Food Security (2023) 15:773–789
https://doi.org/10.1007/s12571-022-01337-1

ORIGINAL PAPER

A healthy diet for a growing population: a case study of Arua, Uganda

Marleen I. Hermelink[1] · Katherine H. Pittore[2] · Adolfo Álvarez Aranguiz[3] · Fatima I. Pereira da Silva[4] · Marlene M. I. Roefs[2] · Robert Kajobe[5] · Richard Malingumu[5] · Huib Hengsdijk[1]

Received: 27 June 2022 / Accepted: 17 November 2022 / Published online: 27 January 2023

Abstract

It is uncertain whether Sustainable Development Goal 2 (SDG2), a healthy diet for all, can be achieved in East Africa given its strong population growth, low agricultural yields, and the high perishability of nutrient-dense foods. We examine the consequences of a locally produced healthy diet on land use in a case study of the Arua district in Uganda. This type of analysis can alert policy makers to looming nutrition gaps and support the selection of alternative solution strategies. Using a linear programming (LP) model and three population growth projections, we estimate the minimum agricultural area needed in 2040 to produce a healthy diet that follows EAT-Lancet dietary diversity guidelines and supplies the average requirements of calories, proteins, Iron, and vitamin A. We also compare in scenarios to what extent i) production intensification, ii) food loss reduction, iii) by-product consumption, and iv) vitamin supplementation could reduce the required agricultural area. Results show that the necessary area to produce a healthy diet in 2040 is 160% larger than Arua's current crop area and would greatly exceed the district's total area. We also show that none of the changes proposed in our scenarios allows a sufficient increase in food production, suggesting that a mix of even more drastic changes across sectors will be necessary. The results underline the challenge for rural areas in East Africa like Arua to provide a healthy diet to its fast growing population, requiring integrated food system changes and policy coordination to orchestrate the increased availability of diverse and nutritious foods.

Keywords Land use · Population growth · Nutritious food · Linear programming · LSMS · Food system · East Africa

1 Introduction

In recent years, it has become increasingly clear that intake of nutritious foods should be part of the food security equation (Willett et al., 2019). Nutrient deficiencies in diets have consequences in the short and long term, from increased risks for diseases to reduced labour productivity. Especially at a young age, nutritional deficiencies may have long-lasting negative impacts on an individual's physical health, mental development, and economic opportunities (United Nations Children's Fund [UNICEF], 2019). Research on food security has therefore shifted

✉ Marleen I. Hermelink
marleen.hermelink@wur.nl

Katherine H. Pittore
katherine.pittore@wur.nl

Adolfo Álvarez Aranguiz
adolfo.alvarezaranguiz@wur.nl

Fatima I. Pereira da Silva
fatima.pereiradasilva@wur.nl

Marlene M. I. Roefs
marlene.roefs@wur.nl

Robert Kajobe
r.kajobe@muni.ac.ug

Richard Malingumu
r.malingumu@muni.ac.ug

Huib Hengsdijk
huib.hengsdijk@wur.nl

1 Wageningen Plant Research, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands

2 Wageningen Centre for Development Innovation, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands

3 Wageningen Livestock Research, De Elst 1, 6708 WD Wageningen, The Netherlands

4 Wageningen Food & Biobased Research, Bornse Weilanden 9, 6708 WG Wageningen, The Netherlands

5 Faculty of Agriculture and Environmental Sciences, Muni University, P.O. Box 725, Arua, Uganda

towards food and nutrition security, acknowledging the importance of consuming not only enough calories, but also fulfilling the needs for micronutrients that are essential for health and development (Food and Agriculture Organization of the United Nations [FAO] et al., 2017; Gil et al., 2019).

In the context of East Africa, a shift in consumption from staple foods such as cereals, tubers, and oils, to more nutrient-dense foods such as fruits, vegetables, legumes, and animal products has been proposed to improve diets (Food and Agriculture Organization of the United Nations [FAO] et al., 2021). However, consequences of such a shift on land use are uncertain. Current yields of nutrient dense foods such as fruits, vegetables, and animal products are low in many parts of East Africa (de Steenhuijsen Piters et al., 2021; Herrero et al., 2014; Paul et al., 2020). In addition, most of these nutritious products are highly perishable, with limited food processing capacities in the region resulting in high post-harvest losses (Porter et al., 2016; United Nations Human Settlements Programme [UN-Habitat], 2021). The combination of East Africa's low yields and high post-harvest losses add to the land resources needed to supply enough nutrient-dense foods. Moreover, East Africa's population is expected to increase steeply in the coming decades. Yearly growth rates for the region are projected at around 2.3% until 2040 (United Nations [UN], 2019), growing from the current 445 million people to potentially 707 million. This population growth will drastically increase the demand for food in the near future (van Ittersum et al., 2016).

In view of the current low yields and high losses of nutritious foods on the one hand, and the projected population increase on the other, it is unclear whether the Sustainable Development Goal of supplying healthy diets for future populations (SDG 2) can be achieved given East Africa's available land resources and its current food system characteristics. This paper explores the feasibility of meeting future healthy diet requirements in the context of East Africa, using the former district of Arua, in the West Nile region of Uganda, as a case study. The district is a typical rural area in East Africa, where fast population growth and low agricultural productivity contribute to poor dietary diversity and high levels of stunting (Uganda Bureau of Statistics [UBoS], 2018). The objective of this paper is to explore the possibilities for providing the population of the Arua district with a locally produced healthy diet in 2040 given the available land area. Using a modelling approach, we (a) analyse in different population growth projections the effect of the local production of a healthy diet on land use compared to the current diet, and (b) explore to what extent i) production intensification, ii) food loss reduction, iii) by-product consumption, and iv) vitamin supplementation could reduce the agricultural area required to produce a healthy diet for the future population of Arua.

The goal of the analysis is to show the overall challenges in terms of land area that transitioning to a healthier, more diverse diet would entail, relevant in the context of policy development. Although food self-sufficiency is not necessarily a goal in and of itself, the analysis of land demand for local production can shed light on possible future gaps between food requirement for a healthy diet and the local food production capacity. This type of analysis contributes to early warning of policy makers to looming food and nutrition gaps and supports the selection and development of strategies to tackle these. The results should be understood as illustrating broadly the challenges that a shift in diet may place on an already challenged food system, rather than to predict the exact amount of land necessary to produce a healthy diet.

We use a linear programming model to match food production and the requirements of a certain diet for the local population at district level. We describe the case study area of Arua in Sect. 2, and outline the modelled food system, the modelling framework, the healthy and current diet, and the simulated scenarios in Sect. 3. We present and discuss results in Sects. 4 and 5, respectively. Final conclusions and implications for the future research and policy agenda are outlined in Sect. 6.

2 Case study area

Arua was a district located in the West Nile area of Uganda (Fig. 1), but was split into the two new districts of Terego and Madi Okollo after an administrative land redistribution in 2020. At the time of data analysis (2019) Arua was still an official district. Our analysis therefore refers to the former Arua district, which is bordered by the Democratic Republic of the Congo (DRC) and the Republic of South Sudan to the West and North respectively. To the East, the Nile forms a natural barrier with the rest of Uganda. In 2018, the local population of the district was 0.95 million (van Dijk et al., 2022). Because of the continuing humanitarian crises in the DRC and South Sudan, the district also hosts a fluctuating refugee population varying from 271,655 in 2018 to 207,070 in 2022 (United Nations High Commissioner for Refugees [UNHCR], 2018, 2022), totalling the district population to around 1.2 million people.

Arua district is largely rural with a single city, also called Arua. The total district area is 4,428 km^2, of which only 1% is urban and 50% (223,241 ha) is cropland (Copernicus, 2018). The rest of the area consists of natural vegetation such as forests (25%), shrublands (19%), and wetlands (2%). The main source of livelihood for most people is subsistence agriculture, characterized by low productivity levels, low external inputs, small scale agricultural production, and limited food processing capacity (Uganda Bureau of

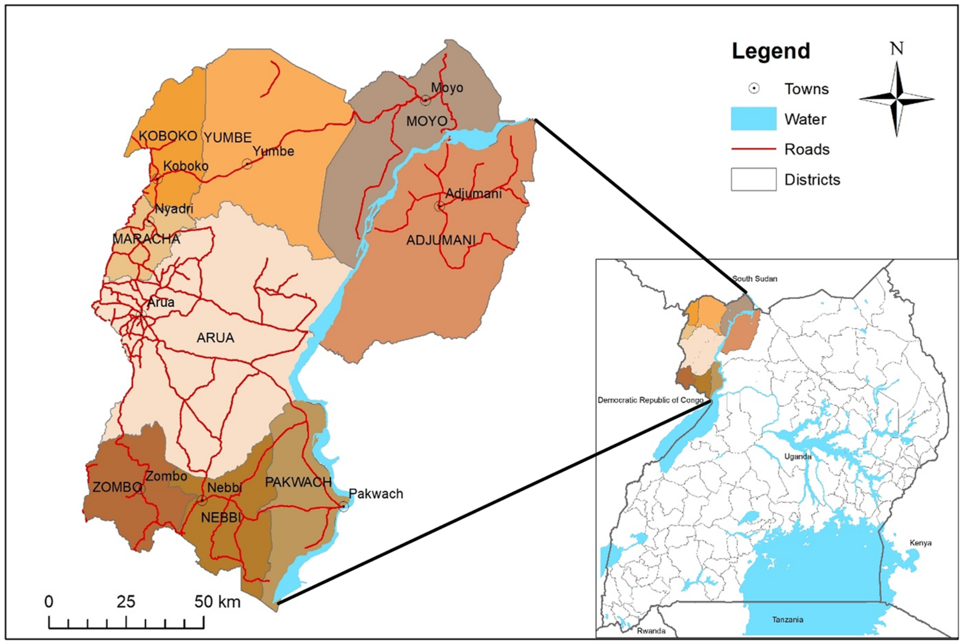


Fig. 1 Map of Uganda and the zoomed in West Nile area, where Arua district is located. District borders shown as they were in 2019

Statistics [UBoS], 2020; United Nations High Commissioner for Refugees [UNHCR] & World Vision Uganda [WVU], 2017; United Nations Human Settlements Programme [UN-Habitat], 2021). Crop production takes place in two rainy seasons, roughly from March to May, and from August to December. Animal production is very limited, with chicken and goats being the most common livestock. Animals are generally kept in scavenging production systems, fed irregularly with household food residues and grazing around the farm (Uganda Bureau of Statistics [UBoS], 2020).

