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Homegardens and the future of food and nutrition security in southwest Uganda

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ABSTRACT

Governments around the world seek to create programs that will support sustainable agriculture and achieve food security, yet they are faced with uncertainty, system complexity and data scarcity when making such choices. We propose decision modeling as an innovative approach to help meet these challenges and offer a case study to show the effectiveness of the tool. We use decision analysis tools to model the possible nutrition-related outcomes of the Ugandan government's long term agricultural development plan termed 'Vision 2040'. The analysis indicates potential shifts in household nutritional contributions through the comparison of the current small-scale diverse systems and the envisioned industrial agricultural systems that may replace them. A Monte Carlo simulation revealed that Vision 2040 plans outperform homegardens in terms of energy and some macronutrients, yet homegardens are likely to be better at producing key vitamins and micronutrients, such as Vitamin A. Value of information calculations applied to Monte Carlo outputs further revealed that gathering more data on the annual yields and nutrient contents of staples, pulses, vegetables, and fruits could improve certainty about the nutrition contribution of both scenarios. We conclude that the development of Uganda's agricultural sector should consider the role that agrobiodiversity in the current small-scale agricultural systems plays in national food and nutrition security. Any changes according to Vision 2040 should also include farmers' voices and current crop management systems as guides for a sustainable food supply in the region. This modeling approach may be a tool for governments to consider agricultural policy implications, especially given the data scarcity and agricultural variability in regions such as East Africa.

1. Introduction

1.1. Political decision making

When deciding about the design of programs that will best meet their goals, governments are faced with a lot of uncertainty; they often have little exact knowledge to guide their decisions. As a consequence of this complexity, political decisions are rarely perfect (Beratan, 2007). Instead, they are often different from, and commonly in direct opposition to, what was expected or desired (Max-Neef, 1992; Shepherd et al., 2015) particularly regarding agricultural systems (Luedeling and Shepherd, 2016).

Development decisions should consider impacts on the wider natural and social environment (Luedeling et al., 2015), yet these are often not taken into account. Instead, political decisions are frequently based almost entirely on perceived technical and economic feasibility. Decision-makers often lack the tools necessary for integrating information into a forecast about possible outcomes (Peterman and Anderson, 1999), particularly given the uncertainty about many of the variables that should be considered (Luedeling et al., 2015). This often proves consequential, because failure to assess the effects of important factors could jeopardize the intended impacts, with the risk that outcomes will not meet stakeholder expectations (Luedeling et al., 2015; Rosenstock et al., 2014). This is particularly problematic given the complexity and strong social aspects of agricultural systems (Luedeling and Shepherd, 2016; Rivera-Ferre et al., 2013) and given the data-scarcity of environ-

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ments such as Sub-Saharan Africa (Luedeling et al., 2015).

1.2. Nutrition

Adequate nutrition is a prerequisite for human development and socioeconomic well-being (Müller and Krawinkel, 2005). Therefore, governments around the world have agreed to end hunger and support sustainable agriculture to achieve food security (United Nations, 2015). Hunger, or acute malnutrition, is defined as not having enough to eat to meet energy requirements, referring specifically to lack of energy, carbohydrates, and fats. Micronutrient deficiency (hidden hunger) is caused by a lack of essential vitamins and minerals in the diet (Biesalski, 2013). Hidden hunger can lead to illness, blindness, impaired development, and premature death. As the name implies, clinical symptoms are not readily apparent with hidden hunger. Those suffering from hidden hunger may be stunted (too short for their age), have poor night vision, and suffer frequently from illness (Biesalski, 2013). Both are major public health problems in Uganda, especially among women and children (UBOS and ICF, 2012). Most of those suffering from hidden hunger in Uganda eat an unbalanced diet with large amounts of foods high in calories but lacking sufficient micronutrients, e.g. staple food crops, and small amounts of micronutrient-rich foods, such as fruits, vegetables, and animal products (Ssewakiryanga, 2015; Whitney et al., under review).

Food selection and preparation is also a critical component of household nutrition (Müller and Krawinkel, 2005) along with poor cooking and preservation methods (Hotz et al., 2012) that may lead to nutritive or anti-nutritive impacts.

1.3. Homegardens

Homegardens are diverse agroforestry systems managed by poor and marginalized smallholder farmers throughout the humid tropics (Galluzzi et al., 2010; Kumar and Nair, 2004). Homegardens in Uganda are important for household nutrition and health (Whitney et al., in preparation). They contain a variety of useful crops and traditional knowledge and supply a crucial diverse and year-round supply of food (Whitney et al., in preparation).

1.4. Industrializing agricultural systems

Agriculture is central to improving food security and reducing poverty in Africa. Recently there has been a renewed focus on policies and programs designed to support domestic agricultural production (Demeke et al., 2014). Uganda has followed this trend by promoting the Vision 2040 policy plan, which includes agricultural industrialization through extension education, greater involvement of the private sector (NPA, 2011), credit schemes, subsidies for land and export promotion (Demeke et al., 2014). The country has a growing and food insecure population (IFPRI, 2016; NPA, 2011; UBOS and ICF, 2012) together with a strong potential for agricultural production (FAO, 2014; UBOS and ICF, 2012; UBOS, 2014b; Weidmann et al., 2010). The long-term planning of Vision 2040 calls for the total transformation of the agriculture sector from the current mode of subsistence farming to commercial production. The policy aims to address food insecurity and malnutrition, largely by targeting agricultural production systems (MAAIF, 2010; NPA, 2007, 2011). The policies of Uganda's Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) outlined in the National Agriculture Policy (MAAIF, 2013) and the Agriculture Sector Development Strategy and Investment Plan (MAAIF, 2010) follow Vision 2040 with a strong focus on agricultural industrialization.

The impetus for the proposed changes relies largely on the experiences of recent economic development in East Asia (NPA, 2007) and outsiders' views of the best path to economic growth. The common narrative holds that economic development requires rapid increases in agricultural productivity (Conceição et al., 2016) and increased food production (Godfray and Garnett, 2014). According to this logic, smallholder farmers do not have the capacity to be agents of economic growth. Therefore, development requires moving populations away from agriculture and away from rural areas (Collier and Dercon, 2014). However, in following this development path, Uganda may experience lower availability and access to diverse food sources, a potentially undesirable phenomenon observed in many countries across the globe (Khoury et al., 2014). One important impact of industrializing farming systems is the loss of many traditional fruits and vegetables throughout Africa (Shackleton et al., 2009), particularly in Uganda (Dweba and Mearns, 2011). Markets may also be risky as the sole source of food security since they do not function, legally or morally, to meet subsistence needs (Sen, 1981). Limited access to food can be a major hindrance to food security (Devereux, 2001; Nyariki and Wiggins, 1997; Webb et al., 2006).

It is important to note that increasing food supply per capita does not necessarily result in less hunger. Policy decisions aimed at increasing agricultural production may be shortsighted in believing that agricultural systems can meet the demand for food solely based on their productive capacity, because food security depends as much on people's ability to access food as on the food's existence. There is, therefore, a need to define yields in terms of nourishment to populations (Cassidy et al., 2013) and for strategies to assist policy decision makers in considering the implications that changes to agricultural systems may have for household nutrition. Analyses and tools are needed that can support decisions by modeling agricultural systems, determining system dynamics, and projecting future implications of system changes (Luedeling and Shepherd, 2016).

