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Exploring solution spaces for nutrition-sensitive agriculture in Kenya and Vietnam

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ABSTRACT

Smallholder agriculture is an important source of livelihoods in South Asia and sub-Saharan Africa. In these regions the highest concentrations of nutritionally vulnerable populations are found. Agricultural development needs to be nutrition-sensitive, and contribute simultaneously to improving household nutrition, farm productivity and environmental performance. We explored the windows of opportunities for farm development and the potential of crop diversification options for meeting household dietary requirements, whilst concurrently improving household economic performance in contrasting smallholder farm systems in Kenya and Vietnam. Farm and household features and farmer perspectives and priorities were integrated into a farm-household model that allowed quantification of a diverse set of nutritional, labour and productive indicators. Using a multi-objective optimization algorithm, we generated 'solution spaces' comprising crop compositions and management configurations that would satisfy household dietary needs and allowed income gains. Results indicated site-specific synergies between income and nutritional system yield for vitamin A. Diversification with novel vegetables could cover vitamin A requirements of 10 to 31 extra people per hectare and lead to greater income (25 to 185% increase) for some households, but reduced leisure time. Although the Vietnamese sites exhibited greater nutrient system yields than those in Kenya, the household diets in Kenya had greater nutrient adequacy due to the fact that the Vietnamese farmers sold greater proportions of their on-farm produced foods. We conclude that nutrition-sensitive, multi-method approaches have potential to identify solutions to simultaneously improve household income, nutrition and resource management in vulnerable smallholder farming systems.

1. Introduction

Sub-Saharan Africa and South-East Asia are two regions in the world where undernutrition is highly prevalent (Ahmed et al., 2007; Gillespie et al., 2015). In these regions the majority of the population depends heavily on agriculture for their food and income (Ahmed et al., 2007; Gillespie et al., 2015). Agricultural intensification has been promoted by many as the main pathway towards improved livelihoods of impoverished smallholder households (Tarawali et al., 2011; Carsan et al., 2014). In the last 50 years, this intensification has largely taken the

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form of increased use of external inputs such as improved seeds and/or livestock, agrochemicals and irrigation with recorded successes, such as yield increases, observed mostly in Asia, but with trade-offs that negatively impact environmental and human health (UNCTAD, 2014; FAO, 2017).

In South-East Asia the Green Revolution with its excessive reliance on external inputs contributed to decreased environmental health leading to reduced and more variable farm productivity and income as well as poorer nutrition (Ramankutty et al., 2018). In contrast, the limited access to external inputs in Sub-Saharan Africa was also associated with adverse, undesirable consequences such as stagnating crop yields and decreased agricultural land expansion into native ecosystems (Carsan et al., 2014; Mutoko et al., 2014). Limited access to external inputs also constrains the maintenance, or increase in the productivity, of newly acquired lands. Use of marginal lands in combination with low external inputs, further exacerbates low farm productivity and contributes consequently to food insecurity and undernourishment among smallholder households. Additionally, to meet human energy requirements, agricultural policies have focused on improving the productivity of staple grains, particularly maize, wheat and rice, whilst neglecting fruit, vegetable, pulse and nut crops essential to address malnutrition in all its forms (under- and over-nutrition and micronutrient deficiencies) (DeFries et al., 2015). This is particularly relevant for global public health, as poor diet quality and in particular, the lack of consumption of fresh fruits, vegetables and legumes is one of the primary risk factors for the global burden of disease (GBD 2016 Risk Factors Collaborators, 2017).

As a consequence of this focus on high-yielding staple crops (DeFries et al., 2015), less supply and higher prices for nutritious foods make them inaccessible to households that need them most (Pingali, 2015; Sibhatu et al., 2015). In Kenya, Masayi and Netondo (2012) show that the production area allocated to traditional staple crops of millet and sorghum as well as indigenous African vegetables has declined and subsequently also their consumption. In Vietnam, increased urbanization and incomes have led to changes in diets whereby traditional foods such as green vegetables, sesame, peanuts and tofu have become less important with increased consumption of animal proteins and heavily refined carbohydrates (Khan and Hoan, 2008; Lachat et al., 2009).

The global trend to promote high-yielding staple foods in development projects and the resultant cereal-centric diets have not only contributed to micronutrient deficiencies and poor health but have also negatively impacted agrobiodiversity, reducing the number of different species and varieties produced. The diversity of species consumed is an important contributor to diet quality (Lachat et al., 2017; DeClerck et al., 2006). Powell et al. (2013) show the emergence of a 'hidden hunger' when insufficient food group diversity is consumed leading to micronutrient deficiencies. These deficiencies in vitamins and minerals (micronutrients) can cause severe and lifelong health issues (GBD 2016 Risk Factors Collaborators, 2017) and also contribute to the burden of malnutrition. Nutritious, indigenous foods, especially those that fall into the dark green leafy vegetable food group, are rich in calcium and folate as well as vitamins A, C and E, contributing to balanced diets (Yang and Keding, 2009). There is therefore a need for nutrition-sensitive agricultural interventions that diversify and increase productivity for both enhanced food and nutrition security. Stephens et al. (2018) summarize four key dimensions when assessing food security; food availability, food access, food utilization and finally the stability of the first three dimensions have over time. The dimensions of food availability, food access and food utilization are addressed in this study. Because our methodological approach aims to develop, visualize and discuss windows of opportunities and snapshots of possible future scenarios (Groot and Rossing, 2011), we do not explicitly address the stability dimension. We use a multi-method approach to integrate farm and household characteristics and farmer objectives to determine how crop diversification could contribute to meeting dietary and income requirements in Kenyan and Vietnamese farming systems.

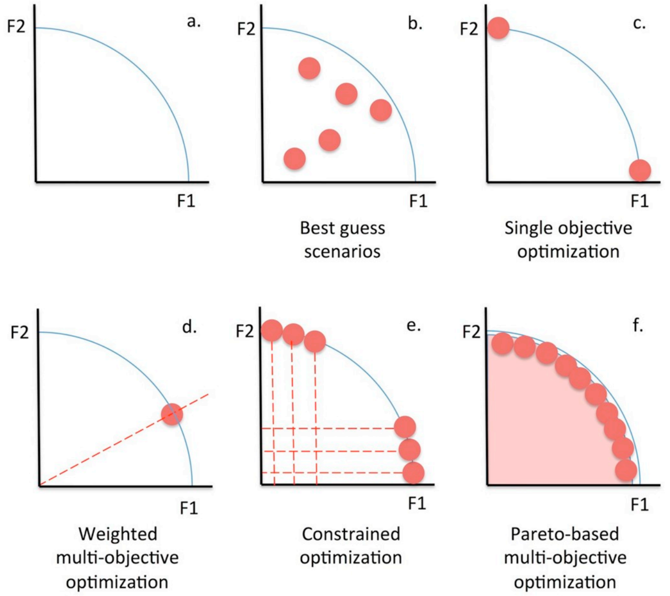

Fig. 1. Solution spaces for different types of optimization of two objectives (F1 and F2) that are maximized.

We use a farm-household model that first provides a baseline assessment of a farming system expressed in a broad set of productive, nutritional, socio-economic and environmental performance indicators. Then, through optimization of multiple, selected indicators the model enables systematic exploration of farm design and innovation options to meet farm production and household livelihood objectives. Rather than identifying scenarios (Fig. 1a–b) or applying single or weighted or constrained optimization (Fig. 1c–e), we explore whole spaces of possible options available to farmers (Fig. 1f) (cf., Groot et al., 2009). Such 'solution spaces' show a larger and broader set of alternative farm configurations that differ in performance of selected outcome indicators, i.e. the window of opportunities, and thereby allow the user to evaluate trade-offs and synergies between different farm management decisions and outcomes.