3 Method

We developed a modelling framework based on a Linear Programming (LP) optimization model, which is a mathematical technique to minimize or maximize a linear objective function subject to linear constraints (Dantzig & Thapa, 2006). This optimization technique is commonly used to quantify land use trade-offs, and was selected due to its relative simplicity, transparency, and low data demand (Bouman et al., 1998; Delmotte et al., 2017; Roetter et al., 2007). This was considered suitable for Arua's data scarce environment, with little to no data available on the food system. The modelling framework estimates the minimum agricultural area in Arua needed for producing a well-defined diet for the whole population, given the district's food system characteristics of productivity and losses and a certain population in terms of size, age, and gender composition. We describe the food system as modelled for Arua in Sect. 3.1, and outline the modelling framework in Sect. 3.2. We subsequently used the modelling framework to estimate the agricultural land requirement for a set of scenarios, with each scenario modelled at three alternative population growth projections of the Shared Socioeconomic Pathways (SSPs) (Sect. 3.3). In the scenarios, we evaluate the impact of producing a healthy diet on land requirements compared to the current diet, and we compare the effectiveness of various potential food system changes in reducing the agricultural land requirements.

3.1 Food system overview

In this subsection we give a general overview of the conceptualized food system for Arua in the LP model, shown in Fig. 2, while going into more detail on the parameterization and assumptions for each element of the food system in Sect. 3.2.3. We assume that agricultural land is used either for a cropping system or as grassland for grazing. We define the concept of a cropping system as a certain sequence of one or more crops per year. An example of a cropping system can be a sequence of two annual crops, such as maize in the first rainy season followed by beans in the second rainy season, or a perennial crop such as papaya or mango. A cropping system produces one or more harvested food products as well as crop residues. A food product has an edible part and a non-edible part (peels and husks). It is also possible to keep animals, which produce animal products. The animals can be fed with the edible and non-edible parts of crop products, with crop residues, and with grass. Post-harvest losses are assumed for both crop and animal food products, leaving the remainder of the food products for human intake. We assume that all food products are consumed in farm gate conditions without further processing, that there are no imports nor

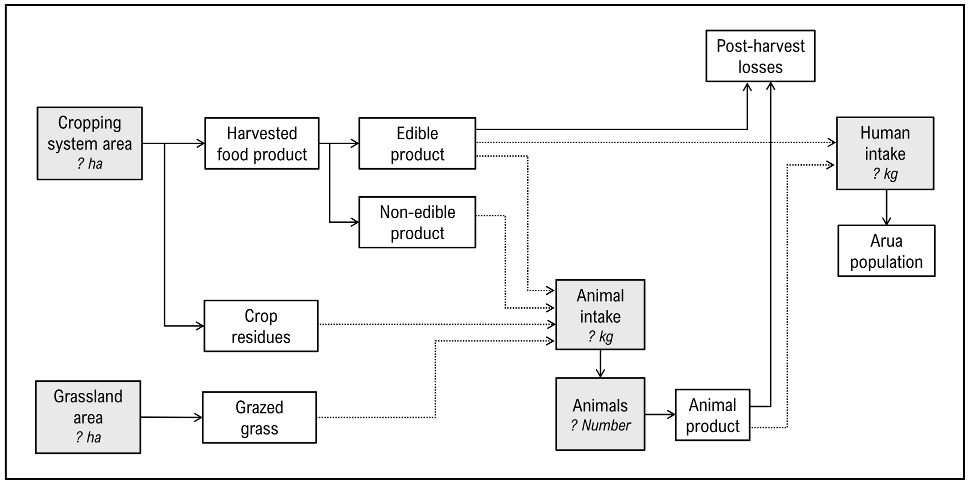


Fig. 2 Schematic representation of the modelled food system of Arua. Gray boxes and dotted lines represent the values calculated by the LP model (i.e., the decision variables), while white boxes and full lines represent parameters

exports to and from the food system, and that the food is divided equally over the population.

In the food system described above, we assume that we know the amount of harvested product and crop residues from each cropping system (i.e., the crop yields), the edible fraction of each harvested food product, the grassland and animal product yields, the post-harvest loss-fractions, and each product's nutritional content. These are the parameters of the model, which we have estimated with fixed constants (Sect. 3.2.3). What we do not yet know are the area of grassland and of each cropping system, the number and type of animals, the amount and type of animal feed sources, and the amount of each food product needed to supply the current and the healthy diet. These are the values that the LP model calculates, referred to as the decision variables.

3.2 Modelling framework

The modelling framework, including the LP model, is illustrated in Fig. 3 and works as follows. We first define the healthy and current diet in terms of food groups and nutrient intakes (Sect. 3.2.1). The diet definitions are implemented as constraints in the LP model to ensure food production meets intake requirements (Sect. 3.2.2). Animal feed requirements are also specified as constraints. Constraints are the restrictions placed on the outcomes of the LP model such that the outcome meets a certain minimum or maximum value. To meet dietary constraints, the LP model can choose from a range of crop and animal products, each with its associated yield, post-harvest loss fraction, and nutritional content parameter. The model calculates the optimum (a) intake

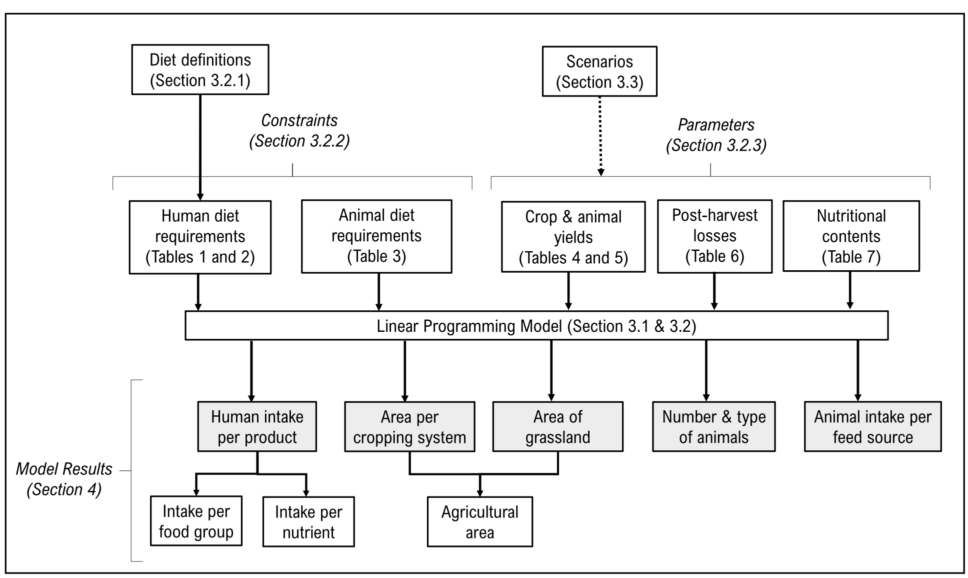


Fig. 3 The modelling framework used to estimate the minimum agricultural area in Arua given the current diet and given a healthy diet. The gray boxes are the values in the food system calculated by the LP model (i.e., the decision variables), corresponding to Fig. 2, represented here as the model's output

of each product, (b) area of each cropping system, (c) area of grassland, (d) number of animals of each type, and (e) amount and type of animal feed sources, such that agricultural area is minimized while still meeting human and animal dietary requirements. From the cropping system areas, the number of animals, and their corresponding yields, the model calculates the production of each food product, and subtracts the amount lost through post-harvest losses and the amount used as animal feed (Fig. 2). The resulting available food is equally divided over the population, resulting in the average intake per person. The LP model therefore chooses the food production options, i.e., cropping systems, grassland, and animal types and feeds, such that it uses the least amount of agricultural land while still meeting dietary requirements (see Appendix B for the complete formulation of the LP model).