Critiques of Vision 2040 also point out possible negative consequences for local communities and the environment (Hansen et al., 2015). Current nutrition efforts are thwarted by high population growth and poor access to land (FAPDA, 2015), and lack of transparency in the planning and budgeting add further difficulty to tracking and sharing progress. Consequently, nutrition-related funding is often spent on activities that are not relevant to nutrition (Adero et al., 2015). Furthermore, robust science-based information to support decisions about the future of farming, and the potential impact on food and nutrition, is lacking. Government decision making is therefore in need of robust scientific support, since many pending agricultural policy decisions stand to affect millions of rural people, millions of hectares of farmland, and they will cost billions of dollars.

1.5. Decision modeling

Decision modeling can help to meet the challenges of system complexity and data scarcity in agricultural development (Luedeling and Göhring, 2016) by offering decision-makers robust models capturing a range of ecological, socioeconomic, cultural and political factors relevant for agricultural systems. Probabilistic simulations of the full range of plausible outcomes of particular interventions can be made by identifying important variables and quantifying the uncertainty around them. Though outcomes projected in this way are often highly uncertain, such modeled outcome distributions often suffice for deciding on a rational course of action for the decision (Peterman and Anderson, 1999). In cases where the remaining uncertainty is too high to immediately decide on the most desirable decision option, decision analysis can provide guidance for what pieces or information decision-makers are lacking (Luedeling et al., 2015). Calculating the value of information (Milner-Gulland and Shea, 2017) for variables within such models allows for prioritization of knowledge gaps that should most urgently be narrowed in order to improve certainty about the decision (Hubbard, 2014; Luedeling et al., 2015).

We use decision analysis tools to model the possible nutrition-related outcomes of the Ugandan government's ‘Vision 2040’ agricultural development. The work presented here seeks to demonstrate the use of decision analysis tools to model the possible nutrition-related

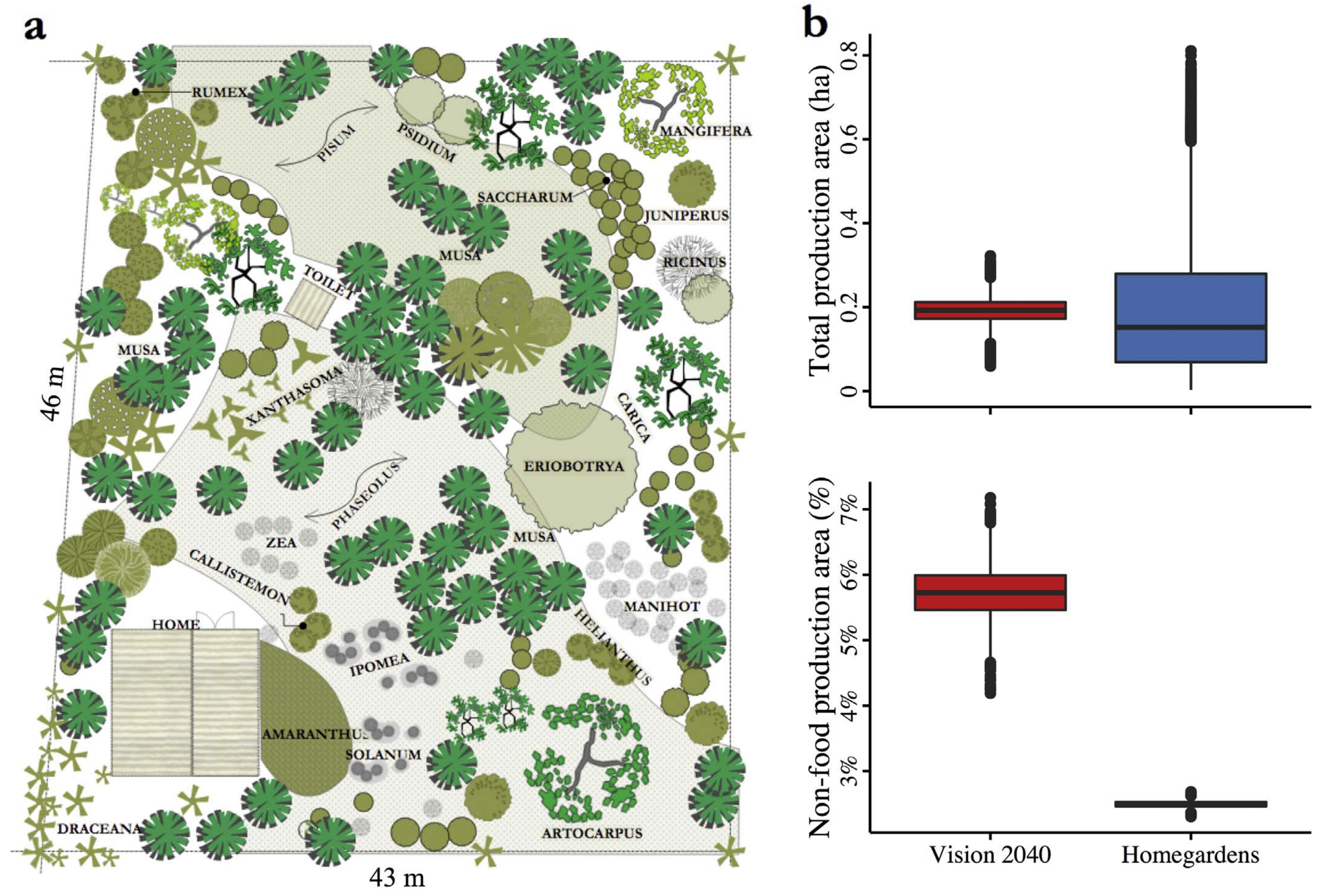

Fig. 1. Differences in land-use between homegardens (HG) and proposed Vision 2040 industrialized farming systems. a. Landscape design example of HG system with home, pathways, and social spaces among a diversity of crops. b. Boxplots of total crop production area (top) and percentage of production area unused or under non-food crops (bottom).

outcomes of plans for shifting cropping practices away from the current homegarden food systems proposed in the Ugandan government's Vision 2040. Models of the possible nutrition-related outcomes of the proposed Vision 2040 transformation of agricultural systems in southwest Uganda are presented.

2. Materials and methods

2.1. Location

The homegardens considered in this analysis are in the Greater Bushenyi district of Western Uganda. The region lies between 1200 and 1700 m above sea level, with 1500 to 2000 mm annual rainfall, and mean monthly temperatures between 18.9 and 19.7 °C. Subsistence homegardens with high crop diversity (c.f. Fig. 1a) are ubiquitous throughout Greater Bushenyi, and they are the main source of food in the region (Whitney et al., in preparation). Greater Bushenyi is well-suited for farming, featuring loamy fertile soils with varying proportions of sand and clay (FAO, 2014).

The Greater Bushenyi district's population density, 64 people per square kilometer, is less than half of the national average (Weidmann et al., 2010). However, a high population growth rate and low average age are likely to exacerbate land scarcity, poverty (per capita GDP 500 USD; UBOS and ICF, 2012), and food insecurity (IFPRI, 2016). Overall, 25% of Uganda's population is living below the poverty line. However, Greater Bushenyi has lower rates of extreme poverty and a lower disparity of wealth than the national average of Uganda (UBOS and ICF, 2012). Agriculture is the main economic activity in Greater Bushenyi, consisting mainly of small-scale producers, who practice dairy farming and grow a wide range of crops, notably staple cooking bananas (*Musa* spp.), robusta and arabica coffee (*Coffea* spp.), and tea (*Camellia sinensis* (L.) Kuntze) (UBOS, 2014b).