The objective of our research was to (i) explore solution spaces defined by contrasting objectives, constraints and decision variables at the farm-household scale, (ii) examine the effects of nutrition-sensitive crop diversification interventions on the economic and human well-being indicators and (iii) compare crop diversification options and constraints between contrasting smallholder farming systems of Western Kenya and Northwest Vietnam.

2. Materials and methods

2.1. Study sites

We chose to study sites in the humid tropics in Kenya and Vietnam since both have highly prevalent undernutrition including deficiencies of vitamin A. In Kenya, approximately 84% of preschool children are vitamin A deficient, while in Vietnam approximately 12% suffer for vitamin A deficiency (WHO, 2009b). Both study sites also have distinct population and natural resource pressures, agricultural input use and market orientations. Within each country, two contrasting sites were selected differing in their structural and functional farm characteristics as well as their market orientation. The Kenyan sites have much higher population densities, lower use of agricultural inputs and, as they sell less of their own food produced, have less market orientation than the Vietnamese sites. Fig. 2 locates the case study sites and Table 1 compares their characteristics.

Farm and household specific data were collected using the survey

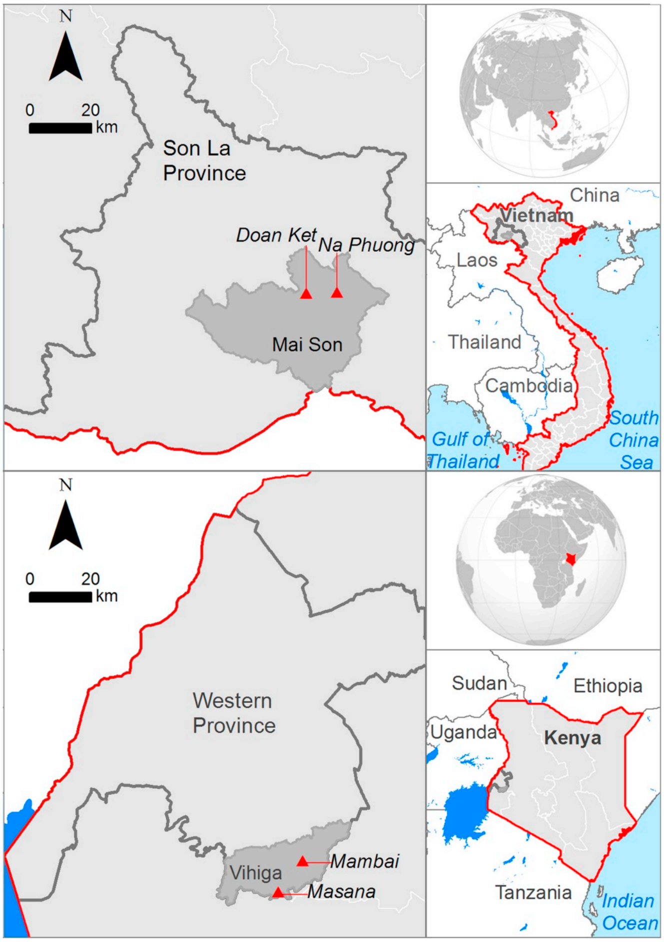

Fig. 2. Location of Na Phuong and Doan Ket villages in Mai Son district, Son La Province in Northwest Vietnam and Mambai and Masana sub-locations in Vihiga County, Western Kenya.

tool IMPACTlite (Rufino et al., 2013), in a semi-structured interview format in October and November 2014. For farm mapping and calculation of field areas, GPS readings were taken of field boundaries. To complement food consumption data collected using IMPACTlite, on two occasions per site, qualitative 24-h food intake recalls were applied with women of reproductive age responsible for the household cooking of foods from ten pre-defined food groups (Kennedy et al., 2010). The IMPACTlite survey tool differentiated foods obtained from on and off farm (e.g. market) production. Structured surveys were performed in both countries, with the same respondents as the 24-h food intake recalls, to determine the frequency at which food items (Tables S1 and S2) were consumed by the household over the course of a year. We created one farm model per site to compare and contrast the differences in the modelled solution spaces across the four sites and between the two countries.

2.2. Modelling framework

Using the multi-objective optimization model FarmDESIGN (Groot et al., 2012), the potential of new land-use and diet composition configurations was explored vis-à-vis their capacity to complete the household dietary composition needs. Nutrition-related indicators on dietary adequacy, diversity and food patterns (Estrada Carmona et al., 2019) and household members as entities in the model and associated household level labour and income indicators (Ditzler et al., 2019) were added to this bio-economic farm-household model. The nutrition-related indicators can now be analysed in relation to the socio-economic indicators such as profitability, household budgets and labour requirements, and environmental indicators such as land-use diversity, nutrient losses and soil organic matter accumulation (Table 2).

FarmDESIGN was used within the framework of the DEED cycle (Describe, Explain, Explore and Design) (Giller et al., 2008). As a starting point, the farm household system is *described* through parameters covering household composition (members, on- and off-farm activities), farm environment (e.g. climate and soils), economics (e.g. farm expenses and labour prices), crops and animals with their related products (e.g. yields, labour required and destinations), manures, fertilizers, buildings and machinery. In the second step, the system is *explained* through economic, social, environmental and nutritional indicators. In the third *exploration* step, some of the parameters used to describe the system can be set as decision variables (i.e. with upper and lower limits on, for instance, crop areas), and some of the indicators used to explain the system can be set as constraints (i.e. upper and lower limits on animal's energy and protein requirements) or as outcome objectives to maximise or minimise. The model runs a Pareto-based Differential Evolution algorithm (Storn and Price, 1997) to generate numerous possible configurations and display them within a solution space. This algorithm is explained in Section 2.2.3. Finally, in the fourth step, a suitable solution can be chosen as a (re)*design* option for the farm.

2.2.1. Model indicators

Farm household systems in FarmDESIGN are explained by a wide range of indicators of which a selection is presented in Table 2. Various indicators can be compared before and after optimization enabling an overview of the effects of the optimization. Indicators describe the productivity of the farm, the socio-economic aspects of the household, the nutritional contribution to household requirements as well as the environmental performance of the farm.

For (detailed) explanations of how productivity, socio-economic and environmental indicators are calculated in FarmDESIGN, we refer to Groot et al. (2012). Nutritional indicators as well as the changes to the household labour and economics calculations are described in more detail by Groot et al. (2017), Ditzler et al. (2019) and Estrada Carmona et al. (2019).

Here we choose four indicators as objectives: household free budget (B_H), leisure time (T_L), nutritional system yield for vitamin A (NSY_{vita}) and intake adequacy for vitamin A (A_{vita}) (Table 2). The maximization of the four objectives in the multiple-optimization facilitates assessing the synergies and trade-offs between improving household income while reducing labour load and vitamin A deficiencies that are present in the study areas (Ngare et al., 2000; WHO, 2009b; NIN, 2010; Laillou et al., 2012).

