Harvesting nutrition

Grain legumes and nutritious diets in sub-Saharan Africa

Ilse de Jager

Propositions

1. Increased consumption of grain legumes supports micronutrient not protein adequacy of the diet
   (this thesis)
2. Enhanced productivity of grain legumes decreases the farm size needed to produce a nutritious diet.
   (this thesis)
3. Exciting discoveries require mundane research.
4. Good researchers are comfortable with being stupid (inspired by an essay of Martin A. Schwartz 'the importance of stupidity in scientific research').
5. Debunking a myth triggers a holistic research perspective.
6. Interdisciplinary research is essential, but should not be conducted at the expense of generating insights within unique disciplines of expertise.
7. Diversity is the key for a good quality of life: diversity in food, friends and work.
8. Development work should take place on a wooden bench in front of a clay hut, not in an air-conditioned five star conference room.

Propositions belonging to the thesis, entitled

"Harvesting Nutrition. Grain legumes and nutritious diets in sub-Saharan Africa"

Ilse de Jager

Wageningen, 18 June 2019

Harvesting nutrition

Grain legumes and nutritious diets in sub-Saharan Africa

Ilse de Jager

Thesis committee

Promotor

Prof. Dr Ken E. Giller
Professor of Plant Production Systems
Wageningen University & Research

Co-promotor

Dr Inge D. Brouwer
Associate professor, Division of Human Nutrition and Health
Wageningen University & Research

Other members

Prof. Dr Paul C. Struik, Wageningen University
Dr Jessica Fanzo, Johns Hopkins University, USA
Prof. Dr Carl Lachat, Ghent University, Belgium
Dr Marrit M. van den Berg, Wageningen University

This research was conducted under the auspices of the Graduate School VLAG (Advanced studies in Food Technology, Agrobiotechnology, Nutrition and Health Sciences).

Harvesting nutrition

Grain legumes and nutritious diets in sub-Saharan Africa

Ilse de Jager

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 18 June 2019
at 4 p.m. in the Aula.

Ilse de Jager
Harvesting Nutrition. Grain legumes and nutritious diets in sub-Saharan Africa,
240 pages

PhD thesis, Wageningen University, Wageningen, the Netherlands (2019)
With references, with summary in English

ISBN: 978-94-6342-935-0
DOI https://doi.org/10.18174/474762

'If you want to go fast, go alone:
if you want to go far, go together'
African saying

Contents

Summary

Low quality diets is the number one risk factor for the global burden of disease. Agriculture is one of the sectors with strong potential to enhance the quality of diets; especially among rural populations in low and middle income countries where malnutrition levels are highest and agriculture is often still the most important source of food and income. In sub-Saharan Africa the availability of nutrient-dense foods such as legumes, dairy, meat, fruits, nuts and seeds has declined while the availability of grains less-dense in protein and micronutrients has increased. The protein and micronutrient intake from sub-Saharan African diets is often estimated to be inadequate. Grain legumes are appreciated for their contribution to dietary protein and micronutrient intake in addition to their benefits in replenishing soil fertility. This thesis describes the research conducted to investigate the potential of grain legume cultivation for nutritious diets of smallholder farming households in sub-Saharan Africa. The research was conducted both at crop level (Chapters 2 and 3) and at whole diet level (Chapters 4 and 5).

The current and potential role of grain legumes on protein, both quantity and quality, and micronutrient adequacy in the diet of rural Ghanaian infants and young children was studied (**Chapter 2**). Energy and nutrient (including amino acids) intakes of breastfed children of 6-8 months (*n*=97), 9-11 months (*n*=97), 12-23 months (*n*=114), and non-breastfed children of 12-23 months (*n*=29) were assessed using a repeated quantitative multi-pass 24-hour recall method. Food-based dietary guidelines that best cover nutrient adequacy within the constraints of the local current dietary patterns were modelled using the linear programming software Optifood (version 4.0.9, Optifood©). 60% of the children consumed legumes with an average portion size of 20 g per day contributing more than 10% of their total protein, folate, iron and niacin intake. The final food-based dietary guidelines included legumes and provided adequate protein and essential amino acids. Adding extra legumes to the food-based dietary guidelines, on top of the current dietary pattern, improved adequacy of calcium, iron, niacin and zinc but not reached sufficient amounts to meet requirements. Although legumes are often said to be the 'meat of the poor' and the current grain legume consumption among rural children does contribute to their protein intakes, the main nutritional benefit of increased legume consumption is improvement of micronutrient adequacy.

Within the framework of a large agricultural legume cultivation project (N2Africa), we studied (**Chapter 3**) the potential to improve children's dietary diversity by comparing

N2Africa and non-N2Africa households in a cross-sectional quasi-experimental design, followed by structural equation modelling and focus group discussions in rural Ghana and Kenya. Participating in N2Africa was not associated with improved dietary diversity of children. However, for soybean in Kenya, structural equation modelling (combining data from N2Africa and non-N2Africa households) indicated that via production for own consumption the dietary diversity of children can be improved, but indicated no effect via income and food purchases and no effect for both pathways in Ghana. Results are possibly related to differences in the food environment between the two countries as was found in the focus group discussions. These findings confirm the importance of the food environment for translation of enhanced crop production into improved human nutrition. This study also showed that in a situation where rigorous study designs cannot be implemented, structural equation modelling is a useful option to analyse whether agriculture projects have the potential to improve nutrition and focus group discussions can provide valuable additional explanatory qualitative information.

For a high quality diet, legumes need to be consumed in combination with other foods from different food groups. Therefore in Chapters 4 and 5, a systems approach was used studying the potential of legumes as well as all other foods cultivated to cover the food needs of households based on the food-based dietary guidelines developed for this thesis. In **Chapter 4**, the current situation was examined among 329 rural Ghanaian households. The food production of about 60% of the households did not cover their required quantities of grains and legumes and none covered their required quantities of vegetables. At nutrient level, the food production of over half the households supplied insufficient calcium (75.7%), vitamin A (100%), vitamin B_{12} (100%) and vitamin C (77.5%) to cover their requirements. The diversity of the production of a household was positively related with their food and nutrient coverage, but not with children's dietary diversity and nutrient adequacy. These findings suggest that the promotion of FBDGs alone is insufficient to lead to improvements in diets. Additional strategies are needed to increase the food availability and accessibility of the households, especially that of fruits and vegetables and also of grain legumes.

In **Chapter 5**, we used a farm-level systems approach to investigated the minimum farm size needed, the optimal crop combination to grow and the potential contribution of mainstream agricultural interventions to provide a nutritious diet and additional income in all seasons of the year for an average rural household in Northern Ghana. Linear programming was applied to model different scenarios and interventions. The food-based dietary guidelines developed for this thesis were used as well as data from other secondary sources for information on seasonal yields, waste factors, crop availability, crop land use

and prices for all crops produced in Northern Ghana. Results indicate that 75% of the household had sufficient farm size (>1.43 ha) to produce their food needs for a nutritious diet. Agricultural interventions increasing the yields of grains and legumes decrease the farm size needed to about 1 ha (17% of households reported a farm size <1 ha). The vegetable and fruit needs cannot be covered by the food produced in the farm during the 'hunger season' unless irrigation is applied. Households need to produce a diversity of foods to cover their food needs from own production. When household do not produce their own food needs, but need income from agriculture to purchase food, our analysis suggests that cultivating one or two of the most lucrative crops (onions and sweet potato), will result in the highest farm income. However, specialization also comes with increased risks, especially for small rural farming households. Using a farm-level system approach provided three major insights. First, considering seasonality is crucial in nutrition-sensitive farming. Ensuring a year-round nutritious diet requires enhanced availability of vegetables and fruits in the hunger season. Second, although staple crops are not nutrient-dense such as vegetables and fruits, increasing their yields may contribute to enhancing diets. It will decrease the farm size needed which enables households to produce sufficient to cover their food needs for a nutritious diet. Third, our approach confirms that smaller farms are unable to produce sufficient food to cover their needs and will depend on their income, both from agriculture and other sources, and the availability of foods on markets to meet their dietary needs.

Overall the results of this thesis show that the main contribution of grain legumes to nutritious diets is in terms of micronutrients intake and not protein intake. Whether a grain legumes cultivation project, such as N2Africa, will result in dietary improvements depends on the characteristics of the food environment, as well as whether a nutrition goal is set and activities such as nutrition behaviour change communication and women's empowerment are included. This thesis also shows that a mixed method design including pathway analysis is a good approach to study nutrition impact of agriculture interventions when RCTs are not possible. Finally, the thesis results show that investigating the gaps in food availability and food needs using a systems approach at farm level provides useful insights to be able to better coordinate and integrate nutrition across agricultural interventions and investments. For future agriculture and nutrition research: specialists from both disciplines should be involved from the start and be able to think outside of their discipline; a shift from research at crop level to whole diet level research is needed using a systems approach; economic and market knowledge are necessary; and testing the practical feasibility of research findings need to be planned and incorporated from the beginning. *Let's harvest nutrition!*

Chapter 1

Introduction

Background

Low quality diets is the number one risk factor for the global burden of disease (Global Burden of Disease Study 2015). Currently, three billion people have low quality diets and many people are malnourished (undernutrition, micronutrient deficiencies and/or overweight), especially in in low and middle income countries (LMICs) (GLOPAN 2016). To achieve the sustainable development goal (SDG) of ending malnutrition by 2030, the Global Panel on Agriculture and Food Systems for Nutrition (GLOPAN) calls for action to reposition "food systems from feeding people to nourishing people" (GLOPAN 2016). The need for agriculture, being an important component of food systems in LMICs, to support better nutrition and health has been specifically recognized in the discussions leading to the SDGs (United Nations 2017). Many agricultural projects are indeed initiated with this vision in mind and show promising benefits on improving diets.

Undernutrition persists, worldwide about one in four children are still stunted and more than two billion people are estimated to be affected by micronutrient deficiencies (UNICEF et al. 2018). Most of the population affected by undernutrition live in LMICs. Particularly young children and women of reproductive age are affected as their nutrient requirements increase due to growth, menarche and/or pregnancy. While globally the number of stunted children is slowly decreasing, Africa is the only region where the number of stunted children has risen and where currently more than one in three children are stunted (UNICEF et al. 2018). In addition, more than half of children under five years worldwide suffer from one or more key micronutrient deficiencies: vitamin A, iodine, iron, zinc and/or folate (FFI et al. 2009). Rates of most micronutrient deficiencies are also highest in sub-Saharan Africa: half of children have inadequate dietary intake of vitamin A (UNICEF 2018) and almost 50% of young children and 70% of pregnant women are affected by anaemia of which about 50% is estimated to be due to iron deficiency (de Benoist et al. 2008). At the same time the number of overweight children and adults (with higher increases among women) is increasing in every region and most rapidly in LMICs (UNICEF et al. 2018; Stevens et al. 2012). Nowadays one quarter of all overweight children live in Africa (UNICEF et al. 2018).

Malnutrition has enormous adverse impacts. During the first 1000 days of a child's life poor nutrition can result in stunted growth having life-long irreversible disadvantages: it impairs mental and physical development and thereby reduce school performance contributing to weakened adult labour productivity (IFPRI 2015). Malnutrition associated with low-quality diets is also the number one risk factor in the global burden of disease (Global Burden of

Disease Study 2015) and is responsible for almost half of all deaths of children under 5 (Black et al. 2013), mostly in LMICs. Overall the social and economic costs of malnutrition are high. The social costs of malnutrition in terms of increased morbidity and mortality has been quantified by the Disability Adjusted Life Years (DALYs). The Global Burden of Disease Study ranked the top risk factors of the global burden of disease by DALYs and showed that six of the top eleven risk factors of the global burden of disease are related to diet (Global Burden of Disease Study 2013; GLOPAN 2016). The global economic costs of malnutrition are high, in Africa and Asia the costs are estimated to be 11% of GDP (IFPRI 2016).

Investment in nutrition, and thereby preventing the adverse impacts of malnutrition, results in extremely high returns: $16 for every dollar invested (IFPRI 2016). Nutrition-specific interventions (see for definitions of key concepts Table 1) that reach the most vulnerable groups such as maternal multiple micronutrient supplementation and promotion of breastfeeding are effective in tackling the immediate determinants of malnutrition. Analysis showed that scaling up 10 key evidence-based nutrition-specific interventions to 90% coverage in 34 high-burden countries could reduce stunting by 20% (Bhutta et al. 2013). But nutrition-specific interventions alone are insufficient, and additional action is required to address the underlying determinants of malnutrition including: food security; caregiving resources at the maternal, household and community levels; and access to health services and a safe and hygienic environment. These interventions are referred to as nutrition-sensitive interventions. Agriculture is one of the sectors with strong potential to enhance impact on nutrition outcomes; especially among rural LMIC populations where malnutrition levels are highest and agriculture is often still the most important source of food and income required for nutrition and health (Pinstrup-Andersen 2012). Agriculture has the potential to improve food availability, food access, dietary quality, income and women's empowerment and thereby to indirectly improve nutrition outcomes (Ruel et al. 2018).

The number one risk factor for the global burden of disease is a low-quality diet (Global Burden of Disease Study 2015). Low-quality diets are often associated with current transformations of food systems driven by climate change, urbanization, income growth and population growth as they fail to provide sufficient, diverse, nutritious and safe food for all (GLOPAN 2016). Food systems that fail to enable quality diets are therefore considered as an underlying cause of malnutrition (GLOPAN 2016). Food systems influence the food environment of consumers and *vice versa* but the degree to which these external factors influence diets and nutrition outcomes of consumers differ for each setting (FAO 2016). In case of 'short chain food systems' in rural settings, the food supply chains are often short and local, and the food environments are mostly limited to one's own food production and informal local markets (HLPE 2017). Therefore most of the foods consumed in these systems come directly from the local area, are sold and bought unprocessed and the availability of food often depends on seasonality. However, in many LMIC the food system has undergone 'modernisation' and regional food systems are becoming integrated into global food systems resulting in changes in the food supply chains, in consumption patterns and in the link between the food system and the food environment (UNEP 2016). When incomes of households rise, households tend to rely less on staple grains and more on animal-sourced foods, vegetables and fruits but at the same time also consume more foods high in sugar, salt and saturated and trans-fats with negative impacts on health (HLPE 2017). Overall among LMIC populations the average diets fall far short of the recommended quantities of fruits, vegetables, dairy and other protein-rich foods (Keats and Wiggins 2014). The availability of legumes, dairy, meat, fruits, nuts and seeds has declined in sub-Saharan Africa while the availability of grains less-dense in protein and micronutrients has increased (Beal et al. 2017). The protein and micronutrient intake from sub-Saharan African diets is often estimated to be inadequate (Beal et al. 2017; Schönfeldt and Hall 2012).

Table 1. Definitions of key concepts

Grain legumes	Grain legumes are crops of the legume family (Fabaceae) cultivated specifically for their seeds for human food and animal feed. The most commonly grown grain legumes in West Africa are cowpea and groundnut, although soybean is increasing in popularity. The leaves of some grain legumes (e.g. cowpea) are also consumed by humans.
Nutrition-specific interventions	Interventions or programs that address the immediate determinants of foetal and child nutrition and development—adequate food and nutrient intake, feeding, caregiving and parenting practices, and low burden of infectious diseases (Ruel and Alderman 2013)
Nutrition-sensitive interventions	Interventions or programs that do not have nutrition as their primary goal but address the underlying determinants of foetal and child nutrition and development—food security; adequate caregiving resources at the maternal, household and community levels; and access to health services and a safe and hygienic environment—and incorporate specific nutrition goals and actions (Ruel and Alderman 2013)

Diet quality	There are many definitions for a good quality healthy diet. Most common criteria mentioned for a healthy diet (FAO 2016; WHO 2015): (1) needs to be *adequate* in energy and nutrients aligned with the specific dietary needs of a consumer; (2) is *diverse*, contains a variety of foods and food groups including fruits, vegetables, legumes and whole grains; (3) is *safe,* free of all hazards that may make food harmful to the health of a consumer; (4) contains little of *components of public health concern* such as free sugar, salt, saturated and trans fats (low intake of highly-processed foods); (5) is *appropriate*, in line with taste preferences, culture and economic resources of a consumer.
Food systems	Food systems comprises 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 outputs of these activities, including socio-economic and environmental outcomes. For nutrition and health outcomes of food systems, three constituent elements are identified of food systems, as entry and exit points for nutrition: *food supply chains* (influence the types of food available and accessible), *food environments* (influence the food choices, food acceptability and diets) and *consumer behaviour* (reflects the choices made by consumers influenced by personal preferences (taste, convenience, culture etc.) and by the existing food environment). (HLPE 2017)
Short chain food systems	In short chain food systems (in High Level Panel Expert (HLPE) report referred to as 'traditional food systems') consumers rely on minimally processed seasonal foods, collected or produced for self-consumption or sold mainly through informal markets. Food supply chains are often short and local, thus access to perishable foods such as animal source foods or certain fruits and vegetables can be limited or seasonal. Food environments are usually limited to one's own production and informal markets may be far from communities (HLPE 2017)
Food environment	The food environment is defined as the "collective physical, economic, policy, and socio-cultural surroundings, opportunities, and conditions that influence people's food and beverage choices" (Swinburn et al. 2015). Herforth and Ahmed (2015) define the food environment as the availability, affordability, convenience and desirability of various foods."

Grain legumes are recognized for their potential significant role in food systems to address future food security and nutritional needs (Ranganathan et al. 2016; GLOPAN 2016). Legumes have the unique ability to fix atmospheric nitrogen in the soil and thereby replenish soil nutrients, reduce fertilizer requirements and increase yield in subsequent crops (Giller et al. 2013). In order to know whether grain legumes indeed are able to address future food security and nutritional needs, we need to understand the role of grain legumes within a healthy diet; the potential underlying pathways from increased grain legume production through increased consumption to improved nutrition outcomes; whether sufficient grain legumes are available to cover the legume needs within a healthy diet and what other food and nutrient gaps exist; and what nutrition-sensitive agricultural interventions have greatest potential to close these food gaps. Figure 1 shows an overview of these knowledge gaps embedded within the theoretical framework of agriculture and nutrition pathways and the food environment.

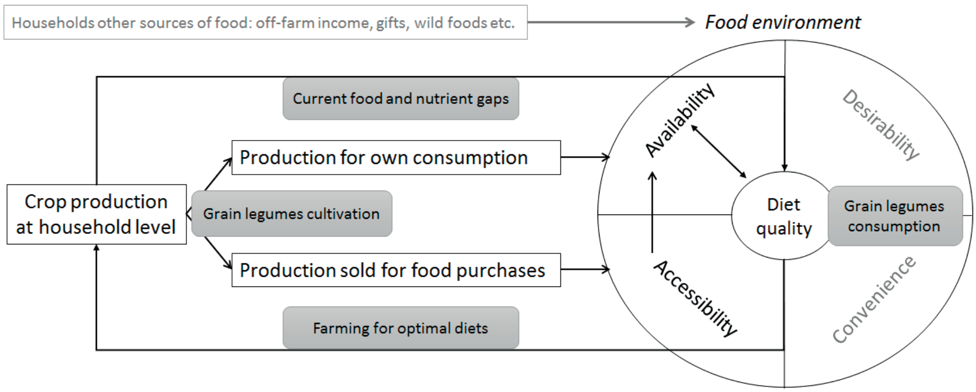

Figure 1. How to harvest nutrition: knowledge gaps of the potential of grain legumes embedded within the theoretical framework of agriculture and nutrition pathways and the food environment

Grain legumes within a healthy diet

Within diets, legumes are appreciated for their contribution to protein and micronutrient intake (Iqbal et al. 2006; Mudryj et al. 2014). Compared with maize, the most commonly consumed staple globally, legumes are better sources of protein and are richer in the key micronutrients folate, niacin, thiamine, calcium, iron and zinc, although nutrient concentration vary considerably between grain legumes, varieties and locations (USDA 2016; FAO 2012; South African MRC 2010). In addition, being a good source of essential amino acids (EAAs) and especially of lysine, grain legumes are complementary to most staple foods, improving the protein quality of the diet (USDA 2016; FAO 2012; South African MRC 2010; National Institute of Nutrition 2017; Mudryj et al. 2014). Protein intake is often estimated to be inadequate and the protein quality of the intake is assumed to be low in LMICs especially in sub-Saharan Africa (Schönfeldt and Hall 2012). Several studies suggest that dietary intake of EAAs may be insufficient in stunted children, especially that of lysine which is the most limiting EAA in cereal based diets (Semba et al. 2016; Ghosh et al. 2012; Gunaratna et al. 2010). Therefore increasing the consumption of grain legumes in sub-Saharan Africa has potential to close the existing protein and micronutrient gaps. Yet evidence on actual consumption and nutrient contribution of grain legumes is limited: available data show large variation between regions and age groups (Mesfin et al. 2015; Abizari et al. 2017). Optimisation studies developing food-based recommendations (FBRs) based on current dietary patterns of infant and young children (IYC) in LMICs, do show that combinations of local foods including grain legumes improve but do not provide adequate amounts of all nutrients (Skau et al. 2014; Talsma et al. 2017; Raymond et al. 2017; Kujinga et al. 2018). However, none of these studies included protein quality (adequacy of EAAs) in their analyses, nor did they test whether inclusion of a further increase of grain legumes consumption would potentially be able to reach protein and nutrient adequacy.

Pathways: from grain legume cultivation to nutrition

The current productivity of most legumes is lowest in LMICs, especially in sub-Saharan Africa (Nedumaran et al. 2015; Pingali 2012). Overall the availability of legumes has decreased as well as other crops high in protein and micronutrients (Beal et al. 2017). Therefore boosting grain legume productivity and production of smallholder farmers in sub-Saharan Africa has the potential to increase both the availability and consumption of grain legumes and improving diets. Literature describes different theoretical pathways through which agriculture may affect nutrition outcomes, both positively and negatively (Herforth and Harris 2014; Ruel and Alderman 2013; Hoddinott 2011). The main pathways that recur in literature are: the production-own consumption, the income-food purchase and the women's empowerment pathways. The production-own consumption pathway is based on the assumption that increased production of food and/or nutritious foods may increase consumption of these foods and/or may add to dietary diversity (Du et al. 2015; Masset et al. 2012). Greater dietary diversity is a good predictor of improved nutrient adequacy of the diet (Kennedy et al. 2007; Moursi et al. 2008). In case of increased legume production, this may lead to increased legume consumption improving dietary diversity and adding to dietary intake of energy, proteins, minerals and B vitamins. The income-food purchase pathway assumes that increased agricultural income through increased production is used for immediate or future household needs, including food and non-food purchases to support improved nutrition outcomes such as dietary diversity (Du et al. 2015). The women's empowerment pathway is a cross-cutting pathway interacting with the production-own consumption and the income-food purchase pathway. In the case of increased legume production, higher women's status may lead to greater control over resources like income from sale of legume produce that in turn may result in intra-household channelling of nutritious foods to the advantage of children and/or to more income spent on nutritious foods (Smith et al. 2003; UNICEF 2011). However, the increase of women's participation in agriculture may trade off with time spent on care practices negatively influencing child nutrition (Barrios 2012; Cunningham et al. 2015).

Earlier reviews of evidence showed that our understanding of what and how agriculture can contribute to nutrition recently was still very limited (Masset et al. 2012; P. R. Berti et al. 2004; Pandey et al. 2016; Girard et al. 2012; Webb and Kennedy 2014). However, as the attention for and implementation of nutrition-sensitive agriculture interventions has increased over the last years, so has the evidence base. A recent review indicates that research published from 2014 onwards show that "nutrition-sensitive agricultural interventions consistently improve household access to nutritious foods and the quality of mothers' and young children's diets" but find very limited impact on stunting (Ruel et al. 2018). Interventions included in this review were biofortification, home gardening, irrigation, value chains, livestock and agricultural extension implemented in LMIC– both impact evaluation studies including experimental and quasi-experimental designs and observational studies reporting associations were included. Only one impact study in the recent review by Ruel et al. (2018) included providing legume seeds as part of an integrated intervention also having components such as behaviour change communication on child feeding through women's groups and the provision of goats and chicken (Ruel et al. 2018). The study found a decrease in wasting and prevalence of infections but not in stunting among children in the intervention group and also found a decrease on women's time spent on child care (Kumar et al. 2018). An earlier study not included in the recent review found that an agricultural and nutrition education project that offered different legume intercrops to farmers in Malawi, increased production of grain legumes as well as frequency of grain legumes consumption by children (Bezner Kerr et al. 2007; Bezner Kerr et al. 2010) but did not report on the impact on dietary diversity. Overall the evidence for agriculture interventions specifically boosting grain legume production and the impact on nutrition and the underlying pathways is still limited.

In general recent studies had stronger programme designs including nutrition objectives, clearer target groups, more rigorous evaluation designs (preferably randomized controlled trials (RCTs)) with better sample size calculations, better data analysis approaches (including control groups for example) and more standardized nutrition outcomes (Ruel et al. 2018). However, weaknesses remained in some studies such as proper comparison groups and lack of baseline information (Ruel et al. 2018). In case of project evaluations, RCTs are often not a practical and/or ethical option. Therefore a 'mixed methods' design is used more frequently in project evaluations as the triangulation of complementary methods may add more rigour (Creswell and Plano Clark 2011). Structural equation modelling (SEM), in combinations with other methods, has not been used in agriculture and nutrition evaluations yet and may be a relevant additional method in this field. In addition, to better understand the findings of agriculture and nutrition evaluations and the underlying pathways, (qualitative) information on the local food environment would be very valuable as it is at the interface between food production and dietary intake. However, limited studies take into account the food environment of consumers in agriculture-nutrition evaluations (Herforth and Ahmed 2015).

Nutritious diets: food and nutrient gaps

People do not consume only one food product such as grain legumes but consume a complete diet consisting of different foods from different food groups. Besides the potential contribution of grain legume cultivation to increased consumption of legumes and dietary diversity, there is the need to take a broader perspective to the potential of the current legume availability to cover the legume needs as part of a healthy diet. Linear programming is a useful tool to model optimised diets based on local actual dietary patterns and costs and to develop sets of food-based dietary recommendations (FBDGs) that best cover the nutrient needs for specific populations. Linear programming is an algorithm for maximising or minimising a given linear objective function subject to a set of constraints. Different tools are developed to optimise diets based on linear programming of which Optifood is one. In the Optifood tool, the desired nutrient intakes are modelled as goals instead of constraints which is often done by other diet optimisation models. This allows for solutions with realistic combinations of local foods but this optimal realistic combination may not necessarily cover all the nutrient needs of a specific target population (Ferguson et al. 2006). As the FBDGs developed by the Optifood programme are based on actual dietary patterns and their costs, it is implicitly assumed that the combination of foods recommended is realistic and feasible to adopt by the target population. The foods recommended are assumed to be available, affordable and acceptable for the target population. However, the analysis is based on the distribution of the types and frequencies of foods consumed, and often uses the extreme ends of these distributions to arrive at FBDGs that cover most of the nutrient needs. It therefore remains unclear whether the foods recommended by the developed FBDGs are indeed available to the population under study and whether the FBDGs can be adopted.

The availability of recommended foods such as grain legumes is a key condition for the adoption of FBDGs and for improving diets in general (Herforth and Ahmed 2015). In short chain food systems in most rural settings in LMICs, the food availability depends largely on one's own production and the nearby local informal markets (HLPE 2017). An understanding of whether and to what extent households can meet their grain legume needs and their other food needs that cover their nutrient requirements through their own production may inform to what extent an intervention boosting legume production is needed to close food gaps and what other agricultural strategies are required to facilitate an enabling food environment for a nutritious diet (as recommended by FBDGs). Diversifying smallholder's own crop production is often mentioned as a potential effective nutrition-sensitive agricultural strategy in short chain food system settings. Two recent reviews show that increasing diversity of crop production of smallholder households in LIMC is indeed associated with more diverse diets (Jones 2017; Sibhatu and Qaim 2018). Nevertheless, limited studies included quantitative (individual) dietary intake data to test this association. To date no studies are conducted investigating whether local developed FBDGs are supported by both the diversity and quantity of the own production of a household and limited studies are conducted investigating the association between crop diversity of own production and diverse diets using individual quantitative dietary intake data.

A nutrition-sensitive farm

When current agricultural production does not support high quality diets, then how should a farm that does support high quality diets look like? And which agricultural interventions are necessary to achieve this optimal farm design? Current mainstream agricultural interventions generally focus on increasing income of rural farming households by improving production of staple crops but are not designed to increase availability of nutritious diets. To contribute to nutritious diets, agricultural interventions need to have an explicit nutrition goal, a component of nutrition behaviour change and include efforts to empower women's status (Ruel et al. 2018). Interventions that include these components are referred to as nutrition-sensitive agricultural interventions. Evaluations of such nutrition-sensitive agricultural interventions are increasingly conducted. Nevertheless, such evaluations do not provide advice to farmers what crops to grow that will ensure availability of foods to fulfil the nutrition needs of their household, as well as income required for other essential items such as housing, clothing, education and health care. Using a systems approach at farm level might provide more insights in what farmers need to grow and what effects mainstream agricultural interventions may have on the availability of a nutritious diet. Seasonality is an important consideration when taking a systems approach and essential in achieving year-round availability of nutritious diets. Almost 60% of sub-Saharan Africa has only one cropping season and a long dry season (Ker 1995). The availability of perishable but often nutrient-dense foods such as, fruits, vegetables and animal source foods is often limited especially towards the end of the dry season (HLPE 2017; Devereux 2009). In this so-called 'hunger season', food prices often increase and consequently also the costs of a nutritious diet increase (Masters et al. 2018). This may result in decreased dietary diversity (Abizari et al. 2017) and in child growth deficits (Fentahun et al. 2018). Investigating the optimal crop combinations in all seasons at farm level may provide insight in the potential contribution of single crop interventions to the overall availability of foods for nutritious diets. Dietary impacts of such mainstream agricultural interventions are rarely studied, although these may contribute to the availability of foods for nutritious diets.

Rationale and objectives

Globally, the prevalence of malnutrition in all its forms remains still high and many people consume low quality diets being the number one risk factor for the global burden of disease. Malnutrition affects the progress towards multiple SDGs, especially the SDG 'end hunger, achieve food security and improved nutrition and promote sustainable agriculture' and urgent action is needed (United Nations 2017). Food systems, and specifically the agricultural sector, are recognized as having an important role in nourishing people (GLOPAN 2016; United Nations 2017). However, our understanding about food systems, food environments, agriculture, food availability and quality diets is limited. The overall aim of this thesis is to provide insight in the potential of grain legumes cultivation for nutritious diets of smallholder farming households in sub-Saharan Africa. To achieve this overall aim, four specific objectives were defined:

- To assess the current and potential role of grain legumes on protein and micronutrient adequacy of the diet of rural Ghanaian infants and young children
- To assess the underlying pathways between grain legumes cultivation and children's dietary diversity in smallholder farming households in Ghana and Kenya
- To assess to what extent the production of smallholder farming households supports the adoption of food-based dietary guidelines in rural Northern Ghana
- To assess the minimum farm size needed, the optimal crop combination to grow and the potential contribution of mainstream agricultural interventions to provide a nutritious diet and additional income in all seasons of the year for an average rural household in Northern Ghana

Outline of thesis

Chapter 2 describes the current and potential role of grain legumes on protein (both quantity and quality) and micronutrient adequacy of diets among infants and young children in rural Northern Ghana using quantitative dietary intake data and linear programming to develop FBRs. A study using mixed methods to assess the underlying pathways between grain legume cultivation and children's dietary diversity in Ghana and Kenya is described in Chapter 3. Chapter 4 reports on a study that explored the food and nutrient gaps in rural Ghana by using the developed FBRs to estimate households' food needs and to what extent their own production fulfilled these needs. A study using a farm-level system approach to investigate the potential of mainstream agricultural interventions to contribute to nutritious diets and additional income of rural Ghanaian households throughout the year is described in Chapter 5. Finally, in Chapter 6, the collective findings of these studies, methodological considerations and suggestions for future research are discussed.

Study setting

The "Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa - N2Africa" project

The study was conducted in the context of an agricultural intervention designed to boost grain legume production: the N2Africa project. N2Africa is a large scale development-to-research project that aims to enable smallholder African farmers to benefit from symbiotic nitrogen fixation by grain legumes through effective production technologies to improve their soil fertility, household nutrition and income (Giller et al. 2013). The main legume crops N2Africa focuses on are common bean (*Phaseolus vulgaris*), chickpea (*Cicer arietinum*), cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea*) and soybean (*Glycine max*). The amount of nitrogen fixed by grain legumes depend on the interaction between the genotype of the legume, the genotype of the rhizobia, the environment and crop management. N2Africa selects and tests potential good legume genotypes and the best matching rhizobia and tries to optimize management practices. Legume technologies are tested by a large number of farmers which allows for tailoring and adapting technologies to specific sites and specific farmers and results in a set of best-fit options for each project area. In addition, N2Africa links science with capacity building, considers women's empowerment, and enhances access to markets through Public-Private Partnerships. N2Africa has been active since 2013 in Ethiopia, Ethiopia, Tanzania and Uganda, and since 2009 in DR Congo, Ghana, Kenya, Malawi, Mozambique, Nigeria, Rwanda and Zimbabwe.

Study area

The study was conducted in two mandate zones of the N2Africa project with contrasting agro-ecological characteristics: in Northern Ghana and in Western Kenya (Table 2). In Northern Ghana, the study was carried out both in Karaga district in Northern Region and Bawku West district in Upper East Region (Figure 1). Among the districts where N2Africa was implemented, these two districts differed most in agro-ecological characteristics and were assumed to best represent Northern Ghana. The quantitative dietary intake study was carried out in a sub-district of Karaga, Karaga sub-district. In Western Kenya, the study was carried out both in Western and Nyanza province in Kenya (Figure 1). Among the locations where N2Africa was implemented, these two provinces differed most in agro-ecological characteristics and were assumed to best represent Western Kenya.

Table 2. Agro-ecological characteristics (Franke et al. 2011) and stunting data (Ghana Statistical Service et al. 2015; National Council for Population and Development (NCPD) 2015) of Northern Ghana and Western Kenya

	Northern Ghana	**Western Kenya**
Cropping season	one season of 5-6 months (from May)	short season of 3 months (from October) long season of 6 months (from March)
Annual temperature	28 °C	21 °C
Annual rainfall	900 to 1040 mm	1350 to 1800 mm
Main crops	maize, rice, sorghum, pearl millet, soybean, cowpea, groundnut and yam	maize, pearl millet, groundnut, tea, beans, cassava and sweet potato
Travel time to urban markets	1 to 7 hours	1 and 5 hours
Population density	50 to 100 inhabitants/km^2	300 to 1200 inhabitants/km^2
Stunted children under 5 years	30 %	26 %

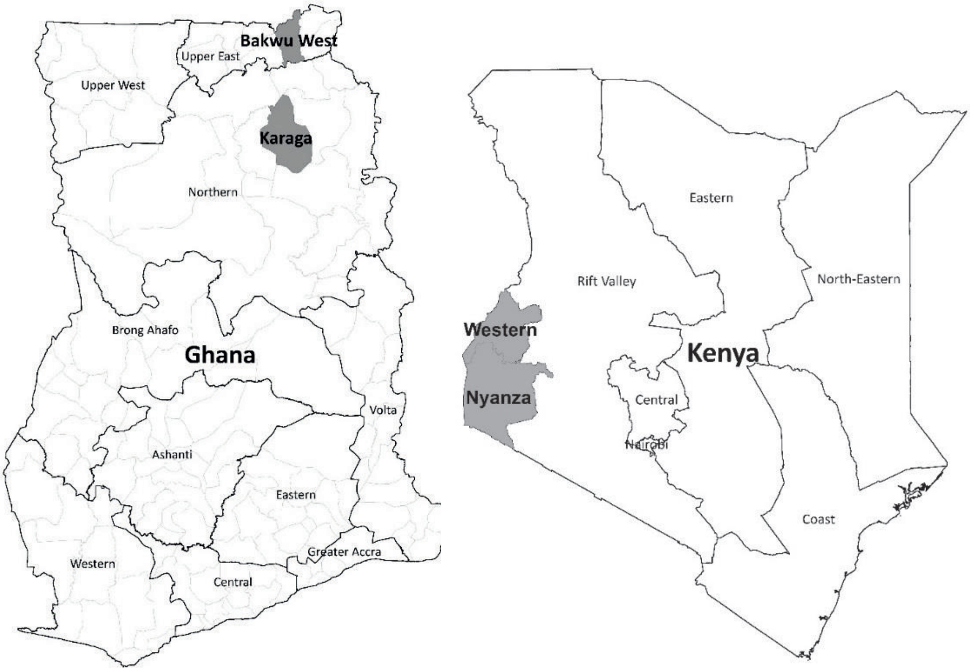

Figure 2. Map of Ghana, Karaga and Bawku west district (left) and map of Kenya, Nyanza and Western province (right)

References

Abizari, A.-R., Azupogo, F., Nagasu, M., Creemers, N., & Brouwer, I. D. (2017). Seasonality affects dietary diversity of school-age children in northern Ghana. *PLoS One, 12*(8), e0183206.

Barrios, P. L. (2012). *Relationship between household srtucture, maternal autonomy and undernutrition in Brazilian children*. The State University of New Jersey, New Brunswick, USA.

Beal, T., Massiot, E., Arsenault, J. E., Smith, M. R., & Hijmans, R. J. (2017). Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLoS One, 12*(4), e0175554.

Berti, P. R., Krasevec, J., & FitzGerald, S. (2004). A review of the effectiveness of agriculture interventions in improving nutrition outcomes. *Public Health Nutrition, 7*(5), 599-609.

Bezner Kerr, R, Berti, P. R., & Shumba, L. (2010). Effects of a participatory agriculture and nutrition education project on child growth in northern Malawi. *Public Health Nutrition, 14*(08), 1466-1472.

Bezner Kerr, R, Snapp, S., Chirwa, M., Shumba, L., & Msachi, R. (2007). Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil feritlity. *Experimental Agriculture, 43*(04), 437-453.

Bhutta, Z. a., Das, J. K., Rizvi, A., Gaffey, M. F., Walker, N., Horton, S., Webb, P., Lartey, A., & Black, R. E. (2013). Evidence-based interventions for improvement of maternal and child nutrition: what can be done and at what cost? *Lancet, 382*, 452-477.

Black, R. E., Victora, C. G., Walker, S. P., Bhutta, Z. a., Christian, P., de Onis, M., Ezzati, M., Grantham-McGregor, S., Katz, J., Martorell, R., & Uauy, R. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet, 382*, 427-451.

Creswell, J. W., & Plano Clark, V. L. (2011). *Designing and conducting mixed methods research*. California, USA: SAGE Publications.

Cunningham, K., Ruel, M., Ferguson, E., & Uauy, R. (2015). Women's empowerment and child nutritional status in South Asia: a synthesis of the literature. *Maternal & Child Nutrition, 11*(1), 1-19.

de Benoist, B., Mclean, E., Egli, I., & Cogswell, M. (2008). Worldwide Prevalence of Anemia 1993–2005: WHO Global Database on Anemia. Geneva, Switzerland: WHO.

Devereux, S. (2009). Seasonality and social protection in Africa. In D. Hughes (Ed.). www.future-agricltures.org: Future agricultures

Du, L., Pinga, V., Klein, A., & Danton, H. (2015). Leveraging agriculture for nutrition impact through the Feed the Future initiative. *Adv Food Nutr Res, 74*, 1-46.

FAO (2012). West african food composition table. Rome, Italy: FAO.

FAO (2016). Influencing food environments for healthy diets. http://www.fao.org/3/a-i6491e.pdf Accessed August 2018.

Fentahun, N., Belachew, T., Coates, J., & Lachat, C. (2018). Seasonality and determinants of child growth velocity and growth deficit in rural southwest Ethiopia. *BMC Pediatrics, 18*, 20.

Ferguson, Darmon, N., Fahmida, U., Fitriyanti, S., Harper, T. B., & Premachandra, I. M. (2006). Design of optimal food-based complementary feeding recommendations and identification of key "problem nutrients" using goal programming. *The Journal of Nutrition, 136*, 2399-2404.

FFI, GAIN, MI, UNICEF, USAID, World Bank, & WHO (2009). Investing in the future. A united call to action on vitamin and mineral deficiencies. Global report 2209. Canada: MI.

Franke, A. C., Rufino, M. C., & Farrow, A. (2011). Characterisation of the impact zones and mandate areas in the N2Africa project. Wageningen, The Netherlands: N2Africa.

Ghana Statistical Service, Ghana Health Service, & ICF International (2015). Ghana demograhic and health survey 2014. Rockville, USA: GSS, GHS and ICF International.

Ghosh, S., Suri, D., & Uauy, R. (2012). Assessment of protein adequacy in developing countries: quality matters. *British Journal of Nutrition, 108 Suppl 2*, S77-87.

Giller, K. E., Franke, A. C., Abaidoo, R., Baijukya, F. P., Bala, A., Boahen, S., Dashiell, K., Katengwa, S., Sanginga, J., Sanginga, N., Simmons, A., Turner, A., Woomer, P. L., Wolf, J. d., & Vanlauwe, B. (2013). N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa. In B. Vanlauwe, P. van Asten, & G. Blomme (Eds.), *Agro-ecological Intensification of Agricultural Systems in the African Highlands* (pp. 156-174). London, UK: Routledge.

Girard, A. W., Self, J. L., McAuliffe, C., & Olude, O. (2012). The effects of household food production strategies on the health and nutrition outcomes of women and young children: a systematic review. *Paediatr Perinat Epidemiol, 26 Suppl 1*, 205-222.

Global Burden of Disease Study (2013). Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet, 386*(9995), 743-800.

Global Burden of Disease Study (2015). Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet, 386*(10010), 2287-2323.

GLOPAN (2016). Food systems and diets: facing the challenges of the 21st century. London, UK.

Gunaratna, N. S., de Groote, H., Nestel, P., Pixley, K. V., & McCabe, G. P. (2010). A meta-analysis of community-based studies on quality protein maize. *Food Policy, 35*(3), 202-210.

Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security, 7*(3), 505-520.

Herforth, A., & Harris, J. (2014). Understanding and applying primary pathways and principles. Brief 1: Improving nutrition through agriculture. Arlington, USA: USAID/Strengthening Partnerships, Results, and Innovations in Nutrition Globally (SPRING) Project.

HLPE (2017). Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. . Rome.

Hoddinott, J. (2011). Agriculture, health, and nutrition: Toward conceptualizing the linkages. Washington DC, USA: IFPRI.

IFPRI (2015). Global Nutrition Report 2015: Actions and accountability to advance nutrition and sustainable development. Washington, DC.

IFPRI (2016). Global nutrition report 2016. From promise to impact: ending malnutrition by 2030. Washington, DC.

Iqbal, A., Khalil, I. A., Ateeq, N., & Sayyar Khan, M. (2006). Nutritional quality of important food legumes. *Food Chemistry, 97*(2), 331-335.

Jones, A. D. (2017). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. *Nutrition Reviews*.

Keats, S., & Wiggins, S. (2014). Future diets: implications for agriculture and food prices. London, UK: ODI.

Kennedy, G. L., Pedro, M. R., Seghieri, C., Nantel, G., & Brouwer, I. (2007). Dietary diversity score is a useful indicator of micronutrient intake in non-breast-feeding Filipino children. *The Journal of Nutrition, 137*(2), 472-477.

Ker, A. (1995). *Farming systems in the African Savanna*. Canada: International Development Research Centre (IDRC).

Kujinga, P., Borgonjen-van den Berg, K. J., Superchi, C., Ten Hove, H. J., Onyango, E. O., Andang'o, P., Galetti, V., Zimmerman, M. B., Moretti, D., & Brouwer, I. D. (2018). Combining food-based dietary recommendations using Optifood with zinc-fortified water potentially improves nutrient adequacy among 4- to 6-year-old children in Kisumu West district, Kenya. *Maternal & Child Nutrition, 14*(2), e12515.

Kumar, N., Nguyen, P. H., Harris, J., Harvey, D., Rawat, R., & Ruel, M. T. (2018). What it takes: evidence from a nutrition- and gender-sensitive agriculture intervention in rural Zambia. *Journal of Development Effectiveness, 10*(3), 341-372.

Masset, E., Haddad, L., Cornelius, A., & Isaza-Castro, J. (2012). Effectiveness of agricultural interventions that aim to improve nutritional status of children: systematic review. *The British Medical Journal, 344*, d8222.

Masters, W. A., Bai, Y., Herforth, A., Sarpong, D. B., Mishili, F., Kinabo, J., & Coates, J. C. (2018). Measuring the Affordability of Nutritious Diets in Africa: Price Indexes for Diet Diversity and the Cost of Nutrient Adequacy. *American Journal of Agricultural Economics*, aay059-aay059.

Mesfin, A., Henry, C., Girma, M., & Whiting, S. J. (2015). Use of pulse crops in complementary feeding of 6-23-month-old infants and young children in Taba Kebele, Damot Gale district, Southern Ethiopia. *J Public Health Afr, 6*(1), 357.

Moursi, M. M., Arimond, M., Dewey, K. G., Trèche, S., Ruel, M. T., & Delpeuch, F. (2008). Dietary diversity is a good predictor of the micronutrient density of the diet of 6- to 23-month-old children in Madagascar. *The Journal of Nutrition, 138*, 2448-2453.

Mudryj, A. N., Yu, N., & Aukema, H. M. (2014). Nutritional and health benefits of pulses. *Applied Physiology, Nutrition and Metabolism, 39*(11), 1197-1204.

National Council for Population and Development (NCPD) (2015). Kenya demographic and health Survey (2014 KDHS): Final Report. Demongraphic and Health Surveys. Nairobi, Kenya: KNBS, Ministry of Health, NACC, KEMRI, NCPD.

National Institute of Nutrition (2017). Indian Food Composition Tables. Hyderabad, India: National Institute of Nutrition (NIN).

Nedumaran, S., Abinaya, P., Jyosthnaa, P., Shraavya, B., Parthasarathy Rao, & Cynthia Bantilan (2015). Grain legumes production, consumption and trade trends in developing countries. Working paper series No 60. ICRISAT research program, markets, institutions and policies. Telangana, India: International Crops Research Institute for the Semi-Arid Tropics.

Pandey, V. L., Mahendra Dev, S., & Jayachandran, U. (2016). Impact of agricultural interventions on the nutritional status in South Asia: A review. *Food Policy, 62*, 28-40.

Pingali, P. L. (2012). Green Revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences, 109*(31), 12302-12308.

Pinstrup-Andersen, P. (2012). The food system and its interaction with human health and nutrition. In *Reshaping agriculture for nutrition and health: an IFPRI 2020 book* (pp. 21-29). Washington DC, USA: IFPRI.

Ranganathan, J., Vennard, D., Waite, R., Dumas, P., Lipinski, B., Searchinger, T., & GLOBAGRI-WRR MODEL AUTHORS (2016). Shifting diets for a sustainable food future. Working paper, installment 11 of creating a sustainable food future. Washington, DC: World Resources Institute.

Raymond, J., Kassim, N., Rose, J. W., & Agaba, M. (2017). Optimal formulations of local foods to achieve nutritional adequacy for 6–23-month-old rural Tanzanian children. *Food Nutr Res, 61*(1), 1358035.

Ruel, & Alderman, H. (2013). Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? *The Lancet, 382*, 536-551.

Ruel, Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security, 17*, 128-153.

Schönfeldt, H. C., & Hall, N. G. (2012). Dietary protein quality and malnutrition in Africa. *British Journal of Nutrition, 108*, 69-76.
Semba, R. D., Shardell, M., Sakr Ashour, F. A., Moaddel, R., Trehan, I., Maleta, K. M., Ordiz, M. I., Kraemer, K., Khadeer, M. A., Ferrucci, L., & Manary, M. J. (2016). Child stunting is associated with low circulating essential amino acids. *EBioMedicine, 6*, 246-252.
Sibhatu, K. T., & Qaim, M. (2018). Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy*.
Skau, J. K. H., Bunthang, T., Chamnan, C., Wieringa, F. T., Dijkhuizen, M. A., Roos, N., & Ferguson, E. L. (2014). The use of linear programming to determine whether a formulated complementary food product can ensure adequate nutrients for 6- to 11-month-old Cambodian infants. *The American Journal of Clinical Nutrition, 99*, 130-138.
Smith, L. C., Ramakrishnam, U., Ndiaye, A., Haddad, L., & Martorell, R. (2003). The importance of women's status for child nutrition in developing countries. *IFPRI research report 131*. Washington DC, USA: IFPRI.
South African MRC (2010). South African Food Data System. http://safoods.mrc.ac.za/,. Accessed February 2018.
Stevens, G. A., Singh, G. M., Lu, Y., Danaei, G., Lin, J. K., Finucane, M. M., Bahalim, A. N., McIntire, R. K., Gutierrez, H. R., Cowan, M., Paciorek, C. J., Farzadfar, F., Riley, L., Ezzati, M., & Global Burden of Metabolic Risk Factors of Chronic Diseases Collaborating, G. (2012). National, regional, and global trends in adult overweight and obesity prevalences. *Population health metrics, 10*(1), 22.
Swinburn, B., Kraak, V., Rutter, H., Vandevijvere, S., Lobstein, T., Sacks, G., Gomes, F., Marsh, T., & Magnusson, R. (2015). Strengthening of accountability systems to create healthy food environments and reduce global obesity. *The Lancet, 385*(9986), 2534-2545.
Talsma, E. F., Borgonjen-van den Berg, K. J., Melse-Boonstra, A., Mayer, E. V., Verhoef, H., Demir, A. Y., Ferguson, E. L., Kok, F. J., & Brouwer, I. D. (2017). The potential contribution of yellow cassava to dietary nutrient adequacy of primary-school children in Eastern Kenya; the use of linear programming. *Public Health Nutrition*, 1-12.
UNEP (2016). Food systems and natural resources. A report of the working group on food systems of the international resource panel Westhoek, H, Ingram J., Van Berkum, S., Özay, L., and Hajer M.
UNICEF (2011). Gender influences on child survival, health, and nutrition: a narrative review. New York, USA: UNICEF.
UNICEF (2018). Coverage at a crossroads: New directions for vitamin A supplementation programmes. New York: UNICEF.
UNICEF, WHO, & World Bank (2018). Level and trends in child malnutrition. USA: UNICEF, WHO & World Bank Group.
United Nations (2017). The Sustainable Development Goals Report 2017. New York, NY: United Nations.
USDA (2016). USDA national nutrient database for standard reference, Release 28. http://www.ars.usda.gov/nea/bhnrc/ndl. Accessed February 2018.
Webb, P., & Kennedy, E. (2014). Impacts of agriculture on nutrition: nature of the evidence and research gaps. *Food Nutr Bull, 35*, 126-132.
WHO (2015). Healthy diet fact sheet no. 394. http://www.who.int/news-room/fact-sheets/detail/healthy-diet. Accessed August 2018.

Chapter 2

Current and potential role of grain legumes on protein and micronutrient adequacy of the diet of rural Ghanaian infants and young children: using linear programming

Ilse de Jager
Karin J. Borgonjen-van den Berg
Ken E. Giller
Inge D. Brouwer

Nutrition Journal 2019, 18(1): 12
doi: 10.1186/s12937-019-0435-5

Abstract

Background: Grain legumes are appreciated for their contribution to dietary protein and micronutrient intake in addition to their benefits in providing income and replenishing soil fertility. They offer potential benefits in developing countries where future food demand is increasing and both undernutrition and overweight co-exist. We studied the current and potential role of grain legumes on protein, both quantity and quality, and micronutrient adequacy in the diet of rural Ghanaian infants and young children.

Methods: Energy and nutrient (including amino acids) intakes of breastfed children of 6-8 months (*n*=97), 9-11 months (*n*=97), 12-23 months (*n*=114), and non-breastfed children of 12-23 months (*n*=29) from Karaga district in Northern Ghana were assessed using a repeated quantitative multi-pass 24-hour recall method. Food-based dietary guidelines that cover nutrient adequacy within the constraints of local current dietary patterns were designed using the linear programming software Optifood (version 4.0.9, Optifood©). Optifood was also used to evaluate whether additional legumes would further improve nutrient adequacy.

Results: We found that 60% of the children currently consumed legumes with an average portion size of 20 g per day (cooked) contributing more than 10% of their total protein, folate, iron and niacin intake. The final sets of food-based recommendations included legumes and provided adequate protein and essential amino acids but insufficient calcium, iron, niacin and/or zinc among breastfed children and insufficient calcium, vitamin C, vitamin B12 and vitamin A among non-breastfed children. The sets of food-based recommendations combined with extra legumes on top of the current dietary pattern improved adequacy of calcium, iron, niacin and zinc but only reached sufficient amounts for calcium among breastfed children of 6-8 months old.

Conclusions: Although legumes are often said to be the 'meat of the poor' and current grain legume consumption among rural children contribute to protein intake, the main nutritional benefit of increased legume consumption is improvement of micronutrient adequacy. Besides food-based recommendations, other interventions are needed such as food-based approaches and/or fortification or supplementation strategies to improve micronutrient adequacy of infants and young children in rural Ghana.

Introduction

Grain legumes can play a significant role in food systems to address future global food security, environmental sustainability and nutritional needs (Ranganathan et al. 2016; GLOPAN 2016; Kissinger 2016). Driven by climate change, urbanization, income growth and population increase, food systems are transforming rapidly and often fail to provide sufficient, diverse, nutritious and safe food for all (GLOPAN 2016; Foresight 2011). Grain legumes are appreciated for their contribution to dietary protein and micronutrient intake in addition to their benefits in providing cash income for smallholders and replenishing soil nutrients. Legumes have the unique ability to fix atmospheric nitrogen in the soil, reduce fertilizer requirements and increase yield in subsequent crops (Giller et al. 2013). Compared with maize, one of the most commonly consumed staple globally, legumes are better sources of protein (20 to 30 percent) and are richer in the key micronutrients folate, niacin, thiamine, calcium, iron and zinc, although nutrient concentration vary considerably between grain legumes, varieties and locations (USDA 2016; FAO 2012; South African MRC 2010). Human nutrient uptake from legume consumption greatly depends on the bioavailability of nutrients (Sandberg 2002; Hurrell 2003). In addition, being a good source of essential amino acids (EAAs), especially of lysine, grain legumes are complementary to most staple foods, improving the protein quality of the diet (USDA 2016; FAO 2012; South African MRC 2010; National Institute of Nutrition 2017; Mudryj et al. 2014). Grain legumes offer potential benefits in developing countries where future food demand is increasing (Foresight 2011) and undernutrition and overweight co-exist (Abdullah 2015).

The current productivity of most legumes is lowest in developing countries, especially in sub-Saharan Africa (Nedumaran et al. 2015; Pingali 2012). Overall the availability of legumes together with dairy, meat, fruits, nuts and seeds has declined in sub-Saharan Africa while the availability of grains less-dense in protein and micronutrients has increased (Beal et al. 2017). Protein intake is often estimated to be inadequate in sub-Saharan Africa, both in terms of quantity and quality (Schönfeldt and Hall 2012). Nevertheless, these estimations were not based on estimated dietary intakes and therefore the evidence is weak. More than 30% of children are stunted in Africa, the only continent where the number of stunted children has risen from 2000 to 2016 (UNICEF et al. 2017). Several cross-sectional studies suggest that dietary intake of essential amino acids (EAAs) are insufficient in stunted children, especially that of lysine which is the most limiting EAA in cereal based diets (Semba et al. 2016; Ghosh et al. 2012; Gunaratna et al. 2010). A recent randomised controlled trial among Ghanaian infants from age 6 to 18 months was conducted and preliminary results showed a dose-response effect of receiving a protein quality and micronutrient-improved complementary food supplement on their growth at 18 months of age (Uauy et al. 2016; Ghosh et al. 2015). Based on food balance sheet data, thet prevalence of inadequate micronutrient intake decreased in sub-Saharan Africa from 1990 due to increased total energy supplies and/or dietary micronutrient density (Beal et al. 2017). Deficiencies in micronutrients such as iron, iodine, vitamin A, folate and zinc affect more than 2 billion people worldwide; again with the highest prevalence in sub-Saharan Africa. The greatest concern is for infants and young children (IYC) as micronutrient deficiencies impair their mental and physical development resulting in life-long irreversible disadvantages (Keats and Wiggins 2014; Muthayya et al. 2013).

Increasing the availability and consumption of legumes in sub-Saharan Africa has potential to close the protein and micronutrient gaps. Suri et al. (2014) found that traditional cereal–legume blends made from locally available ingredients in Ghana had improved protein quality and micronutrients compared with a traditional Ghanaian maize-based complementary food (koko) but still did not meet quality protein and micronutrient recommendations**.** However, optimisation of these food blends, including added fat, amino acids, and micronutrients, may result in meeting nutrient requirements (Suri et al. 2014). Yet evidence on actual consumption and nutrient contribution of legumes is limited. Available data show large variation between regions and age groups. For example, only 44% of rural IYC in southern Ethiopia consumed legumes and/or nuts which contributed less than 4% of their total protein intake (Mesfin et al. 2015). By contrast more than 90% of school-age children in northern Ghana consumed legumes and/or nuts although no information was available on the contribution to protein or micronutrient intake (Abizari et al. 2017). These are the only studies we can find that have investigated the current contribution of legumes to EAAs intakes of IYC in developing countries. Optimisation studies developing food-based recommendations (FBRs) based on current dietary patterns of IYC, show that combinations of local foods including legumes improve but do not provide adequate amounts of all nutrients (Skau et al. 2014; Talsma et al. 2017; Raymond et al. 2017; Kujinga et al. 2018). However, none of these studies included adequacy of EAAs in their analyses, nor did they test whether inclusion of a further increase of legume consumption would potentially be able to reach protein and nutrient adequacy.

We collected quantitative dietary intake data among IYC in rural Northern Ghana and used it to: (a) identify grain legumes consumption and contribution to nutrients in the current diet, (b) identify a set of food-based recommendations that will improve nutrient adequacy within the constraints of local current dietary patterns, and (c) evaluate whether including extra grain legumes on top of what is normally consumed would reduce the number of problem nutrients which are present in relatively high concentrations in grain legumes (protein, EAAs, calcium, folate, iron, niacin and zinc).

Methods

Study area

The study was carried out in Karaga sub-district in the Northern Region of Ghana. Cultivation and consumption of grain legumes, especially cowpea (*Vigna unguiculata* (L.) Walp) and groundnut (*Arachis hypogaea* L.), is common in this region. Karaga sub-district was selected because of high food insecurity and malnutrition. About 32% of children below 5 years old are stunted and 9.4% are wasted (de Jager et al. 2017).

Subjects

Infants and young children between 6-23 months are the primary target of this study divided into the four following groups: breastfed infants between 6-8 months (6-8 BF), breastfed infants between 9-11 months (9-11 BF), breastfed young children between 12-23 months (12-23 BF) and non-breastfed young children between 12-23 months (12-23 NBF). A census was conducted in Karaga sub-district between May-June 2014 to identify all households with children of 6-23 months and collect information on their sex, date of birth (from verifiable documents (health record, weighing card, birth certificate) or estimated based on traditional calendar), breastfeeding status and geographical location by GPS coordinates. A list of all households with children of 6-23 months constituted the sampling frame divided into four sub-frames, corresponding to the four specific groups according to age and breastfeeding state: 6-8 BF, 9-11 BF, 12-23 BF and 12-23 NBF. A random order list was developed for each sub-frame and the first 100 children on this list were selected except in case there were less than 100 children in a group.

Eligibility was defined by the age of the child falling between 6-23 months using the day before the start of data collection as the reference date (30 June 2014). For the breastfed group, eligibility was also defined as receiving both breastfeeding and complementary feeding. Eligibility for the study was cross-checked in the field prior to the start of data collection and ineligible children were randomly replaced with other eligible children in the same community or a nearby community. A sample size of approximately 100 for each of the four groups was chosen based on estimated population mean food serving sizes for commonly-consumed foods in the study area to be within 10% (95% CI), assuming an SD of 50% of the mean serving sizes in the age group and allowing for a 5% rate of attrition. This sample size is comparable to those previously used in studies with linear programming techniques in the literature (Santika et al. 2009). One child per household was selected. In case two or more children in the household qualified for inclusion, one was chosen randomly. Communities of selected children were clustered into three geographic areas: north, central and south. Each cluster was then randomly assigned to a time slot of data collection. A random sample of food vendors within the selected study communities and major markets within the study area were also interviewed to determine prices of foods identified during collection of dietary data. Food price data were used for estimation of quantities of reported foods consumed, as well as to calculate the daily diet costs of each child which in turn was used as a criterion for the final selection of feasible FBRs.

