Applying geo-spatial information for integrating crop, food, and nutrition for a healthier food system in rural Ethiopia

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AEZ	Agro-ecological Zones
AGP	α_1-acid glycoprotein
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
BMI	Body Mass Index
CRP	C-reactive protein
CSA	Central Statistics Agency (of Ethiopia)
DDS	Dietary Diversity Scores
EDHS	Ethiopia Demographic and Health Survey
FAAS	Flame Atomic Absorption Spectroscopy
FANTA	Food and Nutrition Technical Assistance Project
FFQ	Food frequency questionnaire
GLOP	Global Panel on Agriculture and Food Systems for Nutrition
GPS	Global Positioning System
HDDS	Household Dietary Diversity Score
HFIAS	Household Food Insecurity Access Scale
HH	Household
HLPE	High Level Panel of Experts on Food Security and Nutrition
ICFI	Infant and Child Feeding Index
IDDS	Individual Dietary Diversity Score
MDG	Millennium Development Goal
MREC	Medical Research Ethics Committee
MUAC	Mid-upper arm-circumference
NCDs	Non-Communicable Diseases
RS	Remote Sensing
SDG	Sustainable Development Goal
WHO	World Health Organization

Abstract

The world is facing a nutrition crisis. With nearly three billion people having low-quality diets and more than two billion lacking vital micronutrients (e.g., iron, zinc, vitamin A). The economic losses resulting from undernutrition are estimated to be as high as 11% of Gross Domestic Product in low and middle-income countries, annually. Improving the nutritional status of particularly women and children remains a key public health and development priority.

Over the last few decades, although food production has risen globally to significantly help reduce global hunger, access to food and healthy diets still remains a major concern, especially in developing countries. Majority of undernourished people in those countries are smallholder farmers living in rural areas. The current global initiative, Sustainable Development Goal (SDG-2) targets ensuring universal access to safe and nutritious food for all and ending all forms of malnutrition by 2030. If the existing trend of reduction in undernutrition prevalence continues to remain, most developing countries including Ethiopia are less likely to achieve the target. Thus, a context-specific assessment of the existing food system at various scales is important.

Therefore, the present study aims to conduct a comprehensive assessment of diet quality throughout the food system that encompass interrelated activities from food production to consumption and evaluating the outputs of these activities through nutritional status assessment of children and women of child bearing age. The study identifies geographic areas at high risk of undernutrition with potential responsible factors at village, household and individual levels. These provide concerned government sectors and development partners with useful local level information to support informed decision to address nutritionally vulnerable people residing in rural Ethiopia.

1. INTRODUCTION

1.1. Background

With nearly three billion people having low-quality diets and more than two billion lacking vital micronutrients (e.g., iron, zinc, vitamin A), the world is facing a nutrition crisis (GLOP, 2016). In low and middle-income countries, the economic losses resulting from undernutrition are estimated to be as high as 11% of Gross Domestic Product annually (World Bank, 2018). Improving the nutritional status of particularly women and children remains a key public health and development priority. In Eastern Africa, 36% of children under five years in age are chronically undernourished (UNICEF/WHO/World Bank, 2018). Nutritional deficiency throughout this critical life-cycle is among the major causes of physical, cognitive, and social shortcomings later in life, perpetuating the intergenerational cycle of poor human development (Crookston *et al*., 2013; IFPRI, 2017).

Over the last few decades, although food production has risen globally to significantly help reduce global hunger (Gödecke *et al*., 2018; Pingali, 2012), access to food and healthy diets still remains a major concern, especially in Sub-Saharan Africa and parts of Asia (Headey and Ecker, 2013; FAO, 2017; IFPRI, 2017). Majority of undernourished people in those regions are smallholder farmers living in rural areas (FAO, 2014; Hirvonen *et al*., 2016). Therefore, the question as to how smallholder agriculture can be made more responsive to improve nutrition is crucial. However, evidence towards diversification of small-farm production to improve nutrition is inconsistent (Jones, 2017; Sibhatu & Qaim, 2018) and context specific (Ruel *et al*., 2018; Sibhatu *et al*., 2015).

Improving nutrition requires more than just increasing household access to food (Ruel *et al*., 2018). In most developing countries have been directed towards the UN's Millennium Development Goals (MDG) with a target of reducing the prevalence of underweight in children under five between 1990 and 2015 (Murracy, 2015). Accordingly, previous studies assessing food and nutrition security have focused on food availability or access that are mainly concerned with macronutrient (i.e. calorie and sometimes protein) intake, which only reflects the adequacy of the quantity of food consumed but paying little attention to micronutrient (diversified food) intake, which is critical to overall diet quality (Pingali, 2015; Sibhatu & Qaim, 2017). Furthermore, chronic undernutrition in children is a common problem also in areas with surplus crop production; as seen in west Gojam zone of Ethiopia (Motbainor *et al*., 2015; Teshome *et al*., 2009). This implies that isolated interventions would not solve the problem, and hence calls for a food systems-level understanding of problems and designing interventions.

The Ethiopian government has designed strategies to address food insecurity in vulnerable households and to improve nutrition, including the strategy of the government to treat nutrition as a multisectoral challenge and outlining a comprehensive range of approaches to address undernutrition (Gillespie *et al*., 2016; Regass, 2011; Motbainor *et al*., 2016). Despite the implementation of various interventions, food and nutrition insecurity as reflected by the high rates of childhood and maternal undernutrition remains a major public health challenge (Webb *et al*., 2018). The high agroecological diversity among and within regions suggests that a high level of heterogeneity may exist in both the prevalence and causes of undernutrition.

Agroecosystems have an important role in determining food insecurity status, especially for subsistence farmers (Atapattu *et al*., 2011). The study by Motbainor et al. (2016) and Alemu *et al*. (2017a) in northern Ethiopia indicated a significant variation in household food insecurity status among different agro-ecological zones (highland, midland and lowland) and reported inconsistent findings. Related studies by Haile *et al*. (2016) at the national level, Baye *et al*. (2013) in northern Ethiopia and Gebreyesus *et al*. (2015) in southern Ethiopia have shown that chronic malnutrition among children was characterized by non-random spatial distribution. However, identifying areas with a high risk within a general at-risk population is not an end in itself, it is equally important to understand the possible causes of observed spatial heterogeneity using geospatial information.

The food system consists of interconnected activities ranging from food production to consumption and the results of these activities (HLPE, 2017). This approach helps to better understand how the existing food system is functioning and to identify entry points to improve diet and nutritional status as well (Kennedy *et al*., 2018; van Berkum *et al*., 2018).

Therefore, the present study aims to conduct a comprehensive assessment of diet quality in selected rural villages of south Wollo zone, northern Ethiopia encompassing remote sensing-based estimate of food production and diversity, evaluating nutritional composition of available crops, conduct georeferenced household survey, and assess the dietary intake and nutritional status of children and women of reproductive age. In doing so, the study identifies geographic areas at high risk of undernutrition along with the potential responsible factors. These will provide potentially useful local level information on how to address nutritionally vulnerable households in rural Ethiopia.

1.2. Problem statement

Food and nutrition insecurity is a critical challenge affecting the overall development of Ethiopia. According to the Ethiopian Demographic and Health Survey (EDHS, 2016), about 38% of children less than five years of age are chronically malnourished, 56% are anemic and about 30% of women of reproductive age suffer from chronic energy malnutrition. In general, magnitude of malnutrition is worst in rural areas where more than three-fourth of the Ethiopian population lives. The prevalence of malnutrition presents a high level of regional heterogeneity, being the highest in the Amhara region that reports a stunting level of 46% (EDHS, 2016).

The country has made progress through a mix of targeted interventions called nutrition-specific (aimed at preventing or resolving defined nutrition problems in individuals) and nutrition-sensitive interventions for the whole population that deal with underlying causes like agriculture and food security, health, care, education, water and sanitation etc (Ruel *et al*., 2013; Webb *et al*., 2018; Gillespie *et al*., 2016). Of course, the latter is a recently introduced approach. Those different efforts have reduced the prevalence of stunting from 58% in 2000 to 38% in 2016. This figure is still unacceptably high. If the existing trend of reduction continues to remain, the country will be unable to achieve the 2030 target of the Sustainable Development Goal (SDG) of ending all forms of malnutrition. Part of the reason for slow progress lies in overlapping micronutrient deficiencies attributed to consumption of poor-quality diets during the critical life-cycles of human development where the demand of essential nutrients is critical (Webb *et al*., 2018; EDHS, 2016).

Agriculture plays a central role in both food availability and food quality, and is also the main source of income and livelihood in rural settings (CSA, 2014; Sibhatu and Qaim, 2017). Against this background, farm production diversity on these smallholders are often perceived as a potential approach to improve the dietary diversity of household diets and nutritional outcomes (Ruel *et al*., 2018; Jones *et al*., 2014; Remans *et al*., 2011). However, only few studies have assessed the relationship between farm diversity and dietary diversity as well as the possible interplay that may operate between the two (Jones *et al*., 2014; Koppmair *et al*., 2017; Sibhatu *et al*., 2015; Sibhatu and Qaim, 2018).

Even though nutrition is critical to human health, it is not systematically integrated in the assessment of food systems (Ruel *et al*., 2018). However, success of agricultural systems has continually been evaluated mainly on calorie-oriented metrics such as crop yields and economic output (CSA, 2017/18; Cochrane & Bekele, 2018; Clarke *et al*., 2017; Taffesse *et* *al*., 2013; Remans *et al*., 2011). These metrics do not reflect adequate diversity of nutrients necessary for a diet quality (Jones *et al*., 2014).

A human diet requires a number of nutrients in adequate amounts consistently. This can have significant implications for human health especially in locations where food is produced and consumed locally because of the limited availability of food from different sources able to provide with essential nutrients (Oliver and Gregory, 2015). In such systems, the nutritional value of many foods is markedly affected by the concentrations of essential nutrients available in major crops produced locally.

Furthermore, the nutritional composition of crops varies depending on crop variety and environmental conditions (FAO, 2017; Reguera *et al*., 2018; Hornick, 1992). Therefore, in addition to the share of crops in total agriculture diversity, studies suggest the importance of context-specific nutrient composition of available crops in terms of calories and specific micronutrients in order to make appropriate dietary recommendations at local level (Shively and Sununtnasuk, 2015; Wood *et al*., 2017; FAO, 2017).

However, there are limited agroecology-based studies relating environmental factors to nutritional outcome. The existing few studies again presented inconsistent findings with respect to the magnitude of household food insecurity status over the different agroecological zones (Motbainor *et al*., 2016; Alemu *et al*., 2017a). Additionally, little is known about the spatial distribution of women and child undernutrition. Only few studies have assessed the geographic correlates of stunting in children (Haile *et al*., 2016; Hagos *et al*., 2017); however, these studies mainly considered household level factors in assessing the causes of observed spatial heterogeneity. Thus, in-depth analysis and understanding of the spatial distribution of undernutrition in children and women with the potential contributing factors ranging from village to household and individual levels remains to be studied.

Improving diet is the ultimate goal of food systems at individual level (Brown, 2016; GLOP, 2016). Most studies assessing food and nutrition insecurity status have restricted to household level food access and household dietary diversity measures (Hagos *et al*., 2017; Alemu *et al*., 2017a). This diversity measure serves primarily as a proxy measure of socio-economic level of household members to diversify diets (Swindale & Bilinsky 2006a). However, intrahousehold distribution of calories and micronutrients is unlikely to be uniform across household members (Dillon *et al*., 2015). Therefore, individualized assessment of nutritionally vulnerable groups (i.e., early children and women of reproductive age) also deserve research attention.

1.3. Objectives

General objective: ***To evaluate diet quality from food production to nutrition status through integrating remote sensing, field survey and household data.***

Specific Objective 1: ***Combining remote sensing techniques and household survey to investigate relationship between production diversity and dietary diversity***

Research Questions:

How does remote sensing based village level estimate of production and production diversity differ along agro-ecologic zones?

Is production diversity related to dietary diversity?

Specific Objective 2: ***Determining nutrient composition of major crops***

Research Questions:

Does nutrient composition of major crops vary between the agro-ecologic zones?

Do estimates of relative bioavailability of major crops vary for iron, zinc and calcium?

Specific Objective 3: ***Assessing the level of household food insecurity status and intra-household food consumption***

Research Questions:

What is the level of household food (in)security status and adopted coping strategies?

How does the status of household and intra-household variability in food consumption look like?

What are the determinants of household food preference or choice?

Specific Objective 4: ***Evaluating diet quality through nutritional status assessment and identifying hotspot areas of malnutrition.***

Research Questions:

What is the prevalence of undernutrition in children and women of reproductive age?

Are the distributions of children and women undernutrition spatially correlated?

How do village, household and individual level characteristics are related to child and women nutritional status?

The research objectives will be going to assess diet quality over the entire food system, from food production and diversity at village level to household food insecurity status and individual nutrition status (as indicated in figure1).