In the next subsections, we first describe the healthy diet as defined in this study, as well as the estimated current diet, in terms of daily intake levels of food groups and nutrients (Sect. 3.2.1). Then we outline how the dietary intakes of both diets as well as the livestock feed requirements were implemented as model constraints (Sect. 3.2.2), and how crop and animal production have been parameterized in the model (Sect. 3.2.3).

3.2.1 Diet definitions

Healthy diet There is no overall consensus around the definition of a healthy diet, but there is general agreement that the diet should be (a) diverse, incorporating foods from a variety of food groups, and (b) nutritionally adequate, consuming enough macro- and micro-nutrients (Food and Agriculture Organization of the United Nations [FAO] et al., 2021). In this study, we use the guidelines of the EAT-Lancet Commission on intake ranges of different food groups to ensure dietary diversity (Willett et al., 2019) (Table 1). The EAT-Lancet guidelines provide an intake range of different food groups, which, if complied to in combination with an intake of 2500 kcal/p/d, should broadly cover most adult nutritional needs due to the resulting varied diet. The guideline ranges allow for flexibility to obtain calories, proteins, and micronutrients from preferred food groups. However, although the ranges cover nutritional needs roughly, adequate intake of specific nutrients is not guaranteed. To ensure nutritional adequacy, we impose an additional set of requirements on our healthy diet, to meet at least the average requirements for calories, proteins, Iron, and vitamin A (Table 2). These four nutrients were selected to represent nutritional adequacy due to their importance to human health and their widespread deficiency, making them major bottlenecks towards healthy diets (World Food Programme [WFP], 2015). The average requirement is the amount of nutrient intake at which 50% of individuals in an age and sex group are below their requirement, and 50% above, given a normal requirement distribution within the group (Caballero et al., 2003). Although it can be argued that a healthy diet should cover the nutritional demand for the whole population, our aim is to estimate the *minimum* agricultural area. We therefore choose this conservative metric for nutritional adequacy to avoid overestimating nutritional demand. To estimate the population's average requirements we followed standard European guidelines (European Food Safety Authority [EFSA], 2017), taking into account the population's age and gender composition, assuming physical activity levels of an active lifestyle, and assuming body weights based on Marshall (1981). We do not consider elements of moderation into our definition of a healthy diet, such as restricting intakes of salt or alcohol.

Current diet The current diet in Arua was estimated based on household survey data from the Living Standard Measurement Study (LSMS) (Uganda Bureau of Statistics [UBoS], 2020). The LSMS is a multi-topic panel household

Table 1 Daily intake per food group per person (g/person/day) as estimated in the current diet and in the healthy diet (Willett et al., 2019)

	Current Diet	Healthy Diet	
Food Group	Intake (g/p/d)	Minimum Intake (g/p/d)	Maximum Intake (g/p/d)
Cereals	256.3	0	230
Tubers	319.0	0	100
Vegetables – green	3.1	67	200
Vegetables – orange	4.5	67	200
Vegetables – other	1.9	67	200
Fruits	4.9	100	300
Legumes	57.6	0	250
Oils	63.9	20	92
Meat – red	0.1	0	28
Meat – white	0.1	0	58
Eggs	0.3	0	25
Dairy	2.5	0	500
Sweeteners	6.0	0	31

Table 2 Daily intake per person of four nutrients as estimated in the current diet, and average requirements for a healthy diet given the population composition in Arua in 2018 (United Nations High Commissioner for Refugees [UNHCR], 2018)

Nutrient	Unit	Current Diet	Healthy Diet
Calories	kcal/p/d	1,946	2,171
Protein	g/p/d	54	29
Iron	mg/p/d	17	7
Vitamin A	mcg RAE/p/d	131	431

survey conducted regularly on a nationally representative sample of households. Although an estimate of the current diet should ideally be made based on actually consumed food, the available data on food consumption in the LSMS dataset was deemed unsuitable due to a high degree of missing conversion factors, as was also found by Marivoet and Ulimwengu (2021). Other datasets on food consumption for Arua were, to our knowledge, not available. As an alternative, we used the LSMS production data to estimate the local food production. The current diet was then estimated as the total amount of food produced plus the food aid brought into the district, divided equally over the total (local and refugee) population. As data on free market trade was not available, it was assumed that Arua's food imports equal its food exports, with a net zero contribution to the total food availability.
Food crop production was calculated through estimates of seasonal crop areas and yields using the seven available LSMS surveys from 2009 to 2019. The dataset contains crop areas and yields in both seasons for a sample of households in each district of Uganda, with the number of households surveyed per year in Arua fluctuating between 24 to 91.

- Crop areas: With the crop production data of the households sampled in Arua, we computed the percentage area covered by each crop in each season, averaged across the years. We assume that this seasonal crop area distribution is constant across the district and use it to extrapolate from the household sample to the whole district. Using the seasonal crop area distributions and the total crop area in Arua based on remote sensing (Copernicus, 2018), we estimated the total area of each crop in each season.
- Crop yields: Due to the limited records available for fruit and vegetables, yield estimates of these crops included yield records from households in the entire West Nile region, of which the Arua district is a part, while yields of other crops were estimated only with records from households in Arua. After comparing crop yields of both seasons and observing inconsistent and limited differences between seasons, we pooled the yield records to calculate a single seasonal median yield for each crop (Table 4). The low resulting yields reflect the low farming intensity in the region. Yields of secondary edible products such as leaves and seeds were estimated through the harvest index (Appendix A1) but were assumed to be discarded in the current diet. All produced crops were corrected for their edible fractions (Appendix A1).
- Crop production: To estimate the yearly production of each crop, we multiplied the crop yield with the crop area in each season and summed across both seasons.

Animal production was calculated through estimates of the district's total number of animals of each type and their annualized yields as explained below, using all five LSMS surveys between 2011 and 2019 with compatible livestock data. Aquatic food production from the Nile such as fish and shellfish was not included in the current diet due to a lack of accurate production data.

- Number of animals: For each type of animal, we calculated the number of animals per person per year in the sample of households in Arua that were producing milk or eggs and the number that were slaughtered. We assumed the number of producing and slaughtered animals per person is constant across the local population of the district and used this to extrapolate from the household sample to the whole district. The total number of producing and slaughtered animals in Arua was then estimated by multiplying the number of animals per person with Arua's local population size.
- Animal yields: Animal product yields were estimated based on literature, expert knowledge, and LSMS data (Table 5) (see Appendix A2 for procedures). Yields are reported as annualized values to account for an animal's life cycle and herd reproductive needs. As a result of this approach and the overall low farming intensity, animal yields are very low in Arua.
- Animal production: Annualized animal production was estimated for each animal type multiplying the number of producing and slaughtered animals in Arua with their annualized yields.

The total annual food aid brought into the district was estimated based on the total number of refugees in Arua in 2018 and a standard monthly ration received per refugee (United Nations Development Program [UNDP], 2018; United Nations High Commissioner for Refugees [UNHCR], 2018) (Appendix A3). Post-harvest losses of all food products were estimated using food-loss fractions specific to Sub-Saharan Africa (SSA) (Porter et al., 2016), accounting for supply chain length (Appendix A4). After deducting post-harvest losses, the total amount available per food product at district level was estimated as the sum of the amounts produced and brought in as food aid. The total availability per food product was divided equally over the number of people in Arua in 2018 and quantified in terms of the same nutrients and food groups as the healthy diet (Tables 1 and 2) using standardized nutritional contents (Hotz et al., 2012) (Table 7). All products were assumed to be in farm gate condition, without further processing. The resulting estimated current diet is presented in column 1 of Tables 1 and 2. Our estimates of nutritional intakes in the current diet are in line with estimates at national level for Uganda (Marivoet & Ulimwengu, 2021).

3.2.2 LP model constraints

Human diet requirements In the LP model we defined two dietary constraints: food group intakes per person must be between the specified minimum and maximum level, and nutrient intake per person must be above the specified minimum level. The minimum and maximum levels are specified depending on the diet assumed in the scenario. For scenarios assuming a healthy diet, the minimum and maximum food group intakes were specified following the EAT-Lancet recommendations, and the minimum nutrient intakes were set at the average requirements, as outlined in the previous section. For scenarios assuming the current diet, the minimum food group intakes were defined as the current intakes (Table 1), and the maximum intakes were set at 10% above the minimum. The minimum nutrient intakes were set at the current intakes (Table 2).

Animal diet requirements Four animal types currently present in Arua were defined as options for food production in the LP model: dairy cattle, beef cattle, goats, and chicken. For each animal type, a minimum and maximum annual feed intake was defined in terms of dry matter, metabolizable energy, crude protein, and dry matter intake from fibrous feed sources (Table 3). Feeds categorized as fibrous sources were grass, crop residues, edible leaves, and non-edible food fractions (peels and husks). The feed intake requirements were estimated based on animal body weights and annual yield or weight gain (see Appendix A5 for procedures).

3.2.3 LP model parameters

To meet the diet constraints on intake, the model can choose from a range of crop and animal food production options. All options are characterized by productivity (i.e., yields), post-harvest loss, and nutritional content parameters.