Data collection and analysis

Data was collected in Ghana in July 2014 by trained enumerators who had a first degree in nutrition and who spoke the local language. Trained supervisors with previous experience in dietary assessment and who spoke the local language, observed part of the interviews and back-checked survey forms of all interviews. In case of inconsistencies, households were revisited.

Anthropometry

Weight and length of children were measured in duplicate following WHO guidelines (WHO 2008) using an electronic scale (UNIscale: Seca GmbH, Hamburg, Germany) and an UNICEF wooden three piece measuring board with a sliding foot piece. The scale was calibrated daily. Anthropometric indices were calculated based on the WHO Child Growth Standards (WHO Multicentre Growth Reference Study Group 2006) using the WHO SPSS syntax. Children were classified as stunted and wasted if their height-for-age and weight-for-height Z-score was less than minus two, respectively. Children were classified as overweight if their BMI-for-age Z-score was more than two.

Dietary intake assessment

Dietary intakes of the children were assessed using a quantitative multi-pass 24-hour recall method (Conway et al. 2003) with all days evenly distributed over the week. A second recall was carried out for 20% of the children on a non-consecutive day to permit adjustment for day-to-day variation of nutrient intakes. Data was collected in a time period of 3 weeks. Primary caretakers were asked to recall all the foods and drinks consumed in and outside the home by their child during the preceding day and to describe ingredients and cooking methods of any mixed dishes. To assess the amounts of the foods and ingredients, similar foods were weighed to the nearest 2 g using a Soehnle electronic kitchen scale (Plateau Art 65086, Germany). Scales were randomly assigned to the interviewers and calibrated daily. When the actual food was not available in the household, amounts were estimated (in order of priority) as their monetary value equivalents (price paid at the market and converted to quantity that was bought using the food price data collected), compared the weight of other foods (e.g. amount of sugar estimated with weight of same volume of corn flour), in volumes, as their general sizes (small, medium or large) using pictures or in household units (such as a spoon or bowl). Conversion factors were applied to convert these units into grams of the foods consumed to be able to assess nutrient intake. The total volume of each (mixed) dish cooked at the respondents' household and the volume of this dish specifically consumed by the child were measured to determine the proportion of the dish consumed by the child. This proportion was multiplied by the total amount of ingredients used in the preparation of the dish to determine the amount of ingredients consumed. Standard recipes were generated to estimate the weight of ingredients consumed from mixed dishes eaten outside the home by averaging three recipes of different vendors in the local area. For each food consumed by the children, food price data was also collected from three different food sellers in the study area to calculate the price per edible 100 g portion of all foods.

Habitual dietary intake

Energy and nutrient intakes were calculated using nutrient calculation system Compl-eat™ (version 1.0, Wageningen University), including: energy, carbohydrates, fat, protein, EAAs (histidine, isoleucine, leucine, lysine, threonine, tryptophan, valine, aromatic amino acids (AAA, include phenylalanine and tyrosine) and sulphur-containing amino acids (SAA, include methionine and cystine); calcium, vitamin C, thiamine, riboflavin, niacin, vitamin B6, folate, vitamin B12, vitamin A, iron, and zinc. Energy and nutrient intake calculations were based on a food composition table (FCT) specifically created for this study using the West African FCT as primary source (FAO 2012) complemented with data from FCTs from, in order of priority based on date of publication and location with similar dietary pattern, Mali FCT (Barikmo et al. 2004), the United States Department of Agriculture database (USDA 2016) and the Ghana FCT (Eyeson and Ankrah 1975). EAA values in gram per 100 gram protein were derived from the recent elaborate Indian FCT (National Institute of Nutrition 2017) that uses validated methods to measure AAs content in foods, and applied to the protein content derived from the FCTs listed above. If a specific food was not included in the Indian FCT, a similar food from the same food group and with similar protein content was selected. Several processed food items were not included in the Indian FCT; for these items the proportion of ingredients was used to derive the EAAs content. The nutrient composition of breast milk was taken from the WHO as the vitamin A content was reported to be more representative of developing countries (Brown et al. 1998). Energy content of breast milk was assumed to be 65 kcal per 100 g. EAA values in breastmilk were taken from a recent systematic review by Zhang et al. (2013) on amino acid profiles in human milk including a few studies from Africa. Where appropriate, yield (FAO 2012) and nutrient retention factors (USDA 2016; Vásquez-Caicedo et al. 2008) were applied to account for nutrient losses during food preparation. If only the raw food items were included in the Indian FCT these were used assuming the different preparation methods do not affect the relative proportion of EAAs contents. The Atwater general factors for carbohydrate, protein and fat and the recommended metabolisable energy for dietary fibre in ordinary diets (2 kcal or 8.4 kJ/g) were used in calculating energy (FAO 2003). Total vitamin A was calculated as retinol activity equivalent (RAE) by the sum of retinol and 1/12 β-carotene (FAO 2012). Energy and nutrient intake were analysed using statistical software package IBM SPSS (version 23). Normality of distributions was tested visually using QQ plots. Non-normal nutrient intake data were log transformed, resulting in normal distributions. To generate usual intakes, nutrient intakes were adjusted for day-to-day variation using the National Research Council adjustment method (National Research Council 1986; Institute of Medicine 2000). For breastfed children, intake of breastmilk was not measured directly and therefore we assumed average intakes based on estimated energy intakes from breastmilk for populations in low income countries (Brown et al. 1998; Dewey and Brown 2003). The total nutrient intake for breastfed children were computed by their adjusted nutrient intakes plus the nutrient intake from the assumed average breastmilk intakes (Brown et al. 1998). Energy and nutrient intakes are reported as median (25^{th}, 75^{th} percentile) of the distribution of intakes.

The percentage of children for all four groups (6-8 BF, 9-11 BF, 12-23 BF and 12-23 NBF) with energy and macronutrient intakes below their daily requirements (see Additional file A for values used) and with micronutrient intakes below EARs when available (see Additional file B) were also determined. The daily median intake and contribution of grain legumes to energy and nutrient intakes (in mean % ± SD) was determined for all four groups. In addition, we divided our target population of children 6-23 months into two groups: children who did and children who did not consume grain legumes and tested the differences in total energy and nutrient intakes between these two groups with the Mann-Whitney U test. Two-sided *P*-value <0.05 was regarded as statistically significant.

Optimising dietary intake

The linear programming software Optifood (version 4.0.9, Optifood©) was used to design population-specific FBRs (Vossenaar et al. 2017; Talsma et al. 2017; Kujinga et al. 2018). The model parameters were defined per target group and generated using Microsoft® Excel 2010, IBM SPSS (version 23) and Microsoft® Access 2010, based on the 24-hour recall data of the first day. The parameters included: a list of non-condiment foods consumed by ≥ 5% of the target children or ≥ 5 children for the non-breastfed children and excluding fortified foods, for each selected food the price per 100 g of edible food (to determine price of modelled diets) and for each selected food the median serving size for all children who had consumed it. The minimum and maximum number of servings per week for each (sub)food groups were defined as the 5th and 95th percentile distributions of serving counts. The minimum and maximum frequencies per individual food within a (sub)food group was estimated based on percentage of children consuming that food. For energy and nutrient contents of the foods, the FCT table specifically developed for this study was also used in Optifood. All modelled diets had to meet the energy requirements for the specific target group, estimated using reference mean body weight and the FAO/WHO/UNU algorithm for estimating energy requirements (FAO et al. 2004). Thirteen nutrients were considered in the Optifood analysis: total fat, total protein, calcium, vitamin C, thiamine, riboflavin, niacin, vitamin B6, folate, vitamin B12, vitamin A, iron and zinc. EAAs were included in the Optifood analysis as well if at least 10% among one of the target groups had a daily intake below one of their EAAs daily requirements. For fat the requirements were based on the acceptable macronutrient distribution range (ADMR) of 30% of daily energy requirements (FAO 2010); for protein based on average reference mean body weight for age group and algorithm for estimating protein requirement (g/kg), safe intakes (FAO et al. 2007); for EAAs based on daily total protein requirements and algorithms for each EAAs requirements (mg/g protein) using safe intakes (FAO et al. 2007); and for other micronutrients RNIs were used from FAO/WHO (WHO and FAO 2004), except for zinc the RNI from the International Zinc Nutrition Consultative Group's (iZiNCG) reflecting low bioavailability of unrefined cereal-based diets (Brown et al. 2004) was used. Considering the low dietary haem iron with high phytate and fibre in the plant foods commonly consumed by our target groups, 5% bioavailability was assumed for iron (WHO and FAO 2004).

Module 1-3 were used in the Optifood analyses for all target groups. Module 1 was run to check that model parameters generated diets that are feasible for the target population. Module 1 generates 19 different diets including poor, middle and nutrient rich diets and shows the energy range of these diets and a high range is preferred as this shows flexibility of the model. Module 2 was run to identify the best optimised diet that met or come as close as possible to meeting nutrient needs of the target population but is constrained by the minimum and maximum number of servings per week. The objective function was to minimize the deviation of the current diet while reaching the nutrient goals. The best optimised diet was used to select FBRs to test in Module 3, including the food groups with weekly servings above zero and individual foods contributing at least 5% to the intake of one of the nutrients. In Module 3, two diets were modelled for each nutrient of which one maximized nutrients selecting the most nutrient dense foods within each food group to verify the highest possible nutrient intake (the maximised diet) and one minimized nutrients selecting the lowest nutrient dense foods to verify the lowest possible nutrient intake (the minimised diet). The objective function was to respectively minimize and maximize each nutrient. First, module 3 was run without FBR constraints to identify problem nutrients of which the RNI cannot be met by any combination of currently consumed local foods (defined as below 100% RNI in the maximised diets). As Optifood software has a maximum of 14 nutrients that can be considered, nutrients not considered as problem nutrients in all of the four target groups (>100% RNI in maximised diets) were no longer included in the linear programming analyses and replaced by the EAAs that meet the inclusion criteria described above. Second, individual and combined FBRs were tested to identify sets of FBRs that covered >70% of the RNI in the minimized diet for most nutrients and total costs below the 75th percentile of daily diet cost. Nutrient intakes above 70% of RNI in the minimized diet were classified as adequate, for most nutrients this represents at least the EAR, and it allows for comparison with other studies (Kujinga et al. 2018; Talsma et al. 2017; Santika et al. 2009). For each target group, the set of recommendations that achieved >70% of the RNI in the minimized diet for most nutrients but below the 75th percentile of daily diet cost was selected (see Additional file D for the specific criteria used for each group). Third, extra grain legumes were incorporated in this final set of selected FBRs and tested in Module 3 to determine if they improved problem nutrient adequacy. Grain legumes were added when they were consumed by all four groups with a median portion size of above 3 g and when they contained larger concentrations of at least one of the problem nutrients of a target group compared with the staple food maize. The minimum and maximum number of servings per week for each grain legume were set at 7 assuming that the addition of one extra serving of a specific grain legume per day was feasible within the energy constraints. When 7 servings did exceed the energy constraints, the maximal number of servings that were possible within the energy constraints were added. The median portion size for 'new' legumes (consumed by <5% of children in all four target groups) incorporated in final FBRs was calculated as the average of the median portion size per group assuming to be a more feasible portion size than the median portion size of each group being consumed by less than 5% of the target children. Adding a combination of different legumes to the final set of FBRs, was only carried out when it did not exceed the energy constraints. Again, for each target group the set of recommendations that achieved >70% of the RNI in the maximised diet for most nutrients but below the 75th percentile of daily diet cost was selected.

Ethics approval and consent to participate

Clearance to carry out the research was granted by the Noguchi Memorial Institute for Medical Research Institutional Review Board (Ethical Clearance certificate No. NMIMR-IRB CPN 087/13-14). Approval for the study was obtained by the District Assembly, District Health Administration in Karaga and leaders of selected communities. Participation was voluntary and written informed consent was obtained from caregivers of selected children and thumb prints used for those who were not literate. The identity of the IYC and their mothers/caregivers has been kept confidential.

Results

Subject characteristics

In total 337 children were included in the study: 97 children 6-8 BF, 97 children 9-11 BF, 114 children 12-23 BF and 29 children 12-23 NBF. If eligibility criteria were not met, children were reclassified to another group or replaced in the field (Figure 1). In the study area, 42 children of 12-23 months did not receive breastmilk of which 29 children were included as when cross-checked in the field, seven were older than 23 months, five did receive breastmilk and one was from a Korean family with different dietary habits compared with target children.

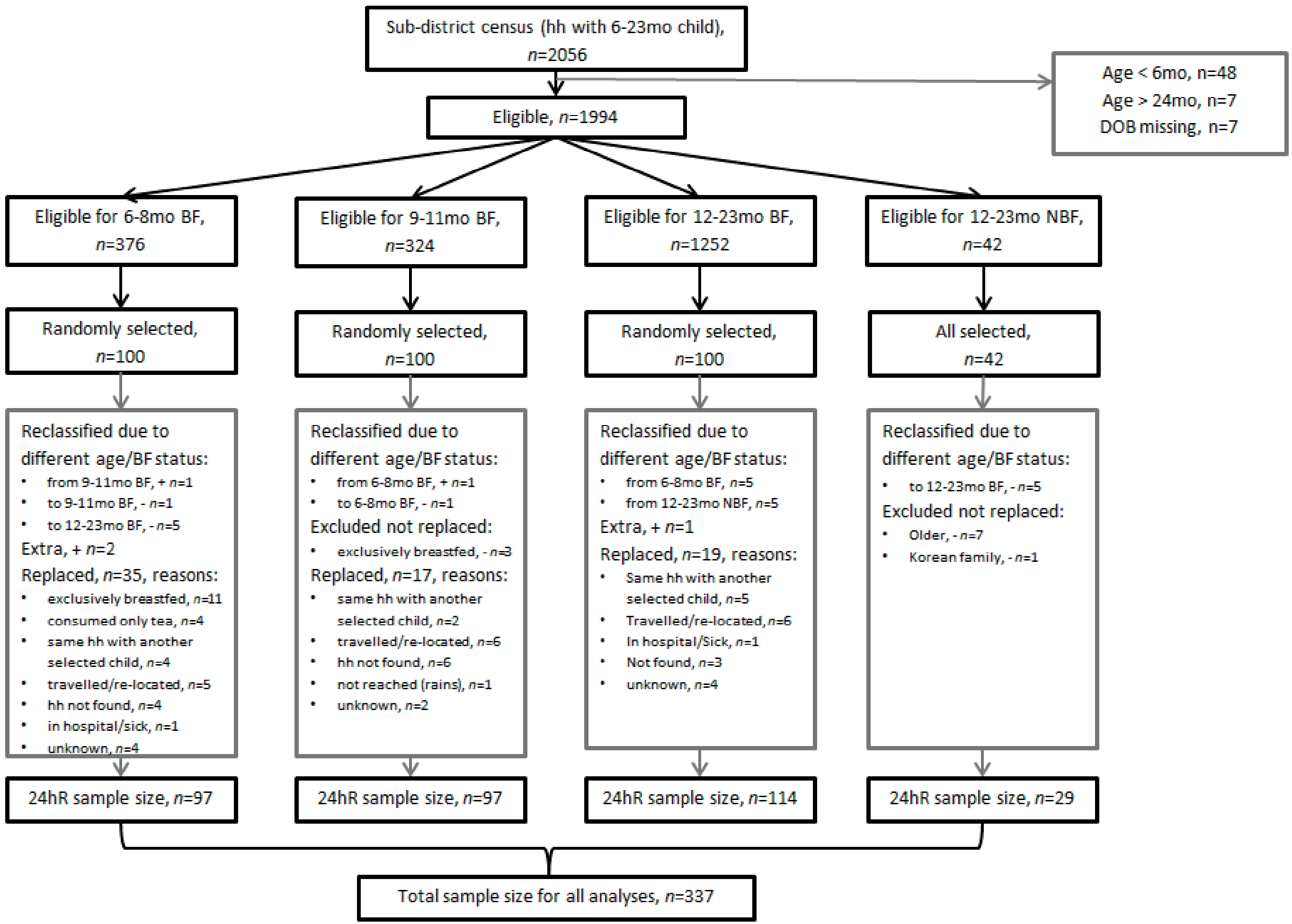

Figure 1. Flow chart of sample selection. hh = household. n=sample size. 6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months. Reclassified=from other age group to this group (different age or breastfeeding status during 24hour recall than census). 24hR=24hour recall.

Children were on average 8, 11, 17 and 21 months old, respectively among children of 6-8 BF, 9-11 BF, 12-23 BF and 12-23 NBF. About 50 % of children were girls in all groups except in group of children 12-23 NBF where 38 % of children were girls. Among children below 12 months about 30 % were stunted, while among the older children above 12 months about 55 % were stunted. Among all children, about 14 % were wasted. One child 12-23 NBF was overweight (Table 1).

Table 1. Nutritional status of children 6 to 23 months old in Karaga district, Northern region, Ghana[a]

Characteristics	6-8 BF *n=97*[b]	9-11 BF *n=97*[c]	12-23 BF *n=114*	12-23 NBF *n=29*
Age, months	7.9 ± 0.9	10.8 ± 1.0	17.1 ± 3.2	20.9 ± 3.3
Sex, girls, % (n)	52.6 (51)	52.6 (51)	50.0 (57)	37.9 (11)
Height for age, z score	-1.2 ± 1.1	-1.6 ± 1.2	-2.2 ± 1.3	-1.9 ± 2.1
Children being stunted % (n)	26.8 (26)	31.9 (31)	53.5 (61)	55.2 (16)
Weight for height, z score	-1.0 ± 1.0	-1.0 ± 1.1	-1.0 ± 0.9	-0.8 ± 1.3
Children being wasted % (n)	14.4 (14)	13.4 (13)	13.2 (15)	13.7 (4)
Body-mass-index for age, z score	-1.1 ± 1.0	-0.9 ± 1.1	-0.7 ± 0.9	-0.4 ± 1.3
Children being overweight, % (n)	0 (0)	0 (0)	0 (0)	3.4 (1)

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months.
[a]Values are mean ± standard deviation unless stated otherwise.
[b]n=96, missing anthropometric measurements information for 1 child.
[c]n=96, missing date of birth and anthropometric measurements information for 1 child

Habitual dietary intake

Data analysis included 337 first dietary recalls and 66 second recalls (20%). In all four groups, with average breastmilk intakes assumed, about 50% of children had an energy intake below their daily requirement (also reflected in the high prevalence of wasted children) while nearly all children had sufficient fat or protein intakes. All children had essential amino acid intakes above their requirements, except for isoleucine, lysine and/or AAA intakes. Micronutrient intakes were generally low, for children above 12 months for almost all nutrients 20% or more children had intakes below their daily requirements. For more than 60% of children above 12 months calcium, folate, and vitamin B12 were below their requirements, and in addition for the non-breastfed children also iron, vitamin A and vitamin C. For children below 12 months, 90% had iron and zinc intakes below their requirements and for folate 50% of 6-8 months old children and 35% of 9-11 months old children (for other nutrients no EARs were available) (Table 2).

Table 2 Daily nutrient intake of children 6 to 23 mo, recommended daily requirements and percent below daily requirements, assuming average breastmilk intake and reference weights

	6-8 BF				9-11 BF				12-23 BF				12-23 NBF			
	n=97				*n=97*				*n=114*				*n=29*			
	Median intake [25th, 75th percentile], recommended daily requirements[a], % below daily requirements[b]															
Energy (kcal)	601	[525, 721]	614	**53, 28**[c]	717	[587, 887]	695	**49, 24**[c]	897	[725, 1168]	886	**47, 22**[c]	983	[773, 1284]	886	38, 24[c]
Fat (g)	28	[27, 31]	20.5	0	29	[27, 36]	23.2	0	33	[28, 40]	29.5	31	22	[13, 29]	29.5	**76**
Protein (g)	11	[10, 15]	9.1	14	14	[11, 20]	10.3	12	21	[15, 28]	11.1	11	27	[20, 35]	11.1	0
Histidine (mg)	*308*	*[260, 383]*	*182*	*0*	*369*	*[300, 520]*	*196*	*0*	*545*	*[388, 727]*	*199*	*1*	*695*	*[551, 918]*	*199*	*0*
Isoleucine (mg)	*442*	*[442, 442]*	*291*	*0*	*413*	*[412, 414]*	*324*	*0*	*369*	*[368, 370]*	*343*	*0*	*3*	*[2, 5]*	*343*	***100***
Leucine (mg)	*1296*	*[1069,*	*601*	*0*	*1467*	*[1243, 2020]*	*664*	*0*	*2182*	*[1630, 2875]*	*697*	*0*	*2669*	*[1921, 3461]*	*697*	*0*
Lysine (mg)	*690*	*[628, 791]*	*519*	*0*	*762*	*[659, 947]*	*561*	*1*	*991*	*[787, 1227]*	*575*	*5*	*991*	*[693, 1302]*	*575*	*17*
SAA (mg)	*441*	*[379, 551]*	*255*	*0*	*522*	*[414, 714]*	*278*	*0*	*756*	*[572, 1010]*	*288*	*1*	*992*	*[653, 1311]*	*288*	*0*
AAA (mg)	*673*	*[673, 673]*	*473*	*0*	*628*	*[628, 629]*	*504*	*0*	*561*	*[561, 562]*	*509*	*0*	*3*	*[2, 5]*	*509*	***100***
Threonine (mg)	*518*	*[460, 627]*	*282*	*0*	*590*	*[500, 785]*	*298*	*0*	*827*	*[631, 1049]*	*299*	*0*	*923*	*[697, 1265]*	*299*	*0*
Tryptophan (mg)	*180*	*[192, 227]*	*77*	*0*	*212*	*[185, 258]*	*82*	*0*	*257*	*[212, 313]*	*82*	*0*	*226*	*[154, 302]*	*82*	*0*
Valine (mg)	*680*	*[579, 861]*	*391*	*0*	*782*	*[650, 1094]*	*437*	*0*	*1174*	*[891, 1520]*	*465*	*2*	*1377*	*[1063, 1950]*	*465*	*0*
Calcium (mg)	202	[193, 239]	400	n/a	208	[187, 258]	400	n/a	227	[199, 280]	500	**95**	158	[95, 305]	500	**86**
Folate (µg DFE)	65	[61, 75]	80	**51**	72	[63, 91]	80	35	92	[75, 119]	150	**76**	81	[59, 139]	150	**66**
Iron (mg)	2	[1, 3]	18.6	**91**	3	[2, 5]	18.6	**91**	5	[3, 8]	11.6	**17**	9	[7, 13]	0	**66**
Niacin (mg)	1.9	[1.6, 3.1]	4	n/a	2.7	[1.9, 4.0]	4	n/a	4.9	[3.2, 6.8]	6	**47**	6.8	[4.7, 10.3]	6	21
Riboflavin (mg)	0.3	[0.3, 0.4]	0.4	n/a	0.3	[0.3, 0.4]	0.4	n/a	0.4	[0.3, 0.6]	0.5	41	0.5	[0.3, 0.7]	0.5	38
Thiamine (mg)	0.3	[0.3, 0.4]	0.3	n/a	0.4	[0.3, 0.5]	0.3	n/a	0.6	[0.4, 0.9]	0.5	18	0.9	[0.7, 1.1]	0.5	0
Vitamin A (µg RAE)	331	[331, 344]	400	n/a	322	[309, 354]	400	n/a	300	[287, 335]	400	24	60	[28, 142]	400	**86**
Vitamin B_6 (mg)	0.2	[0.2, 0.4]	0.3	n/a	0.3	[0.2, 0.5]	0.3	n/a	0.6	[0.4, 0.9]	0.5	25	1.0	[0.7, 1.4]	0.5	3
Vitamin B_{12} (µg)	0.7	[0.7, 0.7]	0.7	n/a	0.6	[0.6, 0.7]	0.7	n/a	0.6	[0.6, 0.6]	0.9	**84**	0.1	[0.0, 0.3]	0.9	**86**
Vitamin C (mg)	27	[27, 30]	30	n/a	28	[25, 32]	30	n/a	28	[25, 32]	30	23	12	[5, 18]	30	**90**
Zinc (mg)	1.6	[1.3, 2.2]	5	**91**	2.1	[1.6, 3.0]	5	**91**	3.2	[2.3, 4.5]	3	13	4.4	[3.3, 6.7]	0	0

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months.
SAA = sulphur-containing amino acids (methionine and cystine); AAA = aromatic amino acids (phenylalanine and tyrosine). **Bold** values = percentages higher than 45.
[a]Recommended daily requirements (used in Optifood analyses): for energy based on average reference body weight for age group and algorithm for estimating energy requirements (Kcal/kg) (FAO, 2004); for fat based on the acceptable macronutrient distribution range (ADMR) of 30% of daily energy requirements (FAO, 2010); for protein based on average reference body weight for age group and algorithm for estimating protein requirement (g/kg) using safe intakes (FAO, 2007); for essential amino acids based on daily total protein requirements and algorithms for each essential amino acid requirements (mg/g protein) using safe intakes (WHO, 2007); for micronutrients RNIs from FAO/WHO (2004).
[b]Percent below daily requirements: for energy and macronutrients requirements used as described above; for micronutrients based on EARs calculated from RNIs (FAO/WHO 2004), using conversion factors (Allen, et al., 2006) except for zinc based on EAR from iZiNCG (2004) assuming unrefined cereal-based diets and for iron based on RNI from FAO/WHO (2004) assuming 5% bioavailability, except for calcium, niacin, riboflavin, thiamine, vitamin A, vitamin B6, vitamin B12 and Vitamin C for children 6 to 11 months for whom EARs are not available *(see Additional files A and B for overview of exact values used)*.
[c]Percent of children below daily requirements based on actual weight.

Overall, 17, 30, 33 and 22 non-condiment foods were consumed, respectively, by more than 5 % of 6-8 BF, 9-11 BF and 12-23 BF children and by more than 5 children of 12-23 NBF (See Additional file C). Sugar, maize flour and anchovies were the foods most commonly consumed foods by all four target groups. Serving sizes in the diet varied between 1 g/d for different fish foods, dried soybean *(Glycine max* (L.) Merril), dried groundnut and dried okro powder to 123 g/d for maize flour and 126 g/d for watermelon. All vegetables were consumed in portion sizes below 30 g/d. Median portion sizes consumed of legumes, nuts and seeds were ranging from 4 to 25 g/day (except for dried soybeans and groundnuts shelled). The estimated 75^{th} percentile of daily diet costs ranges from 0.39 Ghanaian Cedi's (GH₵) for children 6-8 BF to 2.29 GH₵ for children 12-23 NBF (See Additional file D). Additional files C show minimum and maximum frequencies of individual foods consumed per target group, ranging between 0 and 7 times per week. Additional file E shows the minimum and maximum frequencies for sub food groups and food groups consumed, ranging between 0 and 35 times per week.

Cowpea whole, groundnut paste and soybean flour were consumed by all four target groups with median portion sizes above 3 g. Compared with maize, these grain legumes are relatively high in protein, EAAs (especially soybean), iron, zinc, folate and calcium (Table 3). Groundnuts are also relatively high in niacin. Median total daily legumes intake ranged from 5.2g among 6-8 BF children to 35.2g among 12-23 NBF children. Median daily intake from cowpea was the highest (31 ± 43 g/d, *n*=45) while groundnut was consumed by most children (10 ± 16 g/d, *n*=186). Soybean was consumed only by 27 children with median portion sizes of 7 ± 9.5 g/d. Among children of above 12 months, legumes currently contributed more than 10% to total protein, EAAs (especially soybean to lysine and tryptophan, and cowpea to all EAAs), folate (especially cowpea), iron (especially cowpea) and niacin (especially groundnuts) intake (Table 3) and among the non-breastfed children also to energy, fat, calcium, thiamine and zinc intake. In the diet of children below 12 months, the contribution of legumes to energy or any nutrient was below 10% with the largest contribution to protein, iron, niacin and/or zinc. Among all children, 60% consumed legumes and their total energy and most nutrient intakes were better compared with children who did not, except for isoleucine and AAA intakes (Table 3). The same comparison separately for each age group and for breastfed and non-breastfed showed similar results.

Table 3. Grain legumes: nutrient composition per 100 gram edible portion compared with staple food maize[a], percent contribution of all legumes in current diet to nutrient intakes per target group, and comparison of nutrient intakes of children not consuming legumes and children consuming legumes

	Soybean flour	Groundnut paste	Cowpea, whole	Maize	6-8 BF *n=97*	9-11 BF *n=97*	12-23 BF *n=114*	12-23 NBF *n=29*	Children, not consumed legumes *n=135*	Children, consumed legumes *n=202*
	content per 100 gram edible portion				*legume contribution: mean % ± standard deviation*				*median intake [25th, 75th percentile]*	
Daily legume intake[b] (g)					*5.2 ± 22.3*	*5.5 ± 11.3*	*17.0 ± 30.3*	*35.2 ± 36.9*	-	*19.8 ± 31.3*
Energy (kcal)	414	578	320	349	2.0 ± 7.4	2.7 ± 5.2	5.5 ± 7.2	**11.7** ± 10.2	596 [521, 688]	893 [726, 1142]*
Fat (g)	15.9	45.9	1.5	4.1	1.5 ± 5.1	2.8 ± 5.6	7.6 ± 9.8	**23.0** ± 23.9	27 [26, 29]	33 [28, 39]*
Protein (g)	**34.7**	**22.4**	**19.2**	9.2	4.1 ± 12.7	5.6 ± 10.4	**11.0** ± 12.8	**20.3** ± 16.4	11 [10, 14]	21 [15, 28]*
Histidine (g)	***0.8***	***0.5***	***0.63***	*0.25*	*3.8 ± 12.1*	*5.3 ± 9.9*	***10.7*** *± 12.7*	***20.4*** *± 17.0*	*300 [262, 364]*	*539 [404, 726]**
Isoleucine (g)	***1.6***	***1.1***	***0.84***	*0.34*	*3.7 ± 11.4*	*4.9 ± 8.8*	***10.6*** *± 12.0*	***22.0*** *± 17.2*	*441 [412, 442]*	***370*** *[369, 414]**
Leucine (g)	***2.9***	*1.4*	*1.54*	*1.12*	*3.1 ± 10.4*	*4.1 ± 8.0*	*7.6 ± 9.8*	***14.8*** *± 12.6*	*1264 [1068, 1575]*	*2113 [1068, 1575]**
Lysine (g)	***2.7***	***0.8***	***1.36***	*0.24*	*4.0 ± 12.7*	*4.8 ± 9.2*	***11.3*** *± 13.7*	***25.9*** *± 21.6*	*674 [622, 754]*	*942 [779, 1192]**
SAA (g)	***1.1***	***0.6***	*0.40*	*0.34*	*3.0 ± 10.0*	*3.7 ± 7.1*	*7.1 ± 8.8*	***13.8*** *± 11.9*	*426 [375, 525]*	*745 [565, 1030]**
AAA (g)	***2.7***	***2.1***	***1.71***	*0.81*	*3.8 ± 11.9*	*5.4 ± 9.8*	***11.2*** *± 12.8*	***21.4*** *± 17.4*	*672 [628, 673]*	***563*** *[561, 629]**
Threonine (g)	***1.2***	***0.6***	***0.79***	*0.29*	*3.3 ± 10.9*	*4.2 ± 8.0*	*9.0 ± 11.3*	***19.0*** *± 16.4*	*513 [452, 588]*	*804 [624, 1044]**
Tryptophan (g)	***0.6***	***0.2***	***0.17***	*0.06*	*3.1 ± 9.9*	*3.5 ± 6.5*	*8.9 ± 10.6*	***22.4*** *± 18.6*	*187 [174, 210]*	*251 [212, 303]**
Valine (g)	***1.7***	***0.9***	***1.02***	*0.50*	*3.4 ± 11.2*	*4.4 ± 8.5*	*8.8 ± 10.6*	***17.5*** *± 14.6*	*665 [578, 806]*	*1151 [865, 1511]**
Calcium (mg)	**185**	**61**	**61**	19	1.9 ± 7.7	1.3 ± 2.6	4.3 ± 7.7	**12.0** ± 15.2	194 [187, 223]	230 [200, 273]*
Folate (µg DFE)	**133**	**88**	**143**	18.2	4.1 ± 13.8	5.1 ± 9.6	**12.3** ± 15.6	**24.9** ± 22.3	63 [60, 69]	91 [76, 121]*
Iron (mg)	**5.2**	**3.9**	**6.8**	2.9	5.2 ± 17.3	7.1 ± 16.1	**9.5** ± 14.2	**12.3** ± 13.3	2.0 [1.5, 3.0]	5.6 [3.5, 8.5]*
Niacin (mg)	1.2	**14.7**	1.8	1.9	3.8 ± 12.6	7.2 ± 12.7	**14.3** ± 15.9	**20.8** ± 16.6	1.9 [1.5, 2.4]	4.7 [3.2, 6.7]*
Zinc (mg)	**4.3**	**2.0**	**4.1**	1.55	4.5 ± 15.2	5.5 ± 11.6	9.0 ± 13.1	**15.4** ± 14.5	1.6 [1.4, 2.1]	3.2 [2.3, 4.5]*

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months.

SAA = sulphur-containing amino acids (methionine and cystine); AAA = aromatic amino acids (phenylalanine and tyrosine).

Bold values = more than 1.5 times higher nutrient content compared with maize; average above 10% contribution to nutrient intake; and nutrient intakes lower among children consuming legumes compared to children not consuming legumes.

**P <0.05 (comparing nutrient intakes of children who did and did not consume legumes*). The same comparison separately for each age group and for breastfed and non-breastfed showed similar results.

[a]Values are from West African Food Composition Table (2012) with retention factors applied: for soybean and cowpea 'legumes 2-2,5 hours boiled and water used', for groundnut 'nuts boiled', and for maize 'cereal boiled' (USDA). For essential amino acids content, the proportion of amino acids of protein from comparable foods from Indian Food Composition Tables (2017) together with protein content from WAFCT were used.

[b]Daily legume intake in median ± SD, for all children.

Optimised dietary intake

In Module 2 in the best optimised diets for all four groups, groundnut paste and cowpea both contributed more than 5% to the intake of at least four nutrients (See Additional file FF). Breastmilk contributed more than 5% of intake to the highest number of nutrients (13 and 14 nutrients) in all three groups with breastfed children, while in non-breastfed group this was maize flour, cowpea and groundnut paste (11 nutrients) (See Additional file F). In Module 3 for all four groups, the maximised diets for each specific nutrient without recommendations covered the RNI for most nutrients. Among children below 12 months problem nutrients were calcium, iron and zinc, among 12-23 BF children calcium and iron, and among 12-23 NBF children calcium, vitamin B12, vitamin A and vitamin C (Table 4 and See Additional file G). Neither thiamine or vitamin B6 were problem nutrients in all four groups (>100% RNI in the maximised diet) and were therefore excluded for further Optifood analyses while the EAAs isoleucine, AAA and lysine were added (more than 10% children were below daily requirements) but were not identified as problem nutrients. The final sets of FBRs selected did not cover calcium, iron, niacin and/or zinc above 70% of RNI in the minimised diets for breastfed children and calcium, vitamin C, vitamin B12 and vitamin A for non-breastfed children (Table 4).

In all four target groups, at least one of the remaining problem nutrients is present in relatively large amounts in cowpea, groundnut and soybean. Groundnut paste, cowpea and soybean flour were added with a frequency of 7 or less to fit within energy constraints, individually and in combination, to the final set of selected FBRs for each target group. For 6-8 BF group, both the addition of four servings of cowpea and the addition of seven servings of soybean per week increased iron and zinc adequacy but not above 70% of RNI in the minimised diets for both nutrients. The addition of seven servings of soybean per week did increase calcium and niacin to 70% of RNI. The combination of adding soybean and cowpea, also increased iron, zinc and calcium adequacy with the latter above 70% of RNI in the minimised diet but niacin decreased to 51% of RNI covered. Addition of combined additional cowpea, groundnut and/or soybean was only possible for this 6-8 BF group, in all other groups the energy limitations were exceeded. For the 9-11 BF group, even the individual addition of legumes was not possible within the energy limitations except for one serving of groundnut paste per week but this did not increase the nutrient adequacy of calcium, iron and zinc above 70% in the final set of selected FBRs. The addition of seven servings of cowpea per week increased calcium and iron adequacy of children 12-23 BF and iron adequacy of 12-23 NBF children but all not above 70% of RNI in the minimised diet (Table 4). Comparing minimised diets of the final set of selected FBRs and these FBRs in combination with additional servings of legumes, resulted in the final sets of selected FBRs (Table 5). For all groups problem nutrients remained: for breastfed children calcium, iron and/or zinc and for non-breastfed children calcium, vitamin A, vitamin B12 and vitamin C.

Table 5. Final sets of selected food-based recommendations including additional extra recommendations for grain legumes for young children per age group and breastfeeding state, and the remaining problem nutrients

Foods	**6-8BF**	**9-11BF**	**12-23 BF**	**12-23 NBF**
Breast milk	Every day	Every day	Every day	
Vegetables	Every day	2 servings of dark green leafy vegetables	2 servings of dark green leafy vegetables	2 servings of dark green leafy vegetables
Dairy	3 servings		1 serving	
Whole grains	1 serving	3 servings	1 serving	1 serving
Fruits		1 serving	1 serving	
Fish		3 servings		1 serving
Nuts and/or seeds			3 servings	3 servings
Beans	1 serving	1 serving	1 serving	1 serving
Extra cowpea			*1 serving*	*1 serving*
Extra soybean	*1 serving*			
Problem nutrients without addition of extra legumes	calcium, niacin, iron, zinc	calcium, iron, zinc	calcium, iron	calcium, vit. A, vit. B_{12}, vit. C
Problem nutrients with addition of extra legumes	*iron, zinc*	*calcium, iron, zinc*	*calcium, iron*	*calcium, vit. A, vit. B_{12}, vit. C*

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months.

Table 4. Evaluation of nutrient levels per target group for the minimised diets: the final set of selected food based recommendations (FBRs), the selected FBRs plus 1 serving per day groundnut, the selected FBRs plus 1 serving per day cowpea, the selected FBRs plus 1 serving per day soybean flour and the selected FBRs plus combination of groundnut, cowpea and soybean if possible within energy constraints[a]

Food-Based Recommendation	Percentage RNI														≠Nutrients >70 % RNI[b]	GH¢/ day[c]
	Fat	Protein	*Isoleucine*	*Lysine*	*AAA*	Ca	Folate	Iron	Niacin	Riboflavin	vit. A	vit. B_{12}	vit. C	Zinc		
6-8 BF																
Average actual intake[d]	137	121	*152*	*133*	*142*	**51**	81	**11**	**48**	75	83	100	90	**32**	10	-
Without FBR, best-case scenario	214	181	*451*	*213*	*232*	**72**	134	**18**	**92**	**94**	**87**	111	101	**50**	12	0.5
Without FBR, worst-case scenario	128	81	*165*	*109*	*144*	**46**	70	**2**	**27**	**58**	81	91	87	**17**	8	0.1
Selected FBR BF7 + Vegetables21 + Dairy7 + Nuts7 + Beans7	143	161	*397*	*202*	*218*	**65**	129	**13**	**66**	87	85	108	99	**42**	10	0.3
Selected FBR + groundnut paste7	158	180	*453*	*213*	*235*	**66**	136	**15**	91	89	85	108	99	**45**	11	0.4
Selected FBR + cowpea dried4[e]	143	190	*477*	*238*	*242*	**67**	153	**18**	72	91	85	108	100	**53**	11	0.4
Selected FBR + soybean flour7	152	207	*510*	*264*	*258*	70	149	**17**	70	93	85	108	99	**52**	11	0.3
Selected FBR + combined soy+gnt[f]	166	176	*425*	*212*	*233*	**68**	113	**9**	84	88	85	108	99	**35**	11	0.3
Selected FBR + combined soy+cow[f]	136	217	*534*	*288*	*265*	71	166	**20**	**51**	95	85	108	100	**61**	11	0.3
9-11 BF																
Average actual intake[d]	125	136	*127*	*136*	*125*	**52**	90	**16**	**68**	75	81	86	93	**42**	10	-
Without FBR, best-case scenario	204	178	*454*	*181*	*222*	**69**	136	**24**	107	109	**98**	139	124	**55**	11	0.5
Without FBR, worst-case scenario	108	77	*162*	*110*	*135*	**43**	**69**	**3**	**30**	**57**	76	85	81	**20**	8	0.2
Selected FBR BF7 + DGLV14 + Fruits7 + Fish21 + Whole grains21 + Beans7	115	158	*391*	*160*	*199*	**57**	115	**21**	80	96	90	126	110	**51**	11	0.4
Selected FBR + groundnut paste1[e]	116	159	*396*	*161*	*200*	**57**	116	**21**	84	97	90	126	110	**52**	11	0.4
Selected FBR + cowpea dried1	np	Np	*np*	*np*	*np*	np	np	np	np	np	np	np	np	np	np	np
Selected FBR + soybean flour1	np	np	*np*	*np*	*np*	np	np	np	np	np	np	np	np	np	np	np
12-23 BF																
Average actual intake[d]	112	189	*108*	*172*	*110*	**45**	**61**	**43**	82	80	75	**67**	93	107	10	-
Without FBR, best-case scenario	179	251	*673*	*249*	*292*	**75**	112	**65**	123	123	181	**96**	154	147	13	1.1
Without FBR, worst-case scenario	82	108	*259*	*111*	*154*	**33**	**40**	**16.7**	**40**	**51**	**68**	**60**	72	**59**	6	0.4
Selected FBR: BF7 + Fruits7 + Dairy7 + DGLV14 + Nuts21 + Beans7	107	200	*542*	*213*	*251*	**65**	88	**44**	79	105	94	84	129	114	12	0.6
Selected FBR + groundnut paste7	119	218	*596*	*225*	*270*	**66**	92	**47**	98	107	94	84	129	119	12	0.7
Selected FBR + cowpea dried7	108	239	*656*	*268*	*289*	**68**	110	**58**	86	110	94	84	130	145	12	0.7
Selected FBR + soybean flour7	113	237	*638*	*269*	*289*	**69**	98	**50**	81	110	94	84	129	131	12	1.2

Table 4 continued. Evaluation of the worst case scenario nutrient levels per target group for: the final set of selected food based recommendations (FBRs), the selected FBRs plus 1 serving per day groundnut, the selected FBRs plus 1 serving per day cowpea, the selected FBRs plus 1 serving per day soybean flour and the selected FBRs plus combination of groundnut, cowpea and soybean if possible within energy constraints[a]

Food-Based Recommendation	Percentage RNI														≠Nutrients >70 % RNI[b]	GH¢/ day[c]
	Fat	Protein	*Isoleucine*	*Lysine*	*AAA*	Ca	Folate	Iron	Niacin	Riboflavin	Vit. A	Vit. B_{12}	Vit. C	Zinc		
12-23 NBF																
Average actual intake[d]	75	243	***1***	*172*	***1***	**32**	**54**	78	113	100	**15**	**11**	**40**	147	7	-
Without FBR, best-case scenario	162	316	*893*	*249*	*289*	**46**	124	104	212	103	**36**	**7**	**79**	210	11	1.7
Without FBR, worst-case scenario	**21**	131	*393*	*74*	*111*	**7**	**22**	**36**	**57**	**28**	**0**	**2**	**0**	80	5	0.7
Selected FBR: Fish7 + DGLV14 + Nuts21 + Beans7	79	261	*757*	*216*	*248*	**36**	96	79	147	75	**21**	**5**	**50**	164	10	1.0
Selected FBR + groundnut paste 7	117	317	*926*	*253*	*306*	**39**	111	87	207	81	**21**	**5**	**50**	180	10	1.2
Selected FBR + cowpea dried 7	80	334	*966*	*316*	*318*	**41**	136	103	160	85	**21**	**6**	**51**	221	10	1.2
Selected FBR + soybean flour 7	85	298	*852*	*272*	*286*	**40**	107	84	149	80	**21**	**5**	**50**	181	10	1.0

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months, BF7 = average breastmilk 7 times per week (every day), DGLV = dark green leafy vegetables, Meat = meat, fish or egg food group, Nuts = nuts, seeds and unsweetened products sub food group, soy+gnt = soybean flour plus groundnut paste and soy+cow = soybean flour plus cowpea (tested with servings as stated above in table as individual addition). np = not possible within energy constraints.
Bold values = Values below 100% RNI for the best-case scenario and values below 70% RNI for the worst-case scenario of the modelled diets and for average actual intake.
Grey boxes = for each target group the final set of recommendations that achieved >70% of the RNI in the worst-case scenario for most nutrients but below the 75ht percentile of daily diet cost.
[a]Values are expressed as percentage of recommended nutrient intakes (RNI).
[b]Total number of nutrients that are above 70% of RNI.
[c]Total cost of modelled diet per day in Ghanaian Cedi's (GH₵).
[d]Average actual intake = percentage RNI covered by average actual intake of target group.
[e]Highest servings per week possible within energy constraints.
[f]Not possible to combine all three legumes within energy constraints.

Discussion

Among IYC in rural Northern Ghana, 40% currently consumed legumes with an average portion size of about 20 g per day contributing more than 10% of their total protein, folate, iron and niacin intake with largest contributions among older children and non-breastfed children (Table 3). The final sets of FBRs that fit within the current dietary patterns included legumes. These FBRs provided adequate protein and EAAs but not of calcium, iron, niacin and/or zinc among breastfed children and of calcium, vitamin C, vitamin B12 and vitamin A among children 12-23 NBF (Table 5). FBRs combined with extra legumes on top of the current dietary pattern but within energy requirements, improved adequacy of calcium, iron, niacin and zinc but only reached sufficient amounts for calcium among 6-8 BF children.

Legume consumption

Although legume consumption among IYC was relatively common, 40% of our study population consumed no grain legumes while the other 60% consumed only relatively small portion sizes (Table 3). As such, they did not adhere to recommendations promoted by the Ministry of Health in Ghana to consume a cereal-legume complementary food called 'Weanimix' but ate instead a cereal based porridge. 'Weanimix' contains 75 to 80% maize, 10 to 15% soybean or cowpea and 10% groundnut improving the energy and protein content compared with the use of maize alone (Amagloh et al. 2012). The low legume consumption may have several reasons. A study investigating the acceptability of cowpea by caregivers of schoolchildren in rural Northern Ghana, found that despite cowpea being well accepted in the area, availability on the market, high prices, time required to cook cowpea, post-harvest loss due to insect pests and the resulting short storage time were barriers to give cowpeas to their children (Abizari et al. 2013). Although almost all caregivers reported that their schoolchildren like to eat cowpea, half of them thought that cowpeas are not easily digested by children and make them feeling uneasy. Caregivers of IYC in Ethiopia also reported to perceive pulses to be not well tolerated and to cause stomach problems in IYC (Mesfin et al. 2015). In addition, our data was collected in the 'hunger season' which is the longest period after the previous harvest, and therefore probably most rural households run out of legume stock and indeed found it expensive to buy legumes as prices increase a few months after harvest (Mishili et al. 2009) leading to reduced consumption.

Compared with children not consuming legumes, the intake of most nutrients is greater among children consuming legumes (except for isoleucine and AAA), also of nutrients not present in high concentrations in grain legumes such as vitamin A and vitamin C (Table 3). An explanation for this phenomenon may be related to legumes being regarded as ‘‘poor man’s meat’’ (Aykroyd et al. 1982), and children from higher socio-economic status may also consume other (more expensive) micronutrient rich foods in addition to legumes. However, we found no differences in socio-economic status indicators between the households of children consuming or not consuming legumes. A more recent study also reported that legumes are consumed across socio-economic strata (Abizari et al. 2013). A more plausible explanation is that legumes are rarely consumed in isolation, but are often combined in dishes with other micronutrients rich foods such as local vegetables and dried fish. Promoting legume consumption among IYC may therefore also increase consumption of other micronutrient rich foods and improve adequate intake of not only nutrients provided by the legumes.

Legumes and protein gaps

Among our study population, we found that legumes contributed about 5% to total protein intake among children of below 12 months with a larger contribution among older and non-breastfed children (11% and 22% for children 12-23 BF and 12-23 NBF, respectively) (Table 3). These percentage were larger than observed in diets of rural Ethiopian IYC where legumes contributed less than 4% of total protein intake with no difference according to age. Intake of milk and milk products were high in Ethiopian IYC diets, unlike Ghana, and contributed more to protein intake than legumes (Mesfin et al. 2015). With regard to the group of non-breastfed children we had a limited sample size of 29 children (the vast majority of children of this age were still breastfed) and the foods and portion sizes consumed may not be estimated robustly. However, as we sampled all non-breastfed children we consider our estimates to be realistic. As previously found (Mesfin et al. 2015; Uauy et al. 2016; Osendarp et al. 2016), total protein intake from the cereal based diet appears to be more-or-less sufficient in our study population (only 13% of breastfed and none of the non-breastfed children had a protein intake below their requirements). Nevertheless, the quality of protein intake in terms of EAAs might be at stake, especially in diets of stunted children (Ghosh et al. 2012; Semba et al. 2016; Suri et al. 2014). Most children in our study, which also had high prevalence of stunted children, had sufficient EAA intake to meet their requirements (Table 2). Previous studies measured EAA intakes of IYC using a metabolomics approach to measure serum amino acids and food balance sheets (Semba et al. 2016; Ghosh et al. 2012), which might explain the differences compared to our findings. Randomised controlled trials are needed to confirm the relationship between protein quality intake and stunting. In line with our findings, Suri et al. (2014) found that a traditional cereal–soybean blend made in Ghana did meet protein quality requirements except for lysine.

We may have underestimated protein and EAA requirements, as well as overestimated their intake. The established EAA requirements might be insufficient for young children in developing countries where energy deficits and infectious diseases are common and catch-up growth is needed (Semba et al. 2016; Ghosh et al. 2012). In case of an energy deficit, as is the case among more than 20% in all four target groups, part of the protein intake will be converted and used as energy. A diet that is moderately deficient in energy (5% below requirement) can increase protein needs by 10% (Kishi et al. 1978). Calculations of protein needs in relation to energy intake depend on many factors such as age, sex and physical activity and more research is needed for estimations of extra requirements in relation to energy deficit (FAO et al. 2007). In case of infectious diseases, activation of the immune system may limit EAAs to support growth (Kampman-van de Hoek et al. 2016). The absorption and utilization of amino acids in foods is also important to consider as it decreases the effective protein available in the body (Semba et al. 2016). Trypsin in legumes, an anti-nutritive component, for example, reduces protein digestibility up to 50% (Gilani et al. 2005) and we did not correct for protein digestibility in our study. In addition, for the breastfed children in our population it is unsurprising that we found EAAs intake to be sufficient as current EAAs requirements for IYC are based on breastmilk content (FAO et al. 2007) and we assumed average breastmilk intake (Brown et al. 1998). Actual breastmilk intake may be lower than the assumed daily average quantity, especially when meal frequency of complementary feeding increases (Dewey and Brown 2003). Further, EAAs content of breastmilk in rural sub-Saharan Africa may be less than what we assumed based on a recent review with only few studies from Africa with considerably higher concentrations compared to WHO values (Zhang et al. 2013; FAO et al. 2007). Despite our suspicion that we overestimated protein intake as requirements are probably elevated, we did not observe any symptoms of oedema which would indicate protein deficiency.

Among non-breast children, the EAA intakes of isoleucine and AAA did not meet requirements for all children (Table 2). This confirms the benefit of extending breastfeeding also after 1 year of age to cover the EAA requirements (WHO 2009). Like animal-source foods, breastmilk is considered to contain good quality protein as it is highly digestible and contains all EAAs in adequate amounts (Arsenault and Brown 2017). Therefore we expected to find larger numbers of children not meeting EAAs requirements among older non-breastfed children.

Linear programming also showed that both total protein and EAAs were not problem nutrients in the current diet (when also energy needs are met), nor were isoleucine, lysine and AAA problem nutrients among the non-breastfed group. The developed FBRs, when adopted fully, would ensure a protein and EAAs intake far above the requirements and adding extra legumes was not needed to reach adequacy.

Legumes and micronutrient gaps

In contrast to protein and EAAs intake, intake of most micronutrients was generally low in all our four target groups including calcium, folate, iron (except for the non-breastfed children), niacin and zinc (Table 2), the nutrients that are relative high in grain legumes and generally found to be deficient in IYC's diets in developing countries (Dewey 2013; E. Ferguson et al. 2015). These findings confirm the need to improve complementary feeding practises (Dewey and Adu-Afarwuah 2008) for which increasing grain legume intake might be an effective strategy.

Breastfeeding contributed most to all nutrient intakes of children below 12 months (See Additional file F) but after six months breastmilk alone is not sufficient anymore to cover their nutrient requirements (WHO 2009). Given their limited capacity to digest complementary foods (Dewey and Brown 2003), additional nutrient-dense foods are needed to cover all micronutrient requirements but these are often lacking (Osendarp et al. 2016; Abeshu et al. 2016). This is especially the case in developing countries as found in our study, due to two main reasons. First, the availability and affordability of nutrient-dense foods is limited. Second, cultural beliefs and practices limit the provision of nutrient-dense foods to the youngest children (Armar-Klemesu et al. 2016), also in the case of grain legumes (Abizari et al. 2013; Mesfin et al. 2015). Besides the greatest needs of the youngest children for micronutrient-dense foods, they tend not to eat from the family pot whereas older children do (Armar-Klemesu et al. 2016). The family pot is likely to include more nutrient-dense foods compared with foods given to the youngest children. Among non-breastfed children, there is more room in terms of energy for intake of nutrient-dense foods other than breastmilk. Our results suggest that this may have resulted in slightly more sufficient nutrient intakes but only for the nutrients not high in breastmilk such as iron, zinc, folate and niacin (Brown et al. 1998).

As legumes contain relatively large amounts of micronutrients that are inadequate among the majority of our study population and current intake of legumes is low especially among children of below 12 months, increasing legume consumption may improve micronutrient intakes of all our four target groups. This was confirmed by our final sets of FBRs modelled for all our four target groups that all included the recommendation to consume legumes every day: 1 serving of beans for all four target groups and 3 servings of nuts for children of above 12 months (Table 5). Despite the final FBRs did indeed improve the adequacy of calcium, folate, iron, niacin and zinc intake, these FBRs did not achieve the criteria selected to define a low risk of inadequate intakes for all children in the population in all four target groups except for folate. Other studies that developed FBRs using similar methods, also found that these similar problem nutrients could not be covered within the current dietary pattern of young children and additional interventions are needed (Hlaing et al. 2016; Kujinga et al. 2018). As legumes are relatively high in calcium, iron, niacin and zinc we combined the final sets of FBRs with extra recommendations on legumes on top of their dietary pattern. Again this further improved adequacy of remaining problem nutrients in most cases for all groups but only sufficiently improved calcium and niacin adequacy of 6-8 BF children. Despite the high iron and zinc content of legumes, the bioavailability of these nutrients is weak due to the high content of anti-nutrient components such as phytate that can drastically limiting the uptake of these nutrients (Sandberg 2002; Hurrell 2003). Among children 9-11 BF, the final set of FBRs already covered most of energy needs thereby leaving no room for extra legumes within the energy constraints of the current diet. Modelling FBRs including extra legumes outside of the current dietary pattern from the start may (partly) replace FBR of whole grains and potentially could result in adequate intakes of calcium, iron and/or zinc for this group. Further adding soybean, which contains relatively more calcium than other grain legumes, in higher portion size or frequency to FBRs of children of above 9 months may result in adequate calcium intakes. Nevertheless, as soybean is rarely consumed in Northern Ghana (Dogbe et al. 2013) adoption of such a FBR might be challenging.

Implementation of food-based recommendations

As FBRs are based on the actual dietary patterns and their costs, the foods recommended are assumed to be available, affordable and acceptable for the target population (E. L. Ferguson et al. 2004). However, the analysis is based on the distribution of the types and frequencies of foods consumed, and often uses the extremes of these distributions to develop FBRs that cover most nutrient needs. Using these extremes may limit the actual adoption of the FBRs by all IYC, for example, due to beliefs about legume consumption and/or limited availability of legumes in some of the households where probably legume consumption is already low. Therefore before implementation of FBRs, their effectiveness need to be tested, as well as the most effective strategy for behavioural change communication interventions identified (Lamstein et al. 2014), and the potential barriers for adoption investigated. Furthermore, the FBRs first need to be aligned across our target groups (Vossenaar et al. 2017). An additional serving of fish for 12-23 BF children and additional serving of dairy and nuts for 9-11 BF children would align our FBRs for IYC. Nevertheless, adding dairy and nuts to FBRs for 9-11 BF was not possible within energy constraints.

Conclusions

This study showed that current grain legume intake among rural Ghanaian IYC contributes to nutrient intakes especially protein, folate, iron and niacin but in insufficient quantities to reach adequacy of all nutrients. Both current protein and EAAs intake were adequate in our study population making increasing grain legume consumption within the dietary pattern of IYC in rural Ghana unnecessary. Therefore increased consumption of legumes was not needed to improve protein intake. By contrast intake of most micronutrients was low in our study population, and increasing legume consumption within the dietary pattern of IYC in rural Ghana does have potential to increase adequacy of micronutrients. Nevertheless, consumption of additional legume foods resulted in only slight improvements in micronutrient adequacy on top of the current dietary patterns. Therefore other interventions are also needed such as other food-based approaches for example increasing the availability and accessibility of micronutrient-dense foods and/or fortification or supplementation strategies to improve micronutrient adequacy of infants and young children in rural Ghana.

References

Abdullah, A. (2015). The double burden of undernutrition and overnutrition in developing countries: an update. *Curr Obes Rep, 4*(3), 337-349.

Abeshu, M. A., Lelisa, A., & Geleta, B. (2016). Complementary feeding: review of recommendations, feeding practices, and adequacy of homemade complementary food preparations in developing countries – lessons from Ethiopia. *Frontiers in Nutrition, 3*, 41.

Abizari, A.-R., Azupogo, F., Nagasu, M., Creemers, N., & Brouwer, I. D. (2017). Seasonality affects dietary diversity of school-age children in northern Ghana. *PLoS One, 12*(8), e0183206.

Abizari, A.-R., Pilime, N., Armar-Klemesu, M., & Brouwer, I. D. (2013). Cowpeas in Northern Ghana and the factors that predict caregivers' intention to give them to schoolchildren. *PLoS One, 8*(8), e72087.

Amagloh, F. K., Weber, J. L., Brough, L., Hardacre, A., Mutukumira, A. N., & Coad, J. (2012). Complementary food blends and malnutrition among infants in Ghana: A review and a proposed solution. *Scientific Research and Essays, 7*(9), 972-988.

Armar-Klemesu, M., Zakariah-Akoto, S., & Osei-Menya, S. (2016). Feeding infants and young children in Karaga district, Northern region: A focused ethnographic study. Washington D.C., US: GAIN and USAID.

Arsenault, J. E., & Brown, K. H. (2017). Effects of protein or amino-acid supplementation on the physical growth of young children in low-income countries. *Nutrition Reviews, 75*(9), 699-717.

Aykroyd, W. R., Doughty, J., & Walker, A. F. (1982). Legumes in human nutrition, issue 20. 152.

Barikmo, I., Ouattara, F., & Oshaug, A. (2004). Food composition table for Mali. TACAM, research series N 9. Oslo, Norway: Akershus University College.

Beal, T., Massiot, E., Arsenault, J. E., Smith, M. R., & Hijmans, R. J. (2017). Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLoS One, 12*(4), e0175554.

Brown, K. H., Dewey, K. G., & Allen, L. (1998). Complementary feeding of young children in developing countries: a review of current scientific knowledge.

Brown, K. H., Rivera, J. A., Bhutta, Z., Gibson, R. S., King, J. C., Lönnerdal, B., Ruel, M. T., Sandtröm, B., Wasantwisut, E., & Hotz, C. (2004). International Zinc Nutrition Consultative Group (IZiNCG) technical document #1. Assessment of the risk of zinc deficiency in populations and options for its control. *Food Nutr Bull, 25*, S99-203.