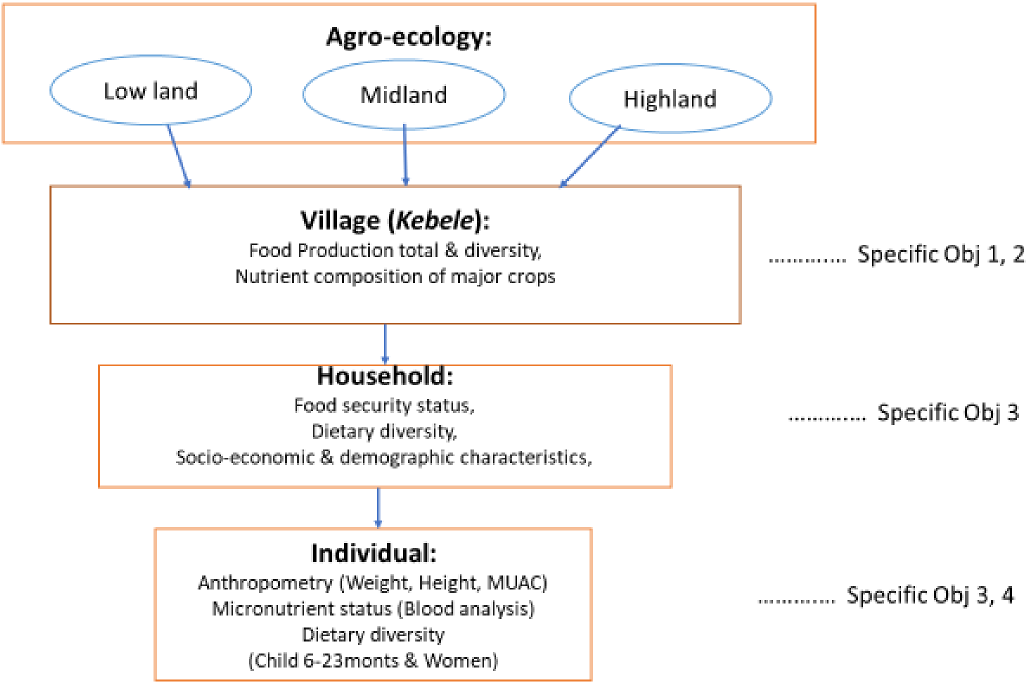


Figure 1: Work flow by objectives

1.4. Conceptual framework

The present study with its developed conceptual framework (Figure 2) will examine how existing food systems influence consumer choices and diets, thus impacting on nutrition and health in rural Ethiopia. There are diverse types of food systems, each with different contributions to global food security and with varying ways of working through food system supply chains (Pengue *et al*., 2018). Therefore, typologies of food systems (traditional, mixed and modern food systems) are useful because they illustrate the complexity of food systems and enable researchers and policy makers to take into account the diversity of systems when designing interventions adapted to a given context (Ericksen *et al*., 2010). In addition, food systems can be considered at different levels, from global to local and multiple food systems may co-exist in any given country simultaneously (HLPE, 2017).

With this understanding, the present conceptual framework considers the traditional food system because of its better representation of the rural Ethiopian context. Some of the characterizing features of traditional food systems include: (1) people generally living in rural areas; (2) the available food in the supply chain is mainly produced by smallholders locally and seasonally; (3) spending on food accounts for a large proportion of the household budget; (4) the surrounding food environment is dependent on local production and reliance on local informal markets; and (5) there is very little information in terms of food promotion/advertising and labelling and limited food processing (HLPE, 2017).

The conceptual framework assumes the following linkages:

- Agroecological zones are a spatial classification of the landscape into area units having similar agricultural and ecological characteristics that strongly influence agriculture practices and crop types (Hurni, 1998). The boundaries between adjacent agroecological zones are also boundaries between types of agricultural crops produced in a given geographic context (Hurni *et al*., 2016; Chamberlin & Schmidt, 2012). Thus, the characteristic of the agroecosystem is one of the factors that may create a spatial variation in the food availability (Simane *et al*., 2013).
- Food production diversity has the potential to influence the diversity of household diets and nutritional outcomes through the diversity of subsistence production (via direct consumption) and/or market-oriented production (indirect effects through increased agricultural income and greater food expenditures) (Jones, 2017). In addition, agricultural- and non-agricultural household income might impact dietary intake through purchase of diverse foodstuffs from the surrounding local food environment (Kanter *et al*., 2015).
- Household (HH) or individual food choice/preference is governed by the two-sided linkages between consumers' personal determinants and the surrounding food environment (HLPE, 2017). Consumer behaviour is clearly influenced by personal preferences, determined by a variety of interpersonal and personal factors including: taste, convenience, purchasing power (income), knowledge and skills, time, sociocultural and demographic factors. However, those consumers' choices are governed by the existing external food environment, which includes food availability and physical access, food price, food quality and safety, information through promotion and labelling (GLOP, 2016).
- The status of women is another key influencing factor for maternal and child dietary intake (Kanter *et al*., 2015; Jones *et al*., 2012). For instance, women's time allocation

to take care of the dependent household members, energy and decision-making power in relation to both agricultural production and household income (agricultural and non-agricultural based) are strongly linked to the nutrition and health status of a household. Therefore, it is specifically referenced in the household quality of care domain of the framework because it is a key pathway affecting nutrition, as per the modified UNICEF conceptual framework by Black *et al*. (2008). The role and impact of female empowerment is deeply rooted within the household where decision-making occurs around food acquisition, income, and dietary sources (Kanter *et al*., 2015).

- Improving the nutrition status of women and children is a high priority for public health and development in low-income countries (Black *et al*., 2008). Since undernutrition in women of reproductive age is strongly associated with poor birth outcome which leads to child undernutrition (Khan & Mohanty, 2018; Abdulahi *et al*., 2017). Diet quality assessment considers individual level diet diversity (Swindale & Bilinsky 2006a), nutritional status of children (anthropometric measurement) and women of reproductive age (anthropometric measurement and micronutrient status) to assess the overall outcome of food system.

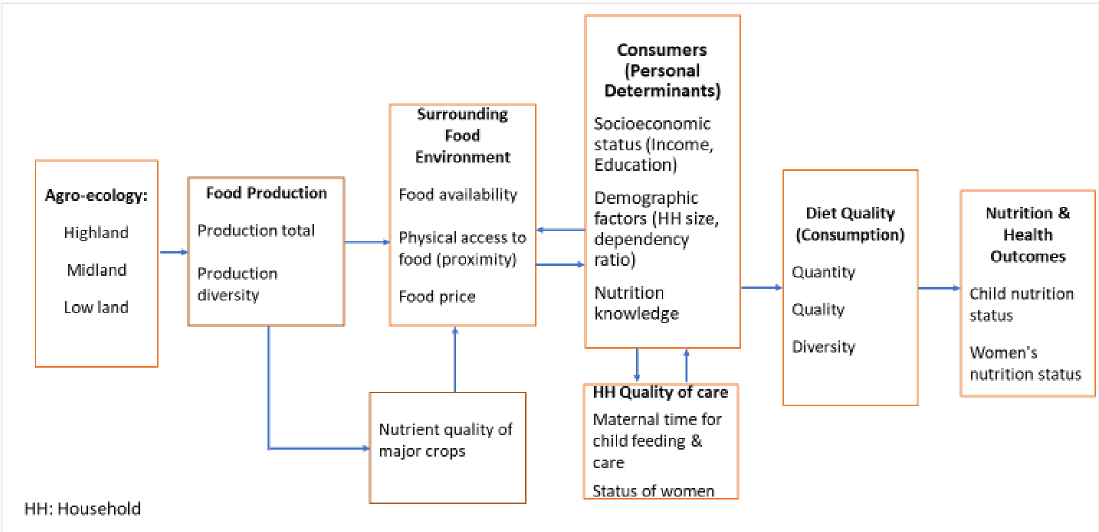


Figure 2: Conceptual framework that shows pathways from agricultural and food systems to nutrition and health. **Source:** Constructed based on: Global Panel on Agriculture and Food Systems for Nutrition (GLOP, 2016); High Level Panel of Experts on Food Security and Nutrition (HLPE, 2017); Herforth and Ahmed (2015); Jones (2017); Kanter *et al*. (2015); Pandey *et al*. (2016); Motbainor *et al*. (2016) and Alemu *et al*. (2017).

2. LITERATURE REVIEW

2.1. Food systems and diet quality

"A food system gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outcomes of these activities—namely nutrition and health status, socio-economic growth, and equity and environmental sustainability" (HLPE, 2017). A better knowledge of food systems, and of the interactions between food supply chains, food environments and consumer behaviour, is crucial to figure out why and how diets are changing and affecting people's nutritional status in a given context (GLOP, 2016). Such understanding is needed to identify ways of intervening to improve food security and nutrition.

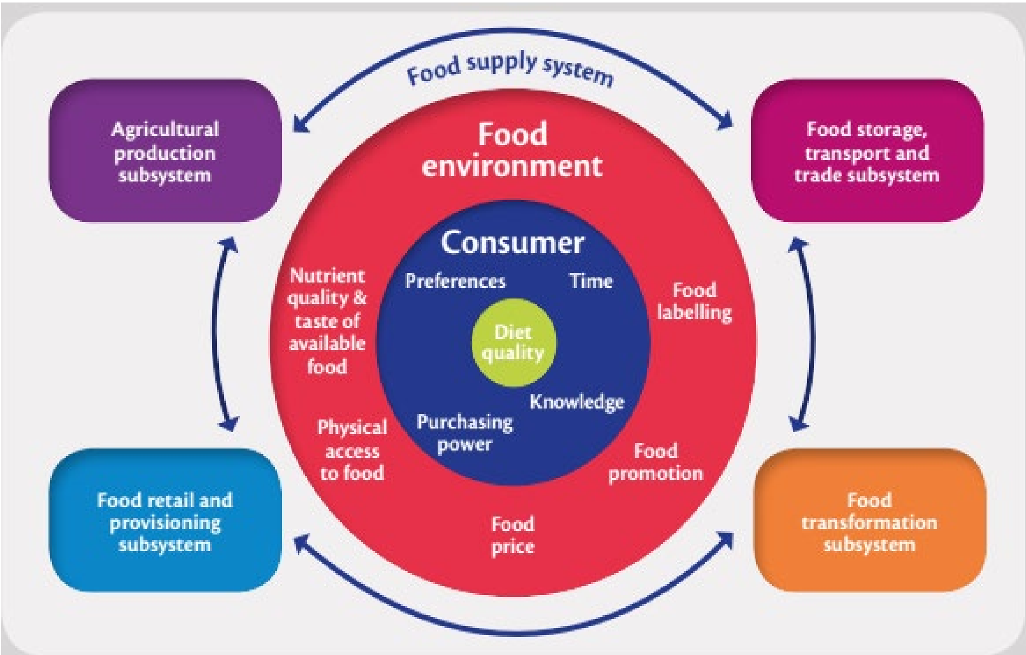


Figure 3: Drivers of food system - the links between diet quality and food systems. Source: Global Panel on Agriculture and Food Systems for Nutrition (GLOP, 2016).

Food environment refers to the physical, economic, political and socio-cultural surroundings, opportunities and conditions that create everyday prompts, shaping people's dietary preferences and choices as well as nutritional status (Swinburn *et al*., 2014; Belon *et al*., 2016). It serves as an interface that mediates the acquisition of foods by people within the wider food system. For producers and rural residents, the food environment consists of the on-farm foods they produce (Powell *et al*., 2015); in addition to their local markets (Herforth & Ahmed, 2015).

Consumer behavior is aimed at understanding why, when, where, and how people consume certain foods or diets, which is important in nutrition intervention (Herforth & Ahmed, 2015). Diet quality is influenced by consumer purchasing power, knowledge, preference. However, the way income is expended is in turn influenced by food environments, which provide the options from which people make decisions about what to eat. In addition, food environments are in turn influenced by broader food supply systems, which themselves are affected by many drivers of change including agriculture production subsystem (GLOP, 2016).

Diet quality and agriculture production subsystem

Food systems are activities whose ultimate goal is individual food consumption (Brown, 2016). Given that many countries are experiencing a multiple burden of malnutrition (undernutrition, overweight and micronutrient deficiency) that pose a question to how well the existing food systems are functioning to ensure consumers dietary needs. Quality diet includes a diversity of foods that are safe and provide appropriate levels of energy and essential micronutrients (GLOP, 2016). Therefore, to end malnutrition in all its forms, improving diet quality in the food systems is crucial.

Agricultural production provides foods that form the basis of the quantity and diversity of products available for human consumption (GLOP, 2016). Therefore, the diversity of local production affects local diets, particularly when producers consume their own production. In such condition, increasing on-farm diversity can have a strong impact on dietary diversity provided that the linkages to more distant markets are weak (Sibhatu *et al*., 2015). However, when food is sold on to markets far away from the location of production and where producers do participate in markets, the role of on-farm production diversity is less significant in contributing to improved diet quality. On the other hand, the diversity that is available to non-farm households is a function of a combination of local, national and global markets, not what is just produced locally (Remans *et al*., 2014).

Types of food system

The typology a food system covering both food supply chains and food environments will help to pinpoint the strengths and weaknesses of each type of food system, as well as the challenges and opportunities they face, and to design context-specific interventions. High Level Panel of Experts on Food Security and Nutrition (HLPE, 2017) identified three broader types: traditional, mixed and modern food systems. In traditional food systems people usually live in rural areas where their diets rely primarily on locally grown staple grains that contain insufficient amounts of protein and micronutrients. People often lack appropriate infrastructure to access distant markets and thus they are limited to local daily and weekly markets. Foods are often not monitored for quality and safety. As already mentioned, in such systems there is also very little food promotion or information.

Mixed food systems represent people living in peri-urban and urban areas and having greater incomes than in traditional food systems. People still have access to local markets, but also to supermarkets that have a wide variety of processed, packaged and fresh foods all year long. However, with the availability and popularity of processed foods, there is an increased intake of saturated and trans fats and sugar and such dietary changes result in an increasing incidence of overweight and obesity and lead to an increased incidence of, and morbidity from, non-communicable diseases (NCDs) such as cardiovascular disease and diabetes (HLPE, 2017).