The objective household free budget, B_H (US\$ year^{-1}) is calculated as farm net income, I_F (US\$ year^{-1}) plus off-farm income, I_O (US\$ year^{-1}) less the sum of the cost of food, C_F (US\$ year^{-1}) and all other household expenses, C_E (US\$ year^{-1}). The objective leisure time, T_L (hours year^{-1}) is calculated as the annual sum of available time for on- or off-farm activities for all members of the household, T_{tot} (hours year^{-1}) less the hours spent on off-farm labour, L_{OF} (hours year^{-1}) and the labour hours required for farm management activities, L_{FA} (hours year^{-1}). L_{FA} (hours year^{-1}) is calculated as the sum of all labour hours required for crop cultivation, L_C (hours year^{-1}), plus the sum of all labour hours required for livestock keeping, L_A (hours year^{-1}), plus the sum of all labour hours required for general farm activities, L_G (hours year^{-1}) i.e. hours required for farm labour that is not directly attributable to a crop or animal enterprise and less the sum of the hours supplied by hired labour, L_H (hours year^{-1}).

The objective nutritional system yield for nutrient *r*, NSY_r (capita

Table 1
Characteristics of Western Kenya and Northwest Vietnam and the four selected case study sites.

Characteristic (Global databases)	Western Kenya Vihiga		Northwest Vietnam Mai Son	
Altitude (m)	1400–1600		500–800	
Topography	Mostly rolling hills, some with rocky granite outcrops, and valleys with streams flowing mainly from northeast to southwest that all drain into Lake Victoria. Mambai has tea plantations and has steeper slopes than Masana which is on flatter, more gently sloping land. There are smaller scattered rocks in Masana and in Mambai there are occasional large boulders.		The valleys have rivers running from northwest to southeast. There are scattered patches of forest. In Na Phuong there are steeper slopes with rain-fed maize on upper slopes and paddies with rice in the lowlands. In Doan Ket, there is a flatter landscape with more fish ponds and occasional hills with rocky outcrops where coffee is grown as a cash crop	
Population density (capita km^{-2})	1043		80	
Ethnicity	Luo & Luhya		Thai Ethnic minority	
Climate	Equatorial		Humid Subtropical	
Soils	Acrisols		Orthic Acrisols and Chromic Luvisols	
Staple food crop	Maize		Paddy rice	
Ave. annual temperature (°C)	20.5		21.8	
Ave. annual rainfall (mm)	1900, bimodal		1400 to 1700, unimodal	
Agro-ecological zones	Upper Midland 1 (UM1) and Lower Midland 1 (LM1)		Northwest Agro Ecological Zone	
Nutritional status	~84% of preschool children suffer from vitamin A deficiency (WHO, 2009b)		~12% of preschool children suffer from vitamin A deficiency (WHO, 2009b)	
Case study sites (own data)	Mambai $n = 10$	Masana $n = 10$	Na Phoung $n = 8$	Doan Ket $n = 9$
Farm size (ha) (ave.)	0.06–0.64 (0.33)	0.12–0.45 (0.29)	0.52–2.30 (1.20)	0.70–5.98 (1.95)
Ave. Household size	4.5	5.0	5.1	4.5
Main crops grown	Maize, beans, tea, napier, sweet potato, banana, kale, cassava	Maize, beans, napier, sweet potato, banana, kale, cassava	Maize, rice	Maize, spring onion, cabbage, French beans, coffee
Main animal types	Cattle, goat, chicken	Cattle, goat, chicken	Chicken, pig	Fish, chicken
Market orientation	Sell tea as cash crop, small quantities of farm products sold locally	Small quantities of farm products sold, located closer to larger Kisumu markets	Sell almost all maize produced to animal feed processors	Sell most vegetables and coffee to local markets and maize to animal feed processors
Subsistence# (%)	85	66	11	2

Proportion of total food crop production that is consumed by the household.

Table 2
A selection of productivity, socio-economic, nutritional and environmental indicators present in the FarmDESIGN model.

Indicators	Units	Used as[a]	Type
Farm area	ha	constraint	Productivity
Livestock units	Tropical Livestock Units	indicator	Productivity
Nutrient system yield (NSY_r)	capita ha^{-1} yr^{-1}	objective	Productivity, Nutritional
Nutrient adequacy (A_r)	% of requirement	objective	Nutritional
Food group sufficiency	% of requirement	constraint	Nutritional
Dietary diversity score	–	indicator	Nutritional
Nutritional functional diversity	–	indicator	Nutritional
Nutrient self-sufficiency	% of consumption	indicator	Nutritional
Leisure time (T_L)	hours yr^{-1}	objective	Productivity, Socio-economic
Farm family labour (T_{tot})	hours yr^{-1}	indicator	Productivity, Socio-economic
Hired labour (L_H)	hours yr^{-1}	indicator	Productivity, Socio-economic
Off farm labour (L_{OF})	hours yr^{-1}	indicator	Productivity, Socio-economic
Off-farm income (I_O)	US$ yr^{-1}	indicator	Socio-economic
Household free budget (B_H)	US$ yr^{-1}	objective	Socio-economic
Operating profit (I_F)	US$ yr^{-1}	indicator	Socio-economic
Costs for food (C_F)	US$ yr^{-1}	indicator	Socio-economic
Other expenditure (C_E)	US$ yr^{-1}	indicator	Socio-economic
Nitrogen soil losses	kg ha^{-1} yr^{-1}	indicator	Environmental
Soil organic matter added	kg ha^{-1} yr^{-1}	indicator	Environmental

[a] 'Used as' presents the use of the indicator in the multi-objective optimization performed in this study either as a constraint or as an objective. Indicators not used in this study are designated 'indicator'. FarmDESIGN allows model users to select indicators and assign them as either a constraint or an objective, or both.

ha^{-1} year^{-1}) is calculated as follows:

$$NSY_r = \frac{\left(\sum_{i=1}^{n} F_i P_{r,i} + \sum_{j=1}^{m} F_j P_{r,j}\right)}{R_r} \times \frac{1}{S} \tag{1}$$

where r is a nutrient (e.g. vitamin A), F_i is the fresh weight produced (kg year^{-1}) of crop product i and $P_{r,i}$ is the content of nutrient r in crop product i (g kg^{-1}), F_j is the fresh weight (kg year^{-1}) of animal product j and $P_{r,j}$ is the content of nutrient r in animal product j (g kg^{-1}), R_r is the dietary reference intake (DRI) for nutrient r for a person per year (g capita^{-1} year^{-1}) and S is the farm surface area (ha). The number of crop and animal products is indicated by n and m. This metric shows the number of people that can be supported per hectare by the current farm configuration in terms of nutrient r (adapted from DeFries et al., 2015).

Food composition tables (FCT) were compiled specifically for this study (Tables S1 and S2). For Kenya, this was based on the national FCT of Tanzania (Lukmanji et al., 2008) supplemented with data from other FCTs (Holtz et al., 2012, SMILING D.5-a, 2013, Stadlmayr et al., 2012, USDA and ARS, 2014 and West et al., 1988). For Vietnam this was based on the Vietnamese FCT, SMILING D.5-a (2013), supplemented with data from other FCTs (Lukmanji et al., 2008; USDA and ARS, 2014). The total energy and nutrient demand per household were calculated as the sum of the energy and nutrient needs per household member with the use of the household composition data (age and gender) together with the individual Recommended Nutrient Intakes (RNI, level of intake that meets the needs for 97.5% of the population). To mimic the estimated average requirement (EAR, reflecting the level of intake that meets the needs of 50% of the population) we used the dietary reference intake of 70% RNI (Otten et al., 2006) (cf. Table S5) comparable to other studies evaluating the nutrient adequacy of modelled diets. (Kujinga et al., 2018; de Jager et al., 2019; Samuel et al., 2019). For the nutrients iron and zinc, the EAR (WHO, 2005) values were used, and adjusted to account for low bioavailability of these nutrients in the diets of these communities. These adjustments were also made following the methodology of Kujinga et al. (2018), de Jager et al. (2019) and Samuel et al. (2019). The total energy and nutrient intake per household were calculated based on the total food intake and the compiled FCTs.