Conway, J. M., Ingwersen, L. A., Vinyard, B. T., & Moshfegh, A. J. (2003). Effectiveness of the US Department of Agriculture 5-step multiple-pass method in assessing food intake in obese and non-obese women. *The American Journal of Clinical Nutrition, 77*(5), 1171-1178.

de Jager, I., Abizari, A.-R., Douma, J. C., Giller, K. E., & Brouwer, I. D. (2017). Grain legume cultivation and children's dietary diversity in smallholder farming households in rural Ghana and Kenya. *Food Security, 9*(5), 1053-1071.

Dewey, K. G. (2013). The challenge of meeting nutrient needs of infants and young children during the period of complementary feeding: An evolutionary perspective. *The Journal of Nutrition, 143*(12), 2050-2054.

Dewey, K. G., & Adu-Afarwuah, S. (2008). Systematic review of the efficacy and effectiveness of complementary feeding interventions in developing countries. *Maternal & Child Nutrition, 4*(s1), 24-85.

Dewey, K. G., & Brown, K. H. (2003). Update on technical issues concerning complementary feeding of young children in developing countries and implications for intervention programs. *Food Nutr Bull, 24*(1), 5-28.

Dogbe, W., Etwire, P. M., Martey, E., Etwire, J. C., Baba, I. I. Y., & Siise, A. (2013). Economics of soybean production: evidence from Saboba and Chereponi districts of Northern region of Ghana. *Journal of Agricultural Science, 5*(12).
Eyeson, K. K., & Ankrah, E. K. (1975). Composition of foods commonly used in Ghana. *Accra, Ghana: Food Research Institute, Council for Scientific and Industrial Research*.
FAO (2003). Food energy – methods of analysis and conversion factors. Report of a technical workshop (FAO food and nutrition paper 77). *Rome: Food and Agriculture Organisation*.
FAO (2010). Fats and fatty acids in human nutrition. Report of an expert consultation. Rome: FAO.
FAO (2012). West african food composition table. Rome, Italy: FAO.
FAO, WHO, & UNU (2004). Human energy requirements. Report of a joint FAO/WHO/UNU expert consultation (FAO food and nutrition technical report series, no. 1). *Rome: Food and Agriculture Organization.*
FAO, WHO, & UNU (2007). Protein and amino acid requirements in human nutrition. *World Health Organization technical report series: 1*.
Ferguson, E., Chege, P., Kimiywe, J., Wiesmann, D., & Hotz, C. (2015). Zinc, iron and calcium are major limiting nutrients in the complementary diets of rural Kenyan children. *Maternal & Child Nutrition, 11*(Suppl Suppl 3), 6-20.
Ferguson, E. L., Darmon, N., Briend, A., & Premachandra, I. M. (2004). Food-based dietary guidelines can be developed and tested using linear programming analysis. *The Journal of Nutrition, 134*(4), 951-957.
Foresight (2011). The future of food and farming. London: The Government Office for Science.
Ghosh, S., Kurpad, A., Tano-Debrah, K., Otoo, G. E., Aaron, G. A., Toride, Y., & Uauy, R. (2015). Role of protein and amino acids in infant and young child nutrition: considerations for the development and delivery of high quality complementary food supplements. *Journal of Nutritional Science and Vitaminology, 61*(Supplement), S195-S196.
Ghosh, S., Suri, D., & Uauy, R. (2012). Assessment of protein adequacy in developing countries: quality matters. *British Journal of Nutrition, 108 Suppl 2*, S77-87.
Gilani, G. S., Cockell, K. A., & Sepehr, E. (2005). Effects of antinutritional factors on protein digestibility and amino acid availability in foods. *Journal of Association of Official Agricultural Chemists International, 88*(3), 967-987.
Giller, K. E., Franke, A. C., Abaidoo, R., Baijukya, F. P., Bala, A., Boahen, S., Dashiell, K., Katengwa, S., Sanginga, J., Sanginga, N., Simmons, A., Turner, A., Woomer, P. L., Wolf, J. d., & Vanlauwe, B. (2013). N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa. In B. Vanlauwe, P. van Asten, & G. Blomme (Eds.), *Agro-ecological Intensification of Agricultural Systems in the African Highlands* (pp. 156-174). London, UK: Routledge.
GLOPAN (2016). Food systems and diets: facing the challenges of the 21st century. London, UK.
Gunaratna, N. S., de Groote, H., Nestel, P., Pixley, K. V., & McCabe, G. P. (2010). A meta-analysis of community-based studies on quality protein maize. *Food Policy, 35*(3), 202-210.
Hlaing, L. M., Fahmida, U., Htet, M. K., Utomo, B., Firmansyah, A., & Ferguson, E. L. (2016). Local food-based complementary feeding recommendations developed by the linear programming approach to improve the intake of problem nutrients among 12–23-month-old Myanmar children. *British Journal of Nutrition, 116*(S1), S16-S26.
Hurrell, R. F. (2003). Influence of vegetable protein sources on trace element and mineral bioavailability. *The Journal of Nutrition, 133*(9), 2973s-2977s.
Institute of Medicine (2000). Dietary reference intakes: application in dietary assessment. Subcommittee on interpretation and uses of dietary reference intakes and the standing committee on the scientific evaluation of dietary reference intakes. (pp. 215-227). Washington, D. C. : National Academic Press.
Kampman-van de Hoek, E., Jansman, A. J. M., van den Borne, J. J. G. C., van der Peet-Schwering, C. M. C., van Beers-Schreurs, H., & Gerrits, W. J. J. (2016). Dietary amino acid deficiency

reduces the utilization of amino acids for growth in growing pigs after a period of poor health. *The Journal of Nutrition, 146*(1), 51-58.

Keats, S., & Wiggins, S. (2014). Future diets: implications for agriculture and food prices. London, UK: ODI.

Kishi, K., Miyatani, S., & Inoue, G. (1978). Requirement and utilization of egg protein by Japanese young men with marginal intakes of energy. *The Journal of Nutrition, 108*(4), 658-669.

Kissinger, G. (2016). Pulse crops and sustainability: A framework to evaluate multiple benefits. Rome, Italy: FAO.

Kujinga, P., Borgonjen-van den Berg, K. J., Superchi, C., Ten Hove, H. J., Onyango, E. O., Andang'o, P., Galetti, V., Zimmerman, M. B., Moretti, D., & Brouwer, I. D. (2018). Combining food-based dietary recommendations using Optifood with zinc-fortified water potentially improves nutrient adequacy among 4- to 6-year-old children in Kisumu West district, Kenya. *Maternal & Child Nutrition, 14*(2), e12515.

Lamstein, S., Stillman, T., Koniz-Booher P., Aakesson, A., Collaiezzi, B., Williams, T., Beall, K., & Anson, M. A., VA: (2014). Evidence of effective approaches to social and behavior change communication for preventing and reducing stunting and anemia: report from a systematic literature review. Arlington, VA: USAID/SPRING Project.

Mesfin, A., Henry, C., Girma, M., & Whiting, S. J. (2015). Use of pulse crops in complementary feeding of 6-23-month-old infants and young children in Taba Kebele, Damot Gale district, Southern Ethiopia. *J Public Health Afr, 6*(1), 357.

Mishili, F. J., Fulton, J., Shehu, M., Kushwaha, S., Marfo, K., Jamal, M., Kergna, A., & Lowenberg-DeBoer, J. (2009). Consumer preferences for quality characteristics along the cowpea value chain in Nigeria, Ghana, and Mali. *Agribusiness, 25*(1), 16-35.

Mudryj, A. N., Yu, N., & Aukema, H. M. (2014). Nutritional and health benefits of pulses. *Applied Physiology, Nutrition and Metabolism, 39*(11), 1197-1204.

Muthayya, S., Rah, J. H., Sugimoto, J. D., Roos, F. F., Kraemer, K., & Black, R. E. (2013). The global hidden hunger indices and maps: an advocacy tool for action. *PLoS One, 8*(6), e67860.

National Institute of Nutrition (2017). Indian Food Composition Tables. Hyderabad, India: National Institute of Nutrition (NIN).

National Research Council (1986). *Nutrient Adequacy: Assessment Using Food Consumption Surveys. Reports of the sub-committee on interpretation and uses of dietary reference intakes and the standing committee on the scientific evaluation of dietary reference intakes* Washington D. C.: National Academy Press.

Nedumaran, S., Abinaya, P., Jyosthnaa, P., Shraavya, B., Parthasarathy Rao, & Cynthia Bantilan (2015). Grain legumes production, consumption and trade trends in developing countries. Working paper series No 60. ICRISAT research program, markets, institutions and policies. Telangana, India: International Crops Research Institute for the Semi-Arid Tropics.

Osendarp, S. J. M., Broersen, B., van Liere, M. J., De-Regil, L. M., Bahirathan, L., Klassen, E., & Neufeld, L. M. (2016). Complementary feeding diets made of local foods can be optimized, but additional interventions will be needed to meet iron and zinc requirements in 6- to 23-month-old children in low- and middle-income countries. *Food Nutr Bull, 37*(4), 544-570.

Pingali, P. L. (2012). Green Revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences, 109*(31), 12302-12308.

Ranganathan, J., Vennard, D., Waite, R., Dumas, P., Lipinski, B., Searchinger, T., & GLOBAGRI-WRR MODEL AUTHORS (2016). Shifting diets for a sustainable food future. Working paper, installment 11 of creating a sustainable food future. Washington, DC: World Resources Institute.

Raymond, J., Kassim, N., Rose, J. W., & Agaba, M. (2017). Optimal formulations of local foods to achieve nutritional adequacy for 6–23-month-old rural Tanzanian children. *Food Nutr Res, 61*(1), 1358035.

Sandberg, A. S. (2002). Bioavailability of minerals in legumes. *British Journal of Nutrition, 88 Suppl 3*, S281-285.
Santika, O., Fahmida, U., & Ferguson, E. L. (2009). Development of food-based complementary feeding recommendations for 9- to 11-month-old peri-urban Indonesian infants using linear programming. *The Journal of Nutrition, 139*, 135-141.
Schönfeldt, H. C., & Hall, N. G. (2012). Dietary protein quality and malnutrition in Africa. *British Journal of Nutrition, 108*, 69-76.
Semba, R. D., Shardell, M., Sakr Ashour, F. A., Moaddel, R., Trehan, I., Maleta, K. M., Ordiz, M. I., Kraemer, K., Khadeer, M. A., Ferrucci, L., & Manary, M. J. (2016). Child stunting is associated with low circulating essential amino acids. *EBioMedicine, 6*, 246-252.
Skau, J. K. H., Bunthang, T., Chamnan, C., Wieringa, F. T., Dijkhuizen, M. A., Roos, N., & Ferguson, E. L. (2014). The use of linear programming to determine whether a formulated complementary food product can ensure adequate nutrients for 6- to 11-month-old Cambodian infants. *The American Journal of Clinical Nutrition, 99*, 130-138.
South African MRC (2010). South African Food Data System. http://safoods.mrc.ac.za/,. Accessed February 2018.
Suri, D. J., Tano-Debrah, K., & Ghosh, S. A. (2014). Optimization of the nutrient content and protein quality of cereal—legume blends for use as complementary foods in Ghana. *Food Nutr Bull, 35*(3), 372-381.
Talsma, E. F., Borgonjen-van den Berg, K. J., Melse-Boonstra, A., Mayer, E. V., Verhoef, H., Demir, A. Y., Ferguson, E. L., Kok, F. J., & Brouwer, I. D. (2017). The potential contribution of yellow cassava to dietary nutrient adequacy of primary-school children in Eastern Kenya; the use of linear programming. *Public Health Nutrition*, 1-12.
Uauy, R., Suri, D. J., Ghosh, S., Kurpad, A., & Rosenberg, I. H. (2016). Low circulating amino acids and protein quality: an interesting piece in the puzzle of early childhood stunting. *EBioMedicine, 8*, 28-29.
UNICEF, WHO, & World Bank Group (2017). Level and trends in child malnutrition. USA: UNICEF, WHO & World Bank Group.
USDA (2016). USDA national nutrient database for standard reference, Release 28. http://www.ars.usda.gov/nea/bhnrc/ndl. Accessed February 2018.
Vásquez-Caicedo, A. L., Bell, S., & Hartmann, B. (2008). Report on collection of rules on use of recipe calculation procedures including the use of yield and retention factors for imputing nutrient values for composite foods (D2.2.9). Brussels, Belgium: EuroFIR.
Vossenaar, M., Knight, F. A., Tumilowicz, A., Hotz, C., Chege, P., & Ferguson, E. L. (2017). Context-specific complementary feeding recommendations developed using Optifood could improve the diets of breast-fed infants and young children from diverse livelihood groups in northern Kenya. *Public Health Nutrition, 20*(6), 971-983.
WHO (2008). Training course on child growth assessment. Geneva: World Health Organisation.
WHO (2009). Infant and young child feeding: model chapter for textbooks for medical students and allied health professionals. Geneva, Switzerland: WHO Press.
WHO, & FAO (2004). Vitamin and mineral requirements in human nutrition. Second edition. *Geneva/Rome: WHO/FAO*.
WHO Multicentre Growth Reference Study Group (2006). *WHO Child Growth Standards: Length/height-for-age, weight-for-age, weight-for-length, weight-for-height and body mass index-for-age: Methods and developments*. Geneva, Switzerland: World Health Organization.
Zhang, Z., Adelman, A. S., Rai, D., Boettcher, J., & Lőnnerdal, B. (2013). Amino acid profiles in term and preterm human milk through lactation: a systematic review. *Nutrients, 5*(12), 4800-4821.

Appendices

Appendix A

Energy, fat, protein and essential amino acid requirements used for calculating percent of children with nutrient intakes below requirements, based on reference weight and actual weight

	children 6-8 mo		children 9-11 mo		children 12-23 mo		
	Ref. weight 7.98 kg	**Actual weight** 7.03 kg	**Ref. weight** 9.03 kg	**Actual weight** 7.54 kg	**Ref. weight** 10.74 kg	**Actual weight BF** 8.48 kg	**Actual weight NBF** 9.43 kg
Energy[a]	**614**	541	**695**	581	**886**	700	778
Fat (g)[b]	**20.5**	18.0	**23.2**	19.4	**29.5**	23.3	25.9
Protein (g)[c]	**9.1**	8.0	**10.3**	8.6	**11.1**	8.7	9.7
Histidine[d]	***182***	160	***196***	163	***199***	157	175
Isoleucine[d]	***291***	256	***324***	271	***343***	270	301
Leucine[d]	***601***	528	***664***	555	***697***	548	611
Lysine[d]	***519***	456	***561***	469	***575***	452	504
SAA (mg)[d]	***255***	224	***278***	232	***288***	226	252
AAA (mg)[d]	***473***	416	***504***	421	***509***	400	446
Threonine[d]	***282***	248	***298***	249	***299***	235	262
Tryptophan[d]	***77***	68	***82***	68	***82***	64	72
Valine[d]	***391***	344	***437***	366	***465***	365	407

Ref. weight = reference weight; SAA = sulphur-containing amino acids (methionine and cystine); AAA = aromatic amino acids (phenylalanine and tyrosine). **Bold values** = are values used for calculating percent of children with nutrient intakes below requirements (in Table 2).

[a]based on average reference or actual body weight for age group and algorithm for estimating energy requirements (kcal/kg) (FAO, 2004)

[b]based on acceptable macronutrient distribution range (ADMR) of 30% of daily energy requirements (FAO, 2010)

[c]based on average reference body weight for age group and algorithm for estimating protein requirement (g/kg), safe intakes (FAO, 2007)

[d]based on daily total protein requirements and algorithms for each essential amino acid requirements (mg/g protein) using safe intakes for 0.5 year old children for 6-8mo group, average of safe intakes for 0.5 years and 1 to 2 years old children for 9-11mo group and safe intakes for 1 to 2 years old children for 12-23mo group (WHO, 2007)

Appendix B

Micronutrient requirements used for calculating percent of children with nutrient intakes below requirements

	children 6-8 mo		children 9-11		children 12-23 mo		
Micronutrients	*RNI[a]*	*EAR[b]*	*RNI[a]*	*EAR[b]*	*RNI[a]*	*EAR[c]*	*CV*
Calcium (mg)	400	n/a	400	n/a	500	**417**	1.2
Folate (µg DFE)	80	**65**	80	**65**	150	**120**	1.25
Iron (mg)[d]	18.6	**6.9**	18.6	**6.9**	11.6	**3.0**	n/a
Niacin (mg)	4	n/a	4	n/a	6	**4.6**	1.3
Riboflavin (mg)	0.4	n/a	0.4	n/a	0.5	**0.4**	1.25
Thiamine (mg)	0.3	n/a	0.3	n/a	0.5	**0.4**	1.25
Vitamin A (µg RAE)	400	n/a	400	n/a	400	**286**	1.4
Vitamin B_6 (mg)	0.3	n/a	0.3	n/a	0.5	**0.4**	1.25
Vitamin B_{12} (µg)	0.7	n/a	0.7	n/a	0.9	**0.7**	1.3
Vitamin C (mg)	30	n/a	30	n/a	30	**25**	1.2
Zinc (mg)[e]	5	**4**	5	**4**	3	**2**	1.2

SAA = sulphur-containing amino acids (methionine and cystine); AAA = aromatic amino acids (phenylalanine and tyrosine); CV = conversion factor. **Bold values** = are values used for calculating percent of children with nutrient intakes below requirements (in Table 2).

[a]RNIs from FAO/WHO (2004) except for zinc based on RNI from iZiNCG (2004)

[b]No conversion factors available for children below 12 months old, except for folate EAR from FAO/WHO (2004), for iron EAR from IOM (2001) and for zinc EAR from iZiNCG (2004)

[c]EARs calculated from RNIs (FAO/WHO 2004), using conversion factors (Allen, et al., 2006) except for iron EAR from IOM (2001) and for zinc EAR from iZiNCG (2004)

[d]Assuming 5% bioavailability

[e]Assuming unrefined cereal-based diets

Appendix C

All non-condiment foods consumed by >5% of target children with a median portion size of at least 1 gram in Karaga district, median serving size (g/day) and percentage of children consuming each food

	6-8 BF		9-11 BF		12-23 BF		12-23 NBF	
Foods	Median amount in g/day (% children consumed), *min - max frequency*							
Added fats								
Oil palm					5 (7)	*0 - 7*		
Oil vegetable Frytol			3 (14)	*0 - 7*	6 (17)	*0 - 7*	6 (21)	*0 - 7*
Vegetable Oil	14 (11)	*0 - 7*	15 (31)	*0 - 7*	13 (52)	*0 - 7*	17 (48)	*0 - 7*
Added sugar								
Sugar white refined	6 (52)	*0 - 7*	9 (52)	*0 - 7*	14 (59)	*0 - 7*	16 (66)	*0 - 7*
Bakery & breakfast cereals								
Biscuit sweet	9 (6)	*0 - 7*						
Bread sugar					50 (6)	*0 - 7*	73 (21)	*0 - 7*
Beverages								
Creamer non diary powder			2 (8)	*0 - 7*	7 (12)	*0 - 7*	6 (24)	*0 - 7*
Dairy products								
Milk cow powder skimmed	3 (7)	*0 - 7*	2 (6)	*0 - 7*	5 (7)	*0 - 7*		
Fruits								
Melon water raw			72 (5)	*0 - 7*	126 (7)	*0 - 7*		
Grains & grain products								
Guinea corn dough whole grain RT[3] boiled	20 (17)	*0 - 3*	22 (20)	*0 - 3*	48 (15)	*1 - 2*	66 (17)	*1 - 7*
Guinea corn flour whole grain RT boiled	40 (19)	*0 - 3*	33 (20)	*0 - 3*	27 (15)	*1 - 2*		
Maize dough whole grain white RT boiled	27 (44)	*0 - 7*	36 (43)	*0 - 7*	50 (37)	*1 - 7*	38 (31)	*1 - 7*
Maize flour whole grain white RT boiled	40 (30)	*0 - 6*	38 (55)	*0 - 7*	65 (76)	*2 - 7*	123 (90)	*3 - 7*
Maize grain dried white RT boiled			11 (8)	*0 - 1*	53 (10)	*0 - 2*	11 (21)	*1 - 7*
Millet dough whole grain RT boiled			10 (6)	*0 - 1*	33 (9)	*0 - 1*		
Millet flour whole grain RT boiled			13 (8)	*0 - 1*	15 (8)	*0 - 1*		

	6-8 BF		9-11 BF	12-23	12-23		6-8 BF	
Foods	Median amount in g/day (% children consumed), *min - max frequency*							
Noodles instant RT boiled			3 (7)	*0 - 4*	9 (6)	*0 - 7*		
Rice local brown unpolished raw RT boiled	40 (11)	*0 - 2*	21 (29)	*0 - 4*	56 (49)	*2 - 6*	103 (48)	*2 - 7*
Rice white polished raw RT boiled			41 (5)	*0 - 3*				
Legumes, nuts & seeds								
Beans soya dried raw RT boiled					1 (7)	*0 - 7*		
Cowpea white dried whole RT boiled	24 (8)	*0 - 7*	10 (11)	*0 - 7*	23 (17)	*0 - 4*	42 (24)	*0 - 7*
Groundnut flour with fat RT boiled			4 (9)	*0 - 7*	5 (11)	*0 - 7*	13 (21)	*0 - 4*
Groundnut roasted paste RT boiled	7 (6)	*0 - 7*	4 (21)	*0 - 7*	8 (44)	*0 - 7*	25 (45)	*0 - 7*
Groundnut shelled dried raw RT boiled							1 (76)	*0 - 7*
Neri roasted RT boiled					4 (8)	*0 - 7*	15 (24)	*0 - 3*
Pigeon peas dried RT boiled					23 (9)	*0 - 2*		
Meat, fish & eggs								
Fish anchovies smoked dried RT boiled	1 (28)	*0 - 7*	2 (56)	*0 - 7*	2 (84)	*0 - 7*	4 (83)	*0 - 7*
Fish herrings smoked dried RT boiled			1 (5)	*0 - 7*				
Mackerel canned in tomato sauce RT boiled			1 (6)	*0 - 7*	1 (7)	*0 - 7*		
Starchy roots & other starchy plant foods								
Cassava dough roasted			3 (5)	*0 - 7*	8 (7)	*0 - 3*		
Cassava flour RT boiled	3 (7)	*0 - 7*	9 (8)	*0 - 4*	9 (9)	*0 - 4*		
Vegetables								
Ayoyo leaves raw RT boiled	5 (14)	*0 - 5*	3 (29)	*0 - 7*	7 (45)	*0 - 7*	18 (31)	*0 - 7*
Bra leaves raw RT boiled	7 (7)	*0 - 2*	8 (17)	*0 - 7*	17 (27)	*0 - 7*	19 (59)	*0 - 7*
Okro fruit dried powder RT boiled			1 (7)	*0 - 1*	3 (14)	*0 - 7*	4 (28)	*0 - 7*
Okro fruit raw RT boiled			12 (14)	*0 - 7*	25 (11)	*0 - 7*	27 (24)	*0 - 7*
Onion bulb raw RT boiled	2 (9)	*0 - 7*	2 (32)	*0 - 6*	2 (50)	*0 - 7*	6 (31)	*0 - 7*
Tomato paste concentrated RT boiled	4 (7)	*0 - 7*	3 (24)	*0 - 7*	5 (37)	*0 - 7*	10 (28)	*0 - 7*
Breastmilk	*660*	*7 - 7*	*616*	*7 - 7*	*549*	*7 - 7*		

6-8 BF = breastfed children of 6-8 mo, 9-11 BF = breastfed children of 9-11 mo, 12-23 BF = breastfed children of 12-23 mo, 12-23 NBF = non-breastfed children of 12-23 mo.

Appendix D

Distribution of daily diet costs[a] per target group

Target group	25th	50th	75th
6 to 8 months BF	0.08	0.18	**0.39**
9 to 11 months BF	0.16	0.34	**0.71**
12 to 23 months BF	0.45	0.77	**1.23**
12 to 23 months NBF	0.99	1.51	**2.29**

[a]Daily diet cost per child were calculated by summing the price of each quantity of a food consumed per child, using the average price per edible 100 g portion (prices were collected from three different food sellers in the area).

Appendix E

Dietary pattern with minimum and maximum servings per week by target group

Food groups & Sub food groups[a]	**6-8 BF**		**9-11 BF**		**12-23 BF**		**12-23 NBF**	
	Servings per week							
	Min	Max	Min	Max	Min	Max	Min	Max
Grains & grain products	**0**	**21**	**0**	**28**	**7**	**28**	**7**	**35**
Whole grains and products	0	21	0	28	7	28	7	35
Refined grains and products	-	-	0	7	0	7	-	-
Starchy roots & other starchy	**0**	**7**	**0**	**7**	**0**	**7**	**-**	**-**
Other starchy plant foods	0	7	0	7	0	7	-	-
Legumes, nuts & seeds	**0**	**21**	**0**	**28**	**0**	**28**	**7**	**28**
Cooked beans, lentils, peas	0	7	0	7	0	7	0	7
Nuts, seeds	0	14	0	21	0	21	0	21
Soybeans and products	-	-	-	-	0	7	-	-
Meat, fish & eggs	**0**	**7**	**0**	**21**	**0**	**14**	**0**	**14**
Small, whole fish, with bones	0	7	0	21	0	14	0	14
Beverages (non-dairy)	**-**	**-**	**0**	**7**	**0**	**7**	**0**	**14**
Other beverages	-	-	0	7	0	7	0	7
Dairy products	**0**	**7**	**0**	**7**	**0**	**7**	**-**	**-**
Fluid/powdered milk (fortified)	0	7	0	7	0	7	-	-
Vegetables	**0**	**21**	**0**	**28**	**0**	**28**	**7**	**35**
Vitamin A source DGLV	0	7	0	14	0	14	0	14
Vitamin A source vegetables	0	7	0	7	0	7	0	7
Other vegetables	0	7	0	7	0	14	0	14
Vitamin C-rich vegetables	-	-	0	7	0	7	0	7
Fruits	**-**	**-**	**0**	**7**	**0**	**7**	**-**	**-**
Other fruit	-	-	0	7	0	7	-	-
Bakery & breakfast cereals	**0**	**7**	**-**	**-**	**0**	**7**	**0**	**7**
Sweetened bakery products	0	7	-	-	0	7	0	7
Added fats	**0**	**7**	**0**	**14**	**0**	**14**	**0**	**14**
Vegetable oil (unfortified)	0	7	0	7	0	7	0	7
Vegetable oil (fortified)	-	-	0	7	0	7	0	7
Red palm oil	-	-	-	-	0	7	-	-
Added sugars	**0**	**7**	**0**	**7**	**0**	**7**	**0**	**7**
Sugar (non-fortified)	0	7	0	7	0	7	0	7
Breastmilk	*6.9*	*7*	*6.9*	*7*	*6.9*	*7*	-	-

6-8 BF = breastfed children of 6-8 mo, 9-11 BF = breastfed children of 9-11 mo, 12-23 BF = breastfed children of 12-23 mo, 12-23 NBF = non-breastfed children of 12-23 mo. Min = 5th percentile of the weekly frequency was used, Max = 95th percentile of the weekly frequency was used.

[a]Food groups and sub food groups are classified as in Optifood

Appendix F

The count of nutrients that foods contributed >5% to specific nutrient intake in the best optimised diet, for each age group (out of 14 nutrients)

Foods	6-8mo BF	9-11mo BF	12-23mo BF	12-23mo NBF
Grains				
Guinea corn dough		2		9
Guinea corn flour		6		
Maize flour whole grain white			8	11
Millet flour whole grain		1		
Rice local brown unpolished raw	5		4	7
Legumes, nuts & seeds				
Cowpea white dried whole	10	7	7	11
Groundnut roasted paste	9	4	6	11
Groundnut flour with fat			4	1
Neri roasted			2	5
Pigeon peas dried			3	
Vegetables				
Ayoyo leaves raw	2		3	6
Bra leaves raw		5	6	6
Okro fruit raw boiled		2	3	3
Tomato paste				2
Meat, fish & eggs				
Fish anchovies smoked dried		1	1	2
Fish herrings smoked dried		1		
Mackerel canned in tomato sauce		1	1	
Beverages (non-dairy)				
Milk cow powder skimmed	8	5	8	
Others (fats, fruits)				
Oil vegetable Frytol		2		3
Melon water raw			4	
Breastmilk	*14*	*14*	*13*	-

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months.

Appendix G

Maximum percentage of RNI covered in the maximised diets, without FBR constraints

Nutrients	6-8 BF	9-11 BF	12-23 BF	12-23 NBF
Energy	174.6	165.9	186.3	223.6
Fat	213.7	204.8	179.3	315.5
Protein	181.1	177.6	251.3	161.9
Isoleucine	*451.3*	*453.5*	*673.2*	*892.9*
AAA	*232.1*	*221.7*	*292*	*289.3*
Lysine	*212.5*	*181.2*	*249.2*	*248.8*
Calcium	71.8	68.7	74.9	45.5
Vitamin C	100.9	123.6	154.2	78.9
Riboflavin	94.4	109.3	123.4	102.7
Niacin	92.4	107.4	123.4	211.8
Folate	134.4	135.5	111.6	124.2
Vitamin B12	110.6	138.8	96.2	6.8
Vitamin A	86.6	97.8	180.5	36.1
Iron	18.1	23.9	65.3	103.6
Zinc	50.0	54.5	147.4	210.2

6-8 BF = breastfed children of 6-8 months, 9-11 BF = breastfed children of 9-11 months, 12-23 BF = breastfed children of 12-23 months, 12-23 NBF = non-breastfed children of 12-23 months. AAA = aromatic amino acids (phenylalanine and tyrosine). Grey boxes = problem nutrients, nutrients below 100% RNI in best-case scenario: not possible to meet by any combination of local foods.

Chapter 3

Grain legume cultivation and children's dietary diversity in smallholder farming households in rural Ghana and Kenya

Ilse de Jager
Abdul-Razak Abizari
Jacob C. Douma
Ken E. Giller
Inge D. Brouwer

Food Security 2017, 9(5): 1053-71
doi: 10.1007/s12571-017-0720-0

Abstract

Boosting smallholder food production can potentially improve children's nutrition in rural Sub-Saharan Africa through a production-own consumption pathway and an income-food purchase pathway. Rigorously designed studies are needed to provide evidence for nutrition impact, but are often difficult to implement in agricultural projects. Within the framework of a large agricultural development project supporting legume production (N2Africa), we studied the potential to improve children's dietary diversity by comparing N2Africa and non-N2Africa households in a cross-sectional quasi-experimental design, followed by structural equation modelling (SEM) and focus group discussions in rural Ghana and Kenya. Comparing N2Africa and non-N2Africa households, we found that participating in N2Africa was not associated with improved dietary diversity of children. However, for soybean, SEM indicated a relatively good fit to the posteriori model in Kenya but not in Ghana, and in Kenya only the production-own consumption pathway was fully supported, with no effect through the income-food purchase pathway. Results are possibly related to differences in the food environment between the two countries, related to attribution of positive characteristics to soybean, the variety of local soybean-based dishes, being a new crop or not, women's involvement in soybean cultivation, the presence of markets, and being treated as a food or cash crop. These findings confirm the importance of the food environment for translation of enhanced crop production into improved human nutrition. This study also shows that in a situation where rigorous study designs cannot be implemented, SEM is a useful option to analyse whether agriculture projects have the potential to improve nutrition.

Introduction

Over two billion people suffer from multiple micronutrient deficiencies worldwide, with high prevalence among young children in sub-Saharan Africa (Muthayya et al. 2013). More than one in three children under five years of age in sub-Saharan Africa are stunted (UNICEF et al. 2015). The majority of malnourished people live in rural areas and depend on agriculture as an important source of the food and income required for their nutrition and health (Pinstrup-Andersen 2012). Agricultural interventions therefore have great potential to improve nutrition, but this potential is yet to be unleashed (Ruel and Alderman 2013). There is a strong call for evidence to support this, based on rigorous research (Masset et al. 2012).

Boosting the production of grain legumes by smallholder farmers is a feasible option to improve nutrition in rural areas. The advantage of grain legumes like cowpea, groundnut and soybean is twofold. First, legumes are unique in that they can fix nitrogen from the air in symbiosis with Rhizobium bacteria, increasing their production and enhancing soil fertility, thus increasing the production of other crops (Giller et al. 2013). Second, compared with maize, which is the most commonly produced and consumed staple in sub-Saharan Africa, legumes are better sources of high quality protein and contain a larger variety and greater concentration of micronutrients (de Jager 2013; FAO et al. 2012; Lukmanji et al. 2008).

Many agricultural interventions aim to increase food production from one or several crop(s) and assume this will result in improved nutrition outcomes. Literature describes many different potential pathways through which agricultural projects may affect nutrition outcomes positively, but also negatively (Du et al. 2015; Hoddinott 2011; Herforth and Harris 2014). The main pathways identified are: crop production for own consumption (the production-own consumption pathway), crop production for income used to purchase food (the income-food purchase pathway) and improvement of women's status in crop production and nutrition (the women's empowerment pathway). The production-own consumption pathway assumes that increased production of nutritious foods increases consumption of these foods and adds to diversity of the household's diet (Du et al. 2015; Masset et al. 2012). Greater dietary diversity results in improved nutrient adequacy of the diet, which is especially important for vulnerable groups like young children (Kennedy et al. 2007; Moursi et al. 2008). Increased legume production may lead to increased consumption of legumes, adding to dietary intake of energy, proteins, minerals and B vitamins, and improved dietary diversity. In Malawi, for example, an agriculture and nutrition education project offering different legume intercrops (including groundnut and soybean) to farmers, resulted in increased cultivation of legumes, increased the frequency of legume consumption by children and improved their nutritional status in villages that were most intensely or longest involved in the project (Bezner Kerr et al. 2007; Bezner Kerr et al. 2010). The authors did not report on the impact on children's dietary diversity. The income-food purchase pathway assumes that increased agricultural income through increased production is used for immediate or future household needs, including food and non-food purchases to support improved nutrition outcomes such as dietary diversity (Du et al. 2015). Results of studies on effects of increased income on dietary intake are inconsistent and vary per country (Keats and Wiggins 2014). Some studies found positive effects (Muhammad et al. 2011; Monteiro 2009) and others found no effects (World Bank 2007; Masset et al. 2012) or suggested negative effects as diets tend to shift from cereals and tubers to meat, fats and sugar (Keats and Wiggins 2014). The women's empowerment pathway is a cross-cutting pathway interacting with the production-own consumption and the income-food purchase pathways. Women's status in the household is often related to children's dietary intake, as found in a study in Northern Ghana by Malapit and Quisumbing (2015). In the case of increased legume production, a greater status of women may lead to increased control over resources related to legume production and more income from the sale of legume produce. In turn, women's greater control over resources may result in the channelling of nutritious foods within households to the advantage of children, and to more income spent on nutritious food and health care, particularly for children (Smith et al. 2003; UNICEF 2011). However, the increase of female participation in agriculture may trade off with time spent on care practices, negatively influencing child nutrition (Barrios 2012; Cunningham et al. 2015).

The food environment, defined as the "collective physical, economic, policy, and socio-cultural surroundings, opportunities, and conditions that influence people's food and beverage choices" (Swinburn et al. 2015), is at the interface between food production and dietary intake, and includes the availability, affordability, convenience and desirability of various foods. For example, the effect of increased legume production on children's dietary diversity may depend on the household's landholding influencing all three pathways. The landholding of households is associated with the quantity of household crop production and the household's agricultural income (Mather 2009). However, the food environment is often not measured in agriculture-nutrition evaluations (Herforth and Ahmed 2015). To better understand the effect of boosting food production on children's dietary diversity, quantitative assessments of the production-own consumption and the income-food purchase pathways are needed, while taking into account the role of women and the food environment.

More rigorous and better designed studies are needed in agriculture and nutrition evaluations (Masset et al. 2012) but these have methodological challenges such as with establishing proper comparison groups, lacking baseline data and matching the project implementation process with rigorous study designs (Menon et al. 2013). A mixed methods design is used more frequently in project evaluations as the triangulation of complementary methods may add more rigour in evaluations (Creswell and Plano Clark 2011). Structural equation modelling (SEM) compares alternative models to assess relative model fit and is a powerful robust method for modelling complex causal paths taken by mediating variables (Garson 2015). SEM has not been used in agriculture and nutrition evaluations and may be a relevant additional method to analyse the complex pathways in this field.

We studied the potential of increased household legume production to improve the dietary diversity of children in two different sub-Saharan African rural settings, Ghana and Kenya, by using a convergent parallel mixed method design (Creswell and Plano Clark 2011) to explore and differentiate the production-own consumption pathway and the income-food purchase pathway. First, we compared children's dietary diversity of households that did or did not participate in an agricultural intervention boosting legume production, using a cross-sectional quasi-experimental study design. Second, we studied the direction, the strength and the relative importance of the production-own consumption and the income-food purchase pathways to acquire insight in how an agricultural intervention may improve children's dietary diversity. We qualitatively studied these pathways through focus group discussions, as well as explored the potential of assessing these pathways through the quantitative method of structural equation modelling.

Methods

Study areas

The study was carried out in Northern Ghana and in Western Kenya with widely contrasting agro-ecological characteristics. Northern Ghana has one cropping season per year of 5 to 6 months starting in May, an average annual temperature of 28 °C and annual rainfall of

900 to 1040 mm. The main crops are maize, rice, sorghum, pearl millet, soybean, cowpea, groundnut and yam. Travel time to urban markets is between 1 to 7 h and human population density is sparse with 50 to 100 inhabitants per km2 (Franke et al. 2011). Western Kenya has a short cropping season of 3 months from October and a long season lasting 6 months from March, an average annual temperature of 21 °C and annual rainfall of 1350 to 1800 mm. The main crops are maize, pearl millet, groundnut, tea, beans, cassava and sweet potato. Travel time to urban markets is between 1 and 5 h and population is dense with 300 to 1200 inhabitants per km2 (Franke et al. 2011). This study was carried out in Karaga district in Northern Region and Bawku West district in Upper East Region in Ghana, and in Western province and Nyanza province in Kenya. These two contrasting locations in Ghana and Kenya were selected because, among the N2Africa project (see next sub-section) locations in these countries, they differed most in agro-ecological characteristics and therefore were assumed to best represent Northern Ghana and Western Kenya.

N2Africa intervention

The study was conducted in the context of an agricultural intervention designed to boost grain legume production, the N2Africa project. N2Africa is a large scale development-to-research project that aims to enable smallholder African farmers to benefit from symbiotic nitrogen fixation by grain legumes through effective production technologies (Giller et al. 2013). Phase I of N2Africa was implemented in Ghana and Kenya from 2009 to 2013 and during that period N2Africa was not designed to be nutrition-sensitive.

Each farmer participating in N2Africa received once a package with seed of an improved legume variety, triple superphosphate (TSP) fertilizer, and in cases where soybean seeds were provided, they also received rhizobia inoculant. Each cropping season from 2009 to 2013 different farmers received a package (18000 and 20000 packages in 2010, 32000 and 55000 in 2011, 75000 and 85000 in 2012 and 2013 in Ghana and Kenya, respectively) (Woomer et al. 2014). In Ghana, farmers received improved seeds of cowpea, groundnut or soybean and in Kenya farmers received improved seeds of soybean or climbing bean. Farmers tested the package on their own fields, with different treatments of seed and fertilizer on sub-plots. In the case of cowpea and groundnut the two treatments included no inputs (control) and with TSP (treatment) for two different varieties. In case of soybean, the four treatments included no inputs (control), with TSP, with inoculants, and with both TSP and inoculants. N2Africa was implemented through groups of farmers of 30 people (in Ghana) and 20–25 people (in Kenya), consisting of a ‘lead’ farmer who was trained in crop management practices directly by N2Africa and 'satellite' farmers who were trained by the lead farmer. In Kenya, some satellite farmers received the package twice and were referred to as 'progressive' farmers. Lead farmers had try-outs of 20 × 30 m with four sub-plots of 10 × 15 m and 'satellite' farmers had try-outs of 20 × 20 m with four sub-plots of 10 × 10 m. Training on processing of legumes, especially soybean, was received by some of the female farmers. These activities were numerous and diverse across eight N2Africa countries and due to the scale of the operation could not be systematically monitored (Woomer et al. 2014).

The training and the testing of different legume technologies on farmer's own fields aimed to motivate farmers to subsequently adopt technologies, thereby increasing both their land under legume cultivation and legume productivity, resulting in increased legume production. In a study carried out among N2Africa participants in 2013, the majority of N2Africa participants reported an increase in legume area cultivated, in legume production and in input use compared with four years ago prior to the N2Africa intervention (Stadler et al. 2016). In Kenya, 52% reported an increase in soybean area cultivated, 81% reported an increase in soybean production and 9% reported using inoculants, 16% P fertilizer or blend and 61% both inputs (input value chains are most advanced in Kenya) after the N2Africa intervention. In Ghana, farmers reported an increase in area under soybean, cowpea and groundnut cultivation of 42%, 36% and 30%, respectively, and reported an increase in soybean, cowpea and groundnut production of 61%, 62% and 37%, respectively. Furthermore, in the case of soybean, 6% reported using inoculants, 19% P fertilizer or blend and 6% both inputs after the N2Africa intervention. For cowpea, 10% reported using P fertilizer or blend, and for groundnut, 15% reported using P fertilizer or blend after the N2Africa intervention (Stadler et al. 2016). Farmer field trials showed that the average increase in soybean, cowpea and groundnut yield after N2Africa was 350 kg/ha, 100 kg/ha and 100 kg/ha, respectively. In the case of full adoption of N2Africa practices (i.e., use of improved seeds, TSP fertilizer and, in the case of soybean, inoculants), the average increase in soybean, cowpea and groundnut yield was 800 kg/ha, 450 kg/ha and 200 kg/ha, respectively (Woomer et al. 2014).

Cross-sectional quasi-experiment and structural equation model

Subject selection

For the cross-sectional quasi-experimental study, infants and young children (6 to 59 months old) from households that participated in the N2Africa project (N2Africa group) and from households that did not participate in N2Africa (non-N2Africa group) were included (Figure 1). A sample size of 400 (200/group), taking into account that 15% of households may refuse to take part in this study, was estimated to be sufficient to detect a difference in height-for-age z-scores (HAZs) of rural Ghanaian and Kenyan children (6 to 59 months old) of 0.4 and assuming an SD of 1.5 HAZ (District Monitoring and Evaluation Team Ghana et al. 1999–2001), at a 5% significance level with 80% power. Reliable estimates of expected differences in children's dietary diversity and its distribution were not available, therefore HAZ was used as the outcome measure for the sample size calculation.

Households were included that had recently participated in N2Africa prior to data collection. For the N2Africa group in Ghana, households were randomly selected from those that received inputs from N2Africa in 2012. These were from villages that had participated in N2Africa since 2010. In Ghana, each village is linked to an agricultural extension agent and each agent has more villages under his or her supervision. For the non-N2Africa group in Ghana, all villages were selected that were under supervision of the same agricultural extension agent as the selected N2Africa villages but that did not participate in N2Africa. From these villages, households were selected by the random walk method (UN 2005). For each agricultural extension agent, the same number of households were selected for the non-N2Africa group as for the N2Africa group. For the N2Africa group in Kenya, households were randomly selected from those that received soybean inputs from N2Africa in the short rainy season in 2010 and in the long rainy season in 2011. For the non-N2Africa group in Kenya, households were randomly selected among those that received N2Africa soybean inputs in the short rainy season in 2013 but had no harvest yet at the time of data collection. In both countries, households were included when a child of 6–59 months of age (if more than one was present, one was selected at random), mother or caregiver of the selected child and N2Africa farmer (N2Africa group) or household head (non-N2Africa group) were present. Households that did not meet these criteria were replaced randomly. For the SEM, data from the children and their households in the

N2Africa and non-N2Africa group selected for the cross-sectional quasi-experimental study were combined.

Data collection

Data were collected in the lean season in Ghana in March 2013 and in Kenya in November and December 2013 by trained interviewers who spoke the local language. Informed consent was obtained from the N2Africa farmers (N2Africa group) or household heads (non-N2Africa group).

Household characteristics and legume production

A structured questionnaire-based interview was conducted. The N2Africa farmer (N2Africa group) or household head (non-N2Africa group) from the household of the selected child was interviewed to collect information on household composition, education, landholding, livestock ownership, assets, sources of income, labour hired-in (whether other people work on the household's field(s), for cash or in kind), labour hired-out (whether household members work on other people's field(s), for cash or in kind). Livestock assets recorded included cattle, donkey, pig, sheep, goat, chicken, guinea fowl, duck and dove. Tropical Livestock Unit conversion factors defined as a mature animal weighing 250 kg (Jahnke 1982) were used to calculate total livestock value in Tropical Livestock Units (TLU) in each household. Household assets included availability of a functioning radio, television, bicycle, motor, corn mill, private and/or commercial vehicle. The total value of assets in each household was calculated by the summed proportion of local market value of each available asset relative to the most expensive asset locally available. Total production of all legume crops from the previous year was recorded in local units together with the quantity used for home consumption, sold, and for other uses. Conversion factors were collected to convert local weight units to kg. In addition, specific information on participation in N2Africa was collected and also whether other legumes or legume-related and nutrition-related interventions provided outside of N2Africa were received during the last four years. The mother or caregiver of the selected child was interviewed on the child's age and sex; and the mother's age, education, occupation and religion.

Children's legume consumption and dietary diversity

A short food frequency questionnaire was administered to mothers or caregivers to collect data on the frequency of consumption of different legumes (groundnut, cowpea, soybean, Bambara groundnut, pigeon pea, climbing bean, kidney bean and mungbean) by children during the last month. Through a qualitative multi-pass 24-h-recall method (Gibson and

Ferguson 2008; FAO 2010), mothers or caregivers were asked to mention all foods and beverages their child had consumed during the preceding 24-h (wakeup-to-wakeup) including anything consumed outside the home. After probing for likely-to-be-forgotten foods such as snacks and fruits, they were asked to give detailed descriptions of the foods and beverages consumed, including ingredients for mixed dishes. The 24-h-recall data were used to calculate an Individual Dietary Diversity Score (IDDS) (FAO 2010), being a count of the number of food groups consumed. Consumption of any amount of food from each food group was sufficient to 'count', except if an item was used as a condiment. We used the seven food groups recommended by WHO et al. (2007) that were validated to reflect nutrient adequacy of children aged 6–23 months. The seven groups included: (1) grains, roots and/or tubers; (2) legumes and/or nuts; (3) dairy products; (4) flesh foods; (5) eggs; (6) vitamin A rich fruits and/or vegetables; and (7) other fruits and/or vegetables (WHO et al. 2007). Fruits and vegetables were classified as vitamin-A rich when they provided 60 retinol activity equivalents (RAE) per 100 g or more (FAO 2010), using the Tanzania Food Composition data base (Lukmanji et al. 2008) for Kenya and the Mali (Barikmo et al. 2004) and West African Food Composition data base (FAO et al. 2012) for Ghana. Consumption of four or more food groups out of these seven is associated with better quality diets of infants and young children of 6–23 months (Working Group on Infant and Young Child Feeding Indicators 2007). Mean IDDS was calculated for all children and separately for children aged 6–23 months and children of 24–59 months. For children of 6–23 months, the proportion of children who had a nutrient diverse diet (IDDS= > 4) was calculated.

Children's nutritional status

Weight and length or height of children were measured following standard procedures (Cogill 2003). Weight was measured with an electronic scale to the nearest 0.1 kg (UNIscale: Seca GmbH, Hamburg, Germany). Height and length was measured with a UNICEF wooden three piece measuring board with a sliding foot or head piece and with a precision of 0.1 cm. Children below 24 months old or who were not able to stand were measured lying down (length). Children aged 24–59 months were measured standing up (height). Both length/height and weight were measured twice for each child and the average of the two measurements was taken. Scales were calibrated with a standard weight each day of data collection. Age was calculated using the date of birth from verifiable documents (health record, weighing card, birth certificate) or estimated based on a traditional calendar or another record (29 children in Ghana and 36 children in Kenya) and the date of the survey. Height and weight measurements were converted into height-for-age, weight-for-height and weight-for-age z-scores using the WHO Child Growth Standards (WHO Multicentre

Growth Reference Study Group 2006) by using the WHO SPSS syntax (WHO 2011). Children who were more than two standard deviations below the reference median of height-for-age, weight-for-height and weight-for-age z-scores were classified to be stunted, wasted and underweight, respectively.

Focus group discussions

Both in Ghana and in Kenya, eight focus group discussions were held, four among female farmers and four among male farmers who participated in the N2Africa project. The discussions were held close to the homes of selected participants and lasted between 1 and 2 h. The discussion was led by a researcher and supported by a trained local translator. Qualitative in-depth information was collected on the production-own consumption and income-food purchase pathways for grain legume production (with a focus on soybean) (Figure 2). The theoretical pathways were used as a topic guide for the discussions. We recorded all discussions and translated and transcribed all the records into English.

Ethical considerations

The study was not subjected to review by a Research Ethics Board. It was part of a development project where participants were included based on implementer preferences and the willingness of participants to participate and did not include random allocation to either the intervention or control group. Approval for the study was obtained from the District Assembly, District Ministry of Agriculture offices and leaders of selected communities. Participation was voluntary and written informed consent was obtained from caregivers of selected children, with thumb prints used for those who were not literate. The identity of the infants and their mothers/caregivers has been kept confidential.

Statistical analysis

Statistical analyses were performed using SPSS (IBM SPSS Statistics 22). Data were checked for normality by visual inspection of histograms and Q-Q plots. Non-normal data were log- or square root-transformed to approach normality. Accordingly, geometric means with 95% confidence intervals (CI) are presented. Two approaches were used to study the potential effect of enhanced grain legume production. First, univariate statistics were applied to test for differences in the characteristics between the non-N2Africa and N2Africa groups.

Second, to explore interdependencies of the variables under study, the data of both the non-N2Africa and N2Africa group combined were used for SEM.

Differences in characteristics between the non-N2Africa and N2Africa groups were analysed with independent T-test (for continuous data), and Chi-Square test (for categorical data) using a post hoc test (adjusted standardized residuals and Bonferroni correction (Beasley and Schumacker 1995)) where the independent variable had more than two categories. Two-sided $P < 0.05$ was regarded as statistically significant.

To quantify and disentangle the various pathways from legume production to children's dietary diversity, SEM (Garson 2015) was used for data on soybean production (targeted by N2Africa in both countries). Path analysis is a technique to explicitly test multivariate causal relations between variables. It tests the likelihood of observing the data given a set of causal relations between household characteristics and the children's dietary diversity. We posited that through the production-own consumption pathway enhanced soybean production in the household (kg) would result in an increased quantity of soybean produce used for home consumption (kg). In turn, an increased quantity of soybean produce used for home consumption should result in increased children's monthly soybean consumption (times per month), increasing children's daily consumption (times per day) of soybean and enhancing children's dietary diversity (IDDS with range of 0 to 7 food groups). In addition, children's daily soybean consumption (times per day) should positively affect IDDS. We posited that through the income-food purchase pathway, enhanced soybean production in the household (kg) results in an increased quantity of soybean produce sold (kg), increased quantity of soybean produce sold results in increased income (total value of household assets), and increased income results in improved children's dietary diversity (IDDS with range of 0 to 7 food groups). Further, we hypothesized that the quantity of soybean produce used for home consumption depends on quantity of soybean produce sold and vice versa. We also hypothesized that larger household land size (ha) results in more soybean production, thereby affecting both pathways. Finally, we posited that enhanced women's status (mother's education, low or high level) will result in improved children's dietary diversity (Figure 2). Studies show that mother's schooling reduces the risk of stunted children (Ruel and Alderman 2013) and therefore education is often used as an indirect measure of women's status. The degree of fit of the hypothesized models to the data was measured by comparing the observed and measured covariance matrices. To account for non-normality of the data, a bootstrap derived chi-square statistic was used (Bollen-Stine bootstrap; 2000 samples). Lack of significant fit ($P > 0.05$) means that the hypothesized model is rejected as a causal explanation of the data. All individual relationships were tested for significance using z statistics. The SEM was performed using AMOS, an add-on module for SPSS (IBM SPSS Amos 23.0.0).

All transcripts from the focus group discussions were read thoroughly several times, focusing on one theme (one of the steps in the pathways), at a time. Key words and phrases were underlined, categorized per theme and separated for women and men participants. Given the objective of this study, the convergence and inconsistencies per theme were classified. This thematic analysis gave insight into which steps of the pathways were or were not present and which factors influenced the absence of steps, according to most participants.

Results

Characteristics of children, their mothers and households

In Ghana, 202 versus 126 children, and in Kenya 154 versus 186 children, were included in the non-N2Africa group and the N2Africa group, respectively (Figure 1). Characteristics of the children, their mothers and households in the non-N2Africa and N2Africa groups were comparable in both countries (Table 1). Ghanaian children were on average 29 months old and Kenyan children 34 months old, with about half being female in both countries. In Ghana and Kenya, the percentage of stunted and wasted children in the non-N2Africa and N2Africa groups did not differ. Chronic and acute malnutrition were more prevalent among Ghanaian children than Kenyan children (32% versus 24% stunted children and 9.4% versus 5.3% wasted children, respectively, $P < 0.05$). In both countries the majority of the mothers of the selected children were farmers. In Ghana more mothers had no education compared with Kenyan mothers (83% versus 15%, $P < 0.05$). In Ghana, but not in Kenya, we found more Muslim mothers (55.8% versus 30.3%) in the N2Africa group compared with the non-N2Africa group. Ghanaian households were comprised of more household members than Kenyan households (11.1 (10.4–11.8) versus 6.2 (6.0–6.4), respectively, $P < 0.05$). In Ghana but not in Kenya, households were larger (12.0 versus 10.5 household members) in the N2Africa group compared with the non-N2Africa group. Also in Kenya but not in Ghana, the child-to-adult ratio was smaller (1.5 versus 1.8) in the N2Africa compared with the non-N2Africa group. Ghanaian households owned about ten times more land than the Kenyan households (13 (12–14) ha versus 1.3 (1.2–1.4) ha, $P < 0.05$). In Ghana but not in Kenya, there were more households with at least one household member who had completed a higher level of education (42.6% versus 21.1%) and households had more varied sources of income (2.5 versus 2.0) in the N2Africa compared with the non-N2Africa group.

Participation in N2Africa and other interventions

Of all N2Africa farmers included in this study, 77.3% were satellite farmers and 22.7% were lead farmers in Ghana while 48.9% were satellite farmers, 50.0% were ‘progressive’ farmers and 1.1% were lead farmers in Kenya. In Ghana 39.5% and in Kenya 71.0% of the participants were female. In Ghana most of the farmers received soybean (74.4%), some cowpea (25.6%) and a few groundnut (2.3%) seeds. More than half of farmers reported to have received fertilizer (60.5%) and about half of farmers who reported to have received soybean seeds said they also received inoculant (38%). In Kenya, all farmers reported to have received soybean seeds and almost all also reported to have received fertilizer (92.9%) and inoculant (91.3%). In both Ghana and Kenya, it was reported that others in their household had received support from N2Africa in the same and/or previous season, respectively 29.5% and 37.7%. In Ghana 96.1% and in Kenya 44% of all farmers reported to have received training from N2Africa in crop management practices and/or training on soybean processing. In Ghana, the training received was mainly related to management practices while in Kenya training was mainly on soybean processing.

Subjects from the non-N2Africa and N2Africa groups reported to have received other legume, legume-related, (human) nutrition and/or nutrition-related interventions provided outside of N2Africa during the last four years. In Ghana and in Kenya, the number of subjects from the non-N2Africa and N2Africa group that reported to have received nutrition and nutrition-related education received outside of N2Africa did not differ (11.4% and 7.4% in Ghana, 2.6% and 1.1% in Kenya). In Ghana but not in Kenya, more subjects from the N2Africa group reported they had received legume or legume-related interventions provided from outside of N2Africa compared with the non-N2Africa group (14.8% versus 5.9%)

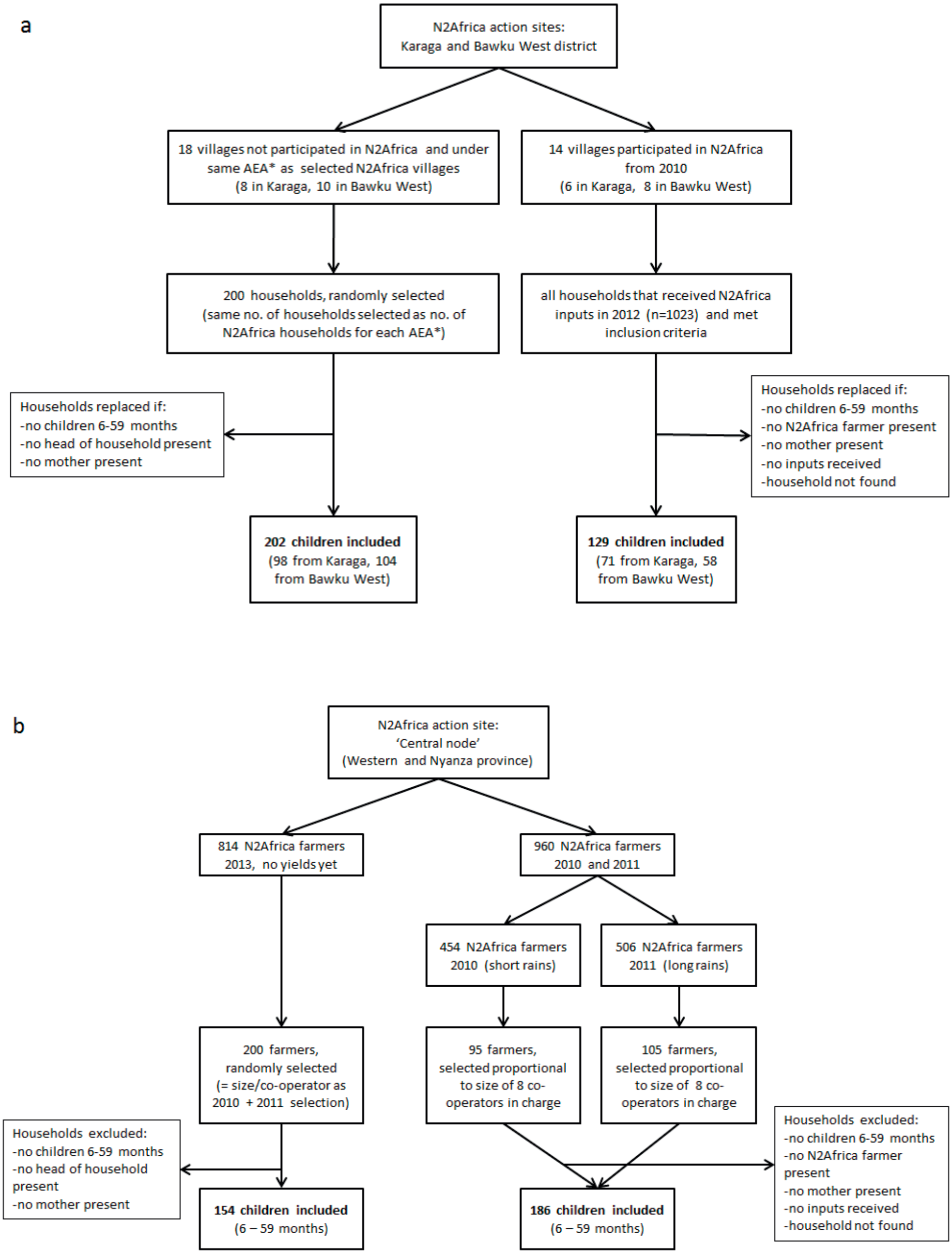

Figure 1. Flow chart of sample selection in Ghana (a) and Kenya (b)

N2Africa = is an agricultural project focused on putting nitrogen fixation to work for smallholder farmers growing legume crops. No. = number. AEA = agricultural extension agent. 'Central node' = action site of N2Africa. Short rain = short cropping season of 3 months from October in Western Kenya. Long rain = long cropping season lasting 6 months from March in Western Kenya. Co-operators = local partners implementing N2Africa project

Table 1. Demographic and social economic characteristics of children aged 6-59 months, their mothers and their households in the non-N2Africa group and the N2Africa group in Ghana and Kenya

	Ghana		Kenya	
	Non-N2Africa (*n*=202)[a]	N2Africa (*n*=129)[a]	Non-N2Africa (*n*=154)[a]	N2Africa (*n*=186)[a]
Characteristics	*% or (geometric) mean (95%CI)*			
Children				
Age, in months	28.4 (26.5-30.2)	30.6 (28.0-33.2)	34.8 (32.5-37.1)	34.1 (31.9-36.3)
Age <24 months, %	37.6	31.0	27.9	25.8
Females, %	48.5	54.3	54.5	48.4
Stunted (chronic malnourished), %	29.7	35.7	27.3	21.5
Wasted (acute malnourished), %	11.4	6.2	4.5	5.9
Mothers of children				
Age, in years	30.5 (29.3-31.6)	30.9 (29.6-32.3)[2]	33.2 (31.5-35.0)	32.0 (30.5-33.5)[2]
Education level[c], %				
None	85.6	78.7	17.1	13.0
Primary education	14.4	19.7	57.9	62.7
Higher education	0.0	1.6	25.0	24.3
Occupation is farmer, %	62.9	72.4	80.4	82.8
Religion (Islam, Christian)[d], %	30.3	55.8**	97.4	98.4
Households of children				
People in household	10.5 (9.7-11.3)	12.0 (11.0-13.4)[2]*	6.1 (5.8-6.4)	6.5 (6.2-6.8)[1]^
Child:adult ratio in household	1.3 (1.2-1.4)	1.2 (1.0-1.3)[2]	1.8 (1.6-2.0)	1.5 (1.4-1.7)[2]*
Highest education in hh[e], %				
None	55.3	31.8*	0.0	0.0
Primary education	23.6	25.6	18.2	13.0
Higher education	21.1	42.6*	81.8	87.0
Total Land size (ha)	13 (12-15)	13 (11-15)[2]	1.4 (1.2-1.6)	1.2 (1.1-1.3)[2]
Livestock (in TLU[f])	3.2 (2.7-3.8)	2.9 (2.3-3.6)[2]	1.1 (1.0-1.4)	1.3 (1.1-1.4)[2]
Assets, total value in hh[g]	0.08 (0.05-0.10)	0.12 (0.08-0.16)[1]^	0.03 (0.02-0.04)	0.03 (0.02-0.04)[1]

Table 1. Continued

	Ghana		Kenya	
	Non-N2Africa (n=202)[a]	N2Africa (n=129)[a]	Non-N2Africa (n=154)[a]	N2Africa (n=186)[a]
Characteristics	*% or (geometric) mean (95%CI)*			
Main source of income, %				
Cropping	83.2	79.1	75.3	67.2
Livestock	12.9	15.5	1.3	3.2
Other[h]	4.0	5.4	23.4	29.6
Number of income sources[i]	2.0 (1.8-2.1)	2.5 (2.3-2.7)^{2}**	2.3 (2.2-2.4)	2.4 (2.3-2.5)^{2}^
Labour hired-in[j], %				
None	16.0	11.6	45.5	46.5
In kind	50.0	42.6	6.5	2.7
For cash	34.0	45.7	48.1	50.8
Labour hired-out[k], %				
None	8.0	7.0	37.0	42.2
In kind	69.7	69.8	9.7	4.3
For cash	22.4	23.3	53.2	53.5

*P <0.05, **P <0.01 (comparing N2Africa and non-N2Adrica within countries). [1] Square root transformation, [2] Log10 transformation.

