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The challenge of achieving basal energy, iron and zinc provision for home consumption through family farming in the Andes: a comparison of coverage through contemporary production systems and selected agricultural interventions

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Abstract

Background: Child undernutrition is persistently high in the central Andes of Peru, and numerous smallholder households fail to meet their basic needs of energy, iron and zinc. Food-based approaches assume household-level nutrition can be improved following agricultural interventions. This study assesses for the first time whether current Andean production systems provide sufficient energy, iron and zinc output to meet household-level requirements and explores the likely effect of commonly promoted food-based approaches. Across four communities, we determined the crop and livestock production output for each household ($n = 165$) during one growing season. The household-level nutritional demand or input was calculated as a function of household composition and daily requirements of energy, iron and zinc as established by FAO/WHO. We examined five scenarios, current practice or *status quo* and four food-based interventions: (1) increased potato yield, (2) introduced biofortified potatoes, (3) promotion of guinea pigs and (4) a mixed strategy combining all of the above.

Results: Under *status quo*, 86, 62 and 76 % of households obtained sufficient production output to meet energy, iron and zinc requirements, respectively. Considering the three parameters simultaneously, 59 % of households were able to meet their energy, iron and zinc requirements. The total crop production among households provided more than the necessary energy, iron and zinc output to meet the demand of all 165 households. Yet, significant differences between households account for individual deficits or surpluses in household-level output–input balances. Potato (*Solanum* spp.), barley (*Hordeum vulgare*) and faba (*Vicia faba*) production was particularly significant in determining the energy, iron and zinc output. Livestock did not make a substantial contribution. The main difference between households with negative versus positive coverage, in terms of household-level production output from agriculture meeting demand (=input), was available cropping area given household size. None of the explored food-based interventions closed the energy, iron and zinc deficit from production among households with negative coverage.

Conclusions: The smallholder production systems analyzed are only partially capable of providing sufficient production output to cover household-level energy, iron and zinc demands. Of the four interventions examined, a mixed

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strategy holds most potential for reducing nutrition gaps. Particularly potato yield increases had a positive effect. The carrying capacity of high-altitude Andean farming systems is strained for households with limited land. Food-based approaches to nutrition under scenarios similar to those reported in this study are advised to balance agricultural interventions with options to enhance off-farm access to food.

Keywords: Food and nutrition security, Smallholder farmers, Food-based approaches, Central Andes, Peru

Background

Agriculture is a vital source of food for farm households in the central Andes of Peru and a main entry point for development interventions aimed at strengthening food security and reducing undernutrition. Food-based approaches to nutrition, particularly those involving enhanced on-farm production to increase yields or to incorporate micronutrient dense components such as microlivestock (e.g., guinea pigs, chickens), biofortified staples or vegetables in smallholder farming systems, are frequently considered to be robust and sustainable alternatives to enhance smallholder food security [1, 2]. Higher or more stable crop yields are expected to influence the availability dimensions of food security, while diet quality from micronutrient rich foods can directly affect food security through utilization. Importantly, enhanced on-farm production as a food-based approach to improve nutrition is considered sustainable. In contrast to non-food-based approaches where nutritional supplementation, for example, must be provided in an ongoing way by agents external to the community, food-based alternatives can be autonomously maintained by farmers.

One underexplored prerequisite for the success of food-based approaches relates to the actual capacity of the smallholder farming system to provide sufficient food or nutrients to cover basic household-level nutritional requirements. Empirical assessments of these crop–livestock systems' energy and nutrient outputs are needed. In addition, analyses of the actual contribution of selected agricultural (food-based) interventions to household-level nutrient availability are critical to fully understand their potential impact.