Crop production The LP model contains the fodder crop grass and 19 food crops, including one to four crops per food group. We selected the most commonly produced crops in Arua in each food group to ensure alignment with current dietary preferences (Uganda Bureau of Statistics [UBoS], 2020). The 19 food crops were combined into 75 cropping systems, with the perennials, cassava, and sugarcane defined as single cropping systems and the rest of the crops combined into double cropping systems. We assumed that vegetables and sesame are only grown in the second, slightly longer, growing season, following LSMS data (UBoS, 2020) (see Appendix B3 for a complete list of all included cropping systems). Grassland was assumed to be permanent pasture. We assumed a constant yield of one or more food products from each crop (Table 4), which we correct for their edible fractions (Appendix A1). The number of hectares allocated to each cropping system and to grassland are model outputs. As a single yield parameter is assumed for each food product, we do not consider geographical crop suitability and the area allocation is therefore not spatially explicit. The sum of the cropping system areas is the total physical crop area. The sum of this crop area and the grassland area is the agricultural area, which is the objective value to be minimized in the LP model.

Animal production The number and type of animals and the amount and type of feed are both outputs of the LP model. We assumed a constant annualized yield for each animal type (Table 5). Options for feed sources in the model are grass, crop residues, food products, and non-edible parts of food products such as peels or husks. The model calculates the optimum number of animals of each type and the associated amount and type of feed, such that the crop area is minimized and human as well as animal dietary requirements are met.

Post-harvest losses For all food products, we assumed a fixed post-harvest loss parameter depending on the food group a product belongs to (Table 6). The assumed fractions include losses during agricultural production, storage and handling, distribution, and consumption. Losses during processing were disregarded due to the limited amount of food processing taking place in Arua.

Nutritional contents Each food product was assumed to have a standardized nutritional content of calories, proteins, Iron, and vitamin A, assuming farm gate conditions (Table 7).

Table 3 Minimum and maximum daily feed intake in terms of dry matter (DM), metabolizable energy (ME), crude protein (CP), and DM from fibrous sources, per animal for each livestock type. Annual intakes were based on the sum of the daily intake

	DM (kg DM)		ME (MJ ME)		CP (kg CP)		Fibre Sources (kg DM)	
Animal Type	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Dairy cattle	8.25	9.08	46.24	50.87	1.24	9.08	4.95	9.08
Beef cattle	5.50	6.05	37.00	40.70	0.90	6.05	3.30	6.05
Goats	0.68	0.74	17.19	18.90	0.17	0.74	0.41	0.74
Chicken	0.07	0.08	0.91	1.00	0.01	0.01	0.00	0.01

Table 4 Crops in the LP model with their corresponding food product(s), and each product's food group categorization and seasonal yield (kg/ha/season). The last four columns indicate the yield estimation method, the harvest condition, the number of observations included in the yield estimate (n), and the LSMS districts used for the yield estimate

Crop	Food Product	Food Group	Yield (kg/ha/s)	Yield Estimation Method	Harvest Condition	n	Districts Included
Maize	Maize	Cereal	994	LSMS data	Dry grain	284	Arua
Sorghum	Sorghum	Cereal	534	LSMS data	Dry grain	197	Arua
Cassava	Cassava root	Tuber	2059	LSMS data	Fresh	302	Arua
	Cassava leaves	Vegetable – green	32	HI	Fresh	-	-
Sweet potato	Sweet potato root	Tuber	2965	LSMS data	Fresh	146	Arua
	Sweet potato leaves	Vegetable – green	6765	HI	Fresh	-	-
Plantain	Plantain	Tuber	2201	LSMS data	Fresh	75	Arua
Mango	Mango	Fruit	5311	LSMS data	Fresh	11	West Nile
Banana	Banana	Fruit	1647	LSMS data	Fresh	142	West Nile
Papaya	Papaya	Fruit	1478	LSMS data	Fresh	3	West Nile
Beans	Beans	Legume	472	LSMS data	Dry grain	243	Arua
Pigeon pea	Pigeon pea	Legume	404	LSMS data	Dry grain	32	Arua
Soybeans	Soybeans	Legume	563	LSMS data	Dry grain	18	Arua
Sesame	Sesame	Oil crop	300	LSMS data	Dry grain	178	Arua
Groundnuts	Groundnuts	Oil crop	485	LSMS data	Dry w. shell	273	Arua
Tomato	Tomato	Vegetable – orange	1502	LSMS data	Fresh	48	West Nile
Cabbage	Cabbage	Vegetable – green	3149	LSMS data	Fresh	18	West Nile
Onion	Onion	Vegetable – other	978	LSMS data	Fresh	24	West Nile
Pumpkin	Pumpkin flesh	Vegetable – orange	2955	LSMS data	Fresh	66	West Nile
	Pumpkin seeds	Oil crop	326	HI	Fresh	-	-
	Pumpkin leaves	Vegetable – green	4188	HI	Fresh	-	-
Eggplant	Eggplant	Vegetable – other	1404	LSMS data	Fresh	16	West Nile
Sugarcane	Sugarcane stalks	Sweeteners	3163	LSMS data	Fresh	19	West Nile
Grass	-	-	6661	Literature	Fresh	-	-

With this assumption, we disregard the impact of multiple factors on nutrient bio-availability, including the effect of food preparation practices, differences between plant and animal source foods, and interactions between different foods (de Pee & Bloem, 2007; Fabbri & Crosby, 2016). As these factors generally increase the food intake needed to meet nutritional requirements, and thus increase the area needed for food production, our calculated minimum area needed to produce the current and a healthy diet are on the conservative side.

Table 5 Animal types in the LP model, with their corresponding food products, food group categorization, and annualized yield (per animal per year). See Appendix A2 for procedures of yield estimates

Animal Type	Food Product	Food Group	Yield	Unit
Dairy Cattle	Beef	Meat	27.4	kg meat/a/y
	Milk	Dairy	230.0	L milk/a/y
Beef Cattle	Beef	Meat	36.6	kg meat/a/y
Goats	Goat Meat	Meat	5.4	kg meat/a/y
Chicken	Chicken Meat	Meat	0.7	kg meat/a/y
	Eggs	Eggs	1.7	kg egg/a/y

3.3 Scenarios

The LP model was used to estimate the minimum agricultural area needed to produce the current or a healthy diet in seven scenarios in 2040. Due to the unpredictability of how the refugee population in Arua will develop towards 2040, the scenarios included only the area necessary to feed the local population of Arua in the future. Each scenario was simulated

Table 6 Loss fractions assumed for food production in the LP model (Porter et al., 2016). See Appendix A4 for overview of losses per supply chain step

Food Group	Food Loss Fraction
Cereals	0.19
Eggs	0.20
Fruits	0.70
Vegetables	0.70
Meat	0.20
Dairy	0.24
Oils	0.23
Legumes	0.23
Tubers	0.38
Sweeteners	0.38

Table 7 Nutrient contents assumed for each food product. All products are assumed to be in farm gate (raw) condition. Source: HarvestPlus (Hotz et al., 2012) unless otherwise specified. w. = with, w.o. = without

Food Product	Condition	Nutrient Contents			
		Calories (kcal/100 g)	Protein (g/100 g)	Iron (mg/100 g)	Vitamin A (mcg RAE/100 g)
Maize	white, dried	365	9.4	2.7	0
Sorghum	dried	360	6.6	0.8	0
Cassava root	fresh	160	1.4	0.3	1
Cassava leaves[a]	fresh	38	3.6	0.9	1500
Sweet potato root	white, fresh	117	2.2	0.8	0
Sweet potato leaves	fresh	35	4.0	1.0	51
Plantain	green, fresh	122	1.3	0.6	56
Mango	ripe, w.o. skin, fresh	65	0.5	0.1	38
Banana	ripe, fresh	89	1.1	0.3	3
Papaya	ripe, fresh	39	0.6	0.1	55
Beans	black, dried	341	21.6	5.0	0
Pigeon pea[b]	mature seeds	343	21.7	5.2	8
Sesame	dried	573	17.7	14.6	0
Groundnuts	dried, no shell	567	25.8	4.6	0
Tomato	ripe, fresh	18	0.9	0.3	42
Cabbage	green, fresh	25	1.3	0.5	5
Onion	fresh	40	1.1	0.2	0
Pumpkin flesh	mature, w. skin, fresh	26	1.0	0.8	369
Pumpkin seeds[c]	w. shell, dried	117	7.0	2.0	0
Pumpkin leaves	fresh	19	3.2	2.2	97
Eggplant	w. skin, fresh	24	1.0	0.2	1
Sugarcane stalks	fresh stalks	54	0.6	1.4	0
Beef	medium fat, fresh	251	18.2	1.9	0
Goat meat	medium fat, fresh	109	20.6	2.8	0
Chicken meat	w.o. bone, meat & skin, fresh	143	12.6	1.8	140
Milk	whole, fresh	60	3.2	0	28
Eggs	whole	251	18.2	1.9	0

[a] Chaiareekitwat et al. (2022)

[b] NutritionData (2018)

[c] MyNetDiary (2021)

three times, with the projected populations following different Shared Socioeconomic Pathways (SSPs) downscaled for Arua (Table 8). The SSPs predict changes in population size as well as age and gender composition, influencing the population's average nutrient requirements. SSP2 is considered Arua's average population growth projection, and SSP1 and SSP3 represent the lower and higher growth projections, respectively. All model simulations were performed in GAMS 32.2.0 using the mixed integer programming (MIP) solver. The following seven scenarios were analysed:

A. **Current diet:** The current diet is maintained.
B. **Healthy diet:** The population consumes a healthy diet.
C. **Healthy diet + production intensification:** The population consumes a healthy diet, and food production is intensified. Crop and livestock yields are assumed 30% higher than current values, as aimed for in the West Nile Agricultural Investment Plan (Muni University, 2021).
D. **Healthy diet + food loss reduction:** The population consumes a healthy diet, and post-harvest food losses in the supply chain are reduced. Post-harvest losses are assumed to decrease by 30%, well below the African Union's pledge to halve post-harvest losses by 2025 (African Union Commission [AUC], 2014).
E. **Healthy diet + by-products consumption:** The population consumes a healthy diet, and 30% of the nutrient-

Table 8 Summary of Shared Socioeconomic Pathways (SSPs) 1, 2, and 3 with regards to population growth, and downscaled population projections for Arua's local population in 2040 (O'Neill et al., 2017; van Dijk et al., 2022)

SSP	SSP Name	Storyline	Arua Population Growth Rate (%)	Arua 2040 Population
SSP1	Sustainability – Taking the green road	The world shifts gradually towards sustainability. Investments in health and education lead to low population growth	1.98	1,558,106
SSP2	Middle of the road	Current social, economic, and technological trends are maintained. Global population growth is moderate	2.60	1,769,723
SSP3	Regional rivalry – A rocky road	Countries focus on domestic issues, with little cooperation to address global problems. Population growth in developing countries is high	3.15	1,986,224

dense edible by-products such as leaves and seeds are consumed (Shackleton et al., 2009).

F. **Healthy diet + vitamin A supplementation:** The population consumes a healthy diet, and vitamin A, the most limiting nutrient in the current diet (Table 2), is supplemented through pills or enriched flour. A supplement covering 30% of the average vitamin A requirement is assumed.
G. **Healthy diet + all four changes:** The population consumes a healthy diet, and production intensification, food loss reduction, by-product consumption, and vitamin A supplementation are all implemented.

Scenarios A and B examine minimum crop area given the current and the healthy diet. Both scenarios were simulated, for each SSP, for the years 2018, 2020, 2030, and 2040. Scenarios C to G were run for each SSP for the year 2040, to compare the individual and combined effect of four food systems changes with the potential to reduce land claims for food production. These scenarios were modelled by changing one (or more, for Scenario G) of the food system characteristics (i.e., the parameters) by 30%, while keeping all other parameters constant. We compared the scenarios to determine to what extent they could contribute to the feasibility of a locally produced healthy diet for all.

4 Results

4.1 LP model cross check

Since the current diet was estimated using Arua's remote sensed total crop area as a reference (Copernicus, 2018), running the LP model for Arua's 2018 population assuming the current diet should result in an agricultural area close to the remote sensing crop area. We verified whether the model results were in line with expectations and within the correct order of magnitude by running a cross-check simulation with the current diet and 2018 population. The simulation resulted in a crop area of 212,212 ha, which is 5% below the crop area determined through remote sensing in 2018, i.e. 223,481 ha (Copernicus, 2018). The slightly lower modelled crop area compared to the reference can be explained by the minimization algorithm of the model. The LP model optimizes a land use combination that allows the production of the current diet with a smaller area than needed in reality. We consider the order of magnitude of the modelled crop area close enough to the remote sensing reference to confirm that the model works as intended.

4.2 Scenarios A & B: current diet vs healthy diet

Arua's projected population growth is reflected in the steeply increasing agricultural area needed to produce both modelled diets (Fig. 4). Following the current diet or the healthy diet in 2040 would require 392,904 and 582,081 ha of crop area, respectively. No grassland was allocated in either scenario because for the current diet (Scenario A) the model supplies livestock feed from sources other than grass, and in the healthy diet (Scenario B) the model does not choose to produce livestock products. The estimated crop areas would need to increase with 76% and 160% in scenario A and B, respectively, compared to Arua's current crop area of 223,481 ha. The area needed to supply a healthy diet in 2040 would be 48% greater than the area needed for the current diet and exceeds the district's total area of 442,800 ha by 139,281 ha. Supplying the healthy diet also requires a shift in relative areas from cereals, tubers, and oils towards vegetables, fruits, and legumes (Fig. 5).

4.3 Healthy diet limiting factors

Figure 6 shows which requirements of the healthy diet in 2040 are most restricting towards area minimization. The optimal solution provides exactly the minimum required number of calories and amount of vitamin A (Fig. 6, left

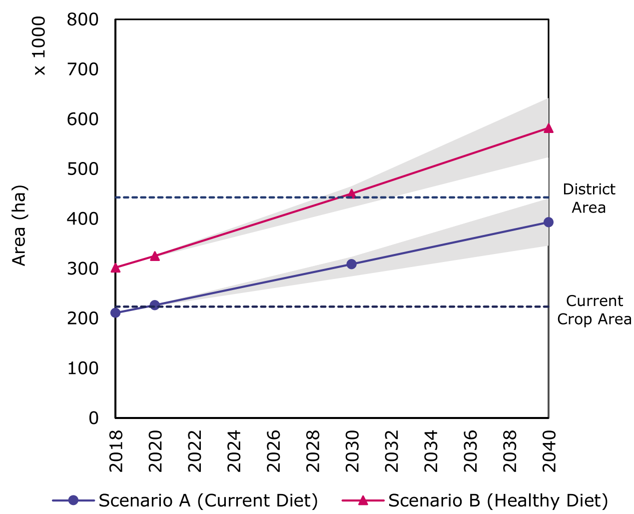


Fig. 4 Minimum crop area required in Arua from 2018 to 2040 to supply the population with the current diet (Scenario A, circle) and the healthy diet (Scenario B, triangle) given a population growth as projected by SSP2. The shaded area is the envelope of crop areas based on SSP1 (lower boundary) and SSP3 (upper boundary). Horizontal dotted lines show the current crop area in Arua and the total district area, as references

pane), meaning that these nutrients pose the heaviest burden on crop area. In the food groups, the solution uses up the maximum allowed intake of cereals, tubers, and oils due to their high caloric content, and provides only the minimum required amounts of fruits, green vegetables, and other vegetables due to their low caloric and vitamin A content (Fig. 6, right pane). The solution does not provide sweeteners such as sugarcane, as their nutritional contribution consists only of calories and none of the other quantified nutrients. Animal products are also not supplied in the solution despite

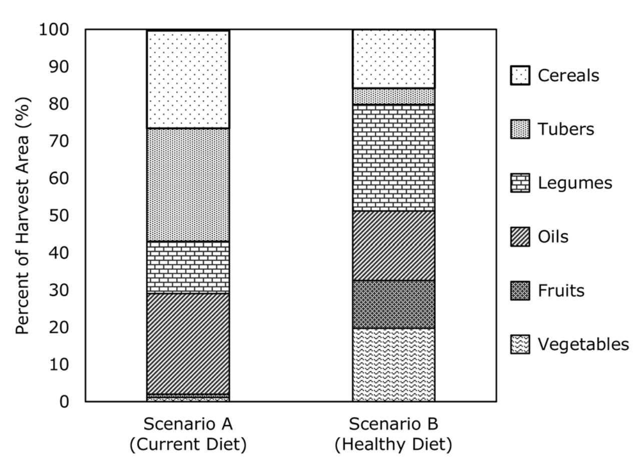


Fig. 5 Distribution of harvest area between food groups given the current diet and healthy diet scenarios for the population of Arua in 2040 following SSP2. Harvest area was defined as the sum of a crop's area across both seasons

their high nutritional value, as the livestock's high protein feed requirements relative to their protein yield makes them an inefficient protein source.

4.4 Scenarios C to G: potential food systems changes

The various food system changes lead to a decrease in crop area needed to produce a healthy diet compared to scenario B (Fig. 7). The scenarios C (Yield increase) and D (Food loss reduction) lead to the largest crop area decreases, 23 and 19%, respectively, compared to scenario B. The scenarios E (By-product consumption) and F (Vitamin A supplementation) result in the smallest decreases, 7 and 2%, respectively. The combination of these food system changes leads to the largest decrease of 41% crop area, and it is the only scenario in which a healthy diet production would be feasible given the district's area.

5 Discussion

Our study shows that, regardless of the diet followed, Arua's projected population increase will require a substantial increase in crop area given its current food system characteristics (Fig. 4). The 76% increase in food crop area needed to maintain the current diet in 2040 would require virtually all other land, including wetlands, forests, and shrublands to be used as cropland. Such a change would lead to massive biodiversity and ecosystem loss. These results are in line with literature pointing at the impending crop area expansion in SSA unless yields are drastically increased (van Ittersum et al., 2016), and with the West Nile's agricultural development plan, largely focused on opening up new land for agricultural production (Muni University, 2021). The study also shows that producing a healthy diet for Arua in 2040 would require 48% more land than producing the current diet. The area required would substantially surpass the districts total area, reflecting a major gap between the future food requirement for a healthy diet and the district's current production capacity. This gap is further exacerbated by the possible unsuitability of natural areas such as shrublands and wetlands to be used for cropping, leaving an even wider food production gap to bridge. The results indicate that SDG2, i.e., a healthy diet for all, would be impossible to supply in Arua in 2040 without major changes to its food system.