Nutritional surveys indicate a prevalence of food insecurity and malnutrition among households in the Greater Bushenyi. In 2015 40% of households were severely food insecure, 45% were moderately food insecure, 10% were mildly food insecure and just 5% were food secure (Whitney et al., in preparation). Body mass index (BMI) of adults over 19 years revealed that 15% of the population were underweight. Evidence of hidden hunger was prevalent among children and their mothers. Nearly half (46%) the children under five years of age were too short for their age (stunted) and 3% were too thin for their height (wasted) (Whitney et al., in preparation). Forty-nine percent of children and 23% of women of reproductive age were anemic, and 40% of children under 5 years of age were vitamin A deficient (UBOS and ICF, 2012).

2.2. Modeling approach and parameters

We built a probabilistic model to predict nutrition implications of converting from traditional homegardens to the industrial agricultural systems planned in Uganda's Vision 2040 by tracing yields to consumption (c.f. Cassidy et al., 2013). Our model included both biophysical and social factors that affect cropping diversity and density and the subsequent yields. Two cropping scenarios were modeled: 1) 102 multilayered diverse homegarden banana plantations intercropped with fruits and vegetables (described in Whitney et al., under review); 2) the Vision 2040 commodity approach dominated by grains, tubers, bananas *Musa* (AAA, ABB, AB), and legumes (MAAIF, 2010; NPA, 2007).

2.2.1. Expert knowledge

We used expert assessment to define the variables most important in the food systems, and the relationships between these variables. The experts' current state of uncertainty on all model parameters was expressed as probability distributions (c.f. Luedeling et al., 2015). We used the well-established ‘calibration training’ procedures (Hubbard, 2014) to build capacity in estimating the state of experts' uncertainty and help them provide accurate estimates by reducing errors of judgment, e.g. estimated ranges that are too wide (under-confidence) or too narrow (overconfidence) (Hubbard, 2014; Luedeling et al., 2015). The resulting distributions represent uncertainty explicitly as probabilities of different possible states of the world (Pannell and Glenn, 2000).

2.3. Estimating uncertainty in nutrition and farming related variables

Socioeconomic and biophysical data were collected in 102 homegardens in 9 villages in Rubirizi, Sheema, and Bushenyi districts in the highlands of Southwestern Uganda from 2014 to 2015. Model parameters (Fig. 2) were based in part on interviews and observations (Whitney et al., under review), along with other literature available on diversity in various local cropping systems (c.f. Eilu et al., 2003; Oduol and Aluma, 1990) and Ugandan government authorities' plans for agricultural industrialization (MAAIF, 2010; NPA, 2007).

Vision 2040 calls for agricultural intensification across Uganda focused on a few crops with potential for commercialization and value addition (NPA, 2007). The Ugandan Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) follows Vision 2040 with plans for the development of systems dominated by staples, pulses (legumes), and export crops (MAAIF, 2010). The staples include cassava (*Manihot esculenta* L.), bananas (*Musa* spp.), rice (*Oryza* spp.), potatoes (*Solanum tuberosum* L.) and maize (*Zea mays* L.). Pulses are mostly beans (*Phaseolus vulgaris* L.). Export crops include tea (*Camellia sinensis* (L.) Kuntze) and coffee (*Coffea* sp.). Homegardens had a greater diversity of crops than Vision 2040 systems (Fig. 3a) with over 200 different crops, grown mostly for food (Whitney et al., under review).

We identified five separate types of crops and 16 nutrients (Fig. 4) for inclusion in our models of the Vision 2040 decision (Fig. 2). Nutrient contents in macronutrients (fiber, carbohydrates, fat and protein), vitamins (beta carotene, folate, niacin, riboflavin, thiamin, and vitamins a, B6 and c) and micronutrients (calcium, iron and zinc) were calculated for each crop type. Nutrients per farm were calculated by modeling distributions for the diversity of crops for homegardens and Vision 2040 farming systems. Input variables included the nutrient content and total area planted, yield, and expected yield increments through fertilizer inputs to those crops (Fig. 2).

Crops were categorized by food group with nutrient contribution based on a food composition table (FCT) for Uganda (Hotz et al., 2012). Cooked food nutrient values were imputed from the raw food based on changes in moisture content and nutrient losses due to cooking (Hotz et al., 2012), similar to the literature on plants and their contributions to human health in Africa (Remans et al., 2011). Distributions describing the uncertainty of specific nutrients per food type (Fig. 4) were guided by the FCT. Specific foods from the FCT table were divided into 4 food categories. The category ‘Fruit’ included fresh fruit and pure fruit juices, ‘Pulse’ included beans, nuts (e.g. peanut [*Arachis hypogaea* L.]]), and oil seeds (e.g. sunflower [*Helianthus annuus* L.]), ‘Spice’ included plants used for food flavoring (e.g. *Capsicum frutescens* L.) and drinks (e.g. *Ocimum gratissimum* L.). ‘Staples’ included starches such as grains, roots and tubers, and cooking bananas.

Accurately estimating crop yields is challenging in the context of African farming systems, characterized by smallholder farms that produce a wide range of diverse crops (Fermont and Benson, 2011; Malézieux et al., 2009). The many possible species combinations, management practices and site-dependent interactions in diverse cropping systems (Luedeling et al., 2016) make strictly empirical approaches unsuitable (Malézieux et al., 2009). Therefore, yield estimate ranges for all crops (Fig. 3b) were necessarily broad as were the Vision 2040 yield increases through chemical fertilizers (staples and pulses only), ranging from zero to over two tons of additional harvest per hectare (Fig. 3c). Possible volume and nutrient losses due to postharvest processing (c.f. Affognon et al., 2015), cooking temperature and cooking duration (Hotz et al., 2012) were also included in our uncertainty distributions.

Homegarden areas averaged about 0.2 ha (Fig. 1b). We estimated larger total farm areas for Vision 2040 farms (e.g. no homes, pathways, or lawns; Fig. 1a, b) and a positive Land Equivalency Ratio (LER) effect for homegardens due to layering and intercropping (c.f. Fig. 1a) (c.f. Mead and Willey, 1980; Malézieux et al., 2009). Total farmed area per household had a broad range (average of around 0.2 ha). Just over half

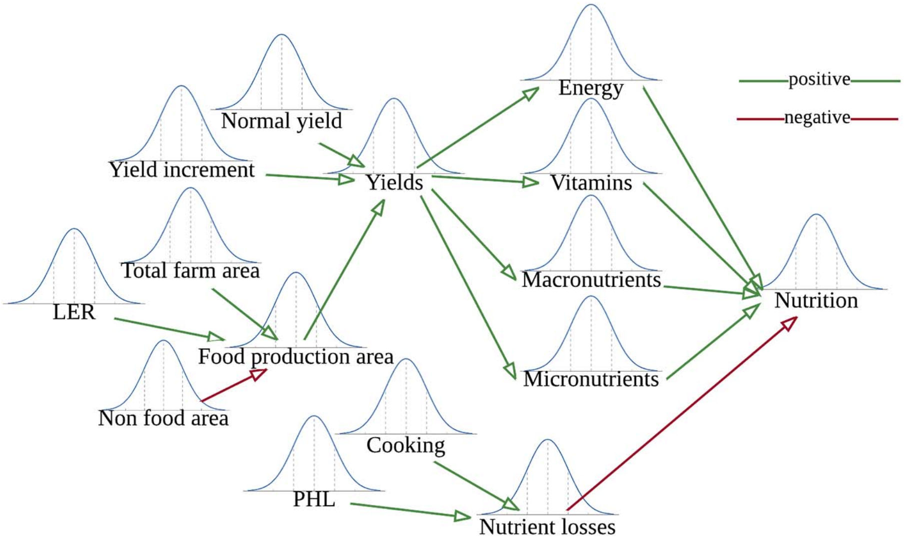

Fig. 2. Model parameters for farm area, yields, and nutrients for fruits, pulses, spices, staples, and vegetables grown in simulated homegarden and Vision 2040 cropping scenarios. Food production area includes total farm area minus non-food area (e.g. walkways, lawn, cash crops) with a Land Equivalency Ratio (LER) for the intercropping and crop layering effects. Yields of all crops are calculated from normal yields and yield increments, e.g. with chemical fertilizers (Vision 2040 only). Nutrient contents in macronutrients (fiber, carbohydrates, fat and protein), vitamins (beta carotene, folate, niacin, riboflavin, thiamin, and vitamins a, B6 and c) and micronutrients (calcium, iron and zinc) are calculated for each crop type. Nutrient losses include cooked food nutrient values and Post Harvest Losses (PHL).