Undernutrition is still prevalent in the Peruvian Andes, disproportionately affecting rural areas [3]. Stunting, or low height for age, is particularly widespread and has been the main focus of attention for governmental and civil society nutrition interventions in Peru. Stunting reflects the cumulative effects of undernutrition and poor health [4]. It is an indication of poor food and/or environmental health and results in long-term restrictions on child growth potential. Between 2000 and 2011, stunting in Peruvian children younger than 5 years of age went down from 31.6 to 19.6 %; anemia dropped from 50.4 to 30.7 % [5]. For the same period, stunting rates in Peru's highland regions dropped from 43.5 to 30.8 %; anemia dropped from 56.2 to 39.9 %. Despite overall progress, the prevalence of anemia in children 6–36 months old has remained disproportionately high with 41.6 % at the national level and 49.6 % in rural areas in 2011 [6]. By 2013, these figures actually increased to 46.4 % nationwide and 51.7 % in rural areas.

The reduction in child malnutrition in Peru is the result of increasingly coordinated government and civil society actions, e.g., a national poverty reduction strategy prioritizing nutrition interventions [7, 8]. Nutrition programs in Peru have focused on improving food access and availability. A conditional cash transfer program (Juntos) for women and food supplementation through the "glass of milk" and "school breakfast" programs have been at the heart of governmental strategies for the last decade [8–10]. Fortification of commonly consumed products, such as wheat flour, noodles or prepackaged school breakfast meals, is also regularly applied in Peru [11, 12], but these do not target infant and young children under 3 years old—the most vulnerable group for nutritional deficiencies and their child development consequences. On the other hand, the strategy of multi-micronutrient powder or sprinkles for children 6–36 months has been applied irregularly by the Peruvian government. In addition, many initiatives have addressed food utilization practices, e.g., improved hygiene and sanitation through nutrition messaging [13].

Meanwhile, agricultural or food-based approaches in the Andes have been predominantly promoted by civil society organizations. Interventions include the promotion of small greenhouses, horticulture, microlivestock, crop diversification and to a lesser extent biofortified crops [14]. In parallel, international development programs have focused their attention on increasing farmer income through inclusive value chain initiatives [15, 16]. Food stability is probably the food security dimension that is least attended by institutional interventions. Yet, Andean practices such as field scattering, mixed crop–livestock portfolios, planting of varietal combinations are still widely used by farmers themselves to maximize stability [17–19].

Research and development organizations frequently assume that agricultural (food-based) interventions will effectively translate into significant household-level nutrition improvements. Different types of social, economic or biophysical factors can impede desired outcomes. On-farm production is taking place in the high Andes as smallholder farmers rapidly diversify their livelihoods through off-farm employment [20–23]. Male farmers are increasingly only part-time involved in agriculture, and as women stay behind, a feminization of agriculture is becoming a reality in many rural areas [24–27]. Moreover, while in some places (temporal) migration has released some of the pressure on the land's ability to sustain food production [28], in others continued demographic pressure and landholding fragmentation reinforce migration and intensify crop and livestock production [29–31].

Particularly where smallholder farming systems may face constraints to production, it is imperative to assess actual carrying capacity and the potential of currently promoted agricultural interventions to enhance it. Carrying capacity defines the balance between land resources and human demands [32–40]. Locally, for smallholder food security, it translates into the total annual crop–livestock output being able to cover household demand for food. Sustainable intensification, it is argued, can extend the carrying capacity of the land to meet human food security needs [41–43]. In Andean agricultural systems, intensification options include the promotion of new varieties, crop biodiversity, homegardens or better practices for soil fertility, handling pests and disease, and storage of target crops, among others [44–51]. The desired outcome of such efforts is to increase the household-level food and nutrient quantity (yield) and quality (diversity, micronutrient density) under current landholding sizes.