5.1 Limiting factors

We identified two main reasons leading to the healthy diet's larger crop area requirement than the current diet. The first reason is the higher intake of calories and vitamin A per

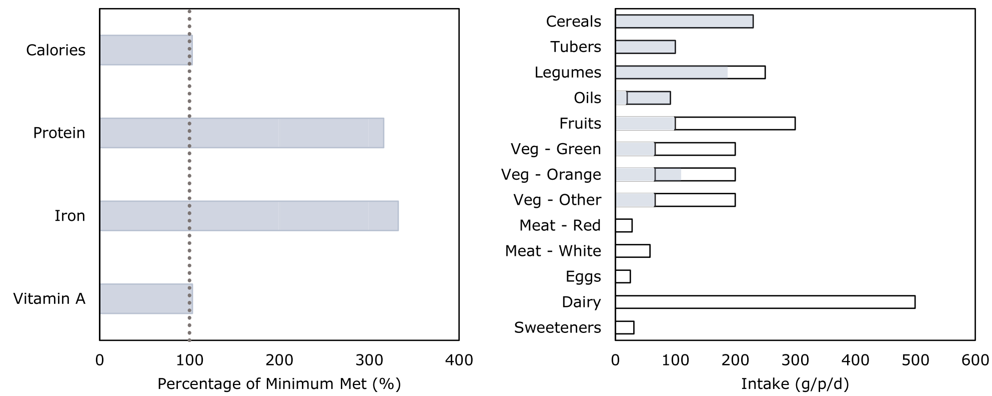


Fig. 6 Optimal intake of (left pane) nutrients and (right pane) food groups for the population of Arua in 2040 following SSP2, such that crop area is minimized but healthy diet requirements are met (Scenario B). Grey horizontal bars represent intake levels calculated by the LP model. Nutrient intake values in the left pane were normalized relative to their minimum intake (vertical dotted line, Table 2). Outlined boxes in the right pane represent healthy intake ranges (min to max) as advised by the EAT-Lancet Commission (Willett et al., 2019)

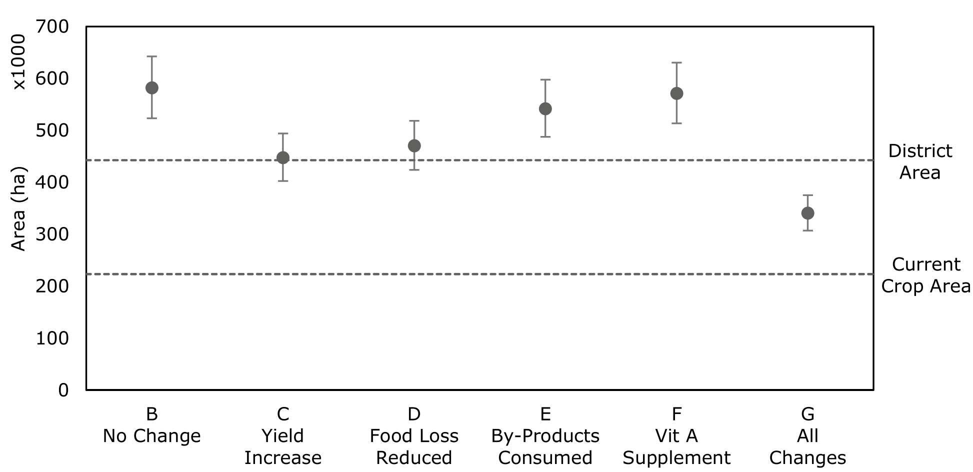
person in the healthy diet (Table 2). Current intakes of both nutrients are below the average requirements and consuming a healthy diet will require a higher intake across the whole population. As calories and vitamin A intake are limiting factors in the provision of a healthy diet (i.e., the constraints are binding, Fig. 6), their higher intake level requires more food per person and thus more crop area. Protein and Iron, on the other hand, seem to be supplied in sufficient amounts by the current diet (Table 2), and meeting the minimum intake does not pose an added strain on crop area (Fig. 6).

The second reason for the healthy diet's larger crop area compared to the current diet is the shift in nutrient sources. Whereas the current diet supplies the vast majority of its calories through cereals, tubers, and oils, the healthy diet supplies part of the calories through fruits and vegetables. Compared to other food groups, fruits and non-orange vegetables have low calorie and vitamin A yields and high post-harvest losses. As a result, their land use efficiency in terms of supplying calories and vitamin A is low. From a crop area minimization point of view, fruits and non-orange vegetables are not efficient, and the model allocates no more than the bare minimum intake of these food groups, while allocating the maximum possible to the calorie-rich cereals, tubers, and oils (Fig. 6).

5.2 Effectivity of food system changes

We compared how effective different changes in Arua's food system could be to reduce the crop area necessary to produce a healthy diet. Policymakers can stimulate the different proposed food system changes as alternative strategies to close the gap to supply a healthy diet. Increasing yields and reducing food losses (Scenarios C and D) were the most effective, decreasing the required crop area by 23 and 19%, respectively. They both alleviate bottlenecks to crop area minimization by reducing the area needed for the same amount of nutrients and food products. By-product consumption of edible leaves and seeds (Scenario E) would allow for more efficient land use,

Fig. 7 Crop area required to supply a healthy diet for Arua in 2040 given the current food system characteristics (Scenario B) and given alternative individual or combined changes in the food system (Scenarios C to G). Dots represent crop areas for the population following SSP2, and bottom and top error bars following SSP1 and SSP3, respectively. Horizontal dotted lines show the current crop area in Arua and the total district area, as references



for example, through harvesting tubers as well as edible leaves from the same area in a single season. As the leaves are classified as green vegetables, consuming them reduces the area needed for other green vegetables such as cabbage. The high vitamin A content of the leaves also allows a smaller area of vitamin A rich orange vegetables. Although this intervention could decrease the required crop area somewhat (7%), it is less effective than the first two interventions as it tackles mostly vitamin A and vegetable production but does not improve calorie availability. Vitamin A supplementation (Scenario F) increases vitamin A availability and thereby allows a lower production of orange vegetables. This has only a very limited effect on the crop area (2%), as it tackles only a single food group, and does not improve calorie availability. The limited effectivity of by-product consumption (Scenario E) and vitamin A supplementation (Scenario F) in reducing crop area is therefore a result of the simultaneous requirement to our healthy diet to meet both food group and nutrient requirements. By consuming all food groups, the diet is broadly nutritionally adequate already, and the increased availability of a specific micro-nutrient has little effect on the crop area. However, it should be noted that this does not mean that these measures are ineffective to improve current diets. Both by-product consumption and vitamin A supplementation can still improve nutritional adequacy of the current diet in Arua, which is still highly deficient in vitamin A (Table 2).

Although all analyzed food system changes can decrease the required crop area for a healthy diet to a certain extent, none of them applied individually is effective enough to reduce crop area below the district area. This signals that none of the changes would be sufficient as a strategy to close the identified gap between healthy diet food requirements and the district's production capacity. Applying all food system changes together has the strongest impact on the required crop area, but even then, approximately half of Arua's current natural habitats would need to be converted into crop area. These results indicate that producing a healthy diet for all in Arua in 2040 would require a mix of changes across multiple sectors of the food system, with changes that go beyond the ones we have analyzed in this paper. Not analyzed in the scenarios but also a possible strategy to help close the identified nutritional gap could be increasing food imports. As self-sufficiency is not a goal in and of itself, import increases could be a pragmatic option to contribute to increased local food availability. However, in the specific case of Arua, large scale import increases may present a challenge, as its geographic location between two food insecure countries and the natural water barrier of the Nile may impede trade flows into the district.

5.3 Methodology limitations

A limitation of this study is the rough characterization of Arua's food system. The current diet was estimated based on food production and food aid estimates, rather than on actual food consumption data. In estimating the current diet, trade flows, aquatic food sources from the Nile, and seasonality of food production and consumption were disregarded. Food was assumed to be distributed equally over the population, disregarding inequalities in food access and distribution. Productivity was generalized into average crop and livestock yields, without considering geographical differences in natural resource availability, nor in agricultural management. Nutritional adequacy was limited to four nutrients, without covering the Calcium deficiency in Uganda pointed out by Marivoet and Ulimwengu (2021) nor the potential vitamin B12 deficiency as a result of low animal product intakes. We also do not consider socio-economic aspects around diets, disregarding regional stigmas of poverty associated with vegetable consumption as well as the population's willingness and financial ability to consume and produce a healthy diet. Despite these methodological limitations, we consider the estimated parameters and results to be the best currently available for a data scarce environment like Arua. However, the results should be interpreted with care and as orders of magnitude, and not as future predictions. With this in mind, the pressing and nutritional gap in the near future to produce a healthy diet for the district's growing population and the relative effect of different food system changes, is still clear.