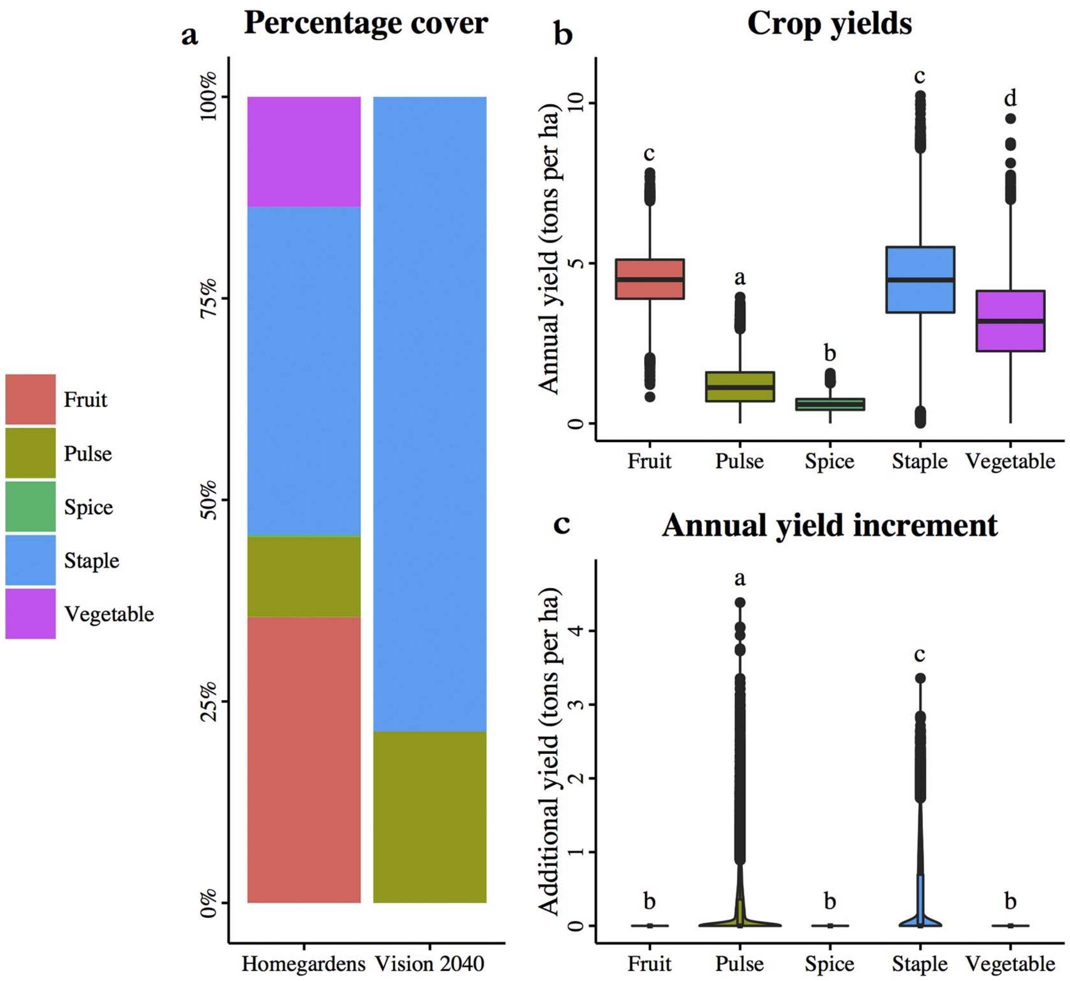

Fig. 3. Crop cover, yields, production areas, and nutrient contents in 10,000 Monte Carlo model runs of 102 homegardens (HG) and 20 government envisioned industrial farms (Vision 2040). a. Percentage cover of fruits, pulses, spices, staples, and vegetables in HG (right) and Vision 2040 (left) systems. b. Mean crop yields per vegetable type c. Yield increments through fertilizer applications. Different letters denote significant difference, $p < 0.05$, ANOVA, Tukey post-hoc.

of the farmers had additional plots of land outside their homegardens. Most of these were single small plots under 500 m^2, while relatively few had areas > 1000 m^2 (Whitney et al., under review).

Currently < 1% of agricultural land in Uganda is used for cash crops (UBOS, 2014a). For the Vision 2040 scenario we estimated a rise to between 4 and 7% of agricultural land area used for cash crops.

2.4. Simulation

Once distributions were defined for all uncertain model parameters (Fig. 2), these were used to run the decision model as a Monte Carlo simulation. The government decision of whether or not to shift agriculture from homegardens to Vision 2040 systems was interpreted as a von Neumann-Morgenstern utility function, i.e. we assumed that the government is seeking to maximize the expected nutritional status of the households. We used R's decisionSupport package for probabilistic analysis of possible outcomes of this decision via Monte Carlo simulation (Luedeling and Göhring, 2016). In this simulation, the model was run 10,000 times for each scenario ("homegardens" and "Vision 2040"), randomly drawing samples from the defined distributions for all input parameters.

Nutrients per farm were calculated by modeling distributions for the diversity of crops for each farming system. Input variables included the nutrient content and total area planted, yield, and yield increments through fertilizer inputs of those crops.

For the production of each nutrient in a given system per system and month:

$$Production_{n,sys,t} = \sum_{c}^{crop\ types} \sum_{p}^{plots} y_{c,t} \bullet inc_{sys,c} \bullet area_{p} \bullet cover_{p,c} \bullet$$
$$1 - unused \bullet content_{c,n}$$

with n = nutrient, sys = system (homegarden, Vision 2040), t = time (month of the year), c = crop types (staples, pulses etc.), p = plots (homegardens or Vision 2040 farms), y = crop yield, inc = yield increase over homegarden system (only for Vision 2040), $area_p$ = area of plot p, $cover_{p,c}$ = fraction of plot p that is covered by crop c, unused = fraction of farm that is not used for crops, $content_{c,n}$ = nutrient n content of crop c.

For the entire year:

$$Production_{n,sys} = \sum_{t}^{all\ months} Production_{n,sys,t}$$

Each model run of the Monte Carlo simulation was based on slightly varying inputs and provided one projection of the decision's nutritional outcome that was plausible given the current state of uncertainty (c.f. Luedeling and Göhring, 2016; Rosenstock et al., 2014). The analysis was run over a 12-month time horizon to produce both monthly and annual nutrient outputs. Separate results were produced for each of the 16 nutrients for the five crop types in each month of the year. Ten thousand such model runs of 102 homegardens and 20 Vision 2040 farms gave over one billion data points.

