to rethink global food security in the post production-deficiency era.

To this aim, I propose a material flow approach that separates demand for food from production, which in turn, equals to market demand and still relies on the result of economic equilibrium approach models. Here, the demand in the material flow approach incorporates the entire global population and considers both nutritional needs and diet preferences, here to forth referred to as "real demand."

Specifically the proposed framework describes the global food system processes, presented by a serial conversion - from physical agricultural production to food production to caloric intake. The framework covers 13 aggregated categories of "Crop Primary Equivalent" and 7 aggregate categories of "Livestock and Fish Primary Equivalent" commodities defined by the United Nations' Food and Agriculture Organization (FAO) for 225 countries listed in the FAO's database (FAOSTAT.2014). The framework is designed to examine differences between market demands, which equal to production globally based on economic equilibrium approach, and real demands, which are based on average nutritional needs and diet preference. The main research question is whether and how global food systems, with or without climate change effects, can fulfill individual's nutritional needs and diet preference by 2050. In addition, this research queries whether global food systems produce more or less than the real demands for food and where the production surplus or deficiency is likely to happen. Its mains hypothesis is whether real global food demand is equal to the market demand in future predictions. Rejecting the hypothesis suggests that addressing food security issues cannot rely on market and market-driven production.

To explore this hypothesis I implement an integrated model for material flow assessment to quantify all future surpluses and deficiencies in all 20 food categories for all countries toward 2050. On the supply side, the model combines future estimates of global food productions under a 2° Celcius global temperature increase scenario from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) and the FAO (Alexandratos & Bruinsma, 2012; Linehan et al., 2013). Although negative climatic impacts are likely to significantly constrain efforts to fulfill global food demand, they do not alone describe the yield gap between food production and desired diet consumption, a direct consequence of population and average diet per capita changes. In terms of consumption, a significant shift of diet, especially in developing regions, can be expected over the next few decades, mostly because over one billion people today, mainly in developing regions, suffer from micronutrition deficiency (Barrett, 2010). To account for this change, on the demand side, the model employs an "a posteriori" approach to construct future scenarios of the global population's preferences of food consumption based on historical food consumption data. Three important assumptions are made in this approach and will be discussed more detailed in section 3. First, market forces, which, according to economic theories, affect people's ability to pay, do not affect people's real preference of diet. Second, inequality of both physical and economic accesses to food is assumed endogenous and homogenous within all aggregate demographic groups at country, regional, and global levels. Third, the material flow approach, a method that assesses physical consequences of agriculture and food uses, freer trade than status quo is assumed globally.

This thesis is divided into four parts. In Section 2, I examine literature on global food systems from four aspects, starting with the discussions on overall food security concept and measurements, and moving on to food production, utilization processes, and demands, respectively. In Section 3, I detail research methods, frameworks, and the modeling. In Section 4, I present and analyze results yielded from the research. Lastly in Section 5, I address the research question and explore the hypothesis.

2. DEFINING AND MEASURING GLOBAL FOOD SYSTEMS

2.1 GLOBAL FOOD SECURITY AND FOOD PRODUCTION

Conceptually the purpose of global food systems is to fulfill needs and desires of human being's food consumption and nutrition intake. A well-established measurement of these systems' performance is the concept of global food security. The definition of global food security primarily from the FAO has continuously changed over time (Heidhues et al., 2004; Thomas, 2006), from mostly considering supply availability and stability to explicitly emphasizing aspects of consumption and diet behaviors. The FAO's most recent definition states that "Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life. Household food security is the application of this concept to the family level, with individuals within households as the focus of concern (Thomas, 2006)." In its latest definition in 2001, the FAO added social access to the originally existed physical and economic access and, more importantly, expanded the definition of food quality from just sufficient to sufficient, safe, and nutritious food and the human's need of food from just dietary needs to dietary needs and food preferences. The development of food security definitions has gradually shifted; however, it did not affect much how researchers perceive global food systems.

Operationally, this definition carries out four dimensions of global food security: availability, stability, access, and utilization (Schmidhuber & Tubiello, 2007), and major research efforts and indicators of determinants that measures policy effects toward food security have been classified within these four dimensions. An example of these indicators is listed in **Table 1 below** (FAO, 2012). The most current list of indicators actually neglects ones of population's diet and demand, which the definition of food security has emphasized. Thus, the primary aim of my research has been to expand the current monocle perspective of food systems solely on production to a more integrated understanding throughout the process of utilization, from agricultural production, food processing, consumption in the marketplace, and individual utilization in the form of diet as shown in **Figure 1 (FAOSTAT.2014)**.

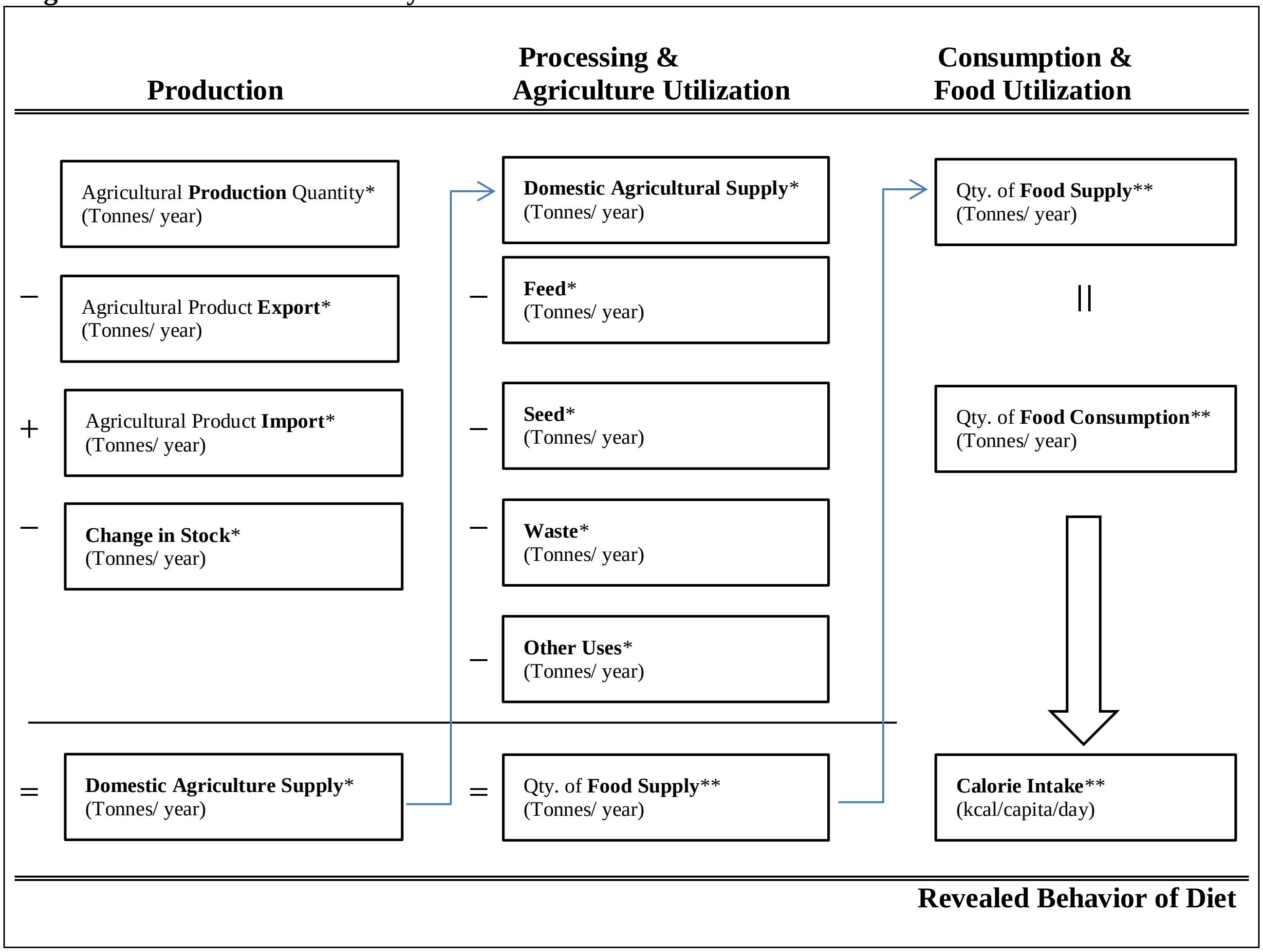
Table 1. FAO's Food Security Indicators

Type of indicator	Source	Coverage
DETERMINANTS OF (INPUTS TO) FOOD INSECURITY		
Availability		
Average dietary supply adequacy	FAO	1990–2012
Food production index	FAO	1990–2012
Share of energy supply derived from cereals, roots and tubers	FAO	1990–2012
Average protein supply	FAO	1990–2012
Average supply of protein of animal origin	FAO	1990–2012
Physical access (conditions for physical access to food)		
Percentage of paved roads over total roads	International Road Federation	1990–2009
Rail lines density	WB	1990–2010
Road density	WB, Transport Division	1990–2009
Economic access (affordability)		
Food price level index	FAO/WB	1990–2010
Utilization		
Access to improved water sources	WHO/UNICEF	1990–2010
Access to improved sanitation facilities	WHO/UNICEF	1990–2010
VULNERABILITY/STABILITY		
Domestic food price volatility	FAO/ILO*	1990–2010
Per capita food production variability	FAO	1980–2010

Per capita food supply variability	FAO	1980–2010
Political stability and absence of violence/terrorism	WB WGI**	1996–2010
Value of food imports over total merchandise exports	FAO	1990–2009
Percentage of arable land equipped for irrigation	FAO	1990–2009
Cereal import dependency ratio	FAO	1990–2009

*International Labour Organization
**World Bank Worldwide Governance Indicators.