In modern food systems, a higher proportion of people tend to live in urban areas, have greater incomes and various food choices. Food is produced often far from where consumers live. Increases in income and education are likely to make people more aware of the relationship between diet, nutrition and health. In addition, the increased access to, and quality of medical care leads to decreased morbidity and even longer lifespans (HLPE, 2017).

In summary, the food system typology described illustrate the complexity and diversity of the problems and challenges faced by the world's current food systems. For instance, as we move from traditional to the modern food system, a decrease in undernutrition prevalence, the food demand of household budget decreases, In the contrary, an increase in the number of food choices, increase in food processing and packaging, increase in year-round availability of food products owing to better food preservation/storage facilities, and the prevalence of obesity and NCDs increase as well. Therefore, the food system elements' interaction and typologies proposed attempt to consider this complexity when designing pathways towards more sustainable food systems that enhance food security, nutrition and health.

2.2. Diets and food system in Ethiopia

Food systems can be considered at different scales ranging from global to local levels with simultaneous existence of multiple food systems within a given country (HLPE, 2017). Ethiopia is a highly diverse country in terms of rural-urban gradients, agroecology, population, and food cultures. For instance, cereals are the main staple in the north, root crops are the main staple in part of the south, and animal-sourced foods are common among pastoralists (Gebru *et al*., 2018). Regardless of the commonalities in the dietary quality gaps observed at the national level, dietary cultures and tastes differ strongly between and within regions and populations and across seasons.

Studies have indicated that the existing food environment in Ethiopia is changing with various factors. Regarding rural and urban food environments, a significantly higher children's dietary diversity is observed in urban areas (EDHS, 2016). The study by Hirvonen & Hoddinott (2017) showed distance from markets are a key determinants of child diet diversity and quantities of consumption. The role of market in household consumption diversity is also indicated by Sibhatu *et al*. (2015). However, rural market integration in Ethiopia is still weak, with an average distance of 11 kilometres to a weekly market for the average rural household (Hirvonen & Hoddinott, 2017). Moreover, households situated farther away from the food markets consume more share of their own produce and less from purchased food.

Seasonality affects the food availability. Therefore, household diets in Ethiopia remain subject to significant seasonal stress and price fluctuations, with lower caloric intake and lower diet diversity in lean seasons (Hirvonen *et al*., 2016). Religion also plays a role in shaping diets during a calendar year where the demand for animal-based products drops down during fasting season and affect the dietary diversity (Sibhatu & Qaim, 2017).

Ethiopia is a very diverse country in terms of agroecological zones, with varying constraints and opportunities for agricultural production across different settings. Agriculture is a main driver for economic growth. However, dietary patterns and gaps have not yet been studied according to this heterogeneity (Gebru *et al*., 2018). Better characterization of the heterogeneity in diets is therefore a remaining topic in order to identify gap and suggest context-specific food-based intervention in rural Ethiopia.

2.2.1. Agroecological zones and Agriculture in Ethiopia

Various factors are responsible for the difference in the type and amount of crop produced across space (Adane *et al*., 2015). Agroecosystem characteristic is one of the factors that may create a spatial variation in household food availability (Simane *et al*., 2013). Agroecological zonation can be defined as a spatial classification of the landscape into area units with similar agricultural and ecological characteristics (Hurni, 1998). Most studies have been referring the agroecological zone classification for Ethiopia by Hurni (1998).

Hurni (1998) employed a set of agroecological zone characterisations for Ethiopia, based on traditional zone designations commonly used by rural residents. He linked these designations with specific elevation and rainfall parameters (dry, wet and moist), which allowed boundaries to be imposed on agroecological zones (Table 1). Furthermore, those boundaries between adjacent zones are also boundaries between agricultural crops. That is why the zones are called '*agroecological zones*' (Hurni *et al*., 2016). However, owing to the changing climate, agroecosystem likely migrate and so do crop production (Simane *et al*., 2013).

Agroecological analysis in Northern Ethiopia by Simane *et al*. (2013) sorted out various potential variables that are important to classify agroecosystem. The authors found out that climate information (mean annual precipitation and temperature) and elevation were by far the most influential variables driving the classification. The finding was generally in agreement with the previous classification with an exception that the midland was further classified into soil type by colour (black, red and brown) and sloping.

Agriculture practices and crop types are strongly influenced by ecological zones, as the country ranges from less than 500 meters above sea level (masl) to more than 3,700 masl. Below 500 masl (*bereha*) there are low level of rainfall and agriculture of any type is only possible with irrigation, while above 3,700 masl no regular crops are grown (Chamberlin & Schmidt, 2012). In Ethiopia, most agricultural production takes place in the *Dega* (highland) and *Weyna Dega* (midland) zones, where land productivity traditionally coincides with the densest rural populations. The lowland (*Kolla*) is also remarkable next to the above two zones (Chamberlin & Schmidt, 2012).

Agriculture continues to be the major source of employment for Ethiopians, particularly for those living in rural areas (Admassie *et al*., 2015). About eighty percent of Ethiopians reside in rural areas, most of them are smallholders occupying on average less than a hectare of land per household whereas constitute nearly 90% of the total number of farms (Rapsomanikis, 2015). Smallholder production is dominated by five major cereal crops (teff, wheat, maize, sorghum, and barley) accounting for almost three-quarters of the total cultivated area (Taffesse *et al*., 2012). Crop choice within the grain-based systems varies widely, as these systems are found from *kolla* to *wurch* altitudinal bands, in moisture conditions ranging from dry to wet (Chamberlin & Schmidt, 2012) (Table 1).

Table 1: Traditional ecological zones and selected crop altitudinal ranges (Hurni, 1998).

Altitude (Meters above sea level)	Less than 900mm Dry	900 to 1400mm Moist	More than 1400mm Wet
More than 3700			**HIGH WURCH** *none*
3700 to 3200		**MOIST WURCH** barley	**WET WURCH** barley
3200 to 2300 m		**MOIST DEGA** barley, wheat, pulses	**WET DEGA** barley, wheat, pulses/oilseeds
2300 to 1500 m	**DRY WEYNA DEGA** wheat, teff, (maize)	**MOIST WEYNA DEGA** maize, sorghum, teff, wheat, oilseeds, barley, (enset)	**WET WEYNA DEGA** teff, maize, enset, oilseeds, barley
1500 to 500 m	**DRY KOLLA** (sorghum), (teff)	**MOIST KOLLA** sorghum, (teff), pulses/oilseeds	
Below 500 m	**BERHA** *only irrigated crops*		

Annual rainfall (mm)

Notes: Crops in parentheses have restricted distribution within the zone and/or grow under less than ideal conditions in these areas. Blank cells indicate not applicable.

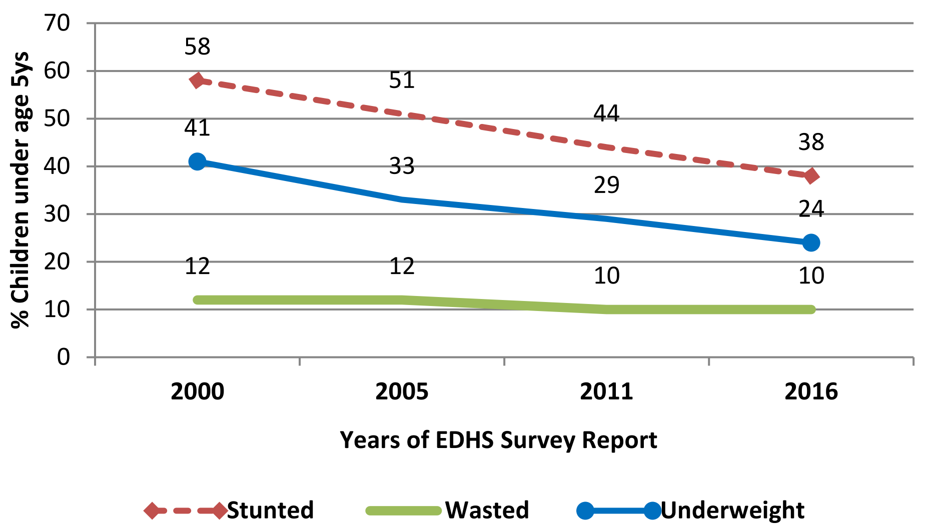
Agriculture in Ethiopia is generally rainfed, dependent on two rainy seasons. The small rainy season during spring (*belg*) typically occurs between March and May and the main rainy season during summer (*meher*) takes place between June and October (Sibhatu and Qaim, 2017; Hirvonen *et al*., 2015). Seasonal patterns vary by region. However, in most regions the summer rains, which usually occur between July and August, are rather more important than the spring rains (CSA, 2016). The summer season accounts for over ninety percent of total crop production in Ethiopia (Taffesse *et al*., 2012). In most regions, the summer season harvest occurs between September and November (CSA, 2016).

Agriculture plays a central role in Ethiopia's economic development and food security (Beyero *et al*., 2015). Owing to the distribution of improved seed and fertilizer, crop production has got the greatest growth accounting for one-third of all GDP growth (Gillespie *et al*., 2016; Bachewe *et al*., 2015). However, much of the pathway between agriculture and nutrition appeared to consist of leveraging agriculture as a source of food, with less consideration being given to the issue of dietary diversity (Beyero *et al*., 2015).

2.2.2. Maternal and child nutrition status in Ethiopia

In recent years, the country has shown some progress in reducing undernutrition. However, it still remains a serious issue. The 2016 Ethiopia Demographic and Health Survey (EDHS) indicated that 38 percent of children under the age of five suffer from chronic undernutrition (stunting) nationally (Figure 2). While this has fallen from 58 percent in 2000, it is still a serious development concern (Web *et al*., 2018). The World Health Organization indicates the severity of stunting by prevalence ranges, with 30–39% considered as high and ≥ 40% very high (WHO, 2019).

Figure 4: Trends of malnutrition indices in children under 5 years of age in Ethiopia



Relatively more progress has been made in the numbers of children who are underweight. However, little improvements over the ten-years period in the prevalence of acute malnutrition (wasting), which fell only slightly from 12 percent in 2000 to 10 percent in 2016 (EDHS, 2016).

Maternal malnutrition is a global problem having a significant consequence on both maternal and infant survival, as well as acute and chronic disease and economic productivity (Beyero *et al*., 2015). About thirty percent of women of reproductive age are chronically malnourished with a Body Mass Index (BMI) of less than 18.5kg/m^2. Anaemia prevalence is also high, 23 percent in women 15-49 years old, having haemoglobin concentration less than 12g/dL (EDHS, 2016).

Nutritional status in Ethiopia is the result of interactions between food security - including availability, accessibility and utilization - practices of child feeding, access to health care and cultural norms, among other factors (Beyero *et al*., 2015). Disparities in nutritional status between rural and urban areas also persist, with children in rural areas more likely to be stunted than those in urban areas with a prevalence of 40% and 25%, respectively (EDHS, 2016). Likewise, the proportion of women with anaemia is notably higher in rural (25%) than in urban areas (16%).

2.3. Food production diversity and consumption diversity

Having enough food to eat does not imply adequate nutrition. Improved nutrition requires divers and high quality diet besides better access to food (FAO, 2015). The level of dietary diversity is considered to be a good proxy indicator of overall nutritional status of individuals, which is achieved through consumption of required macro- and micronutrients from a range of foods (Ruel, 2003; Arimond *et al*., 2010). Increasing dietary diversity is thus an important strategy to improve nutrition and health. This implies that agricultural production also needs to be diversified (Pingali, 2015).

Nutrition is critical to human health. However, it is still not systematically integrated into the assessments of agricultural and food systems (Ruel *et al*., 2018). It is usually considered that the diversity of agricultural goods produced by a country is a strong predictor for food supply diversity in low-income countries. On the other hand, national income and trade are better predictors in middle- and high-income countries (Remans *et al*., 2014). Irrespective of rhetoric arguing that enhanced agriculture results in improved nutrition and health, there is limited empirical proof about the potential link across these sectors (Masters *et al*., 2014; Ruel *et al*., 2018). Therefore, recent studies have been highlighting the need for further studies to better understand how agriculture and food systems can be made more nutrition-sensitive in particular situations (Islam *et al*., 2018; Ruel *et al*., 2018).

2.3.1. Food production diversity and dietary diversity linkages

Studies have been using farm production diversity to assess diversity in dietary intake and nutritional outcomes at different levels: at individual, household and village levels (Jones *et al*., 2014; Remans *et al*., 2011; Shively & Sununtnasuk, 2015). Multiple pathways through which farm diversity could result in dietary diversity are illustrated through a number of recent agriculture-to-nutrition linkages. These pathways include increased income, lowered food prices, more nutritious on-farm produce, and women's empowerment (Gillespie *et al*. 2012; Ruel *et al*. 2013; Kanter *et al*., 2015; Herforth and Ahmed, 2015). The pathway through consumption of own-produced foods and through income from the sales of agricultural production are predominantly being researched (Hoddinott, 2011; Sibhatu *et al*., 2015). However, these pathways are context specific and governed by various internal household factors as well as external food environment.