Probabilistic sensitivity analysis is often used in evaluating decisions (Luedeling et al., 2015; Strong et al., 2014). The expected value of

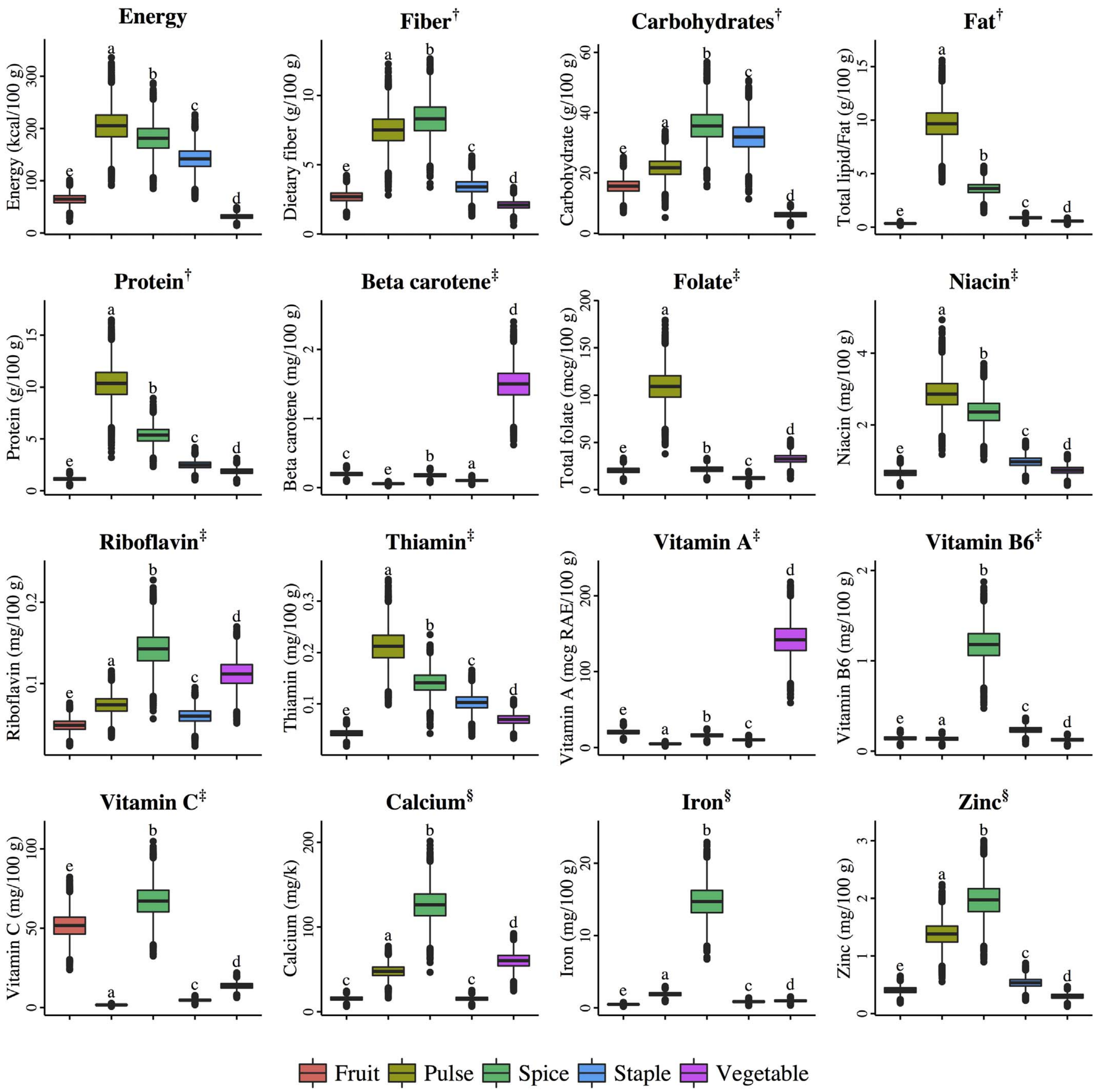

Fig. 4. Nutrients of selected crops per 100 g of yields in 10,000 Monte Carlo model runs for 102 homegardens (HG) and 20 envisioned industrial farms (Vision 2040). Energy, macronutrient (fiber, carbohydrates, fat, protein), vitamins (beta carotene, folate, niacin, riboflavin, thiamin, vitamin A, vitamin B6, vitamin C), and micronutrient (calcium, iron, zinc) contents per 100 g of foods derived from fruits, pulses, spices, staples, and vegetables produced in HG and Vision 2040 agricultural systems.

perfect information (EVPI) is the difference between the expected value of a decision made with perfect information and the expected value of the decision with current imperfect information (Hubbard, 2014). Here we used EVPI to quantify the expected benefit of updating the model (Strong et al., 2014) for each input parameter, to reveal the sensitivity of the recommended land use choice to uncertainty about that parameter. EVPI is normally expressed in monetary units as the maximum price a decision maker should be willing to pay in order to gain access to perfect information (Hubbard, 2014). However, this is only possible where outcomes are expressed in monetary terms. Here we express the EVPI in natural units (c.f. Felli and Hazen, 1999) of the respective nutrients. We used EVPI to calculate the sensitivity of the system preference indicated by our model to the uncertainty in model parameters, based on the systems' ability to provide the respective nutrients. Means for all model parameters were tested with ANOVA and Tukey's honestly significant difference (HSD) post-hoc test.

Model nutrient outputs were compared with intake recommendations for nutrients according to the Dietary Reference Intake (DRI) Estimated Average Requirement (EAR) nutrient recommendations, calculated with the Interactive DRI for Healthcare Professionals (National Academies of Science, 2016) for the (national and regional) average household size of five (two adults and three children under 18) (UBOS and ICF, 2012; UBOS, 2014b). Medians for monthly nutrient outputs were tested with Mann-Whitney-Wilcoxon tests.