Presently, Andean farming systems are under great strains to provide sufficient output to meet the demands of the households that (partially) depend on agriculture for food security. Among other influences, land fragmentation [52–54], interruption of communal rotation designs [55, 56], shortened fallow cycles [30, 55, 57, 58], soil degradation manifested as negative macronutrient and soil organic matter balances [43, 59–63], pest and disease intensity [64, 65], expansion of agricultural activities into higher altitudes exposed to extreme weather [66–68], and higher risk of harvest loss [69] may all compromise the basic capacity of agricultural systems and common development interventions to meet household-level nutrients demands. A deepened understanding of these intervening factors is beyond the scope of the current study. However, by taking the case of selected communities in central Peru, our research contributes with a much-needed estimate of current smallholder production system carrying capacity in terms of basic energy and micronutrient provision from agriculture. Through modeled scenarios we present a novel analysis of the capacity of specific agricultural interventions, or so-called food-based approaches, to increase the output of energy, iron and zinc from agriculture.

The purpose of our research is to examine whether agricultural output under current farming practice actually provides sufficient energy, iron and zinc output to meet household demand or input. We adopt the concept of carrying capacity to measure and compare the basic capacity of farming systems to cover household-level energy and micronutrient (iron and zinc) requirements through agriculture. Further, we explore variability among households and conditions associated with either positive or negative balances. To evaluate the contribution of food-based approaches to improve household-level balances, we analyze the effect of four agricultural intervention options. The outcome of these analyses are household-level balances: on-farm production output *versus* household-level demand for energy, iron and zinc.

The selected food-based interventions correspond to the strategies currently pursued by different development actors (NGOs and research for development centers): (i) enhancing potato yield, (ii) introducing biofortified potatoes, (iii) promoting guinea pigs and (iv) a combined approach. These interventions aim to eventually enhance smallholder household food and nutrition security with an emphasis on maternal child nutrition, support healthy livelihood outcomes and reduce vulnerability in the long-term [8, 70, 71]. The future implementation of such interventions would benefit from the present study. By providing an empirical assessment of the current carrying capacity of smallholder production systems and modeling specific interventions, our findings offer researchers and development practitioners information to feed into their nutrition and food security strategies.

Research methods

Research area

This study was conducted in four highland communities in the Huancavelica region, central Peru: Ccasapata, Ccollpaccasa, Sotopampa and Chopccapampa (Fig. 1). The communities were representative of the region with typical mixed production systems and high rates of child malnutrition and anemia. They were part of a McKnight Foundation-funded project researching the relationship between agrobiodiversity and nutrition and were selected on the basis of ethnicity, poverty and importance of agriculture. Geopolitically, the communities are part of Yauli district, Huancavelica province. Ethnically they belong to the so-called *Chopcca* nation, a Quechua speaking self-proclaimed indigenous group of 2000 households (9210 people), settled in an ex-hacienda adjudicated to them following a land reform in 1969 [72, 73]. Along with microfragmentation of landholdings, production