Another point of consideration is the effect of the refugee population on Arua's future food supply and crop area requirements. The refugee population was included in the cross-check simulation of the situation in 2018 but was left out in the scenario analyses. This choice was made to avoid over-estimating the food demand in the future, as stability in the DRC and South Sudan by 2040 could lead to an outflow of refugees from Arua back to their homes. However, if the refugee population would stay in Arua and grow at the same rate as the local population, producing a healthy diet in 2040 given SSP2 would require a crop area increase of 177% relative to current crop area, and of 200% if food aid for refugees is stopped. These figures further emphasize the pressing food and nutritional gap and the need to make drastic changes to Arua's food system, to be able to supply a healthy diet not only to the local population but also to the refugees it welcomes.

6 Conclusion

Our study shows that the crop area in Arua needs to increase drastically in the coming decades to feed a rapidly growing population. Producing a healthy diet for the population in 2040 would require almost 50% more land to produce than the current diet. The required land would substantially surpass the district's total area, indicating a major nutritional gap between the future food required for a healthy diet and the district's current production capacity. A healthy diet would also require an intake shift from staple crops to fruits, vegetables, and legumes, as well as a higher intake of calories and vitamin A. We have also shown that the analysed food system changes will not be sufficient to enable the production of a healthy diet in Arua in 2040. We conclude that a mix of changes across sectors will be necessary, and that changes will have to be even more drastic than those sketched in our scenarios. With this conclusion, we underline the challenge ahead for rural areas in East Africa like Arua, as some of the analysed food system changes are already massive challenges in and of themselves. The provision of healthy diets in this type of areas will require integrated food system changes and policy coordination to orchestrate the needed shifts and increases in food availability.

The methodology developed could also be applied in other regions or at different scales. The method can support the identification of the main bottlenecks to a healthy diet in a specific context and facilitate policy development to address those bottlenecks. The method can be expanded to include other objectives that are relevant in a development context, as a healthy diet is just one of the issues at the top of policy agendas. In Uganda, policy development also focuses on socio-economic development, climate change mitigation and adaptation, and biodiversity conservation (National Planning Authority [NPA], 2020). The developed method can help to make trade-offs among such development objectives explicit but requires further research.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12571-022-01337-1.

Acknowledgements We would like to thank Inge Brouwer and Asaah Ndambi for sharing their insights on human nutrition and livestock production in the context of Uganda, respectively. We would also like to thank Gerbert Roerink for preparing Fig. 1, and two reviewers for their valuable comments on an earlier version of the paper.

Data and code availability Data and code are available on request.

Declarations

Ethical approval This study was commissioned and financed by the Wageningen University & Research "Food Security and Valuing Water" program (KB-35–005-001), which is supported by the Dutch Ministry of Agriculture, Nature and Food Security.

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

References

African Union Commission [AUC]. (2014). *Malabo declaration on accelerated agricultural growth and transformation for shared prosperity and improved livelihoods*. Retrieved February 2022, from https://www.nepad.org/caadp/publication/malabo-declaration-accelerated-agricultural-growth

Bouman, B. A. M., Schipper, R. A., Nieuwenhuyse, A., Hengsdijk, H., & Jansen, H. G. P. (1998). Quantifying economic and biophysical sustainability trade-offs in land use exploration at the regional level: A case study for the Northern Atlantic Zone of Costa Rica. *Ecological Modelling, 114*(1), 95–109. https://doi.org/10.1016/S0304-3800(98)00121-5

Caballero, B., Trugo, L. C., & Finglas, P. M. (2003). *Encyclopedia of food sciences and nutrition*. Elsevier Science B.V.

Chaiareekitwat, S., Latif, S., Mahayothee, B., Khuwijitjaru, P., Nagle, M., Amawan, S., & Müller, J. (2022). Protein composition, chlorophyll, carotenoids, and cyanide content of cassava leaves (*Manihot esculenta Crantz*) as influenced by cultivar, plant age, and leaf position. *Food Chemistry, 372*(1), 131173. https://doi.org/10.1016/j.foodchem.2021.131173

Copernicus. (2018). *Copernicus land cover viewer*. Retrieved January 2022, from https://doi.org/10.5281/zenodo.3518038

Dantzig, G. B., & Thapa, M. N. (2006). Linear programming 1: Introduction. *Springer, New York*. https://doi.org/10.1007/b97672

de Pee, S., & Bloem, W. (2007). The bioavailability of (pro) vitamin A carotenoids and maximizing the contribution of homestead food production to combating vitamin A deficiency. *International Journal for Vitamin and Nutrition Research, 77*(3), 182–192. https://doi.org/10.1024/0300-9831.77.3.182

de Steenhuijsen Piters, B., Dijkxhoorn, Y., Hengsdijk, H., Guo, X., Brouwer, I., Eunice, L., Tichar, T., Carrico, C., Conijn, S., & Oostewechel, R. (2021). *Global scoping study on fruits and vegetables: Results from literature and data analysis*. Wageningen Economic Research [WEcR]. https://doi.org/10.18174/552129

Delmotte, S., Couderc, V., Mouret, J. -C., Lopez-Ridaura, S., Barbier, J. -M., & Hossard, L. (2017). From stakeholders narratives to modelling plausible future agricultural systems. Integrated assessment of scenarios for Camargue, Southern France. *European Journal of Agronomy*, *82*(1), 292–307. https://doi.org/10.1016/j.eja.2016.09.009

European Food Safety Authority [EFSA]. (2017). *Overview on dietary reference values for the European Union population as derived by the EFSA panel on dietetic products, nutrition and allergies*. Retrieved September 2021, from https://www.efsa.europa.eu/sites/default/files/assets/DRV_Summary_tables_jan_17.pdf

Fabbri, A. D. T., & Crosby, G. A. (2016). A review of the impact of preparation and cooking on the nutritional quality of vegetables and legumes. *International Journal of Gastronomy and Food Science, 3*(1), 2–11. https://doi.org/10.1016/j.ijgfs.2015.11.001

Food and Agriculture Organization of the United Nations [FAO], Economic Comission for Africa [ECA], & African Union Commission [AUC]. (2021). *Africa regional overview of food security and nutrition 2020: Transforming food systems for affordable healthy diets*. https://doi.org/10.4060/cb4831en

Food and Agriculture Organization of the United Nations [FAO], International Fund for Agricultural Development [IFAD], United Nations Children's Fund [UNICEF], World Food Programme [WFP], & World Health Organization [WHO]. (2017). *The state of food security and nutrition in the world 2017. Building resilience for peace and food security*. https://www.fao.org/3/I7695e/I7695e.pdf

Gil, J. D. B., Reidsma, P., Giller, K., Todman, L., Whitmore, A., & van Ittersum, M. (2019). Sustainable development goal 2: Improved targets and indicators for agriculture and food security. *Ambio, 48*(7), 685–698. https://doi.org/10.1007/s13280-018-1101-4

Herrero, M., Havlik, P., McIntire, J., Palazzo, A., & Valin, H. (2014). *African livestock futures: Realizing the potential of livestock for food security, poverty reduction and the environment in Sub-Saharan Africa*. Office of the Special Representative of the United Nations Secretary General for Food Security and Nutrition & the United Nations System Influenza Coordination [UNSIC]. https://pure.iiasa.ac.at/id/eprint/11154/

Hotz, C., Lubowa, A., Sison, C., Moursi, M., & Loechl, C. (2012). *A food composition table for Central and Eastern Uganda*. International Food Policy Research Institute [IFPRI] & International Center for Tropical Agriculture [CIAT]. https://www.ifpri.org/publication/food-composition-table-central-and-eastern-uganda

Marivoet, W., & Ulimwengu, J. M. (2021). Mapping the nutrient adequacy of farm production and food consumption to target policy in Uganda. *Development Policy Review, 40*(3), 12596. https://doi.org/10.1111/dpr.12596

Marshall, W. A. (1981). *Body weights and heights by countries*. Food and Agriculture Organization [FAO], World Health Organization [WHO], & United Nations University [UNU]. Retrieved October 2021, from https://www.fao.org/3/m2846e/M2846E00.htm#TOC

Muni University. (2021). *Draft West Nile agricultural investment plan*. Muni University.