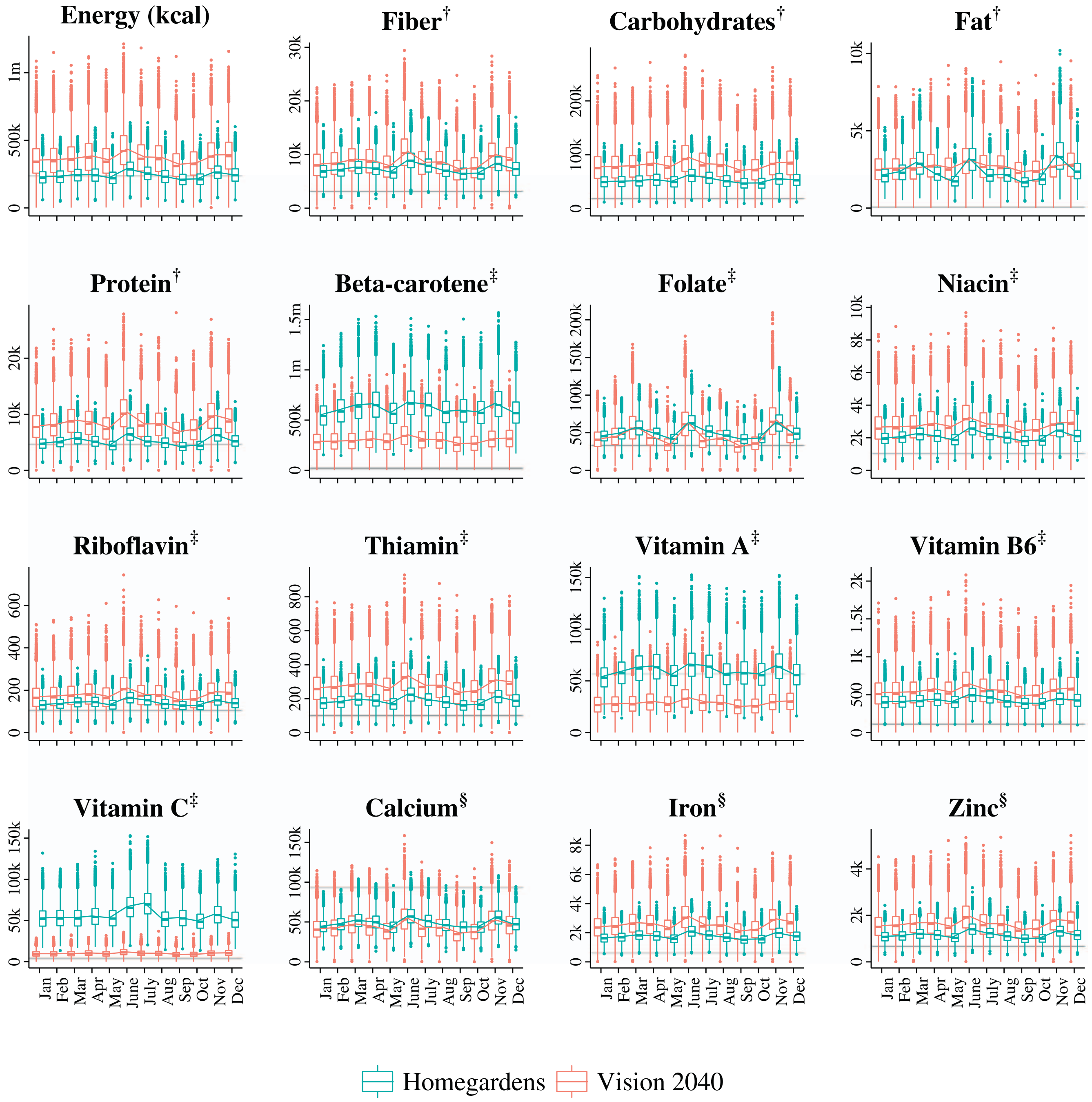

Fig. 5. Monthly nutrient contributions in 10,000 Monte Carlo model runs of 102 homegardens (HG) and 20 government envisioned industrial farms (Vision 2040). Energy, macronutrient (fiber, carbohydrates, fat, protein), vitamins (beta carotene, folate, niacin, riboflavin, thiamin, vitamin A, vitamin B6, vitamin C), and micronutrient (calcium, iron, zinc) contents of fruits, pulses, spices, staples, and vegetables produced in HG (blue) and Vision 2040 (red) agricultural systems. Grey lines across graph represent minimum Estimated Average Requirement for a household of 4.7 adults and 2.3 children. † = macronutrients, ‡ = vitamins, § = micronutrients. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

Vision 2040 production systems had 3% more land area than homegardens due to the removal of houses and pathways (Fig. 1a). However, these systems were largely mono-crops and were often planted with commercial non-food products, whereas homegardens used more of the cropped land area for food production and were multilayered (Fig. 1a, b).

Model parameters crop cover, yields, production areas, and nutrient contents were different for the five separate types of crops and 16 nutrients (Figs. 3 and 4).

Monte Carlo simulation results provide plausible projections of nutritional outcomes of Vision 2040 transformation given the current state of uncertainty (Figs. 5 and 6). The majority of model runs indicated that both systems can meet the minimum EAR for a family of five (Table 1) for fiber, carbohydrates, beta-carotene, niacin, riboflavin, thiamin, vitamin B6, vitamin C, iron, zinc, and fat (which has no minimum requirement) (Fig. 5). However, foods from crops were unlikely to meet the minimum nutritional needs for a household in either homegardens or Vision 2040 scenarios (Fig. 5). Supplementary foods (e.g. non-plant foods and off-farm sourced foods) would be needed to supply the minimum EAR for vitamin A and calcium given

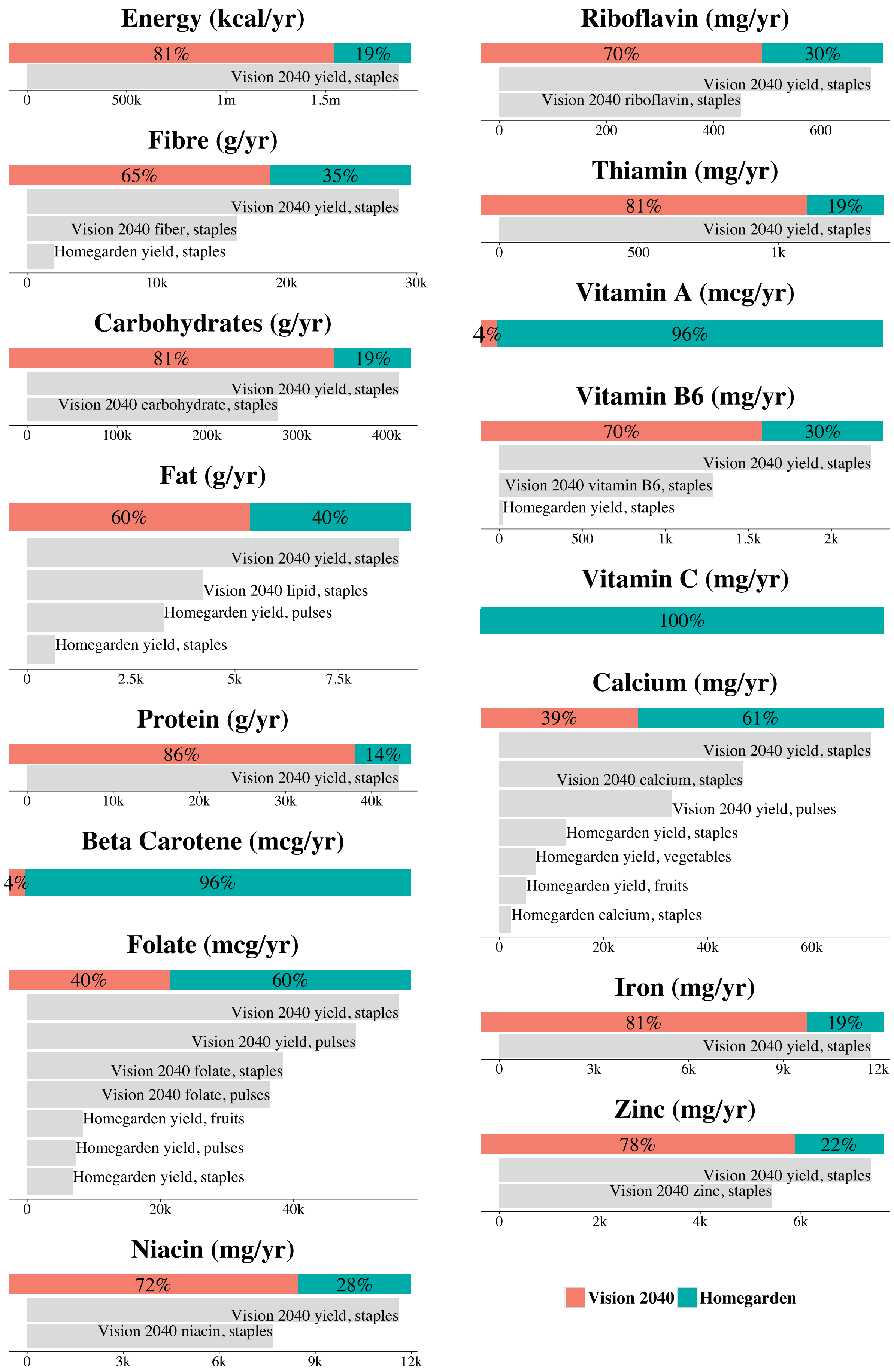

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Fig. 6. EVPI calculations for sensitivity of the system preference to uncertainty in model parameters: annual nutrient contributions in 10,000 Monte Carlo model runs of 102 homegardens (HG) and 20 government envisioned industrial farms (Vision 2040). Energy, macronutrient (fiber, carbohydrates, fat, protein), vitamins (beta carotene, folate, niacin, riboflavin, thiamin, vitamin A, vitamin B6, vitamin C), and micronutrient (calcium, iron, zinc) contents of fruits, pulses, spices, staples, and vegetables produced in HG and Vision 2040 agricultural systems.