[a]See Appendix 1 for missing data per variable and group

[b]Values are percentage, geometric mean (95%CI), mean (95%CI). Transformation type applied is indicated for geometric values

[c]Highest completed education of the mother: none, primary education (primary school and/or literacy class or Arabic school) or higher education (secondary and/or tertiary education)

[d]Percentage of mothers who are Islamic in Ghana and who are Christian in Kenya (major religion in area).

[e]Highest completed education in the household: none, primary education or higher education (details see [c]).

[f]Tropical livestock Units (TLU) defined as a mature animal weighing 250 kg, conversion factors: cattle (0.7), pig (0.2), sheep, goat (0.1), chicken, guinea fowl, duck, dove (0.01) (Jahnke 1982)

[g]Summed proportion (calculated in local market prices in Ghana Cedi's and Kenyan shilling relative to most expensive asset) of assets available in household. Conversion factors for Ghana and Kenya, respectively: radio (0.001, 0.002), TV (0.011, 0.011), bicycle (0.013, 0.013), motor (0.150, 0.149), corn mill (0.210, 0.213), private (1, 1) and commercial vehicle (1, 1)

[h]Other sources of income include casual labour, trade, other business, salaried job, remittances and pension.

[i]Total number of different sources of income.

[j]Other people work on the household's field(s): none, in kind or for cash.

[k]Household members in the household who work on other people's field(s): none, in kind or for cash.

Household legume production

In Ghana and in Kenya, the total household production of all grain legumes was comparable in the two groups (Table 2). However, the proportion of households cultivating legumes was greater in the N2Africa group compared with the non-N2Africa group (100% versus 88.1% in Ghana and 100% versus 94.8% in Kenya, respectively). In Ghana, less of total household legume production was used for home consumption than in Kenya (37% versus 65% of production, $P < 0.05$). In Ghana but not in Kenya, less of total household legume production was used for home consumption in the N2Africa households compared with the non-N2Africa group (29% versus 43%). Different results were found for the individual grain legumes. In Ghana and in Kenya, more N2Africa households cultivated soybean compared with the non-N2Africa group (90.7% versus 75.2% and 94.1% versus 18.2%, respectively) but among the farmers who grew soybean the total production of soybean and percentage used for consumption or sold did not differ between groups in both countries. In the case of cowpea, in Ghana fewer households in the N2Africa group cultivated cowpea compared with the non-N2Africa group (40.3% versus 55.4%) and less of the cowpea production was used for consumption (52% versus 69%), with no differences between groups in Kenya. Total production and percentage sold did not differ for cowpea between the non-N2Africa and N2Africa groups in Ghana and Kenya. In both Ghana and Kenya, the proportion of households that cultivated groundnut and that cultivated other legumes not received from N2Africa, their total production, and their percentage sold did not differ between the non-N2Africa and N2Africa groups. This was also the case for the percentage of production used for home consumption, except for groundnut in Ghana where fewer households used them for consumption in the N2Africa group compared with the non-N2Africa group (3% versus 7%).

Children's legume consumption and dietary diversity

In both Ghana and Kenya, children's monthly frequency of consumption of soybean, groundnut, cowpea and other legume varieties not distributed through N2Africa did not differ between the non-N2Africa and N2Africa groups, except that Ghanaian children's monthly frequency consumption of cowpea was greater in the N2Africa group than in non-N2Africa group (12.6 versus 9.8, respectively) (Table 3). Compared with Kenyan children, the monthly frequency of soybean consumption was greater among children in Ghana (30.5 (26.4–35.0) versus 6.4 (5.3–7.8) times, P-value <0.05). However, 24-h-recall data showed

Table 2. Cultivation of grain legumes, their total production and percentage consumed or sold[a] reported in the non-N2Africa group and the N2Africa group in Ghana and in Kenya

	Ghana		Kenya	
	Non-N2Africa (*n*=202)[b]	N2Africa (*n*=129)[b]	Non-N2Africa (*n*=154)[b]	N2Africa (*n*=186)[b]
	% or (geometric) mean (95%CI)[c]			
Soybean				
Households cultivated, %	75.2	90.7**	18.2	94.1*
Yield of 0[d], %	1.3	2.6	7.1	1.7^
Household production (kg)[e]	271 (218-337)	257 (194-340)[2]	13 (9-21)	9 (7-10)[2]^
Consumed (%)[f]	15 (10-20)	10 (6-15)[1]	64 (52-76)	65 (60-70)
Sold (%)[f]	32 (25-41)	30 (23-39)[1]	23 (12-33)	22 (18-26)
Cowpea				
Households cultivated, %	55.4	40.3**	8.4	13.4
Yield of 0[d], %	3.6	3.8	0.0	8.0
Household production (kg)[e]	82 (63-106)	73 (49-109)[2]	6 (3-10)	5 (3-8)[2]
Consumed (%)[f]	69 (62-77)	52 (40-64)*	50 (28-72)	73 (60-87)^
Sold (%)[f]	24 (17-31)	27 (16-37)	20 (0-40)	9 (2-15)
Groundnut[g]				
Households cultivated, %	51.0	54.3	36.4	34.4
Yield of 0[d,], %	1.9	1.4	1.8	6.3
Household production (kg)[e]	460 (366-577)	584 (410-830)[2]	14 (10-20)	12 (9-17)[2]
Consumed (%)[f]	7 (4-10)	3 (2-5)[2]*	66 (58-75)	74 (67-81)
Sold (%)[f]	51 (43-59)	55 (45-65)	22 (15-30)	17 (10-23)
Other legumes[h]				
Households cultivated, %	53.5	46.3	94.2	90.9
Yield of 0[d], %	1.9	0.0	0.7	0.0
Household production (kg)[e]	73 (56-95)	69 (49-98)[2]	20 (17-24)	16 (14-19)[2]^
Consumed (%)[f]	76 (69-83)	70 (58-82)	66 (61-70)	69 (65-73)
Sold (%)[f]	8 (3-12)	9 (3-16)	18 (14-22)	15 (11-18)
All legumes[i]				
Households cultivated, %[h]	88.1	100**	94.8	100**
Yield of 0[d], %	0.0	3.1*	0.7	0.0
Household production (kg)[e]	495 (396-620)	501 (371-677)[2]	26 (22-32)	28 (24-33)[2]
Consumed (%)[f]	43 (37-48)	29** (23-35)	65 (61-69)	65 (62-69)
Sold (%)[f]	40 (34-45)	43 (37-49)	18 (15-22)	21 (17-24)

*P<0.05, **P<0.01, ^P<0.10 (comparing N2Africa and non-N2Adrica). [1]square root, [2]log10 transformation
[a]Other uses of grain legume production include: used for seeds, given back to N2Africa, stored or unknown
[b]See Appendix 1 for missing data per variable and group
[c]Values are %, geometric mean (95%CI) or mean (95%CI), transformation applied indicated for geometric values
[d]Percentage of households who cultivated soybean but had no yield
[e]Total yield in kg of previous year reported by farmers who did cultivated specific legume, excl. cases no yield
[f]Mean of percentage of total yield used for home consumption or sold
[g]Reported shelled yield in kg is conversed to unshelled yield by conversion factor 0.4.
[h]Reported other legumes cultivated (not N2Africa). Ghana: Bambara, Kenya: climbing, kidney and mung beans
[i]All legumes cultivated per household summed

that in Ghana soybean was consumed mostly as a condiment and not in large portions. After excluding condiment-consumption of soybean, the monthly frequency of consumption of all legumes by children in Ghana was still greater than in Kenya (61.1 (54.9–67.7)) versus 22.1 (19.6–24.9) times per month, respectively, $P < 0.05$). Also the daily frequency of children's legume consumption in Ghana was greater than in Kenya (1.5 (1.3–1.7)) versus 0.3 (0.2–0.4) times per day, $P < 0.05$). In Ghana but not in Kenya, the daily overall consumption of legumes by children was more frequent in the N2Africa group than in the non-N2Africa group (1.9 (1.6–2.2)) versus 1.4 (1.2–1.6) times per day, $P < 0.05$).

Table 3. Reported times of soybean, groundnut, cowpea and other grain legumes consumed per month of children 6–59 months by their mother or care-giver in the non-N2Africa group and the N2Africa group in Ghana and in Kenya

	Ghana		Kenya	
	Non-N2Africa (*n*=202)	N2Africa (*n*=129)	Non-N2Africa (*n*=154)	N2Africa (*n*=186)
Legume consumption, (times/month)[a]	*geometric mean (95%CI)*			
Soybean	30.8 (25.4-36.8)	30.0 (23.8-36.9)[1]	5.7 (4.1-7.7)	7.2 (5.5-9.2)[2]
Groundnut	26.7 (22.6-31.1)	30.8 (25.3-36.9)[1]	0.3 (0.1-0.6)	0.1 (0.0-0.3)[1]
Cowpea	9.5 (7.9-11.4)	12.6 (10.3-15.3)[2]*	n/a	n/a
Other legumes[b]	8.9 (7.2-11.0)	10.0 (7.8-12.7)[2]	10.0 (8.7-11.5)	8.9 (7.6-10.5)[2]
All legumes[c]	97.3 (85.3-110.0)	103.5 (89.4-118.6)[1]	21.9 (18.4-26.2)	22.3 (18.9-26.3)[2]
All without soybean[d]	58.3 (50.3-66.7)	65.8 (56.0-76.4)[1]	-	-

**P*<0.05, ^*P*<0.10 (comparing N2Africa and non-N2Adrica within countries)
[1]square root transformation, [2]log10 transformation
[a]Reported times of legume consumption during the last month of a child 6-59 mo by the mother or caregiver
[b]Other legumes, not received from N2Africa. In Ghana: pigeon pea and Bambara beans. In Kenya: mung bean, kidney bean and climbing bean
[c]All legumes consumed summed
[d]All legumes consumed summed without soybean in Ghana. In Ghana soybean is mostly used as a condiment

In both countries, almost all children consumed grains, roots and/or tubers (94.6% versus 93.8% in Ghana and 99.4% versus 99.5% in Kenya, in the non-N2Africa and N2Africa groups respectively) and fruits and vegetables (83.7% versus 89.1% in Ghana and 100% versus

94.6% in Kenya, in the non-N2Africa and N2Africa groups) (Table 4). In Ghana and also in Kenya, the proportion of children who consumed dairy products, meat foods and eggs was similar in the non-N2Africa group compared with the N2Africa group. In Ghana (but not in Kenya), more children in the N2Africa group consumed legumes, nuts and seeds than in the non-N2Africa group (86.8% versus 77.2%, respectively) and oils and fats (79.1% versus 62.9%), but fewer consumed fruits and vegetables rich in vitamin A (34.1% versus 47%). In Kenya (but not in Ghana), fewer children consumed fruits and also vegetables in the N2Africa group compared with those in the non-N2Africa group (94.6% versus 100%).

Table 4. Percentage of children 6–59 months who consumed a specific food groups in the non-N2Africa group and in the N2Africa group in Ghana and in Kenya

	Ghana		Kenya	
	Non-N2Africa (*n*=202)	N2Africa (*n*=129)	Non-N2Africa (*n*=154)	N2Africa (*n*=186)
Food group		%		
1. Grain, roots and tubers	94.6	93.8	99.4	99.5
2. Legumes, nuts and seeds	77.2	86.8*	40.3	42.5
3. Dairy products	20.3	20.9	68.8	67.7
4. Flesh foods	87.1	89.1	36.4	32.8
5. Eggs	1.5	0.8	1.9	2.2
6. Vitamin A fruits + vegetables	47.0	34.1*	76.6	76.9
7. Other fruits and vegetables	83.7	89.1	100	94.6*
Oils and fats[a]	62.9	79.1*	97.4	94.1

*$P<0.05$ (comparing N2Africa and non-N2Adrica within countries)
[a]Oils and fats are not included in individual dietary diversity score

Dietary diversity of children in the non-N2Africa group and the N2Africa group did not differ (Table 5). This was also the case for children below 24 months of age, children above 24 months and children who were not breastfed. However, dietary diversity was less among breastfed children in the N2Africa households than in the non-N2Africa group (3.7 versus 4.2, respectively) in Kenya, but not in Ghana. The percentage of children who had an IDDS of 4 or above among children below 24 months (reflecting a nutrient adequate diet) was similar in the N2Africa group compared with the non-N2Africa group in Ghana (60.0% and 65.8%) and also in Kenya (62.5% and 76.7%).

We found no associations between demographic and socioeconomic characteristics of households (household's highest completed education level, mother's education level, household size, landholding, livestock, household's assets and number of income sources) and nutrition indicators for the children, either in the N2Africa or in the non-N2Africa groups.

Table 5. Individual dietary diversity score (IDDS) of children 6–59 months in the non-N2Africa group and the N2Africa group in Ghana and in Kenya

	Ghana		**Kenya**	
	Non-N2Africa (*n*=202)[a]	N2Africa (*n*=129)[a]	Non-N2Africa (*n*=154)[a]	N2Africa (*n*=186)[a]
Characteristics	*Mean (SD) or %*			
IDDS (7 food groups, 0 to 7)[b]				
All children	4.1 (1.4)	4.2 (1.3)	4.2 (0.9)	4.2 (1.0)
children age 6-23 months	3.5 (1.7)	3.2 (1.7)	4.1 (0.9)	3.8 (1.2)
children age 24-59 months	4.5 (0.9)	4.6 (0.8)	4.3 (0.9)	4.3 (0.9)
Children receiving breastmilk, %	*42.5*	*38.1*	*24.3*	*22.2*
children non-breastfed	4.4 (0.9)	4.6 (0.8)	4.2 (0.9)	4.3 (0.9)
children breastfed	3.7 (1.7)	3.4 (1.6)	4.2 (0.8)	3.7 (1.1)*
Minimum dietary diversity, IDDS >=4[c]				
children age 6-23 months, %	65.8	60.0	76.7	62.5

*P<0.05 (comparing N2Africa and non-N2Adrica within countries).

[a]See Appendix 1 for sample size per group: children age 6-23 months, children age 24-59 months, children non-breastfed and children breastfed

[b]Individual Dietary Diversity Score is computed by sum of seven food groups being consumed: 1. Grains, roots and tubers, 2. Legumes, nuts and seeds, 3. Dairy products, 4. Flesh foods, 5. Eggs, 6. Vitamin A rich fruits and vegetables and 7. Other fruits and vegetables (WHO et al. 2007)

[c]An IDDS of 4 or more in infants and young children reflect a nutrient adequate diet (WHO et al. 2007)

Production-own consumption pathway and income-food purchase pathway

In Ghana the hypothetical model of the production-own consumption pathway and the income-food purchase pathway was not consistent with the data (X^2(df) = 62.13 (24), P = 0.00) (Figure 2a), while in Kenya the hypothetical model was consistent with the data (X^2(df) = 22.59 (24), P = 0.64) (Figure 2b). In Ghana, both pathways included non-significant paths. In Kenya, there was only a small positive indirect effect of soybean production on the dietary diversity of children through the production-own consumption pathway, but there was no effect of soybean production on children's dietary diversity through the income-food purchase pathway. The effect of soybean production on the IDDS was very low: a multiplication of individual path coefficients showed that an increase of soybean production by 1 kg led to an increase of 0.00075 IDDS points. Therefore to have a meaningful effect on children's IDDS an increase in household's soybean production of at least 1000 kg is needed. Based on soybean production of 800 kg/ha after full adoption of N2Africa interventions (Woomer et al. 2014), an increase of 1000 kg means expansion of 1.2 ha under soybean cultivation. This is highly unlikely, especially in Kenya where the average land size of a household is 1.3 ha. However, children's monthly soybean consumption was not directly related with children's dietary diversity. Household land size was positively related with the production of soybean and total household assets in both models, but mother's education was not related with children's dietary diversity ($P = 0.06$) in the Kenyan model.

In focus group discussions in both Ghana and Kenya, female N2Africa participants more commonly referred to the production-own consumption pathway and males to the income-food purchase pathway with regard to enhanced soybean production. Comparing Ghanaian and Kenyan N2Africa participants, Ghanaian participants referred less to the production-own consumption pathway but rather referred more to the income-food purchase pathway for enhanced production of soybean. In Ghana, few comments were made about soybean consumption and these comments were mixed: 'my children are a bit more healthy because they like to eat soybean' but also 'I have not seen any direct effect of soybean consumption on my health'. By contrast in Kenya, participants were overall positive about soybean consumption: 'it makes children strong', 'soy is so sweet' and 'their health has changed to good health'. In both Ghana and Kenya, participants reported they had received training on soybean processing and learned how to use soya in their local dishes. Further, Ghanaian participants were positive about the soybean market in Northern Ghana ('it gives more money than maize' and 'if your yield is a lot, then you can sell to get money') while Kenyan participants mentioned that there was no market for soybean ('price for soybean is less than for maize' and 'it is difficult to sell soybean'). The remarks on the income-food purchase pathway were not consistent in both countries. The 'extra' income was said to be spent in a wide range of different ways, including 'to pay school fees', 'household items', 'hire people to work on their land', 'buy more food', 'to buy fertilizer', 'to buy seeds', 'for pressing needs' and 'to save for the purchase of a motorbike'. Some farmers mentioned the income was used to buy more food but they did not mention whether they buy nutritious foods and whether this improved their children's diet. Also income was spent on school fees or seeds that theoretically may have an indirect effect on human nutrition, but it remains unclear whether this was the case.

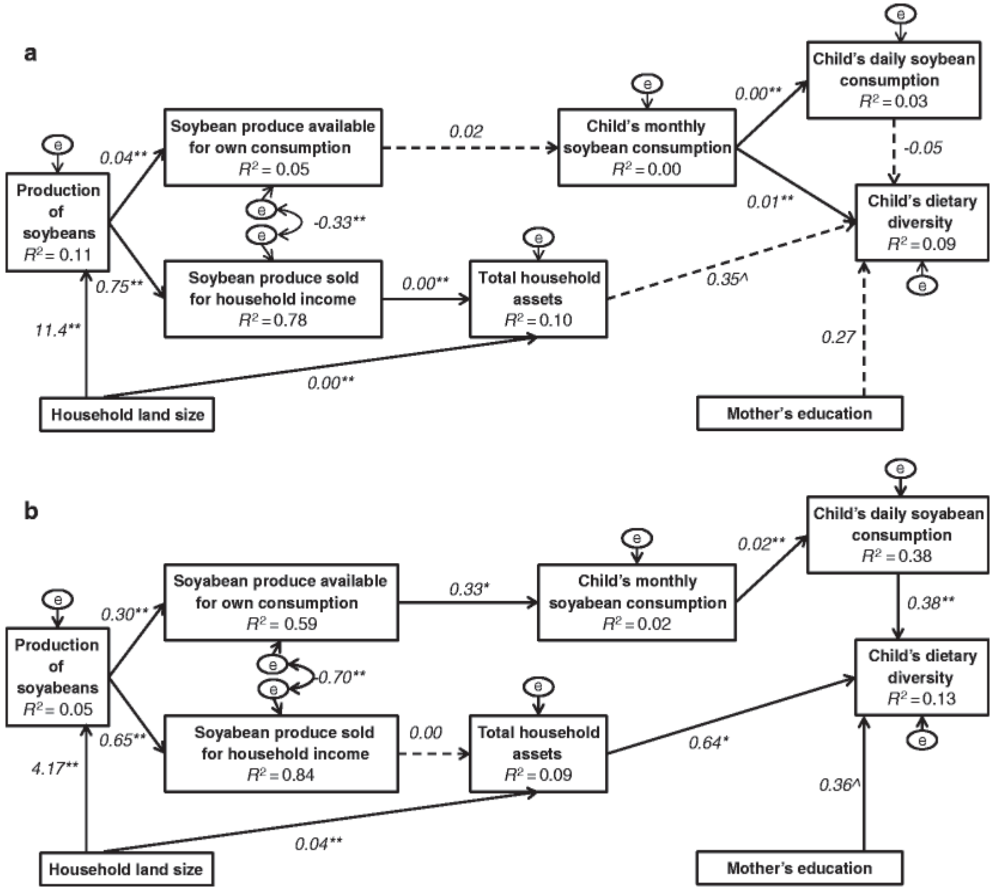

Figure 2. Explorative structural equation model of the effect of soybean production on dietary diversity of children 6–59 months of age through the production-own consumption pathway and income-food purchase pathway in: (a) rural Northern Ghana (**n** ***= 260) and (b) in rural Western Kenya (*****n** ***= 197)***

Ghana ***a****: X2(df) = 62.13 (24),* P *= 0.00 and Kenya* ***b:*** *X^2(df) = 22.59 (24),* P *= 0.64 (corrected with Bollen-stine bootstrap). Values are unstandardized regression coefficients (^*P *< 0.10, **P *< 0.05, ***P *< 0.01, path coefficients not significantly different from zero are shown by broken lines). Value between error terms of soybean yield available for own consumption and for household income is the estimated correlation. Part of the variance explained by the model (R2) is given under the variable names. 'e' is the unexplained variation. Appendix 2 shows cases excluded. Appendix 3 specifies indicators used in model. Appendix 4 and 5 provide the co-variance matrix for Figure 2a and 2b, respectively.*

Discussion

We found no association between participating in this agricultural intervention designed to boost grain legume production and the dietary diversity of children based on a cross-sectional quasi-experimental study. SEM indicated a relatively good fit to the posteriori model in Kenya but not in Ghana, and in Kenya only the production-own consumption pathway for soybean was fully supported, with no effect through the income-food purchase pathway. Focus group discussions showed that the Ghanaian and Kenyan context of soybean production and consumption differed in the attribution of positive characteristics, variety of local soybean-based dishes, it being a relatively new crop, involvement of women in soybean cultivation, presence of markets, and being treated as a food or cash crop.

N2Africa and children's nutrition outcomes

More households were cultivating grain legumes, especially soybean, in the N2Africa group (100% in Ghana and in Kenya) than in non-N2Africa group (88.1% in Ghana and 94.8% in Kenya) but we found no differences in total grain legume production among the households cultivating legumes between the two groups in neither Ghana nor Kenya. The absence of differences in grain legume production might be due to weak implementation of the N2Africa intervention in Ghana and weak adoption of N2Africa in Kenya. In Ghana only 60.5% of participating farmers reported to have received fertilizer and less than half of farmers who received soybean seeds reported they had received inoculant. In Kenya, farmers selected for this study received N2Africa soybean inputs in the short cropping season (from October) in 2010 and/or in long cropping season (from March) in 2011 while the legume production data collected for this study included production from the short cropping season in 2012 and long cropping season in 2013. Therefore the effect of the N2Africa intervention in Kenya on the amount of household legume production depended on the degree of adoption of improved production technologies after participating in N2Africa. Adoption may have been restricted as the current availability of rhizobial inoculants in Africa is limited (Ronner et al. 2016), as is the availability and affordability of fertilizers and good quality seeds for rural smallholder farmers. N2Africa participants, both in Ghana and Kenya, reported in the focus group discussions that there was indeed a restricted availability of promoted N2Africa inputs and that fertilizers were too expensive. Contrary to our findings, a previous study conducted across eight countries (including

Ghana and Kenya) found that N2Africa participants reported increased grain legume production (Stadler et al. 2016).

We found no differences in children's nutrition outcomes between the non-N2Africa and N2Africa groups in Ghana and Kenya, both not in frequency of consumption of the targeted grain legumes nor in diversity of the diet. Our findings are in line with earlier findings from reviews (Masset et al. 2012; Girard et al. 2012) that suggest there is limited evidence of agricultural interventions having significant positive impacts on child nutrition. Other studies (Berti et al. 2004; Pandey et al. 2016) found that without additional programming in other areas relevant for positive nutrition outcomes, such as gender or nutrition, agricultural programs are unlikely to have a significant positive impact on nutrition. The N2Africa project did include training on soya processing and targeted inclusion of 50% female participants but during the first phase did not include nutrition-specific training or other gender-related interventions. Also the fact that we found no differences in legume production between the non-N2Africa and N2Africa group, may explain why we found no difference in children's nutrition outcomes. Furthermore, potential nutrition outcomes resulting from N2Africa may not be sustained from harvest until the end of the lean season, the time data were collected in Ghana and Kenya. Due to the cross-sectional nature of the study, the absence of an association between participation in N2Africa and positive child nutrition outcomes cannot be attributed to a specific cause.

Methodological limitations

Our study suffered from several methodological limitations that hampered our ability to detect an impact of N2Africa on human nutrition (Masset et al. 2012; Girard et al. 2012). Both the lack of detectable increased household legume production and improved children's nutrition outcomes in the N2Africa group compared with the non-N2Africa group, could be due to the limitations related to the cross-sectional quasi-experimental study design we used. Due to the character of the intervention, we could not randomize households to N2Africa or non-N2Africa groups. Absence of randomization may cause differences between treatment groups. To overcome this problem, we matched N2Africa villages with non-N2Africa villages that were under supervision by the same agricultural extension agent in Ghana and we matched N2Africa participants with participants that had recently received N2Africa support but had not yet harvest targeted grain legumes in Kenya. Furthermore, we assumed little spill-over from the N2Africa intervention in our control groups. Comparative studies in four N2Africa countries, including Ghana and

Kenya, showed that 60–100% of the farmers interviewed shared seed of soybean, cowpea and groundnut with others but very few farmers shared the key technologies of the N2Africa intervention, rhizobium inoculants and P-fertilizer (Woomer et al. 2014). The N2Africa and non-N2Africa groups seem comparable as few differences in child's, their mother's and household's characteristics were found at the time of interview and detected differences in characteristics were not associated with children's nutrition outcomes. We also do not have data at a baseline before N2Africa started for these specific villages and cannot rule out potential differences between N2Africa and non-N2Africa households before the intervention. The latent differences between the two groups and the absence of a baseline limited our ability to find differences in household grain legume production and nutrition outcomes between N2Africa and non-N2Africa groups.

In this study dietary diversity was used as a proxy for diet quality, which may also have limitations. IDDS does not differentiate among foods within a food group. This may have two consequences. First, if children already consume grain legumes, the addition of another grain legume to a child's diet will not enhance his or her IDDS even though the added food, in our case soybean, has a better nutrient profile compared with other targeted grain legumes. Adding soybean to the diet therefore may contribute to improved nutrient adequacy of the diet but will not be reflected in an increase of IDDS in this study. However, a recent study among rural Kenyan women showed that food-based scores were only slightly more strongly associated with nutrient adequacy compared with the food group-based scores (Ngala et al. 2015). Second, if children already consume the promoted grain legume, they may consume increased amounts of this grain legume that may contribute to nutrient adequacy yet this will not be reflected in his or her IDDS. A review of dietary diversity studies suggested that scores might be improved by inclusion of portion size requirements (Ruel 2003), however, measuring portion sizes in the field is challenging (Martin-Prevel et al. 2010). Further, in our study grain legume production was self-reported by N2Africa participants (N2Africa group) and head of households (non-N2Africa group), reflecting their previous year's produce for each grain legume individually. Self-reported measures of land size and crop production are known to be inaccurate (Carletto et al. 2013).

In addition to the methodological limitations of the current study, limitations in the design of the N2Africa project itself may have hampered the ability to find differences in children's nutrition outcomes between the N2Africa group and non-N2Africa group as well. For a thorough evaluation of the potential nutrition impact of N2Africa, a rigorous monitoring and evaluation system needs to be in place, including indicators along the potential impact pathways towards nutrition outcomes (McDermott et al. 2015; Gelli et al. 2015). For example, no data was available for whether and which crops were replaced by improved varieties of grain legume in the N2Africa intervention, which may affect household's overall crop diversity and the quantity of crops available in the household, and in turn may affect the diet. In case grain legume production replaces part of the maize production it may positively affect the diet while if it replaces all vegetables produced it may negatively affect the diet. Some recent studies show that improved crop diversity is positively related to improved household dietary diversity (Jones et al. 2014) but others show no relation (Rajendran et al. 2014). Limited data on intermediate indicators along the impact pathways hampered the ability to identify explanations for potential impact on nutrition outcomes.

Production-own consumption pathway and income-food purchase pathway

SEM indicated a relatively good fit to the posteriori model in Kenya but not in Ghana. The hypothetical model for Ghana needs improvement. In Kenya we did find an effect through the production-own consumption pathway but not through the income-food purchase pathway. Through the production-own consumption pathway in Kenya, an increase of 1000 kg of household's soybean production may lead to a modest increase of 0.75 in IDDS. This relative high increase in soybean production is necessary because a small part of the produce may be consumed in the household and from what is consumed within the household little may end up on the plates of children. Differences in five characteristics of the food environment in Ghana compared to Kenya may explain that neither pathway was present in Ghana and only the production-own consumption pathway was present in Kenya. First, Kenyan N2Africa participants indicated the absence of a good market for soybean while Ghanaian participants indicated there was a relatively good and stable market for soybean compared with maize. Also Kenyan participants indicated that the lack of a nearby soybean market was one of the reasons they decided not to sell their soybean produce. This explains the stronger association between increased soybean production and greater quantity of soybean used for own consumption in Kenya compared with Ghana. In Kenya, soybean was a relatively new crop while in Ghana it has been widely cultivated since the 1990s (in the non-N2Africa group by 18.2% of households in Kenya versus 75.2% in Ghana). The better established market for soybean in Ghana may have strengthened the income-food purchase pathway instead of the production-own consumption pathway. Second, Kenyan N2Africa participant's opinions on the taste and beliefs about potential health benefits from the consumption of soybean were overall more positive compared with those of Ghanaian participants. In Ghana, soybean was mainly consumed in the form of 'dawadawa', similar to a bouillon cube, and thus consumed by all household members in very small amounts. However, in contrast to Ghana, overall fewer grain legumes are consumed by infants and young children in Kenya which leaves more room for increasing the intake of soybean. In addition, Kenyan participants reported a wider variety of local dishes prepared with soybean. These factors may also have led to more soybean production for home consumption in Kenya compared with Ghana. Third, in Ghana soybean production was weakly associated with the quantity of soybean used for own consumption and strongly with quantity sold, implying soybean was used as a cash crop. This result confirms statistics from the Food and Agriculture Organisation (FAO 2011). Ghanaian N2Africa households cultivated less cowpea but more soybean compared with non-N2Africa households, indicating a possible replacement of cowpea by soybean. As cowpea is mainly used for home consumption, this may suggest that increased soybean production may have led to a reduction of availability of other legume crops for home consumption. Fourth, enhanced legume production in households where children already consume grain legumes, as in Ghana, may not affect the frequency of legume consumption and/or IDDS but may increase portion sizes consumed. Preliminary analyses from a later survey conducted in Northern Ghana in Karaga district showed that children's daily portion sizes of cowpea, groundnut and soybean (Brouwer et al. unpublished) were associated with household's production of these grain legumes. This suggests that an increase in household's grain legume production may have led to the increased quantity of grain legumes consumed by children in Ghana. As the present study did not include portion sizes in the calculation of IDDS, the potential of the production-own consumption pathway may have been underestimated in Ghana. Fifth, the proportion of female participants in N2Africa in Kenya was high (above 70%) compared to Ghana (below 40%). A stronger women's decision-making power and control over resources like increased legume production and income from the sale of legume produce, may lead to the channelling of nutritious foods within households to the advantage of children, and to more agricultural income spent on nutritious food and health care for the family, particularly for children (Smith et al. 2003; UNICEF 2011). Female N2Africa participants indeed reported in the focus group discussions more often that the (extra) grain legume produce was used for own consumption, including their children's consumption.

In this study education was used as an indirect measure of women's status while women's status incorporates multiple more direct domains like decision-making-power, mobility and attitude towards domestic violence (Lee-Rife 2010; Cunningham et al. 2015). A majority of the mothers of children had not completed any form of education or only completed primary school. The absence of variation in mother's education level may also explain the absence of an association with children's IDDS in our study. Further, household assets were used as an indicator of household income but this may not be representative for total household income including the increased agricultural income.

An agricultural project not designed to be nutrition-sensitive that results in increased availability of a promoted food for home consumption may improve nutrition outcomes, but our findings suggest this depends on the food environment. Based on the focus group discussions and SEM analysis of the production-own consumption and income-food purchase pathways, it appears that a project such as N2Africa has more potential to improve children's dietary diversity through the production-own consumption pathway in a context where (a) farmers attribute positive characteristics towards the targeted nutritious food, (b) a wide variety of local dishes already include the promoted food, (c) women are involved, and d) the targeted food is relatively new and considered as a food crop and not a cash crop. In addition, if there is a strong market available for the promoted food, there is a likelihood that farmers prefer to sell the promoted food instead of keeping it for home consumption. Whether this income is used for improving children's nutrition seems unpredictable or less than expected (Herforth and Ahmed 2015). Thorough understanding of the food environment is therefore necessary to improve the nutrition-sensitivity of agricultural interventions to predict whether boosting legume production may improve the dietary diversity and nutrition outcomes of children.

The cross-sectional quasi-experimental study lacked the methodologically-rigorous design needed to find and draw firm conclusions on associations. In situations where rigorous study designs cannot be implemented or are not part of project evaluation, SEM in a mixed method design is a useful option to analyse whether agriculture projects have the potential to translate in improved nutrition. To our knowledge, our study was the first to use SEM in analysing the theoretical pathways from crop production to improved human nutrition in an explorative way. Further experimental studies are needed to confirm the direction and strength of the identified individual relationships between components within the pathways.

References

Barikmo, I., Ouattara, F., & Oshaug, A. (2004). Food composition table for Mali. TACAM, research series N 9. Oslo, Norway: Akershus University College.

Beasley, T. M., & Schumacker, R. E. (1995). Multiple regression approach to analyzing contingency tables: Post hoc and planned comparison procedures. *The Journal of Experimental Education, 64*(1), 79-93.

Berti, P. R., Krasevec, J., & FitzGerald, S. (2004). A review of the effectiveness of agriculture interventions in improving nutrition outcomes. *Public Health Nutrition, 7*(5), 599-609.

Bezner Kerr, R, Berti, P. R., & Shumba, L. (2010). Effects of a participatory agriculture and nutrition education project on child growth in northern Malawi. *Public Health Nutrition, 14*(08), 1466-1472.

Bezner Kerr, R, Snapp, S., Chirwa, M., Shumba, L., & Msachi, R. (2007). Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil feritlity. *Experimental Agriculture, 43*(04), 437-453.

Brouwer, I. D., Jager, I. d., Borgonjen, K., Azugpo, F., Fooij, M., Folson, G., & Abizari, R. (2016). Background Technical Report: Development of Food-Based Recommendations using Optifood – Ghana Global Alliance of Improved Nutrition (GAIN).

Carletto, C., Savastano, S., & Zezza, A. (2013). Fact or artifact: The impact of measurement errors on the farm size–productivity relationship. *Journal of Development Economics, 103*, 254-261.

Cogill, B. (2003). Anthropometric indicators measurement guide. Washington DC, USA: Food and Nutrition Technical Assistance (FANTA) Project, FHI 360.

Creswell, J. W., & Plano Clark, V. L. (2011). *Designing and conducting mixed methods research*. California, USA: SAGE Publications.

Cunningham, K., Ruel, M., Ferguson, E., & Uauy, R. (2015). Women's empowerment and child nutritional status in South Asia: a synthesis of the literature. *Maternal & Child Nutrition, 11*(1), 1-19.

de Jager, I. (2013). Nutritional benefits of legume consumption at household level in rural areas of sub-Saharan Africa. *Background document*. Wageningen, The Netherlands: N2Africa.

Du, L., Pinga, V., Klein, A., & Danton, H. (2015). Leveraging agriculture for nutrition impact through the Feed the Future initiative. *Adv Food Nutr Res, 74*, 1-46.

FAO (2010). Guidelines for measuring household and individual dietary diversity. Rome, Italy: FAO.

FAO (2012). West african food composition table. Rome, Italy: FAO.

Franke, A. C., Rufino, M. C., & Farrow, A. (2011). Characterisation of the impact zones and mandate areas in the N2Africa project. Wageningen, The Netherlands: N2Africa.

Garson, G. D. (2015). *Structural Equation Modeling* (Blue Book Series). Asheboro, USA: Statistical Associates Publishing.

Gelli, A., Hawkes, C., Donovan, J., Harris, J., Allen, S. L., de Brauw, A., Henson, S., Johnson, N., Garrett, J., & Ryckembusch, D. (2015). Value chains and nutrition: A framework to support the identification, design, and evaluation of interventions. (Vol. Discussion Paper 01413). Washington DC, USA: IFPRI.

Gibson, R. S., & Ferguson, E. L. (2008). An interactive 24-hour recall for assessing the adequacy of iron and zinc intakes in developing countries. *HarvestPlus Technical Monograph 8*. Washington DC, USA & Cali, Colombia: IFPRI & CIAT.

Giller, K. E., Franke, A. C., Abaidoo, R., Baijukya, F. P., Bala, A., Boahen, S., Dashiell, K., Katengwa, S., Sanginga, J., Sanginga, N., Simmons, A., Turner, A., Woomer, P. L., Wolf, J. d., & Vanlauwe, B. (2013). N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa. In B. Vanlauwe, P. van Asten, & G. Blomme (Eds.), *Agro-ecological Intensification of Agricultural Systems in the African Highlands* (pp. 156-174). London, UK: Routledge.

Girard, A. W., Self, J. L., McAuliffe, C., & Olude, O. (2012). The effects of household food production strategies on the health and nutrition outcomes of women and young children: a systematic review. *Paediatr Perinat Epidemiol, 26 Suppl 1*, 205-222.

Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security, 7*(3), 505-520.

Herforth, A., & Harris, J. (2014). Understanding and applying primary pathways and principles. Brief 1: Improving nutrition through agriculture. Arlington, USA: USAID/Strengthening Partnerships, Results, and Innovations in Nutrition Globally (SPRING) Project.

Hoddinott, J. (2011). Agriculture, health, and nutrition: Toward conceptualizing the linkages. Washington DC, USA: IFPRI.

Jahnke, H. E. (1982). *Livestock production systems and livestock development in tropical Africa*. Kiel, Germany: Vauk.

Jones, A. D., Shrinivas, A., & Bezner-Kerr, R. (2014). Farm production diversity is associated with greater household dietary diversity in Malawi: Findings from nationally representative data. *Food Policy, 46*, 1-12.

Keats, S., & Wiggins, S. (2014). Future diets: implications for agriculture and food prices. London, UK: ODI.

Kennedy, G. L., Pedro, M. R., Seghieri, C., Nantel, G., & Brouwer, I. (2007). Dietary diversity score is a useful indicator of micronutrient intake in non-breast-feeding Filipino children. *The Journal of Nutrition, 137*(2), 472-477.

Lee-Rife, S. M. (2010). Women's empowerment and reproductive experiences over the lifecourse. *Social Science & Medicine, 71*(3), 634-642.

Lukmanji, Z., Hertzmark, E., Mlingi, N., Assey, V., Ndossi, G., & Fawzi, W. (2008). Tanzania Food Composition Tables. Dar es Salaam, Tanzania: MUHAS, TFNC, HSPH.

Malapit, H. J. L., & Quisumbing, A. R. (2015). What dimensions of women’s empowerment in agriculture matter for nutrition in Ghana? *Food Policy, 52*, 54-63.

Martin-Prevel, Y., Becquey, E., & Arimond, M. (2010). Food group diversity indicators derived from qualitative list-based questionnaire misreported some foods compared to same indicators derived from quantitative 24-hour recall in urban Burkina Faso. *The Journal of Nutrition, 140*(11), 2086s-2093s.

Masset, E., Haddad, L., Cornelius, A., & Isaza-Castro, J. (2012). Effectiveness of agricultural interventions that aim to improve nutritional status of children: systematic review. *The British Medical Journal, 344*, d8222.

Mather, D., Donocan, C., & Boughton, D. (2009). Measuring the impact of public and private assets on household crop income in rural Mozambique: 2002-2005. Michigan State, USA: Michigan State University.

McDermott, J., Johnson, N., Kadiyala, S., Kennedy, G., & Wyatt, A. J. (2015). Agricultural research for nutrition outcomes–rethinking the agenda. *Food Security, 7*(3), 593-607.

Menon, P., Rawat, R., & Ruel, M. (2013). Bringing rigor to evaluations of large-scale programs to improve infant and young child feeding and nutrition: the evaluation designs for the Alive & Thrive initiative. *Food Nutr Bull, 34*(3 Suppl), S195-211.

Monteiro, C. A. (2009). The decline in child malnutrition in Brazil. *Cadernos de Saúde Pública, 25*, 950-950.

Moursi, M. M., Arimond, M., Dewey, K. G., Trèche, S., Ruel, M. T., & Delpeuch, F. (2008). Dietary diversity is a good predictor of the micronutrient density of the diet of 6- to 23-month-old children in Madagascar. *The Journal of Nutrition, 138*, 2448-2453.

Muhammad, A., Seale, J. L., Meade, B., & Regmi, A. (2011). International Evidence on Food Consumption Patterns *An Update Using 2005 International Comparison Program Data. TB-1929*. USA: USDA, Economic Research Service.

Muthayya, S., Rah, J. H., Sugimoto, J. D., Roos, F. F., Kraemer, K., & Black, R. E. (2013). The global hidden hunger indices and maps: an advocacy tool for action. *PLoS One, 8*(6), e67860.

Ngala, S. A. (2015). *Evaluation of dietary diversity scores to assess nutrient adequacy among rural Kenyan women*. Wageningen University, Wageningen, The Netherlands.

Pandey, V. L., Mahendra Dev, S., & Jayachandran, U. (2016). Impact of agricultural interventions on the nutritional status in South Asia: A review. *Food Policy, 62*, 28-40.

Pinstrup-Andersen, P. (2012). The food system and its interaction with human health and nutrition. In *Reshaping agriculture for nutrition and health: an IFPRI 2020 book* (pp. 21-29). Washington DC, USA: IFPRI.

Rajendran, S., Afari-Sefa, V., Bekunda, M., Dominick, I., & Lukumay, P. J. (2014). *Does crop diversity contribute to dietary diversity? Evidence from integration of vegetables into maize based farming systems in Tanzania.* Paper presented at the 88th Anual Conference, Paris, France,

Ronner, E., Franke, A. C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., Heerwaarden, J. v., & Giller, K. E. (2016). Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. *Field Crops Research, 186*, 133-145.

Ruel, & Alderman, H. (2013). Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? *The Lancet, 382*, 536-551.

Ruel, M. T. (2003). Operationalizing dietary diversity: A review of measurement issues and research priorities. *The Journal of Nutrition, 133*(11), 3911S-3926S.

Smith, L. C., Ramakrishnam, U., Ndiaye, A., Haddad, L., & Martorell, R. (2003). The importance of women's status for child nutrition in developing countries. *IFPRI research report 131*. Washington DC, USA: IFPRI.

Stadler, M., van den Brand, G. J., & Ronner, E. (2016). N2Africa Early Impact Survey, Phase I. *Progress document*. Wageningen, The Netherlands: N2Africa.

Swinburn, B., Kraak, V., Rutter, H., Vandevijvere, S., Lobstein, T., Sacks, G., Gomes, F., Marsh, T., & Magnusson, R. (2015). Strengthening of accountability systems to create healthy food environments and reduce global obesity. *The Lancet, 385*(9986), 2534-2545.

UN (2005). Designing Household Survey Samples: Practical Guidelines. New York, USA: UN DESA.

UNICEF (2011). Gender influences on child survival, health, and nutrition: a narrative review. New York, USA: UNICEF.

UNICEF, WHO, & World Bank Group (2015). Levels and trends in child malnutrition. USA: UNICEF, WHO & World Bank Group.

WHO (2011). WHO Child Growth Standards: SPSS syntax file. http://www.who.int/childgrowth/software/en/. Accessed May 2018.

WHO, UNICEF, USAID, AED, UCDAVIS, & IFPRI (2007). Indicators for assessing infant and young child feeding practices. Conclusions of a consensus meeting held 6–8 November 2007 in Washington DC, USA. Geneva, Switzerland: WHO.

WHO Multicentre Growth Reference Study Group (2006). *WHO Child Growth Standards: Length/height-for-age, weight-for-age, weight-for-length, weight-for-height and body mass index-for-age: Methods and developments*. Geneva, Switzerland: World Health Organization.

3

Woomer, P. L., Huising, J., Giller, K. E., Baijukya, F. P., Kantengwa, S., Vanlauwe, B., Boahen, S., Franke, A. C., Abaidoo, R., Dianda, M., Sanginga, J., Ronner, E., Brand, G. J. v. d., & Schilt, C. (2014). N2Africa: Final Report of the first Phase - 2009 - 2013. Wageningen, The Netherlands: N2Africa.

Working Group on Infant and Young Child Feeding Indicators (2007). Developing and validating simple indicators of dietary quality of infants and young children in developing Countries *Additional analysis of 10 data sets*. Washington DC, USA: USAID.

World Bank (2007). *From Agriculture to Nutrition: Pathways, Synergies, and Outcomes*. Washington DC, USA: The International Bank for Reconstruction and Development / The World Bank.

Appendices

Appendix 1

Number of missing data cases per table or figure, variable and group

Table	Variable	Ghana		Kenya	
		Non-N2Africa	N2Africa	Non-N2Africa	N2Africa
	No. of missing cases				
Table 1	Mother's age	3	1	4	2
	Mother's education level	1	2	2	1
	Mother's occupation	0	0	1	0
	Mother's religion	1	0	0	0
	People in household	0	1	0	0
	Household's highest education	3	0	0	1
	Household 's total land size	1	1	1	0
	Household's livestock	0	1	0	0
	Household's total assets	0	1	0	0
	Household's labour import	2	0	0	1
	Household's labour export	0	0	0	1
Table 2	Cowpea yield, uses	0	0	1	0
	Total production of groundnut	0	0	0	1
	Groundnut yield, uses	0	0	0	2
	Cultivation of other legumes	0	21	0	0
	Total production other legumes	2	0	0	0
	Other legumes, uses	0	0	3	1
	All legumes, uses	0	0	3	1
Table 5	Children receiving breastmilk	2	3	2	1
	Sample size per group (N)				
Table 5	Children age 6-23 months	76	40	43	48
	Children age 24-59 months	126	89	111	138
	Children non-breastfed	115	78	115	144
	Children breastfed	85	48	37	41

Appendix 2

Cases excluded for structural equation modelling

Figure	Country	Cases excluded	No. cases excluded	N model
Figure 3	Kenya (*n*=340)	Households no soybean cultivation	137	197
		Households no yield	5	
		Households missing information on mother's education	1	
Figure 4	Ghana (*n*=313)	Households no soybean cultivation	62	260
		Households no yield	5	
		Households missing information on mother's education	1	
		Households missing information on total land size	1	

Appendix 3

Indicators used for structural equation modelling

Model variables	Indicators
Production of soybeans	Total reported soybean production (in kg)
Soybean yield available for own consumption	Reported soybean production used for own consumption (in kg)
Soybean yield sold for household income	Reported soybean production sold for household income (in kg)
Total household assets	Value of total household assets available in the household (summed proportion (calculated in local market prices in Ghana cedi and Kenyan Shilling relative to most expensive asset) of assets available in household, for specific conversions see Table 1)
Child's monthly soybean consumption	Child's frequency of soybean consumption per month (times/month)
Child's daily soybean consumption	Child's frequency of soybean consumption per day (times/day)
Child's dietary diversity	Child's individual dietary diversity score (1 to 7 food groups, WHO)
Household land size	Total land size owned by household (ha)
Mother's education	Mother of child completed a form of education (no=0, yes=1)

Appendix 4

Co-variance matrix for structural equation modelling, Ghana (*n*=260)

	Production of soybeans	Soybean yield available for own con-sumption	Soybean yield sold for household income	Total household assets	Child's monthly soybean con-sumption	Child's daily soybean con-sumption	Child's dietary diversity	Household land size	Mother's education
Mean (SD)	557 (670)	63 (116)	373 (568)	0.21 (0.39)	44 (40)	0.2 (0.5)	4.1 (1.4)	19 (20)	0.2 (0.4)
Production of soybeans	449842.62								
Soybean yield available for own consumption	17696.60	13475.79							
Soybean yield sold for household income	335865.63	3154.08	323006.24						
Total household assets	57.42	2.74	57.27	.16					
Child's monthly soybean consumption	-8652.73	200.35	-6893.36	-1.43	1593.89				
Child's daily soybean consumption	-24.24	6.66	-32.31	.00	3.53	.24			
Child's dietary diversity	51.17	16.32	4.34	.04	14.52	.02	1.85		
Household land size	4323.84	-42.15	3587.15	2.09	-108.07	-.04	-1.05	380.39	
Mother's education	-32.05	2.79	-28.71	-.01	.13	.01	.03	-.37	.13

Appendix 5

Co-variance matrix for structural equation modelling, Kenya (*n*=197)

	Production of soybeans	Soybean yield available for own con-sumption	Soybean yield sold for household income	Total household assets	Child's monthly soybean con-sumption	Child's daily soybean con-sumption	Child's dietary diversity	Household land size	Mother's education
Mean (SD)	17 (31)	9 (12)	7 (22)	0.08 (0.23)	23 (29)	0.4 (0.9)	4.2 (1.0)	1.5 (1.7)	0.9 (0.3)
Production of soybeans	976.63								
Soybean yield available for own consumption	296.63	152.43							
Soybean yield sold for household income	630.91	143.01	485.17						
Total household assets	0.21	0.28	-0.15	0.05					
Child's monthly soybean consumption	128.28	50.27	74.38	0.47	845.41				
Child's daily soybean consumption	3.47	1.51	1.77	0.01	16.23	0.83			
Child's dietary diversity	2.59	0.98	1.00	0.04	2.80	0.25	0.96		
Household land size	11.83	5.01	5.89	0.11	5.66	0.23	0.37	2.83	
Mother's education	-0.78	-0.28	-0.43	0.01	-0.77	-0.01	0.05	-0.05	0.12

Chapter 4

Food and nutrient gaps in rural Northern Ghana: Does production of smallholder farming households support adoption of food-based dietary guidelines?

Ilse de Jager
Ken E. Giller
Inge D. Brouwer

PLoS ONE 2018, 13(9): e0204014
doi: 10.1371/journal.pone.0204014

Abstract

Food-based dietary guidelines (FBDGs) provide guidance to policy makers, the private sector and consumers to redesign food systems and to improve diets of vulnerable populations. As appropriate FBDGs are based on the actual dietary patterns and their costs, it is assumed that the recommended foods are available, affordable and acceptable for the population under study. Using quantitative dietary intake data of young children in rural Northern Ghana, we developed local FBDGs and studied whether these are supported by the diversity and quantity of the production of a household among 329 households. At household level, the developed FBDGs were, on average, unable to sufficiently cover the household requirements for fat (60.4% of recommended nutrient intake (RNI)), calcium (34.3% RNI), iron (60.3% RNI), vitamin A (39.1% RNI), vitamin B_{12} (2.3% RNI) and vitamin C (54.6% RNI). This implies that even when these FBDGs are fully adopted the requirements for these nutrients will not be met. In addition, the nutrient needs and food needs (according to the developed FBDGs) of a household were only marginally covered by their own food production. The food production of over half the households supplied insufficient calcium (75.7%), vitamin A (100%), vitamin B_{12} (100%) and vitamin C (77.5%) to cover their needs. The food production of about 60% of the households did not cover their required quantities of grains and legumes and none covered their required quantities of vegetables. Further analysis of the food gaps at district and national level showed that sufficient grains were available at both levels (267% and 148%, respectively) to meet requirements; availability of legumes was sufficient at district level (268%) but not at national level (52%); and vegetables were insufficient at both levels (2% and 49%, respectively). Diversifying household food production is often proposed as a means to increase the diversity of foods available and thereby increasing dietary diversity of rural populations. We found that the diversity of the production of a household was indeed positively related with their food and nutrient coverage. However, the diversity of the production of a household and their food and nutrient coverage were not related with children's dietary diversity and nutrient adequacy. Our results show that the production of a households does not support the adoption of FBDGs in rural Northern Ghana, especially for vegetables. This suggests that the promotion of FBDGs through nutrition education or behaviour change communications activities alone is insufficient to lead to improvements in diets. Additional strategies are needed to increase the food availability and accessibility of the households, especially that of fruits and vegetables, such as diversification of the crops grown, increased production of specific crops and market-based strategies.

Introduction

Current transformations of food systems driven by climate change, urbanization, income growth and population growth are often associated with unhealthy diets as they fail to provide sufficient, diverse, nutritious and safe food for all (GLOPAN 2016). Among low and middle income country (LMIC) populations the average diets fall far short of the recommended quantities of fruits, vegetables, dairy and other protein-rich foods (Keats and Wiggins 2014). Undernutrition persists, especially in rural areas of sub-Saharan Africa where one in three children is chronically malnourished and micronutrient deficiencies prevail (UNICEF et al. 2015; Muthayya et al. 2013). This impairs physical and mental development resulting in a life-long disadvantage (WHO and UNICEF 2003). Simultaneously the number of overweight children is increasing (UNICEF et al. 2015). One of the many causes of malnutrition lies in low-quality diets (GLOPAN 2016). Malnutrition associated with low-quality diets is the number one risk factor in the global burden of disease (Global Burden of Disease Study 2015). Food-based dietary guidelines (FBDGs) provide guidance to policy makers, private sector and consumers to redesign food systems and to improve diets of vulnerable populations (GLOPAN 2016). However, FBDGs are largely absent in LMICs and especially in Africa where only 7 out of 58 countries have official FBDGs (van ‘t Erve et al. 2017).

FBDGs that provide sufficient nutrients required by LMIC populations have recently been developed using linear programming (Talsma et al. 2017; Kujinga et al. 2018). These studies based their analysis on actual dietary patterns and their costs – in doing so they implicitly assumed that the developed FBDGs are available, affordable and acceptable for the population under study (E. L. Ferguson et al. 2004). However, their analysis is based on the distribution of the types and frequencies of foods consumed, and often uses the extreme ends of these distributions to arrive at FBDGs that cover most of the nutrient needs. Using extremes values may limit the adoption of local FBDGs as the recommended quantity of foods may not be available, affordable and/or accepted by the targeted population. It therefore remains unclear whether the developed FBDGs are supported by the local food system.

The availability of recommended foods is a key condition for the adoption of FBDGs (Herforth and Ahmed 2015) (Figure 1). Although most people in rural areas do not depend solely on their own agricultural production for their food and income, their production is often the most important source of food (Pinstrup-Andersen 2012).The price farmers receive for their produce is often not enough to cover the retail price of foods that they decided not to grow. Therefore rural households tend to prefer to intensify their own production of food crops for home consumption and to sell only the surplus that is produced after all their food needs have been met (Leahy 2018). In addition, many rural households have an income based mainly on the sale of their produce: in rural Northern Ghana over 80% of households reported that all or three quarters of their income was from their own food production (Franke and de Wolf 2011). In general, two main pathways make the production of households available for improved diets and nutrition outcomes in LMICs (Du et al. 2015). The first pathway refers to crop production for own consumption (the production-own consumption pathway) and assumes that increased production of nutritious foods increases consumption of these foods and adds to diversity of the diets of the household and of individuals (Du et al. 2015). The second pathway refers to production sold for household income and assumes that agricultural income through sale of production is used for immediate or future household needs, including food purchases to support improved dietary diversity (the income-food purchase pathway) (Du et al. 2015). In addition, this assumes the required foods are available at local markets. Market access may have larger positive effects on the dietary diversity of households than the diversity of the production of households (Sibhatu et al. 2015). Although agriculture income growth may not be sufficient to ensure improved dietary diversity, it seems to increase the share of vegetable, fish and tuber consumption (A. Dillon et al. 2015). Two recent reviews show that increasing diversity of crop production of smallholder households in LIMC is associated with more diverse diets at household and individual level (Jones 2017; Sibhatu and Qaim 2018). Therefore, it is hypothesized that the production of households, either via the production-own consumption pathway or via the income-food purchase pathway, contributes to the diversity and quantity of foods available and accessible for household consumption and thereby determines whether and to what extent adoption of FBDGs is possible.

An understanding of whether and to what extent households can meet their food and nutrient needs through their own production and how this is associated with the quality of a children's diet may inform what strategies are required to further facilitate adoption of FBDGs to improve diets of vulnerable groups in rural areas. To this end we used dietary intake data of young children in rural Northern Ghana to develop local FBDGs and studied whether these are supported by the quantities and diversity of foods produced at household and district level. At national level we studied whether FBDGs are supported by national food availability per capita (accounting for food imports, exports and waste). In addition, we studied whether diversifying the production of households own food production has potential to increase the diversity of foods available and accessible and thereby increasing children's dietary diversity and nutrient adequacy.