Empirical evidence on the link between production and consumption diversity based on household-level data from Indonesia, Kenya, Ethiopia, and Malawi have shown on-farm production diversity is positively associated with dietary diversity in some situations, but not generalizable in all (Sibhatu *et al*., 2015). The authors used aggregate (national) level secondary data from subsistence-oriented, smallholder farmers growing various food crops and keeping livestock primarily for own consumption in Ethiopia and Malawi. On the other hand, they used a sample survey of primary data at a specific region within Indonesia and Kenya among smallholder farmers that grow cash crop for market. The result shows that household dietary diversity is higher in Indonesia and Kenya than in Ethiopia and Malawi owing to the sample farms in Indonesia and Kenya are more specialized in the production of cash crops and purchases diverse kinds of food from market irrespective of the production diversity.

Additional studies from Sub-Saharan Africa indicates the link between agriculture and nutrition follows different pathways. Dillon *et al*. (2015) in rural agricultural households in Nigeria revealed that the linkage was primarily through the effect of agricultural revenue on dietary diversity. In this context, production diversity is less relevant than it may be in other situations owing to specialization of famers in producing only two crops. On the contrary, studies from Malawi both at national level (Remans *et al*., 2014) and at household level (Jones *et al*., 2014) demonstrate a positive association between farm production diversity and dietary diversity. Similar positive association is also reported by Kumar *et al*. (2015) among children in subsistence households from rural Zambia.

Specialization by farmers in producing limited crops like in the case by Dillon *et al*. (2015) may have opportunities and threats as well. Increases in agricultural production revenue may affect dietary diversity through increases in household purchasing power of nutritious foods and a wider variety of food in general. However, specialisation by all producers in limited staple crops may lower food prices and the revenue of producers (Kumar *et al*., 2015). Given these general equilibrium effects, the effects of increased production and specialisation are not necessarily welfare increasing. Furthermore, increases in agricultural revenue may also lead to increased demand for nutrient rich foods by net producers, driving prices higher, and actually reducing consumption of nutrient rich foods. For these reasons, increases in agricultural revenue may not necessarily lead directly to increased household dietary diversity (Kumar *et al*., 2015).

In summary, the strength of associations between production diversity and dietary diversity vary by context. Furthermore, most existing studies relating production diversity to dietary diversity have restricted to use household dietary diversity score (HDDS) as a dietary diversity measure. HDDS is a measure that indicate the economic ability of the household to access various food groups and validated against calorie availability (Hoddinott and Yohannes 2002; Ruel *et al*., 2003) but not a measure of nutrient adequacy (Kennedy *et al*., 2013). Individual level dietary diversity score is aimed to evaluate the nutrient adequacy (Ihab *et al*., 2015).

Some of the studies relating food production diversity to consumption have focused mainly on plant-based food products as a metrics (Wood, 2018; Oyarzun *et al*., 2013). Given that food production diversity with a combined measure of crops and livestock products are shown to correlate positively with a better nutrition outcome (Romeo *et al*., 2016; Ekesa *et al*., 2008; Koppmair *et al*., 2017). Attention has been given to household's animal source foods/food products availability as well.

Moreover, aggregate national level secondary data by Sibhatu *et al*. (2015) from different countries may hide the possible association that may have existed in specific regional situations in Ethiopia and Malawi. As there are evidence from Malawi that reported increased production diversity may have positive effects on smallholder nutrition (Jones, 2017). Similarly, Jones *et al*. (2014) demonstrated a positive association between farm production diversity and dietary diversity in Malawi. The authors additionally indicated that the magnitude of association was larger in women-headed households than men-headed.

Furthermore, increases in agricultural revenue may not necessarily lead directly to increased household dietary diversity. However, allocation and utilization of the generated household income to buy more diverse food depends on the decision how income is distributed (Dillon *et al*., 2015), as well as the role of external food environment or village level food availability is important.

2.3.2. Village level production diversity

Village level food production strongly governs the choice that households make in rural areas of developing countries. In sub-Saharan Africa, food consumption and expenditure data in selected study villages by Remans *et al*. (2011) show that more than average proportion of food consumed in smallholder subsistence farmers comes from own production. The authors indicated that an aggregated village level production delivers a greater proportion of foods consumed; for instance, 70% in Malawi, 75% in Kenya and 82% in Uganda. Similarly, around 75% Zambia's rural poor are small-scale farmers relying almost entirely on subsistence agriculture (Kumar *et al*., 2015).

Likewise, Ethiopia is one of the countries with the highest share of subsistence production in household food consumption (GLOP, 2016; Hirvonen & Hoddinolt, 2017). National level data provided by Sibhatu and Qaim (2017) indicates that the average share of rural households calorie consumption from subsistence production varies seasonally; accounting for two-third in postharvest, with gradual minimal reduction in lean seasons and the rest of the consumption share is covered from local market. Hirvonen and Hoddinott (2017) presented a negative relationship between distance to the nearest food market and the proportion of rural household consumption from own produce.

Furthermore, Abay and Hirovene (2017) compared households distance (near vs far) to market and nutritional status of children in northern Ethiopia and they found out that children's body weight-based nutritional status indicators are subjected to considerable seasonal fluctuations – irrespective of their households' market access. This indicates in one hand, the market imperfection to supply year-round foods from external sources and on the other hand, the existing village level (local) market is strongly dependent on what is produced at the village level.

Several studies measured production diversity in terms of a simple count of the number of crop species produced on a farm, or a combination of crop and livestock species (Sibhatu *et al*., 2015; Jones *et al*., 2014; Lachat *et al*., 2018). Some other studies have used diversity in relation to the presence or absence of nutritional attribute and functional diversity (Jones *et al*., 2014; Remans *et al*., 2011; Wood, 2018). However, Koppmair *et al*. (2017) argue that simple species count may not necessarily reflect diversity from a dietary point of view. To better account for the dietary perspective, the use of production diversity score defined by the number of nutritional relevant food groups produced is considered important and widely being used by recent studies (Malapit *et al*., 2015; Sibhatu & Qaim, 2018; Hirvonen & Hoddinott, 2017).

In most studies assessing farm production diversity, production information is found based on counting of crop types from household survey or farmer level recall (Remanns *et al*., 2011; Dillon *et al*., 2015; Jones *et al*., 2014; Sibhatu *et al*., 2015). Regarding quantitative estimation, recent studies by Gourlay *et al*. (2017) from Uganda; Abay *et al*. (2018) and Desiere and Jolliffe (2018) from Ethiopia presented errors reported in production information by farmers. Moreover, production estimates in heterogeneous smallholder farming systems often rely on labour-intensive surveys that are not easily scalable, nor exhaustive (Lambert *et al*., 2018).

Smallholder farms dominate in many parts of the world, mainly in Sub-Saharan Africa. However, the small size of the fields, the high degree of heterogeneity within these fields, and lack of clarity in field boundaries make it challenging and requires a specialized methodology to accurately map agricultural land cover (Debats *et al*., 2016). With this regard, recent developments in high-resolution and very high-resolution remote sensing data come up with new opportunities to work in heterogeneous smallholder systems. Sentinel-2 gained the attention for cropland mapping and monitoring because of the high spatial (10 m) resolution and with 5 days revisiting time (Kanjir *et al*., 2018; Lambert *et al*., 2018). Similarly, other studies have achieved efficient land cover classifications of smallholder farming systems using very high-resolution (VHR) imagery from WorldView-2 and WorldView-3 (Debats *et al*., 2016; Neigh *et al*., 2018; Alabi *et al*., 2016). A fusion of Sentinel-2 images with PlanetScope images to take advantage of their spatial, temporal and spectral resolution suggested to be used in agronomy (Gasparovic *et al*., 2018)

The present study will address major shortcomings of previous studies by using village level quantification of major food crops using remote sensing-based estimate of total production and production diversity. Attention will also be given to livestock ownership and animal source food products through household survey. In addition, a measure of dietary diversity that could capture nutrient adequacy will be considered. The study will compare these relationships in the context of different agro-ecological zones.

2.4. Nutritional composition of major crops

To achieve healthy food system, in addition to measuring food supply diversity, it is equally important to measure nutrients provided by those different food items (Remans *et al*., 2014). Nutrient composition of foods are detailed sets of information on the nutritionally important components of foods and provide values for energy, macronutrients (protein, carbohydrates, fat), micronutrients (vitamins and minerals) and other important food components such as fibre.

Nutrient content can vary as much between different varieties of the same crops, as they do among different crops (Charrondiere *et al*., 2013). Food composition can vary significantly either because of natural differences (e.g. soil, genetics, climate) or because of differences due to nutrient expressions or fortification. Thus, up-to-date food composition data preferably at the local level are of fundamental importance in nutrition because food composition data lacking update may lead to wrong research results and wrong policy decisions particularly in nutrition, agriculture, and health (FAO, 2017). Like most sub-Sahara African countries, food composition data now in use in Ethiopia was updated two decades ago in 1998 (EHNRI, 1998); however, a number of improved crop varieties have continually been introduced since then (Micha *et al*., 2018).

The study by Shively and Sununtnasuk (2015) indicated the need for future research to identify a precise nutritional benefits of household crop composition, which could be done by assessing the nutritional value of harvests in terms of calories or specific micronutrients, rather than the weight or share of crops in total agricultural diversity.

However, unavailability of local level nutrient values of foods shown to limit further investigations in studies relating farm production to nutrition (Wood, 2018; Remans *et al*., 2014). Remans *et al*. (2014) used global database for nutrients composition. However, they did not consider some endogenous crops that are not available in the global database. Wood (2018) used nutritional composition database of West Africa to assess nutrition adequacy in one region within Senegal. As nutritional composition varies based on crop variety and environmental conditions, the importance of context-specific nutrient values that account for variation in nutrient contents is strongly suggested (FAO, 2017; Wood, 2018).

Furthermore, previous studies relating nutrition composition to farm production had limitations in their consideration that the amount of nutrients in a food is likely to be the amount of nutrients consumed (Remans *et al*., 2011; Remans *et al*., 2014; Wood, 2018), that did not account the availability of enhancers and inhibitors affecting the absorption of those nutrients by the human body. In addition, their reference composition data was not specific to the context of the study to make consumption related recommendation.

2.4.1. Essential mineral micronutrients and antinutrients in predicting bioavailability

Essential mineral deficiencies are not only caused by a lower dietary intake. Many other diet-related factors affect the absorption such as the total content of the minerals and anti-nutrients, the processing applied and mineral interactions (Gibson *et al*., 2010). In addition, individual- or host-related factors are also an important determinant (Hailu and Addis, 2016; Gibson *et al*., 2010). A combination of these factors is generally estimated through different measures of bioavailability. Bioavailability is the proportion of an ingested nutrient in food that is absorbed and utilized through normal metabolic pathways (Hurrell, 2002).

Plant-based food source of mineral micronutrients (like iron, zinc, and calcium) absorption are reduced in the presence of anti-nutrients such as phytates, polyphenols and tannins (Feitosa *et al*., 2018). The presence of anti-nutrients forms insoluble complexes mainly with those essential minerals, thereby intensely restrict their digestion and absorption. Thus, low bioavailability of the minerals can lead to deficiencies particularly in the population where plant-based staple crops are the major source of food (Gupta *et al*., 2015). The levels of these essential minerals and their bioavailability have been predicted and ranked using *in vitro* method like antinutrient-to-mineral molar ratios (Etcheverry *et al*., 2012).

Phytic acid (phytate) is the major storage form of phosphorous in cereals and legumes (Coelho *et al*., 2002). It is the foremost antinutrient that forms complex with essential minerals, reducing the digestive availability in the gastrointestinal tract because of the absence of intestinal phytase enzymes in humans (Gupta *et al*., 2015). This inhibitory effect of phytate on mineral absorption was well-established and in agreement with *in vivo* studies that fractional absorption of iron, zinc, and calcium has been reported to be significantly lower from diets with a high content of phytate than from diets with a lower phytate content (Hurrell *et al*., 2003; Hambidge *et al*., 2005).

Phytate to mineral molar ratios have been used to estimate relative mineral bioavailability and compared with a desirable molar ratio (critical values) for mineral absorption of phytate to iron < 1, phytate to zinc < 15, phytate to calcium < 0.24 (Al Hasan *et al*., 2016; Gibson *et al*., 2010; Frontela *et al*., 2009).

Recent studies have used molar ratios of phytate to micronutrients to estimate the relative bioavailability of minerals from plant-based food, for comparisons made among crop types and within crop varieties (Krishnan & Meera, 2017; Dragičević *et al*., 2018). Suma & Urooj (2014) compared mineral contents at different processing stages of pearl millet flour. Similarly, Gibson *et al*. (2010) evaluated the relative bioavailability of minerals (iron, zinc and calcium) in indigenous and commercially processed plant-based complementary foods.

However, phytate to micronutrient molar ratios of available major crops grown in different agroecological zones were not compared as a potential predictor of essential mineral nutrients available for absorption which helps to identify crop types or varieties with the desired molar ratio to make context specific diet-related recommendations.

2.5. Household food security status and intra-household food consumption

The World Food Summit of 1996 defined food security as existing "when "all people, at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Food security is defined by three interrelated dimensions: *food availability* or the existence of food at a particular place and time as provided through production or trade; *food access* or the ability of a person or group to acquire food through purchase, barter, or trade; and *food utilization* or the ability to use and obtain nourishment from food, including the food's nutritional value and how the body assimilates nutrients (Brown, 2016). Therefore, the stability of the dimensions of food security leads to changes in food security outcomes.

Food security is an intricate sustainable development issue linked to health and nutrition. In addition to eliminating all forms of malnutrition (Target 2.2), addressing the challenges of hunger and food insecurity through ensuring access to safe, nutritious and sufficient food for all (Target 2.1) is the second goal of Sustainable Development Goal (SDG) of the 2030 Agenda.