The intake adequacy for a nutrient r, A_r (%) is calculated as follows:

$$A_r = \frac{(H_{I,r} - H_{D,r})}{H_{D,r}} \times 100 \tag{2}$$

where $H_{I,r}$ is the household intake of a nutrient r (kg year^{-1}) and $H_{D,r}$ is the household required demand for nutrient r (kg year^{-1}).

In the optimization, to reflect the limited availability of arable land, the minimum household vitamin A requirement and a balanced feed ration for livestock, constraints were placed on total farm area, vitamin A adequacy and ruminant intake of dry matter, energy and protein (Tables S3 and S4).

In order to generate farm configurations that differ in economic productivity, labour demands, nutritional system yield of, and household intake adequacy for vitamin A, the areas of the currently grown crops and of new intervention crops, and the destination of crop products were defined as decision variables (Tables S3 and S4).

2.2.2. *Intervention crops*

Focus group discussions (FGDs) held in the study sites guided the selection of nutritious crops as part of the project's nutrition-sensitive interventions. Crops were selected for their market potential and their ability to close nutrient gaps, particularly vitamin A, through consumption. Selected crops, hereafter called 'intervention crops', included grains, pulses, dark green leafy vegetables and orange fleshed fruits and vegetables as these have a high vitamin A content. In Kenya, farmer-chosen crops included African nightshade (*Solanum americanum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), crotalaria (*Crotalaria brevidens* Benth.), beans (*Phaseolus vulgaris* L.), groundnuts (*Arachis hypogaea* L.), kale (*Brassica oleracea* var. *acephala* L.), pumpkin (*Cucurbita maxima* Duch.), purple amaranth (*Amaranthus blitum* L.), soybeans (*Glycine max* (L.) Merr.) and spiderplant (*Cleome gynandra* L.). In Mambai, there were fewer intervention crops chosen in the FGDs than in Masana. Some intervention crops were also modelled as intercrops with maize (*Zea mays* L.). The modelled intervention crops can be seen in Table S3.

In Vietnam, 15 intervention crops were chosen by the farmers during the FGDs. Nonetheless, due to limited production data availability, we only used four in this modelling exercise: mustard greens (*Brassica juncea* (L.) Czern.), orange-fleshed (OF) sweet potato (*Ipomoea batatas,* Lam.), water spinach (*Ipomoea aquatica* Forsk.) and French beans (*Phaseolus vulgaris* L.). The same four intervention crops were used for both sites (Table S4).

Expected crop yields, labour requirements and cultivation costs were determined through combinations of survey data, expert opinion and literature review (Table 3). We set the area allocated to each intervention crop as a decision variable, ranging from zero area in the current situation up to the maximum farm area. The only exception being water spinach area for the farm Na Phuong where this

Table 3
Parameters for the annual expected yields, labour requirements, cultivation costs and fertilization costs for the modelled intervention crops in Kenya and Vietnam.

Crop	Crop Product(s)	Yield[#] (kg ha^{-1})	Labour (hours ha^{-1})	Cultivation costs (US$ ha^{-1})[§]	Fertilizer costs (US$ ha^{-1})
African nightshade	Leaves	2500	5000	2.95	118
Beans	Dried beans	1200	6000	2.46	236
Cowpea	Grains	500	6000	2.95	236
	Leaves	1300			
Crotalaria	Leaves	2000	5000	2.95	118
Groundnuts	Groundnuts unshelled	700	7000	14.73	118
	Groundnut residues	700			
Maize & groundnuts	Maize	2500	8000	29.47	236
	Green maize residues	2500			
	Dry maize residues	2000			
	Groundnuts unshelled	500			
	Groundnut residues	500			
Soybean	Soybeans	1200	7000	19.64	236
	Residues	1500			
Maize & soybean	Maize	2500	8000	29.47	236
	Green maize residues	2500			
	Dry maize residues	2000			
	Soybeans	1000			
	Soybean residues	1000			
Pumpkin	Leaves	4000	8000	2.95	118
	Fruits	3000			
Purple amaranth	Grains	500	5000	1.96	118
	Leaves	3000			
Spider plant	Leaves	3000	5000	2.95	118
Kale	Leaves	5000	7000	1.96	236
Mustard greens	Leaves	8000	4000	0.15	138
OF sweet potato	Tubers	10,000	2000	0.53	0
Water spinach	Leaves	15,000	4500	0.22	138
French beans	Fresh beans	15,000	7000	0.26	171

[#] Fresh harvested yield [§] Other than labour and fertilizer costs, 1 US$ = 101.81 Kenyan Shillings and 1 US$ = 22,665.46 Vietnamese Dong as at 30/11/2016.

intervention crop was restricted to the area currently used for irrigated rice (Table S3 and S4).

2.2.3. Multi-objective optimization

The multi-objective optimization uses a Pareto-based Differential Evolution algorithm (Storn and Price, 1997; Radhika and Chaparala, 2018). The complete mathematical explanation with the corresponding formulae, used in FarmDESIGN is described by Groot et al. (2012), however we briefly summarize the optimization process in this section. In the first iteration of the model the following steps occur. Two sets of new configurations are created, assigning random values within the ranges of the modelled decision variables to 80% of the configurations. The remaining 20% retain their original values. The solution space created by these two sets is extremely diverse. The variety in the decision variables (genotypes) creates diversity in farm performance that is measured by the indicators (phenotypes). New configurations from both populations are assigned a Pareto rank and a value indicating how crowded they are with respect to other solutions within the solution space. The configurations that outperform all other configurations in more than one of the set objectives have a rank of one. Removing these configurations, the ranking continues with the remaining configurations that outperform at least one objective, assigning them rank two, continuing until all configurations are ranked. Low ranking configurations are analogous to the fittest individuals in a population in evolutionary terms. The configurations from both populations are compared using a pairwise comparison and the fittest solutions are used as the 'parents' for the next iteration. If the compared solutions have the same Pareto rank then the least crowded configurations in the solution space have preference, ensuring that new spaces are explored rather than concentrating in one spot. In all following iterations only a new set of 'competitor' configurations are generated by uniform cross-over (i.e. allele by allele). The probability of cross-over and the amplitude of mutation are adjustable exploration parameters. The competitor configurations are compared with the parents by their Pareto rank and crowding and again the best phenotypes selected. Each iteration of the model can be seen as a new generation of farming household systems in a population that is progressing towards optimality. We used 4000 iterations per run to reveal a Pareto frontier that forms with optimized solutions in a stable solution space.

3. Results

3.1. Case study farm descriptions

3.1.1. Mambai and Masana (Kenya)

Both farms made positive net incomes, yet at the household level, with the costs for the food consumed and other expenditures deducted, both had a negative household free budget (Table 4). In both farms, gross margins[1] for crop products were greater than gross margins[2] for animal products. Tea in Mambai and bananas in Masana provided the greatest absolute returns (US$ 165 and US$ 158, respectively) and traditional vegetables the greatest returns per hectare (US$ 7956 ha^{-1} and US$ 3418 ha^{-1} respectively). The areas dedicated to grow traditional vegetables were small, however the returns for these crops are high.