Figure 1. Data of Global Food Systems from FAOSTAT



Namely, I proposed a three-step process that covers the four dimensions of food security, quantifies utilization, and incorporates diet behaviors. The first step is agricultural production, which covers availability, and access stability dimensions. In this step, physical yield of all agricultural produce for all kinds of food under variation forces including global climate change is estimated. Also, as global production can be treated as one system, total domestic supply is equal to the sum of global production, and domestic agriculture supply in an individual area is a result of global trade and change in domestic inventory. Thus, whether demand for food in one region can be fulfilled is determined by economic access at country level. The second step is processing and agriculture utilization of food commodities under the utilization dimension. This step conceptualizes a long physical process that converts all kinds of agricultural commodities into food and takes into account uses of agriculture commodities for feed, seed, other means such as biofuel, and waste. The third step describes the process of food consumption and food utilization, in which food is converted into nutrition from agriculture made available for food. This step, which covers an access dimension at domestic level and the utilization dimension, is important in calibrating the understanding of an area's diet behavior from consumption calculations by weight and by calorie. Thus, although some food commodities in a diet portfolio might contain low caloric density, standardizing diet in the measurements by weight and by energy ensures that some diet behavior is not neglected due to single measurement. In following sections, I will examine each of the three steps.

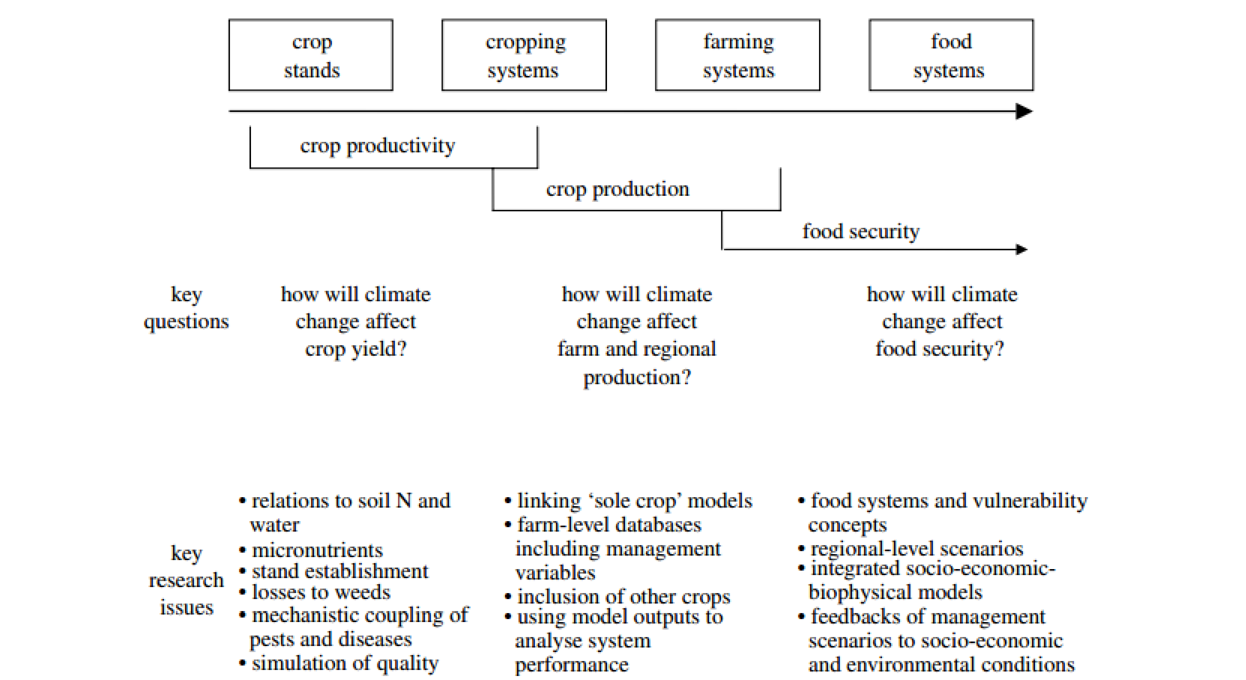
2.2 GLOBAL FOOD PRODUCTION AND CLIMATE CHANGE

In this section, I examine factors that would alter production systems, which helps us understand how variations in the production system affect food security. In particular, this section addresses the relationship between climate change and food security, as climate change, especially increased climate variability, is one of the greatest challenges to food systems (Pielke Sr et al., 2007; Vermeulen, Campbell, & Ingram, 2012). A summary of the many perspectives from different literature is shown in Figure 2 (Gregory, Ingram, & Brklacich, 2005).

One important dimension of this literature focuses on productivity, describing the food systems from biological and physical factors and yielding fundamental knowledge about how limitations and interactions among these factors affect production systems. From this perspective, global agricultural output can be theoretically determined by the factors such as arable land, available fresh water, and skilled labor, given constant physical assets of farming, suitable climate conditions and soil quality, landscape and geographic location, and species of crops and livestock (Alexandratos & Bruinsma, 2012; Bruinsma, 2003; Byerlee, 1996; Gornall et al., 2010). Warming temperature impacts agriculture in many forms, such as variations in precipitation, change in crop's growth patterns, and extreme climatic events, all influencing the level of food security from local to global level (Gregory et al., 2005; Solomon, 2007). For example, Rosenzweig and Parry's global agriculture model (1994) suggested that effects of global warming from doubling carbon dioxide in the atmosphere will only lead to a small decrease of food production, but create great disparity of food availability between developed and developing countries, and adaptation effort can do little at the farm level (Rosenzweig & Parry, 1994). Globally, empirical studies also show that development progresses of agriculture and climate change effects on various foods are distributed unevenly across countries and food sectors (Alexandratos, 1999).

Other research covers production systems, specifically focusing on production technology. Production technology is a way to adapt to climate change effects, although they vary considerably across regions. Lobell et al's recent study explores how effects of climate change on production systems affect food security by both sorting out regions with the most malnourished population and ranking the importance of crops, determined by the amount of daily calorie intake it provides to an average person (Lobell et al., 2008). Findings suggest that climate impacts would vary substantially among individual regions according to different biophysical resources, management, and other factors. By identifying major areas of concern, the study recommends that switching production systems from highly-impacted to less-impacted crops could be one viable adaptation option in maintaining food supply.

Figure 2. The changing nature of key research issues and frequently asked questions at a range of different scales moving from crop production to food security.



Source: (Gregory et al., 2005)

These findings indicate significant threats to food security if the status quo holds and suggest that if there is no modification of human activities, the physical aspect of food production systems would eventually fail to meet global needs. These findings indicate the need for more integrated research that extends to human aspects, namely the roles of market, technology advancement, and equality of access to food.

Academia, governments, and international organizations are aware of this need. In the past two decades, another dimension for assessing global agriculture production has emerged in the form of global agriculture models that integrate both biophysical and economic aspects. These models, allow scholars and policymakers to examine outcomes from defined or projected environmental, economic, and social scenarios. They also discuss and measure a wide range of issues, such as: 1. how crop yields respond to various socio-economic scenarios given various climate scenarios (Parry, Rosenzweig, Iglesias, Livermore, & Fischer, 2004); 2. how economic growth that increases production through increase demand and how poverty impedes it (FAO, 2012; Schneider et al., 2011); 3. how to make investment on technology advancement which increases agricultural productivity and on adaptation which safeguards livelihood from negative food security outcomes (Rosegrant & Cline, 2003; Ziska et al., 2012); 4. how trade encourages production (Bruinsma, 2003; Vatn, 2002); and 5. how climate impacts on agriculture affect poverty (Hertel, Burke, & Lobell, 2010). However, despite abundant research on global food production to date, studies that predict global agriculture and food production toward 2050 under given social and climate scenarios remain rare and exist only in two published reports, *World Agriculture towards 2030/2050, the 2012 Revision* by the FAO and *Global food production and prices to 2050* by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (Alexandratos & Bruinsma, 2012; Linehan et al., 2013).

Although the above listed studies answer different problems, they remain focused on the production side. These studies also share three common assumptions. First, at global level, demand equals production. Second, production meets the demand of those with economic access, and issues associated with economics access are resolved through economic development, measured by increase of per-capita Gross Domestic Product growth or income. Third, technology advancement is usually referred to increasing or maintaining productivity. As the goal of my focus on production is to understand food security, these assumptions yield three fundamental questions. First, since more than 800 million people are still undernourished today, real demand for food and agriculture should necessarily be larger than production. How do we redefine global food demand? Second, when demand is measured in monetary terms, real needs for nutrition are ruled out, given lack of economic access. What would be a better measure? Third, larger agricultural output does not necessarily correlate to larger nutrition utilization. When concerns on technology have focused on productivity aspects to adapt to negative climate effects, technology advancements that improve utilization of agricultural produce towards nutrition are omitted. What should be the right role for technology in global food systems? Later in the discussion I will review and addresss these questions.