The recent report on the state of food insecurity in the world (FAO, 2018) estimates the number of people undernourished in 2017 to have increased to 821 million – around one out of nine people worldwide. The report notes that the majority of those people live in the developing world. The share Ethiopia with undernourished people in 2015-17 is 22 million (FAO, 2018).

In the rural part of Ethiopia, the extent of agricultural production determines the household food availability, since food is mainly derived from household's own production (Adane *et al*., 2015). Therefore, to bring logically appropriate intervention in geographically heterogenous areas, understanding the local context is crucial. With this regard agroecological analysis is found to be important (Simane *et al*., 2013). However, limited studies have given attention to examine food security and nutrition across different agroecological zones (Alemu *et al*., 2017a; Motbianor *et al*., 2016; Alemu *et al*., 2017b; Hagos *et al*., 2014; Sibhatu and Qaim, 2017).

The existing few studies that examined food security status of households in relation to the agro-ecological gradient have resulted in inconsistent findings at different scales. This holds true for local as well as studies from sub-Saharan Africa. The study by Maswa *et al*. (2014) from western Kenya have reported that households in drier zones (lowlands) are better food secured than their highland counterparts. On the other hand, South African study by Chakona1 and Shackleton (2018) found households in highland had lower prevalence of food insecurity.

Likewise, Yirgu *et al*. (2013) indicated that highlanders were better attained optimal per-capita calorie requirements and hence are better food secured as compared to lowlanders in southern Ethiopia. Conversely, findings from northern Ethiopia (west and east Gojjam) by Motbainor *et al*. (2016) indicated households in highland and midland are twice more likely to be food insecure compared to lowlanders. Surprisingly, Alemu *et al*. (2017) from northern Ethiopia (east Gojjam) presented highland and lowland agroecological zones were identified as a significant hot spot areas of food insecurity compared with midland areas.

However, some of those studies had methodological limitations. For instance, mixed assessment of households from urban, peri-urban and rural settings irrespective of their variations in the extent of involvement in agriculture and market interplay (Motbainor *et al*., 2016; Chakona1 and Shackleton, 2018). Additionally, inefficient comparison with under-representation of total sample size allocation over the three agroecological zones: highland (9%), midland (60%) and lowland (31%) is seen as a case by Motbainor *et al*. (2016).

Other observed limitation is the use of household dietary diversity score (HDDS) to address child specific dietary adequacy assessments by Hagos *et al*. (2014). As indicated previously, HDDS aims to identify the economic ability of the household to access a variety of foods (Swindale & Bilinsky 2006a). Individual dietary diversity score (IDDS) is aimed to evaluate the nutrient adequacy of an individual (Ihab *et al*., 2015). Even though HDDS may deliver important information concerning the dietary options that may be available for individual household members (Romeo *et al*., 2016), intra-household food distribution is not always equal (Villa *et al*., 2011) owing to various reasons like gender, age, caring practice of household for dependent household members, etc. Therefore, it has been argued that more research is needed to examine at individual level rather than household level dietary diversity (Dillon *et al*., 2015).

Food insecurity is among the foremost determinants of child undernutrition. Depending on the severity of household food insecurity status, households manage shortage of food with different mechanisms including reduction in diet quality (Farzana *et al*., 2017; Alemu *et al*., 2017a), reduce the quantity of food that the family members served (Coates *et al*., 2007; Farzana *et al*., 2017; Alemu *et al*., 2017a). Such adjustments may lead to calorie and micronutrient deficiencies among vulnerable family members.

In summary, studies presented the existence of spatial variations in food insecurity status at national and sub-national levels. Therefore, this highlight designing and planning future interventions using country or regional level evidence might mask the true picture of spatial distribution of the problem at local context (micro level). The importance of microlevel evaluation of food security status also suggested by Alemu *et al*. (2017a).

Furthermore, most of the aforementioned studies mainly focused on a single dimension of food security (i.e., food access) that was assessed by household food insecurity access score and partly complemented with household dietary diversity scores. This gives a call for further evaluations with additional components of food security and more specific indicators for nutrition outcome measures targeting nutritionally-vulnerable household members in rural areas. With this respect, the present study will evaluate intrahousehold level food utilization among children 6 – 23 months and women of child bearing age in terms of adequacy of diet consumed along the different agroecological zones in addition to household food access measure.

2.6. Diet quality and nutritional status of individuals

Improving nutritional status of women and children remains a high public health and development priority low-income and middle-income countries (Black *et al*., 2008). Since nutritional deficiencies throughout these critical life-cycles are among the major causes of physical, cognitive, and social shortcomings later in life, perpetuating the intergenerational cycle of poor human development (Crookston et al., 2013; IFPRI, 2017).

Globally, 22% children under five years in age were affected by chronic undernutrition (stunting) in 2017, where the magnitude was significantly higher in eastern Africa 36% (UNICEF/WHO/World Bank, 2018). Likewise, undernutrition in women of reproductive age result in the deficiency of essential nutrients in Ethiopia, where 23 % of women are anemic and 30 % are underweight (BMI < $18.5 kg/m^2$) (EDHS, 2016), which pose threat to physical, mental and social well-being of women themselves as well as for the health of their offspring (Black *et al*., 2008).

A women's nutrition status prior to conception influences fetal growth, particularly, low body-mass index in women of reproductive age is associated with intrauterine growth restriction of the fetus and result in low birth weight which lead to child undernutrition (Black *et al*., 2013; Khan & Mohanty, 2018; Abdulahi *et al*., 2017). Child growth restriction often begins in utero and continues for the first two years of life (Victora *et al*., 2010). The main window of opportunity to prevent undernutrition is thus from pre-pregnancy to 24 months of child age (i.e., partly explained by the first 1000 days of life) (Pietrobelli & Agosti, 2017).

Nutrition from 6 – 23 months of life

During the first six months after birth, breastmilk is recommended as the exclusive source of nutrition necessary for early infant health and development. As an infant grows and develops, it experiences physiological shifts in nutrient and energy requirements that can no longer be satisfied by breast milk alone (Solomons & Vossenaar, 2013). Therefore, it is necessary to introduce nutritionally adequate complementary foods along with continued breastfeeding for the period 6 to 24 months of age.

In comparison to adults, infants have very different nutritional needs since they double their birth weight in the first six months and triple it by the end of the first year, which means that they have higher energy requirements and certain key vitamins and minerals than adults relative to their size (Kathy, 2010). Since much of this growth occurs during the complementary feeding period, children are required to consume adequate amounts, frequency and using a variety of foods to cover the essential nutrients needed (Comerford *et al*., 2016). However, in many countries less than a fourth of infants 6–23 months of age meet the criteria of dietary diversity and feeding frequency that are appropriate for their age (WHO, 2018). This makes the complementary feeding a vulnerable period that malnutrition starts in many infants and contributing significantly to the high prevalence of undernutrition in children under five years of age world-wide (WHO, 2018).

Indicators of nutrition status

Three anthropometric indicators of nutritional status of children namely stunting (low height-for-age), underweight (low weight-for-age) and wasting (low weight-for-height) are the standardized measures of nutritional status of children (WHO, 2006; WHO, 2012). While stunting is a measure of linear growth retardation and cumulative growth deficits in children

(Kandala *et al*., 2011). Wasting measures body weight in relation to height and describes current nutritional status. However, underweight is a composite index which takes into account both acute malnutrition (wasting) and chronic malnutrition (stunting), but it does not distinguish between the two (Kandala *et al*., 2011; Kinyoki *et al*., 2015).

Stunting is the most reliable indicator since it is less sensitive to temporary food shortages. Although the cause is multifactorial, stunting is largely attributed to the deficiency for calories/protein and essential micronutrients available to the body tissues or inadequate intake over a long period of time (Kandala *et al*., 2011). Children with a Z-score below two standard deviations from the median of the WHO reference population is considered to be undernourished, for all the three anthropometric indicators (WHO, 2006).

Mid-upper arm circumference (MUAC) is also another body measurement method which could be used both in children and adults. Body mass index (BMI) is also a common measure to indicate chronic energy deficiency in adults. It is obtained after dividing body weight in kilograms by squared height in meters. In addition, biochemical indicators are also used to determine desired nutrients status from collected samples including blood, which is useful to validate data obtained from dietary methods and able to detect early changes (Shrivastava *et al*., 2014).

Causes of undernutrition

Studies on child undernutrition have highlighted potential causal factors consistent with the UNICEF conceptual framework for improving child nutrition (UNICEF, 2014). The framework indicates child malnutrition results from a series of immediate (individual level), underlying (household or family level), and basic (societal level) causes which work in synergy, where determinants at one level influence other levels.

The immediate causes operate at the individual level through inadequate food intake and disease. The underlying causes focus on household food (in)security, inadequate health services, unhealthy household environment, inadequate care and feeding practices. The basic causes reflect socio-cultural, structural, economic and political processes within society which result in inadequate financial, human, physical and social capital that influence household access to adequate quantity and quality of resources (UNICEF, 2014). Thus, as determinants of child undernutrition at one level influence others, comprehensive evaluation at different levels will help to identify and direct effective interventions.

Micronutrients in women of reproductive age

In women of reproductive age micronutrient deficiencies are known to impair their health, growth and development of their offspring, and as a result affect pregnancy outcome (Gernand *et al*., 2016). Women in low-income countries are often vulnerable to micronutrient deficiencies due to various reasons: inadequate dietary intake owing to either lack of food availability or lack of knowledge to diversify diet, sociocultural norms and gender-based discrimination require women to put their family members before their own health and nutritional needs, and frequent occurrence of infectious diseases (Darnton-Hill, 2012). Therefore, they often enter pregnancy undernourished, and the additional demands of micronutrients by pregnancy may further aggravate micronutrient deficiencies with an adverse health consequence to the fetus (Gernand *et al*., 2016).

Iron, vitamin A, and zinc are among the most common micronutrient deficiencies in women (Harika *et al*., 2017). Iron deficiency has an adverse effect on productivity and cognition in the general population and is the leading cause of anemia during pregnancy, contributing to maternal and perinatal mortality and low birth weight (Burke *et al*., 2014; Gernand *et al*., 2016). Vitamin A deficiency can cause impaired vision (e.g., night blindness) and immune function, and may result in preterm birth and infant mortality (Tielsch *et al*., 2008). Zinc deficiency is a risk factor with an adverse long-term effect on growth, immunity, and metabolic status of offspring (Liu *et al*., 2018). Poor maternal zinc status has been also associated with intrauterine growth retardation, preterm birth and reduced birth weight (Chaffee & King, 2012; Gernand *et al*., 2016).

From the literatures indicated above, women's nutritional statuses both underweight (low BMI) and micronutrient (iron, zinc and vitamin A) deficiencies are shown to restrict fetal uterine growth and leads to low birth-weight, which is the major contributor to stunting. However, the geographic correlates in the distribution of undernutrition of women were not studied as a predictor of both maternal and child nutrition outcomes.

Geographical location has an impact on the underlying determinants of nutrition which directly or indirectly controls the availability and accessibility of foods partly due to agricultural patterns (Khan & Mohanty, 2018). For instance, Gebreselassie *et al*. (2013) shown that variation in the diet consumption pattern over a small geographic scale in southern Ethiopia has presented a significant variation in vitamin A status (serum retinol level) between women who consume maize as a staple diet and those reported enset (*Enset ventricosum*).

Child undernutrition

Stunting is a serious public health problem in developing countries and its consequence goes beyond the childhood period. It can have long-term effects on cognitive development, educational performance, lower economic productivity in adulthood and maternal reproductive outcomes (Dewey & Begum, 2011). Increased risk of non-communicable diseases was also documented in adulthood (Stein *et al*., 2005). Hence, such evidences have contributed to the growing consensus that tackling childhood stunting is a high priority for reducing the global burden of disease and promoting economic development (Dewey & Begum, 2011).

Majority of the studies on child nutritional status have described prevalence of undernutrition among under-five children and analysed socioeconomic, demographic and cultural factors associated with child undernutrition as indicated in recent systematic reviews in sub-Saharan Africa (Akombi *et al*., 2017) and in Ethiopia (Abdulahi *et al*., 2017). However, the prevalence of undernutrition in Ethiopia significantly vary among regions and exhibit intra-regional heterogeneity. Little is known about the spatial distribution of child undernutrition; only few studies have assessed the geographic correlates of child undernutrition (Haile *et al*., 2016; Hagos *et al*., 2017).

Haile *et al*. (2016) used national level secondary data from 2011 EDHS and found out that the spatial distribution of stunting in children under five years old is non-random in Ethiopia, with higher prevalence of stunting in the northern Ethiopia. Hagos *et al*. (2017) used primary data at meso-scale in one district of southern Ethiopia and shown that stunting presented spatial autocorrelation. However, in evaluating the potential risk factors of stunting, the studies had limitations in considering child specific dietary intake data rather used a measure for entire household. In addition, indicators of breastfeeding and complementary feeding practice of children were not included. Furthermore, Amhara region is known for its high agroecological heterogeneity and high burden of child undernutrition, no study specifically addressed spatial distribution of child undernutrition in the region.

Therefore, the present study aims to investigate the spatial correlate of undernutrition in women of reproductive age and children in Amhara region, northern Ethiopia. In addition, the study evaluates the potential responsible factors for childhood undernutrition taking in to account the anthropometric and micronutrient status of women of reproductive health as an additional predictor. The study will also consider the aforementioned limitations of previous studies.