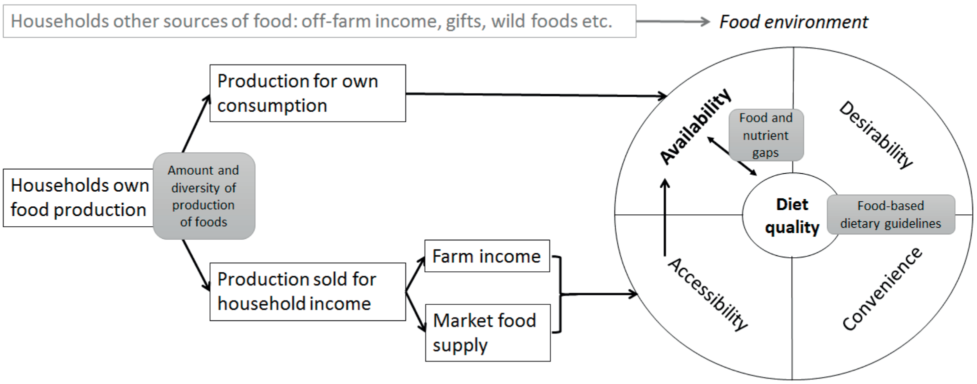

Figure 1. The production-own consumption and the income-food purchase pathways are two pathways that contribute to the availability and accessibility of food: a key condition for the adoption of food-based dietary guidelines to improve diet quality

Methods

Study area

The study was carried out in Karaga sub-district in the Northern Region of Ghana. Northern Ghana has one cropping season that lasts 5 to 6 months starting in May, an average annual temperature of 28°C and annual rainfall of 900 to 1040 mm. The main crops in Northern Ghana are maize, rice, cowpea and yam. Travel time to urban markets is between 1 to 7 hours and population density is sparse with 50 to 100 inhabitants per km^2 (Franke et al. 2011). Karaga district was selected from Northern Region because of high food insecurity and malnutrition. About 32% of children below 5 years old are stunted and 9% are wasted (Ilse de Jager et al. 2017).

Study population and sampling strategy

A census was conducted in Karaga sub-district between May-June 2014 to identify all households with children of 6-23 months and collect information on their sex, date of birth, breastfeeding status and geographical location by GPS coordinates. A list of all households with children of 6-23 months in Karaga sub-district constituted the sampling frame divided into four sub-frames corresponding to the four age groups. A random order list was developed for each sub-frame and the first 100 children on this list were selected. To develop local FBDGs using linear programming software (e-Optifood©), the study population was divided into four specific groups according to age and breastfeeding state: 6-8 months breastfed, 9-11 months breastfed, 12-23 months breastfed and 12-23 months non-breastfed . A household was defined as 'a person or group of related or unrelated persons who live together in the same housing unit, sharing the same housekeeping and cooking arrangements, and who acknowledge an adult male or female as the head of the household'.

Eligibility was defined by the age of the child falling between 6-23 months using the day before the start of data collection as the reference date (30 June 2014). For the breastfed groups, eligibility was also defined as receiving both breastfeeding and complementary feeding. Eligibility for the study was cross-checked in the field prior to the start of data collection and ineligible children were randomly replaced with other eligible children in the same community or nearby community. A sample size of approximately 100 per group was determined based on estimated population mean food serving sizes for commonly consumed foods in the study area to be within 10% (95% CI), assuming an SD of 50% of the mean serving sizes in the age group and allowing for a 5% rate of attrition (Santika et al. 2009). One child per household was selected. In case two or more children in the household qualified for inclusion, one was randomly chosen. Communities of selected children were clustered into three geographic areas: north, central and south. Each cluster was then randomly assigned to a time slot of data collection. For this study, children of households that either did not farm (n=7) or had no harvest during the last year (n=1) were excluded. A random sample of food vendors within the selected study communities and major markets within the study area were also interviewed to determine prices of foods identified during collection of dietary data.

Data collection and analysis

Data was collected in Ghana in July 2014 by trained enumerators who had a first degree in nutrition and who spoke the local language. Trained supervisors with previous experience in dietary assessment and who spoke the local language observed some of the interviews and back-checked data forms of all interviews. In case of inconsistencies, the survey supervisors ensured that households were revisited. Dietary assessment was conducted with the mother or primary caretaker of the selected children. A structured questionnaire-based interview was conducted with the head of household of the selected child to collect information on household composition, education, occupation, sources of income, religion, total cultivated land, distance to closest market and available functioning assets (radio, television, bicycle, motor, corn mill, private and/or commercial vehicle). Total value of assets in each household was calculated in Ghanaian Cedi's (GH₵) by estimated local market value and converted into purchasing power parity in US dollar using the conversion factor of 2014 of 1.032 (2016). Details on data collection and analysis can be found in supplementary material (Appendix 1).

Children's nutritional status

Weight and length of children were measured following standard procedures. Length and weight measurements were converted into height-for-age, weight-for-height, weight-for-age and BMI-for-age z-scores based on the WHO Child Growth Standards by using the WHO SPSS syntax. Children who were more than two SD below reference median of height-for-age, weight-for-height and weight-for-age z-scores were classified to be stunted, wasted and underweight. Children who were more than two SD above reference median of BMI-for-age were classified to be overweight.

Food composition table

A food composition table was specifically created for this study (sFCT) using nutrient values primarily from the West African Food Composition Table (FAO 2012) and complemented with values from other sources. Energy and the following nutrients: protein, carbohydrates (by difference), fat, water, calcium, iron, zinc, vitamin A (RAE), folate, vitamin C, thiamine, riboflavin, niacin, vitamin B_6, and vitamin B_{12} were derived.

Children's dietary intake

Dietary intakes of the children were assessed using a quantitative multi-pass 24-hour recall (24hR) (Gibson and Ferguson 2008). All days of the week were captured and randomly assigned to subjects to account for day-to-day variation in dietary intake. Data was collected within a time period of 3 weeks.

Children's dietary diversity: Dietary intake data was used to calculate the individual dietary diversity score (IDDS) being a count of the number of seven different food groups consumed, including: (i) grains, roots and/or tubers; (ii) legumes and/or nuts; (iii) dairy products; (iv) flesh foods; (v) eggs; (vi) vitamin A rich fruits and/or vegetables; and (vii) other fruits and/or vegetables (WHO et al. 2007). Consumption of any quantity of food from each food group was sufficient to 'count', except if an item was used as a condiment. Fruits and vegetables were classified as vitamin-A rich when they provided at least 60 retinol activity equivalents (RAE) per 100 g. Consumption of at least four out of these seven is associated with adequate dietary quality of children of 6-23 months (WHO et al. 2007). Median IDDS and the proportion of children who had a nutrient diverse diet (IDDS=>4) were calculated.

Children's nutrient adequacy: Nutrient intakes were calculated based on the sFCT and using nutrient calculation system Compl-eat^{TM} (version 1.0, Wageningen University). To generate usual intakes, nutrient intakes were adjusted for within-person variation using the National Research Council adjustment method (National Research Council 1986; Institute of Medicine 2000). For breastfed children, intake of breastmilk was not measured directly and therefore we assumed average intakes based on estimated energy intakes from breastmilk for populations in low income countries (K. G. Dewey and K. H. Brown 2003; Brown et al. 1998). The total nutrient intake for breastfed children were computed by their adjusted nutrient intakes plus the nutrient intake from the assumed average breastmilk intakes (Brown et al. 1998). Intakes of 11 key micronutrients were assessed: iron, zinc, calcium, vitamin A, vitamin C, thiamine, riboflavin, niacin, vitamin B_6, folate, and vitamin B_{12}. Except for iron, the probability of adequacy (PA) of each nutrient was calculated based on their respective estimated average requirements (EARs) and distributions (WHO and FAO 2004, 2006) (Appendix 2). EAR represents the quantity of a nutrient that ensures the needs of 50% of the population. For iron, probability of adequacy values from Institute of Medicine (IOM 2001) were used as the distribution of iron requirement is skewed (Appendix 3). Considering the low dietary haem iron with high phytate and fibre in the plant foods commonly consumed by young children, PA values for iron were adjusted for 5% bioavailability. In agreement with the International Zinc Nutrition Consultative Group (iZiNCG), the EAR for zinc was also adjusted for 15% bioavailability for unrefined cereals based diets (Brown et al.

2004). Mean PA for each nutrient was calculated for breastfed children of 6-11 months (except for vitamin A, vitamin C, thiamine, riboflavin, niacin and vitamin B6 intakes as information on the EAR and distributions for these nutrients for this age group are not available), breastfed children of 12-23 months and non-breastfed children of 12-23 months. For breastfed and non-breastfed children of 12-23 months, the mean probability of adequacy (MPA) was calculated, computed as the average of the PA of the 11 nutrients.

Optimised diet for non-breastfed children of 12-23 months: Dietary intakes were used as input for linear programming to develop an optimised diet for non-breastfed children of 12-23 months. First, the dietary intake data was used to define the model input parameters. These parameters included: a list of non-condiment foods consumed by ≥5 of the non-breastfed children of 12-23 months; the serving size of each food defined as the median serving size for all children who consumed the food; and the minimum and maximum number of servings per week for each food group and sub-food group defined as the 5th and 95th percentiles, respectively. The maximum number of servings per individual food within a subgroup was estimated based on percentage of children consuming that food. An energy constraint was used to ensure the modelled diet provided the average energy requirement for children of 12-23 months, estimated using their mean body weight (as measured in the study) and the FAO/WHO/UNU algorithm for estimating energy requirements (FAO et al. 2004). Thirteen key nutrients were considered in the Optifood analysis: total fat, total protein, iron, zinc, calcium, vitamin A, vitamin C, thiamine, riboflavin, niacin, vitamin B6, folate, and vitamin B12. The FAO/WHO Recommended Nutrient Intakes (RNIs), representing the amount of a nutrient that ensures the needs of nearly all the population (97.5%), were used for all nutrients (WHO and FAO 2004), except zinc which was defined by iZiNCG's RNI for unrefined cereal based diets (Brown et al. 2004). For fat, the average requirement of 30% of total energy was used. For iron 5% bioavailability and for zinc 15% bioavailability was assumed (as described above). Second, Optifood linear programming software (version 4.0.9, e-Optifood©) was used to generate diets that best cover the nutrient needs of the target population. Nutrient intakes above 70% of RNI were classified as adequate, for most nutrients this represents at least the EAR, and it allows for comparison with other studies (Kujinga et al. 2018; Talsma et al. 2017; Santika et al. 2009).

Production of households

The head of household of the selected child was interviewed to collect information on all crops cultivated during the previous year and the total production of the crop in local units together with the quantity used for home consumption, sold and/or other uses. Conversion factors were collected to convert local units to kg. The household crop production data was used to compute two measures of household crop diversity, both for total household production and quantity of household production used for home consumption. A simple crop count variable, used in previous studies to assess farm biodiversity (Jones et al. 2014; Remans et al. 2011), was computed by the sum of the total number of different crops cultivated by a household during the previous year. We quantified household crop production diversity using the Shannon-Wiener index that combines richness (number of crops) and evenness (distribution of quantity of production of different crops). The Shannon-Wiener index is defined as $H' = -\sum (p_i \log(p_i))$, where p_i is the relative abundance of occurrence of the *i*th crop produced by the household calculated as the proportion of the quantity of the *i*th crop to the total quantity of crops produced (total crop yield).

Food prices

A market survey was conducted to determine the price per edible 100g portion of all foods consumed by the children as identified in the 24hR. Enumerators bought food from food sellers within the communities visited and in the main markets within the research area. Each food was bought from three different food sellers and the price per 100 g edible portion from each seller was determined. For each food an average of the three prices were recorded as the price per 100 g edible portion. The average price per 100 g edible portion was used in converting monetary values of foods given during the 24hR to their weight equivalents and was used together with the total household crop production data (corrected for waste factors) to estimate total farm income and monetary value of total foods needed in the household.

Food and nutrients coverage of households

A household roster was filled including information for all individual household members on sex, age and physiological state (menstruation, pregnancy, lactating). The household composition data was used to calculate the total optimised food needs and nutrient needs of a household. For children below 23 months old we adjusted their nutrient needs by subtracting the nutrient intakes from average breastmilk intakes (Brown et al. 1998; K. G. Dewey and K. H. Brown 2003), as these nutrients do not need to be supplied by food. We assumed all children below 23 months old were breastfed (Ghana Statistical Service et al. 2015).

The food coverage of a household was defined by the coverage of their food and food group needs from an optimised diet by their production. The optimised diet for non-breast children of 12-23 months was used to estimate the optimised food needs for all household members. Dietary patterns of this group were assumed to best resemble the food consumed in the household as most members do not consume breastmilk. Although not all foods consumed by adults might be given to young children (Amugsi et al. 2015) it was found that generally the diets of children after one year of age are integrated into family diets in our study location (Armar-Klemesu et al. 2016). First, based on the household composition data, each household member was given a consumer unit respective to their age, sex and physiological state. We calculated consumer units for the different groups (by age, sex and physiological) by using their respective EARs of each of the 11 key nutrients relative to the EARs of women 19-50 years who are not pregnant or lactating (consumer unit is set to 1). For each group, an average was calculated of all these 11 consumer units of all key nutrients (Appendix 4). For a child of 12-23 months the consumer unit was determined at 0.5. We used this approach to assure nutrient needs of all household members were more or less covered by the optimised diet. Second, the optimised food needs of a 12-23 months old child were doubled to arrive at the total foods needed for 1 consumer unit. For each household the consumer units were summed and these were multiplied by the optimised foods needed for one consumer unit to arrive at total household food and food group needs in kg per year. Third, the food coverage of a household was computed as the proportion of the foods and food groups produced by the household compared with the foods and food groups needed when adopting the FBDGs. Food groups were defined as in Optifood and foods and food groups were included if they were both recommended in the optimised diet and produced by households. Median household food coverage was calculated and the percentage of households above 100% food coverage at food and food group level. In addition, the proportion of households covering 100% or more of a specific number of food(s) (0 to 6) and food group(s) (0 to 3) was calculated. Similarly, these measures were also computed for the production of a household that was specifically reported to be used for home consumption. Assuming that the income from the foods produced is used to purchase other foods, the food coverage of a household in monetary value was calculated as the proportion of the monetary value of their production compared with the monetary value of their food needs. Median household food coverage based on monetary value was calculated as well as the percentage of households above 100% food coverage.

The nutrient coverage of a household was defined by the coverage of their nutrient needs by their production. The total energy and nutrient needs per household were calculated as the sum of the energy and nutrient needs per household member with the use of the household composition data together with the individual RNIs. The energy and nutrients supplied by the production of a household was calculated using the sFCT, that include adjustments for nutrient losses during cooking as described above but not for other post-harvest losses. For each household, the coverage of each nutrient was calculated as the proportion of the total quantity of nutrient produced and the total quantity of the nutrient needed. All individual nutrient coverages were truncated at 100%. Median household energy and nutrient coverages and the percentage of households below 70% of energy and nutrient coverage were calculated. The average coverage of all macro- and micro-nutrients was calculated. Similarly, these measures were also computed for nutrients supplied by the production of a household that was specifically reported to be used for home consumption.

Food coverage at household, regional and national level

For the household level, as described above, we calculated the median household food group coverage. For the district level, mean household food group coverage was calculated. As the mean also includes extreme values, it represents the potential of the district to cover the district's food group needs. For an estimation of food group coverage at national level, the recommended total kg per food group per capita was compared with the total kg per food group available per capita per year, using the methodology of Keats and Wiggins (2014). As Ghana and other West African countries have no (or not sufficiently specific for this analysis) national FBDGs (van 't Erve et al. 2017; FAO 2017), the South African FBDGs (Vorster et al. 2013) were used to calculate the recommended kg per food group per capita per year. The total food available per food group per capita per year was calculated from most recent data available from 2011 from the Food Balance Sheets accounting for food imports, exports and waste (FAO 2013). The quantity of different foods available per food group were summed and foods were included as was described by the South African guidelines.

Statistical analysis

Statistical analyses were performed using SPSS (IBM SPSS Statistics 22) and R version 3.5.0 (R Core Team 2018). Data were checked for normality by visual inspection of histograms and Q-Q plots. Differences in the food and nutrient coverage of a household between the total quantity of their production and the total quantity of their production used for home consumption was analysed using Wilcoxon signed rank sum test (for continuous data) and McNemar Chi-square test (for categorical data). Differences in PA of 11 key nutrients and MPA of these nutrients between breastfed children of 12-23 months and non-breastfed of

12-23 months were analysed with Wilcoxon-Mann-Whitney test. The effects on the nutrition outcomes for a household (food and nutrient coverage) and a child (MPA and IDDS) of the diversity of the production of a household (crop count and Shannon-Wiener index), of the food coverage of a household (no. of food groups covered and overall coverage in GHS) and of the nutrient coverage of a household (% micronutrients covered and % macronutrients covered) were estimated using linear mixed models, taking location as a random factor (nested within main independent variable of specific model) and socio-economic and demographic household characteristics as fixed factors in the model to control influences of these characteristics. A recent review shows socio-economic factors are related with dietary patterns in LMICS (Mayén et al. 2014). The effect of count-dependent variables was estimated using Poisson regression models (no. of food groups covered) and a quasi-binomial regression models (IDDS). *P* value <0.05 was regarded as statistically significant.

Ethical considerations

Clearance to carry out the research was granted by the Noguchi Memorial Institute for Medical Research Institutional Review Board (Ethical Clearance certificate No. NMIMR-IRB CPN 087/13-14). Approval for the study was obtained by the District Assembly, District Health Administration in Karaga and leaders of selected communities. Participation was voluntary and written informed consent was obtained from caregivers of selected children and thumb prints used for those who were not literate. The identity of the infants and their mothers/caregivers has been kept confidential. Caregivers were compensated with a 500 g sachet of iodized salt for their time.

Results

Characteristics of the study population

In total 329 households were included in the study (Figure 2). The selected children in the households were on average 12 months old, with about half being female (Table 1). Of all children 40% were stunted, 13% wasted and 1 child was overweight. More than half of the children had an IDDS of 4 or higher, reflecting a nutrient adequate diet (WHO et al. 2007).

Information on the exact foods and their quantities consumed by our study population is published elsewhere (I. de Jager et al. submitted). On average the mean probability of adequacy (MPA) of 11 micronutrients was 52% for breastfed children of 6-11 months, 49% for breastfed children of 12-23 months and 50% for non-breastfed children of 12-23 months (Table 2). Only thiamine, riboflavin and vitamin B_6 had a probability of adequacy (PA) of 50% or more in all three groups. The PA of vitamin A and vitamin C were greater among breastfed children of 12-23 months than among those that were not breastfed (65% vs 12% and 72% vs 8%, respectively, $P<0.05$) while adequacies of calcium, iron, zinc, thiamine, niacin, vitamin B_6 and vitamin B_{12} intake were less. The majority of the mothers and heads of household had not completed any formal education (93% and 85%). Their main occupation was farming which was the source of most of their income. Almost all households had a male household head and were Muslim. Households consisted on average of 14 members, with 6 adults and 3 children below 5 years old. Travel distance to the closest market was on average 60 minutes. On average households cultivated 5 ha with four different crops of which three were used for home consumption. Most households produced grains (97%) and legumes, nuts and seeds (84%) but only 8% of households produced vegetables.

Table 2. Probability of adequacy of micronutrients of children's current diet

	Breastfed children 6-11 mo *(n=185)*	Breastfed children 12-23 mo *(n=113)*	Non-breastfed children 12-23 mo *(n=31)*
Nutrients		*Mean % (95%CI)*	
Calcium	16.6 (12.6-20.6)	3.7 (0.5-6.8)	13.1 (1.2-25.1)*
Iron	1.9 (0.7-3.0)	15.0 (11.6-18.4)	46.5 (35.4-57.5)*
Zinc	13.3 (9.7-16.9)	80.5 (74.9-86.1)	95.5 (89.8-101.1)*
Vitamin A	NA	64.5 (61.1-68.0)	11.7 (0.4-22.9)*
Thiamine	NA	80.0 (73.6-86.4)	96.0 (89.4-102.6)*
Riboflavin	NA	54.2 (46.4-62.1)	65.1 (49.5-80.7)
Niacin	NA	50.2 (42.1-58.2)	75.3 (62.7-87.9)*
Vitamin B_6	NA	72.8 (65.4-80.2)	92.9 (84.2-101.7)*
Folate	62.4 (57.5-67.2)	23.5 (16.7-30.2)	32.5 (17.1-47.9)*
Vitamin B_{12}	84.5 (82.6-86.3)	24.8 (19.7-29.9)	13.3 (1.0-25.5)*
Vitamin C	NA	71.8 (65.9-77.6)	7.9 (0.0-16.6)*
MPA[a]	*NA*	*49.2 (44.9-53.4)*	*50.0 (43.3-56.6)*

*P <0.05, Wilcoxon-Mann-Whitney test comparing breastfed and non-breastfed children 12-23 months
[a]MPA=Mean Probability of Adequacy is a summary measure of nutrient adequacy based on calculated probability of adequacy for calcium, iron, zinc, vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12} and vitamin C based on their respective estimated average requirements (EAR) and distributions

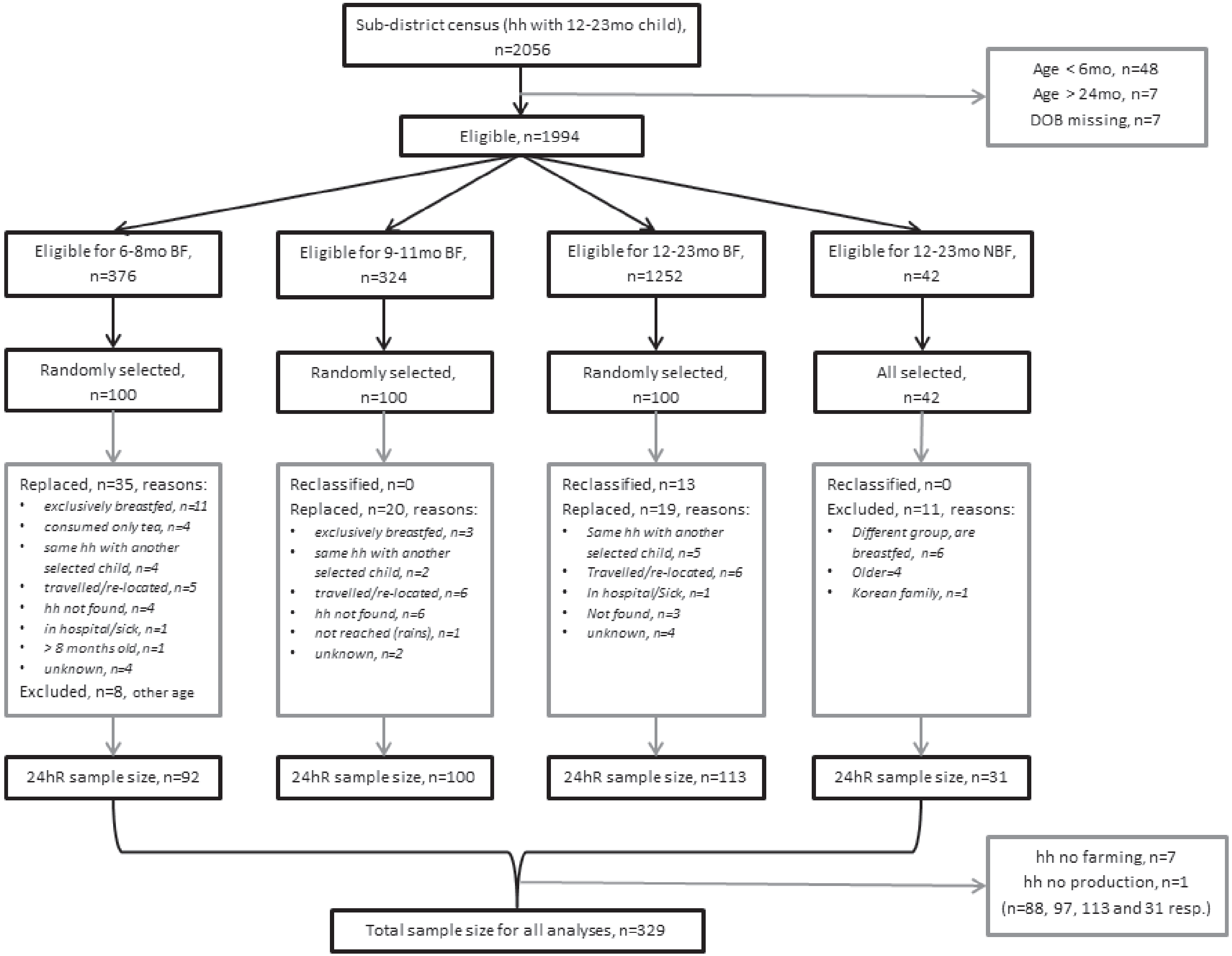

Figure 2. Flow chart of sample selection. hh = household. n=sample size. BF=breastfed. NBF=non-breastfed. Reclassified=from other age group to this group (different age or breastfeeding status during 24hour recall than census). 24hR=24hour recall.

Table 1. Demographic and social economic characteristics of children aged 6 to 23 months, their mothers and head of household and their households (*n*=329)

	Median (IQR) or %
Children characteristics	
Age (in months)[a]	11.6 (8.2)
Female, %	51.1
Stunted[b], %	39.8
Wasted[b], %	13.3
Overweight[b], %	0.3
Dietary diversity	
IDDS[c] (0-7)[a]	4 (4)
IDDS[d] ≥ 4 (min. dietary diversity)[b], %	56.8
% consuming food group	
Grains, roots and tubers	96.4
Legumes and nuts	60.8
Dairy products	13.7
Flesh foods	60.8
Eggs	1.5
Vitamin A rich fruits and vegetables	49.8
Other fruits and vegetables	49.2
Mother and head of hh[e] characteristics	
Education level completed, mother/head of hh[e]	
None, %	92.7/84.5
Primary education, %	3.6/8.8
Higher education, %	3.6/6.4
Occupation, mother/head of hh[e]	
Farmer	63.5/80.5
Trader	18.2/9.4
Income, mother/head of hh[e, f]	
None, %	19.1/6.1
Mainly farm income, %	59.3/75.4
Mainly off-farm income, %	21.0/18.2
More than 7 GHS/week[g], %	15.5/31.0
Household characteristics	
Household size	14 (13)
Adults in household	6 (6)
Children <5 years in household	3 (3)
Female headed households, %	1.5
Muslim, %	90.3
Market distance[h], reported in minutes	60 (75)
Total cultivated area (ha)	5 (6.5)
Total value of assets in hh[e, i] (PPP US dollar)	1579 (1550)
Crop diversity, total production/for consumption	
Crop count (Richness)	4 (2)/3 (2)
Shannon-Wiener Index	1.0 (0.6)/0.8 (0.5)

[a]One missing value: date of birth, n=328, [b]Two missing values: 1 date of birth and 1 anthropometry measurements, n=327, [c]Individual dietary diversity score (IDDS), [d]An IDDS of 4 or more in infants and young children reflect a nutrient adequate diet (WHO et al. 2007), [e]hh = household, [f]Two missing values for mothers and one missing value for head of household, [g]Estimated to be above average income per capita in the study location, [h]15 missing values: 3 missing, 8 households not visit market and 4 households where the mother does not go to market, n=314, [i]Summed value of functioning assets in the household using estimated local market prices, expressed in Purchasing Power Parity (PPP) in US dollar (1 Ghanaian cedi = 0.9690 PPP US dollar)

Best optimised diet

The best optimised diet for non-breastfed children of 12-23 months old (representing 0.5 consumer unit) includes on an annual basis 2.3 kg of fats (fortified vegetable oil), 42.9 kg of grains (mainly white maize flour), 21.8 kg of legumes, nuts and seeds (mainly cowpea (*Vigna unguiculata)* and groundnut paste (*Arachis hypogaea*)), 1.6 kg of meat, fish (smoked anchovies) and eggs, and 26.3 kg of vegetables (mainly okro (*Abelmoschus esculentus),* and kenaf leaves (*Hibiscus cannabinus)*) (Table 3). The optimised diet covers less than 70% of the RNI of calcium (33%), vitamin A (30%), vitamin B_{12} (2%) and vitamin C (42%) (S4 Table). Converting this optimised diet to other household members using CUs resulted in deficits of the same nutrients. In addition to these problem nutrients, energy (65%), fat (57%), iron (31%) and folate (67%) were also below 70% of the RNI for women 19-50 years (1 CU). On average for all household members combined energy, fat and iron were also below 70% of the summed RNI of households (in % median (IQR): 67.7 (2.9), 60.4 (2.3) and 60.3 (13.0), respectively) (Appendix 5).

Coverage of the food and food group needs from an optimised local diet of a household by their production

Own food production allowed about 60% of households to cover their needs for maize and groundnut, less than 40% for rice and sorghum, and less than 5% for cowpea and okro. At food group level, including also other foods produced belonging to the same food groups, about 60% of households did cover their grain and legume needs but none covered their vegetables needs from their own production (Table 4). Most households covered one or two of their food group needs by their own production (40.7% and 41.3%, respectively) (Table 5). Comparison of the monetary value of all household foods needed with the value of all household foods produced, showed that 63.8% of households were able to cover their food needs while 36.2% were not even if they used all of their income from sales of their own crop production to purchase food (Table 4). Among these 36.2% of households, 65% neither the household head nor the mother had an off-farm income as their main source of income, suggesting that about 20% of all households were unable to cover their food needs from their own food production (either by direct consumption or via farm income) and/or off-farm income.

Table 3. Best optimised local feasible diet for children not breastfed 12-23 months old: recommended servings per week, median servings size and recommended serving size per year

Foods[a] per food group	Servings /week	Median serving size (g)	Quantity (kg) /year
	Children not breastfed 12-23 mo (0.5 CU[b])		
Added fats			
Vegetable oil fortified	7	6.4	2.3
Grains			
Sorghum dough	2	66.4	6.9
Maize dough, white	1	38.4	2.0
Maize flour, white	4.3	125.0	28.0
Maize grain, dried white	1	11.0	0.6
Rice brown, unpolished	1	102.7	5.4
Legumes, nuts & seeds			
Cowpea, white dried	4	41.6	8.7
Groundnut flour	2	12.5	1.3
Groundnut roasted, paste	7	25.2	9.2
Groundnut shelled, dried	7	1.0	0.4
Melon seed, roasted	3	14.5	2.3
Meat, fish and eggs			
Anchovies, smoked	7	4.5	1.6
Vegetables			
Jute leaves	4	18.3	3.8
Kenaf leaves	7	18.9	6.9
Onion bulb	5	5.7	1.5
Okro fruit, dried	7	4.2	1.5
Okro fruit	7	27.5	10.0
Tomato paste	5	9.7	2.5

[a]Scientific/local names for some of the foods are as following: sorghum (Sorghum bicolor), cowpea (Vigna unguiculata), groundnut (Arachis hypogaea), melon seed (Cucumis melo seeds/neri), jute leaves (Corchorus olitorious /ayoyo leaves), kenaf leaves (Hibiscus cannabinus/bra leaves) and okro (Abelmoschus esculentus/okro)
[b]CU=consumer unit

Table 4. Coverage of foods and food groups^ from an optimised diet of a household by their production

% food coverage[a]		Total household production (n=329)		Household production used for consumption (n=328)	
	No. of hh[b] producing crop	*Median[a] (IQR)*	*% of hh[b] > 100%*	*Median[a] (IQR)*	*% of hh[b] > 100%*
Food level[c]					
Maize	311	134 (206)	62.0	111 (145)*	54.3*
Rice	132	0 (607)	37.7	0 (103)*	25.6 *
Sorghum	1	0 (28)	18.2	0 (6)*	15.5*
Cowpea	24	0 (0)	3.3	0 (0)*	1.8
Groundnut	220	125 (416)	54.1	34 (100)*	25.0*
Okro	24	0 (0)	0.3	0 (0)*	0.0^^
Food group level[c,d]					
Grains	318	150 (244)	61.4	96 (123)*	48.2*
Legumes	277	160 (291)	62.6	26 (71)*	17.7*
Beans	216	118 (344)	51.4	0 (31)*	11.9*
Nuts, seeds	220	103 (343)	50.2	28 (82)*	22.0*
Vegetables	25	0 (0)	0.3	0 (0)*	0.0^
All foods in monetary value[e]		138 (196)	63.8		

^Foods and food groups are defined as by Optifood and included if they are both recommended in the optimised diet and produced by households

*P <0.05, Wilcoxon signed rank sum test (continuous data) and McNemar Chi-square test (categorical data) comparing total household own production and household own production used for consumption, ^^McNemar Chi-square test was not computed because one of variable is constant for all cases

[a]Quantity crop produced/quantity crop needed*100; crop needs for children below 23 months are adjusted by subtracting the nutrient intakes from average breastmilk intakes

[b]hh = household

[c]Sorghum flour, maize flour, okro fruit raw and dried, onion bulb, jute leaves and kenaf leaves quantities needed are corrected for waste

[d]Grains produced include sorghum, maize, rice, and millet; legumes produced include Bambara groundnut, cowpea, pigeon pea, soybean (Glycine max) (food group: beans) and groundnut (Arachis hypogaea) (food group: nuts and seeds); vegetables produced include okro, tomatoes and cucumber

[e]Total food production of a household in Ghanaian Cedi's (potential farm income)/total value of foods needed in Ghanaian Cedi's (GHS)*100

Table 5. Coverage of foods and food groups from optimised diet of a household by their production

No. of foods/ groups covered[a]	Total household production (n=329)	Household production used for consumption (n=328)
	% of hh[b]	*% of hh*[b]
Food level		
0	9.4	23.2
1	31.0	41.2
2	39.2	25.0
3	15.2	9.1
4	5.2	0.9
5 – 6	0.0	0.0
Food group level		
0	17.6	44.8
1	40.7	44.5
2	41.3	10.7
3	0.3	0.0

[a]Number of foods and number of food groups covered (≥100%) by households
[b]Percentage of households that cover a specific total number of foods and food groups

Coverage of energy and nutrient needs of a household by their production

Overall 62% of the total quantity of micronutrients required by households was covered by their production. Less than 50% of the households covered their quantity of calcium, vitamin A, vitamin B_{12} and vitamin C required by their own food production (<70% of RNI). Overall 89% of total macronutrient requirements were covered by the production of a household, only fat was short (74%). Less than 50% of households covered the quantity of nutrients required by the household for most nutrients from their own production they indicated was consumed (Table 6).

Table 6. Coverage of energy and nutrients needs of a household by their production

	Total household production (n=329)		Household production used for consumption (n=328)	
% nutrient coverage[a]	*Median % (IQR)*	*% of hh[b] >70%*	*Median % (IQR)*	*% of hh[b] >70%*
Energy (kcal)	100 (40)	70.2	45 (51)*	**29.6***
Macronutrients				
Protein (g)	100 (0)	88.1	78 (55)*	57.6*
Fat (g)	74 (75)	51.7	23 (30)*	**11.6***
Carbohydrate (g)	100 (0)	88.1	100 (37)*	70.7*
Micronutrients				
Calcium (mg)	33 (55)	**24.3**	9 (12)*	**1.2***
Iron (mg)	80 (58)	56.5	35 (44)*	**20.4***
Zinc (mg)	100 (25)	78.4	52 (61)*	**36.6***
Vitamin A (µg)	0 (2)	**0.0**	0 (0)*	**0.0**^
Thiamine (mg)	100 (0)	90.9	100 (30)*	75.0*
Riboflavin (mg)	74 (60)	52.6	31 (41)*	**15.9***
Niacin (mg)	100 (17)	77.5	63 (67)*	**45.7***
Vitamin B_6 (mg)	100 (0)	87.5	89 (48)*	64.9*
Folate (µg)	89 (58)	59.3	26 (33)*	**13.1***
Vitamin B_{12} (µg)	0 (0)	**0.0**	0 (0)	**0.0**^
Vitamin C (mg)	0 (51)	**22.5**	0 (15)*	**4.0***
Overall				
Macronutrients[c]	89 (26)	81.8	65 (36)*	**43.3***
Micronutrients[d]	62 (26)	**34.0**	38 (30)*	**3.4***

*P <0.05, Wilcoxon signed rank sum test (continuous data) and McNemar Chi-square test (categorical data) comparing total household own production and household own production used for consumption, ^McNemar Chi-square test was not computed because one of variable is constant for all cases

Bold = values that are less than 50% of households covered 70% of RNI of a specific nutrient

[a]Quantity of nutrient produced/quantity nutrient needed*100; nutrient needs for children below 23 months are adjusted by subtracting the nutrient intakes from average breastmilk intakes; **v**alues at 100% cover the nutrient requirements per household per day (values higher than 100 percent are truncated to 100); compared with recommended nutrient intakes (RNI), except for energy (energy requirements), protein (safe level), fat (total fat in grams), carbohydrates (Recommended Daily Allowance) and vitamin A (mean requirements)

[b]hh = household

[c]Macronutrients covered = average coverage of all macronutrients (protein, fat and carbohydrates)

[d]Micronutrients covered = average coverage of all 11 key micronutrients (calcium, iron, zinc, vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12} and vitamin C)

The diversity of the production of households, the food and nutrient coverage of households and the children's dietary diversity and nutrient adequacy

The diversity of the production of households was positively related with their food and nutrient coverage as well as the food coverage of households with their nutrient coverage. An increase of 1 unit of the Shannon-Wiener index resulted in households having 173 GH₵ extra value of foods produced to cover their needs. As maize costs 2,40 per kg, this means a households is able to buy 72 kg of extra maize during a year and with an average household size of 14 members it can cover 14 gram extra maize of the 168 grams needed by 1 CU per day. The diversity of the production of households, and the food and nutrient coverage of households were not related to their children's dietary diversity and nutrient adequacy. Results were similar for the total production of households and their production used for home consumption except for the latter where crop count was positively related with children's IDDS (Table 7). Among the households that did not fully cover their food needs by their own production estimated in monetary value, we also tested whether having off-farm income was associated with better nutrient adequate diets for children. The households where the mother and/or head of household reported they earned income off-farm did not have children with more nutrient adequate diets than households who did not (IDDS of 3.3(1.8) versus 3.6(1.8) and MPA of 52.6(23.3) versus 50.0(20.5), both *P*-value >0.05).

Comparison of food group coverage at household, district and national level

The food groups grains, legumes and vegetables were included as these were included in the optimised diet. Grain needs were amply covered by the production of households or national food availability (accounting for imports, exports and waste) at household (150%), district (267%) and national level (148%). At household and district level legume needs were also amply covered by production (160% and 268%, respectively) but not at national level (52%). At all levels, vegetable needs were not covered by the production of households or national food availability: at household and district level vegetable coverage was only 0% and 2% and at national level 49% (Figure 3).

Table 7. Associations between the diversity of the production of households, the food and nutrient coverage of households and the children's diet (*n*=329), using linear mixed models.

	Household food coverage		Household nutrient coverage (RNI)		Children's diet	
	Food groups[a] (0-3)	All foods covered in GH₵[b] (%)	Micro-nutrients covered[c] (%)	Macro-nutrients covered[d] (%)	MPA[e] (%)	IDDS[f] (0-7)
			unstandardised Beta			
Total production of households (n=329)						
Production diversity						
Crop count[g]	0.1*	53.7*	6.4*	6.2*	0.00	0.02
Shannon-Wiener Index[h]	0.7*	172.9*	23.4*	26.4*	-0.05	-0.04
Food coverage						
Food groups covered[a] (0-3)			19.8*	22.6*	-0.01	-0.20*
All foods covered in GH₵[b] (%)			0.1	0.1	0.00	0.00
Nutrient coverage						
Micronutrients covered[c] (%)					0.00	0.00
Macronutrients covered[d] (%)					0.00	0.00
Production for home consumption of households (n=328)						
Production diversity						
Crop count[g]	0.1*		6.1*	7.7*	0.00	0.79*
Shannon-Wiener Index[h]	0.3*		18.5*	23.9*	-0.02	1.08
Food coverage						
Food groups covered[a] (0-3)			20.8*	28.5*	-0.03	-0.70
Nutrient coverage						
Micronutrients covered[c] (%)					0.00	-0.04
Macronutrients covered[d] (%)					0.00	-0.05

*P<0.05. Corrected for: household size, age household head and wife of household head, education household head and wife of household head, total household cropped area, household market distance, total value of household assets and random effect of location (nested within main independent fixed factor of specific model); for count dependent variable Food group Poisson regression was modelled, for IDDS a quasi-binomial regression

[a]Food groups covered = total number of food groups in a household that quantity needed is covered by household own production (grains, legumes and/or vegetables)

[b]All foods covered=total own production in GH₵ (potential farm income)/total value of foods needed in GH₵*100

[c]Micronutrients covered = average coverage of all 11 key micronutrients (calcium, iron, zinc, vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12} and vitamin C)

[d]Macronutrients covered = average coverage of all macronutrients (protein, fat and carbohydrates)

[e]MPA=Mean Probability of Adequacy: summary measure of nutrient adequacy based on probability of adequacy for calcium, iron, zinc, vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12} and vitamin C based on their respective estimated average requirements (EAR) and distributions. Only for children 12-23 months old

[f]Individual dietary diversity score (IDDS) is computed by sum of seven food groups being consumed: 1. Grains, roots and tubers, 2. Legumes, nuts and seeds, 3. Dairy products, 4. Flesh foods, 5. Eggs, 6. Vitamin A rich fruits and vegetables and 7. Other fruits and vegetables (WHO et al. 2007)

[g]Crop count = the sum of the total number of different crops cultivated in a household during the previous year

[h]Shannon-Wiener Index = combines richness (number of crops) and evenness (distribution of quantity of production of different crops)

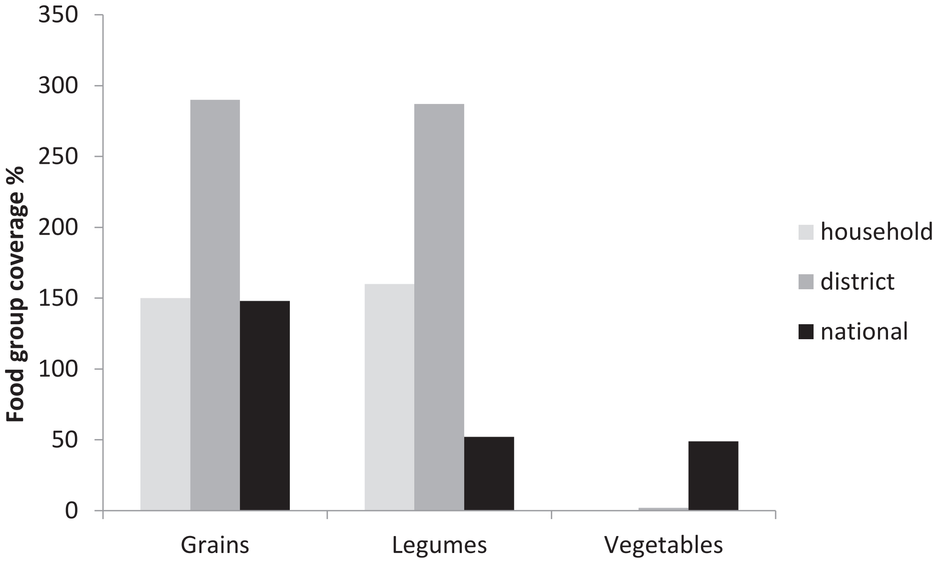

Figure 3. Coverage food groups at household, district and national level. Values at household level are in median (IQR); values at district level are mean (SD) based on household means from study population representing district coverage potential; and values at national level are percentages coverage (kg national food availability per capita/recommended food per capita (South African food-based dietary guidelines)*100). The grains food group at the national level also includes starchy roots (the South African guidelines does not include separate recommendations) which was not included at household and district level.

Discussion

The availability of recommended foods is a key condition for the adoption of food based dietary guidelines (FBDGs). We found that the production of households only partly covered the quantity and diversity of foods recommended by FBDGs and the nutrients required for all household members. Whereas the diversity of the production of households was positively associated with their food and nutrient coverage, there was no relationship with their child's dietary diversity and nutrient adequacy.

Scope of the study

Before discussing the results in detail, it is important to consider the scope of our study. First, although we sampled all non-breastfed children of 12-23 months in the district, our

FBDGs are modelled based on dietary intake data from a relatively small sample size of 31 children as the vast majority of children of this age were breastfed. As we do not have dietary intake data from other household members (non- breastfed), the FBGDs from the non-breastfed children of 12-23 months were used to estimate optimised food needs for all household members. Dietary patterns may differ between young children and adults: in Ghana not all foods consumed by mothers were also given to young children (Amugsi et al. 2015). In addition, out of home consumption is probably more common among older household members (Lachat et al. 2012), indicating that we might overestimate the reliance on own production. Therefore we probably underestimate the variety of foods consumed by households and our results reflect a worst-case scenario. However, in general the diets of children older than one year are integrated into family diets in our study location (Armar-Klemesu et al. 2016) suggesting that the diets of young children are similar to that of adults. The possibility remains that households to which the non-breastfed 12-23 months old children belong may differ from other households with 12-23 months olds in the district as only few households had children in this age group who were not breastfed. However, we found no differences in household characteristics such as education, occupation and household size. In addition, the age of children in the non-breastfed group is higher compared to breastfed children in the same age group (mean of 21 months versus 17 months). The recent Ghanaian Demographic Health Survey also found a decrease in breastfed children with 91% of children being breastfed at age 12-17 months while 50% at age 20-23 months old (Ghana Statistical Service et al. 2015). This suggests that towards the age of two, less children are being breastfed in the study location and not that households necessarily differ in their beliefs and practices of feeding their younger children. Second, we used consumer units to translate the food needs according to the FBDGs for non-breastfed children of 12-23 months to the food needs of other household members. The consumer units were based on the average of estimated average requirements (EARs) of 11 key micronutrients relative to the EARS of women of reproductive age. However, individual nutrient needs differ for groups according to age, sex and physiological state. For example, pregnant women have a greater need of iron. However, when translating the optimised food needs of non-breastfed children of 12-23 months to food needs at household level, on average similar nutrients were below 70% of RNI (S4 Table). Third, dietary intake data was collected during one period of the year and cannot necessarily be extrapolated to other periods. Data was collected at the start of the rainy season (July 2014), also referred to as the 'hunger season' as this is the period of longest time from the previous harvest when crops are in the field but not yet producing food. The timing of the study was specifically chosen to coincide with the period of greatest food deficits. This may affect both children's dietary intake data and food price data. Most children in our study did not consume fruits and only little vegetables. Seasonal variations in consumption of fruits, legumes, roots and plantains was reported among preschool children in Ghana and Malawi (Ferguson et al. 1993). A recent study also found differences in dietary diversity among school children between the dry and rainy season in Northern Ghana, especially less vitamin A-rich fruits and vegetables were consumed during the dry season (Abizari et al. 2017). Conducting the study later in the rainy season could have resulted in larger fruit and more vegetable intakes, and therefore in FBDGs that better cover vitamin A and vitamin C requirements but also result in larger nutrient and food gaps. Food prices also tend to fluctuate during the year with prices depressed around harvest and highest prices during the 'hunger season'. Due to urgent cash needs farmers tend to sell their surplus harvest and then end up buying food to cover the shortfall of foods at a time when prices are high (Poulton et al. 2006). Therefore the total monetary value of households own food production might be overestimated while the cost of food needs is probably not. When comparing monetary value of households own food production and monetary value of foods needs we might overestimate the coverage of households food needs by household own food production. Ideally, we should have collected dietary intake and food price data at least during two seasons, both hunger and harvest season. Fourth, our results depend on the quality of dietary recall data, the food composition data, assumed bioavailability of nutrients and RNI used. We used a multiple-pass procedure (Gibson and Ferguson 2008) to minimize bias in our dietary intake data. For collecting data on the production of households of the previous year, we also used a recall-based approach prone to systematic recall bias of foods and quantities of foods produced as well. Consumption of fruits and vegetables is often underestimated, especially of fruits that are mainly consumed as a snack (Gibson et al. 2017; Gewa et al. 2009), and fruits and vegetables are mostly cultivated in small quantities and often underreported. In addition, we did not include data on livestock that may also be available in the household and may have underestimated food diversity and especially the farm income of households as small-scale livestock rearing serves mostly as safety net to quickly access cash for emergency (medical) or planned expenditures (school fees) in Northern Ghana (Roelen 2017). However, as these are mostly non-food expenditures, not including livestock will probably not have a major effect on our estimation of diversity of foods available in the household. Besides, the effect on our estimated nutrient gaps will also be limited as the consumption of animal sourced foods was extremely low in our study location.

Current diets and FBDGs

We found that 40% of rural Northern Ghanaian infants and young children were stunted and their nutrient intakes were far below the required quantities: the probability of adequacy for most nutrient intakes was below 50%. This confirms the low quality diet and the need for FBDGs. Yet the FBDGs developed for non-breastfed children of 12-23 months using Optifood were unable to cover their calcium, vitamin A, vitamin B_{12} and vitamin C requirements. Their diet contained little if any animal-sourced foods (resulting in low calcium, vitamin A and vitamin B_{12} intakes), nor fresh fruits and vegetables (resulting in low vitamin A and vitamin C intakes) (WHO and FAO 2006), as is typical for average diets of LIMC populations (Keats and Wiggins 2014). A similar dietary pattern was also found among school age children in Northern Ghana (Abizari et al. 2017), as well as probabilities of adequacy of 0% for calcium, vitamin A, vitamin B_{12} and vitamin C intake among schoolchildren not receiving school feeding (Abizari et al. 2014). In line with our results, only 56% of children of 6-59 months consumed vitamin A rich foods in Northern Ghana (Ghana Statistical Service et al. 2015) and 75.8% of children under 5 years were deficient in vitamin A (WHO 2009a). Calcium, vitamin B_{12} and vitamin C are often neglected as key micronutrients due to the lack of strong evidence of direct associations of deficiencies with adverse health outcomes (WHO and FAO 2006). The addition of vitamin C to a meal enhances the absorption of non-haem iron and therefore a low vitamin C intake may exacerbate iron deficiency, especially when diets contain few animal-sourced foods. In Ghana, 82.1% of children of 6-59 months in Northern Ghana are anaemic (haemoglobin $<$ 110 g/L) and one of the most common causes in Ghana is inadequate dietary intake of iron (Ghana Statistical Service et al. 2015). However, surprisingly, the optimised diet was able to cover iron and also zinc intakes for non-breastfed children of 12-23 months (not for children of 6-8 months, 9-11 months and 12-23 months receiving breastmilk), often identified as being difficult to cover for young children (K. G. Dewey and K. H. Brown 2003). Maize and cowpea mostly contributed to both iron and zinc intakes, and green leafy vegetables to iron intake and brown rice to zinc intake. Overall in Ghana, the prevalence of anaemia decreases with increasing age of children although is still prevalent among older children (Ghana Statistical Service et al. 2015). As zinc deficiency is associated with stunting (Kvestad et al. 2017), and stunting levels are high among our study population, and often multiple micronutrient deficiencies coexist, it is likely that zinc deficiency is also common among children in Ghana (Adu-Afarwuah et al. 2008).

Nutrient and food gaps

The FBDGs developed in our study were based on extremes of the distribution of the types of foods consumed and on frequencies to arrive at FBDGs that cover most of the nutrient needs of our target group. Therefore, barriers in the food environment to adopt our FBDGs, such as lack of food accessibility, desirability and availability in households may exist. This was indicated by the high prevalence of iron and probably of zinc deficiency in Ghana despite the ability of the FBDGs to cover iron and zinc needs. Also, we found that for more than half of the households their own food production could allow to cover most of their micronutrient needs except for calcium, vitamin A, vitamin B12 and vitamin C. For other micronutrients not all households covered their needs, for example 43.5% of households were unable to cover their iron needs and 31.6% their zinc needs with their own production. This suggests that foods rich in specific nutrients have to be acquired through market, and in case of low (farm and off-farm) income, this may limit the intake of these nutrients and in turn limit the adoption of FBDGs. For successful adoption of these FBDGs, sufficient quantities of the recommended foods need to be available. About 60% of households produced sufficient grains and legumes themselves to cover their own needs. At district level both grain and legume production exceeded the requirements of the population within the district, yet this does not necessarily mean that FBDGs can be adopted by all households. To attain an adequate distribution of the grains and legumes produced to cover the needs of all individual households, regional and district markets need to function well and the farm income of households should be sufficient. The majority of households (97.5%) in our study population accessed local markets although their investment costs and time to do so varied. Unfortunately, we have no specific information on the quantity and diversity of foods available on these local markets. Maize (the main grain produced locally) is mostly grown for consumption, groundnuts and cowpea are partly grown for consumption and partly for sale, while soybean is mainly grown for sale and rarely consumed (Dogbe et al. 2013). Although total legume production exceeds the district's needs, there may be insufficient legumes available for purchase from local markets. A proportion of cowpea and groundnut is traded (half of households grow groundnuts for both home consumption and cash in Northern region (Adzawla et al. 2016)) through the main regional market in Tamale whereas all of the soybean is exported from the region to meet the national demand for livestock feed. In addition, B. Dillon and Barrett (2017) found that generally sub-Saharan Africa has imperfect markets. Thus although production exceeds the district's needs, legume crops might insufficiently be available for purchase from local markets since legumes are partly treated as cash crops. Nevertheless, the sale of the produce of households will contribute to their ability to buy foods that are available on the market. For 36.2% of households their overall farm income, measured as the total monetary value of their own crop production, was insufficient to cover the costs of their food needs. However, in 35% of these households either the household head or the mother or both had their main source of income off-farm that may be used to buy food to cover their needs. Yet this was not the case for the remaining 65% of these households. This suggests that overall about 20% of all households were unable to cover their food needs as they did not produce enough food and also lack other off-farm income sources. However, we have no information on the actual level of total off-farm income of households, as well as on other sources of food such as gifts, in kind, livestock and/or wild foods. Generally smallholder farmers in sub-Saharan Africa have other activities besides crop production, especially better-off smallholders achieve successful livelihood diversification (Alobo Loison 2015). Nevertheless, as for most rural households in Northern Ghana farm income is still the main source of income (Franke and de Wolf 2011), our results suggest that for more than half of the households their own food production is sufficient to cover their food needs. However, besides assuming well-functioning markets, this also assumes that all available income would be used to purchase the quantities and diversity needed to fulfil the dietary needs of households, an assumption that most likely rarely holds (Herforth and Ahmed 2015; Jones 2017). At national level, grain production currently exceeds food needs but legume production does not. A recent analysis showed opposite results for grains but needs were compared with own production only and did not include, for example, rice imports (van Ittersum et al. 2016). Vegetables needs were not covered at household, district and national level. Together with fruits, there is often a shortage of vegetables in LMICs (Keats and Wiggins 2014; Siegel et al. 2014). Further, compared with commodity crops like cereals, oilseeds and livestock, investment in agricultural research on vegetables in developing countries is limited (World Bank 2014). The restricted availability of vegetables limits adoption of FBDGs.

Diversifying crop production

Overall our study results show that the production of households partly supports the adoption of FBDGs in rural Northern Ghana. Diversifying crop production is often mentioned as a potential solution for increasing the diversity of foods available and thereby increasing dietary diversity of rural LIMC populations. Two recent reviews, of studies mostly conducted in sub-Saharan Africa suggests that agricultural biodiversity has a consistent association with more diverse diets at household and individual level (Jones 2017; Sibhatu and Qaim

2018). However, the magnitude of the association is very small – African farms need to produce some nine additional species to increase dietary diversity by one food group (Sibhatu and Qaim 2018) – and is stronger when current cropping system are less diverse(Jones 2017; Sibhatu and Qaim 2018). We found that the diversity of the production of households was positively associated with their food and nutrient coverage but not with the quality of their children's diet. To our knowledge, ours is the first study that included intermediate indicators such as the food and nutrient coverage of households: most other studies did not include validated IDDS for children 6 to 23 months old and/or quantitative dietary intake data (mean probability of adequacy). Our results suggest that increased diversity of the production of households does improve food and nutrient availability that may potentially cover the needs of the household. Farms with low crop biodiversity, as in our study are where households on average produce only four different crops, are associated with larger increases in dietary diversity when production is diversified than farms with already high crop biodiversity (Jones 2017). Nevertheless, we found no association with children's diet, both their dietary diversity and the mean probability of nutrient adequacy of their diet. In the case of children's dietary diversity this may be partly due to the fact that each food produced will add to households crop diversity regardless if they belong to the same food group while this is not the case if more foods from the same food group are consumed by children (Peter R. Berti 2015). But we also do not find an association for the food and nutrient coverage of households with their children's diet and for crop diversity with nutrient adequacy of their children's diet. Overall these results are in line with what Sibhatu and Qaim (2018) concluded from their quantitative meta-analysis, there is little evidence that increasing farm production diversity is a direct and effective strategy to improve smallholder diets and nutrition. They argue that further increasing production diversity in subsistence-oriented settings may maintain subsistence and reduce market opportunities. Therefore diversity at district scale may be more important in making sure that affordable diverse foods are available at local markets. This way rural households do not need to diversify their own production which may entail income losses through foregone gains from specialization (Sibhatu and Qaim 2018). Ecker (2017) also concludes that in Ghana, where most regions undergo economic transformation, policies and programmes that support rural income growth may be more effective in improving dietary quality than those that promote farm production diversification. However, this depends on how income is spent. Another study conducted in the same location shows no improvements via the income pathway on children's nutrition outcomes (Ilse de Jager et al. 2017). The role of markets need to be analysed in greater detail while studying the relation of farm production diversity and improving diets of rural LIMC populations.

Implications and conclusion

Our study has several implications for future strategies to enhance rural diets and for research. First, as our FBDGs already show that with the existing local crops and the habitual dietary intakes certain nutrient requirements cannot be fulfilled, alternative options need to be considered. A recent study evaluating the implementation of FBDGs in Indonesia also shows that other strategies are needed to improve nutrient adequacy of vulnerable groups in addition to the adoption of FBDGs (Hlaing et al. 2016). For example, strategies to enhance the productivity, production and/or consumption of foods rich in the nutrients that are in short supply (calcium, vitamin A, vitamin B_{12} and vitamin C) such as (dark green leafy) vegetables, beans, fruits and animal source foods. A recent randomized controlled trial in Burkina Faso showed that a homestead food production programme combined with a behaviour change communication programme significantly improved several child outcomes (Olney et al. 2015). Nutrition-specific interventions like food fortification or supplementation are additional effective strategies to increase intake of these nutrients. As such, the national vitamin A supplementation program can significantly contribute to closing the Vitamin A gap, but coverage must be improved as only 44% of children of 6-59 months in Northern region in Ghana received supplementation (Ghana Statistical Service et al. 2015).

Second, as we found that their own food production was not able to cover the food needs of many households, interventions are needed to increase the availability and/or accessibility of especially vegetables for all households and of grains and legumes for some households. Interventions increasing the production and/or improving productivity of these crops are needed in addition to interventions to promote the adoption of FBDGs. Besides production-oriented interventions, interventions that improve market accessibility of these foods may also be effective in covering the identified food gaps, assuming that households obtain sufficient farm and/or off-farm income to buy the quantity and diversity of foods needed and they are willing to spend their income as recommended. We found that most households sell part of their production, decreasing the food coverage at household level but increasing their farm income and potential food purchasing power. Therefore the availability of diverse foods at local markets, such as stimulation of vegetable production for local markets, may contribute to covering household food needs. However, market interventions are not easily implemented in remote settings and household production interventions may have higher short-term potential impact (Remans et al. 2015; Luckett et al. 2015).

Our results show that although local FBDGs are based on actual dietary patterns and costs, the quantity and diversity of the production of households can limit their ability to adopt the FBDGs. Therefore, the promotion of food-based dietary guidelines through nutrition education or behavioural change communications activities alone is not enough to lead to improvements in diets. Additional strategies are required such as agricultural- and market-based strategies in combination with nutrition specific interventions such as food fortification and home fortification**.** These offer opportunities to further facilitate adoption of recommendations and provide additional support to improve diets of vulnerable populations.

References

Abizari, A.-R., Azupogo, F., Nagasu, M., Creemers, N., & Brouwer, I. D. (2017). Seasonality affects dietary diversity of school-age children in northern Ghana. *PLoS One, 12*(8), e0183206.