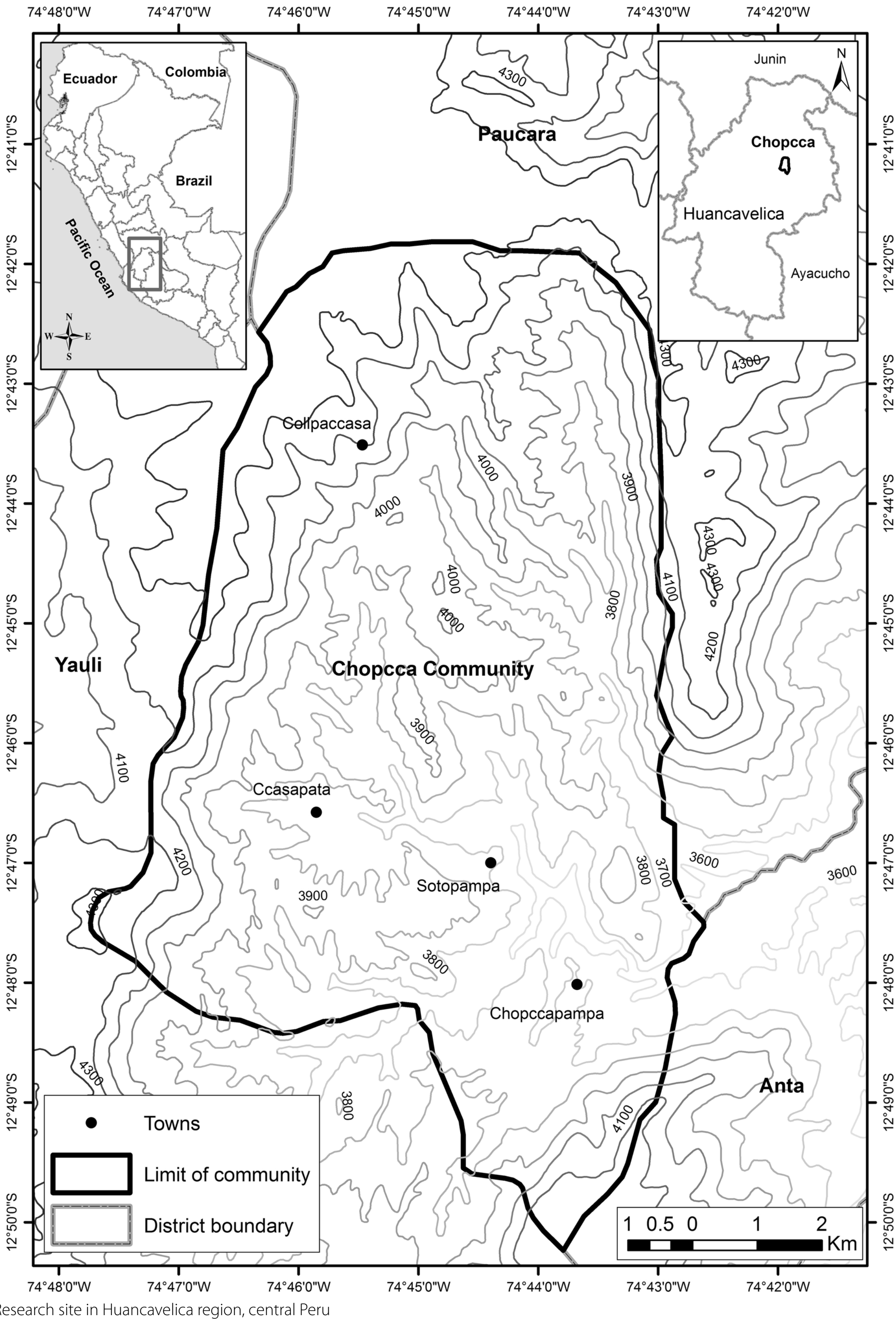

Fig. 1 Research site in Huancavelica region, central Peru

conditions in Chopcca have been exacerbated through land degradation [74]. Within the study site, households manage mixed crop–livestock systems with fields located between 3600 and 4500 m of altitude. All agriculture is rain-fed. Important crops include potato (Solanum spp), oca (*Oxalis tuberosa*), olluco (*Ullucus tuberosus*), mashua (*Tropaeolum tuberosum*), barley (*Hordeum vulgare*), faba (*Vicia faba*), lupine (*Lupinus mutabilis*) and oats (*Avena sativa*). Livestock includes cattle, sheep, llama, pig, poultry and guinea pig [73, 74].

Huancavelica is one of the most food insecure regions in Peru [75, 76]. At the time of this study, stunting affected 19.6 % of children under five years old nationwide, yet in Huancavelica these figures reached 54.2 %, the highest in the country [77]. Stature as indicator of the overall nutritional condition among women in reproductive age was also lowest in Huancavelica at 3 cm under the national average [77]. Energy, vitamin A, iron and zinc coverage are reported to be lowest in rural areas including Huancavelica [78, 79]. In 2012, 49.4 % of children under five years of age in the district of Yauli were stunted [80]. According to the most recent study in the four Chopcca communities, 44.2 % of children under 3 years old who attended the local health facilities were stunted (Z score < −2 SD) and more than 75 % of children between 6 and 24 months old did not meet their daily recommended iron and zinc requirements [74, 81]. Such high incidence of malnutrition coexists with diverse crop–livestock portfolios and traditional farming practices [74, 82, 83].