Nutritionally, both farms do not produce sufficient food on farm to supply household subsistence needs, in particular for dietary energy (kcal), calcium, iron, zinc, vitamin A and vitamin B12 (Fig. 3a & c) and purchased foods are needed to supplement their diets (Fig. 3b & d). Mambai and Masana households consumed 85% and 66% of their produced crop products, respectively. Households were able to sell some crop and animal produce (Table 4) to purchase food (mainly maize) to meet their energy need, however some micronutrients such as

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[1] Gross margin for crop products is calculated as returns (yield (kg ha^{-1}) * area (ha) * price (US$ kg^{-1})) less cultivation costs (US$ ha^{-1} * area).

[2] Gross margin for animal products is calculated as returns (production (kg day^{-1}) * 365 days * price (US$ kg^{-1}) less annual costs (feeds + bedding + interest + general (US$)).

Table 4
Modelled farm baseline characteristics: selected indicators from FarmDESIGN for four case study farms in Kenya (Mambai and Masana) and Vietnam (Doan Ket and Na Phuong).

Type	Indicator	Units	Kenya		Vietnam	
			Mambai	Masana	Doan Ket	Na Phuong
Household	Farm area	ha	0.22	0.42	1.17	0.64
	Household size	capita	6	7	5	5
	Livestock units	TLU	2.1	2.7	11.55	6.10
	Livestock density	TLU ha^{-1}	9.85	6.42	9.91	9.59
	Labour balance	hours yr^{-1}	0	0	0	0
Labour	Off farm labour	hours yr^{-1}	0	720	320	400
	Hired labour	hours yr^{-1}	217	0	0	0
	Farm family labour	hours yr^{-1}	5678	3483	5697	6230
Income	Farm net income	US$ yr^{-1}	1312	1053	4864	3110
	Off-farm income	US$ yr^{-1}	0	212	243	333
	Costs for food	US$ yr^{-1}	1781	1269	1992	1635
	Other expenditure	US$ yr^{-1}	584	184	833	439
	Total expenditure	US$ yr^{-1}	2365	1453	2825	2078
	Proportion food costs*	%	75	87	71	79
	Household free budget	US$ yr^{-1}	-1053	−187	2281	1370
Environment	Soil organic matter added	kg ha^{-1} yr^{-1}	776	490	692	832
	Nitrogen soil losses	kg ha^{-1} yr^{-1}	98	71	193	327
Nutrition	NSY_{vita}	capita ha^{-1} yr^{-1}	8.3	2.7	6.1	4.2
	A_{vita}	%	−50	−42	−71	−32
	Degree of subsistence#	%	85	66	2	11

1 US$ = 101.81 Kenyan Shillings and 1 US$ = 22,665.46 Vietnamese Dong as at 30/11/2016. TLU: Cow = 1.25, Heifer = 0.85, Calf = 0.55, Pig = 0.25, Goat = 0.2, Chicken = 0.01 and Fish = 0.005. * Proportion of food costs in total expenditure (food costs + other expenditure). # Proportion of total crop production that is dedicated to household own consumption.

calcium, iron, zinc and vitamin A remained in deficit at the household level (Fig. 3).

3.1.2. *Doan Ket and Na Phuong (Vietnam)*

Both farms had positive household free budgets largely supported by the sale of maize and French beans. Doan Ket had the highest net farm income (Table 4) with the greatest contribution stemming from animal production (annual gross margin US$ 3892). The high annual returns were from the pig fattening enterprise they ran (US$ 6689), which combined with their successful horticultural crop production (gross margin from cropping of US$ 2231), resulted in Doan Ket having the highest household free budget.

Nutritionally, both modelled farms appeared to produce enough calories and micronutrients (with the exception of calcium and vitamin B12) to meet household demand (Figs. 3e & g). However, the modelled Doan Ket household's diet appeared deficient in magnesium, calcium, iron, riboflavin, folate and vitamins A and C (Fig. 3f); the farm sold much of its produce (98% of crop production), and their food purchases failed to meet the household nutrient demands. On the other hand, Na Phuong household consumed 11% of their crop produce, but still only achieved a similar level of household nutrient adequacy to Doan Ket, shown by the inadequate supply of magnesium, calcium, iron, riboflavin, folate and vitamins A and B12 (Fig. 3h).

3.2. *Exploration of solution spaces of case study farms*

For the Mambai farm there was a synergy between household free budget and NSY_{vita} (Fig. 4a), i.e. the household free budget increases with an increase in production of vitamin A. In contrast, the solution spaces of the other three farms indicated a trade-off between these two objectives. The synergy in the solution space of the Mambai farm was also visible in the similarity of the crop allocation trend noticeable as the household free budget and the NSY_{vita} increased in Fig. 5a and e, respectively. As household free budget and NSY_{vita} increased, area allocated to banana decreased and area allocated to the intercrop of maize, bean and kale increased.

For all farms there was a trade-off between household free budget and leisure time (Fig. 4b). The more labour invested, with the corresponding reduction in leisure time, the more financial rewards there were to be gained. However, for the farms Doan Ket and to some degree Masana, there were portions within the solution space in which there was some synergy, allowing simultaneous increases in leisure time and free budget. For Doan Ket, this synergy was the result of configurations with an increasing area of crops with a high value crop product such as maize (sold for animal feed) combined with a decreasing area of fruit trees with their low labour requirement. In Masana, traditional vegetables that require more labour but have a higher vitamin A content were out-competed by the valuable cash crop lettuce. The trade-offs between household free budget and leisure time were also visible as mirrored patterns noticeable in the Fig. 5a and i, b and j, c and k and d and l.

The exploration yielded configurations where originally grown crops were replaced by the new intervention crops for only small percentages of the total farm area (Fig. 5). Most intervention crops were allocated to less than 5% of total farm area with a few exceptions. For Mambai and Masana, some additional area was allocated to kale (2–13%), and to pumpkin (0–6%). In Doan Ket, OF sweet potato (0–6%) and in Na Phuong, OF sweet potato (0–8%) and water spinach (0–2%) were introduced. The increased kale area in Mambai (both monocropped and intercropped with maize and bean) (Fig. 5a & e) would allow for higher NSY_{vita} without increasing farm size (Fig. 5a & c). The increases in the NSY_{vita} were achieved through allocation of even very small portions of land to the intervention crops kale, pumpkin, OF sweet potato and water spinach given their high vitamin A content.