Abizari, A.-R., Buxton, C., Kwara, L., Mensah-Homiah, J., Armar-Klemesu, M., & Brouwer, I. D. (2014). School feeding contributes to micronutrient adequacy of Ghanaian schoolchildren. *British Journal of Nutrition, 112*(6), 1019-1033.

Adu-Afarwuah, S., Lartey, A., Brown, K. H., Zlotkin, S., Briend, A., & Dewey, K. G. (2008). Home fortification of complementary foods with micronutrient supplements is well accepted and has positive effects on infant iron status in Ghana. *The American Journal of Clinical Nutrition, 87*(4), 929-938.

Adzawla, W., Donkoh, S. A., Nyarko, G., O'Reilly, P. J., Olayide, O. E., Mayes, S., Feldman, A., & Azman, H. R. (2016). Adoption of Bambara groundnut production and its effects on farmers' welfare in Northern Ghana. *African Journal of Agricultural Research, 11*(7), 583-594.

Alobo Loison, S. (2015). Rural livelihood diversification in sub-Saharan Africa: a literature review. *The Journal of Development Studies, 51*(9), 1125-1138.

Amugsi, D. A., Mittelmark, M. B., & Oduro, A. (2015). Association between maternal and child dietary diversity: an analysis of the ghana demographic and health survey. *PLoS One, 10*(8), e0136748.

Arimond, M., & Ruel, M. T. (2004). Dietary diversity is associated with child nutritional status: evidence from 11 demographic and health surveys. *The Journal of Nutrition, 134*, 2579-2585.

Armar-Klemesu, M., Zakariah-Akoto, S., & Osei-Menya, S. (2016). Feeding infants and young children in Karaga district, Northern region: A focused ethnographic study. Washington D.C., US: GAIN and USAID.

Barikmo, I., Ouattara, F., & Oshaug, A. (2004). Food composition table for Mali. TACAM, research series N 9. Oslo, Norway: Akershus University College.

Berti, P. R. (2015). Relationship between production diversity and dietary diversity depends on how number of foods is counted. *Proceedings of the National Academy of Sciences, 112*(42), E5656.

Brown, K. H., Dewey, K. G., & Allen, L. (1998). Complementary feeding of young children in developing countries: a review of current scientific knowledge.

Brown, K. H., Rivera, J. A., Bhutta, Z., Gibson, R. S., King, J. C., Lönnerdal, B., Ruel, M. T., Sandtröm, B., Wasantwisut, E., & Hotz, C. (2004). International Zinc Nutrition Consultative Group (IZiNCG) technical document #1. Assessment of the risk of zinc deficiency in populations and options for its control. *Food Nutr Bull, 25*, S99-203.

Cogill, B. (2003). Anthropometric indicators measurement guide. Washington DC, USA: Food and Nutrition Technical Assistance (FANTA) Project, FHI 360.

de Jager, I., Abizari, A.-R., Douma, J. C., Giller, K. E., & Brouwer, I. D. (2017). Grain legume cultivation and children's dietary diversity in smallholder farming households in rural Ghana and Kenya. *Food Security, 9*(5), 1053-1071.

de Jager, I., Borgonjen-van den Berg, K., Giller, K. E., & Brouwer, I. D. (submitted). Current and potential role of grain legumes on nutrient adequacy of the diet of Ghanaian infants and young children.

Dewey, K. G., & Brown, K. H. (2003). Update on technical issues concerning complementary feeding of young children in developing countries and implications for intervention programs. *Food Nutr Bull, 24*(1), 5-28.

Dillon, A., McGee, K., & Oseni, G. (2015). Agricultural production, dietary diversity, and climate Variability. *The Journal of Development Studies, 51*(8), 976-995.

Dillon, B., & Barrett, C. B. (2017). Agricultural factor markets in Sub-Saharan Africa: An updated view with formal tests for market failure. *Food Policy, 67*, 64-77.

Dogbe, W., Etwire, P. M., Martey, E., Etwire, J. C., Baba, I. I. Y., & Siise, A. (2013). Economics of soybean production: evidence from Saboba and Chereponi districts of Northern region of Ghana. *Journal of Agricultural Science, 5*(12).

Du, L., Pinga, V., Klein, A., & Danton, H. (2015). Leveraging agriculture for nutrition impact through the Feed the Future initiative. *Adv Food Nutr Res, 74*, 1-46.

Ecker, O. Economic transformation and diets in rural Ghana: does farm production diversity (still) matter? In O. Ecker (Ed.), *Third Global Food Symposium, April 28-29, University of Goettingen, Germany, 2017*

Eyeson, K. K., & Ankrah, E. K. (1975). Composition of foods commonly used in Ghana. *Accra, Ghana: Food Research Institute, Council for Scientific and Industrial Research*.

FAO (2010). Guidelines for measuring household and individual dietary diversity. Rome, Italy: FAO.

FAO (2012). West african food composition table. Rome, Italy: FAO.

FAO (2013). FAOSTAT: Food balance sheet. Rome, Italy: FAO.

FAO (2017). Food-based dietary guidelines. Accessed May 2018.

FAO, WHO, & UNU (2004). Human energy requirements. Report of a joint FAO/WHO/UNU expert consultation (FAO food and nutrition technical report series, no. 1). *Rome: Food and Agriculture Organization.*

Ferguson, Gibson, R. S., Opare-Obisaw, C., Osei-Opare, F., Lamba, C., & Ounpuu, S. (1993). Seasonal food consumption patterns and dietary diversity of rural preschool Ghanaian and Malawian children. *Ecology of Food and Nutrition, 29*(3), 219-234.

Ferguson, E. L., Darmon, N., Briend, A., & Premachandra, I. M. (2004). Food-based dietary guidelines can be developed and tested using linear programming analysis. *The Journal of Nutrition, 134*(4), 951-957.

Franke, A. C., & de Wolf, J. J. (2011). *N2Africa baseline report*.

Franke, A. C., Rufino, M. C., & Farrow, A. (2011). Characterisation of the impact zones and mandate areas in the N2Africa project. Wageningen, The Netherlands: N2Africa.

Gewa, C. A., Murphy, S. P., & Neumann, C. G. (2009). A comparison of weighed and recalled intakes for schoolchildren and mothers in rural Kenya. *Public Health Nutrition, 12*(8), 1197-1204.

Ghana Statistical Service, Ghana Health Service, & ICF International (2015). Ghana demograhic and health survey 2014. Rockville, USA: GSS, GHS and ICF International.

Gibson, R. S., Charrondiere, U. R., & Bell, W. (2017). Measurement errors in dietary assessment using self-reported 24-hour recalls in low-income countries and strategies for their prevention. *Advances in Nutrition: An International Review Journal, 8*(6), 980-991.

Gibson, R. S., & Ferguson, E. L. (2008). An interactive 24-hour recall for assessing the adequacy of iron and zinc intakes in developing countries. *HarvestPlus Technical Monograph 8*. Washington DC, USA & Cali, Colombia: IFPRI & CIAT.

Global Burden of Disease Study (2015). Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet, 386*(10010), 2287-2323.

GLOPAN (2016). Food systems and diets: facing the challenges of the 21st century. London, UK.

Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security, 7*(3), 505-520.

Hlaing, L. M., Fahmida, U., Htet, M. K., Utomo, B., Firmansyah, A., & Ferguson, E. L. (2016). Local food-based complementary feeding recommendations developed by the linear programming approach to improve the intake of problem nutrients among 12–23-month-old Myanmar children. *British Journal of Nutrition, 116*(S1), S16-S26.

Institute of Medicine (2000). Dietary reference intakes: application in dietary assessment. Subcommittee on interpretation and uses of dietary reference intakes and the standing committee on the scientific evaluation of dietary reference intakes. (pp. 215-227). Washington, D. C. : National Academic Press.

IOM (2001). Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium and zinc. *Dietary Reference Intakes. Washington, D.C: Food and Nutrition Board, Institute of Medicine*.

Jones, A. D. (2017). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. *Nutrition Reviews*.

Jones, A. D., Shrinivas, A., & Bezner-Kerr, R. (2014). Farm production diversity is associated with greater household dietary diversity in Malawi: Findings from nationally representative data. *Food Policy, 46*, 1-12.

Keats, S., & Wiggins, S. (2014). Future diets: implications for agriculture and food prices. London, UK: ODI.

Kujinga, P., Borgonjen-van den Berg, K. J., Superchi, C., Ten Hove, H. J., Onyango, E. O., Andang'o, P., Galetti, V., Zimmerman, M. B., Moretti, D., & Brouwer, I. D. (2018). Combining food-based dietary recommendations using Optifood with zinc-fortified water potentially improves nutrient adequacy among 4- to 6-year-old children in Kisumu West district, Kenya. *Maternal & Child Nutrition, 14*(2), e12515.

Kvestad, I., Hysing, M., Shrestha, M., Ulak, M., Thorne-Lyman, A. L., Henjum, S., Ueland, P. M., Midttun, O., Fawzi, W., Chandyo, R. K., Shrestha, P. S., & Strand, T. A. (2017). Vitamin B-12 status in infancy is positively associated with development and cognitive functioning 5 y later in Nepalese children. *American journal of Clinical Nutrition 105*(5), 1122-1131.

Lachat, C., Nago, E., Verstraeten, R., Roberfroid, D., Van Camp, J., & Kolsteren, P. (2012). Eating out of home and its association with dietary intake: a systematic review of the evidence. *Obes Rev, 13*(4), 329-346.

Leahy, T. (2018). Why have food security projects failed in rural Africa? In U. o. Auckland (Ed.). Auckland: Project for Media in the Public Interest (PMPI).

Luckett, B. G., DeClerck, F. A., Fanzo, J., Mundorf, A. R., & Rose, D. (2015). Application of the nutrition functional diversity indicator to assess food system contributions to dietary diversity and sustainable diets of Malawian households. *Public Health Nutrition, 18*(13), 2479-2487.

Mayén, A.-L., Marques-Vidal, P., Paccaud, F., Bovet, P., & Stringhini, S. (2014). Socioeconomic determinants of dietary patterns in low- and middle-income countries: a systematic review. *The American Journal of Clinical Nutrition, 100*(6), 1520-1531.

Muthayya, S., Rah, J. H., Sugimoto, J. D., Roos, F. F., Kraemer, K., & Black, R. E. (2013). The global hidden hunger indices and maps: an advocacy tool for action. *PLoS One, 8*(6), e67860.

National Research Council (1986). *Nutrient Adequacy: Assessment Using Food Consumption Surveys. Reports of the sub-committee on interpretation and uses of dietary reference intakes and the standing committee on the scientific evaluation of dietary reference intakes* Washington D. C.: National Academy Press.

Olney, D. K., Pedehombga, A., Ruel, M. T., & Dillon, A. (2015). A 2-year integrated agriculture and nutrition and health behavior change communication program targeted to women in Burkina Faso reduces anemia, wasting, and diarrhea in children 3–12 months of age at baseline: a cluster-randomized controlled trial. *The Journal of Nutrition, 145*(6), 1317-1324.

Pinstrup-Andersen, P. (2012). The food system and its interaction with human health and nutrition. In *Reshaping agriculture for nutrition and health: an IFPRI 2020 book* (pp. 21-29). Washington DC, USA: IFPRI.

Poulton, C., Kydd, J., & Dorward, A. (2006). Overcoming market constraints on pro-poor agricultural growth in sub-Saharan Africa. *Development Policy Review, 24*(3), 243-277.

Remans, R., DeClerck, F. A. J., Kennedy, G., & Fanzo, J. (2015). Expanding the view on the production and dietary diversity link: Scale, function, and change over time. *Proceedings of the National Academy of Sciences of the US, 112*(45), E6082-E6082.
Remans, R., Flynn, D. F. B., DeClerck, F., Diru, W., Fanzo, J., Gaynor, K., Lambrecht, I., Mudiope, J., Mutuo, P. K., Nkhoma, P., Siriri, D., Sullivan, C., & Palm, C. A. (2011). Assessing nutritional diversity of cropping systems in African villages. *PLoS One, 6*, e21235.
Roelen, S. (2017). Exploring the current status of ruminant value chains in northern Ghana, and the role of grain legume residues as a livestock feed resource. MSc Thesis. Wageningen: Wageningen University.
Santika, O., Fahmida, U., & Ferguson, E. L. (2009). Development of food-based complementary feeding recommendations for 9- to 11-month-old peri-urban Indonesian infants using linear programming. *The Journal of Nutrition, 139*, 135-141.
Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences, 112*(34), 10657-10662.
Sibhatu, K. T., & Qaim, M. (2018). Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy*.
Siegel, K. R., Ali, M. K., Srinivasiah, A., Nugent, R. A., & Narayan, K. M. V. (2014). Do we produce enough fruits and vegetables to meet global health need? *PLoS One, 9*(8), e104059.
Talsma, E. F., Borgonjen-van den Berg, K. J., Melse-Boonstra, A., Mayer, E. V., Verhoef, H., Demir, A. Y., Ferguson, E. L., Kok, F. J., & Brouwer, I. D. (2017). The potential contribution of yellow cassava to dietary nutrient adequacy of primary-school children in Eastern Kenya; the use of linear programming. *Public Health Nutrition*, 1-12.
UNICEF, WHO, & World Bank Group (2015). Levels and trends in child malnutrition. USA: UNICEF, WHO & World Bank Group.
USDA (2016). USDA national nutrient database for standard reference, Release 28. http://www.ars.usda.gov/nea/bhnrc/ndl. Accessed February 2018.
van 't Erve, I., Tulen, C. B. M., Jansen, J., van Laar, A. D. E., Minnema, R., Schenk, P. R., Wolvers, D., Rossum, C. T. M. v., & Verhagen, H. (2017). Overview of elements within national food-based dietary guidelines. *European Journal of Nutrition & Food Safety, 7*(1), 1 - 56.
van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P. A. J., van Loon, M. P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J. H. J. R., Ouattara, K., Tesfaye, K., & Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences, 113*(52), 14964-14969.
Vorster, H. H., Badham, J. B., & Venter, C. S. (2013). An introduction to the revised food-based dietary guidelines for South Africa. *S Afr J Clin Nutr, 26*(3), 1 - 164.
Vossenaar, M., Knight, F. A., Tumilowicz, A., Hotz, C., Chege, P., & Ferguson, E. L. (2017). Context-specific complementary feeding recommendations developed using Optifood could improve the diets of breast-fed infants and young children from diverse livelihood groups in northern Kenya. *Public Health Nutrition, 20*(6), 971-983.
WHO (2009). Global prevalence of vitamin A deficiency in populations at risk 1995 - 2005: WHO global database on vitamin A deficiency. Geneva: WHO.
WHO, & FAO (2004). Vitamin and mineral requirements in human nutrition. Second edition. *Geneva/Rome: WHO/FAO*.
WHO, & FAO (2006). *Guidelines on food fortification with micronutrients*. Geneva: WHO Press.
WHO, & UNICEF (2003). Global strategy for infant and young child feeding. Geneva: WHO.

WHO, UNICEF, USAID, AED, UCDAVIS, & IFPRI (2007). Indicators for assessing infant and young child feeding practices. Conclusions of a consensus meeting held 6–8 November 2007 in Washington DC, USA. Geneva, Switzerland: WHO.
WHO Multicentre Growth Reference Study Group (2006). *WHO Child Growth Standards: Length/height-for-age, weight-for-age, weight-for-length, weight-for-height and body mass index-for-age: Methods and developments*. Geneva, Switzerland: World Health Organization.
World Bank (2014). Learning from World Bank history: agriculture and food-based approaches to address malnutrition. (Vol. Agricultural and Environmental Sciences Discussion). Washington, D.C. : World Bank.

Appendices

Appendix 1

Details on data collection and analysis

Children's nutritional status

Weight was measured with an electronic scale to the nearest 0.1 kg (UNIscale: Seca GmbH, Hamburg, Germany). Length was measured with a UNICEF wooden three piece measuring board with a sliding foot piece and with a precision of 0.1 cm. Children were measured lying down. Both length and weight were measured twice for each child and the average of the two measurements was taken. Scales were calibrated with a standard weight at the start of each day of data collection. Age was calculated using the date of birth from verifiable documents (health record, weighing card, birth certificate) or estimated based on traditional calendar.

Food composition table

Where appropriate, yield (FAO 2012) and nutrient retention factors (USDA 2016; Vásquez-Caicedo et al. 2008) were applied to account for nutrient losses during cooking. The Atwater general factors for carbohydrate, protein and fat and the recommended metabolizable energy for dietary fibre in ordinary diets (2 kcal or 8.4 kJ/g) are used in calculating energy (FAO 2003). Total vitamin A (RAE) was calculated as the sum of retinol and 1/12 β-carotene (FAO 2012).

Children's dietary intake

Primary caretakers were asked to recall all the foods and drinks consumed in and outside the home by their child during the preceding day and to describe ingredients and cooking methods of any mixed dishes. Duplicate amounts of all foods and ingredients of mixed dishes consumed were weighed to the nearest 2g using Soehnle electronic kitchen scale (Plateau Art 65086, Germany). Scales were randomly assigned to the interviewers and calibrated with a known weight each day. When duplicates were not available in the household, amounts were estimated (in order of priority) as their monetary value equivalents, in weight-to-weight estimates with other foods (e.g. amount of sugar estimated with weight of same volume of corn flour), in volumes, as their general sizes (small, medium or large) using pictures or in household units. The total volume of each (mixed) dish cooked at the respondents' household and the volume of this dish specifically consumed by the child were measured to determine the proportion of the dish consumed by the child. This proportion was multiplied by the total amount of ingredients used in the preparation of the dish to determine the amount of ingredients consumed by the child. Standard recipes were generated to estimate the grams of ingredients consumed from mixed dishes eaten outside the home by averaging three recipes of different vendors in the local area. Conversion factors were developed to convert monetary values, weight-to-weight measures, volumes, sizes and household units to their gram weight equivalents.

Children's nutrient adequacy: Except for iron, the probability of adequacy (PA) of each nutrient was calculated based on their respective estimated average requirements (EARs) and distributions (WHO and FAO 2004, 2006) (S1 Table). The following formula was used in SPSS: PA=PROBNORM [(adjusted individual intake-EAR)/SD], where the PROBNORM function clarifies whether the probability of the individual intake is above the EAR. For iron, probability of adequacy values from Institute of Medicine (IOM 2001) were used as the distribution of iron requirement is skewed (Appendix 3).

Optimised diet for non-breastfed children of 12-23 months: The Optifood analysis comprises of four steps (Ferguson et al. 2006; Daelmans et al. 2013) but for this study we only ran the first two steps: (1) to check that model parameters ensure realistic diets; and (2) to identify two realistic diets that meet or come as close as possible to meeting nutrient needs of the target population. One of the two modelled diets uses the median number of servings of foods (takes into account habitual food pattern: 'food pattern diet') while the other diet uses the extremes of the distributions ('no food pattern diet'). We used the no food pattern diet for this study as this diet best covered requirements of all 13 key nutrients.

Appendix 1 continued.

Food coverage at household, regional and national level

The recommended and nationally supplied quantity of food groups per capita per year, and the percentage coverage of the recommended food groups by national food supply

Food group	Recommended SA[a], kg/capita/year, report	Supply[b] kg/capita/year, report	Coverage, %
Starchy foods	356	527	**148.0**
Vegetables	82	40	**48.8**
Fruit	55	172	**312.7**
Dry beans, split peas, lentils, soya	27	14	**51.9**
Fish, chicken, lean meat, eggs	37	47 *(27 from fish)*	**127.0**
Milk, maas (fermented milk), yoghurt	55	9.4	**17.1**
Fat, oil	13	6.9	**53.1**
Sugar (incl. sugar cane)	13	16.5	**126.9**

[a]Quantities as recommended by the South African food-based dietary guidelines, based on average for adult men and women

[b]Quantities based on most recent data available from 2011 from the Food Balance Sheets accounting for food imports, exports and waste

Appendix 2

Estimated average requirements (EAR) and distributions of zinc, calcium, vitamin A, vitamin C, thiamine, riboflavin, niacin, vitamin B_6, folate, and vitamin B_{12} for children 6 to 12 months old and children 1 to 3 years old[a, b]

	Infants 6 to 12 months old			Children 1 to 3 years old		
Nutrient	RNI	**EAR**	**SD[c]**	RNI	**EAR**	**SD[d]**
Zinc (mg), low bioavailability	5[e]	4[e]	0.5	3	2[e]	0.5
Calcium (mg)	400	300[f]	50	500	370[g]	64.75
Vitamin A (µg)	400	n/a	n/a	400	286[g]	57.2
Vitamin C (mg)	30	n/a	n/a	30	25[g]	2.5
Thiamine (mg)	0.3	n/a	n/a	0.5	0.42[g]	0.04
Riboflavin (mg)	0.4	n/a	n/a	0.5	0.42[g]	0.04
Niacin (mg)	4.0	n/a	n/a	6	4.6[g]	0.69
Vitamin B_6 (mg)	0.3	n/a	n/a	0.5	0.42[g]	0.04
Folate (µg)	80	65[f]	7.48	150	120[f]	15
Vitamin B_{12} (µg)	0.7	0.6[f]	0.05	0.9	0.7[f]	0.105

RNI = Recommended nutrient intake. EAR = Estimated average requirements. SD = standard deviation. n/a = not available.

[a] All values are taken from WHO/FAO (2004) unless otherwise stated

[b] Values for EAR are adjusted for an assumed bioavailability (WHO/FAO, 2004): EAR refers to intake of the nutrients and not the physiological need for the absorbed nutrient

[c] All SDs for infants 6 to 12 months were calculated based on RNI and EAR, using conversion factor RNI/EAR; if EARs were not available, SDs could not be calculated

[d] All SDs for children 1 to 3 years were calculated based on EAR and CV (SD=CV*EAR/100). CV is assumed to be 10% for all micronutrients except 15% for niacin (IOM, 2002), 20% for vitamin A (IOM, 2002), 17.5% for calcium (WHO/FAO 2004) and conversion for zinc, folate and vitamin B_{12} were calculated with RNI/EAR

[e] Values are taken from iZiNCG (2004)

[f] EAR taken from WHO/FAO (2004)

[g] EAR back-calculated from RNI (Recommended Nutrient Intake) (WHO/FAO, 2004)

Appendix 3

Probability of adequacy values for iron for children 6 to 12 months old and children 1 to 3 years old, assuming 5% bioavailability

Probability of adequacy	6-12 months, 10% bioavailability[a]	6-12 months, total absorbed[b]	6-12 months, 5% bioavailability[c]	1-3 years, 5% bioavailability[d]
0	<3.01	0.301	**<6.02**	**<3.64**
0.04	3.02-3.63	0.302-0.363	**6.03-7.26**	**3.65-4.46**
0.07	3.64-4.35	0.364-0.435	**7.27-8.70**	**4.47-5.54**
0.15	4.36-5.23	0.436-0.523	**8.71-10.46**	**5.55-7.06**
0.25	5.24-5.87	0.524-0.587	**10.47-11.74**	**7.07-8.35**
0.35	5.88-6.39	0.588-0.639	**11.75-12.78**	**8.36-9.58**
0.45	6.40-6.90	0.640-0.690	**13.80**	**9.59-10.84**
0.55	6.91-7.41	0.691-0.741	**14.82**	**10.85-12.20**
0.65	7.42-7.93	0.742-0.793	**15.86**	**12.21-13.75**
0.75	7.94-8.57	0.794-0.857	**17.14**	**13.76-15.80**
0.85	8.58-9.44	0.858-0.944	**18.88**	**15.81-18.94**
0.92	9.45-10.15	0.945-1.025	**20.50**	**18.95-21.82**
0.96	10.16-10.78	1.016-1.078	**21.56**	**21.83-24.52**
1	>10.78	>1.078	**>21.56**	**>24.52**

[a]Values from Tables 1-3 from IOM 2001
[b]Calculated total absorbed iron needed, assuming 10% bioavailability
[c]Calculated total absorbed iron needed, assuming 10% bioavailability (total absorbed needed when assuming 10% bioavailability*0.1/0.05)
[d]Values from WHO/FAO 2006

Appendix 4

Consumer units (CU) for translation of optimised diet for non-breastfed children 12 to 23months old to optimised food needs for all household members

Groups WHO	Calcium	Zinc	Iron	Vit A	Thiamine	Riboflavin	Niacin	Vit B6	Folate	Vit B12	Vit C	*Average*
						Consumer Units (CU)						
0 - 6 months	0.1	**0.8**	0	0	0.1	0.1	0.1	0	0	0	0	*0.4*
7 - 12 months	0.1	0.5	0.5	0	0.2	0.2	0.3	0.2	0	0	**0.7**	*0.5*
1 - 3 months	0.3	0.2	0.4	0	0.3	0.2	0.4	0.3	0.2	0.1	0.1	*0.5*
4 - 6 y	0.6	0.6	0.5	0.7	0.5	0.5	0.6	0.4	0.5	0.5	0.7	*0.6*
7 - 9 y	0.7	0.6	0.5	0.9	0.8	0.8	0.9	0.7	0.8	0.8	0.8	*0.7*
Females, 10 - 14 y[a]	1.3	1.0	**0.6**	**1.4**	1.0	1.0	1.1	0.9	1.0	1.0	1.0	*1.0*
Females, 10 - 14 y[b]	1.3	1.0	0.7	**1.4**	1.0	1.0	1.1	0.9	1.0	1.0	1.0	*1.0*
Females, 15 - 18 y	1.3	1.3	1.0	1.4	1.0	1.0	1.1	0.9	1.0	1.0	1.0	*1.1*
Males, 10 - 14 y	1.3	1.0	**0.7**	1.4	1.2	1.1	1.1	1.0	1.0	1.0	1.0	*1.1*
Males, 15 - 18 y	1.3	**1.6**	0.9	1.4	1.2	1.1	1.1	1.0	1.0	1.0	1.0	*1.1*
Females, 19 - 50 y	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	*1.0*
Females, 51 - 65 y	1.3	1.0	**0.5**	1.0	1.0	1.0	1.0	1.2	1.0	1.0	1.0	*1.0*
Males, 19 - 50 y	1.0	**2.1**	**0.7**	1.1	1.2	1.1	1.1	1.0	1.0	1.0	1.1	*1.1*
Males, 51 - 65 y	1.0	**2.1**	**0.7**	1.1	1.2	1.1	1.1	1.3	1.0	1.0	1.1	*1.2*
Females, 65+ y	1.3	1.0	**0.5**	1.1	1.0	1.0	1.0	1.2	1.0	1.0	1.1	*1.0*
Males, 65+ y	1.3	**2.1**	**0.7**	1.1	1.2	1.1	1.1	1.3	1.0	1.0	1.1	*1.2*
Pregnant women	**1.2**	1.7	**3.8**	1.4	1.3	1.3	1.3	1.5	1.6	**1.1**	1.3	*1.6*
Lactating women	1.0	1.3	**0.7**	**1.7**	1.5	1.4	1.2	1.5	1.4	1.2	**1.7**	*1.3*

Consumer units are based on EARs of each nutrient (WHO/FAO 2004) for specific group relative to EAR of women 19 to 50 years old who are not pregnant or lactating. Averages of the consumer units of all 11 nutrients were calculated for each group (average are calculated for each row). Average consumer units are used to calculate quantity of foods needed for each household member based on FBDGs for non-breastfed children 12 to 23 months old. **Bold** = 0.4 or more CU difference of a specific nutrient with average CU for all nutrients for a specific group.

[a]pre-menarche

[b]menarche

Appendix 5

Coverage of energy and nutrient requirements for children 12-23 months old, women 19 to 50 years old and at household level by the optimised diet

	Children 12-23mo (0.5CU)	**Women 19-50yrs (1CU)**	**All household members**
Nutrients	Coverage %, RNI	Coverage %, RNI	Median (IQR)
Energy (Kcal)	107.4	**64.9**[a]	**67.7 (2.9)**
Macronutrients			
Protein	304.8	118.3[c]	100.0 (0.0)[f]
Fat	125.4	**56.8**[b]	**60.4 (2.3)**
Carbohydrates	-	143.0[d]	100.0 (0.0)[f]
Micronutrients			
Calcium	**33.2**	**33.2**	**34.3 (2.4)**
Iron	78.0	**30.8**	**60.3 (13.0)**
Zinc	150.7	100.4	85.7 (9.9)
Vitamin A	**30.2**	**48.2**[e]	**39.1 (2.7)**
Thiamin	142.7	129.6	100.0 (0.0)[f]
Riboflavin	98.6	89.6	88.4 (3.2)
Niacin	168.4	144.3	100.0 (0.0)[f]
Vitamin B6	153.1	117.7	100.0 (0.0)[f]
Folate	89.4	**67.0**	73.5 (2.2)
Vitamin B12	**2.3**	**2.2**	**2.3 (0.1)**
Vitamin C	**42.1**	**56.0**	**54.6 (4.0)**

Bold = coverage below 70% of RNI
[a]energy requirements WHO 2001, assume moderate activity
[b]WHO 2010 AMDR, based on energy requirements
[c]Safe level
[d]Recommended Dietary Allowance
[e]Mean requirements
[f]constant, all households have a coverage of 100%

Chapter 5

Seasonality and nutrition-sensitive farming in rural Northern Ghana

Ilse de Jager
Gerrie W. J. van de Ven
Marcel T.M.H. Lubbers
Ken E. Giller
Inge D. Brouwer

Under review

Abstract

Background: Agriculture has great potential to enhance human nutrition. Yet current assessments do not provide direction to farmers what to grow on their farm to ensure year-round availability of the foods nor the income required to fulfil the needs of the household members. Using a farm-level systems approach, we investigated the minimum farm size needed, the optimal crop combination to grow and the potential contribution of mainstream agricultural interventions to provide a nutritious diet and additional income in all seasons of the year for an average rural household in Northern Ghana.

Methods: We applied linear programming to model different scenarios and interventions. We used data from a dietary intake study to retrieve an optimised diet for an average household in Northern Ghana and data from other secondary sources for information on seasonal yields, waste factors, crop availability, crop land use and prices for all crops produced in Northern Ghana.

Results and discussion: Results indicate that for an average rural household of 14 persons in Northern Ghana the farm size required to produce the food needs for a nutritious diet is 1.43 ha. Agricultural interventions increasing the yields of grains and legumes decrease the farm size needed to about 1 ha. The vegetable and fruit needs cannot be covered by the food produced in the farm during the 'hunger season' unless irrigation is applied. Households need to produce a diversity of foods to cover their food needs from own production. When household do not produce their own food needs, but need income from agriculture to purchase food, our analysis suggests that cultivating one or two of the most lucrative crops (onions and sweet potato), will result in the largest farm income. However, specialization also comes with increased risks, especially for small rural farming households.

Conclusion: Using a farm-level system approach provided three major insights. First, considering seasonality is crucial in nutrition-sensitive farming. Ensuring a year-round nutritious diet requires enhanced availability of vegetables and fruits in the hunger season. Second, although staple crops are not nutrient-dense such as vegetables and fruits, increasing their yields may contribute to enhancing diets. It will decrease the farm size needed which enables households to produce sufficient to cover their food needs for a nutritious diet. Third, our approach confirms that smaller farms are unable to produce sufficient food to cover their needs and will depend on their income, both from agriculture and other sources, and the availability of foods on markets to meet their dietary needs.

Introduction

Agriculture has great potential to enhance human nutrition. This is especially the case among rural populations in low and middle income countries where malnutrition is most severe (UNICEF et al. 2018) and agriculture remains the most important source of food and income (Pinstrup-Andersen 2012). To increase income of farming households, current mainstream agricultural interventions primarily target improved production of staple crops and not the availability of nutritious diets. Agricultural interventions can improve nutrition through two main pathways: increased production can lead to more consumption, or increased production can lead to more income that can be used to purchase foods (Du et al. 2015; Herforth and Harris 2014). Agricultural interventions may translate in better nutrition in terms of dietary diversity and micronutrient intake when they have an explicit nutrition goal, add a component of nutrition behaviour change and include efforts to empower women's status (Ruel et al. 2018).

Evaluations of these nutrition-sensitive agricultural interventions, however, do not provide advice to farmers what to grow to ensure year-round availability of the foods or the income required to fulfil the nutrition needs of their household. Income is needed for foods not produced on the farm as well as for other essential items such as housing, clothing, education and health care (Anker 2006). For rural households that depend largely on natural resources for their livelihood, increasing agricultural incomes is critical to escape poverty (Klasen et al. 2016).

To better understand what farmers need to grow and what effects investments in agricultural interventions have on the availability of a nutritious diet, a systems approach must address three issues. First, the variability of available foods across seasons must be addressed as this is essential in achieving year-round nutritious diets. Almost 60% of sub-Saharan Africa, the region with the highest prevalence of stunted children and micronutrient deficiencies (UNICEF et al. 2018), has only one cropping season and a long dry season (Ker 1995). Especially towards the end of the dry season (often referred to as the 'hunger period'), availability of perishable but often nutrient-dense foods such as, fruits, vegetables and animal source foods is limited (HLPE 2017; Devereux 2009). Further, prices of key foods and consequently the costs of a nutritious diet increase (Masters et al. 2018) while dietary diversity may decrease (Abizari et al. 2017) resulting in child growth deficits (Fentahun et al. 2018). Second, most agricultural interventions focus on improving yields of major cereals such as wheat, maize and rice (Khoury et al. 2014) through use of improved varieties, improved management with fertilizers, irrigation and reducing post-harvest losses. Investigating crop combinations may provide insight in the potential contribution of single crop interventions to the overall availability of foods for nutritious diets. Third, evaluations of impact of agricultural practices on diets are generally limited to interventions such as home gardens or nutrition-sensitive agriculture interventions that include specific nutrition goals. Dietary impacts of mainstream agricultural interventions are rarely studied, although these may contribute to the availability of foods for nutritious diets.

We investigated the minimum farm size required, what crops should be grown and the potential contribution of mainstream agricultural interventions to provide a nutritious diet throughout the year and additional income, using data from rural households in Northern Ghana. Our systems approach may facilitate prioritizing mainstream agricultural interventions, both in research and policy context, that may have potential to contribute to improve availability of foods for nutritious diets.

Methods

Study area

We selected Karaga sub-district in the Northern Region of Ghana for this study based on the high incidence of food insecurity and malnutrition. Based on data from 2014, about 32% of children below 5 years old were stunted and 9% were wasted (de Jager et al. 2017). Karaga district has one rainy season from May till October-November. The average annual temperature is 28°C and annual rainfall is 900 to 1040 mm. The main crops cultivated are maize, rice, cowpea and yam. The population density is relatively sparse (50-100 inhabitants per km^2) (Franke et al. 2011).

Dietary intake study

A dietary intake study was carried out in Karaga sub-district among 337 children of 6 to 23 months of age. Data was collected in July 2014 by trained enumerators with a first degree in nutrition and who spoke the local language. Dietary intake of the children was assessed through the mother or caretaker using a quantitative multi-pass 24-hour recall (24hR) (Gibson and Ferguson 2008). All days of the week were captured and randomly assigned to subjects to account for day-to-day variation in dietary intake. Data was collected within a period of 3 weeks. Additionally, a structured questionnaire based interview with the head of household was used to collect information for all individual household members on sex, age and physiological state (menstruation, pregnancy, lactating), information on education, occupation, sources of income, religion, total cultivated land, distance to closest market, recall on the crops produced and their estimated yields during the last year. In addition, prices of the foods consumed were collected in a market survey. Details on the study population and methods for data collection are described by de Jager et al. (2018).

Characteristics of the study population

In the dietary intake study of 337 children, 40% were stunted and more than 40% had an individual dietary diversity score below 4 reflecting a nutrient inadequate diet (WHO et al. 2007). In most households farming was the main occupation and the main source of income of both the household head and of the mother of the child selected for the dietary intake assessment. Most households had a male household head and were Muslim. Travel distance to the closest market was on average 1 hour. Households cultivated on average 2.1 ha with four crops of which three were used for home consumption. Most households produced grains (97%), legumes, nuts and seeds (84%) and only 8% of households produced vegetables. Further details of the study population are described elsewhere (de Jager et al. 2018).

Optimal nutrient adequate diet for an average household

A linear programming tool e-Optifood© was used to develop optimal diets. The children enrolled in the dietary intake study were divided into four groups according to age and breastfeeding state: 6-8 months breastfed, 9-11 months breastfed, 12-23 months breastfed and 12-23 months non-breastfed. For our analysis, we included all non-condiment foods consumed by ≥5% of the non-breastfed children of 12-23 months. Optifood© was used to calculate a diet that best fits the nutrient requirements of non-breastfed children of 12-23 months considering their habitual diet patterns and costs (Ferguson et al. 2006). Thirteen key nutrients were considered: total fat, total protein, iron, zinc, calcium, vitamin A, vitamin C, thiamine, riboflavin, niacin, vitamin B6, folate, and vitamin B12. Details on development of these optimised diets are described by de Jager et al. (2018).

Based on the household information and the respective estimated average requirements (EARs) of 11 key micronutrients, we calculated the number of consumer units in a household relative to women 19-50 years not pregnant or lactating (denoted one consumer unit), see Appendix 1 for details. A child of 12-23 months was determined at 0.5 consumer units. The food needs per consumer unit were based on the optimized diet for non-breast children of 12-23 months multiplied by two. In our study region the diet of children older than one year is integrated in the family diet (Armar-Klemesu et al. 2016). The number of consumer units for an average household were multiplied by the optimised food needs per consumer unit to arrive at total household food needs in g per day and in kg per season of 3 months (see below for the definition of a season). This translation of the results of Optifood to an average household ensured that nutrient needs of all household members were approximately met by this diet. The diet covered all nutrients above 70% of the summed recommended nutrient intake (RNI) of an average household, except for fat for which 53% was covered (Appendix 2). For most nutrients an intake above 70% of the RNI represents at least the EAR. The 70% cut-off is also used by others allowing for comparison (Kujinga et al. 2018; Talsma et al. 2017; Santika et al. 2009). We set the minimum fat intake at 30% of total energy intake while the required range is 20 to 35% (FAO 2010), therefore the coverage of fat needs is still above the lower boundary of the adequate range.

Crop availability and market information

We used secondary data sources for yields, waste factors, crop availability, crop land use and prices for all crops produced in Northern Ghana. We checked the data for plausibility with local experts.

Seasons. We divided the year into four seasons of three months based on the typical period of the dry season and the rainy/cropping season in Northern Ghana, combined with periods of food deficits: the first part of the dry season from November to January without food deficits (Season 1), the second part of the dry season from February to April with food deficits (Season 2), the first part of the rainy season from May to July with food deficits (Season 3), and the second part of the rainy season from August to October without food deficits (Season 4).

Crops cultivated. Crops cultivated in Northern Ghana and included in our analysis are based on: the recall of crop cultivation of households that participated in the dietary intake study, all foods consumed by the infants and young children in the dietary intake study, and the crops reported in Northern Ghana in the Living Standards Measurement Study (LSMS) carried out from 2009-2010 (Institute of Statistical Social and Economic Research (University of Ghana) and Economic Growth Center (Yale University) 2009). We excluded foods that are picked from the wild as they are not cultivated by farmers and information on their availability is missing.

Yield. Average yields of all crops were based on secondary sources in the following order: average yields in Karaga district in 2006 from Ministry of Agriculture (MoFA) (SRID MoFA 2006), average yields in Ghana in 2015 from MoFA (SRID MoFA 2015) and average yields in Ghana in 2016 from FAOSTAT (FAO 2016). If average yields for specific crops were missing we used other sources or assumed yields from comparable crops. We assumed yields were already corrected for harvest losses. To assess the effects of different interventions we also used improved crop yields in our analyses. We included best attainable yields: the largest yields attained in field experiments in a specific area (Tittonell and Giller 2013) for cowpea, groundnut and soybean in Northern Ghana (Kermah et al. 2017). For other crops we used other secondary sources in the following order: modelled rain fed crop yields (Global Yield Gap Atlas 2018) and best attainable yield of a crop or a comparable crop in regions with comparable ago-ecological characteristics. These best attainable yields were corrected for the fact that most crop yields realized on farms begin to plateau when they reach about 80% of the best yields (Lobell et al. 2009; Cassman et al. 2003). In addition, we used yields 50% above the current average yields assuming these yields as more realistic scenarios of improved yields by interventions at rural farming households.

Waste. Yields were corrected for waste as not all parts of a crop are consumed, based on the USDA food composition table (USDA 2016). In case waste factors were missing, the waste factor of a comparable crop was used.

Crop availability per season. Crop availability was based on data from the LSMS for Northern Ghana (Institute of Statistical Social and Economic Research (University of Ghana) and Economic Growth Center (Yale University) 2009). Each household reported for each crop the start and the end month of the cropping season, whether the crop was stored and the percentage lost during storage. In addition, we used the FAO cropping calendar for the Guinea savannah zone in Ghana for the length of the growth period per crop (FAO 2018). We combined both information sources to determine in which seasons crops are available taking storage losses into account. Some crops can be cultivated twice a year. If data for a specific crop was missing, data of a comparable crop was used. We included interventions in our analysis that can expand the availability of crops: irrigation (only for crops that were not available in specific seasons) and improved storage (considering locally feasible options such as drying of vegetable leaves).

Duration of land use per cropping cycle. We used the same information sources as for crop availability, to determine the duration of the land use by a crop and the specific seasons. For vegetables with a short cropping cycle of about half the length of a season as defined in this study, we assumed that, considering land preparation, spreading of harvesting or other management issues, the cropping cycle covers a full season. Fruit trees, being perennials, occupy land year round.

Food prices per season. We used the data on food prices collected through the market survey of the dietary intake study in July 2014, the first part of the rainy season (Season 3) (de Jager et al. 2018). Prices fluctuate throughout the year. Therefore we derived relative price fluctuations per month for sorghum, maize, millet, rice, cassava and yam in Tamale over the past 12 years to translate our price data for the other seasons. We used the relative price fluctuations of one of these specific foods for other foods with comparable availability throughout the year.

Testing farm designs and interventions for nutrient adequate diets

We applied linear programming (LP), using the software package General Algebraic Modelling System (GAMS), to test what farm designs and which agricultural interventions resulted in nutritious diets in all seasons. The optimised food needs for an average household per season were used to calculate the total needs of each food group. These food group needs were the main constraints included in the model. We calculated the minimum farm size needed to cover the food group needs per season of an average household in Northern Ghana for different scenarios:

Minimizing crop area per season:
Minimise ($Total\_Area_s$) [ha],
where $Total\_Area_s$ is total farm size per season s.

We used the largest area required across the four seasons, which represents the minimum farm size to achieve a nutritious diet, as an upper farm size constraint in the subsequent calculations. We then maximized the revenue from farming, defined as the monetary value of crop produce sold minus the costs of foods purchased, for an average household in Northern Ghana:

Maximizing revenue:
Maximise (Revenue = $\sum_c Value\_total\_crop\_sold_c - Total\_cost\_food\_purchased$)
[GH₵]
where *Value_total_crop_sold*$_c$ is total monetary value of sold produce of crop *c* and *Total_cost_food_purchased* is the total cost of foods purchased.

We assumed the cost of production to be zero as generally input use is limited and mainly family labour is used in the study area. The value of home produced and consumed foods is not included in the revenue, implying that the calculated revenue is available for other household needs than food. We calculated the maximum revenues for different farming interventions (described below) relative to the revenues without interventions (based on average crop yields), both for GH₵/year and GH₵/year/ha.

We defined different scenarios for meeting a nutritious diet of a household. A scenario where all food group needs are covered by on-farm production, allowing only foods that could not be produced on farm (non-crop foods) or that are not available in specific seasons to be purchased. The costs for purchases are covered by crop sales. This scenario is further referred to as 'with priority for food needs covered by own production' (A). In the second scenario all food group needs are covered by on-farm production that can either be consumed or sold to purchase foods needed. This scenario is further referred to as 'without priority for food needs covered by own production' (B). We combined both scenarios separately with a range of different farming interventions: (1) no intervention, based on average crop yields; (2) expanding availability of crops in food groups that could not be covered by own production based on (2a) storage and (2b) irrigation using average crop yields; (3) improved yields of grains, starchy crops, legumes and vegetables based on (3a) best attainable crop yields and (3b) yields increased by 50% of the average (see Figure 1). The mathematical description of the models is included in Appendix 3.

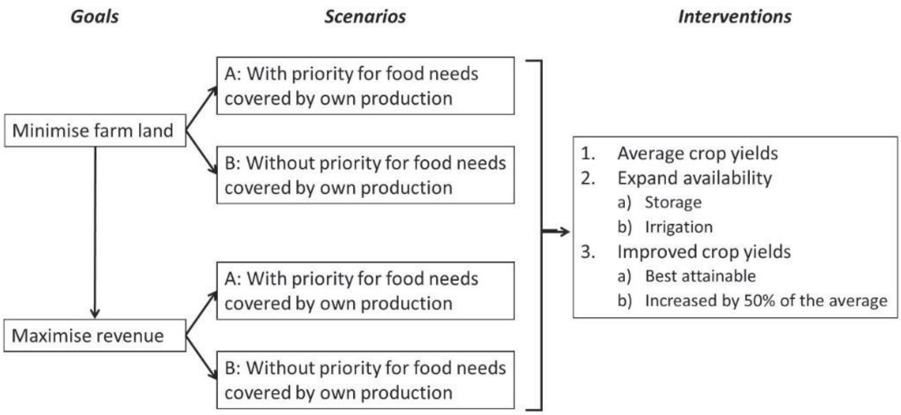

Figure 1. Goals, scenarios and interventions to cover a nutritious diet in all seasons of an average household in Northern Ghana

Results

Optimal nutrient adequate diet for an average household

The median number of household members was 14 with one infant between 0 to 12 months, five children between 1 to 9 years, one female and one male of 10 to 18 years, three females of above 19 years of which two are lactating, and two males of above 19 years. An average household in Karaga district consisted of 12.2 consumer units (Appendix 4).

For the optimal diet as calculated by Optifood, we excluded the reported large portion sizes of fresh milk consumption of two children in our study population. We consider milk consumption as uncommon in Ghana based on our own field observations and on FAO's food balance sheets showing a milk supply of only 20 ml per capita per day (FAO 2013). The optimal diet per season for an average household included 206 kg of whole grains, 21.2 kg of starchy plant foods, 92.4 kg of beans, 69 kg of nuts and seeds, 14.4 kg of soybeans, 67.9 kg of dark green leafy vegetables, 16.7 kg of vitamin A source other vegetables, 61.2 kg of vitamin C rich vegetables, 14.4 kg of other vegetables, 262.7 kg of other fruits, 3.4 kg of small fish with bones, 64.6 kg of eggs, 14.5 kg of fortified vegetable oil and 22.3 kg of fortified milk powder (Table 1).

Table 1. Food and food group needs of the optimised diet for children not breastfed of 12-23 months and for an average household

	Children not breastfed 12-23 months (0.5 CU)			Average household (12.2 CU)	
Foods per food group	**Servings/ week**	**Median serving**	**Quantity g/day**	**Quantity g/day**	**Quantity kg/season[a]**
Grains				*2257*	*206.0*
Maize dough	1	38.4	5.5	134	
Maize flour	3	125	53.6	1305	
Maize grain	1	11	1.6	37	
Millet dough	2	53.2	15.2	366	
Millet flour	1	18.8	2.7	61	
Rice brown	1	102.7	14.7	354	
Starchy foods				*232*	*21.2*
Cassava flour	2.5	26.7	9.5	232	
Beans, lentils, peas				*1013*	*92.4*
Cowpea	4	41.6	23.8	586	
Pigeon peas	3	40.8	17.5	427	
Nuts, seeds				*756*	*69.0*
Groundnut	7	25.2	25.2	610	
Melon seeds	3	14.5	6.2	146	
Soybeans and				*158*	*14.4*
Soybeans, dried	4	1.8	1.0	24	
Soybeans flour	3	13.2	5.7	134	
DGLV				*744*	*67.9*
Ayoyo (jute) leaves	4	18.3	10.5	256	
Baobab leaves	1	8.2	1.2	24	
Bra (kenaf) leaves	7	18.9	18.9	464	
Vit. A-rich vegetables				*183*	*16.7*
Tomato paste	5	9.7	6.9	171	
Tomato powder	2	1.7	0.5	12	
Vit. C-rich vegetables				*671*	*61.2*
Okro fruit	7	27.5	27.5	671	

DGLV=Dark green leafy vegetables, Vit.=Vitamin.

[a]Recommended quantity per season of 3 months (91.25 days)

5

Table 1. Continued

	Children not breastfed 12-23 months (0.5 CU)			Average household (12.2 CU)	
Foods per food group	**Servings/ week**	**Median serving**	**Quantity g/day**	**Quantity g/day**	**Quantity kg/season[a]**
Other vegetables				*158*	*14.4*
Onion bulb	7	5.7	5.7	134	
Okro fruit powder	2	4.2	1.2	24	
Other fruits				*2879*	*262.7*
Watermelon	7	117.9	117.9	2879	
Fish, small with				*37*	*3.4*
Mackerel canned in	7	1.3	1.3	37	
Eggs				*708*	*64.6*
Egg guinea fowl	7	28.8	28.8	708	
Vegetable oil,				159	14.5
Oil vegetable Frytol	7	6.4	6.4	159	
Fluid/powdered milk,				*244*	*22.3*
Milk powder, cow	7	10.0	10.0	244	

DGLV=Dark green leafy vegetables, Vit.=Vitamin.
[a]Recommended quantity per season of 3 months (91.25 days)

Farm size

The average farm size reported by the household in the dietary intake study is 2.1 ha. The frequency distribution of reported farm size of the households from the dietary intake study is shown in Figure 2. The majority of the households have a farm size below 3 ha (65% of the households), with 45% of the households below 2 ha and 17% below 1 ha.

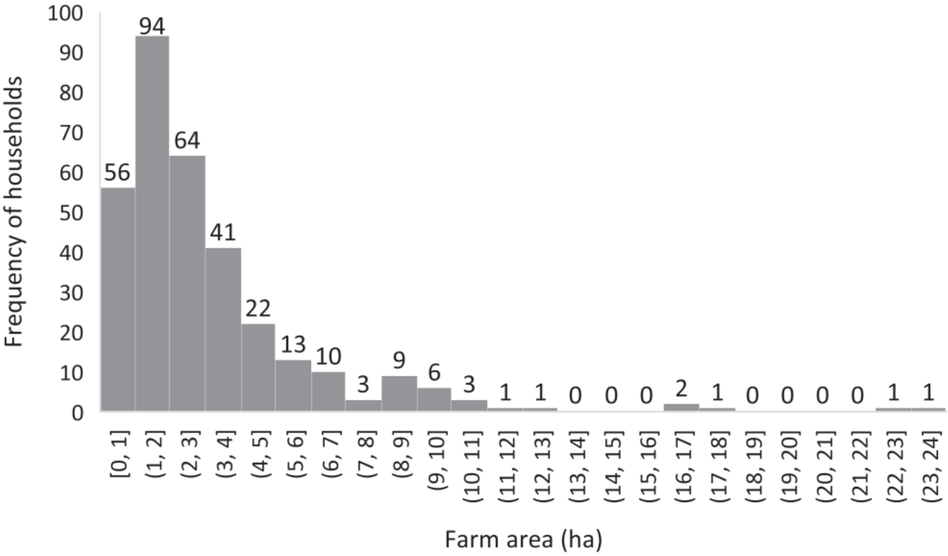

Figure 2. Frequency of households per range of farm size (n=329, 1 excluded in figure with farm size of 45 ha)

Crop production, availability and prices

The following crops were produced and/or consumed in Northern Ghana: maize (*Zea mays*), millet (*Eleusine coracana* and *Pennisetum glaucum*), sorghum (*Sorghum bicolor*), rice (*Oryza sativa*), cassava (*Manihot esculenta*), cocoyam (*Colocasia esculenta*), plantain (*Musa* x *paradisiaca*), sweet potato (*Ipmoea batatas*), yam (*Dioscorea* spp.), cowpea (*Vigna unguiculata*), pigeonpea (*Cajanus cajan*), cashew nut (*Anacardium occidentale*), groundnut (*Arachis hypogaea*), sesame seeds (*Sesamum indicum*), soybean (*Glycine max*), ayoyo leaves (*Corchorus olitorious*), bra leaves (*Hibiscus cannabinus*), amaranth (*Amaranthus cruentus*), okro (*Abelmoschus esculentus*), tomatoes (*Solanum lycopersicum*), onion leaves (*Allium cepa*), cucumber (*Cucumis sativus*), eggplant (*Solanum melongena*), onions (*Allium cepa*), yellow melon (*Cucumis melo*), watermelon (*Citrullus lanatus*), melon seeds (neri), shea butter (*Vitellaria paradoxa*), orange (*Citrus sinensis*), mango (*Mangifera indica*), papaya (*Carica papaya*) and baoba (*Adansonia digitata*). Table 2 presents the yields for the different crops. The average yield for grains was between 0.8 and 1.6 t ha^{-1}, for starchy foods between 9.4 and 10.9 t ha^{-1} (for cassava, cocoyam and sweet potato we assumed average yields of 10 t ha^{-1} (van Vugt and Franke 2018) instead of the average yields reported for Karaga and Ghana as we considered these to be unrealistically low based on our own observations in the region), for legumes between 0.7 and 1.2 t ha^{-1}, for dark green leafy vegetable 9 t ha^{-1}, for other vegetables between 8.3 and 23.2 t ha^{-1}, and for fruits between 7.3 and 26.1 t ha^{-1}. For the scenario of best attainable yields, secondary data showed that the yields for grains could increase to 2.6 and 5.9 t ha^{-1} with highest increase for sorghum, for legumes to 1.4 and 4.5 t ha^{-1} with highest increase for soybean, and for starchy foods to 40 t ha^{-1}. We did not find any data for best attainable vegetable yields. Vegetables and fruits were not available in the second part of the dry season (Season 2) (Appendix 5). In this season, also the least number of crops were on the land. In case of local storage methods and/or irrigation possibilities, the availability of vegetables and fruits could be expanded into the next season. The food prices and their fluctuations across seasons are given in Appendix 5.

Table 2. Crops produced in Northern Ghana: average yields, average yields increased by 50%, and best attainable yields

Crops cultivated per food group	Average yield (t ha^{-1})	Average yield + 50% (t ha^{-1})	Best attainable yield[a] (t ha^{-1})
Grains			
Maize	1.6	2.3	5.9
Millet	0.8	1.2	2.6
Sorghum	0.9	1.4	5.5
Rice	1.5	2.3	4.7
Starchy foods			
Cassava	10.0	15.0	40.0
Cocoyam	10.0	15.0	40.0
Plantain	10.9	16.4	40.0
Sweet potatoes	10.0	15.0	40.0
Yam	9.4	14.1	40.0
Beans, lentils, peas			
Cowpea	1.2	1.8	2.3
Pigeon peas	1.2	1.8	2.2
Nuts, seeds			
Cashew nuts	0.6	-	-
Groundnut	0.7	1.1	1.4
Melon seeds	0.1	-	-
Sesame seeds	0.1	-	-
Soybeans and products			
Soybeans	0.8	1.2	4.5

- = no best yield available/not modelled

[a]the largest yields attained in field experiments in a specific area

Table 2. Continued

Dark green leafy vegetables			
Ayoyo (jute) leaves	9.0	13.5	-
Bra (kenaf) leaves	9.0	13.5	-
Amaranth	9.0	13.5	-
Vitamin C rich vegetables			
Okro	23.2	34.7	-
Tomatoes	8.3	12.5	-
Onion leaves	9.2	13.8	-
Other vegetables			
Cucumber	13.8	20.7	-
Onion	18.8	28.2	-
Eggplant	8.9	13.3	-
Other fruits			
Yellow melon	15.4	-	-
Watermelon	26.1	-	-
Shea fruit	0.8	-	-
Orange	19.9	-	-
Mango	7.3	-	-
Papaya	19.4	-	-

- = no best yield available/not modelled

[a]the largest yields attained in field experiments in a specific area

Scenario A: priority to cover food needs by own production

Minimum farm size

With average yields in scenario A, a total farm size of 1.43 ha is needed to produce food covering the needs of an average household in Northern Ghana by own production (Figure 3). For all interventions, the minimum farm size is determined by the area needed in the second part of the rainy season (Season 4). When increasing yields of different food groups (Intervention 3, Figure 1), the minimum farm size needed for food production decreased. In case of best attainable yields (3a) or a 50% yield increase (3b) for grains 1.02 and 1.24 ha are needed, respectively, and for legumes 1.00 and 1.15 ha, respectively. A 50% yield increase of starch crops did not influence the minimum farm size required. Increased yields of vegetables by 50% of their average, showed a minimal decrease in total farm size to 1.42 ha.

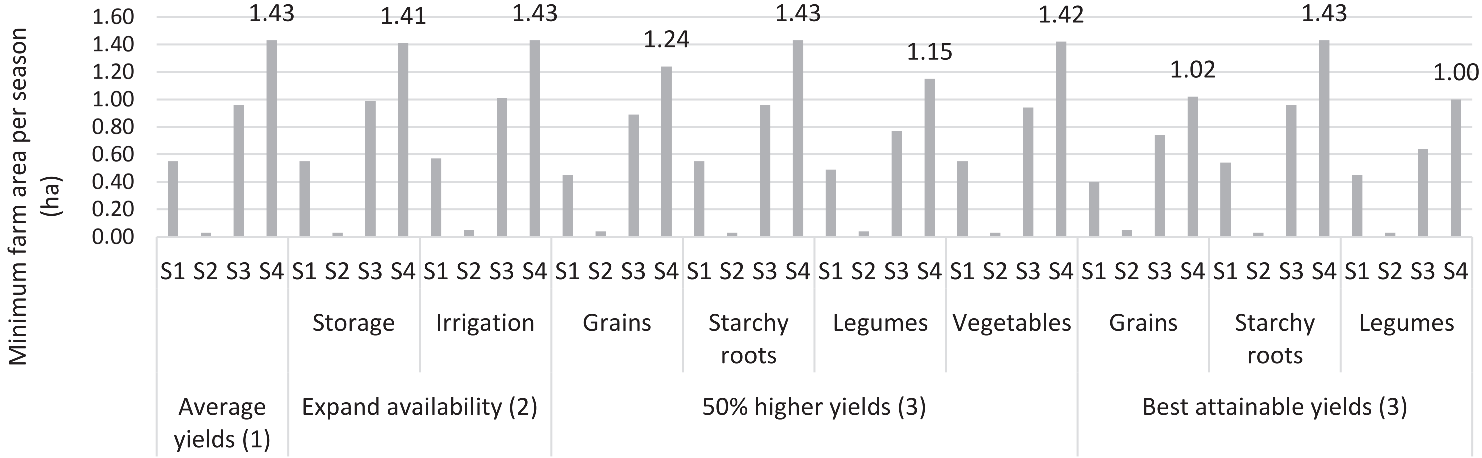

Figure 3. Minimum farm size needed for an average household in Northern Ghana to produce food that covers needs by own production (Scenario A) *S1= November to January (dry period), S2= February to April (dry period), S3= May to July (rainy period), S4= August to October (rainy period). Expand availability=expand availability of vegetables and fruits. Storage= local feasible options such as drying of vegetable leaves but does not include cooling of fruits. Best attainable yields= the largest yields attained in field experiments in a specific area. 50% higher yields=yields 50% above the average yields. The numbers in brackets refer to the intervention (Figure 1)*

Maximum revenue

In this scenario, for each intervention the available farm size was set to the value obtained in Season 4 (Figure 3), as explained in the previous section. Purchases of non-crop foods such as vegetable oil, fish, eggs, powdered milk, required a minimum amount of 5300 GH₵ per year. Additionally, as vegetables and fruits were not available in Season 2, they needed to be purchased at an extra cost of 200 GH₵, except in case of expanding availability (Intervention 2, Figure 1) by storage (2a: 50 GH₵ extra) and irrigation (2b: no extra costs). All available land was cultivated in all seasons except for the second part of the dry season (Season 2) (Table 3) due to lack of water. Under irrigation (2b) also in Season 2 all land was cultivated, resulting in the largest revenue, more than twice that of the standard average yields (Intervention 1). Storage (2a) did not increase revenue. Only improving vegetable yields substantially increased revenue (with 142% compared to average yields in GH₵/year/ha). Improving yields of grains, starchy roots and legumes did not increase revenue compared with standard average yields. But improving yields of grains and legumes did decrease land size needed (as mentioned above) and in case of legumes the revenue in GH₵/year/ha remained similar to standard average yields (with 93% and 90%, respectively for best yields (3a) and 50% higher yields (3b)).