MyNetDiary. (2021). *Pumpkin seeds-in-shell*. Retrieved October 2021, from https://www.mynetdiary.com/food/calories-in-pumpkin-seeds-in-shell-by-compliments-cup-699855-0.html

National Planning Authority [NPA]. (2020). *Third national development plan (NDPIII) 2020/21 – 2024/25*. Retrieved January 2022, from http://www.npa.go.ug/wp-content/uploads/2020/08/NDPIII-Finale_Compressed.pdf

NutritionData. (2018). *Nutrition facts label for Pigeon peas (red gram), mature seeds, raw*. Retrieved October 2021, from https://nutritiondata.self.com/facts/legumes-and-legume-products/4369/2

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., & Kok, K. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change, 42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Paul, B. K., Groot, J. C. J., Maass, B. L., Notenbaert, A. M. O., Herrero, M., & Tittonell, P. A. (2020). Improved feeding and forages at a crossroads: Farming systems approaches for sustainable livestock development in East Africa. *Outlook on Agriculture, 49*(1), 13–20. https://doi.org/10.1177/0030727020906170

Porter, S. D., Reay, D. S., Higgins, P., & Bomberg, E. (2016). A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. *Science of the Total Environment, 571*(1), 721–729. https://doi.org/10.1016/j.scitotenv.2016.07.041

Roetter, R. P., Van den Berg, M., Laborte, A. G., Hengsdijk, H., Wolf, J., Van Ittersum, M., Van Keulen, H., Agustin, E. O., Son, T. T., & Lai, N. X. (2007). Combining farm and regional level modelling for integrated resource management in East and South-East Asia. *Environmental Modelling & Software, 22*(2), 149–157. https://doi.org/10.1016/j.envsoft.2005.07.015

Shackleton, C. M., Pasquini, M. W., & Drescher, A. W. (2009). *African indigenous vegetables in urban agriculture*. Earthscan. https://publications.cta.int/media/publications/downloads/1537_PDF.pdf

Uganda Bureau of Statistics [UBoS]. (2018). *2016 Uganda demographic and health survey*. Retrieved April 2021, from https://dhsprogram.com/pubs/pdf/FR333/FR333.pdf

Uganda Bureau of Statistics [UBoS]. (2020). *Living standard measurement study. National panel survey*. The World Bank. Retrieved August 2021, from https://microdata.worldbank.org/index.php/catalog/3902

United Nations [UN]. (2019). *World population prospects 2019*. Retrieved April 2022, from https://population.un.org/wpp/DataQuery/

United Nations Children's Fund [UNICEF]. (2019). *The state of the world's children 2019*. Retrieved April 2022, from https://www.unicef.org/reports/state-of-worlds-children-2019

United Nations Development Program [UNDP]. (2018). *Understanding land dynamics and livelihoods in refugee hosting districts of Northern Uganda*. Retrieved January 2021, from https://www.ug.undp.org/content/uganda/en/home/library/human_development/Understanding_Land_Dynamics_and_livelihood_in_Refugee_hosting_Districts_of_Northern_Uganda.html

United Nations High Commissioner for Refugees [UNHCR]. (2018). *Uganda refugee response monitoring. Settlement fact sheet of Imvepi camp settlement in June 2018.* Retrieved December 2020, from https://reliefweb.int/sites/reliefweb.int/files/resources/reach_uga_gap_analysis_imvepi_04dec2018.pdf

United Nations High Commissioner for Refugees [UNHCR]. (2022). *Refugee response portal - Uganda*. Retrieved October 2021, from https://data2.unhcr.org/en/country/uga

United Nations High Commissioner for Refugees [UNHCR], & World Vision Uganda [WVU]. (2017). *Inter-agency livelihood assessment targeting refugees and host communities in Imvepi and Rhino camp settlements*. Retrieved February 2021, from https://www.wvi.org/sites/default/files/Livelihood%20report-lowres.pdf

United Nations Human Settlements Programme [UN-Habitat]. (2021). *Economic development assessment in West Nile region, Uganda.* Retrieved September 2021, from https://unhabitat.org/economic-development-assessment-in-west-nile-region-uganda

van Dijk, M., Kuiper, M., de Lange, T., & Levin-Koopman, J. (2022). *Subnational projections of income and poverty for Ethiopia: A dynamic spatial microsimulation approach*. 25th Annual Conference on Global Economic Analysis: Accelerating Economic Transformation, Diversification and Job Creation, Virtual Conference.

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. (2016). Can Sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences, 113*(52), 14964–14969. https://doi.org/10.1073/pnas.1610359113

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., & Wood, A. (2019). Food in the anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet, 393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

World Food Programme [WFP]. (2015). *Food consumption score nutritional quality analysis*. Retrieved August 2021, from https://documents.wfp.org/stellent/groups/public/documents/manual_guide_proced/wfp277333.pdf?_ga=2.127268237.161883587.1652271303-121957187.1649411410

M.I. (Marleen) Hermelink is a researcher at Wageningen University and Research (WUR), focusing on land use and food security. She has a background in crop modelling and operations research, with her work mainly focused on cross-sectoral modelling analyses. She specializes in the application of decision analysis and optimization techniques as tools to generate insights for policy development and multi-stakeholder decision processes. She combines modelling of the natural world with socio-economic analyses into decision support systems, with applications in the Dutch sustainable energy transition at the Netherlands Organization for Applied Scientific Research (TNO) and more recently exploring interactions between land use, food production, climate change, and healthy diets at WUR.

K. H. (Katherine) Pittore is nutrition and food security specialist at Wageningen Centre for Development Innovation She has an MSc in Public Health Nutrition from the London School of Hygiene and Tropical medicine and a diverse range of expertise include capacity development, supporting effective advocacy and policy engagement, nutrition and food security programming in developing and humanitarian contexts, market-systems thinking for nutritional programmes, realist evaluation for advocacy programmes and a growing interest in nutrition and food security in urban contexts. For the past eight years she has been working for organizations working on translating research into action, and she is interested in supporting effective co-creating of knowledge with partners.

A. (Adolfo) Álvarez Aranguiz has worked as a ruminant nutritionist for the last 30 years, mainly focused on dairy farming. He has a strong expertise in nutrition and feeding in different dairy systems: from extensive and intensive grassing to highly intensive, and from high to basic tech systems. He also has a strong expertise in fodder and forage production, by-product use, feed and supplement formulation, temperate and tropical grasses and forages, crops and fodders.

F.I. (Fátima) Pereira da Silva As research and innovation project manager, Fátima sets up and leads large projects, ranging from European granted cooperation projects to customer specific projects in the Postharvest domain. To lead a team of professionals with different technical backgrounds and personal talents in achieving a common goal is her drive. The focus of her projects in the last 18 years has been on the development of advanced postharvest technologies and learning about the quality of fruit and vegetables, contributing in this way to the increased consumption of these healthy and sustainable products. She has also worked several years in the packaging and potato processing research area. She holds a master's degree in food technology.

M.M.I. (Marlene) Roefs is a Planning, Monitoring & Evaluation and Learning (PM&EL) specialist. She holds a PhD in Social Psychology from Vrije Universiteit, Amsterdam. Marlene supports organisations and partnerships in the public, private and civil sectors in designing strategies, planning their interventions, monitoring progress, evaluating impact and continuous learning (PM&EL). She has lived for many years in South(ern) Africa where she worked mainly with governments and international aid organisations in developing research capacity, good governance and PM&EL. She is one of the founders of the South African Monitoring and Evaluation Association (SAMEA). Currently, she leads the Managing for Impact cluster at the Centre for Development Innovation at Wageningen UR. Marlene has a keen interest in food and nutrition security, sustainable agriculture, governance, and human behaviour in uncertain or unstable contexts. Over the past years, she has become more involved in agriculture and human development in Eastern Africa.

R. (Robert) Kajobe Professor Robert Kajobe is a Research Professor and the Acting Dean Faculty of Agriculture and Environmental Sciences, Muni University, Arua, Uganda. He holds a PhD in Pollination and Bee Biology from Utrecht University, The Netherlands and a Master of Science in Beekeeping from the same University. He also holds a Master's in Public Administration from Uganda Management Institute (UMI), Kampala and a Bachelor of Science in Forestry from Makerere University, Kampala, Uganda. Before joining Muni University, Professor Kajobe worked at the National Agricultural Research Organization (NARO) in various capacities including being the founding Director of NARO's Rwebitaba Zonal Agricultural Research and Development Institute (Rwebitaba ZARDI). Professor Kajobe's accomplished career reflects

20 years' experience in research, agricultural policy analysis, leadership, human resources management, resource mobilization and organizational development in universities, agricultural research organizations, NGOs and private sector. He has published over 18 Journal articles, 3 books and 4 book chapters.

R. (Richard) Malingumu is an assistant lecturer of soil science in the Department of Environmental Sciences, at Muni University, Arua, Uganda. He holds an MSc in Soil Science from Makerere University, Kampala, Uganda, Postgraduate Diploma in Business Administration from Uganda Management Institute, Kampala, Uganda, BSc in Agricultural Land use and Management from Makerere University, Kampala, Uganda and a Postgraduate Certificate in Farming Systems and Rural Livelihoods from Wageningen University and Research (WUR), The Netherlands. He previously worked as a research assistant for five (5) years in the International Institute of Tropical Agriculture (IITA), Uganda. Before leaving IITA to join Muni University, he worked in the Banana Agronomy Project in Uganda & Tanzania. His areas of research interests are; soil fertility and chemistry, soil conservation and erosion control, soil classification and mapping, land use and planning. He has published two (2) journal articles, one (1) conference proceeding and one (1) technical brief.

H. (Huib) Hengsdijk is an agronomist at Wageningen University and Research (WUR) focusing on agriculture and natural resources management across the globe. A common denominator of his work is the assessment and exploration of improving resource use efficiencies in agricultural systems. He has a background in agrosystems modelling at different scales, from assessing the crop yield potentials and variability at plot level, designing innovative cropping systems at farm level to exploring food production potentials at regional level. He has been working on capacity building projects in vegetable production and the use of geo-data for crop insurance in Indonesia, and the control of potato late blight in Bangladesh. Recently, he also worked on agricultural production for the biobased economy.