2.3 UTILIZATION OF AGRICULTURAL PRODUCTS

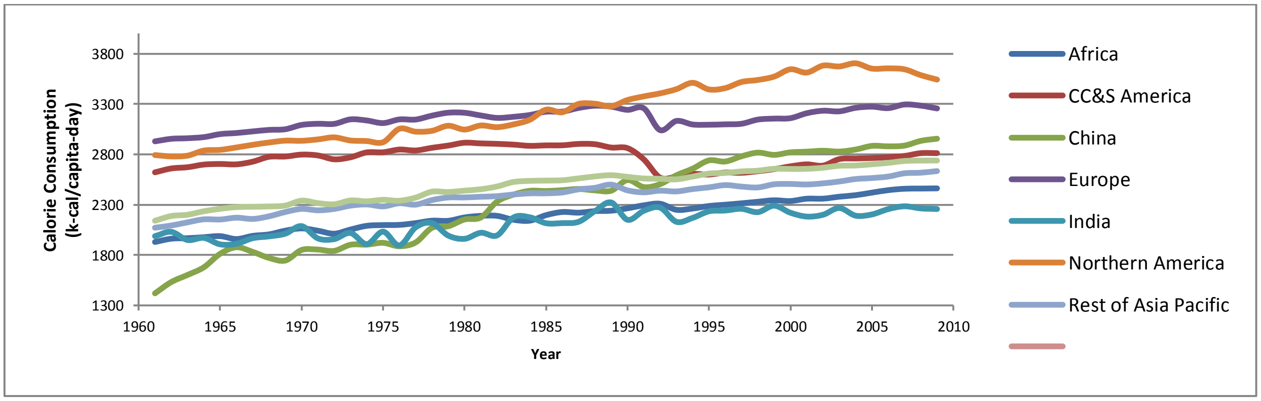
In the context of global food systems and food security, utilization is one of four pillars of food security concept. The FAO only defines utilization of food as “the way the body makes the most of various nutrients in the food”(The EC - FAO Food Security Programme, 2008). FAO further elaborates this definition: “Sufficient energy and nutrient intake by individuals is the result of good care and feeding practices, food preparation, diversity of the diet, and intra-household distribution of food. Combined with good biological utilization of food consumed, this determines the nutritional status of individuals.” However, this definition does not provide sufficient operational use to either create measures for or improve food security. Scholars have discussed the lack of measures and data for food utilization (Barrett, 2010). To this aim, the FAO’s Statistics Division, which collects global food and agricultural data, developed a set of definitions that clearly distinguishes food and agricultural utilizations and describes elements of supply and utilization: “from stocks + production (agriculture) + imports = exports + feed + seed + waste + processing for food + food + other utilization.” (FAO Statistics Division, 2014). Using the equation the FAO is able to establish accounts by which it can associate purposes of use and available agriculture productions. Explicitly in the equation, food utilization, namely “processing for food” and “food,” represents only a part of agriculture utilization, while implicitly the FAO equates food utilization with consumption of food. The agriculture utilization equation yields two major questions when research seeks to tackle food security issues: 1.) while feed and seed create future production of its or other kind of food, how can waste, a disposable share of edible food, be reduced so that needs of larger production decreases? 2.) in food utilization, how efficiently can populations convert food from mass to nutrition, and how do we measure it?

To both questions, a recent estimate of food waste/loss at the globally aggregate level suggests that, roughly one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tons per year (Gustavsson, Cederberg, Sonesson, Van Otterdijk, & Meybeck, 2011). However, researchers also quite commonly agree that there is no firm evidence to estimate good losses globally and in developing countries based on available historical data, leading to a grand challenge in predicting food waste associate with economic development activities (Gustavsson et al., 2011; Parfitt, Barthel, & Macnaughton, 2010). One conclusion from these global waste studies indicates that global food waste/loss is understudied, and further research is urgent for addressing food security issue, especially for a large part of developing world.

2.4 DIET AND DEMAND OF FOOD

Historical data of global food consumption per capita has shown a significant increase from 2,373 k-cal/person-day in 1969/1971 to 2,772 k-cal/person-day in 2005/2007 (Figure 3) (Alexandratos & Bruinsma, 2012). Figure 4 further shows population and per-capita food consumption changes during the same period. The magnitude of change, equal to total food consumption, between 1961 and 2009, has been astonishing. While there is no doubt that global food demand will continue to rise in the foreseeable future, mostly as a function of population growth, economic development, and diet changes, predicting changes in global food demand will remain a challenge..

Figure 3. Historical Calorie Consumption by Region, 1961-2009.



(FAOSTAT.2014)

One practical approach in estimating global food demand is to use market demand (or effective demand), which predominantly equates global demand to production and finds equilibrium by incorporating commodity supply, demand, trade, and prices for populations in modeled countries/regions (Alexandratos & Bruinsma, 2012; Linehan, Thorpe, Andrews, Kim, & Beaini, 2012; Rosegrant, Leach, & Gerpacio, 1999). This approach can help to examine policy and market scenarios for modeled countries. However, one endogenous factor that the approach omits, by the nature of its design, are populations in poverty that possess very limited to no access to markets. Meeting the market demand does not necessarily mean assuring food security (Rosegrant, Paisner, Meijer, & Witcover, 2001). This omission can be quite significant: an estimate indicates that one billion people will still live in extreme poverty (US $2 a day) in 2015 (The World Bank Group, 2014). Since one in seven people today might have little access to markets, this approach may yield solutions to food security that are distorted and biased against this particular segment of the global population and yield consumption estimates that do not reflect overall consumption behavior and the true demand.

Another approach is to find statistical fit by regressing per-capita Gross Domestic Product (GDP) on per-capita calorie consumption per day data, and then predict future food consumption based on future GDP projection (Tilman, Balzer, Hill, & Befort, 2011). This approach generates results with great statistical significance, with higher R^2 numbers (0.773 with four variables and 0.787 with seven variables) and very low p-values (lower than 0.0001), indicating that nutrition demand will double in 2050. Since many international and governmental agencies put considerable efforts in predicting individual countries' and regions' GDP, to plug predicted GDP data into specified fit lines would conveniently provide future food consumptions figures. Despite nice model specifications for the highly aggregate food consumption forecast, this approach, using per-capita GDP square root as a function of food consumption in calorie, faces similar problems to the first approach.

In order to address the food secure demand, some research has shifted focus from market demand to diet that ensures healthy nutrition of human needs. A review of global food consumption patterns concludes that drivers of food consumption, including income, urbanization, trade liberalization, westernization led by transnational food corporations and food industry marketing, retail modernization, and consumer attitude and behavior, would impose new and complex challenge to ensuring a sufficient supply of staples and of micronutrient-rich food. Moreover, inputs from the health sector are necessary to make food policy effective (Kearney, 2010).

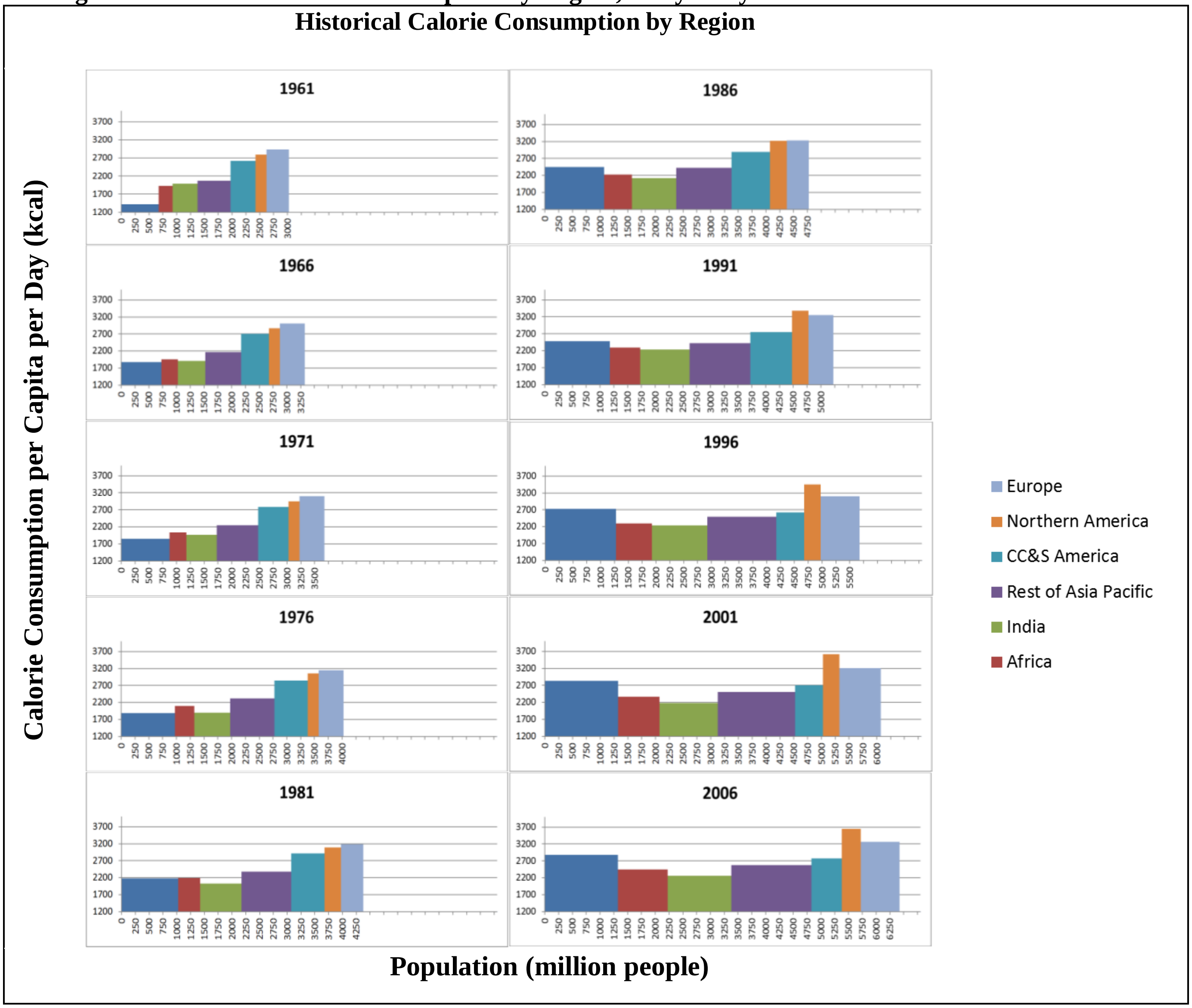
From these studies, it is also important to remark that, global market demand or diet to some extent will shift toward meat from current healthier plant-based diet (Kearney, 2010; Keyzer, Merbis, Pavel, & Van Wesenbeeck, 2005; Rosegrant et al., 1999). This trend of diet shift represents enormous challenges on global food security and food systems, especially considering health outcomes (Hawkesworth et al., 2010). To tackle global food security research and policy must go beyond calories alone and consider the balance of macronutrients for healthy diet (Hawkesworth et al., 2010).