4. Discussion

We compared and contrasted the farming systems of the Kenyan and Vietnamese smallholder farmers showing how their diets and production patterns differed according to their resources and market orientation. We explored solution spaces and identified trade-offs and synergies at the farm scale between contrasting objectives and decision variables, and examined the effects of nutrition sensitive interventions on economic, social and nutritional indicators. The model generated crop compositions and space-time configurations that satisfied household nutritional requirements. Yet the intervention crops were not

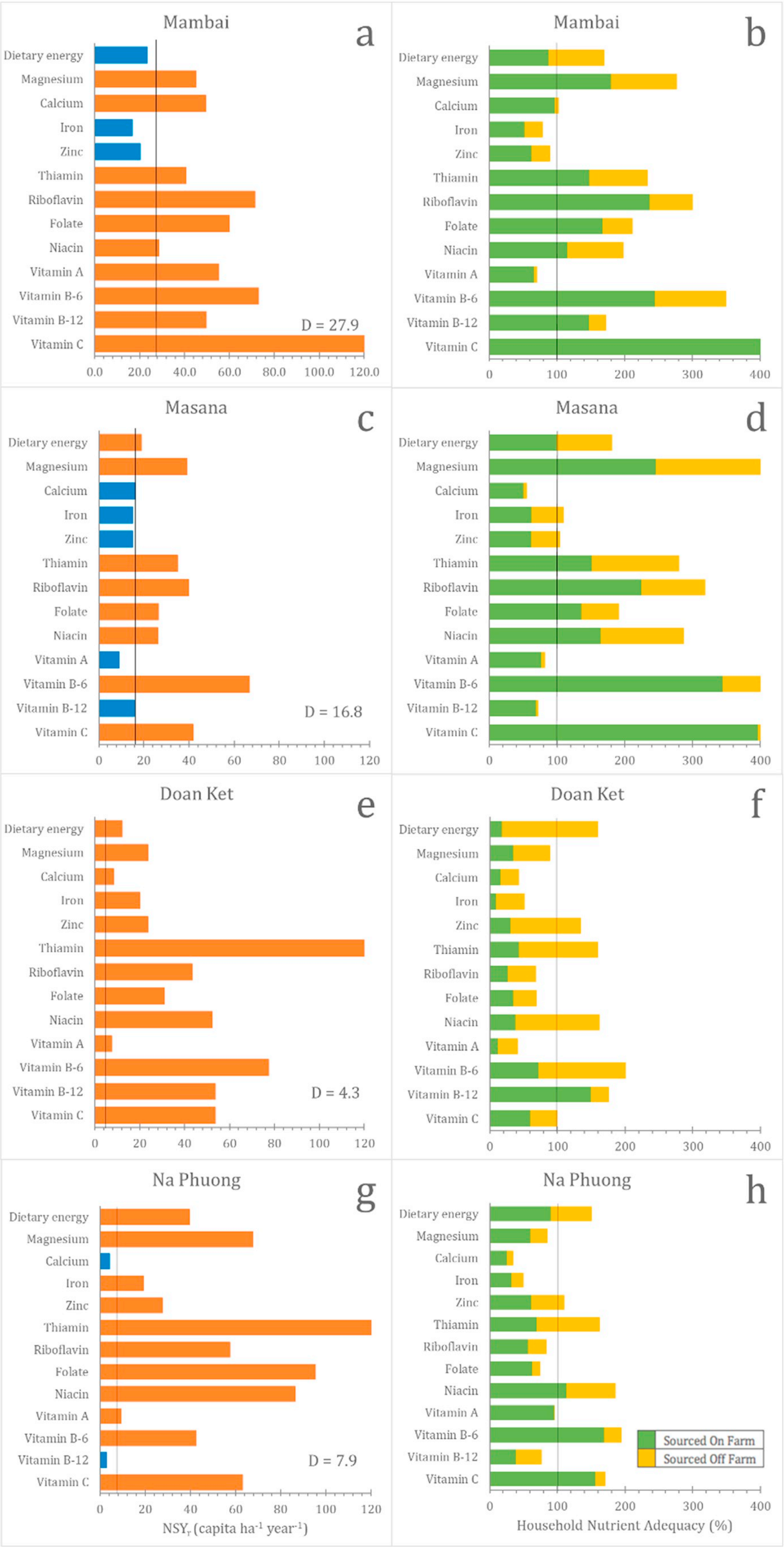

Fig. 3. Nutrient System Yield (NSY$_r$) and household nutrient adequacy for 13 nutrients for the four case study farms in Kenya (Mambai and Masana) and Vietnam (Doan Ket and Na Phuong). In graphs a, c, e and g the black vertical lines indicate the household member density (D) (household members divided by farm area and measured in capita ha^{-1}), orange and blue indicate nutrients for which there is respectively, sufficient and insufficient produced on farm for home consumption. In graphs b, d, f, and h the black vertical lines indicate diets where 100% adequacy is reached, i.e. that the household's dietary requirement for that nutrient is fulfilled, the colours represent the source of the nutrients. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

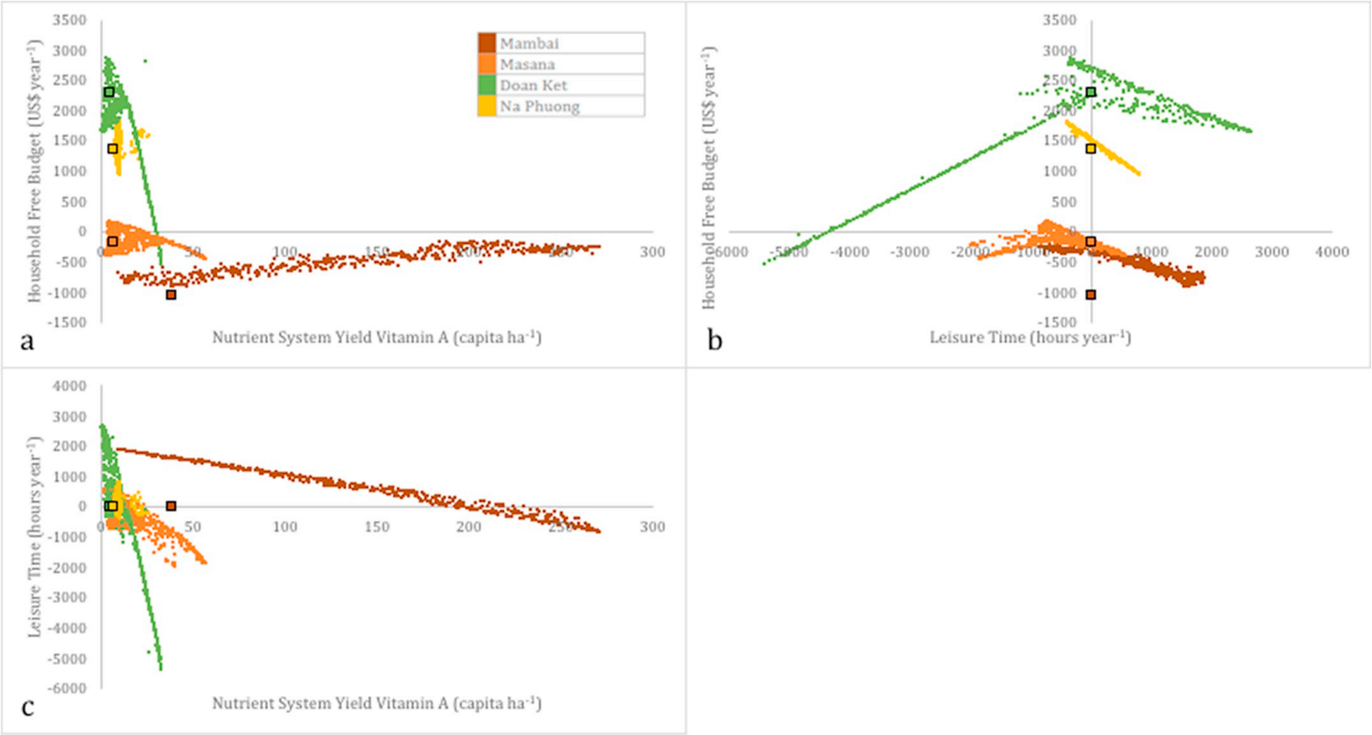

Fig. 4. Performance of alternative farm configurations in terms of three objectives, household free budget, nutrient system yield for vitamin A and leisure time for the farms Mambai (brown), Masana (orange), Doan Ket (green) and Na Phuong (yellow). The coloured squares indicate the performance of the respective original farm configurations (baseline). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