3. RESEARCH METHODOLOGY

3.1. Description of the study area

The study will be conducted in Amhara regional state, northern part of Ethiopia (Figure 3), where the prevalence of stunting in children in the region (46 %) exceeds the national average (38 %) (EDHS, 2016). In the region, Beshelo sub-basin (between 38.2°E to 39.6°E longitudes and 10.8°N to 11.9°N latitude) covers parts of South Wollo, North Wollo and South Gonder administrative zones of the region (Wodaje, 2016). According to the International Water Management Institute (IWMI, 2009), Beshelo sub-basin is one of the 18 major sub-basins of Blue Nile and it has an estimated area of 13,243 km^2.

Topographically, its altitude ranges from 1,170 to 4,260 masl and the agro-ecological zone ranging from the warm-semiarid lowlands to cold-moist highlands. The elevation of about 45% of the sub-basin is in between 2400 meter and 3200 meters; 40% of the area has an elevation range of 1500 meter to 2400 meter while the elevation of about 12% of the area is in between 3200 meter and 3700 meter above mean sea level (Wodaje, 2016). The long-term mean annual rainfall of the sub-basin ranges from 720 mm to 1298 mm (Wodaje, 2016).

South Wollo Zones of the Amhara region is one of most food-insecure areas in Ethiopia (Barrett & Maxwell, 2005). According to the Central Statistical Agency of Ethiopia (2013), South Wollo Zone had an estimated total population of 3,087,132 for the year 2017. The majority (83%) of the population of the zone are rural inhabitants, with female to male sex ratio of one.

The study is planned to be conducted in two districts of south Wollo zone, namely, Dessie Zuria and Kutaber districts (Figure 3). The selected districts better represent the major agroecological zones (AEZ) of the sub-basin, rural villages, and accessible for the collection of perishable samples. Six villages/*kebeles* from the two districts were tentatively selected. Those villages represent the three agroecological zones: Kolamote and Goro Mender represent *Weinadega* or midland (AEZ-1); Degamote and Alansha Werkaya representing *Dega* or highland (AEZ-2); and Atent Mesberiya and Liwich represents *Wurch* or upper-highland (AEZ-3).

3.2. Sample size determination and sampling techniques

The sample size of 439 households were determined, considering 46% prevalence of stunting in children in Amhara region (EDHS, 2016) and assuming 5% marginal error and 95%

confidence level and a none response rate of 15%. Based on these assumptions, the actual sample size for the study was determined using single population proportion sample size estimation (Hajian-Tilaki, 2011):

$$n = \left[Z^2_{\alpha/2}\, P(1-P) \right] / d^2$$

Where (n) is the required sample size, ($Z^2_{\alpha/2}$) is z-score for 95% confidence interval, (d^2) marginal errors, *(P)* prevalence the parameter

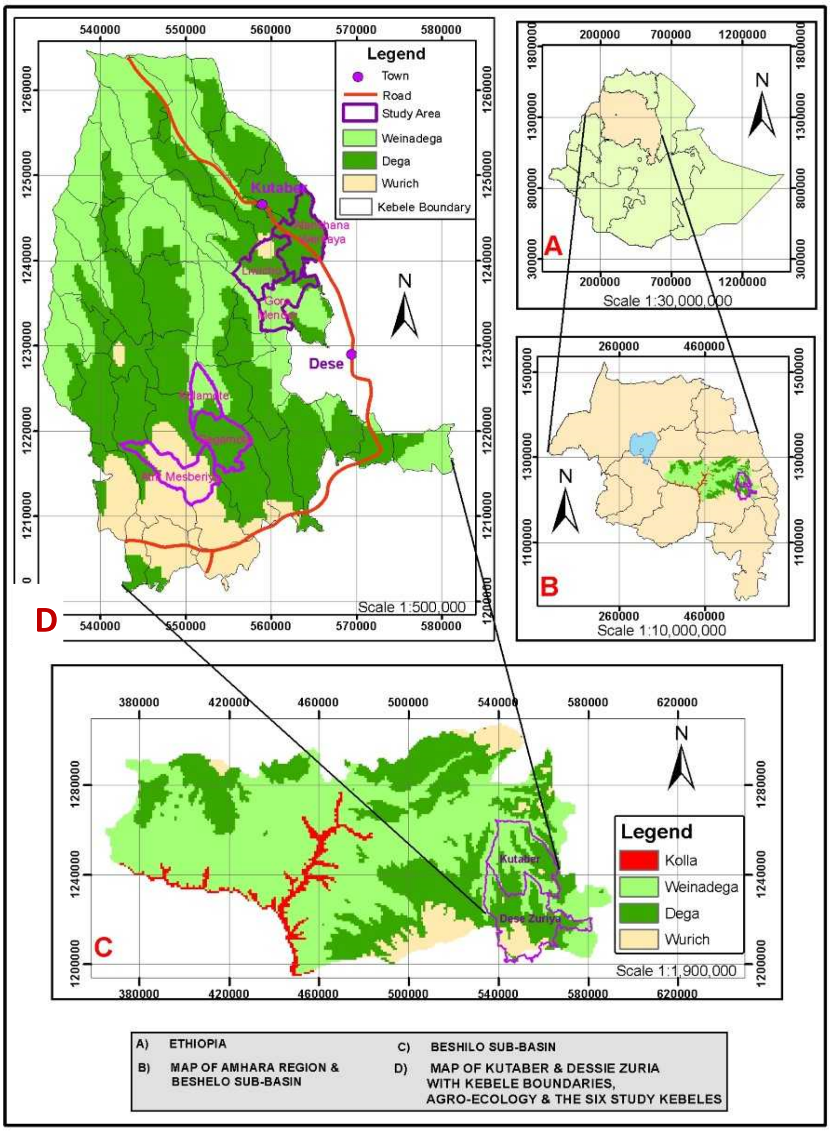


Figure 5: Study area map. (A, represents Ethiopia; B, map of Amhara region; C, Besilo-basin; D, Map of Kutaber and Dessie Zuria districts with kebele boundaries, agroecology & the six study villages). *Kolla* for low land, *Weinadega* for midland, *Dega* for highland and *Wurch* for upper highland.

The total sample size will be allocated proportionally to the number of households having children (6-23 months) and women (18-49 years of age) in each selected village. Households having study subjects of interest will be chosen by a systematic random sampling technique from a sampling frame. Household registration folder at health-posts in the villages will serve as a sampling frame. When there will be more than one child satisfying the inclusion criteria in the same household, one of them will be selected randomly.

3.3. Research Design and Data Collection Methods

A quantitative research approach will be followed at different levels (village, household and individual) with a cross-sectional nature along the major growing season of the study area. Structured survey questionnaire will be used to generate information on households' socio-economic and demographic characteristics, food production, food security status and household level dietary consumption. Similarly, individual level dietary information will be acquired through questionnaire, body measurement, and blood sample collection. High resolution satellite images will be used in this study. Field level data on crop production will be collected. Village level information regarding agriculture growing seasons, sowing and harvesting time-lines will be acquired from key informants (local agriculture experts and village leaders). Health related information will be collected from health extension workers as well. A detailed method per each specific objective is given below.

3.3.1. Specific objective 1

Combining remote sensing techniques and household survey to investigate relationship between production diversity to dietary diversity

The overall approach involves three main steps: (i) mapping crop types in the study area; (ii) estimating aggregated village level crop production; and (iii) link to household survey so as to relate production diversity to individual dietary diversity score.

Crop type classification

An average farm size distribution per household in Ethiopia is 0.96 hectare (ha) with higher regional variation. In the study region (Amhara) even though the average farm size is 1.09 ha, about 33.4% of the households own less than 0.5 ha (Heady *et al*., 2014). Images from Sentinel-2 sensor has been used in tropical smallholder agricultural systems that are characterized by high intra- and inter-field spatial variability and where satellite observations are disturbed by the presence of clouds (Lebourgeois *et al*., 2017; Lambert *et al*., 2018; Jin *et al*., 2017). However, to increase the chance of obtaining cloud free images and to map smaller crop fields, this study will fuse Sentinel-2 images with Planet images to take advantage of their spatial, temporal and spectral resolution. The study will use images across the entire major growing season of Ethiopia (*Meher*) that extend from June and October (Sibhatu and Qaim, 2017; Hirvonen *et al*., 2015) where more than 90 % of the total crop production taking place in the country (Taffesse *et al*., 2012).

In all the three AEZ sample villages, object based supervised classification will be used to discriminate major crop types within a crop land. Crops mapping will use object-based approach which is spatially more consistent than those mapped using the pixel as the smallest analysis unit (Belgiu and Csillik, 2018).

Reference ground dataset will be collected for each crop type with a minimum of 50 sample points to create polygons as a subset following stratified sampling (strata being crop type). Those ground reference points will be splitted into training (70%) and the remaining (30%) reserved for validation. This will be done in such a way that the training and validation samples are located in different agricultural parcels (Belgiu and Csillik, 2018).

Different machine learning classifiers will be used including random forest, support vector machine or relevance support vector to identify crops from satellite images (Breiman, 2001; Cortes & Vapnik, 1995; Tipping, 2000). The accuracies of the classifications obtained will be evaluated in terms of overall accuracy, producer's accuracy, user's accuracy metrics (Congalton, 1991) using the validation sample kept for this purpose as indicated above.

Additionally, satellite image time series is challenged by: (1) the shortcoming of samples availability; (2) the irregular temporal sampling of images and the missing information in the datasets (e.g. cloud contamination) that can obscure the analysis; and (3) the variability of pseudo-periodic phenomena (e.g. vegetation cycles, which are influenced by weather conditions) (Petitjean et al. 2012). One method that addresses these issues is Dynamic Time Warping (DTW), which is recently applied in the analysis of satellite image time series (Belgiu and Csillik 2018; Maus 2016; Petitjean et al. 2012; Petitjean and Weber 2014). This method will be considered to identify crop types from smallholder farms.

Estimating total production

Total production estimate will be obtained by field size of production and the average crop yields per crop type. Grain yield will be measured on a subset of selected fields for the dominant crop types in the villages. Field selection will follow a stratified sampling approach considering factors affecting crop yield: natural factors (slope, soil type) and farm management factors (application of inputs, which could be affected by owners economic status/farm plot size) (Meshesha & Abeje, 2018). In addition, local agriculture experts will also be consulted regarding the field selection considerations for crop yield.

There will be different fields per crop type. On each selected field, field boundaries will be recorded with a GPS. Within each field, three quadrants of 4-m^2 will be randomly selected for measurement replications per field (Meshesha & Abeje, 2018). Quadrants selection considers the separation distance of 10-m from the nearest tree crown or field boundary (to avoid edge effects) (Lambert et al., 2018). Within the selected quadrant above ground biomass of crop will be cut and weighed (destructive sampling method) and then grain yield for each crop type estimated per quadrant at field level during harvesting.

Grain yield will be estimated based on a threshing ratio or harvest index (i.e., weight of grain divided by total weight of above ground biomass). Quantitative estimates of yield will employ empirical models based on linear regressions between yield measurements generated from field and spectral vegetation indices (VIs) from earth observation (Equation 1). The potential of this approach has already been demonstrated in smallholder farms (Lambert *et al.*, 2018; Meshesha & Abeje, 2018, Azzari *et al.*, 2017; Jin *et al.*, 2017). The study will use better performing VIs (NDVI, EVI, etc) for each crop types as suggested by Johnson (2016) and a recent study by Meshesha & Abeje (2018) from northern Ethiopia. In addition, random forest will be evaluated in the study to identify the most relevant VI computed on red-edge bands of Sentinel-2 to be used as input in the final model. The importance of VI will be assessed using the mean decrease in Gini index measures implemented in random forest.

Linear regressions between VI and field level yield averaged at parcel level for each crop type.

$$\bar{y}_j = \alpha_j \times VI + \beta_j + \in_j \qquad (1)$$

With α_j, β_j the coefficients of the yield linear regressions for each crop type j; *VI* vegetation index of choice for a particular crop type j; $\in_j$ the error on those regressions and $\bar{y}_j$ yield for of crop type j.

The determination coefficient (R^2) computed for each linear regression serves as performance indicator. The yield regression models will be validated using part of the data set by computing Root Mean Square Error (RMSE).

$$RMSE_{fo} = \sqrt{\frac{\sum_{i=1}^{N}(z_{fi} - z_{oi})^2}{N}} \qquad (2)$$

Where: $RMSE_{fo}$, Root Mean Square Error difference between observed & predicted values; z_{fi}, forecasted value; z_{oi}, observed value; N = sample size.

Finally, crop type classification and yield estimation will be combined for production estimates. The production estimate then corresponds to the average crop yields (Equation 1) multiplied by corresponding crop area (Lambert *et al*., 2018).

Measure of production diversity

Based on the agricultural data from field and household survey production diversity indicators will be estimated. Several studies measured production diversity in terms of a simple count of the number of crop species produced on a farm, or a combination of crop and livestock species (Sibhatu *et al*., 2015; Jones *et al*., 2014). However, a simple species count does not necessarily reflect diversity from a dietary point of view (Koppmair *et al*., 2017). To better account for the dietary perspective, the use of production diversity score defined as the number of nutritional relevant food groups produced is considered important (Malapit *et al*., 2015; Sibhatu & Qaim, 2018; Hirvonen & Hoddinott, 2017).