Table 1
Ranges for daily Estimated Average Requirement (EAR) of macronutrients, vitamins, and micronutrients, lower ranges often for elderly and people with low activity, upper ranges are often for pregnant and lactating women.

	Estimated Average Requirement (EAR)[a]			
	Child (1–18)		Adult (> 18)	
Nutrient	Lower	Upper	Lower	Upper
Energy (kcal/day)	992	3152	2403	3067
Fiber[b] (g/day)	19	38	21	38
Carbohydrates[b] (g/day)	100	130	130	210
Fat[b]	not determined			
Protein[b] (g/day)	13	52	56	71
Beta carotene[c] (mcg/day)	18	74	52	75
Folate[c] (mcg/day)	150	600	300	600
Niacin[c] (mg/day)	5	14	9	14
Riboflavin[c] (mg/day)	0.4	1.3	1.1	1.3
Thiamin[c] (mg/day)	0.4	1.2	1	1.2
Vit A[c] (mcg RAE/day)	210	885	625	900
Vit B6[c] (mg/day)	0.4	1.7	1.1	1.7
Vit C[c] (mg/day)	13	96	39	100
Calcium[d] (mg/day)	500	1100	800	1100
Iron[d] (mg/day)	3	23	5	8.1
Zinc[d] (mg/day)	2.5	10.9	6.8	10.9

[a] Source: National Academies of Science (2016).
[b] Macronutrients
[c] Vitamins
[d] Micronutrients

the outputs from either system (Fig. 5). Monthly nutrient production was significantly ($p < 0.01$) different in all months for all nutrients with the exception of folate in March.

The totality of all model runs revealed probability distributions illustrating the nutrient contribution of different farming systems.

Results of EVPI calculations (Fig. 6) revealed many variables for which reduction in uncertainty would enhance clarity on which of the two alternative systems produces more of the various nutrients. EVPI was highest for yields and nutrient contents of staple crops and pulses in Vision 2040 systems and, to a lesser extent, in homegardens. EVPI was also high for the yield of fruits and vegetables, calcium content of fruits, vegetables, and pulses (Fig. 6) and folate content of fruits, vegetables, and pulses in homegarden yields.

Homegardens and Vision 2040 systems performed differently over the course of the year in terms of energy, macronutrients (fiber, carbohydrates, fat, protein), vitamins (beta carotene, folate, niacin, riboflavin, thiamin, vitamin A, vitamin B6, vitamin C), and micronutrients (calcium, iron, zinc) produced from fruits, pulses, spices, staples, and vegetables (Fig. 5). The minimum EAR for fiber, carbohydrates, beta-carotene, niacin, riboflavin, thiamin, vitamin B6, vitamin C, iron, zinc, and fat could be met with plant yields from the average homegarden or Vision 2040 system. Outputs for Vision 2040 systems show much broader ranges of uncertainty but tend to outperform homegardens in all nutrients except for fat, beta-carotene, folate, vitamin A, vitamin C, and calcium. They also tend to meet the minimum EAR for energy and protein throughout the year. However, only homegarden outputs met the minimum EAR for folate throughout the year and the minimum requirement for vitamin A in most months.

4. Discussion

Here we have used Monte Carlo simulation to help determine the outcomes of shifting agricultural practices on human nutrition. The model presented included variables for which data was not readily available (Fig. 2). This was made possible through the use of tools that incorporate uncertainty in decision outcome forecasting (c.f. Peterman and Anderson, 1999; Luedeling and Shepherd, 2016; Luedeling et al., 2015). Considering such variables is critical in rational decision making, which should include all factors that are important for a decision – not only those that happen to be described by good datasets (Luedeling et al., 2015; Rosenstock et al., 2014). When decision makers omit important variables with high uncertainty and instead concentrate on hard data (e.g. easily measured or already known), they may be missing very important parts of the picture (Luedeling et al., 2015; Rosenstock et al., 2014). Furthermore, characterizing all the relevant variables in agriculture-related decisions with hard data can be difficult or even impossible (Peterman and Anderson, 1999). This study is a demonstration of incorporating uncertainty into quantitative analysis of agricultural systems to support decision-making processes.

We chose to model the agricultural industrialization proposed in Vision 2040 as a decision aimed at attaining the best possible welfare outcome (Luedeling and Göhring, 2016). We considered the entire spectrum of uncertainty in the current and proposed cropping systems (Fig. 2). In general, the shift to Vision 2040 farming systems seems unlikely to succeed as a mechanism to solve nutrition insecurity and end hunger. In terms of macronutrients for addressing protein-energy malnutrition and meeting the energy requirements of a growing population in Uganda, the Vision 2040 system looks more favorable (Fig. 5). However, homegarden systems were better at producing the minerals and vitamins necessary to combat hidden hunger (e.g. Vitamin A) according to the minimum EAR (Table 1 and Fig. 5). Model outputs suggest that maintaining homegardens for important nutrients (e.g. vitamin A and vitamin C; Figs. 5 and 6) may be the favorable strategy for maintaining nutrition.

4.1. Parameterization

Although yields of staples and pulses were higher in scenarios of the Vision 2040 cropping systems due to the addition of fertilizers (Fig. 3c) the model included high uncertainty in the yields of all crop types in both scenarios (Fig. 3b). This high uncertainty in yield data stems from the lack of land-use data e.g. regarding intercropping effects, non-uniform cropping areas, a wide range of farm sizes and non-harvested crops (Fermont and Benson, 2011; Remans et al., 2011). Accurately estimating crop yields is challenging in the context of African farming systems, characterized by smallholder farms that produce a wide range of diverse crops (Fermont and Benson, 2011; Malézieux et al., 2009). The many possible species combinations, management practices and site-dependent interactions in diverse cropping systems (Luedeling et al., 2016) make strictly empirical approaches unsuitable (Malézieux et al., 2009). Estimates of the total yield available for consumption were also challenged by the variability in postharvest losses. Nevertheless, our modeled yield parameters (Fig. 3) were still within the ranges of past studies on farmers' estimated and actual measured yields (c.f. Fermont and Benson, 2011; Remans et al., 2011) and the literature for postharvest losses (Affognon et al., 2015).

The modeled production area in homegardens (Fig. 1b) was positively influenced by crop layering, consistent with past studies on crop interactions (c.f. Mead and Willey, 1980; Malézieux et al., 2009). Farm size, < 0.2 ha (Fig. 1b) was at the low end of the range of homegarden sizes (0.02–2 ha) in Uganda (Oduol and Aluma, 1990). Total farm area in Uganda may extend to farmland owned outside the homegarden, which can be as much as 70% of the farmland in rural areas (UBOS and ICF, 2012) but is either non-existent or consists of very small parcels in the study area (Whitney et al., under review).