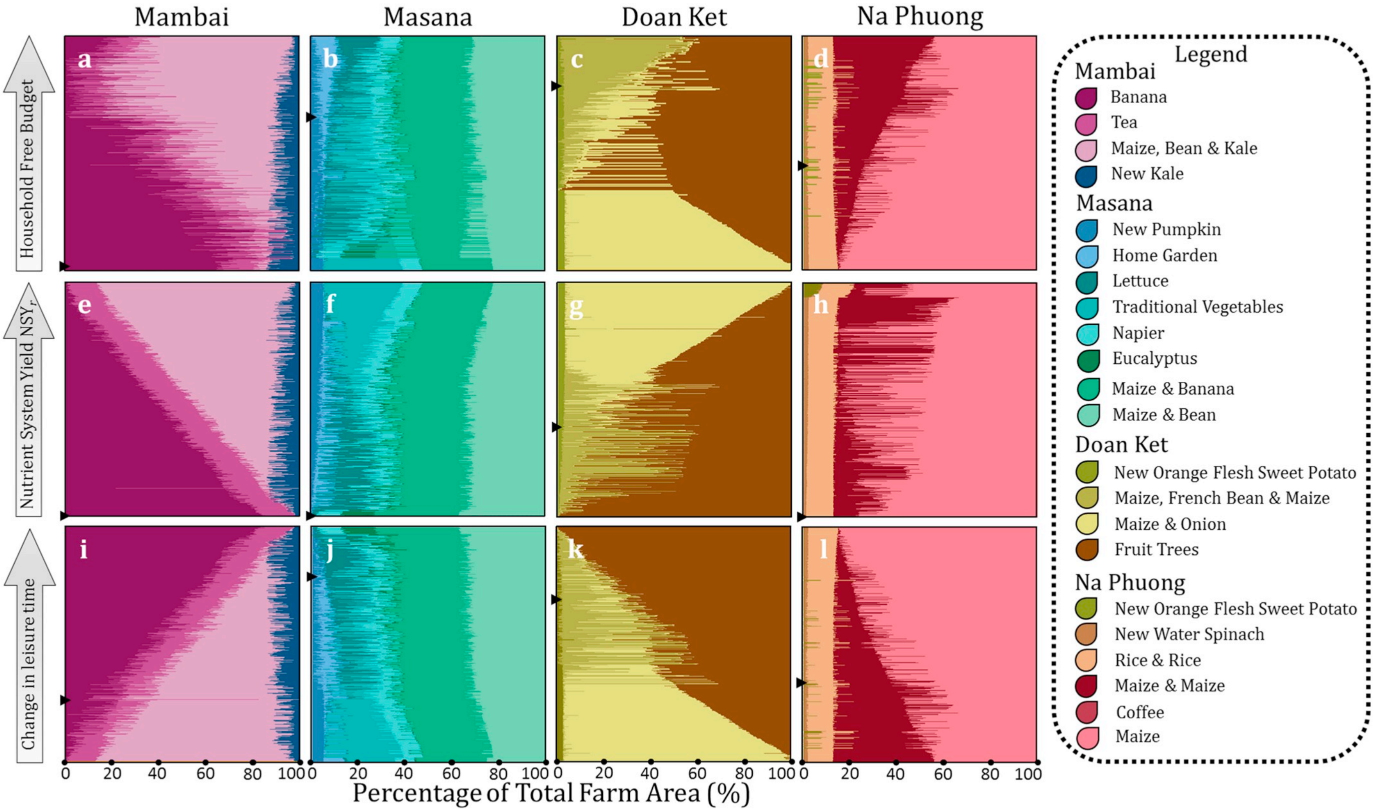

Fig. 5. The allocation of different percentages of total farm area to the current and new land-use decision variables, for the complete set of alternative farm configurations generated for the farms Mambai, Masana, Doan Ket and Na Phuong horizontally arranged along an axis of increasing household free budget (top), increasing nutrient system yield (centre) and increasing change in household leisure time (bottom). The black triangle indicates the original value for the household free budget, the nutrient system yield and the leisure time for each farm.

selected to replace currently grown crops to any large scale. However, we have demonstrated the use of an integrated model to explore these trade-offs and synergies at the farm-household scale.

The findings of this study show that, although the modelled Vietnamese farms produced ample nutrients to meet the nutritional requirements of the household, their actual consumed food (mostly purchased off-farm with most on-farm produce sold) reflected a diet deficient in several nutrients. Nationally, Vietnam has made drastic improvements in nutrition during the last two decades, however the last national nutrition survey indicated that vitamin C and iron deficiencies remain a problem (NIN, 2010). More recent regional studies find similar diet quality results and suggest that vitamin A, zinc, folate and vitamin B12 deficiencies are also present, with vitamin A, B12 and zinc deficiencies specifically identified as public health concerns (Laillou et al., 2012). Furthermore, Nguyen et al. (2014) show that micronutrient intakes among poor populations in Northern Vietnam are suboptimal. The Northwest region is predominately populated with minority ethnic groups, and the data used in this study were specifically from the Thai ethnic minority group. In the Northwest, minority ethnic groups suffer higher rates of economic and nutritional poverty compared to the national average. No studies have been published on diets within the Thai minority groups, however two studies looking at an aggregated population of minority groups in Vietnam show that micronutrient deficiencies and insufficient dietary intakes are still prevalent in these populations, particular in the remote rural areas of Vietnam (NIN, 2010; Huong et al., 2013; Nguyen et al., 2014).

The two Kenyan farms on the other hand, did not produce sufficient nutrients on farm as measured by the NSY_r (Fig. 3a and c), but supplemented their diet through the purchase of food off-farm, resulting in adequacy in the majority of the modelled nutrients Fig. 3b and d). A diagnostic survey carried out in a season of plenty (September to October 2014) and in a lean season (April 2015) in Vihiga, showed that more than 50% of children had intakes below the Estimated Average Requirements (EAR) for calcium, iron and zinc in both seasons and for also for vitamin A and folate in the lean season (Oduor et al., 2018). Another survey carried out in Vihiga in November to December 2015, showed that more than 50% of women had intakes below the EAR for iron, calcium and vitamin B12 (Bioversity unpublished data). That the Kenyan models did not produce sufficient nutrients on farm to satisfy the household requirements, should also be seen in the light of the fact that the population density in Vihiga is more than ten-fold of that in Mai Son (Table 1). The larger area of the Vietnamese farms, with similar numbers of household members to the Kenyan farms, means household densities (in capita ha^{-1}) are far higher in Kenya (see household density 'D' in Fig. 3). So, even though the shortage of land in Vihiga is a major constraint to the smallholder farmers in that region, the results from this study show that the modelled Kenyan household's diets matched their requirements more adequately than the Vietnamese households.

Vietnamese household income was higher than Kenyan households, even though the relative proportions of food costs to other expenditure were similar (Table 4). Thus, the Vietnamese households had greater household free budgets. Furthermore, the agricultural policies in Northwest Vietnam support smallholder farmers with an adequate supply of agricultural inputs and markets for their produce (FFTC-AP, 2014; World Bank, 2016). In Kenya, these enabling policies and governmental support are, since the devolution of power to the counties in 2012, less effectively implemented in Western Kenya (Simiyu, 2015). Yet, despite being larger, more market oriented, and thus having a greater operating profit, the households in Vietnam were not adequately nourished (cf. Table 4 and Fig. 3).