In general, with all interventions a diversity of foods were produced throughout the year including: maize, rice, cowpea, groundnut, soybean, watermelon, sweet potatoes, bra leaves, amaranth, okro, onion, papaya and watermelon (Table 3). In case of storage (2a) and irrigation of vegetables and fruits (2b), some other and/or additional dark green leafy vegetables, vitamin C rich vegetables and fruits were produced. For different farm sizes, different crop combinations were selected. Two things drive these results of the crop combinations selected. First, the model needed to fulfil the constraints to cover the food needs for an optimal diet by own crop production. Second, the goal of the model is to maximize revenue. These drivers result in the selection of crops with largest yields to fulfil the optimal diet constraints (minimizes the land needs) and for the remaining land crops with the highest price per ha. In these scenarios farmers produced (almost) all their food needs themselves and therefore have (almost) no costs of foods that need to be purchased.

Table 3. Maximum revenue^ for average household in Northern Ghana with priority to cover food needs by own production (scenar io A)

	Farm size cultivated (ha)		Maximum revenue		Crops harvested			
	S1, S3, S4	*S2*	*GH₵/year*	*GH₵/year/ha*	*S1*	*S2*	*S3*	*S4*
1. Average yields	1.43	0.26	116600 (100%)	81538 (100%)	maize, rice, cowpea, groundnut, soybean, watermelon	sweet potatoes	bra leaves, amaranth, okro, onion, papaya	maize, cowpea, groundnut, soybean, bra leaves, okro, onion, watermelon
					differences compared with 'average yields' scenario			
2. Expand availability[a]								
a. Storage[b]	1.41	0.33	88%	90%	-	-	*ayoyo leave, no: bra leaves*	*oranges, no: bra leaves, okro, watermelon*
b. Irrigation	1.43	1.43	227%	227%	*ayoyo leaves, amaranth, okro, onion*	*onion, watermelon*	-	*no: bra leaves, okro, onion*
3. Improved crop yields								
a. Best yields[c]								
grains	1.02	0.38	54%	75%	*no: rice*	-	-	*oranges, no: watermelon*
starchy roots	1.43	0.26	111%	111%	-	-	-	-
legumes	1.00	0.22	65%	93%	-	-	-	*oranges*
b. 50% higher yields[d]								
grains	1.24	0.31	78%	90%	-	-	-	*oranges, no: watermelon*
starchy roots	1.43	0.26	102%	102%	-	-	-	-
legumes	1.15	0.28	72%	90%	-	-	-	*oranges, no: watermelon*
vegetables	1.42	0.31	141%	142%	-	-	-	*oranges, no: watermelon*

^Maximal revenue is the monetary value of own production minus the costs of foods purchased (5300 GH₵/year for non-crop foods plus additional 200 GH₵ for vegetables and fruits in Season 2 (5500 GH₵/year), except in case of expanding availability (for storage: 50 GH₵ extra (5350 GH₵/year), for irrigation: none (5300 GH₵/year))

S1= November to January (dry period), S2= February to April (dry period), S3= May to July (rainy period), S4=- August to October (rainy period)

- =no differences in crops harvested compared with 'average yields' scenario

[a]expand availability of vegetables and fruits

[b]storage includes local feasible options such as drying of vegetable leaves

[c]the largest yields attained in field experiments in a specific area

[d]yields 50% above the average yields

Scenario B: without priority to cover food needs by own production

Maximum revenue

The available land area for each intervention in Scenario B was maintained as in Scenario A (areas in Season 4 in Figure 3). In Scenario B with no priority to cover food needs by own crop production, for all interventions, all produce was sold and all food needs are purchased by the revenues from crop production. The total costs of the optimal diet for the average household were 9900 GH₵/year (Table 4). The total farm size is cultivated in all seasons for all interventions. In this scenario the crop combinations selected, are only driven by the goal of the model to maximise revenue and therefore crops were selected that yield the highest price per ha. For most interventions, sweet potatoes and onions are grown. Sweet potatoes are planted in the first part of the dry season (Season 1) and harvested in the second part (Season 2) and onions are harvested both in first and second part of the rainy season (Season 3 and 4). Only in case of irrigation, onions were harvested in each season. Therefore this scenario resulted in the largest relative revenue of 185% compared to standard average yields in GH₵/year/ha. Improving vegetable yields is, similar to results in scenario A, the most lucrative with 147% increased revenue in GH₵/year/ha. Only improving yield of starchy roots (best yields, 3a) also increased revenue (127%) compared to standard average yield, but for none of the other crops improving their yields resulted in larger revenues.

Minimum farm size

To cover food needs without a priority for own production (Scenario B), 0.10 ha cultivated with onions was sufficient to earn 9900 GH₵/year. The intervention with improved yields for vegetables (3b; onions) showed a farm size of 0.07 ha is sufficient.

Table 4. Maximum revenue^ for an average household in Northern Ghana without priority to cover food needs by own production for consumption (scenario B)

	Farm size cultivated (ha)	Maximum revenue		Crops harvested			
	S1, S2, S3, S4	*GH₵/year*	*GH₵/year/ha*	*S1*	*S2*	*S3*	*S4*
1. Average yields	1.43	279400	195385	none	sweet potatoes	onion	onion
					differences compared with 'average yields' scenario		
2. Expand availability[a]							
a. Storage[b]	1.41	99%	100%	-	-	-	-
b. Irrigation	1.43	185%	185%	*onion*	*onion, no: sweet potatoes*	-	-
3. Improved crop yields							
a. Best yields[c]							
grains	1.02	70%	99%	-	-	-	-
starchy roots	1.43	127%	127%	-	-	-	-
legumes	1.00	69%	98%	-	-	-	-
b. 50% higher yields[d]							
grains	1.24	86%	99%	-	-	-	-
starchy roots	1.43	104%	104%	-	-	-	-
legumes	1.15	80%	99%	-	-	-	-
vegetables	1.42	146%	147%	-	-	-	-

^Maximum revenue is the monetary value of own production minus the costs of foods purchased. In all scenarios all food needs are purchased and the total minimum costs to purchase all
food needs is 9900 GH₵/year for an average household in Northern Ghana.
S1=season from November to January (dry period), S2=season from February to April (dry period), S3=season from May to July (rainy period), S4-season from August to October (rainy period)
- =no differences in crops harvested compared with 'average yields' scenario
[a]expand availability of vegetables and fruits as we found they cannot be harvested throughout the year
[b]storage includes local feasible options such as drying of vegetable leaves
[c]the largest yields attained in field experiments in a specific area
[d]yields 50% above the average yields

Discussion

In this study we investigated the minimum farm size needed, what crops to grow and the potential contribution of mainstream agricultural interventions in order to provide a nutritious diet and additional income in all seasons of the year for an average rural household in Northern Ghana. We applied linear programming to model different scenarios and interventions. We used data from a dietary intake study to retrieve an optimised diet for an average household in Northern Ghana and data from other secondary sources for information on seasonal yields, waste factors, crop availability, crop land use and prices for all crops produced in Northern Ghana.

Scope of the study

Modelling different scenarios provides useful insights on potential possibilities and limitations of complex situations, taking into account different aspects together. As the model results largely depend on the data used and assumptions made, the potential implications on our results need to be acknowledged before discussing our findings. First, we were limited by the availability of primary and secondary data, especially of seasonally specific data of crop yields, crop availability and crop prices. For crop availability throughout the year no data were available at all as seasonality in relation to agricultural activities, food availability and a nutritious diet is rarely studied in detail. Second, we had to make assumptions for those lacking data which may have influenced our model results. For example, with regard to the crop yield data, we assumed that the yields as reported by the Ministry of Agriculture excluded harvest loss. If this was not the case, we have overestimated the actual yields and underestimated the minimum farm size. With regard to the seasonal food prices, we used monthly price data for sorghum, maize, millet, rice and cassava and assumed similar fluctuations throughout the year for other crops. However, for vegetables the fluctuations may have been more extreme as they are perishable and not available without irrigation in dry seasons. Further we assumed labour and input costs to be negligible as generally mainly family labour is used and input use is low in our study area. Nevertheless, labour is reported to be a major constraint in Ghana (Nin-Pratt and McBride 2014) and inputs are needed to get best attainable yields and possibly also for a 50% yield increase. Therefore we probably overestimated the land that actually can be cultivated in all seasons due to labour constraints as well as the maximum revenue as costs of production are not accounted for and market prices are used as sales prices, neglecting price differences related to presence of middlemen. Hence, we cannot draw conclusions with regard to the absolute revenue values calculated. However, the scenarios and interventions are assessed consistently, based on the available data and literature, and hence, we trust that the relative differences reflect reality. We reported relative revenues for all scenarios compared with the standard average yield. We checked the sensitivity of the models to prices and found that the relative revenues are not affected (Appendix 6) and thus comparison between scenarios is valid. Third, the calculated minimal costs for our optimal diet of 9900 GH₵ per year for an average household of 14 members are within the range of the reported food expenditures in the LSMS (Ghana Statistical Service 2014) but at the lower end of the distribution. This corresponds with our optimal diet costs as our costs are minimized. Another recent study that calculated the price of an optimal diet in Ghana, reported a cost of 4.68 GH₵ per person (Anker 2006), comparable to the costs of our modelled optimised diet in Optifood of 4.30 GH₵ per person. Fourth, we did not include livestock rearing in the model which may also contribute to the availability of animal-sourced foods in a household. The optimal diet included only eggs as animal-sourced foods that also may be provided by livestock rearing but in our model we assumed it to be purchased. In Northern Ghana, small-scale livestock rearing serves mostly as a safety net to quickly access cash for emergency (medical) or planned expenditures (school fees) (Roelen 2017). As these are non-food expenditures and only few animal-sourced foods were included in our optimal diet, excluding livestock is assumed to have limited effect on our results with regard to covering the food needs. However, with regard to the effect on our revenue, results depend on how much a household can earn from livestock rearing and how much land is needed for feed.

Farm size

The model results suggest that the average farm size of households in rural Northern Ghana should be sufficient to produce their food needs for a nutritious diet. Assuming average crop yields, a minimum farm size of 1.43 ha is needed to cover the food needs from own production. Households in the dietary intake study reported a median farm size of 2.1 ha with 75% of the households above 1.43 ha. A legume cultivation project (N2Africa) in the same region reported an average farm size of 2.8 ha (Franke et al. 2011). Therefore farm size does not (yet) seem to be a limiting factor in rural Northern Ghana to produce the food needed for a nutritious diet. Further, with the expected population growth (Population

Reference Bureau 2018) and the further division of household farm land area by inheritance, it is expected that household land area will decrease in future. For households with smaller farmer sizes, our study results indicate that increasing yields, especially of legumes and grains, is an option to enable households to cover their food needs for a nutritious diet. But in most cases interventions increasing yield will also increase the costs of inputs. As households with smaller farm sizes also tend to be poorer in terms of total value of household assets per household member (positive correlation in the dietary intake study, r=0.81, n=329, *P*-value=0.00), this may limit the success of yield increasing interventions.

Seasonality

Our findings show that household vegetable and fruit dietary needs cannot be covered by home production during the second part of the dry season, the so-called hunger season, unless irrigation is available. In general in rural settings in LMICs, food availability indeed varies between seasons and access to perishable but often nutrient-dense foods such as fruits and vegetables can be limited (HLPE 2017). During the hunger season, the food availability and accessibility is often inadequate, as stored supplies are exhausted and market demands are high, leading to high food prices (Devereux 2009). Masters et al. (2018) reported that the costs of a diverse diet in Ghana fluctuated throughout the seasons as was also reflected in our price data. Another recent study in Northern Ghana found a less diverse diet among school children during the end of the dry season compared with the end of the growing season, especially less vitamin A-rich fruits and vegetables were consumed during the dry season (Abizari et al. 2017). Seasonal variations in consumption of fruits, legumes, roots and plantains was also reported among preschool children in Ghana (Ferguson et al. 1993). In addition, diseases are more prevalent and labour demands are strongest at the start of the rainy season, which both further increase the demand for foods to cover increased nutrient and energy requirements in the period when least food is available (Devereux 2009), especially of perishable foods such as vegetables and fruits. Expanding availability of vegetables and fruits by irrigation of vegetables and some fruits (watermelon), can cover the needs of all food crops of the household by own farm production. Rice and vegetables dominate the small irrigated crop sector in Ghana, with 50% of vegetable production being irrigated, often in combination with rice on the same fields (FAO 2014). Effective irrigation techniques such as treadle and solar pumps may close food gaps in the hunger season. A review of the linkages between irrigation, food security and nutrition indeed concluded that irrigation contributed to improving food security but there is no evidence of impacts on nutrition due to a lack of studies that included nutrition outcomes (Domènech 2015). Expanding availability of vegetables for example by drying of vegetable leaves for consumption during the hunger season were only able to partly close the vegetable gaps in our models.

Crops cultivated

The model results suggest that households need to produce a diversity of foods to cover their food needs by their own production (scenario A). For all interventions and achieving minimal farm size needs, the following locally available foods need to be produced in different amounts to cover the needs for a nutritious diet: maize, rice, cowpea, groundnut, soybean, watermelon, sweet potatoes, bra leaves, amaranth, okro, onion, papaya and watermelon. However, an earlier study in the same area found that 60% of the households did not produce enough grains and legumes and none of the households produced sufficient vegetables to cover their needs on a yearly basis (de Jager et al. 2018), indicating that other factors are limiting. Model results indicate that households need to grow a wide variety of crops for their own food provisioning and it may be difficult to adapt their crop rotations due to labour constraints (Nin-Pratt and McBride 2014), seasonality and knowledge about the cultivation of specific crops. Also not all farmers will achieve the average yields.

Our model results also suggest that when household do not need to produce their own food needs (scenario B), producing one or two of the most lucrative cash crops and purchasing all their food needs will result in the highest revenue. Although specialization in the most profitable crop is a short term economic option to increase income of rural households (Klasen et al. 2016; Sibhatu and Qaim 2018), small farms will rarely produce only one or two crops to avoid the risks related to diseases, weather and market shocks. In addition, due to inelastic food markets the scenario of producing only one or two profitable crops is unrealistic as the market will become saturated when applied by many households. Markets and infrastructure need to function well: all of the cash crops need to be sold and sufficient diverse foods need to be available and affordable at the market at the right time. In addition to the need of well-functioning markets, the income also needs to be used to purchase the quantities and diversity of foods needed to cover the food and nutrient needs of a household, an assumption that rarely holds (Jones 2017; Herforth and Ahmed 2015). Therefore to ensure that mainstream agricultural interventions will result in nutritious diets they need to be nutrition-sensitive and include behaviour change communication strategies and activities enhancing women’s empowerment (Ruel et al. 2018).

Agricultural interventions

Among the mainstream agricultural interventions tested and compared with average yields, irrigation and increasing yield of vegetables resulted in the relative highest revenue in both scenarios A and B. With irrigation, crop cultivation can be extended to more seasons also including the opportunity of extra vegetables (our findings show as being most lucrative) to be cultivated. Although irrigation scenarios resulted in a doubled relative revenue compared to standard yields, the costs of irrigation are not included in our model and will probably significantly reduce the relative revenue. Due to the initial investment required for irrigation, it is unlikely to be a feasible option for poorer households. Increased vegetable yields scenario, includes cultivation of onion, watermelon and sweet potato suggesting these to be the most lucrative. These crops are currently indeed considered to be the most lucrative cash crops in Northern Ghana by local experts (Fusta Azupogo, Personal Communication, December 2018). Increasing yields of grains, starchy roots and legumes did not increase revenue compared with standard average yields. But increasing yields of grains and legumes did decrease land size needed while, especially for legumes, resulting in similar revenues as standard average yield scenario. This implies that increasing yields of legumes and grains, provided they can improve management and/or afford inputs, will allow households with a limited farm size to maintain a similar level of revenue while covering their food needs for a nutritious diet.

Conclusion

A farm-level system approach provides valuable insights in the optimal crop combination and potential contribution of mainstream agricultural interventions in achieving nutritious diets in all seasons. Our results show that the average farm size of households in rural Northern Ghana should be sufficient to produce the food needs for a nutritious diet. However, unless irrigation is available, the household's vegetable and fruit dietary needs cannot be covered during the so-called hunger season by home production. Increasing yields of legumes and grains will allow households with a limited farm size to maintain a similar level of revenue while covering their food needs for a nutritious diet. When farm size is not limited, increasing yields of vegetables and irrigation are most lucrative. When household do not produce their own food needs and need income from agriculture to purchase food, our analysis suggests that specialization in cash crop production will result in the largest farm income. However, specialization comes with increased risks related to diseases, weather and market shocks. To ensure mainstream agricultural interventions will indeed result in nutritious diets they need to be nutrition-sensitive and include behaviour change communication strategies and activities enhancing women's empowerment (Ruel et al. 2018). Using a farm-level system approach provided three major insights. First, considering seasonality is crucial in nutrition sensitive farming. Ensuring a year-round nutritious diet requires enhanced availability of vegetables and fruits in the hunger season. Second, although staple crops are not nutrient-dense such as vegetables and fruits, increasing their yields may contribute to enhancing diets. It will decrease the farm size needed which enables households to produce sufficient to cover their food needs for a nutritious diet. Third, our approach confirms that smaller farms are unable to produce sufficient food to cover their needs and will depend on their income, both from agriculture and other sources, and the availability of foods on markets to meet their dietary needs.

References

Abizari, A.-R., Azupogo, F., Nagasu, M., Creemers, N., & Brouwer, I. D. (2017). Seasonality affects dietary diversity of school-age children in northern Ghana. *PLoS One, 12*(8), e0183206.

Anker, R. (2006). Living wages around the world: A new methodology and internationally comparable estimates. *International Labour Review, 145*(4), 309-338.

Armar-Klemesu, M., Zakariah-Akoto, S., & Osei-Menya, S. (2016). Feeding infants and young children in Karaga district, Northern region: A focused ethnographic study. Washington D.C., US: GAIN and USAID.

Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality. *Annual Review of Environment and Resources, 28*(1), 315-358.

de Jager, I., Abizari, A.-R., Douma, J. C., Giller, K. E., & Brouwer, I. D. (2017). Grain legume cultivation and children's dietary diversity in smallholder farming households in rural Ghana and Kenya. *Food Security, 9*(5), 1053-1071.

de Jager, I., Giller, K. E., & Brouwer, I. D. (2018). Food and nutrient gaps in rural Northern Ghana: Does production of smallholder farming households support adoption of food-based dietary guidelines? *PLoS One, 13*(9), e0204014.

Devereux, S. (2009). Seasonality and social protection in Africa. In D. Hughes (Ed.). www.future-agricltures.org: Future agricultures

Domènech, L. (2015). Improving irrigation access to combat food insecurity and undernutrition: A review. *Global Food Security, 6*, 24-33.

Du, L., Pinga, V., Klein, A., & Danton, H. (2015). Leveraging agriculture for nutrition impact through the Feed the Future initiative. *Adv Food Nutr Res, 74*, 1-46.

FAO (2010). Fats and fatty acids in human nutrition. Report of an expert consultation. Rome: FAO.

FAO (2013). FAOSTAT: Food balance sheet. Rome, Italy: FAO.

FAO (2014). Ghana: Irrigation market brief. Rome: FAO.

FAO (2016). FAOSTAT: crop statistics for Ghana.

FAO (2018). FAO Crop calendar. http://www.fao.org/agriculture/seed/cropcalendar/searchbycountry.do. Accessed October 2018.

Fentahun, N., Belachew, T., Coates, J., & Lachat, C. (2018). Seasonality and determinants of child growth velocity and growth deficit in rural southwest Ethiopia. *BMC Pediatrics, 18*, 20.

Ferguson, Darmon, N., Fahmida, U., Fitriyanti, S., Harper, T. B., & Premachandra, I. M. (2006). Design of optimal food-based complementary feeding recommendations and identification of key "problem nutrients" using goal programming. *The Journal of Nutrition, 136*, 2399-2404.

Ferguson, Gibson, R. S., Opare-Obisaw, C., Osei-Opare, F., Lamba, C., & Ounpuu, S. (1993). Seasonal food consumption patterns and dietary diversity of rural preschool Ghanaian and Malawian children. *Ecology of Food and Nutrition, 29*(3), 219-234.

Franke, A. C., Rufino, M. C., & Farrow, A. (2011). Characterisation of the impact zones and mandate areas in the N2Africa project. Wageningen, The Netherlands: N2Africa.

Gibson, R. S., & Ferguson, E. L. (2008). An interactive 24-hour recall for assessing the adequacy of iron and zinc intakes in developing countries. *HarvestPlus Technical Monograph 8*. Washington DC, USA & Cali, Colombia: IFPRI & CIAT.

Global Yield Gap Atlas (2018). Global Yield Gap and Water Productivity Atlas. www.yieldgap.org. Accessed October 2018.

Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security, 7*(3), 505-520.

Herforth, A., & Harris, J. (2014). Understanding and applying primary pathways and principles. Brief 1: Improving nutrition through agriculture. Arlington, USA: USAID/Strengthening Partnerships, Results, and Innovations in Nutrition Globally (SPRING) Project.

HLPE (2017). Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. . Rome.

Institute of Statistical Social and Economic Research (University of Ghana), & Economic Growth Center (Yale University) (2009). Socioeconomic Panel Survey: 2009-2010. Ghana. In T. W. B. Development Economics Data Group (DECDG) (Ed.). Washington DC: Living Standards Measurement Study (LSMS).

Jones, A. D. (2017). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. *Nutrition Reviews*.

Ker, A. (1995). *Farming systems in the African Savanna*. Canada: International Development Research Centre (IDRC).

Kermah, M., Franke, A. C., Adjei-Nsiah, S., Ahiabor, B. D. K., Abaidoo, R. C., & Giller, K. E. (2017). Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. *Field Crops Research, 213*, 38-50.

Khoury, C. K., Bjorkman, A. D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L. H., & Struik, P. C. (2014). Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences of the United States of America, 111*, 4001-4006.

Klasen, S., Meyer, K. M., Dislich, C., Euler, M., Faust, H., Gatto, M., Hettig, E., Melati, D. N., Jaya, I. N. S., Otten, F., Pérez-Cruzado, C., Steinebach, S., Tarigan, S., & Wiegand, K. (2016). Economic and ecological trade-offs of agricultural specialization at different spatial scales. *Ecological Economics, 122*, 111-120.

Kujinga, P., Borgonjen-van den Berg, K. J., Superchi, C., Ten Hove, H. J., Onyango, E. O., Andang'o, P., Galetti, V., Zimmerman, M. B., Moretti, D., & Brouwer, I. D. (2018). Combining food-based dietary recommendations using Optifood with zinc-fortified water potentially improves nutrient adequacy among 4- to 6-year-old children in Kisumu West district, Kenya. *Maternal & Child Nutrition, 14*(2), e12515.

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annual Review of Environment and Resources, 34*(1), 179-204.

Masters, W. A., Bai, Y., Herforth, A., Sarpong, D. B., Mishili, F., Kinabo, J., & Coates, J. C. (2018). Measuring the Affordability of Nutritious Diets in Africa: Price Indexes for Diet Diversity and the Cost of Nutrient Adequacy. *American Journal of Agricultural Economics*, aay059-aay059.

Nin-Pratt, A., & McBride, L. (2014). Agricultural intensification in Ghana: Evaluating the optimist's case for a Green Revolution. *Food Policy, 48*, 153-167.

Pinstrup-Andersen, P. (2012). The food system and its interaction with human health and nutrition. In *Reshaping agriculture for nutrition and health: an IFPRI 2020 book* (pp. 21-29). Washington DC, USA: IFPRI.

Population Reference Bureau (2018). 2018 World Population Data Sheet. Washington D.C.: PRB.

Roelen, S. (2017). Exploring the current status of ruminant value chains in northern Ghana, and the role of grain legume residues as a livestock feed resource. MSc Thesis. Wageningen: Wageningen University.

Ruel, Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security, 17*, 128-153.

Santika, O., Fahmida, U., & Ferguson, E. L. (2009). Development of food-based complementary feeding recommendations for 9- to 11-month-old peri-urban Indonesian infants using linear programming. *The Journal of Nutrition, 139*, 135-141.

Sibhatu, K. T., & Qaim, M. (2018). Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy*.

SRID MoFA (2006). Average yield of major crops in Karaga district in Northern Ghana.

SRID MoFA (2015). Average yield of selected commodities in Ghana.

Talsma, E. F., Borgonjen-van den Berg, K. J., Melse-Boonstra, A., Mayer, E. V., Verhoef, H., Demir, A. Y., Ferguson, E. L., Kok, F. J., & Brouwer, I. D. (2017). The potential contribution of yellow cassava to dietary nutrient adequacy of primary-school children in Eastern Kenya; the use of linear programming. *Public Health Nutrition*, 1-12.

Tittonell, P., & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research, 143*, 76-90.

UNICEF, WHO, & World Bank (2018). Level and trends in child malnutrition. USA: UNICEF, WHO & World Bank Group.

USDA (2016). USDA national nutrient database for standard reference, Release 28. http://www.ars.usda.gov/nea/bhnrc/ndl. Accessed February 2018.

van Vugt, D., & Franke, A. C. (2018). Exploring the yield gap of orange-fleshed sweet potato varieties on smallholder farmers' fields in Malawi. *Field Crops Research, 221*, 245-256.

WHO, & FAO (2004). Vitamin and mineral requirements in human nutrition. Second edition. *Geneva/Rome: WHO/FAO*.

WHO, UNICEF, USAID, AED, UCDAVIS, & IFPRI (2007). Indicators for assessing infant and young child feeding practices. Conclusions of a consensus meeting held 6–8 November 2007 in Washington DC, USA. Geneva, Switzerland: WHO.

Appendices

Appendix 1

Consumer units (CU) for translation of modelled optimised diet for non-breastfed children 12 to 23months old to optimised diet for an average household

Groups WHO	Calcium	Zinc	Iron	Vitamin A	Thiamine	Riboflavin	Niacin	Vitamin B6	Folate	Vitamin B12	Vitamin C	*Average*	*Average, merged groups**
	Consumer Units (CU)												
0 - 6 months	0.1	**0.8**	0	0	0.1	0.1	0.1	0	0	0	0	*0.4*	*0.5*
7 - 12 months	0.1	0.5	0.5	0	0.2	0.2	0.3	0.2	0	0	**0.7**	*0.5*	
1 - 3 y	0.3	0.2	0.4	0	0.3	0.2	0.4	0.3	0.2	0.1	0.1	*0.5*	
4 - 6 y	0.6	0.6	0.5	0.7	0.5	0.5	0.6	0.4	0.5	0.5	0.7	*0.6*	*0.7*
7 - 9 y	0.7	0.6	0.5	0.9	0.8	0.8	0.9	0.7	0.8	0.8	0.8	*0.7*	
Females, 10 - 14 y, pre-menarche	1.3	1.0	**0.6**	**1.4**	1.0	1.0	1.1	0.9	1.0	1.0	1.0	*1.0*	
Females, 10 - 14 y, menarche	1.3	1.0	0.7	**1.4**	1.0	1.0	1.1	0.9	1.0	1.0	1.0	*1.0*	*1.1*
Females, 15 - 18 y	1.3	1.3	1.0	1.4	1.0	1.0	1.1	0.9	1.0	1.0	1.0	*1.1*	
Males, 10 - 14 y	1.3	1.0	**0.7**	1.4	1.2	1.1	1.1	1.0	1.0	1.0	1.0	*1.1*	*1.1*
Males, 15 - 18 y	1.3	**1.6**	0.9	1.4	1.2	1.1	1.1	1.0	1.0	1.0	1.0	*1.1*	
Females, 19 - 50 y, premenopausal	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	*1.0*	
Females, 51 - 65 y, menopausal	1.3	1.0	**0.5**	1.0	1.0	1.0	1.0	1.2	1.0	1.0	1.0	*1.0*	*1.0*
Females, 65+ y	1.3	1.0	**0.5**	1.1	1.0	1.0	1.0	1.2	1.0	1.0	1.1	*1.0*	
Pregnant women	**1.2**	1.7	**3.8**	1.4	1.3	1.3	1.3	1.5	1.6	**1.1**	1.3	*1.6*	*1.6*
Lactating women	1.0	1.3	**0.7**	**1.7**	1.5	1.4	1.2	1.5	1.4	1.2	**1.7**	*1.3*	*1.3*
Males, 19 - 50 y	1.0	**2.1**	**0.7**	1.1	1.2	1.1	1.1	1.0	1.0	1.0	1.1	*1.1*	
Males, 51 - 65 y	1.0	**2.1**	**0.7**	1.1	1.2	1.1	1.1	1.3	1.0	1.0	1.1	*1.2*	*1.2*
Males, 65+ y	1.3	**2.1**	**0.7**	1.1	1.2	1.1	1.1	1.3	1.0	1.0	1.1	*1.2*	

Consumer units are based on EARs of each nutrient (WHO/FAO 2004) for specific group relative to EAR of women 19 to 50 years old who are not pregnant or lactating. Averages of the consumer units of all 11 nutrients were calculated for each group (average are calculated for each row). Average consumer units are used to calculate quantity of foods needed for each household member based on optimised diet for non-breastfed children 12 to 23 months old.
***Bold** = 0.4 or more CU difference of a specific nutrient with average CU for all nutrients for a specific group.*

***For the calculation of the total consumer units needed for an average household**: we used the median number of household members for different groups (infants of 0-12 months, children of 1-9 years, females of 10-18 years, males of 10-18 years, females ≥18 years, pregnant women, lactating women and males ≥19 years) and their respective calculated consumer unit. When within a specific age group there are different consumer units (different age categories in one group), the highest consumer unit was used.

Appendix 2

Coverage of energy and nutrient needs by optimised diet for non-breastfed children of 12-23 months old (optimised diet used to translate to household food needs) and an average household

	Children 12-23 months, non-breastfed (0.5 CU)	Average household (12.2 CU)
Nutrients	Coverage %, RNI	
Energy (Kcal)[a]	107.4	70
Macronutrients		
Fat[b]	304.8	**53**
Protein[c]	125.4	157
Micronutrients		
Calcium	**33.2**	81
Iron	78.0	**67**
Zinc	150.7	104
Vitamin A[d]	**30.2**	104
Thiamin	142.7	149
Riboflavin	98.6	131
Niacin	168.4	166
Vitamin B6	153.1	102
Folate	89.4	**69**
Vitamin B12	**2.3**	76
Vitamin C	**42.1**	110

Bold = coverage below 70% of RNI. The nutrients needs of an average household are calculated by the sum of the nutrient needs of the median number of persons for each specific age and/or sex group, selecting the person with the highest energy needs within the group assuming he/she also has the highest needs of other nutrients.
[a]energy requirements WHO 2001, assume moderate activity
[b]WHO 2010 AMDR, based on energy requirements
[c]Safe level.
[d]Recommended safe intakes.

Appendix 3

Mathematical description of models

Indices

s = seasons

f = food groups

c = crops

Data

$Foodgroup\_requirement_{f}$ = For each food group: requirements [kg/season]

$Yield_{c}$ = For each crop: yield [kg/ha]

$Waste\_factor_{c}$ = For each crop: quantity of crop consumed [% of crop consumed]

$Food\_availability\_season_{s,c}$ = For each season, for each crop: yield corrected for storage losses [% yield available]

$On\_farm\_food\_availability_{f,s}$ = For each food group, for each season: crops available [1=yes, 0=no]

$Area\_needed\_croppingcycle_{s,c}$ = For each season, for each crop: land occupation [1=yes, 0=no]

$Food\_prices_{s,c}$ = For each season, for each crop: price [GH₵/kg]

$Valid\_foodgroup\_crop\_combi_{f\ c}$ = For each food group, for each crop: membership [1=yes, 0=no]

$No\_food\_in\_season_{s,f,c}$ = For each season, for each food group, for each crop: availability [0=no crops available, >0=crops available]

Variables

$Total\_area$ = Total farm size [ha]

$Total\_area\_season_{s}$ = Per season: farm size occupied [ha]

$Revenue$ = Total farm income from own produce minus costs of foods purchased to cover food group requirements [GH₵]

$Xarea_{s,f,c}$ = Per season, per food group, per crop: total land area allocated to production [ha]

$Crop\_produced_{s,f,c}$ = Per season, per food group, per crop: total production [kg]

Crop_consumed_from_farming$_{s,f,c}$ = Per season, per food group, per crop: total consumed from own production to cover food group requirements [kg]

Crop_supplied$_{s,f,c}$ = Per season, per food group, per crop: total supplied not from own production [kg]

Cost_crop_supplied$_{s}$ = Per season: total costs of crops supplied not from own production [GH₵]

Non_crop_supplied$_{s,f,c}$ = Per season, per food group, per crop: total non-crop food supplied [kg]

Cost_non_crop_supplied$_{s}$ = Per season: total costs of non-crop foods supplied [GH₵]

Value_total_crop_sold$_{f,c}$ = Per food group, per crop: total monetary value of own produce sold [GH₵]

Minimize farm size, priority for food needs covered by own production

Objective:

Minimise crop land:

Minimise (*Total_Area*)   [ha]

Subject to:

Sum of total area allocated per season is smaller or equal to total area allocated:

$\sum_s Total\_area\_season_s \leq Total\_area$ [ha]

For each season, for each food group and for each crop the sum of area allocated is smaller or equal to total area allocated per season, for all food groups that can be produced on the farm and for all valid food group and crop combinations:

$\sum_{f,c} Xarea_{s,f,c} \leq Total\_area\_season_s$ $\forall f$ produce on farm *and* $\forall$ valid *f*,*c*-combinations [ha]

Area allocated per season per food group per crop is equal to area allocated in season 1 per food group per crop (same formula for season 2, 3 and 4), for all food groups that can be produced on the farm and for all valid food group and crop combinations and for all crops available in season:

$Xarea_{s,f,c} = Xarea_{s1,f,c}$ [ha]
$\forall$ *f* produce on farm *and* $\forall$ valid *f*,*c*-combinations *and* $\forall$ *c* using land *and* $\forall$ *c* available in season 1

Total sum of the quantity of a crop produced per season per food group is greater or equal to total sum of crop consumed from farming to cover food group requirements per season corrected for waste and storage losses, for all food groups that can be produced on the farm and for all valid food group and crop combinations and for all crops available in season:

$$\sum_s Crop\_produced_{s,f,c} \geq \sum_s Crop\_consumed\_from\_farming_{s,f,c} * \left(\frac{1}{Waste\_factor_c}\right) * \left(\frac{1}{Food\_availability\_season_{s,c}}\right) \quad [kg]$$
$\forall$ *f* produce on farm *and* $\forall$ valid *f*,*c*-combinations *and* $\forall$ *c* available in season

Total quantity of a crop produced is equal to allocated area per season per food group per crop times the yield of the crop, for all food groups that can be produced on the farm and for all valid food group and crop combinations and for all crops available in season:

$Crop\_produced_{s,f,c} = Xarea_{s,f,c} * Yield_c$
$\forall$ *f* produce on farm *and* $\forall$ valid *f*,*c*-combinations *and* $\forall$ *c* available in season [kg]

Sum of quantity of crops consumed from farming to cover food group requirements per season (for crop available in season) plus sum of quantity of crops supplied per food group per season (for crops not available in season) is both:

equal or greater to the food group requirements:

$$\sum_c Crop\_consumed\_from\_farming_{s,f,c} \ (\forall\ c \text{ available in season}) + \sum_c Crop\_supplied_{s,f,c} \ (\forall\ c \text{ not available in season and } \forall \text{ cheapest crop from } f) \geq Foodgroup\_requirement_f$$
$\forall$ *f* produce on farm *and* $\forall$ valid *f*,*c*-combinations [kg]

and equal or greater to the sum of the food group requirements per season:

$\sum_{s,c} Crop\_consumed\_from\_farming_{s,f,c}$ ($\forall$ c available in season) $+$
$\sum_{s,c} Crop\_supplied_{s,f,c}$ ($\forall$ c not available in season and $\forall$ cheapest crop from f) $\geq$
$\sum_{s} Foodgroup\_requirement_{f}$
$\forall$ *f* produce on farm *and* $\forall$ valid *f*,*c*-combinations [kg]

Total quantity of a crop that need to be supplied per food group per season is none, for all food groups where crop(s) are available in a season:

$Crop\_supplied_{s,f,c} = 0$ $\forall$ *f* where *c* are available in a *s* [kg]

Total monetary value of crop sold per food group is equal to sum of crop produced per season per food group times price of crop per season minus sum of crop consumed from farming to cover food group requirements per season corrected for waste and storage losses times price of crop per season, for all food groups that can be produced on the farm and for all valid food group and crop combinations and for all crops available in season:

$Value\_total\_crop\_sold_{f,c} = (\sum_{s} Crop\_produced_{s,f,c} * Food\_prices_{c,s})$ -
$(\sum_{s} Crop\_consumed\_from\_farming_{s,f,c} * \left(\frac{1}{Waste\_factor_{c}}\right) * (\frac{1}{Food\_availability\_season_{s,c}}) *$
$Food\_prices_{c,s})$
$\forall$ valid *f*,*c*-combinations *and* $\forall$ *c* available in season [GH₵]

Total costs of crops supplied per season is equal to sum crops supplied per food group per season times price of the crop per season, for all food groups that can be produced on the farm and for all valid food group and crop combinations and for cheapest crop available in a food group:

$Cost\_crop\_supplied_{s} = \sum_{f,c} Crop\_supplied_{s,f,c} * \ Food\_prices_{c,s}$
$\forall$ *f* produce on farm *and* $\forall$ valid *f*,*c*-combinations *and* $\forall$ cheapest crop from f [GH₵]

Total quantity of non-crop foods needed per season per food group is equal to the total quantity of crops supplied equal to food group requirements, for all food groups that cannot be produced on the farm and for all valid food group and crop combinations and for cheapest crop available in a food group:

$Crop\_supplied_{s,f,c} = Foodgroup\_requirement_{f}$
$\forall$ f not produced on farm *and* $\forall$ valid f,c-combinations *and* $\forall$ cheapest crop from f
[GH₵]

Total costs of non-crop foods supplied per season is equal to sum foods supplied per food group per season times price of the crop per season, for all food groups that cannot be produced on the farm and for all valid food group and crop combinations and for cheapest crop available in a food group:

$Cost\_non\_crop\_supplied_{s} = \sum_{f,c} Crop\_supplied_{s,f,c} * Food\_prices_{c,s}$
$\forall$ f not produced on farm *and* $\forall$ valid f,c-combinations *and* $\forall$ cheapest crop from f
[GH₵]

Total costs of foods supplied is equal to the sum of costs of crops supplied and cost of non-crop foods supplied, for all valid food group and crop combinations:

$Total\_costs\_food\_supplied = \sum_{s} Cost\_crop\_supplied_{s} + Costs\_non\_crop\_supplied_{s}$
[GH₵]

Total value of crops sold per food group is equal to total costs of food supplied, for all valid food group and crop combinations:

$\sum_{f,c} Value\_total\_crop\_sold_{f,c} = Total\_costs\_food\_supplied$ $\forall$ valid f,c-combinations [GH₵]

Revenue is equal to sum of total value of crops sold per food group minus costs of foods supplied:

Revenue = $\sum_{f,c} Value\_total\_crop\_sold_{f,c} - Total\_costs\_food\_supplied$

$\forall$ valid f,c combinations [GH₵]

Maximize revenue, priority for food needs covered by own production

Objective:

Maximise revenue:
Maximise (Revenue = $\sum_{f,c} Value\_total\_crop\_sold_{f,c} - Total\_costs\_food\_supplied$)

$\forall$ valid f,c combinations [GH₵]

Subject to:

Same as Model1,
except this model is **not subject to**:

Total value of crops sold per food group is equal to total costs of food supplied, for all valid food group and crop combinations:

$\sum_{f,c} Value\_total\_crop\_sold_{f,c} = Total\_costs\_food\_supplied$ $\forall$ valid f,*c*-combinations [GH₵]

and in addition **is subject to**:

$\sum_{f,c} Xarea_{s,f,c} \leq$ land constraint (outcome from model1)

Maximize revenue, no priority for food needs covered by own production

Objective:

Maximise revenue:
Maximise {Revenue = $\sum_{f,c} Value\_total\_crop\_sold_{f,c} - Total\_costs\_food\_supplied$

$\forall$ valid f,c combinations [GH₵]

Subject to:

Same as Model2,
except this model is also **not subject to**:

Total quantity of a crop that need to be supplied per food group per season is none, for all food groups where crop(s) are available in a season:

$Crop\_supplied_{s,f,c} = 0$ $\forall f$ where *c* are available in a *s*

Minimize farm size, no priority for food needs covered by own production

Objective:

Minimise crop land:

Minimise {*Total_Area*}

Subject to:

Same as Model1,
except this model is **not subject to**:

Total quantity of a crop that need to be supplied per food group per season is none, for all food groups where crop(s) are available in a season:

$Crop\_supplied_{s,f,c} = 0 \quad \forall f$ where c are available in a s

Appendix 4

Average household composition (n=337) for each sex and age group[a] and for the whole household: median number, consumer unit for specific group and consumer unit for average household

Groups	Median [25th, 75th]	CU[b] group	CU[b] average household
Infants, 0-12 mo	1 [0, 1]	0.5	0.5
Children, 1-9 y	5 [3, 7]	0.7	3.5
Females, 10-18 y	1 [0, 2]	1.1	1.1
Males, 10-18 y	1 [0, 2]	1.1	1.1
Females, >19 y	3 [2, 6]	1.0	1.0
Pregnant women, >19 y	*0 [0, 1]*	*1.6*	*0*
Lactating women, >19 y	*2 [1, 2]*	*1.3*	*2.6*
Males, >19 y	2 [1, 4]	1.2	2.4
Total household members	14 [9, 21]		12.2

[a]Groups are based on the groups as defined by WHO and FAO (2004) for EARs of nutrients
[b]CU=consumer unit (for calculation see Appendix 1)

Appendix 5

Descriptive data used in the model

f = food group (1 to 14)

f	**Food group description**	***f* requirement** *average hh in kg/s*	***f* availability on farm per s** *o=no, 1=yes*					
			s1	s2	*s2*[a]	*s2*[b]	s3	s4
1	vegetable_oil	14.51	0	0	*0*	*0*	0	0
2	whole_grains_and_products	205.95	1	1	*1*	*1*	1	1
3	cooked_beans	92.44	1	1	*1*	*1*	1	1
4	nuts_and_seeds	68.99	1	1	*1*	*1*	1	1
5	soybeans_and_products	14.42	1	1	*1*	*1*	1	1
6	starchy_plant_foods	21.17	1	1	*1*	*1*	1	1
7	small_fish_with_bones	3.38	0	0	*0*	*0*	0	0
8	eggs	64.61	0	0	*0*	*0*	0	0
9	vitamin_A_source_darkgreenleafyvegetables	67.89	1	0	*1*	*1*	1	1
10	vitamin_A_source_other_vegetables	16.70	0	0	*0*	*0*	0	0
11	vitamin_C_rich_vegetables	61.23	1	0	*1*	*1*	1	1
12	other_vegetables	14.42	1	0	*0*	*1*	1	1
13	other_fruit	262.71	1	0	*0*	*1*	1	1
14	fluid_powdered_milk_fortified	22.27	0	0	*0*	*0*	0	0

[a]*Availability in second season for storage scenario.*
[b]*Availability in second season for irrigation scenario.*

s = season (1 to 4)

s1	Nov_Jan_dry1
s2	Feb_April_dry2
s3	May-July_rain1
s4	Aug_Oct_rain2

c = crops (names are used in modelling)

crop_name	***f***	**Yield** *Kg/ha*	**Yield**[a] *Kg/ha*	**Yield**[b] *Kg/ha*	**Yield**[c] *Kg/ha*	**Waste** *factor*	**Crop availability**[d] *(harvest+storage loss)*				**Land needed** *o=no, 1=yes*				**Food prices** *GH₵/kg*			
							s1	s2	s3	s4	s1	s2	s3	s4	s1	s2	s3	s4
sorghum_guineacorn	2	930	930	**5520**	**1395**	1.00	1.00	0.88	0.88	0.88	1	0	1	1	3.85	3.28	3.60	4.07
maize_1	2	1560	1560	**5920**	**2340**	1.00	0.90	0.90	0.00	1.00	0	0	1	1	2.12	2.00	2.30	2.23
maize_2	2	1560	1560	**5920**	**2340**	1.00	1.00	0.90	0.90	0.00	1	0	0	1	2.12	2.00	2.30	2.23
millet_1	2	770	770	**2560**	**1155**	1.00	0.88	0.88	0.00	1.00	0	0	1	1	5.06	4.05	4.40	5.10
millet_2	2	770	770	**2560**	**1155**	1.00	1.00	0.88	0.88	0.00	1	0	0	1	5.06	4.05	4.40	5.10
rice_1	2	1500	1500	**4720**	**2250**	1.00	0.96	0.96	0.00	1.00	0	0	1	1	3.01	2.64	3.10	3.32
rice_2	2	1500	1500	**4720**	**2250**	1.00	1.00	0.96	0.96	0.00	1	0	0	1	3.01	2.64	3.10	3.32
cassava	6	3350	**10000**	**40000**	**15000**	0.84	1.00	0.98	0.98	0.98	1	0	1	1	1.36	1.26	1.40	1.41
yam	6	9400	9400	**40000**	**14100**	0.86	0.94	0.94	0.00	1.00	1	1	1	1	1.54	1.73	1.90	1.56
cocoyam	6	6490	**10000**	**40000**	**15000**	0.86	0.94	0.94	0.00	1.00	1	0	1	1	1.54	1.73	1.90	1.56
plantain	6	10900	10900	**40000**	**16350**	0.69	0.94	0.94	0.00	1.00	1	1	1	1	1.54	1.73	1.90	1.56
sweetpotatoes_1	6	1870	**10000**	**40000**	**15000**	0.75	0.00	1.00	0.94	0.94	1	1	0	0	1.54	1.73	1.90	1.56

sweetpotatoes_2	6	1870	**10000**	**40000**	**15000**	0.75	0.94	0.00	1.00	0.94	0	1	1	0	1.54	1.73	1.90	1.56
cowpea_1	3	1230	1230	**2272**	**1845**	1.00	0.82	0.82	0.00	1.00	0	0	1	1	5.52	4.42	4.80	5.57
cowpea_2	3	1230	1230	**2272**	**1845**	1.00	1.00	0.82	0.82	0.00	1	0	0	1	5.52	4.42	4.80	5.57
pigeonpea_1	3	1200	1200	**2218**	**1800**	1.00	0.82	0.82	0.00	1.00	0	0	1	1	1.96	1.56	1.70	1.97
pigeonpea_2	3	1200	1200	**2218**	**1800**	1.00	1.00	0.82	0.82	0.00	1	0	0	1	1.96	1.56	1.70	1.97
bambaragroundnut_1	4	700	700	**1432**	**1050**	1.00	0.95	0.95	0.00	1.00	0	0	1	1	6.40	5.61	6.60	7.06
bambaragroundnut_2	4	700	700	**1432**	**1050**	1.00	1.00	0.95	0.95	0.00	1	0	0	1	6.40	5.61	6.60	7.06
neri	4	140	140	140	140	1.00	1.00	0.90	0.90	0.90	1	0	0	1	4.17	3.55	3.90	4.41
bongu	4	140	140	140	140	1.00	1.00	0.90	0.90	0.90	1	1	1	1	7.60	6.46	7.10	8.02
cashewnut	4	560	560	560	560	1.00	1.00	0.90	0.90	0.90	1	1	1	1	7.60	6.46	7.10	8.02
soybean_1	5	810	810	**4480**	**1215**	1.00	0.82	0.82	0.00	1.00	0	0	1	1	2.88	2.30	2.50	2.90
soybean_2	5	810	810	**4480**	**1215**	1.00	1.00	0.82	0.82	0.00	1	0	0	1	2.88	2.30	2.50	2.90
ayoyoleaves_1	9	9000	9000	9000	**13500**	0.94	0.00	0.00	1.00	0.95	0	0	1	0	4.95	3.96	4.30	4.30
ayoyoleaves_2	9	9000	9000	9000	**13500**	0.94	0.95	0.00	0.00	1.00	0	0	0	1	4.95	3.96	4.30	4.30
ayoyoleaves_irrigated1	9	9000	9000	9000	**13500**	0.94	1.00	0.95	0.00	0.00	1	0	0	0	4.95	3.96	4.30	4.30
ayoyoleaves_irrigated2	9	9000	9000	9000	**13500**	0.94	0.00	1.00	0.95	0.00	0	1	0	0	4.95	3.96	4.30	4.30
braleaves_1	9	9000	9000	9000	**13500**	0.94	0.00	0.00	1.00	0.95	0	0	1	0	1.04	0.83	0.90	0.90
braleaves_2	9	9000	9000	9000	**13500**	0.94	0.95	0.00	0.00	1.00	0	0	0	1	1.04	0.83	0.90	0.90
braleaves_irrigated1	9	9000	9000	9000	**13500**	0.94	1.00	0.95	0.00	0.00	1	0	0	0	1.04	0.83	0.90	0.90
braleaves_irrigated2	9	9000	9000	9000	**13500**	0.94	0.00	1.00	0.95	0.00	0	1	0	0	1.04	0.83	0.90	0.90
amaranthusleaves_1	9	9000	9000	9000	**13500**	0.94	0.00	0.00	1.00	0.95	0	0	1	0	2.42	1.93	2.10	2.10
amaranthusleaves_2	9	9000	9000	9000	**13500**	0.94	0.95	0.00	0.00	1.00	0	0	0	1	2.42	1.93	2.10	2.10
amaranthusleaves_irrigated1	9	9000	9000	9000	**13500**	0.94	1.00	0.95	0.00	0.00	1	0	0	0	2.42	1.93	2.10	2.10

amaranthusleaves_irrigated2	9	9000	9000	9000	**13500**	0.94	0.00	1.00	0.95	0.00	0	1	0	0	2.42	1.93	2.10	2.10
Baobableaves[e]	9	-	-	-	-	0.94	-	-	-	-	-	-	-	-	1.04	0.83	0.90	0.90
okro_1	11	23160	23160	23160	**34740**	0.86	0.00	0.00	1.00	0.95	0	0	1	0	1.73	1.38	1.50	1.50
okro_2	11	23160	23160	23160	**34740**	0.86	0.95	0.00	0.00	1.00	0	0	0	1	1.73	1.38	1.50	1.50
okro_irrigated1	11	23160	23160	23160	**34740**	0.86	1.00	0.95	0.00	0.00	1	0	0	0	1.73	1.38	1.50	1.50
okro_irrigated2	11	23160	23160	23160	**34740**	0.86	0.00	1.00	0.95	0.00	0	1	0	0	1.73	1.38	1.50	1.50
tomatoes_1	11	8300	8300	8300	**12450**	0.91	0.00	0.00	1.00	0.00	0	0	1	0	2.67	3.30	3.30	3.30
tomatoes_2	11	8300	8300	8300	**12450**	0.91	0.00	0.00	0.00	1.00	0	0	0	1	2.67	3.30	3.30	3.30
tomatoes_irrigated1	11	8300	8300	8300	**12450**	0.91	1.00	0.00	0.00	0.00	1	0	0	0	2.67	3.30	3.30	3.30
tomatoes_irrigated2	11	8300	8300	8300	**12450**	0.91	0.00	1.00	0.00	0.00	0	1	0	0	2.67	3.30	3.30	3.30
onion_leaves_1	11	9220	9220	9220	**13830**	0.94	0.00	0.00	1.00	0.95	0	0	1	0	4.78	5.90	5.90	4.84
onion_leaves_2	11	9220	9220	9220	**13830**	0.94	0.95	0.00	0.00	1.00	0	0	0	1	4.78	5.90	5.90	4.84
onion_leaves_irrigated1	11	9220	9220	9220	**13830**	0.94	1.00	0.95	0.00	0.00	1	0	0	0	4.78	5.90	5.90	4.84
onion_leaves_irrigated2	11	9220	9220	9220	**13830**	0.94	0.00	1.00	0.95	0.00	0	1	0	0	4.78	5.90	5.90	4.84
cucumber_1	12	13820	13820	13820	**20730**	0.71	0.00	0.00	1.00	0.00	0	0	1	0	2.67	3.30	3.30	2.71
cucumber_2	12	13820	13820	13820	**20730**	0.71	0.00	0.00	0.00	1.00	0	0	0	1	2.67	3.30	3.30	2.71
cucumber_irrigated1	12	13820	13820	13820	**20730**	0.71	1.00	0.00	0.00	0.00	1	0	0	0	2.67	3.30	3.30	2.71
cucumber_irrigated2	12	13820	13820	13820	**20730**	0.71	0.00	1.00	0.00	0.00	0	1	0	0	2.67	3.30	3.30	2.71
pepper_1	12	9300	9300	9300	**13950**	0.82	0.00	0.00	1.00	0.00	0	0	1	0	3.30	3.30	3.30	2.71
pepper_2	12	9300	9300	9300	**13950**	0.82	0.00	0.00	0.00	1.00	0	0	0	1	3.30	3.30	3.30	2.71
pepper_irrigated1	12	9300	9300	9300	**13950**	0.82	1.00	0.00	0.00	0.00	1	0	0	0	3.30	3.30	3.30	2.71
pepper_irrigated2	12	9300	9300	9300	**13950**	0.82	0.00	1.00	0.00	0.00	0	1	0	0	3.30	3.30	3.30	2.71
onion_1	12	18830	18830	18830	**28245**	0.90	0.00	0.00	1.00	0.95	0	0	1	0	4.37	5.40	5.40	4.43

onion_2	12	18830	18830	18830	**28245**	0.90	0.95	0.00	0.00	1.00	0	0	0	1	4.37	5.40	5.40	4.43
onion_irrigated1	12	18830	18830	18830	**28245**	0.90	1.00	0.95	0.00	0.00	1	0	0	0	4.37	5.40	5.40	4.43
onion_irrigated2	12	18830	18830	18830	**28245**	0.90	0.00	1.00	0.95	0.00	0	1	0	0	4.37	5.40	5.40	4.43
palmnut_pulp[f]	12	-	-	-	-	1.00	-	-	-	-	-	-	-	-	1.71	1.46	1.60	1.60
eggplant_1	12	8880	8880	8880	**13320**	0.81	0.00	0.00	1.00	0.00	0	0	1	0	3.30	3.30	3.30	2.71
eggplant_2	12	8880	8880	8880	**13320**	0.81	0.00	0.00	0.00	1.00	0	0	0	1	3.30	3.30	3.30	2.71
eggplant_irrigated1	12	8880	8880	8880	**13320**	0.81	1.00	0.00	0.00	0.00	1	0	0	0	3.30	3.30	3.30	2.71
eggplant_irrigated2	12	8880	8880	8880	**13320**	0.81	0.00	1.00	0.00	0.00	0	1	0	0	3.30	3.30	3.30	2.71
melon_yellow	13	15400	15400	15400	15400	0.51	1.00	0.00	0.00	0.00	1	0	0	1	1.30	1.60	1.60	1.60
watermelon_1	13	26100	26100	26100	26100	0.51	0.00	0.00	0.00	1.00	0	0	1	1	0.46	0.50	0.50	0.49
watermelon_2	13	26100	26100	26100	26100	0.51	1.00	0.00	0.00	0.00	1	0	0	1	0.46	0.50	0.50	0.49
watermelon_irrigated1	13	26100	26100	26100	26100	0.51	0.00	1.00	0.00	0.00	1	1	0	0	0.46	0.50	0.50	0.49
watermelon_irrigated2	13	26100	26100	26100	26100	0.51	0.00	0.00	1.00	0.00	0	1	1	0	0.46	0.50	0.50	0.49
sheafruit_pulp	13	770	770	770	770	0.74	0.95	0.00	0.00	1.00	1	1	1	1	0.10	0.10	0.10	0.10
orange_1	13	19900	19900	19900	19900	0.74	0.00	0.00	0.00	1.00	1	1	1	1	1.20	1.30	1.30	1.26
orange_2	13	19900	19900	19900	19900	0.74	1.00	0.00	0.00	0.00	1	1	1	1	1.20	1.30	1.30	1.26
mango_1	13	7250	7250	7250	7250	0.71	0.00	0.00	1.00	0.00	1	1	1	1	1.84	1.84	1.60	1.60
mango_2	13	7250	7250	7250	7250	0.71	0.00	0.00	0.00	1.00	1	1	1	1	1.84	1.84	1.60	1.60
papaya_1	13	19395	19395	19395	19395	0.62	0.00	0.00	1.00	0.00	1	1	1	1	1.84	1.84	1.60	1.60
papaya_2	13	19395	19395	19395	19395	0.62	0.00	0.00	0.00	1.00	1	1	1	1	1.84	1.84	1.60	1.60
tomato_paste_concentrated	10	-	-	-	-	1.00	-	-	-	-	-	-	-	-	18.3	18.3	18.3	18.3
vegetable_oil_fortified	1	-	-	-	-	1.00	-	-	-	-	-	-	-	-	11.8	11.8	11.8	11.8
small_fish_with_bones	7	-	-	-	-	0.84	-	-	-	-	-	-	-	-	12.0	12.0	12.0	12.0

eggs	8	-	-	-	-	0.88	-	-	-	-	-	-	-	-	9.50	9.50	9.50	9.50
fluid_powdered_milk_fortified	14	-	-	-	-	1.00	-	-	-	-	-	-	-	-	8.70	8.70	8.70	8.70

[a]*Average yields with adjusted yields for starchy roots (cassava, cocoyam, sweet potatoes (van Vugt and Franke 2018) that are assumed more realistic than reported averages for Karaga and for Ghana.*

[b]*Best yields are either modelled best water limited yields or yields based on best attainable yields found, both corrected for the fact that most average farm yields often begin to plateau when they reach 80% of best yields (Lobell et al. 2009; Cassman et al. 2003)*

[c]*50% increased yields based on average yields.*

[d]*Availability for storage scenario for all leafy vegetables (ayoyo, bra, amaranth and onion leaves): assumed 0.95 availability outside of season that is harvested (drying of leaves).*

[e]*Baobab leaves are not actively grown, 'picked from the wild' but can be bought from the market.*

[f]*Palmnuts are produced in the south of Ghana (very rare in the North) but can be bought on the market.*

Appendix 6

Maximum revenue^ for an average household in Northern Ghana with priority to cover food needs by own production (scenario A), for 100% and 80% of the prices assumed

	Farm size cultivated (ha)		Maximum revenue (100% prices)			Maximum revenue (80% prices)		
			absolute	***relative***		***absolute***	***relative***	
	S1, S3, S4	*S2*	*GH₵/year*	*GH₵/year*	*GH₵/year/ha*	*GH₵/year*	*GH₵/year*	*GH₵/year/ha*
1. Average yields	1.43	0.26	116600	116600 (100%)	81538 (100%)	93300	93282 (100%)	100%
2. Expand availability[a]								
a. Storage[b]	1.41	0.33	102900	88%	90%	82300	88%	89%
b. Irrigation	1.43	1.43	264200	227%	227%	211400	227%	227%
3. Improved crop yields								
a. Best yields[c]								
grains	1.02	0.38	62700	54%	75%	50200	54%	75%
starchy roots	1.43	0.26	129000	111%	111%	103200	111%	111%
legumes	1.00	0.22	75500	65%	93%	60400	65%	93%
b. 50% higher yields[d]								
grains	1.24	0.31	91100	78%	90%	72908	78%	90%
starchy roots	1.43	0.26	118700	102%	102%	94934	102%	102%
legumes	1.15	0.28	84000	72%	90%	67253	72%	90%
vegetables	1.42	0.31	164400	141%	142%	131498	141%	142%

S1=season from November to January (dry period), S2=season from February to April (dry period), S3=season from May to July (rainy period), S4-season from August to October (rainy period). - =no differences in crops harvested compared with 'average yields' scenario

[a]expand availability of vegetables and fruits as we found they cannot be harvested throughout the year

[b]storage includes local feasible options such as drying of vegetable leaves

[c]the largest yields attained in field experiments in a specific area

[d]yields 50% above the average yields

Chapter 6

Discussion

Discussion

Agriculture has strong potential to enhance the quality of diets; especially among rural populations in low and middle income countries (LMICs) where malnutrition levels are highest and agriculture is often the most important source of food and income. The need for food systems and especially for agriculture to support better nutrition and health has been recognized in the discussions leading to the SDGs (United Nations 2017). In sub-Saharan Africa the availability of nutrient-dense foods such as legumes, dairy, meat, fruits, nuts and seeds has declined while the availability of grains less-dense in protein and micronutrients has increased (Beal et al. 2017). Grain legumes are appreciated for their benefits in replenishing soil fertility (Giller et al. 2013) and mostly for their contribution to dietary protein (Iqbal et al. 2006; Mudryj et al. 2014). But are grain legumes the poor man's meat? How and to what extent can grain legume cultivation enhance diets? The understanding and insight in the potential of grain legume cultivation for nutritious diets is limited. This thesis aims to fill this knowledge gap using data of smallholder farming households in sub-Saharan Africa.