3. METHODOLOGY, FRAMEWORK, AND MODELING

3.1 FRAMEWORK AND ASSUMPTIONS

This research constructs material flows of food from agriculture production, to food supply, and to calorie intake, using available data, in order to identify relationships between different steps in the food chain from the historical and geographical patterns. Thus, the framework starts with the fundamental definitions of FAOSTAT datasets (FAOSTAT.2014). First, I am interested in measuring agriculture utilization, how much food is available out from agricultural produce. The calculation for agriculture utilization is presented in formula (1).

Figure 4. Historical Calorie Consumption by Region, every five years between 1961 and 2009



(FAOSTAT.2014)

$$F_{ijt}^{A} = DS_{ijt}^{A} - FEED_{ijt}^{A} - Other_{ijt}^{A} - WS_{ijt}^{A} - SEED_{ijt}^{A}. \quad (1)$$

where

i represents individual area (country or region),

j represents the type of crop or livestock group, t represents year,

F^A_{ijt} is the actual total amount of food commodity, j, in area i, in year t, consumed as food (in tons),

DS^A_{ijt} is actual total domestic supply of food commodity of j, in area i, in year t (in tons),

$FEED^A_{ijt}$ is the actual amount of food commodity, j, in area i, in year t, used as feeds (in tons),

$Other^A_{ijt}$ is the actual amount of food commodity, j, in area i, in year t, consumed by other means (in tons),

WS^A_{ijt} is the actual amount of food commodity, j, in area i, in year t, wasted(in tons),

$SEED^A_{ijt}$ is the actual amount of food commodity, j, in area i, in year t, used as seeds (in tons).

It is worth noting that, given proper data, the denotation i can represent areas at country, region, and global level. For future projection, (1) can be re-written in exactly the same form to (1.1), in which the superscript P denotes "projected."

$$F^P_{ijt} = DS^P_{ijt} - FEED^P_{ijt} - Other^P_{ijt} - WS^P_{ijt} - SEED^P_{ijt}. \quad (1.1)$$

As F^A_{ijt} is always equal to or smaller than DS^A_{ijt}, for all i, j, t, I rewrite (1) in (2).

$$F^A_{ijt} = ATF^A_{ijt} * DS^A_{ijt}, ATF^A_{ijt} \in (0,1) \quad (2)$$

where

ATF^A_{ijt}, coefficient of "Agriculture to Food," represents the ratio of actual agriculture utilization from historical data, indicating the proportion of domestic supply of food commodity of j, in area i, in year t, that is converted into food consumption.

For future projection, (2) can also be re-written in exactly the same form to (2.1).

$$F^P_{ijt} = ATF^P_{ijt} * DS^P_{ijt}, ATF^P_{ijt} \in (0,1) \quad (2.1)$$

Second, I am interested in measuring food utilization, how much energy consumed based on one unit of food consumption. The calculation for food utilization is presented in formula (3), and (3.1) for future projection.

$$C^A_{ijt} = MTC^A_{ijt} * F^A_{ijt} \quad (3)$$

$$C^P_{ijt} = MTC^P_{ijt} * F^P_{ijt} \quad (3.1)$$

where

C^A_{ijt} is the actual total amount of energy taken from commodity j, in area i, in year t (in k-calories),

MTC^A_{ijt}, coefficient of “Mass to Calories,” represents the ratio of actual food utilization from historical data, indicating the magnitude of energy conversion that one ton of food commodity j, in area i, in year t, can generate (k-calories/ ton).

And the calculation for getting C^A_{ijt} is presented in formula (4), and for C^P_{ijt} in (4.1).

$$C^A_{ijt} = Pop^A_{it} * c^A_{ijt} * 365 \text{ (days/year)} \tag{4}$$

$$C^P_{ijt} = Pop^P_{it} * c^P_{ijt} * 365 \text{ (days/year)} \tag{4.1}$$

where

c^A_{ijt} is the actual average daily per-capita energy taken from commodity j, in area i, in year t (in k-calories/person-day),

Pop^A_{ijt} is the actual population in area i, in year t (person).

For all j, c^A_{ijt} actually represents a historical diet portfolio of area i in year t. With proper historical data, using the three formulas above, not only MTC and ATF for a given food commodity in a given area, at country, region, or global level, can be measured, but also can inferences of future MTC^P_{ijt} and ATF^P_{ijt} estimates from the historical data be made. Thus, given MTC^P_{ijt}, ATF^P_{ijt}, and Pop^P_{it} estimates, where the superscript P represents “projected,” calculation of future DS^R_{ijt}, meaning required future domestic supply of agriculture commodities, can inferred based on the diet portfolio of c^P_{ijt}. Therefore, the difference between real demands, DS^R_{ijt}, and estimates of future domestic supply of agriculture commodities, DS^P_{ijt}, can be measured with formula (5).

$$\Delta DS_{ijt} = DS^P_{ijt} - DS^R_{ijt}, for\ all\ t > 2009 \tag{5}$$

where

DS^P_{ijt} is projected future domestic supply of food commodity of j, in area i, in year t (in tons),

ΔDS_{ijt} denotes the difference between the projected supply and the real future demand of food commodity, j, in area i, in year t (in tons).

The projected future domestic supply of food commodity, DS^P_{ijt}, refers to the possible food production. At global level, total agricultural production is equal to the sum of domestic supply of food commodities, because production excess in one place is exported to another place where market demand exists. So theoretically DS^P_{ijt} in individual area is actually the amount of agricultural supply at market equilibrium, given economic and environmental constraints, such as income distribution and climate conditions (Gerbens-Leenes & Nonhebel, 2005; Linehan et al., 2012; Rosegrant et al., 2001; Tilman et al., 2011; Valin, Havlik, Mosnier, & Obersteiner, 2010).

From formulas (1) - (5) and (1.1) – (4.1), the difference between the average daily per-capita energy and desired daily per-capita energy taken from commodity j, in area i, in year t (in k-calories/person-day), Δc_{ijt}, can also be calculated using the formula (6).

$$\Delta c_{ijt} = c_{ijt}^{P} - c_{ijt}^{R}, \ for\ all\ t > 2009 \quad (6)$$

In order to calculate Δc_{ijt}, both obtaining a historical dataset of F_{ijt}^{A}, DS_{ijt}^{A}, C_{ijt}^{A}, and c_{ijt}^{A}, and estimating c_{ijt}^{R}, Pop_{it}^{P}, DS_{ijt}^{P}, MTC_{ijt}^{P}, and ATF_{ijt}^{P}, are critical. As mentioned in Section 1, three assumptions must hold in order to make the material flow approach effective. First, market forces, which according to economic theories affect people's ability to pay, do not affect people's real preference of diet. This assumption aligns with the hypothesis of the research. Failure to reject the hypothesis (from small Δc_{ijt} and ΔDS_{ijt}) means that the market is an effective tool to fulfill real demands. Second, inequality of both physical and economic accesses to food is assumed endogenous and homogenous within all aggregate demographic groups at country, regional, and global levels. At aggregate levels, this assumption means that MTC_{ijt}^{P}, and ATF_{ijt}^{P} is an average result of access distribution. Third, for applying the material flow approach, freer trade than status quo is assumed globally. This assumption means that, under less tariff burden, food commodity flows more freely to market where demand is unfulfilled, leading to more accurate measures of ΔDS_{ijt}, a term that is a consequence after international trade.

The following sections discuss sources of F_{ijt}^{A}, DS_{ijt}^{A}, C_{ijt}^{A}, c_{ijt}^{A}, Pop_{it}^{P}, and DS_{ijt}^{P}. Furthermore, I also discuss how I estimate MTC_{ijt}^{P} and ATF_{ijt}^{P} and construct scenarios of c_{ijt}^{R}.