Regarding the solution spaces generated, crop choices by FarmDESIGN suggested crop space-time compositions that offered a synergy between NSY_{vita} and household income for the Kenyan farm models. Increasing areas grown to kale as a monocrop, or intercropped with maize, showed a trend of increasing income and supply of vitamin A for the modelled farm in Mambai. In Masana, closer to the urban centre of Kisumu, increasing the area of the cash crop lettuce, improved household income, but traditional vegetables improved NSY_{vita} to a greater extent in the model. This study however, did not examine the market potential of lettuce, a crop not widely grown in Vihiga County, yet the Masana farmer spoke favourably about this crop. The modelled farm in Doan Ket showed a trend of improved household income and NSY_{vita} replacing maize and onion bulbs with fruit trees. However, with the addition of more maize and French bean a trade-off between profit and labour emerged. In the Na Phuong farm, maize (with its easily saleable crop product that is not consumed by the household) was not out-competed by the intervention crops. Maize, a recent cash crop, appeared to provide great scope to increase household income, although the boom in its production has undesirable negative social and environmental consequences like increased erosion (Hauswirth et al., 2015; Castella et al., 2016) and is not consumed by households as it is sold for processing into animal feed.

The solution spaces shown in Figs. 4 and 5 provide supporting material for farmer discussions. The suitability of different configurations in the solution spaces and the desirability of these novel configurations by the farmers has not been ascertained. That, theoretically the intervention crops have potential to improve household nutrition, does not imply that they will be adopted or utilised in the expected/modelled way for sale or consumption. However, the approach provides an opportunity to evaluate the impact of nutrition-sensitive agriculture interventions *a priori* which can guide farmers towards taking objective decisions.

The size and shape of the solution spaces depend on internal factors, as parameterized in FarmDESIGN, and external drivers like prices and policies, and these can reflect changes to private, public and social benefit as described by Groot and Rossing (2011). Further, solution spaces allow for the identification of efficient policy instruments (Parra-López et al., 2009) and assessment of resilience and vulnerability of farm-household systems (Groot et al., 2016).

The novel approach taken in this study to add nutritional and household level indicators to the farm level bio-economic model FarmDESIGN provided a more integrated view of the effects of proposing changes to smallholder farming systems. We showed that FarmDESIGN is equally capable of analysing and exploring new options for farming systems along many gradients such as population densities, structural and institutional support, market integration and market orientation. The analysis and exploration took a wide range of multidisciplinary indicators into account: productivity, socio-economic, nutritional and environmental. Considering the wide range of indicators that can be included, FarmDESIGN is well positioned to analyse and optimise multiple Sustainable Development Goals (SDGs) as adopted by the United Nations (2015). This makes FarmDESIGN a comprehensive, multi-facetted tool for informing discussions between policy-makers, researchers, extension officers and farmers (or other stakeholders) on the effects of (sustainable) intensification and nutrition-sensitive agriculture interventions, or in highlighting the trade-offs and synergies between various SDGs in differing locations and circumstances.

This study had some limitations. The recording of household foods purchased off-farm was prone to error. The accuracy of the respondent's estimates of food quantities and consumption frequency over the past 12 months from memory could have been over- or underestimated. A "fixed" ratio was used to determine the weights bought from market and the weights home-consumed. However, it remains difficult to record all the diversity of food sourced off-farm, with sources from many locations; wild harvested, gifts from relatives, food eaten at markets, in restaurants, etc. (Hebert et al., 1998; Deaton and Grosh, 2000; Kolodziejczyk et al., 2012). Water used for drinking was not recorded, and as water is potentially a good source of calcium (WHO, 2009a), when the recommended 1.5 l per day are consumed, this might explain the low values for calcium seen in Fig. 3. Assumptions were also made on an equal distribution of food within the household which is often not the case (Alderman et al., 1995; Haddad et al., 1996). Heads of households usually receive the largest portions with the choicest foods, while women and children, who are the most nutritionally vulnerable, often have difficulty accessing more nutrient-dense foods (e.g. meat, milk or eggs) (Udry et al., 1995; Hyder et al., 2005). Recording accurate labour data is also challenging (Arthi et al., 2018), and considering that leisure time was used as an optimization objective, possible imbalances between the estimated labour requirements for the novel intervention crops and the recorded labour for current crops could have resulted in intervention crops not being allocated to any large scale in the generated configurations presented in this study. The risks involved in making these changes were not included in this analysis.

The difference in household member density between the smallholder farms in Vietnam versus those in Kenya, (values for D, Fig. 3) made an equal comparison difficult, however this was particularly useful in demonstrating the gradient of resource constraint, and how it increased with increasing population pressure while the proportion of on farm produced nutrients consumed increased. The Kenyan households had diets composed of greater proportions of on farm produced foods (more subsistence oriented) and had a more adequate diet that satisfied more nutrients requirement as opposed to the Vietnamese households that had a more market oriented dietary supply and a poorer dietary quality.

The presence or absence of a link between agrobiodiversity and dietary diversity has been widely researched and documented (Termote et al., 2012; Keding and Cogill, 2013; Jones et al., 2014; Sibhatu et al., 2015; Ng'endo et al., 2016; Jones, 2017; Lachat et al., 2017; Rajendran et al., 2017; Mellisse et al., 2018; Sibhatu and Qaim, 2018). Although potentially a question that could be answered using the FarmDESIGN model, in this study we have not attempted to determine whether this direct link exists. What is certain from the current literature, is that the relationship is complex, can follow multiple pathways (Baudron et al., 2017) and can be confounded by many factors. Further research directions could focus on the participatory processes of dissemination and discussion of the results to, and with, the farmers.

5. Conclusions

We have presented a whole farm multi-objective modelling exercise in four contrasting farm-household systems. The proposed multi-method approach and the model used, facilitates assessing and designing multifunctional agricultural landscapes for improved diet quality and incomes. This approach aims to jointly improve food and nutrition security, sustainable use of natural resources, biodiversity and ecosystem services conservation, both for human and environmental health. We have analysed and compared four case study villages in two countries, to examine the scope for and effect of different nutrition sensitive interventions on economic, environmental and nutritional indicators in contrasting contexts. We explored windows of opportunities for sustainable redesign and innovation in farming systems using the solution spaces generated by the whole farm model FarmDESIGN to reveal trade-offs and synergies between contrasting objectives and decision variables. The relevant objectives analysed were household free budget, household leisure time and system-level yield of vitamin A. This integrated study allowed us to conclude that:

- Despite the modelled Vietnamese sites exhibiting greater nutrient system yields (NSY_r) than those in Kenya, the modelled household diets in Kenya had greater nutrient adequacy due to the fact that the Vietnamese farmers sell greater proportions of their on-farm produced foods;
- According to our multi-objective model explorations, substitution of only small areas of the currently grown crops by 'intervention' crops would be sufficient to improve various nutritional and livelihood indicators, in both Kenya and Vietnam;
- Farmers in all locations faced the classic trade-off between income and labour, more income required more labour. Three of the four case study farms also showed a trade-off between household free budget and nutrient system yield for vitamin A (NSY_{vita}), while the case study farm in Mambai (Kenya) exhibited synergy between these two objectives.

Options exist for farmers to improve on the objectives analysed here. We were able to quantify possible improvements in these objectives, however further research and participation of farmers is required to ascertain the desirability and feasibility of these promising options, to be able to include risk assessments of new configurations, and to determine their perceptions on such diversification options.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2019.102774.

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