In order to fill this knowledge gap, a framework was developed based on the theoretical concepts of agriculture and nutrition pathways and the food environment (Figure 1). The main pathways that recur in literature through which agriculture may affect nutrition outcomes are: the production-own consumption and the income-food purchase pathway (Du et al. 2015; Masset et al. 2012). The food environment links agricultural production and income on the one hand with consumption on the other hand. The food environment is defined as the availability, affordability, convenience and desirability of various foods (Herforth and Ahmed 2015) that affects people's food choices and therefore diet quality. This thesis focusses on the food availability and affordability in the food environment, as agricultural production of rural households will most directly affect these two elements. The different studies in this thesis were embedded within this framework. The framework was studied at two levels: (1) at crop level, addressing the potential role of grain legumes in relation to diet quality (Chapter 2) and the potential of grain legumes production of households and nutrition outcomes (Chapter 3) and (2) at whole diet level, using a systems approach, investigating on the one hand the current contribution of the crop production in a household to high quality diets (Chapter 4) and on the other hand the optimal combination of crop production to ensure a high quality diet in all seasons (Chapter 5).

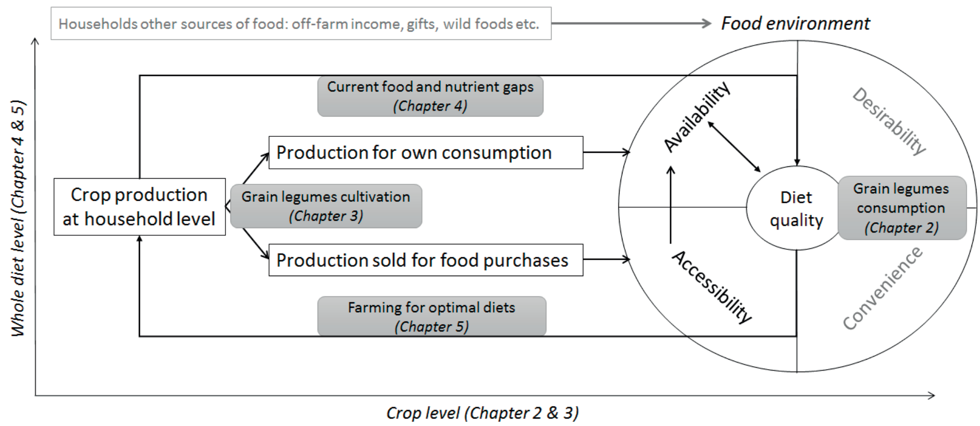

Figure 1. How to harvest nutrition: overview of the focus of each chapter embedded within the theoretical framework of agriculture and nutrition pathways and the food environment, studied at crop and whole diet level

The main findings of this thesis are summarized in Table 1. In summary, the results of the studies at crop level of this thesis show that current legume intakes of infants and young children (IYC) are relatively low. The current energy and nutrient intakes of IYC are mostly insufficient, including micronutrients that are rich in legumes. However, the total protein and essential amino acids (EAAs) in the current diet of the majority of IYC was sufficient except for some of the EAAs among the non-breastfed IYC. Food-based dietary guidelines (FBDGs) based on the local dietary pattern included legumes and, when fully adopted, will be able to provide sufficient protein and EAAs but not all micronutrients. Additional consumption of legumes over and above the current dietary pattern improved adequacy of calcium, iron, niacin and zinc but did not reach sufficient levels to meet their requirements. Thus, although legumes are often said to be the 'meat of the poor' and the current grain legume consumption does contribute to the protein and EAAs intake of rural children, the main nutritional benefit of increased legume consumption is improvement of micronutrient and not protein adequacy (Chapter 2). In Chapter 3 the pathways from legume cultivation towards nutrition outcomes were studied. The results from structural equation modelling (SEM), showed that via the soybean production-own consumption pathway, dietary diversity of children in Kenya was increased. However, this was not observed in Ghana and not found for the income-food purchase pathway in both countries. This showed the importance of contextualization, and the inconsistent results in Ghana and Kenya are possibly related to differences in the food environment between the two countries.

The results of the studies at the whole diet level of this thesis show that more than 60% of the households produced insufficient legumes, grains and vegetables to fulfil the food needs of all household members as recommended by the FBDGs. The diversity of crop production of households was positively related with their nutrient and food coverage, but not with children's dietary diversity and nutrient adequacy (Chapter 4). Finally, the analysis of the optimal combination of crop production to ensure a high quality diet in all seasons show that the average farm size of households in rural Northern Ghana should be sufficient to produce their food needs for a nutritious diet. However, unless irrigation is available, the household's vegetable and fruit dietary needs cannot be covered during the so-called hunger season by home production. When farm size available is limited, increasing yields of legumes and grains will reduce the farm size needed while both maintaining similar level of revenue and covering their food needs for a nutritious diet. When farm size is not limited, increasing yields of vegetables and irrigation are most lucrative. The best option to increase the farm income of households is through specialization in cash crop production, but this comes with increased risks related to diseases, weather and market shocks (Chapter 5).

In this chapter first the main methodological considerations of this thesis are discussed. Second, the contribution of this thesis to improved understanding of the potential of grain legume cultivation for nutritious diets is reflected on. Third, the relevance of investigating agriculture and nutrition impacts from a systems approach at farm level using a diet lens instead of focussing on one crop, food or nutrient is discussed. Finally, implications of our findings for improving the effect of agricultural interventions, specifically for grain legumes, on nutritious diets within food systems in low- and middle- income populations are suggested.

Methodological considerations

The key methodological issues relevant for the internal validity of the findings in this thesis are described in the following paragraphs including a discussion of the study designs, the study population and the self-reported data used.

Table 1. Main findings

	Objectives	Main results
Crop level	**Chapter 2**	*Type:* cross-sectional *Population:* children of 6-23 months in Karaga district in Northern Ghana
	• Current and potential role of grain legumes in nutrient adequacy	• 60% consumed legumes with a portion size of 20 (± 31) g/day, contributing >10% to total protein, folate, iron and niacin intake • Final FBRs included legumes, provided sufficient protein but not all micronutrients • Additional legumes improved adequacy of calcium, iron, niacin and zinc but only reached sufficient level for calcium among breastfed children of 6-8 months
	Chapter 3	*Type:* cross-sectional quasi-experimental *Population:* children of 6-59 months and their households in Ghana and Kenya
	• Grain legume cultivation and children's dietary diversity • In-depth analyses of main pathways: production-own consumption and income-food purchase pathway	• No association between participating in a project improving legume cultivation and dietary diversity of children • SEM showed a good fit for soybean via the production-own consumption pathway in Kenya, not in Ghana and not via the income-food purchase pathway • Differences in food environment in Ghana and Kenya may explain different findings
Whole diet level	**Chapter 4**	*Type:* cross-sectional *Population:* households in Karaga district in Northern Ghana
	• Comparison household food production with their food and nutrient needs • Assessment association between the diversity of food production and nutrition outcomes	• Food production of >50% of households supplied insufficient calcium (76% of households), vitamin A (100%), vitamin B12 (100%) and vitamin C (78%) • Food production of >60% of households supplied insufficient grains and legumes, and of 100% insufficient vegetables • Diversity of food production was positively related with nutrient and food coverage, not with children's dietary diversity and nutrient adequacy
	Chapter 5	*Type:* cross-sectional *Population:* households in Karaga district in Northern Ghana
	• Assess minimum farm size, optimal crop combination and potential contribution of mainstream agricultural interventions to provide a nutritious diet in all seasons	• Minimum farm area of 1.43 ha needed to cover household food needs by own production; irrigation needed to cover vegetable and fruit needs in all seasons • A diversity of crops must be produced to cover food needs • Best option to increase farm income of households is by specialization in cash crop production, but this comes with increased risks • Increasing legumes and grains yield reduce farm size needed while maintaining level of revenue. Increasing yields of vegetables and irrigation are most lucrative

Study design

To investigate the effect of grain legume cultivation on nutritious diets of smallholder farming households in sub-Saharan Africa, a randomized controlled trial is preferred (Mercer et al. 2007; Masset et al. 2012). A randomized controlled trial is most rigorous research design to determine a cause–effect relation between an intervention and an outcome. The studies in this thesis were conducted within the N2Africa project which aims to enhance production of grain legumes and other crops (Giller et al. 2013). It was not possible to set up a randomised control trial for two main reasons. First, N2Africa was implemented before designing the studies for this thesis and the baseline data collected did not include nutrition indicators. Second, rural farming households participated on a voluntarily basis and, therefore, selecting a comparison group using randomisation was not possible. As a consequence, all our studies have a cross-sectional study design and no cause-effect conclusions can be drawn. However, different methods were combined, both quantitative and qualitative methodologies (cf. Creswell and Plano Clark 2011), to add more rigour to the study results as the flaws of different methods used can be neutralized and their different benefits strengthened (Hussein 2009).

A cross-sectional quasi-experimental study design, focus group discussions, structural equation modelling (SEM), and linear programming were used. A cross-sectional quasi-experiment was the best feasible option to investigate the association between participation in a legume cultivation project and nutrition indicators of rural farming households. The challenge of a cross-sectional design is to identify a control group that is comparable with the intervention group. We identified a control group by matching the participating farmers in the N2Africa project with control farmers (similar selection process) while making sure that potential spill-over (different villages) was limited. After data collection we also checked whether the control group differed from the intervention group and found no differences in socio-economic characteristics between the two groups. However, as we also had no baseline data our cross-sectional design is not rigour to draw firm conclusions. The additional focus group discussions enriched our findings with qualitative data on the characteristics of the food environment of our study population, resulting in better understanding of our findings. Qualitative research is a valuable complement to quantitative research (Borland 2001). To our knowledge, SEM is not applied in agriculture and nutrition evaluations yet but appeared to be a useful method as it can model complex causal paths mediated by multiple variables (Garson 2015), such as the theorized pathways from agriculture to nutrition. In addition, as SEM does not compare groups separately but analyses the interdependencies of variables based on a theoretical framework, it avoids the potential biases of not having a proper comparison group. Further, linear programming was used to develop optimal local feasible dietary guidelines (Optifood© software) and to model what crops to grow and the potential contribution of mainstream agricultural interventions in order to provide a nutritious diet in all seasons (software package GAMS). Linear programming allows for modelling different goals at the same time and modelling different complex scenarios. Additionally, both SEM and linear programming allow to use a systems approach valuable for understanding complex problems such as nutrition (Schneider and Hoffmann 2011). Thus, although all studies in this thesis have cross-sectional designs, the combination of different methods used provided rigour to the study designs and therefore also insight in the potential effect of grain legume cultivation on nutritious diets of smallholder farming households.

Study population

Infants and young children (IYC) are one of the most vulnerable groups for undernutrition and improving their complementary feeding is an important window of opportunity (Black et al. 2013). Legumes are essential for nutrient adequate complementary feeding among IYC in rural Northern Ghana, as the FBDGs developed in this thesis showed. However, we can speculate whether this was the best population to use for answering some of our research questions, mainly with regard to: (1) the potential for improvement of the intake of the quality of proteins; and (2) the representativeness for the household diet.

The potential of grain legumes to improve the quality of protein intake may have been underestimated as the established EAAs requirements for IYC are based on breastmilk content and most IYC were breastfed in the study population. In our studies average breastmilk intake was assumed (cf. Brown et al. 1998) resulting in sufficient EAAs intake. However, breastmilk intake may be less than the assumed daily average quantity especially when meal frequency of complementary feeding increases (Dewey and Brown 2003). In addition, the assumed EAAs content of breastmilk was based on a recent review on breastmilk composition which included only a few studies from Africa (Zhang et al. 2013) and actual average content may differ in rural sub-Saharan Africa. Although our assumption with regard to breastmilk intake and content may not hold, we also found that non-breastfed children also had sufficient EAAs intake and the final FBRs based on usual dietary pattern also provided sufficient protein and EAAs. Therefore we assume our study population is appropriate for studying the potential of grain legumes on the quality of protein intake.

Further, the modelled optimised diet of non-breastfed children of 12 to 23 months old was used to estimate optimal diets at household level in both studies described in Chapter 4 and 5. We assume our study population to adequately represent the household diet. First, in general the diets of children older than one year are integrated into family diets in our study population. Rarely special meals are prepared for young children: they mainly eat from the family pot (Armar-Klemesu et al. 2016). Second, although the sample size of non-breastfed children in the study population was relatively small (29 children), all eligible non-breastfed children in the study location were included and therefore their dietary pattern is accurately estimated. Third, although we expected that households of non-breastfed children are atypical as most children in this age category are breastfed, the households of non-breastfed children did not differ in social economic characteristics from households of breastfed children. Fourth, on average the non-breastfed children of 12 to 23 months included in the study were older compared with the breastfed children of 12 to 23 months. The Ghanaian Demographic Health survey found indeed that towards the age of 2 years the prevalence of breastfed children sharply decreases (Ghana Statistical Service et al. 2015). Thus generally the prevalence of breastfed children up to the age of 2 years is high in Ghana. Therefore both the potential differences in the diets between the non-breastfed children and other household members as well as between households of non-breastfed and breastfed children are probably negligible and we assume our study population to adequately represent the household diet.

Self-reported data

The majority of the data used in this thesis is self-reported. In Chapter 3 and 4 self-reported yields and farm size by our target households were used and in Chapter 5 secondary sources for yield data used were often also self-reported. Self-reported yield and farm size are often inaccurate. For example, during data collection in the field, it was clear that hectares and acres are often confused and households had problems recalling the exact yield of different crops over the past year. Households with smaller farm sizes tend to overestimate their yields (Carletto et al. 2013) and therefore our findings might be too positive. Information on whether farm sizes tend to be over- or underestimated by our target population is not available and the potential effect on our findings cannot be estimated. With regard to the dietary data, collected by qualitative and quantitative 24-hour recall, errors in recalling food intake might have occurred. Nevertheless misreporting was minimized by: using a multiple-pass procedure (Gibson and Ferguson 2008), using household measures of respondents to estimate portion sizes, calibration of weighing scales, training of interviewers, direct supervision, checking collected data in the field and random assignment of interviewers.

Grain legume cultivation and nutrition

This thesis shows that legume consumption among IYC contribute to protein and micronutrient adequacy of their diet. The potential effect of legume consumption to nutrient adequacy of IYC's diet was assessed at three different levels: current dietary intakes, FBDGs based on current dietary pattern and FBDGs with additional legumes outside of the current dietary pattern. First, the contribution of the current legume consumption to nutrient intake of IYC showed that 60% of the children currently consumed legumes with an average portion size of 20 g per day contributing more than 10% of their total protein and majority of the EAAs intake and to the intakes of the micronutrients folate, iron and niacin. The total protein and EAAs in the current diet of the majority of IYC was sufficient except for some of the EAAs among the non-breastfed IYC. Findings of studies concerning the adequacy of protein intake from cereal based diets are inconsistent: some found that total protein intake from cereal based diets appears to be sufficient (Uauy et al. 2016; Mesfin et al. 2015), others did not find that the quality of the cereal based protein in terms of EAAs was sufficient (Semba et al. 2016; Ghosh et al. 2012). The current energy and micronutrient intakes of IYC were mostly insufficient. Thus overall children consumed legumes and these did contribute to their total protein and the quality of protein intake as well as their micronutrients intake but overall the micronutrient intakes were insufficient. Second, FBDGs were developed that are based on the current local dietary patterns and costs and therefore the foods recommended are assumed to be available, affordable and acceptable for the population under study. The FBDGs developed in this thesis include advice to consume legumes and when fully adopted adequately cover protein and EAAs requirements and improve micronutrients intake but not provide adequate amounts for all micronutrients. Other FBDGs developed for IYC in LMICs also included legumes and resulted in an adequate amount of total protein and an improved amount of micronutrients but not sufficiency in all micronutrients (Talsma et al. 2017; Raymond et al. 2017; Kujinga et al. 2018). Although legume consumption was on average part of IYC's dietary pattern, still 40% of our study population did not consume legumes, as was also found in Ethiopia among rural IYC (Mesfin et al. 2015). In case the diets of IYC do not yet include legumes in the quantities as recommended by the developed FBDGs, interventions that promote the adoption of FBDGs including increasing legume consumption may improve protein and especially micronutrient intakes of these IYC. Third, increasing the advice of legume consumption, additional to the FBDGS based on the habitual diet, has no effect on protein and EAAs intake and only slightly enhance micronutrient adequacy but still not sufficiently to meet requirements. Thus based on the results of this thesis we conclude that legume consumption contributes to protein (but is not required to fulfil the requirements) and micronutrient adequacy and legumes are included in FBDGs but do not provide sufficient micronutrient intake. Increasing consumption of legumes on top of the FBDGs does not result in sufficient micronutrient intake.

A few points need to be considered with regard to the results on grain legume consumption and contribution to protein intake. The established protein and EAAs requirements may be insufficient for young children in LMICs, where energy deficits and infectious diseases are common and catch-up growth is needed increasing requirements (Semba et al. 2016; Ghosh et al. 2012). In case of an energy deficit, as is the case among more than 20% of the studied population, part of the protein intake will be converted and used as energy. A diet that is moderately deficient in energy (5% below requirement) can increase protein needs by 10% (Kishi et al. 1978). Calculations of protein needs in relation to energy intake depend on many factors though such as age, sex and physical activity and more research is needed for estimations of extra requirements in relation to energy deficit (FAO et al. 2007). Therefore when protein requirements are increased in case of energy deficits, infections and required catch-up growth, additional legumes may improve protein intakes when also providing sufficient energy. We found no literature that studied this potential effect of additional legume consumption on protein taking into account both increased protein and energy requirements.

Legume consumption among IYC may contribute to protein and micronutrient adequacy of their diet but does increased legume availability also contribute to dietary improvements? The cross-sectional quasi-experiment in this thesis found no association between households participating in a grain legume cultivation project and the dietary diversity of their young child in Ghana and Kenya. The evidence for agriculture interventions that boost grain legume production and the impact on nutrition and the underlying pathways is limited: two studies found positive impacts of increased legume production on changes in underweight of children in Malawi (Bezner Kerr et al. 2010) and on wasting among young children in Tanzania (Kumar et al. 2018) but both found no effect on stunting and one study found more households reported feeding legumes to their children compared with control households (Bezner Kerr et al. 2007). Besides, based on the flaws of our study design as discussed before, several explanations might clarify why we did not find an association. First, we also found no difference in total grain legume production between households participating in the N2Africa project and households that did not. Therefore we cannot expect to find an association with increased legume consumption and improved dietary diversity due to differences in legume availability. The other studies in Malawi and Tanzania did find differences in legume production between their study groups. Second, if children already consumed legumes before implementation of a grain legume cultivation project, we do not expect any improvements in their dietary diversity (as measured qualitatively) by consuming (more) legumes due to increased availability of grain legumes. Improvements may still be possible if income earned by legume production is used to buy foods that improve dietary diversity. However, as our SEM analyses showed, the income pathway did not improve dietary diversity, indicating that income was not used to buy foods that improve dietary diversity. Third, agricultural programs are unlikely to translate in positive impacts on nutrition when no additional programming such as behaviour change communication and gender empowerment are included (Pandey et al. 2016; Berti et al. 2004). The other grain legume intervention studies included other components such as a nutrition education component while the N2Africa project did not include these components during the first project phase, in which this study was conducted. Except for Kenya, where a nutrition education component (mainly instructions for soybean recipes) was included which might have contributed to our positive SEM result in the Kenyan context. Fourth, the increased production of legumes when resulted from more land cultivated under legumes, might have led to a decreased cultivation of other crops as rural households are generally limited by farm size and labour availability for crop cultivation. Therefore a systems approach, as discussed in the next section, is useful to give more insight in the role of grain legume cultivation for nutritious diets.

The SEM analysis (combining data from both intervention and control households and investigating the potential pathways from grain legume production to children's diet) did show that increased legume availability may contribute to dietary improvements. However, only in Kenya and only when increased production was used for household consumption, not via the income pathway and not in Ghana. These different results for Ghana and Kenya show that besides legume availability other factors of the food environment appeared to be important in the translation of grain legume cultivation towards dietary improvements. We found that the following characteristics were supporting increased legume consumption: positive attributes toward consumption of legumes by children, the existence of local dishes with legumes, if it is a women's crop, if market accessibility is limited (legumes were consumed instead of sold), if it is a food crop and not a cash crop. Others also highlighted the importance of women's empowerment (Malapit and Quisumbing 2015; Ruel et al. 2018; Cunningham et al. 2015) and the role of markets (Dillon and Barrett 2017; Sibhatu et al. 2015; Ruel et al. 2018) in the food environment in translation of agricultural interventions into improved nutrition outcomes. Another study in Ghana found that the main barriers of cowpea consumption were: availability (especially in hunger season), prices, post-harvest losses, time to cook and digestion problems (Abizari et al. 2013).

Based on the results of the cross-sectional study, the SEM analysis and focus group discussions, we conclude that a grain legume cultivation project such as the N2Africa project does not necessarily result in dietary improvements. Whether a grain legume cultivation project result in dietary improvements depend on the characteristics of the food environment, as well as whether specific activities are included such as behaviour change communication and women's empowerment. In addition, a specific nutrition objective needs to be included, which was not the case in the first phase of N2Africa, as highlighted in literature this is also a prerequisite for contributing to dietary improvements (Ruel and Alderman 2013).

Agriculture and nutrition: how to best harvest nutrition?

The first chapters of this thesis focus on the role of grain legumes but people do not consume only one food product such as grain legumes but consume a complete diet consisting of different foods. One of the criteria of a high quality diet is a diet that contains a diversity of foods and food groups including fruits, vegetables, legumes and whole grains (WHO 2015; FAO 2016). Greater dietary diversity results in improved nutrient adequacy of the diet (Kennedy et al. 2007; Moursi et al. 2008). The FBDGs that we developed also included a variety of foods such as vegetables, fruits, legumes, dairy and whole grains. Thus to investigate the role of grain legume cultivation as well as other agricultural crop cultivation interventions in achieving nutritious diets, we first questioned whether crop production of households supports the adoption of FBDGs (current situation, Chapter 4). And when this was not the case, the next question is how should a farm look like to support FBDGs with regard to farm size and crop combination, and which interventions are necessary to achieve this optimal farm design (optimised situation, Chapter 5). We addressed both questions using a systems approach at farm level, considering the production of all crops and all food needs for nutritious diets in a household. For the second question (Chapter 5), we also considered seasonal influences and in addition to the production-own consumption pathway also the income-food purchase pathway by including revenue from farming in our modelling. A systems approach considers relations among different components, plans for the implications of their interaction and requires transdisciplinary thinking (Leischow and Milstein 2006). Below, we will first discuss the results of these two questions specifically with regard to grain legumes followed by a reflection of the usefulness of a systems approach for reshaping food systems for nutritious diets.

Grain legumes

For almost half of all households the legume production did not cover the required quantities of legumes in a situation where all household members fully adopt the recommended optimised diets based on local FBDGs. Therefore these households depend on the market to fulfil their legume needs. Based on legume production data in Karaga district as a whole, availability seems sufficient to cover the legumes needs of the district. This suggests that to cover the legume needs of all households in Karaga, increasing total legume production might not be essential. Other interventions such as market accessibility and legume availability and affordability at local markets, as well as behaviour change communication interventions might be more effective. However, as at national level legume availability was found to be insufficient, a high demand from other districts in Ghana might increase prices as well as result in decreased availability of legumes in Karaga district. Increasing legume productivity of Karaga households that were not able to cover their legume needs as recommended by the FBDGs may enable them to produce legumes on a smaller farm area making them less dependent on the market for their legume needs. Increasing yields of legumes for households with limited farm size available, will enable them to both maintain a similar level of revenue and cover their food needs for a nutritious diet. If legume cultivation is promoted, our modelling results showed that a variety of legume crops need to be promoted and not just one to cover their food needs for a nutritious diet. However, we need to keep in mind that both studies (Chapter 4 and 5) did not include that legumes in the farm may also enhance yield of other crops through their soil fertility benefits (as recognized by the N2Africa project and also included as one of their project goals) (Franke et al. 2018).

Systems approach

Both Chapter 4 (current situation) and 5 (optimised situation) used a systems approach and showed what gaps exist in the food availability of a household to cover their optimal food needs. These studies are useful examples on how to analyse the current gaps in food availability to cover food needs, as deemed necessary by GLOPAN (2016): 'a 'high-quality diet' lens must guide policy decisions to reshape food systems'. Analysis of dietary gaps is seen as a crucial first step by GLOPAN to identify policy actions to achieve healthy diets. These gaps provide useful insights in what agricultural interventions and/or other nutrition-sensitive and nutrition-specific interventions are needed (see for description and examples Table 1 in the introduction chapter of this thesis) and will have most impact on improving the quality of diets.

One of the major challenges in the gap-analysis approach is the need to define high quality diets and sound metrics to asses diet quality. There are many different definitions for a high quality diet but three dimensions are key: dietary diversity, nutrient adequacy and moderation. Metrics are needed that include these key dimensions as well as foods and/or food groups rather than nutrients. FBDGs are a useful reflection of a high quality diet. However, FBDGs are largely absent in low-income countries (only in 2 out of 31 countries have nationally approved FBDGs) and limited in lower middle-income countries (12 out of 51 countries) (GLOPAN 2016). The main challenge in the development of FBDGs are the limited availability of required individual quantitative dietary intake data. The collection of quantitative 24-hour recalls takes a great deal of time, human and financial resources. Potentially, the use of routinely conducted Household Consumption and Expenditure Surveys (HCES) can be used for estimation of individual quantitative dietary intakes but this needs to be validated with other dietary intake methods such as a quantitative 24-hour recalls (Bermudez et al. 2012). A study in Guatemala showed that HCES can serve as a proxy for primary dietary data to develop FBDGs (Knight and Woldt 2017). The other challenge in using FBDGs in the identification of dietary gaps is the translation of the individual population-specific FBDGs to other levels at which a system analysis needs to be conducted. For this study FBDGs were developed for IYC from one specific district and subsequently analyses were done at household level for this district, needing to assume diets of IYC were similar to that of other household members. The intra-household distribution of foods also needs to be considered in the analysis of dietary gaps at household level. Besides household level, analysis of dietary gaps at district, regional or (sub)national level are also needed so governments and others are able to invest in nutrition in an integrated and coherent way, as also recognized in the global nutrition report (Development Initiatives 2017). Others have done similar dietary gap analysis at national level using FAO Food Balance Sheet data on country-level food supply (Kuyper et al. 2017). But the many underlying assumptions in this approach such as the translation to per capita food availability based on energy equivalents and selecting a reference of a 'healthy diet' when FBDGs are absent (in this example a diet that was tested in the USA but used in Cameroon context) need to be validated before widely used (Coates et al. 2017). In addition, such an analysis at national level still needs to be accompanied by analyses at least at regional level to account for the differences in dietary patterns within a country. The ability to zoom in and out at different levels is an important characteristic of system level analyses.

A systems approach might bring new insights with regard to the potential of different agricultural interventions for nutritious diets. Nutrition-sensitive agricultural interventions are generally limited to interventions that focus on nutrient-dense crops such as fruits, vegetables, fish, eggs, milk, biofortified crops and do not include agricultural interventions that focus on cereals. As cereals are not nutrient-dense it is generally assumed that these interventions will not contribute to nutritious diets or even have adverse effects (Headey and Hoddinott 2016; Jones and Ejeta 2016). However, our modelling results using a systems approach at farm level (Chapter 5), suggest differently: increased productivity of cereal cultivation can contribute to nutritious diets by giving households with small farm size the opportunity to produce the crops needed to fulfil their food needs for a nutritious diet. Irrigation can help to close dietary gap of vegetables and fruits during the hunger season. Besides the production for own consumption, the income-food purchase pathway is relevant to include as farm income is generally main driver of farmers. Therefore we included both pathways in our modelling. Irrigation and increased productivity of vegetable cultivation result in highest relative revenue compared to other interventions and no intervention (average yields). However, these mainstream agricultural interventions need to be nutrition-sensitive. As pointed out earlier in this discussion, food availability and affordability alone are not sufficient to result in nutritious diets (Pandey et al. 2016; Berti et al. 2004). For an agricultural intervention to be nutrition-sensitive, additional components need to be included such as nutrition behaviour change communication and women's empowerment, and specific nutrition goals included (Ruel et al. 2018).

Further, these mainstream agricultural interventions need to be part of a systems approach in which the focus is not on a single crop but on the combination of crops that are necessary for a nutritious diet. This requires a certain level of coordination or governance taking a nutrition lens within the agricultural sector, as well as across sectors to make sure that other sectors also contribute to closing the identified dietary gaps. While a paradigm shift towards a multi-sectoral approach to nutrition is evolving, currently specific single sector approaches are still most common approach to tackling the malnutrition problem (Noack and Pouw 2015). The recommendation "think multisectorally, and act sectorally" (World Bank, 2013) suggests stimulating dialogue across sectors at the planning, monitoring, and review stages such as identification of dietary gaps, while ensuring that each sector uses its unique expertise to implement and contribute to closing dietary gaps (Ruel et al. 2018).

Conclusions

This thesis shows that show that main contribution of grain legumes to nutritious diets is in terms of micronutrients intake and not protein intake. Therefore we cannot confirm based on our study that grain legumes are indeed the poor man's meat. A project promoting grain legume cultivation, such as N2Africa, will not necessarily result in dietary improvements. Whether such a project will result in dietary improvements depend on the characteristics of the food environment, as well as whether a nutrition-specific goal is set and activities such as nutrition behaviour change communication and women's empowerment are included. This thesis also shows that a mixed method design including pathway analysis is a good approach to study nutrition impact of agriculture interventions when RCTs are not possible. Finally, the thesis results show that investigating the gaps in food availability and food needs using a systems approach at farm level provides useful insights to be able to better coordinate and integrate nutrition across agricultural interventions and investments. Let's harvest nutrition!

Recommendations and future research

Based on the results of this thesis we defined a list of recommendations and a list with suggestions for future research.

Recommendations:

- There is a need to shift from arguing that legumes are important for protein intake to recognising that they are important for micronutrient intake.
- The effect of grain legume cultivation on improved diets depend on the context. The contextualisation of research is important and this requires the use of mixed methods, both quantitative as well as qualitative research. Mixed method designs including pathway analysis might provide more insights in interdisciplinary research questions than a RCT.
- To achieve dietary improvements, a grain legume project such as N2Africa, needs to include a nutrition-specific goal from the start (and nutritionist specialists), as well as interventions such as nutrition behaviour change communication and women's empowerment.

- A thorough analysis of the food environment, using a systems approach, prior to implementation of the project will provide useful insights on what project activities have highest potential to result in dietary improvements. These activities may include: (1) activities with regard to legumes specifically (where are the largest gaps between legume needs and legume production); (2) activities with regard to other crops (what are the other crop gaps and is there potential to cooperate with other projects), and (3) which specific activities for nutrition behaviour change communication and women's empowerment (to be able to build on existing knowledge on legumes, whether legumes are already a women's crop or not for example).
- A systems approach is important for nutrition. Instead of implementing single crop interventions, we need to start from a whole diet perspective. This requires governance at a higher level (farm, district, region, national) and corresponding research methodologies such as SEM and linear modelling that can investigate pathways in more detail and also take into account relevant factors in the food environment including seasonality and the role of markets. A grain legume cultivation intervention that is implemented together with a vegetable cultivation intervention and behaviour communication strategies for adopting local FBDGs, may be very effective in improving nutrition outcomes when (seasonal) gaps in the availability and needs of legumes and vegetable are large.
- Increasing productivity of cereal crops is not by definition not nutrition-sensitive. For households with a limited farm size, increased productivity of cereals can help in such a way that these households are able to produce the crops needed to fulfil their food needs for a nutritious diet. But only under the condition that the intervention ensures that the farm area under cereal decreases instead of increases and the intervention is combined with activities such as behaviour change communication and women's empowerment.
- To improve nutrition universally, better, more regular and disaggregated data are needed. 'If we don't know what people are eating, we will not be able to design effective interventions to improve diets' (Development Initiatives 2017). If better data is available and thorough analyses of existing dietary gaps are in place, governments and others can use this to invest in nutrition and coordinate nutrition activities across sectors in an integrated way, and sector specific interventions and research can focus on developing their discipline specific knowledge.

Future research:

- Due to the absence of (national representative) food consumption data, we need to study whether other non-food consumption data such as household consumption and expenditure surveys can also be used to investigate the gaps between food availability and food needs based on food-based dietary recommendations.
- The feasibility of the modelling results, both the FBDGs as well as the optimised farm-level results, need to be tested in the field among our study population. FBDGs need to be tested by designing and implementing a nutrition behaviour change communication intervention that promote adoption of FBDGs among infants and young children, measuring quantitative dietary intake at end line. In addition, focus group discussions need to be conducted among caregivers of the infants and young children included to identify barriers and enablers in adoption of the FBDGs. The optimised farm-level results can be tested by using trials for improved practices, offering to implement one of the potential agricultural interventions for nutritious diets, measuring the key indicators related to the intervention and the whole diet at baseline and end line as well as collecting qualitative information.
- For reliable research using a systems approach for agriculture and nutrition evaluations, continuous research is needed on location-specific food composition and location- and seasonal- specific crop yields, crop availability and crop prices.
- Due to our globalizing food system, markets play an increasingly significant role in nutrition and agriculture, also in rural areas. Therefore economic and market knowledge are necessary in nutrition and agriculture evaluations.
- For future agriculture and nutrition research: specialists from both disciplines should be involved from the start and be able to think outside of their discipline, a shift from research at crop level to whole diet level research is needed using a systems approach (including exploring and testing the usefulness of different methods) and testing the practical feasibility of research findings need to be planned and incorporated from the beginning.

References

Abizari, A.-R., Pilime, N., Armar-Klemesu, M., & Brouwer, I. D. (2013). Cowpeas in Northern Ghana and the factors that predict caregivers' intention to give them to schoolchildren. *PLoS One, 8*(8), e72087.

Armar-Klemesu, M., Zakariah-Akoto, S., & Osei-Menya, S. (2016). Feeding infants and young children in Karaga district, Northern region: A focused ethnographic study. Washington D.C., US: GAIN and USAID.

Beal, T., Massiot, E., Arsenault, J. E., Smith, M. R., & Hijmans, R. J. (2017). Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLoS One, 12*(4), e0175554.

Bermudez, O. I., Lividini, K., Smitz, M. F., & Fiedler, J. L. (2012). Estimating micronutrient intakes from Household Consumption and Expenditures Surveys (HCES): an example from Bangladesh. *Food Nutr Bull, 33*(3 Suppl), S208-213.

Berti, P. R., Krasevec, J., & FitzGerald, S. (2004). A review of the effectiveness of agriculture interventions in improving nutrition outcomes. *Public Health Nutrition, 7*(5), 599-609.

Bezner Kerr, R, Berti, P. R., & Shumba, L. (2010). Effects of a participatory agriculture and nutrition education project on child growth in northern Malawi. *Public Health Nutrition, 14*(08), 1466-1472.

Bezner Kerr, R, Snapp, S., Chirwa, M., Shumba, L., & Msachi, R. (2007). Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil feritlity. *Experimental Agriculture, 43*(04), 437-453.

Black, R. E., Victora, C. G., Walker, S. P., Bhutta, Z. a., Christian, P., de Onis, M., et al. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet, 382*, 427-451.

Borland, K. W. (2001). Qualitative and Quantitative Research: A Complementary Balance. *New Directions for Institutional Research, 2001*(112), 5-13.

Brown, K. H., Dewey, K. G., & Allen, L. (1998). Complementary feeding of young children in developing countries: a review of current scientific knowledge.

Carletto, C., Savastano, S., & Zezza, A. (2013). Fact or artifact: The impact of measurement errors on the farm size–productivity relationship. *Journal of Development Economics, 103*, 254-261.

Coates, J., Rogers, B. L., Blau, A., Lauer, J., & Roba, A. (2017). Filling a dietary data gap? Validation of the adult male equivalent method of estimating individual nutrient intakes from household-level data in Ethiopia and Bangladesh. *Food Policy, 72*, 27-42.

Creswell, J. W., & Plano Clark, V. L. (2011). *Designing and conducting mixed methods research*. California, USA: SAGE Publications.

Cunningham, K., Ruel, M., Ferguson, E., & Uauy, R. (2015). Women's empowerment and child nutritional status in South Asia: a synthesis of the literature. *Maternal & Child Nutrition, 11*(1), 1-19.

Development Initiatives (2017). Global nutrition report 2017: Nourishing the SDGs. Bristol, UK: Development Initiatives.
Dewey, K. G., & Brown, K. H. (2003). Update on technical issues concerning complementary feeding of young children in developing countries and implications for intervention programs. *Food Nutr Bull, 24*(1), 5-28.
Dillon, B., & Barrett, C. B. (2017). Agricultural factor markets in Sub-Saharan Africa: An updated view with formal tests for market failure. *Food Policy, 67*, 64-77.
Du, L., Pinga, V., Klein, A., & Danton, H. (2015). Leveraging agriculture for nutrition impact through the Feed the Future initiative. *Adv Food Nutr Res, 74*, 1-46.
FAO (2016). Influencing food environments for healthy diets. http://www.fao.org/3/a-i6491e.pdf Accessed August 2018.
FAO, WHO, & UNU (2007). Protein and amino acid requirements in human nutrition. *World Health Organization technical report series: 1*.
Franke, A. C., van den Brand, G. J., Vanlauwe, B., & Giller, K. E. (2018). Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agriculture, Ecosystems & Environment, 261*, 172-185.
Garson, G. D. (2015). *Structural Equation Modeling* (Blue Book Series). Asheboro, USA: Statistical Associates Publishing.
Ghana Statistical Service, Ghana Health Service, & ICF International (2015). Ghana demograhic and health survey 2014. Rockville, USA: GSS, GHS and ICF International.
Ghosh, S., Suri, D., & Uauy, R. (2012). Assessment of protein adequacy in developing countries: quality matters. *British Journal of Nutrition, 108 Suppl 2*, S77-87.
Gibson, R. S., & Ferguson, E. L. (2008). An interactive 24-hour recall for assessing the adequacy of iron and zinc intakes in developing countries. *HarvestPlus Technical Monograph 8*. Washington DC, USA & Cali, Colombia: IFPRI & CIAT.
Giller, K. E., Franke, A. C., Abaidoo, R., Baijukya, F. P., Bala, A., Boahen, S., et al. (2013). N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa. In B. Vanlauwe, P. van Asten, & G. Blomme (Eds.), *Agro-ecological Intensification of Agricultural Systems in the African Highlands* (pp. 156-174). London, UK: Routledge.
GLOPAN (2016). Food systems and diets: facing the challenges of the 21st century. London, UK.
Headey, D. D., & Hoddinott, J. (2016). Agriculture, nutrition and the green revolution in Bangladesh. *Agricultural Systems, 149*, 122-131.
Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security, 7*(3), 505-520.
Hussein, A. (2009). The use of triangulation in social sciences research: Can qualitative and quantitative methods be combined? *J Comp Soc Work, 4*(1).
Iqbal, A., Khalil, I. A., Ateeq, N., & Sayyar Khan, M. (2006). Nutritional quality of important food legumes. *Food Chemistry, 97*(2), 331-335.
Jones, A. D., & Ejeta, G. (2016). A new global agenda for nutrition and health: the importance of agriculture and food systems. [Editorial Material]. *Bull World Health Organ, 94*(3), 228-229.

Kennedy, G. L., Pedro, M. R., Seghieri, C., Nantel, G., & Brouwer, I. (2007). Dietary diversity score is a useful indicator of micronutrient intake in non-breast-feeding Filipino children. *The Journal of Nutrition, 137*(2), 472-477.

Kishi, K., Miyatani, S., & Inoue, G. (1978). Requirement and utilization of egg protein by Japanese young men with marginal intakes of energy. *The Journal of Nutrition, 108*(4), 658-669.

Knight, F. A., & Woldt, M. (2017). Use of Guatemalan Household Consumption and Expenditure Survey (HCES) Data to Develop Optifood Food-Based Recommendations. Washington D.C.: FHI 360/FANTA.

Kujinga, P., Borgonjen-van den Berg, K. J., Superchi, C., Ten Hove, H. J., Onyango, E. O., Andang'o, P., et al. (2018). Combining food-based dietary recommendations using Optifood with zinc-fortified water potentially improves nutrient adequacy among 4- to 6-year-old children in Kisumu West district, Kenya. *Maternal & Child Nutrition, 14*(2), e12515.

Kumar, N., Nguyen, P. H., Harris, J., Harvey, D., Rawat, R., & Ruel, M. T. (2018). What it takes: evidence from a nutrition- and gender-sensitive agriculture intervention in rural Zambia. *Journal of Development Effectiveness, 10*(3), 341-372.

Kuyper, E. M., Engle-Stone, R., Arsenault, J. E., Arimond, M., Adams, K. P., & Dewey, K. G. (2017). Dietary gap assessment: an approach for evaluating whether a country's food supply can support healthy diets at the population level. *Public Health Nutr, 20*(13), 2277-2288.

Leischow, S. J., & Milstein, B. (2006). Systems Thinking and Modeling for Public Health Practice. *American Journal of Public Health, 96*(3), 403-405.

Malapit, H. J. L., & Quisumbing, A. R. (2015). What dimensions of women's empowerment in agriculture matter for nutrition in Ghana? *Food Policy, 52*, 54-63.

Masset, E., Haddad, L., Cornelius, A., & Isaza-Castro, J. (2012). Effectiveness of agricultural interventions that aim to improve nutritional status of children: systematic review. *The British Medical Journal, 344*, d8222.

Mercer, S. L., DeVinney, B. J., Fine, L. J., Green, L. W., & Dougherty, D. (2007). Study Designs for Effectiveness and Translation Research: Identifying Trade-offs. *American Journal of Preventive Medicine, 33*(2), 139-154.e132.

Mesfin, A., Henry, C., Girma, M., & Whiting, S. J. (2015). Use of pulse crops in complementary feeding of 6-23-month-old infants and young children in Taba Kebele, Damot Gale district, Southern Ethiopia. *J Public Health Afr, 6*(1), 357.

Moursi, M. M., Arimond, M., Dewey, K. G., Trèche, S., Ruel, M. T., & Delpeuch, F. (2008). Dietary diversity is a good predictor of the micronutrient density of the diet of 6- to 23-month-old children in Madagascar. *The Journal of Nutrition, 138*, 2448-2453.

Mudryj, A. N., Yu, N., & Aukema, H. M. (2014). Nutritional and health benefits of pulses. *Applied Physiology, Nutrition and Metabolism, 39*(11), 1197-1204.

Noack, A.-L., & Pouw, N. R. M. (2015). A blind spot in food and nutrition security: where culture and social change shape the local food plate. [journal article]. *Agriculture and Human Values, 32*(2), 169-182.

Pandey, V. L., Mahendra Dev, S., & Jayachandran, U. (2016). Impact of agricultural interventions on the nutritional status in South Asia: A review. *Food Policy, 62*, 28-40.

Raymond, J., Kassim, N., Rose, J. W., & Agaba, M. (2017). Optimal formulations of local foods to achieve nutritional adequacy for 6-23-month-old rural Tanzanian children. *Food Nutr Res, 61*(1), 1358035.

Ruel, & Alderman, H. (2013). Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? *The Lancet, 382*, 536-551.

Ruel, Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security, 17*, 128-153.

Schneider, K., & Hoffmann, I. (2011). Nutrition Ecology—A Concept for Systemic Nutrition Research and Integrative Problem Solving. *Ecology of Food and Nutrition, 50*(1), 1-17.

Semba, R. D., Shardell, M., Sakr Ashour, F. A., Moaddel, R., Trehan, I., Maleta, K. M., et al. (2016). Child stunting is associated with low circulating essential amino acids. *EBioMedicine, 6*, 246-252.

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences, 112*(34), 10657-10662.

Talsma, E. F., Borgonjen-van den Berg, K. J., Melse-Boonstra, A., Mayer, E. V., Verhoef, H., Demir, A. Y., et al. (2017). The potential contribution of yellow cassava to dietary nutrient adequacy of primary-school children in Eastern Kenya; the use of linear programming. *Public Health Nutrition*, 1-12.

Uauy, R., Suri, D. J., Ghosh, S., Kurpad, A., & Rosenberg, I. H. (2016). Low circulating amino acids and protein quality: an interesting piece in the puzzle of early childhood stunting. *EBioMedicine, 8*, 28-29.

United Nations (2017). The Sustainable Development Goals Report 2017. New York, NY: United Nations.

WHO (2015). Healthy diet fact sheet no. 394. http://www.who.int/news-room/fact-sheets/detail/healthy-diet. Accessed August 2018.

Zhang, Z., Adelman, A. S., Rai, D., Boettcher, J., & Lőnnerdal, B. (2013). Amino acid profiles in term and preterm human milk through lactation: a systematic review. *Nutrients, 5*(12), 4800-4821.

Thank you! Bedankt! Tipaya! Tipusiya! Asante!

The moment is really here: the end of my PhD adventure. We did it!

What did we do? As this is probably the first and maybe only part you will read, I am happy to share here with you the shortest summary of more than 5 years of work. We found that grain legumes (cowpea, groundnut, soybean) add to protein and micronutrient intake of rural Ghanaian and Kenyan children. But only increasing the production of grain legumes of their farming households does not improve the diets of these children. To improve their diets, increasing grain legume production needs to be combined with interventions that will increase the availability and accessibility of fruits and vegetables and nutrition specific interventions such as to promote food-based dietary guidelines (like 'de schijf van vijf' in the Netherlands).

Who is we? Many great people joined me on my PhD adventure to whom I would like to say: Thank you! Bedankt! Tipaya! Tipusiya! Asante Sana!

First of all, I am very thankful that so many *children and their families in Northern Ghana and Western Kenya* were willing to participate in our studies and offer some of their precious time. And thank you chiefs in Northern Ghana for asking how this research would help their villages. I really hope that it was time well spent and that these research results together with others will eventually help to contribute to more nutritious diets and all the benefits that come along with that in your villages. And of course it was great meeting so many Talata's in the field! Tipaya! Tipusiya! Asante Sana!

Inge – I was so sure I was not going to study in Wageningen like both my parents did. When I did decide to do my masters in Wageningen, I was at least sure I would not do my thesis with you as my supervisor (being a study friend of my parents). But you were, both for my master thesis as well as for my PhD. And I am very glad you were! You were such a great supervisor – giving the feeling that everything is possible, always being positive, asking critical questions and being very supportive in showing you believe in me. I enjoyed our inspiring and fun discussions and (field) trips. Bedankt!

Ken – I am glad you took this nutritionist on board within N2Africa and giving me the opportunity to do this PhD research. I enjoyed our interesting discussions (eventually even slightly changing your beliefs about legumes and dietary protein, right?) and your frankness in sharing your opinions and ideas (like why not to use the word 'traditional'). Thank you!

Razak – I feel very lucky that I got to work with you! You taught me a lot about the country I was born in and how to deal with fieldwork and PhD challenges. We literally did a lot of sweating in the field - still not having to pee after drinking 6 litres of water – but we mainly had lots of fun! And I never thought I would make someone outside of the Netherlands happy by bringing 'dropjes'. Tipaya!

Gloria – Elise was so right that you are the best field assistant that anyone can get but even more: a great friend! I am thankful that I had you by my side when dealing with challenges in the field and I enjoyed all our dinners. I hope our paths will cross again! Asante sana!

Research assistants – You were great! Thank you for the hard work, the perseverance in our quest to find 'N2Africa farmers', the fun (eating waakye in the back of the car and travelling with a guinea pig on my lap – my pants needed to get washed) and the friendships! Mashwal, it was great to meet you recently in Accra and hear about your work for the World Bank. And Hassan, I hope I will see you play football in the Ghanaian national team one day.

The many other great helpers in the field – Thank you Froukje, Fusta, Merel and Sophia for 'sweating' in the field and thinking along with my research. And Fusta, for asking critical questions also during stressful field moments. I regret that you will not be there for my defence but I hope your fieldwork is going well and you can spend time with your daughter. Thank you drivers for getting us to places that did not seem reachable and Hassan also for turning out to be of great help with our anthro measurements. And Benjamin (SARI), Basit (IITA) and Samuel and the MoFA offices in Tamale and Zebilla in Ghana, and Freddy and the CIAT offices in Nairobi and Maseno in Kenya – thank you for helping set up our studies.

Nutrition department – Thanks to you all! Thank you 'international nutrition group' for our discussions, travels, coffees and delicious dinners: Tesfaye, Santiago, Fusta, Laura, Elise, Ibukun, Marijke, Aregash, Eric, Prosper, Arli, Lowela, Aafke, Lucy, Karin, Alida, Saskia, Jeanne. Karin, thank you for the help and fun in the field and fighting together with Optifood. And thank you all my great roommates at the hot hidden room in the Biotechnion and at Helix for sharing frustrations and having fun. And PhD committee, thank you for the fun time organising activities together. Jasmijn and Karen, thank you for the secretarial help.

Plant Production Systems Group - Thanks to you all! You are a great group! Thank you for all the 'gezellige' lunches and interesting conversations. Esther, Renske and Greta for all the coffees and train rides. Jannike, for walking the final path of our PhDs together. Bob, thank you for helping me out with conducting the SEM analyses. Gerrie, thank you for our discussions and enlightening me on how to do this 'mysterious' modelling. Marcel, thank you for the help with GAMS. Charlotte, Linda and Ria, thank you for all the friendly administrative help.

N2Africa colleagues - Thank you all for making this a great project to work in!

My great friends – for being there and for all the so-needed fun outside of my PhD adventure. Irene, Lotte, Maite, Saar, Eva and Maud, I am happy that your 'open doors' were around the corner. And I am thankful for the 'Utrecht mama's' WhatsApp group where we can share all our ups and downs and give me the feeling you are still next doors. Thank you 'H3' for being such a lively house to start off my PhD adventure and being good friends. And 'voedingmiepjes', I am happy we still meet up!

Esther and Aafke – my two paranymphs, colleagues and great friends! Thank you for wanting to sit with me on stage. But most of all thank you for all the so-needed, helpful and fun coffees together. Esther, I am happy to have shared my PhD adventure within N2Africa with you from the start and the ups and downs of doing a PhD. 'After' you will always be my best 'husband'. Let's keep on drinking many more (digital) coffees together!

Family – Jacqueline and André: How did it happen? Your daughter doing a PhD in Wageningen combining both of your study backgrounds? Thank you for your always positive support and the special trips with both of you together in Ghana! Arno, thank you for your always sincere interest and being the best brother. And special thanks to Nina who dedicated quite some hours to make this thesis look great with your artwork! And thank you family of Roy, I feel like I have an extra family. And Anke thank you for taking care of Mara so I could actually bring this PhD adventure to an end.

Mara and Sam - Mara, coming home from a frustrating day of PhD work and finding you at home dancing or laughing out loud together with Roy – you made me feel like the happiest person in the world! You are a great clown! Sam, thank you for keeping me healthy during the last stretch of my PhD adventure – forcing me to go to bed early, limiting my coffee and chocolate intake and distracting me from too much PhD stress with your dance moves in my belly. Mara and Sam, you make me realise what is most important in life. Thank you for adding so much laughter, love and happy chaos to my life! I am looking forward to further exploring the world together with you!

Roy – I am so happy I had you by my side during my PhD adventure, you were my best supporter and distraction. You motivated me to challenge myself and gave me the comfort that I could bring this adventure to a successful completion. You can make things pleasantly more simple when I tend to make things more complicated. You were able to let me forget about the PhD (at least for a bit) and we went on many great adventures together the last 5 years, even some I was never expecting to go on (moving to the US!). Thank you for being you... 'and is why I love you' ;) Let's continue our ginger adventures!

About the author

When Ilse de Jager was born she was also given a Ghanaian name: Talata. Talata means 'born on Tuesday' in one of the local languages in Northern Ghana. And that is where she was born on 22 April 1986 and where she conducted the majority of her PhD research. She lived in Ghana up to the age of 2 and subsequently lived in Wageningen, Indonesia and Zoetermeer during the first 18 years of her life.

After a year of volunteer work in Ghana, Spanish classes in Peru, work and travel, she moved to Maastricht where she studied Health Sciences at Maastricht University. During her bachelor Health Sciences, she followed courses at the University of Guelph in Canada, did an extra minor in Globalization and Diversity, and worked as a research assistant analysing data of a study on determinants of nutritional status of adolescents in rural Sudan. This last experience contributed to the realization that her passion lies with health and nutrition in developing countries. Therefore, she decided to conduct the MSc programme in Human Nutrition at Wageningen University. She conducted fieldwork for her MSc thesis in India on the efficacy of the local vitamin-C rich fruit guava with mung bean based meal on improvement of iron status of rural children. She also conducted an internship at the organisation for development cooperation (ICCO) on exploring linkages between food security programmes and nutrition.

Since her MSc graduation in 2012, she first worked as a research assistant at the Human Nutrition group after which she joined the Plant Production Systems group at Wageningen University. She was involved in the monitoring and evaluation of potential nutritional impacts of the N2Africa project: putting nitrogen fixation to work for smallholder farmers growing legume crops in Africa. This led to the start of her PhD research within the context of this project, both at the Plant Production Systems group and the Division of Human Nutrition in 2014. N2Africa ended up as one of the winning projects of the 2013 Harvesting Nutrition Contest initiated by the World Bank and Ilse shared her research results at the World Bank during the award ceremony. She attended several national and international conferences and courses in the field of international nutrition and in 2018 she was selected and participated in the European Nutrition Leadership Programme in Luxembourg. Recently, she moved to the Bay area in California, ready for new work and life adventures.

List of publications

Peer reviewed scientific publications

de Jager, I., Borgonjen-van den Berg, K., Giller, K. E., & Brouwer, I. D. (2019). Current and potential role of grain legumes on nutrient adequacy of the diet of Ghanaian infants and young children. *Nutrition Journal, 18*(1), 12.

de Jager, I., Giller, K. E., & Brouwer, I. D. (2018). Food and nutrient gaps in rural Northern Ghana: Does production of smallholder farming households support adoption of food-based dietary guidelines? *PLoS One, 13*(9), e0204014.

de Jager, I., Abizari, A.-R., Douma, J. C., Giller, K. E., & Brouwer, I. D. (2017). Grain legume cultivation and children's dietary diversity in smallholder farming households in rural Ghana and Kenya. *Food Security, 9*(5), 1053-1071.

Bolhuis, D. P., Gijsbers, L., de Jager, I., Geleijnse, J. M., & de Graaf, K. (2015). Encapsulated sodium supplementation of 4weeks does not alter salt taste preferences in a controlled low sodium and low potassium diet. *Food Quality and Preference, 46*(Supplement C), 58-65.

de Jager, I., van de Ven, G. W. J., Lubbers, M. T. M. H., Giller, K. E., & Brouwer, I. D. (under review). Seasonality and nutrition-sensitive farming in rural Northern Ghana.

Conference proceedings

de Jager, I., Giller, K. E., & Brouwer, I. D. Let's harvest nutrition! . In *3rd Annual Agriculture, Nutrition & Heath (ANH) Academy Week, Accra, Ghana, 2018*

de Jager, I., Giller, K. E., & Brouwer, I. D. Does local food availability support implementation of food-based dietary recommendations in northern Ghana? In *International Conference on Nutrition ICN/IUNS, Buenos Aires, Argentina, 2017*

de Jager, I., Abizari, A., Douma, J. C., Giller, K. E., & Brouwer, I. D. Grain legume cultivation and children's dietary diversity in smallholder farming households in rural Ghana and Kenya. In *Pan-African Grain Legume and World Cowpea Conference Livingstone, Zambia, 2016*

de Jager, I., Ronner, E., Brouwer, I. D., & Giller, K. E. Child's nutritional benefits of grain legume cultivation within the N2Africa project in Northern Ghana and Western Kenya. In *4th Annual Leverhulme Centre for Integrative Research on Agriculture and Health (LCIRAH) Conference, London, England, 2014*

de Jager, I., Ronner, E., Franke, A. C., Brouwer, I. D., & Giller, K. E. Nutritional benefits of grain legume cultivation within the N2Africa project in Northern Ghana. In *First International Conference on Global Food Security, Noordwijk, the Netherlands, 2013*

Scientific reports, film and magazine publications

Brouwer, I. D., de Jager, I., Borgonjen, K., Azupogo, F., Rooij, M., Folson, G., & Abizari, A. (2017). Background Technical Report. Development of Food-Based Recommendations using Optifood - Ghana. Washington DC, USA: GAIN.

de Jager, I. (2013). Nutritional benefits of legume consumption at household level in rural areas of sub-Saharan Africa. *Background document*. Wageningen, The Netherlands: N2Africa.

N2AfricaTV (2013). Nutritional benefits of grain legume cultivation within the N2Afria project in Northern Ghana. (pp. 23:16). http://www.n2africa.tv/.

Louwerens, T. (2018). Ghana is not helped by dietary guidelines alone. *Resource WUR*.

Sikkema, A. (2014). World Bank applauds N2Africa nutrition project. *Resource WUR*.

Overview of completed training activities

Discipline specific conferences and meetings	Country	Year
Agriculture, Nutrition and Health Academy Week	Accra, Ghana	2018
International Conference on Nutrition ICN/IUNS	Buenos Aires, Argentina	2017
International Conference on nutrition and growth	Amsterdam, The Netherlands	2017
Pan-African Grain Legume and World Cowpea Conference	Livingstone, Zambia	2016
Agriculture, Nutrition and Health Academy Week	Addis Ababa, Ethiopia	2016
Harvesting Nutrition Celebration, World Bank	Washington D.C., USA	2014
High level forum on International Maternal and Child Nutrition (WUR)	Wageningen, The Netherlands	2014
LCIRAH Conference, London school of Hygiene (LSHTM)	London, United Kingdom	2014
N2Africa meetings (PPS, WUR)	Wageningen, The Netherlands	from 2013
Elsevier Global Food Security Conference	Noordwijkerhout, The Netherlands	2013

Discipline specific courses	Institute	Year
Food composition data in nutrition	VLAG	2015
Exposure assessment	VLAG	2014
Optifood training	London School of Hygiene (LSHTM)	2014
Master class Confounding	VLAG	2014
Agriculture nutrition linkages course (Ethiopia)	CDI	2013

General Courses		
European Nutrition Leadership Program	ENLP	2018
Presenting with Impact	WUR	2015
Techniques for writing a scientific paper	WUR	2015
Competence assessment	WUR	2015
PhD carousel	WUR	2014
Data analysis	Erasmus University - NIHES	2014
Regression analysis	Erasmus University - NIHES	2014

Optional courses and activities		
PhD committee	Division of Human nutrition	2015 – 2017
Development PhD proposal	VLAG	2014 – 2015
Lunch meetings	PPS	2013 – 2018
Bi-weekly staff seminar	Division of Human nutrition	2013 – 2018

The research described in this thesis was financially supported by the Plant Production Systems Group, Wageningen University, by the Bill & Melinda Gates Foundation through the project N2Africa: Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (www.N2Africa.org), and by a grant from The Global Alliance for Improved Nutrition (GAIN: www.gainhealth.org).

Financial support for printing this thesis was kindly provided by Wageningen University.

Artwork by: Nina van Rijn

Printed by: ProefschriftMaken