Production diversity score with ten food groups will be used, including: All starchy staple foods; Beans and peas; Nuts and seeds; Dairy; Flesh foods; Eggs; Vitamin A-rich dark green leafy vegetables; other vitamin A-rich vegetables and fruits; other vegetables; other fruits (FAO & FHI, 2016). If a farm produces several species that belong to the same food groups, the production diversity score will be smaller than the simple species count. For comparison among villages, the study additionally considers simple crop species count as the indicator of farm production diversity.

Household survey

Farm diversity will be assessed based on the total number of different crop species planted including in homestead gardens, the total number of owned livestock of each species and animal source food products produced at household (HH). Those number of crop species and animal source food products will be grouped in to nutrition relevant food groups as indicated above. Socio-economic (wealth index, education), demographic factors (HH size, age of HH head), market access (distance to market, market participation), and farm characteristics (cultivated area, agriculture revenue per production season) will be assessed.

Measure of dietary diversity

Dietary diversity will be measured in terms of dietary diversity scores (DDS), a common indicator that counts the number of food groups consumed over a certain reference period (Ruel, 2003; Gibson & Ferguson, 2008). According to FAO & FHI (2016), individual dietary diversity score of women having ten food groups will be used as an indicator for dietary adequacy. The study plan to use a dietary intake pattern from one-week food consumption recalls (Koppmair *et al*., 2017).

Analytical approach

Dietary diversity is a count variable. A common approach for count data models is to use a Poisson estimator (Greene, 2002). The regression models described in equations (3) and (4) have dietary diversity as the dependent variable.

To analyse the relationship between farm production diversity and dietary diversity, we use the following regression model:

$$DD_{ij} = \alpha_0 + \alpha_1 PD_i + \epsilon_{ij} \tag{3}$$

where DD_{ij} is dietary diversity of individual j living in household i and PD_i is production diversity in farm household i. ϵ_{ij} is a random error term, and α_0 and α_1 are coefficients to be estimated.

The model in equation (3) includes only production diversity as explanatory variable. Yet, there may also be other factors that could influence dietary diversity, such as market access and other socio-economic and demographic characteristics. To better understand the role of such other factors, the regression model extend as follows (4):

$$DD_{ij} = \alpha_0 + \alpha_1 PD_i + \alpha_2 M_i + \alpha_3 H_i + \epsilon_{ij} \tag{4}$$

where M_i is a predictor variable capturing market access and H_i is for other socio-economic and demographic variables, including farm size, household size, education and other indicators of household i. In addition, hierarchical multiple regression analysis will also be considered to sequentially relate predictor variables to dietary diversity. In this case, dietary diversity score will be classified into a score of below median diet diversity ($\leq$ 4), and medium and above ($\geq$ 5).

3.3.2. Specific objective 2

Determining nutrient composition of major crops

Common crops grown in the selected study areas will be identified from the previous objective and samples per crop type will be obtained from the field in the study villages. Selection of representative samples from the field will be done following crops sampling protocol for nutrient analysis by Stangoulis & Sison (2008). Crops will be thoroughly cleaned, and any foreign materials and broken seeds will be removed and dried. Then will be milled to fine particle using stainless steel laboratory miller to avoid extrinsic mineral contamination (Gibson & Ferguson, 2008) and stored in an airtight container at 4–6°C until used for subsequent analysis.

Proximate Analysis

The proximate content of the samples will be determined in dry matter basis according to Association of Official Analytical Chemists (AOAC, 2000). The Kjeldahl method will be employed to determine protein. Crude lipids will be extracted with petroleum ether, using a Soxhlet apparatus and ash contents (gravimetric) will also be determined based on methods outlined in AOAC (2000). Total carbohydrate will be calculated by difference method (summing the proportions of moisture, crude protein, ash, and crude fat and subtracting the sum from 100) (Manzi *et al*., 2004). Gross energy will be calculated based Nguyen et *al.* (2007) and will be expressed in calorie, considering protein and carbohydrates both provide 4 calories per gram, while fat provides 9 calories per gram.

Mineral and Antinutrient Analysis

Zinc, calcium and iron contents will be determined using flame atomic absorption spectroscopy (FAAS) after ashing the samples (Osborne and Voogt, 1978). Standard analytical procedures will be followed to determine antinutrients (phytate). The molar ratio between antinutrient and mineral will be obtained after dividing the mole of antinutrient with the mole of the minerals (Woldegiorgis *et al*., 2015).

Statistical Analysis

The analysis will be carried out in triplicates for all determinations and the results of the triplicate will be expressed as mean ± standard deviation. Students t-test or Analysis of Variance (ANOVA) will be used to compare nutrients if there exist the same crop type with different variety and crops grown in different agroecological zones. Significance of the differences will be considered at p-value less than 0.05 and means separation will be done by *post hoc* test. Molar ratios of minerals to antinutrients will be compared to the acceptable level of the ratios. Similarly, between crops comparison for molar ratios of minerals to antinutrients will be carried out.

3.3.3. Specific objective 3

Assessing the level of household food security status and intra-household food consumption

In this section, the following information will be collected through household survey: household food access and adopted coping strategies used to manage household food shortage, intrahousehold variability in diet diversity between women and children over a similar reference period. Household data on socio-economic, demographic characteristics, nutrition and health related information will also be collected.

Household food security

Household level food insecurity status of previous month (30 days) will be assessed using the Household Food Insecurity Access Scale (HFIAS) (Coates *et al*., 2007). This score is used to assign households to one of the four food insecurity levels (food secure, mildly food insecure, moderately food insecure and severely food insecure) based on the frequencies of affirmative responses to the nine questions describing food insecurity scenarios. The scale comprises of 9 questions (worry about food, unable to eat preferred foods, eat just a few kinds of foods, eat foods they really do not want eat, eat a smaller meal, eat fewer meals in a day, no food of any kind in the household, go to sleep hungry, go a whole day and night without eating). The tool assesses the level of anxiety and uncertainty of the participants about household food supply, insufficient quality of food and insufficient food intake (Swindale & Bilinsky, 2006b).

The standard procedure for scoring HFIAS by Coates *et al*. (2007) will be used: zero is attributed if the event described by the question never occurred; 1 point if it occurred 1 or 2 times during the previous 30 d (rarely); 2 points if it occurred 3–10 times (sometimes); and 3 points if it occurred >10 times (often). For each household, the HFIAS score corresponds to the sum of these points and could range from 0 (food security) to maximum score 27 (severe food insecurity).

A household is considered food secured when none of the 9 scenarios are experienced or only sporadic "concern about food" is reported (first scenario). Food insecure if the response were “sometimes” or “always” to one or more of the nine occurrence questions. A severely food insecure household experiences one of the last three scenarios (running out of food, going to bed hungry, or going a whole day and night without eating).

Additionally, information on adopted coping strategies that people use to manage household food shortage will be assessed to determine the magnitude of food insecurity using comparative coping strategy index (Maxwell & Caldwell, 2008). This tool has five standard coping strategies with varying severity weights given in parentheses: eating less-preferred foods (1.0); borrowing food/money from friends and relatives (2.0); limiting portions at mealtime (1.0); limiting adult intake (3.0); and reducing the number of meals per day (1.0). Studied households will be asked *how often* if there have been times that they experienced the aforementioned strategies when they did not have enough food or money to buy food over seven days reference period preceding the survey. Total household score will be computed by summing weighted score (frequency * weight). For a quantitative household survey, the results will be comparable at the household level and averages will be comparable at higher village levels (Maxwell & Caldwell, 2008).

Household Diet Diversity

Assessing the diversity of foods consumed at household level using the Household Dietary Diversity Score (HDDS; Swindale and Bilinsky 2006a), based on a 24 h recall of foods consumed by any HH member from 12 food groups, including (i) cereals/breads, (ii) beans, (iii) potatoes and other roots/tubers, (iv) vegetables, (v) fruits, (vi) eggs, (vii) milk and milk products, (viii) fish, (ix) meat, (x) oil, fat or butter, (xi) sugar or honey, and, (xii) coffee and tea the day and night prior to the survey. The total number of food groups consumed will be used to classify households into lowest, medium and high dietary diversity. Households consumed three or less food groups considered low dietary diversity. Households consumed four or five food groups considered medium and those households consumed six or more food groups categorized as high. Geographic location of selected households will be collected using a hand-held Global Positioning System (GPS) device.

Child dietary assessment

Infant and Child Feeding Index (ICFI) will be used assess feeding practices of children (Moursi *et al*., 2008). It is an important indicator to collect information on key components of young child feeding practices and helps to determine the influence of complementary feeding practices on nutritional status of children (Lohia & Udipi, 2014). ICFI is a composite measure of infants feeding, in addition to breastfeeding status, mothers will be interviewed about infants complementary feeding practices including frequency of consumption of food groups, dietary diversity and feeding frequency per day. Dietary diversity scores will be calculated using seven food groups based on guidelines proposed by the Food and Nutrition Technical Assistance Project (FANTA, 2006). Food frequency questionnaire (FFQ) will be used to assess food group frequency score.

The ICFI scores will be added up giving a possible range of 0–9 for each age group (6-8months, 9-11monts and 12-24months). For all age groups, ICFI score of 0–5 considered low, 6–7 medium, and 8–9 high (Moursi *et al*., 2008). Median dietary diversity scores from seven food groups will be classified as low (0–2), medium (3–4) and high (> 4) according to Arimond and Ruel (2004).

Intrahousehold variability in diet diversity

Individual dietary diversity score between women and children will be used to assess diet intake adequacy over a similar reference period. Women's dietary consumption score from ten food groups will be recategorized into the seven groups recommended for children; then mothers' and children's dietary diversity will be compared. The purpose is to identify food groups that are available in the household as measured by mothers' dietary diversity are provided to children or vise-versa due to various reasons. Therefore, comparison of each food group consumption between women and child will made (Gebremedhin *et al*., 2017).

Data quality measures

Information on household food consumption will be collected using the previous 24-hours as a reference period (24-hour recall) since longer reference periods result in less accurate information due to imperfect recall (Swindale and Bilinsky 2006a). Household food and diet related questions will be administered to an individual who is responsible for food preparation, or if that person is unavailable, of another adult who was present at home and ate in the household the preceding day. Regarding when to collect the data, Swindale and Bilinsky (2006a) suggest during the period of greatest food shortages (such as immediately prior to the harvest) to capture changes in HDDS over time.

However, because of the cross-sectional nature of the present study, data will be collected once during the period in which adult members of the farming households are available around home (at post-harvest). However, HFIAS will assess and capture the preceding one-month duration of household food access before the survey. In addition, for the dietary intake assessment, commonly available foods for consumption in the villages will be assessed prior to the survey and will be listed down under each food group for ease of recall by respondents.

During the pretesting of study tools, HFIAS questions that are not straightforward will be modified in a way that is better understood by the respondents. This is will be done through rephrasing or adding local (context-specific) examples with still maintaining their core meaning as suggested by Gebreyesus *et al*. (2015). Cronbach's alpha measure will be done for internal consistency of the questionnaires.

Statistical Analysis

Descriptive statistics will be used to present household food security status, women's and child diet diversity score, adopted coping strategy index, infant and child feeding index. Comparison will be made between women and children in terms of consumption of each food groups consumed. Hierarchical multiple regression analysis will be used to relate household food preference as indicated by household diet diversity to various predictor variables including household food security status, socio-economic, and demographic factors.

3.3.4. Specific objective 4

Evaluating diet quality through nutritional status assessment and identifying hotspot areas of malnutrition

In this sub-section, from eligible participants, body measurement (anthropometry) will be carried out in both women and children, which includes body weight, height, mid-upper arm circumference. Micronutrient status will be evaluated for iron, vitamin A, and zinc by using the appropriate biomarkers with their respective cutoff values appropriate to non-pregnant women.

Eligibility Criteria

Inclusion Criteria

- 6-24 months of age for children
- 15-49 years for women of reproductive age (non-pregnant).
- The informed consent form has been read and signed by the women or caregiver (or has been read out to in case of illiteracy)

Exclusion Criteria

- Blood losses (surgery, accident), donations or transfusions during the past 4 months before study start.
- Participants taking part in other studies requiring the drawing of blood
- Taking nutritional supplements containing vitamins and minerals
- Long-term medication (except contraceptives for women of reproductive age)
- Any severe metabolic, gastrointestinal kidney or chronic disease such as diabetes, hepatitis, cancer, hypertension or cardiovascular diseases (according to the participants own statement).

Anthropometric measurements

Anthropometry is the measurement of body parameters to indicate nutritional status. Anthropometric data (weight, height/length) will be collected from children aged 6–23 months and women of reproductive age. A digital weighing scale designed in 100gram graduation will be used to measure weight. Length/height measurements will be taken with a precision of 0.1cm. For children height-for-age, weight-for-height and weight-for-age will be calculated using the WHO growth standard (WHO, 2006), Z-scores below −2.0 will be used generally to classify a child as stunted, wasted or underweight. Whereas, Z-scores below −3.0 indicate severe and −3 to <−2 for moderate forms of the condition. Z-scores for normal (−2 to +2). The anthropometric scores will be calculated using WHO Anthro software (v3.2.2) (WHO, 2009).