3.2 DATA AND TWO CLIMATE-PRODUCTION SCENARIOS

This research groups countries and food types in order to yield neat analysis. For country grouping, the research uses countries and areas listed in FAOSTAT database. Two hundred and twenty five countries (or areas) are covered in the dataset; I group all countries into seven regions based on the size of population such that results can be shown at a simpler aggregate level with less significant population difference. These areas are for countries and regions $\boldsymbol{i}$. For constructing modernized diet, I use member countries of the Organisation for Economic Co‐operation and Development (OECD) to represent the developed world. Grouping of world countries is listed in Table 2 below.

Table 2. Grouping of World Regions

Region 1. Africa		
Algeria	Gabon	Nigeria
Angola	Gambia	Réunion
Benin	Ghana	Rwanda
Botswana	Guinea	Saint Helena, Ascension and Tristan da Cunha
Burkina Faso	Guinea-Bissau	Sao Tome and Principe
Burundi	Kenya	Senegal

Cameroon	Lesotho	Seychelles
Cape Verde	Liberia	Sierra Leone
Central African Republic	Libya	Somalia
Chad	Madagascar	South Africa
Comoros	Malawi	Sudan (former)
Congo	Mali	Swaziland
Côte d'Ivoire	Mauritania	Togo
Democratic Republic of the Congo	Mauritius	Tunisia
Djibouti	Mayotte	Uganda
Egypt	Morocco	United Republic of Tanzania
Equatorial Guinea	Mozambique	Western Sahara
Eritrea	Namibia	Zambia
Ethiopia	Niger	Zimbabwe

Region 2. Caribbean, Central, and South America (CC&S America)		
Anguilla	Dominican Republic	Nicaragua
Antigua and Barbuda	Ecuador	Panama
Argentina	El Salvador	Paraguay
Aruba	Falkland Islands (Malvinas)	Peru
Bahamas	French Guiana	Puerto Rico
Barbados	Grenada	Saint Kitts and Nevis
Belize	Guadeloupe	Saint Lucia
Bolivia (Plurinational State of)	Guatemala	Saint Vincent and the Grenadines
Brazil	Guyana	Suriname
British Virgin Islands	Haiti	Trinidad and Tobago
Cayman Islands	Honduras	Turks and Caicos Islands
Chile	Jamaica	United States Virgin Islands
Colombia	Martinique	Uruguay
Costa Rica	Mexico	Venezuela (Bolivarian Republic of)
Cuba	Montserrat	
Dominica	Netherlands Antilles	

Region 3. China
China

Region 4. Europe		
Albania	Greece	Portugal
Andorra	Holy See	Republic of Moldova
Austria	Hungary	Romania
Belarus	Iceland	Russian Federation
Belgium	Ireland	San Marino
Bosnia and Herzegovina	Italy	Serbia
Bulgaria	Latvia	Slovakia
Croatia	Liechtenstein	Slovenia
Czech Republic	Lithuania	Spain
Denmark	Luxembourg	Sweden
Estonia	Malta	Switzerland
Faroe Islands	Monaco	The former Yugoslav Republic of Macedonia
Finland	Montenegro	kraine
France	Netherlands	United Kingdom
Germany	Norway	
Gibraltar	Poland	

Region 5. India
India

Region 6. Northern America		
Bermuda	Greenland	United States of America
Canada	Saint Pierre and Miquelon	

Region 7. Rest of Asia		
Afghanistan	Kiribati	Qatar
American Samoa	Kuwait	Republic of Korea
Armenia	Kyrgyzstan	Samoa
Australia	Lao People's Democratic Republic	Saudi Arabia
Azerbaijan	Lebanon	Singapore
Bahrain	Malaysia	Solomon Islands
Bangladesh	Maldives	Sri Lanka
Bhutan	Marshall Islands	Syrian Arab Republic
Brunei Darussalam	Micronesia (Federated States of)	Tajikistan
Cambodia	Mongolia	Thailand
Cook Islands	Myanmar	Timor-Leste
Cyprus	Nauru	Tokelau
Democratic People's Republic of Korea	Nepal	Tonga
Fiji	New Caledonia	Turkey
French Polynesia	New Zealand	Turkmenistan
Georgia	New Zealand	Tuvalu
Guam	Niue	United Arab Emirates
Indonesia	Northern Mariana Islands	Uzbekistan
Iran (Islamic Republic of)	Occupied Palestinian Territory	Vanuatu
Iraq	Oman	Viet Nam
Israel	Pakistan	Wallis and Futuna Islands
Japan	Palau	Yemen
Jordan	Papua New Guinea	
Kazakhstan	Philippines	

OECD Countries		
Australia	Hungary	Portugal
Austria	Iceland	Republic of Korea
Belgium	Ireland	Slovakia
Canada	Israel	Slovenia
Chile	Italy	Spain
Czech Republic	Japan	Sweden
Denmark	Luxembourg	Switzerland
Estonia	Mexico	Turkey
Finland	Netherlands	United Kingdom
France	New Zealand	United States of America
Germany	Norway	
Greece	Poland	

For food commodity grouping, this research follows the FAO's commodity grouping definition for both crop and livestock listed in FAOSTAT's Food Balance Sheet. Twenty highly integrated food categories with thirteen from crops primary equivalent and seven from livestock and fish primary equivalent shown in Table 3 below (FAOSTAT.2014). These food groups are for food types $\boldsymbol{j}$.

Table 3. Food Commodity Groups

Crop Primary Equivalent	Livestock and Fish Primary Equivalent
1. Alcoholic Beverages	1. Animal Fats
2. Cereals - Excluding Beer	2. Aquatic Products, Other
3. Fruits - Excluding Wine	3. Eggs
4. Oilcrops	4. Fish, Seafood
5. Pulses	5. Meat
6. Spices	6. Milk - Excluding Butter
7. Starchy Roots	7. Offals
8. Stimulants	
9. Sugar & Sweeteners	
10. Treenuts	
11. Vegetable Oils	
12. Vegetables	
13. Sugarcrops	

In addition, this research constructs the material flow with three sources of data in order to measure ΔDS_{ijt} and Δc_{ijt} toward 2050.

1. Global population estimate per area, during year 1961 and 2050 (FAOSTAT.2014; The World Bank Group, 2014), used for $\boldsymbol{Pop_{it}^{A}}$ and $\boldsymbol{Pop_{it}^{P}}$.
2. Food consumption (tonnes), used for $\boldsymbol{F_{ijt}^{A}}$, and domestic supply (tonnes), used for $\boldsymbol{DS_{ijt}^{A}}$, from Commodity Balances Sheet and Food consumption (k-cal/capita-day), used for $\boldsymbol{c_{ijt}^{A}}$ from Food Supply Sheet of FAOSTAT, during 1961 and 2009 (FAOSTAT.2014)
3. Future production estimates under two scenarios, used for $\boldsymbol{DS_{ijt}^{P}}$, represent current climate condition and under 4° Celsius increase- until 2050(Alexandratos & Bruinsma, 2012; Linehan et al., 2013)

There exists relatively little research studying future food production globally covering all food commodity groups comprehensively toward 2050 and considering climate change scenarios. The exceptions are two studies: a). *"World Agriculture toward 2030/50"* from the FAO (Alexandratos & Bruinsma, 2012) and b). *"Global food production and prices to 2050"* from Australian Bureau of Agricultural and Resource Economics and Sciences under Australian Government's Department of Agriculture, Fishery, and Forestry (ABARES) (Linehan et al., 2013). Although the two studies also focus on main food groups, they also provide estimates on non-main food groups. A summary of future agricultural production change estimates is shown in Table 4.

Table 4. Annual Agricultural Production Change under Two Climate Scenarios, 2009-2050

Estimated production growth rates per annum, 2009-2050			
Scenario:	Present Climate Condition	4-6℃ Increase	Present Climate Condition
Source:	ABARES	ABARES	FAO
Food Category			
Alcoholic Beverages	1.010	1.006	1.007
Cereals - Excluding Beer	1.013	1.008	1.009
Fruits - Excluding Wine	1.008	1.005	1.007
Oilcrops	1.010	1.006	1.013
Pulses	1.010	1.006	1.007
Spices	1.010	1.006	1.007
Starchy Roots	1.008	1.005	1.010
Stimulants	1.010	1.006	1.007
Sugar & Sweeteners	1.010	1.006	1.013
Treenuts	1.010	1.006	1.007
Vegetable Oils	1.008	1.005	1.007
Vegetables	1.008	1.005	1.007
Sugarcrops	1.010	1.006	1.013
Animal Fats	1.010	1.006	1.009
Aquatic Products, Other	1.010	1.006	1.009
Eggs	1.010	1.006	1.011
Fish, Seafood	1.010	1.006	1.009
Meat	1.016	1.016	1.013
Milk - Excluding Butter	1.016	1.016	1.011
Offals	1.016	1.016	1.009

3.3 UTILIZATION ASSUMPTIONS AND DIET SCENARIOS

To measure Δc_{ijt} and ΔDS_{ijt}, it is important to make proper assumptions of MTC_{ijt}^{P} and ATF_{ijt}^{P} for future utilization processes. According to historical data, MTC_{ijt}^{A} and ATF_{ijt}^{A} were quite consistent at global and regional levels, especially in the past 10 years. At country level, data shows huge fluctuations mainly due to missing country-level data and location-specific diet, which means an entire commodity group does not appear in the diet of the entire area, both at regional and country levels. The assumptions of MTC_{ijt}^{P} and ATF_{ijt}^{P} deal with the two problems.