The relatively even monthly rainfall combined with the mixture of annual and perennial crops allow farmers to continuously plant and harvest throughout the year. While this constitutes an additional challenge in estimating yields in the Ugandan context (Fermont and Benson, 2011), it results in relatively continuous nutrient supply throughout the year in both Vision 2040 and homegardens (Fig. 5). However, a dip in nutrients for both scenarios in December to January and August to September corresponds to a mild hunger period at that time. The spikes in June and July correspond to harvest time, when there are more excess crops (Fig. 5).

4.2. EVPI

The variables with the highest information value (Fig. 6) could be interpreted as priorities for measurements to be undertaken to reduce the uncertainty around the decision (Luedeling et al., 2015; Rosenstock et al., 2014). Estimating the EVPI is not common (Strong et al., 2014) because of the additional model development and model run time required (Hubbard, 2014; Strong et al., 2014) and due to lack of demand from decision makers and research funding bodies (Strong et al., 2014). Taking measurements of particular variables that emerged as priorities according to the EVPI (Fig. 6) and re-running the analysis with updated input data could have enhanced clarity on the results (c.f. Luedeling et al., 2015). However, in the present case, initial outcome distributions sufficed for deciding on a rational conclusion for the decision (c.f. Peterman and Anderson, 1999; Luedeling et al., 2015) for most nutrients. Nevertheless, the EVPI may be useful to inform the design and prioritization of future research (Hubbard, 2014; Strong et al., 2014) or to learn about the specific outcomes for nutrients such as vitamin B6 (Fig. 6). Reducing uncertainty on influential variables may help reduce the range of plausible outcomes (Hubbard, 2014; Luedeling et al., 2015) for all nutrients except for beta carotene and vitamin A. Therefore, future studies that seek to understand more about the exact differences between Vision 2040 and homegarden systems (especially for nutrients where the differences are relatively small, such as fiber, fat, and calcium) should investigate the yields and nutrient contents of staples, pulses, and vegetables, and the ways in which these are processed and consumed.

4.3. Beyond growing and consuming food

Homegardens are currently the primary source of food in the region, offering a diverse range of products (Whitney et al., under review, in preparation) and nutritional benefits, and yet malnutrition is still prevalent (Whitney et al., in preparation). This is because agricultural production forms part of a food system that is in turn embedded in a larger complex of social, political and ecological systems, all of which can influence human nutrition (Biesalski, 2013; Webb et al., 2006).

As farmers adapt to the market economy, many traditional foods are likely to disappear from the food system, as is already the case with many traditional fruits and vegetables in Uganda and throughout Africa (Dweba and Mearns, 2011; Shackleton et al., 2009). Food consumption in the new market-based food systems under Vision 2040 will be dependent on availability on markets and whether or not it is actually purchased. The preferred traditional foods of formerly rural farmers may no longer be available in the new urban and market-oriented food system. Furthermore, there is little chance that displaced and urbanized former homegardeners will seamlessly merge into the affluent urban society and no guarantee that they will have the purchasing power to meet their subsistence needs.

4.4. Limitations of the model

We drew the limits of our model at the boundaries of the Vision 2040 decision to industrialize cropping systems (Fig. 2) and did not include all external socio-economic, political, and biological factors affecting nutrition pathways. Many of the causes of malnutrition are not directly related to food growing and consumption alone. Malnutrition can also be caused by repeated illness and infection (Müller and Krawinkel, 2005), lack of safe water, poor hygiene and sanitation (UBOS and ICF, 2012), poor nutrition habits, and lack of nutrition education (Ssewakiryanga, 2015). Food and nutrition insecurity affects people who cannot access adequate food irrespective of food availability (Devereux, 2001). It often results from lack of access and poor ability to utilize food, and unstable social conditions (Sen, 1981). Immediate causes of malnutrition in Uganda, for example, include inadequate dietary intake due to factors such as poor infant and young child feeding practices (Ssewakiryanga, 2015; UBOS and ICF, 2012; Whitney et al., in preparation).

Considering only plants also limited the scope of our model. Vitamin B12 is not included in this study, as it is only present in fortified plant foods and animal products. Notably, many farmers in the study area had livestock along with plentiful sources of other animal food including termites (*Macrotermes bellicosus* Smeathman), grasshoppers (*Ruspolia nitidula* Scopoli), and Tana lungfish (*Protopterus annectens* Owen), which were available in large quantities when in season. Vision 2040 also calls for increasing livestock as a part of industrializing agricultural systems.

4.5. Solutions

The success of any decision to address food insecurity depends on how well it has been contextualized within the broader socio-economic and ecological influencing factors (Anderson, 2015; Tijhuis et al., 2012). Nutrition may best be addressed through programs that facilitate access to nutrition education and medicine (Tijhuis et al., 2012) to ensure that nutrients produced actually get consumed (Remans et al., 2011; Webb et al., 2006). Furthermore, interventions targeting nutrition may better address nutritional needs if they introduce, promote, or conserve crops that can add nutritional value to crops already available in the system (Remans et al., 2011) rather than through replacement of cropping systems. More attention should be paid to the sustainable intensification of local food systems (Godfray and Garnett, 2014) rather than complete transformation. This may also serve to increase rather than decrease the genetic resources supporting diverse food production (Khoury et al., 2014). Very large agricultural systems may not be an appropriate vehicle for encouraging growth in African societies (Collier and Dercon, 2014). Some of these efforts can even be hindrances to nutrition related development priorities, including food security (Khoury et al., 2014).

However, improving cropping systems alone may not be enough to address food insecurity. It is necessary to think beyond the growing and consumption of food, when considering decisions about agricultural production systems. Food insecurity may be better addressed by building pathways to health care and education, as well as a focus on socially compatible nutritious foods and cooking methods (Anderson, 2015; Ssewakiryanga, 2015; Tijhuis et al., 2012).

Decisions on agricultural policy under Vision 2040 should consider not only the uncertainty about food shortages but also the many other risks such as the low capacity of Uganda's economy to benefit from international linkages in trade (Hansen et al., 2015) and the lack of transparency in regional and local government planning and budgeting (Adero et al., 2015). To impact national nutrition, coordinated and well-designed programs are needed. These should be transparent and seek to engage and collaborate with regional leadership and local communities.

5. Conclusions

The current study demonstrates how, through the inclusion of uncertainty in probabilistic modeling, robust guidance on decision-making is possible without expensive long-term data collection. Inevitably, modeling simplifies a very complicated reality in order to uncover some important relationships. The current study, therefore, represents an attempt to obtain as objective an overview as possible of the general desirability of the changes Vision 2040 agricultural systems might entail for household nutrition for the Greater Bushenyi region and for Uganda.

We conclude that the development of the agricultural sector of Uganda should consider the role that agrobiodiversity in small-scale agricultural systems, such as the homegardens of Greater Bushenyi, plays in national food security. The future of farming systems in Uganda should provide both abundant and nutritious foods. Food security efforts should therefore be focused on increasing the ability for people to access not only adequate but also diverse foods. Any upscaling according to Vision 2040 should include farmers' voices and current crop management systems as guides for a sustainable food supply.

This model can be considered as a forecast of what is likely to happen. However, it can also be regarded as policy advice, which may sway opinions, and generate awareness within Uganda's government. What the work shows is that homegardens are important mechanisms – not only for food security. In the case that Vision 2040 agricultural systems are introduced, there is no guarantee that the displaced and urbanized former homegardeners will be able to purchase the food that the proposed Vision 2040 systems will produce. Instead, many of these rural farmers may transform to urban poor.

The modeling approach presented may be a useful tool to help governments forecast agricultural policy implications, especially given the data scarcity in East Africa.

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