In women chronic energy deficiency will be assessed using body mass index (BMI; kg/m^2). Cut-off points for BMI are as follows: <18.5 underweight or chronic energy deficiency; 18.5–24.9 normal; 25.0–29.9 overweight; ≥30.0 obese. Underweight is further classified in to: at-risk for energy deficiency (17.0–18.4), moderate (16.0–16.9) and <16.0 severe chronic energy deficiency (Wirth *et al*., 2018). Mid-upper arm-circumference (MUAC) of the women will be measured to the nearest 0.1 cm, using MUAC tape. The measurement will be taken on the middle left arm at relaxed position, without any clothing and with optimal tape tension. Undernutrition is defined as MUAC less than 22 cm (Ferro-Luzzi & James, 1996; Gebreselassie *et al*., 2013)

Blood sample collection, serum extraction, and laboratory analysis

From apparently healthy women of reproductive age (15–49 years), approximately 5 mL of venous blood will be drawn into plain tubes. The blood will be clotted for 20 minutes and centrifuged at 3000 rpm for 10 minutes. Serum will be extracted and transferred immediately into screw-top vials/cryovials. The samples will be appropriately labelled transported in icebox, protected from direct light, and kept frozen at −20 ºC until analyzed (Gebreselassie *et al*., 2013; Wirth *et al*., 2018).

Hemoglobin concentrations will be adjusted for elevation and, for women, smoking status using World Health Organization guidelines (WHO, 2011). Following this adjustment, Hemoglobin concentrations less than 12 g/dL will be used to classify non-pregnant women as anemic, with concentrations of <8, 8–10.9, and 11–11.9 g/dL denoting severe, moderate and mild anemia, respectively (WHO, 2011).

Ferritin concentrations <15 µg/L will be used to define iron deficiency in women (WHO, 2011). Ferritin concentrations will be adjusted for inflammation using each subject's C-reactive protein (CRP) and/or α_1-acid glycoprotein (AGP) values applying the method suggested by Thurnham *et al*. (2010). Iron deficiency anemia defined by both low serum ferritin and low haemoglobin levels. Serum zinc concentration considered deficient at <10.7µmol/L or 70 µg/dL (De Benoist, 2007). Vitamin A (serum retinol) is deficient at <0.7µmol/L (WHO, 1996).

Statistical Analysis

Spatial pattern of occurrences of women undernutrition (underweight, anemia and other micronutrients deficiency) and child undernutrition (stunting, wasting, & underweight) will be explored within the whole study area (between villages) using Anselin Local Moran's *I* analysis tool to test whether the distribution of undernutrition is random over space. If distribution is not random, it helps to identify significant spatial clusters (Anselin *et al*., 2006). A significant negative z-score indicating spatial heterogeneity; whereas, a significant positive z-values indicates either higher or lower value clusters of undernutrition or a combination of both (Anselin, 2016).

A multilevel logistic regression model will be used due to the hierarchical structure of the sample and the binary outcome (Austin & Merlo, 2017; Uthman, 2008). The dependent variables, nutritional status of child and women of reproductive age, have a binary outcome of either the occurrence of undernutrition or not. Several multilevel logistic regression models will be fitted. The first will be the null model, it will incorporate only agroecological zone-specific random effects to model between-agroecological zone variation in nutrition status. The subsequent models will add village level production diversity, household level characteristics, and individual level covariates sequentially one after the other as indicated in Austin & Merlo (2017). The outputs of the analyses will be presented using estimated regression coefficients and odds ratio with their respective 95% CI. Appropriate statistical software will used for analysis.

Explanatory variables at child level (sex, age, birth interval, diet diversity score, and duration of exclusive breastfeeding), women level (age, education, nutrition knowledge, health-seeking behavior and nutrition status), household level (wealth status, household food security status, dependency ratio, household size, household head's gender), and village level (food production diversity) will be considered in the study for the logistic models. Women's health-seeking behavior will be assessed from her experience of pre-natal attendance, medical assistance at delivery, child vaccination, and immunization during pregnancy. The explanatory variables considered are found significant predictors of child and women's nutrition status in several previous studies (Haile *et al*., 2016; Hagos *et al*., 2017; Gebreselassie *et al*., 2013; Bhowmik & Das, 2018; Uthman, 2008).

Prior to running the model, variables will be tested for normality and the explanatory variables will also be checked for collinearity using variance inflation factor. Independent variables that will have P value <0.25 in the bivariate analysis will be considered as a potential predictor for the multivariate model (Bursac *et al*., 2008). Finally, how well the model fit the data will be checked and separate models will be fitted for the two outcome variables of interest, women and child undernutrition. To this end, the deviance information criterion (DIC) statistic will be used for each model to evaluate model performance; a model with lower DIC is considered as one with a better fit (Spiegelhalter *et al*., 2014). Descriptive statistics will also be used to analyse prevalence of undernutrition among children and women.

4. ETHICAL CONSIDERATION

The study will be conducted after obtaining approval for the protocol from the Ethics Committee of ITC and Institutional Review Boards from the Addis Ababa University, College of Natural and Computational Sciences (CNCS). In addition, a support letter from the Center for Food Science and Nutrition, CNCS, Addis Ababa University and a permission letter from Amhara regional and other administrative hierarchies will be written to the local administrators of the selected study villages/*kebeles*.

The overall objective of the study, risks and benefits of participating in the study will be clearly presented. When the participants are willing to take in the study, written informed consent will be obtained from the mother, head of the household or guardian in the house. The consent form will be signed by the data collector and witnessed by the team member (see Annex 1 for information sheet and consent form).

Interviews, height and weight measurements will be assessed and measured during household survey. Blood sample collection will be done in the nearest health facility within the village. All the information collected from participants will be kept confidential.

Finally, we will construct village-level prevalence maps rather than point maps to depict the specific location of households. This will be done to avoid the risk of linking confidential data to the particular spatial location of the households in the study.

6. EXPECTED OUTCOME OF THE STUDY

Unlike MDG with its limited focus of reducing hunger and underweight, the SDG requires all countries and their citizens to act together to ensure universal access to safe and nutritious food for all (Target 2.1) and to end all forms of malnutrition by 2030 (Target 2.2) (Development Initiatives, 2017; Ritchie *et al*., 2018). In line with this, Ethiopia also declared to end child malnutrition by 2030 through the *Seqota* Declaration (MoH, 2016). Setting targets is a good first step, but actions need to follow. Such actions again need to be supported by evidence at different scales. The present study therefore aims to provide a relevant information through assessing diet quality throughout the food system from production to consumption and evaluating the output of these activities through assessing nutritional status of individuals.

Since quality diets include sufficiency, diversity and safety, it is necessary to resolve all forms of malnutrition, ranging from extreme hunger and undernutrition to overnutrition, mainly through foods rich in nutrients (Webb *et al*., 2018). Food production diversity will be evaluated in terms of nutritional relevant food group that are considered important for diet adequacy. Nutrient density of available crops will be determined for macro and micro-nutrients concentration. In addition, household food security status and the geographic distribution of undernutrition among children and women's will be identified. These findings will reflect the status of essential nutrients availability and helps to identify what are the deficient/inadequate nutrient or food group(s) in the study area, as well as the spatial distribution of undernutrition will be identified for further consideration at village, household and individual levels.

Furthermore, as the study introduces remote sensing-based production estimate and diversity in smallholder farmland in the study area, this could further be used as a metrics to strengthen the agriculture-nutrition assessment link. Ethiopia has recently developed nutrition-sensitive agriculture strategy (MoANR & MoLF, 2016), showing that strong attention has been given by the government to improve nutrition through agriculture (Ruel *et al*., 2018). To this end, the present study will provide evidence for the implementation and ongoing assessment of this strategy; and thereby contribute to the national nutrition policy goal of reducing child and women undernutrition as well.

Generally, the study identifies geographic areas at high risk of undernutrition with potential responsible factors and thus provide concerned government sectors and development partners with useful local level information on how to address nutritionally vulnerable rural Ethiopians. The approach may help in assessing diet quality throughout the food system in other areas with similar context within the country or beyond.

6. ANTICIPATED LIMITATIONS OF THE RESEARCH

The cross-sectional nature of the study will restrict analysis to the potential relationship between nutritional status of children and women with several explanatory factors. Thus, results will be interpreted as associational rather than causal. However, with the help of statistical models that are able to control for potential confounders, the association and unique contribution of predictors will be identified.

The current political situation in Ethiopia with absence of peace and stability all over the country could affect the data collection process and overall study plan. In addition, the budget allocated to the field survey work may not be sufficient - taking in to account the economic and political situation of the country at present the living condition and services needed are obtained at relatively high cost. Frequent travelling, accommodation expenses, allowance to health professionals involved in collection of blood sample as the study is expected to do assessments at field, household, and individual levels.

7. FIELD WORK FINANCIAL PLAN

Table 2: Financial Plan

Ser No.	Activity	Quantity or (days of service)	Unit price €	Total €
1	Round trip Air ticket (Addis to Bahir Dar) *	2	200	400
2	Round trip Air ticket (Addis to Kommbolcha)	4	200	800
3	Accommodation	(180)	20	3,600
4	Enumerators /Assistants	3 (120)	15	5,400
5	Health professionals	(90)	30	2,700
6	Supervisor visit (transport & accommodation)	5	400	2,000
7	Fuel and lubricants	-	-	1,500
8	Training data collectors and tool pre-test	(3)	300	900
9	Stationary	1	300	300
10	Data clerk (data entry) **	1	300	300
11	Workshop attendance (International & national)	2		2,700
			Sub-total	20,600
			Contingency 15 %	3,090
			Grand total	**23,690**

N.B. Assuming that laboratory reagents/test kits, cost of analysis and satellite imagery expenses will be covered separately.

* To obtain permission and support letter from Amhara regional state.

** Data entry from paper-based questionnaire into statistical tool/software

8. RESEARCH TIMETABLE

Table 3: Research Time Table

Year	2018						2019												2020												2021												2022					
Month	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Stay in NL or Ethiopia	NL								ET												NL								ET												NL							
Activity																																																
Proposal writing	■	■	■	■	■	■	■	■																																								
Qualifier								■																																								
Tool dev't for data collection									■	■	■																																					
Preparation for field work											■	■																																				
Pre-testing data collection tools												■	■																																			
Field work (Field survey)													■	■	■	■	■																															
Field work (household survey)																		■	■	■																												
Crop nutrient analysis (lab)																			■	■																												
Micronutrient analysis (serum)																				■	*																											
Data organization & analysis																						■	■	■	■																							
Taking courses (at ITC)																							■	■	■	■	■	■	■																			
Writing paper 1 and 2																								■	■	■	■	■	■	■																		
Data analysis objective 3 & 4																															■	■	■	■														
Writing paper 3 & 4																																	■	■	■	■	■	■	■	■	■	■						
Synthesis and writing (thesis)																																										■	■	■	■	■		
Finalize and submit																																															■	
Thesis defense																																																■

* May require extension of Ethiopian stay by 1 month [Household survey]

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ANNEX 1: INFORMATION SHEET AND CONSENT

Information sheet

Greetings!

We are conducting a study entitled "Applying geo-spatial information for integrating crop, food and nutrition for a healthier food system in rural Ethiopia" which is a PhD research project of Centre for Food Science & Nutrition, College of natural and computational sciences, Addis Ababa University and Earth Observation Science, University of Twente (ITC), The Netherlands.

The study aims to conduct a comprehensive assessment of diet quality over the entire food systems (from production to consumption) through gathering data from remote sensing, agriculture field, household survey and individual's nutritional assessment in selected villages/*kebeles* in Amhara regional state, South Wollo zone, Ethiopia. This will provide potentially useful local level information on how to address among nutritionally vulnerable people residing in rural Ethiopia.

If you and your child participate in the study, you will receive your nutritional status assessment (body measurement) and level of micronutrients for free. If we detect that you (women of reproductive age) with severe anaemia (Haemoglobin <8g/dL), you will be given referral memo for medical visit for treatment.

We do not expect any relevant risks in this study. However, the collection of blood samples includes the small risks of bruise, infection and/or superficial inflammation and discomforts during having blood drawn. These risks will be minimized by using sterile equipment and technique and having done the blood collections by experienced medical laboratory technicians or nurses under medical supervision.

Whatever information you provide will be kept confidential and anonymous. The results from this study will only be used for the purpose of further improving mothers' and children's health and nutrition.

You have the right to refuse from participating in this research, if you do not wish to. You also have full right to withdraw at any time without explaining the reason why.

Experienced and trained data collectors conduct interviews at your residence. The interview, anthropometric measurement will take about 1 hour.

If you need any further explanation at any point, you can contact Mr. Habtamu Guja Bayu (Mobile +251966904768). If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact of the Ethics Committee of the Faculty of Geo-Information Science and Earth Observation that has reviewed & approved this research project (ec-itc@utwente.nl).

Do you have any questions?

Do you agree to participate in the study?

If yes, read the consent form to the participant, date and sign it. If no, thank and proceed to the next participant.

Consent Form for "*Applying geo-spatial information for integrating crop, food and nutrition for a healthier food system in rural Ethiopia*"

I have been informed about the objectives, risks and benefits of the study. I have also been informed about my rights not to participate in the study and withdraw any time without any consequences. I have been able to ask questions about the study and my questions have been answered to my satisfaction. I understand that taking part in the study involves: a survey questionnaire to be completed by the enumerator; body measurement and collection of blood samples.

I understand that personal information collected about me that can identify me will not be shared beyond the study team. However, I agree that my information may be shared with other researchers for future research studies that may be similar to this study.

Based on the information provided above, I have agreed to participate in the study.

_____________________ _____________________ ________

Name of **participant** (legal representative) Signature Date

I have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

____________________________ _________________________ __________

Name of **witness** Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

__________________________ ____________________ _________

Researcher's/Data collector's name Signature Date