MTC_{ijt}^{P} and ATF_{ijt}^{P} firstly use the average of MTC_{ijt}^{A} and ATF_{ijt}^{A} in the past ten years at country, region, and global levels for all future years until 2050. The assumption is supported by the empirical evidence in the past ten years especially at the very aggregate level. However, missing data is still an issue with this approach. So secondly, if MTC_{ijt}^{P} or ATF_{ijt}^{P} at regional level is zero, I replaced them with data at global level, and used the values of the regional-level average for the zeros at country level. This data adjustment approach is based on a consideration that diet behavior and utilization practices associated with it in one area should be similar to surrounding areas'. With MTC_{ijt}^{P} or ATF_{ijt}^{P} available, estimating the relationship between calorie consumption and domestic supply of agriculture commodities become possible. Next, I constructed diet scenarios.

In this paper, two future diet scenarios are constructed to obtain future per-capita calorie consumption, c_{ijt}^{R}, for all area and food commodity groups. The first scenario, eat-as-usual-2009, assumes that populations in all areas have the same diet behavior show by 2009 data through 2050. The second scenario, eat-like-OECD, assumes that populations in less developed countries of non-OECD group will gradually shift their diet toward the average of populations in the developed countries of OECD group during 2009 - 2050, while populations in the OECD group will remain with the same diet of 2009. Both scenarios, with a five-year interval, are summarized in **Table 5**.

Table 5. Future Scenarios of Global Diet, 2009 - 2050

Eat-as-usual-2009									
Commodity Groups (k-calories per capita-day)	**2009**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Alcoholic Beverages	66.7	76.8	85.6	94.8	104.3	114.1	124.1	134.4	144.8
Cereals - Excluding Beer	1291.8	1251.7	1218.0	1184.2	1150.5	1117.0	1083.9	1051.2	1019.0
Fruits - Excluding Wine	2.0	2.2	2.4	2.5	2.7	2.8	3.0	3.1	3.3
Oilcrops	55.9	55.7	55.5	55.4	55.2	55.1	54.9	54.7	54.5
Pulses	62.2	60.6	59.0	57.1	54.9	52.5	49.8	46.9	43.7
Spices	9.2	9.0	8.8	8.5	8.2	8.0	7.7	7.4	7.1
Starchy Roots	136.3	132.1	128.4	124.4	120.0	115.2	109.8	103.7	97.0
Stimulants	6.7	8.5	10.0	11.5	13.1	14.7	16.3	17.9	19.6
Sugar & Sweeteners	224.4	253.5	278.1	303.0	328.1	353.5	379.1	404.9	431.0
Treenuts	14.4	16.2	17.8	19.3	20.9	22.5	24.2	25.8	27.5
Vegetable Oils	276.9	307.0	332.5	358.4	384.7	411.4	438.4	465.7	493.2
Vegetables	87.3	85.0	83.5	82.4	81.6	81.1	81.0	81.3	82.0
Sugarcrops	3.6	3.2	2.8	2.3	1.9	1.4	1.0	0.5	0.0
Animal Fats	60.5	69.9	78.0	86.2	94.6	103.2	112.0	120.8	129.9
Aquatic Products, Other	1.8	1.6	1.5	1.4	1.2	1.1	1.1	1.0	0.9
Eggs	35.0	36.7	38.3	40.1	42.0	44.2	46.5	49.0	51.7
Fish, Seafood	33.1	35.8	38.1	40.6	43.2	45.9	48.7	51.7	54.7
Meat	230.3	243.8	256.2	269.8	284.4	300.2	317.0	334.8	353.7
Milk - Excluding Butter	133.8	153.2	169.7	186.5	203.6	220.9	238.4	256.2	274.2
Offals	6.7	6.8	6.9	7.0	7.2	7.3	7.5	7.7	7.9

Eat-like-OECD									
Commodity Groups (k-calories per capita-day)	**2009**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Alcoholic Beverages	66.7	65.0	63.8	62.7	61.7	60.8	60.0	59.3	58.7
Cereals - Excluding Beer	1291.8	1291.5	1290.7	1289.5	1287.9	1285.8	1283.4	1280.6	1277.5
Fruits - Excluding Wine	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Oilcrops	55.9	55.9	55.9	55.9	56.0	56.0	56.2	56.3	56.5
Pulses	62.2	63.6	64.7	65.8	66.9	68.0	69.1	70.2	71.2
Spices	9.2	9.3	9.4	9.5	9.5	9.5	9.6	9.6	9.6
Starchy Roots	136.3	138.1	139.9	142.0	144.3	146.8	149.5	152.4	155.5
Stimulants	6.7	6.6	6.5	6.4	6.3	6.2	6.1	6.0	6.0
Sugar & Sweeteners	224.4	223.3	222.5	221.7	221.0	220.2	219.5	218.7	218.0
Treenuts	14.4	14.3	14.2	14.1	14.0	13.9	13.8	13.7	13.6
Vegetable Oils	276.9	275.2	273.9	272.7	271.5	270.5	269.6	268.8	268.0
Vegetables	87.3	85.5	84.1	82.6	81.0	79.5	78.0	76.4	74.9

Sugarcrops	3.6	3.7	3.8	3.8	3.9	3.9	4.0	4.0	4.0
Animal Fats	60.5	59.6	58.9	58.2	57.5	56.8	56.2	55.6	55.0
Aquatic Products, Other	1.8	1.8	1.7	1.6	1.6	1.5	1.4	1.4	1.3
Eggs	66.7	65.0	63.8	62.7	61.7	60.8	60.0	59.3	58.7
Fish, Seafood	1291.8	1291.5	1290.7	1289.5	1287.9	1285.8	1283.4	1280.6	1277.5
Meat	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Milk - Excluding Butter	55.9	55.9	55.9	55.9	56.0	56.0	56.2	56.3	56.5
Offals	62.2	63.6	64.7	65.8	66.9	68.0	69.1	70.2	71.2

Because no existing data for estimating the real diet is available today, the assumption here is to equate area average to the diet of people who do not have access to market.

4. RESULTS & ANALYSIS

4.1 FUTURE PRODUCTION AND DIET-BASED DEMAND

Figure 5 shows the both historical and future estimates for global aggregate calorie consumption and production under two climate scenarios. While both scenarios of future production estimates, one with current climate conditions and one with temperature increase at 4-6℃ compared to pre-industrialization level, show continuous growth from historical patterns, both diet scenarios show even higher real demands. Although all the trajectories of aggregate calorie volume show significant increases in Figure 5, Figure 6 conveys quite a different future.

Figure 5. Global Calorie Consumption & Production Volume

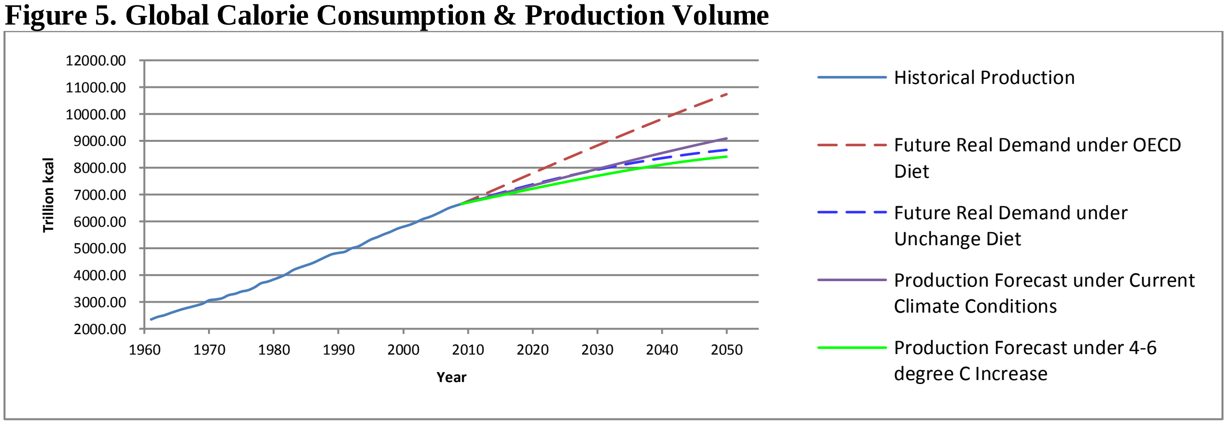
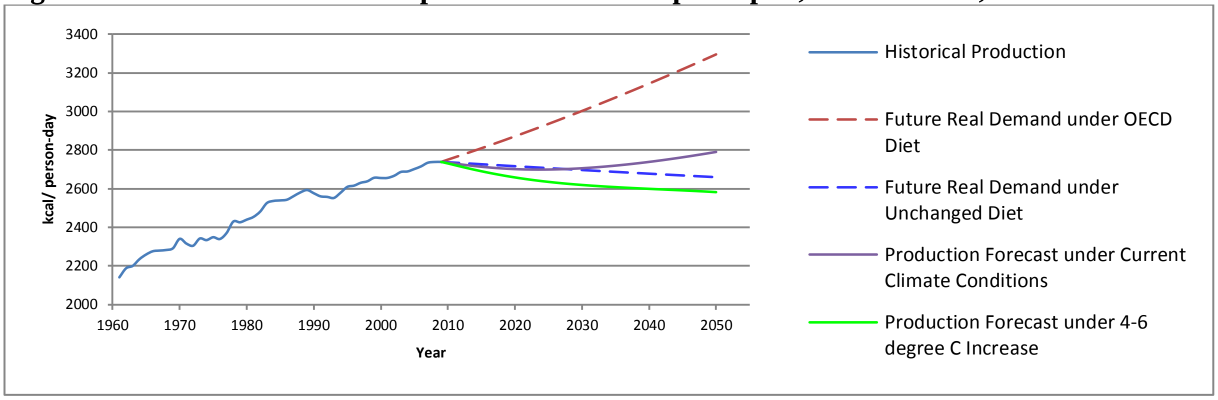


Figure 6 shows both historical global per-capita calorie consumption and future estimates of production and real demand under the same climate scenarios. On the per-capita basis, both production scenarios do not outgrow population expansion. If current climate conditions remain, global food production roughly yields the same amount of calories on the per-capita basis, while under the 4-6℃ increase scenario, per-capita production of calorie decreases noticeably. The trajectories of future real demands hold quite different patterns. The real per-capita demand under globally unchanged diet decreases slightly, while the real per-capita demand under the westernized diet increases significantly. These gaps do not occur homogeneously among all commodity groups. The following section quantifies these differences.

Figure 6. Global Calorie Consumption & Production per capita, All Scenarios, 1961 to 2009

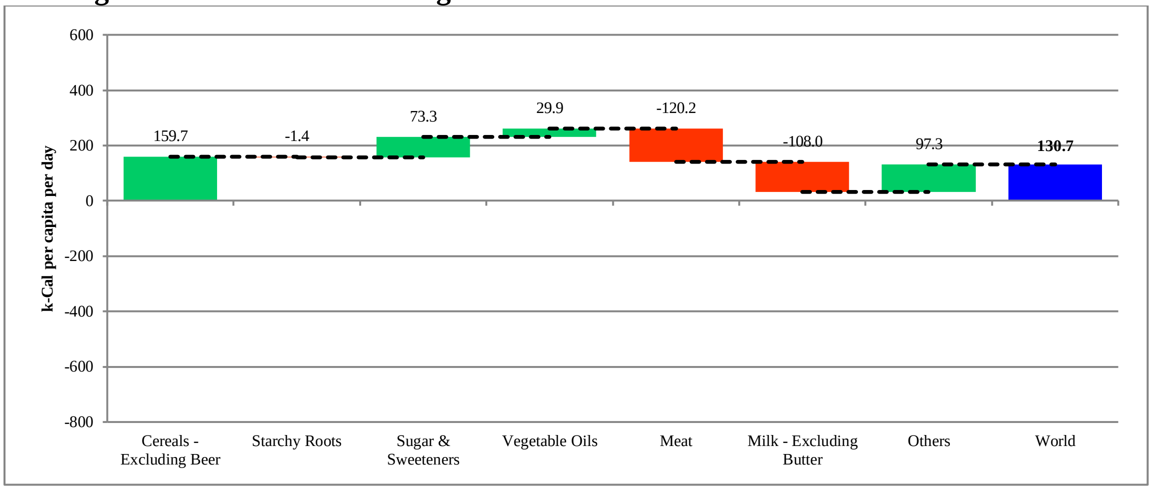


4.2 GAPS BETWEEN PRODUCTION AND REAL DEMAND

Figure 7 shows the gaps between the real demands and forecasted supply of calories in major food groups in 2050. Fourteen food commodities are summaries in "Others" for better figure presentation.

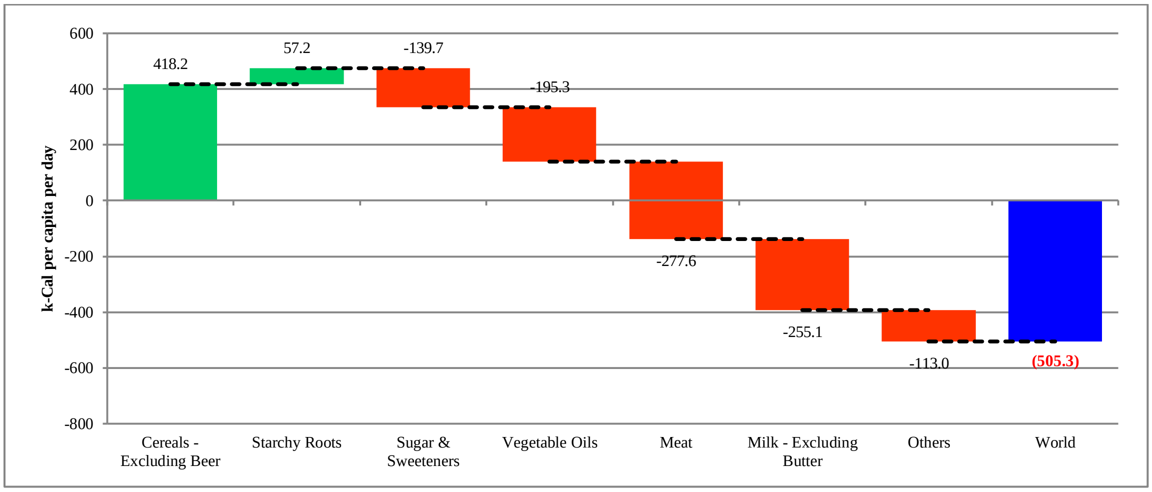
Figure 7. Gap between Real Demand and Forecasted Supply in 2050

Figure 7-1. Scenario: Unchanged Diet under Current Climate



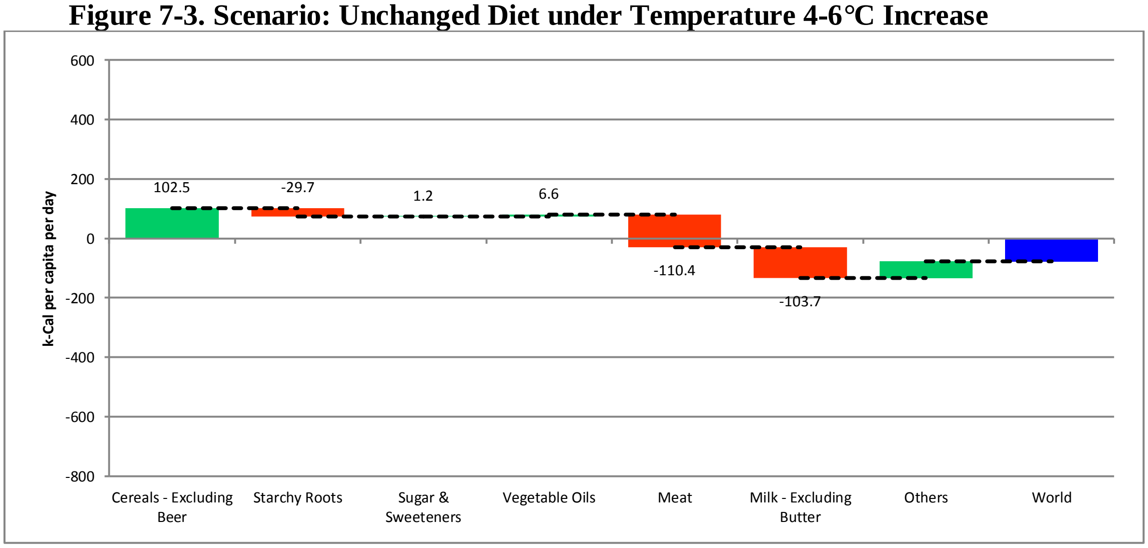
The Figure 7-1 demonstrates the most conservative outlook in the model, showing a slight surplus of 130.7 k-calories/person-day compared to 2009 average. Cereals (159.7 k-cals/person-day), Sugar & Sweeteners (73.3 k-cals/person-day), and Others (97.3 k-cals/person-day) principally contribute to the surplus, while Meat (-120.2 k-cals/person-day) and Milk – Excluding Butter (-108.0 k-cals/person-day) offset half of it. Differences in Starchy Roots and Vegetable Oils are relatively insignificant.

Figure 7-2. Scenario: Shifting Diet under Current Climate



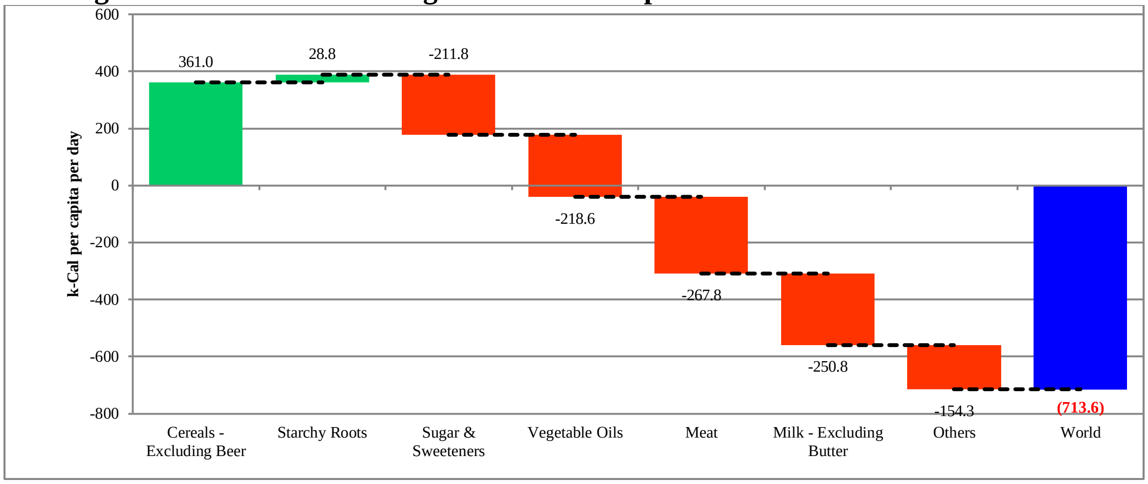
The Figure 7-2 demonstrates the inability of global food systems to fulfill a shifting diet with mild climate conditions, resulting a large deficit of -505.3 k-calories/person-day compared to 2009 average. Cereals (418.2 k-cals/person-day) and Starchy Roots (57.2 k-cals/person-day) together still contribute measurable surpluses. However, large deficits, added up to more than twice the surpluses, occur in all other food groups. Compared to Figure 6-1, which is under the same climate conditions for production globally, people eat less Cereal and Starchy Roots and prefer to consume much more other foods, especially Sugar & Sweeteners and Vegetable Oils.

Figure 7-3. Scenario: Unchanged Diet under Temperature 4-6℃ Increase



The Figure 7-3 shows that, taking climate change at 4-6℃ Increase scenario into account, even if the diet remains the same globally, the food production systems still fails in fulfilling population's real demand, yielding a deficit of -77.5 k-calories/person-day compared to 2009 average. All food groups show little deviation from the 2009 average. Cereals (102.5 k-cals/person-day) contributes the most surplus in the scenario, but the surplus, similar to the Figure 6-1, is offset by Meat (-110.4 k-cals/person-day) and Milk – Excluding Butter (-103.7 k-cals/person-day).

Figure 7-4. Scenario: Shifting Diet under Temperature 4-6°C Increase



The Figure 7-4 demonstrates the worse scenario of all, leading to a large deficit of -713.6 k-calories/person-day compared to 2009 average. Although production in all food groups in this scenario are lower than ones in the current climate scenario, Cereals (361.0.5 k-cals/person-day) and Starchy Roots (28.8 k-cals/person-day) are still abundant from the demand perspective. A shift towards a westernized diet widens the gaps in all other food groups, especially Sugar & Sweeteners (-211.8 k-cals/person-day), Vegetable oils (-218.6 k-cals/person-day), and Others (-154.3 k-cals/person-day).

4.3 DISCUSSION

In agreement with the literature, results from this study show that rising temperature does not significantly undermine the ability of the global food production systems to maintain basic global food security, based on a measurement of 2,000 k-cals/person/day. However, climate change impact will affect the choices of food that people are likely to have in the future. Considering both diet-based demand estimates (current diet and OECD diet), agriculture production will not meet average people's demand for the most part, especially under higher climate change impact scenarios (temperature 4-6°C Increase)

Considering these results, five points concerning the model and analysis are worth further consideration: a. Underestimation of food security, b. Data accuracy, c. Diet behaviors, and d. Access inequality and distribution issue.

a. Underestimation of food security

The model uses the 2009 diet as the benchmark for both the measurement of the average OECD diet, which in the diet-shifting scenario is the number towards which developing countries gradually shift, and for the measurement of the unchanged diet of global countries in the other diet scenario. While the assumption is that, in 2009, global food supply equals real demand, it does not reflect real conditions. If the 2009 status quo real demand is higher than the supply, at least in some food commodity groups, then the model very likely underestimates the gaps it projects. As there are no comprehensive studies that estimate diet values in and across all countries worldwide, I choose to use two scenarios that might yield a possible range of the future food security outcomes, while not overstating it.

b. Data accuracy

Missing data from the sources are mostly associated with developing countries. Thus, there is no fact-based estimate for these countries, and a reasonable approximation approach is to refer these countries' diet averages to their regional average. Improved dataset can help yield better understanding of these countries' food security outcome, especially in countries where food security issue is more severe.

c. Diet behaviors

This research employs only two diet scenarios. In the diet-shifting scenario in the model, the change of diet in developing counties to the OECD's average is linear over time toward 2050, while the diet in OECD countries remains static. In the diet-static scenario, diet in all countries remains static. These diet patterns are oversimplified since there is evidence that, diet behaviors in the OECD countries have evolved in different directions in the past decade. While there has been significant reduction of calorie intake in European countries because of less meat and dairy products and more vegetable, fruit, and entertainment food consumption, in the US calorie intake has remained high. Further examination of changes in patterns of food consumption maybe necessary to generate more accurate future estimations (e.g. such as for example, applying Kuznets Curve on the food consumption).

In addition, diet change most likely does not occur in a linear pattern, and even an aggregate linear pattern would include quite dynamic changes in individual food commodity groups. For example, China experienced strong increase in consumption of meat, eggs, sugar, and vegetable oils since the late 70's and vegetables since late 80's, but it also kept flat or decreasing consumptions of many other food commodities, such as starchy roots and cereals. This means, imposing a uniformed pattern could yield biased outcomes. Due to unavailable data and studies on diet patterns globally, such simplified patterns have to be made.

d. Access inequality and distribution issue

In the "Shifting Diet under Temperature 4-6°C Increase" scenario, substantial surpluses and deficits coexist in different food commodity groups. These gaps likely reflect access inequality in food security issues globally in the future. With an economic equilibrium approach, which yields future production estimates, consumer's willingness to pay (and ability to pay) has been taken into account. What is left out from the economic equilibrium approach are the preference of those who do not hold access to food, economically and physically. The assumption to the average diet of those who are poor enough is made based on the average of those who have access to food. While more research is necessary to understand the diet preference of those who do not have market access, the current assumption of the poor's diet might be reasonable, if not too conservative. However, the large gaps indicate that future inequality of food distribution may widen, as rich countries and people would consume all preferred food, leaving poor countries and people with less or no choice. Although this research does not address food distribution issues, the results could incur more severe food security outcomes than what is conventionally believed, especially from the production perspective.

5. CONCLUSION

The estimates of global real food demands based on the material flow approach such as the one presented in this thesis deviate significantly from the future production estimates that are based on the economic equilibrium approach. The results suggest that addressing global food security issues requires re-thinking through the processes from production to diet. The study shows that climate change and westernized diet impose significantly different impacts among food commodities- large oversupplies in cereals and significant shortage of supply in other food commodity groups. These gaps of projected supply and demand of food not only reveal severe issues of inequality of access for the global food security in the future, especially in developing countries, but also suggest the need for significant adjustments in the food production and utilization processes. The heterogeneity of both climate and diet-shifting impacts on global food systems also means that focusing on food production or calorie supply alone would fail the course of global food security in the long run.

While most of the current literature positions production at the center of food security issues globally, this research model bridges current scholarship centered on production and market to human's real needs considering average diet and utilization processes under climate change, instead of people's ability to pay for food. Although the scenarios constructed in the study are limited by available data and literature, four main points can be drawn from the study.

Climate change will limit people's food choices, especially in developing world. As climate change unequally undermines the food systems' ability to produce food, the levels of scarcity of different food commodities will vary. Although it is likely that there will be sufficient food supply compared with the 2,000 k-cal/person-day standard, poor people and countries will likely suffer the most and be forced to consume less preferred food.

Healthy and preference-based diet should be the center of food security, not the amount of calorie. No single region in this research has experienced an average per-capita calorie intake of less than 2,000 k-cal/person-day, but there are still 842.3 million people who are undernourished in 2011 (FAO, 2012) .

This fact indicates that distribution of food is more of an issue than production in combatting global food insecurity. However, according to FAO's definition: "…access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life," having sufficient amount of calorie supply does not necessarily guarantee food security, either. But in most of operational measurements, discussions about food security separate diet and preferences from the quantitative amount of calorie intake. To explore the ultimate question of food security, this research attempts to re-focus food security to include diet and preference, bringing health outcomes of certain diet behaviors to the center of food security discussions. Thus, more research in understanding how diet evolves, how people determine food preferences, and how the choices and lack of choice affect health outcomes, is necessary.

Significant adjustments in food production systems are necessary to achieve real "food security." Excess of supply in food commodities, such as cereals, results in further waste and adverse environmental impacts. Meanwhile, food production systems of many other food commodity groups do not fulfill the poor's dietary needs and preferences. Therefore, policy interventions to address the ineffectiveness of food systems in meeting needs for food security should focus on adjusting the production directly toward desired dietary and health outcomes, rather than on producing more tons, calories, and profits.

Innovations in the utilization processes may help close the gaps. Technology in utilization processes help achieve desired dietary outcomes and food preferences from less required supply. Such technology may include more efficient distribution system that shortens the duration of food transportation, better storage, or food processing facilities that reduce waste in making food. Emerging technology also includes using plants to simulate the tastes of animal proteins, such as vegetable mayonnaise manufactured from soybean. Such technological development breaks the boundary of food sources and tastes, making food preferences easier to be fulfilled.

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