Data collection

We conducted a detailed structured survey with 185 households with children between 6 and 36 months of age in close collaboration with local stakeholders (village authorities, public health posts). The study received ethics approval from the Research Ethics Committee of the Instituto de Investigación Nutricional (IIN). Informed consent was given verbally by each participant prior to the application of the survey. Trained teams implemented surveys shortly after the main harvests during the months of July and August (2010). All interviewers spoke Quechua. The survey was the main tool used to collect qualitative and quantitative information on household composition, crop–livestock portfolios, cropping areas (m^2), production output (kg), among other parameters. Field sizes were checked through direct measurements. Potato yields were determined through direct measurement within 6 m^2 unit areas at the field level. Measurements of 251 and 172 fields containing bred and landrace potato cultivars, respectively, were taken during the 2008, 2009 and 2012 growing seasons. These represented fields from 165 households. The number of animals for cattle, horse, llama, sheep, pig, poultry and guinea pig was recorded during the main survey in 2010.

Data calculations

On-farm production

For each household, the total annual on-farm production (=output) and household-level demand (=input) for energy in kilocalories (kcal), iron in milligrams (mg) and zinc in milligrams (mg) were calculated. Household-level output is a function of the number of fields/household, crop area/field (m^2), crop yields/species (kg/m^2) and the number of animals annually consumed. Crop and animal production totals (kg) were converted into energy (kcal), iron and zinc (mg) output based on content values provided by the Instituto de Investigacion Nutricional (IIN) and reported in the Peruvian Food Table [84]. Animal production output was based on household-level number of animals per species and conservative expert-validated calculations: (1) typical reproductive rates for each species; (2) offspring survival rates under the environmental conditions of the study site; (3) total number of animals (progenitors and offspring) potentially available for household consumption; (4) average meat and visceral mass in kg, including edible abdominal and thoracic organs, per animal for each species (Table 1). Total edible and available meat and viscera in kg were generated for each species reported per household. Cows and horses were not considered in calculations of meat and viscera output as these are generally not consumed but rather used for milk production and transport, respectively. Households' number of cows therefore translated into total kg of cheese produced from average milk output. Chicken, apart from roosters, provide eggs (1 unit/day/chicken for 90 days of the year), meat and visceral mass.

Household demand

Annual household-level requirement for energy, iron and zinc is a function of household composition in terms of gender and age for each member multiplied by Daily Recommended Intakes (DRI) of energy (kcal), iron (mg) and zinc (mg) per person for the 365 days of the year [85, 86]. Daily energy requirements were calculated according to an activity level of 1.75 of the basal metabolic rate (BMR) for adult women assuming an average weight of 55 kg and an activity level of 1.90 of the BMR for adult men with an average weight of 60 kg, considering farm work in both cases. Thus, adult women were attributed a daily requirement of 2300 kcal for the 18–29 age range; 2250 kcal for the 30–59 age range; and 2050 kcal above 60 years of age. For women with infants under 12 months old, there was an additional daily requirement of 505 kcal for lactation. For adult men, the daily energy requirement was 3050 kcal for the 18–29 age range; 2950 kcal for the

Table 1 Livestock reproduction rates and weights in the Chopcca systems of Huancavelica region, central Peru

Species	Male-to-female ratio	Offspring per female per year	Meat weight (kg) per animal	Visceral weight (kg) per animal
Sheep	1:10	1	12.1	3.5
Cow[a]	0:1	0.5[b]	–	–
Llama	1:10	0.5[b]	28.9	15.5
Guinea Pig	1:6	5	0.75[c]	–
Chicken	1:3	0	2.6	0.3
Pig	0:1	5	52.5	5.3

[a] Only dairy consumption; 94.5 kg of cheese/cow/year

[b] 1 offspring every 2 years and not included in calculations

[c] Includes visceral weight

30–59.9 age range; and 2450 kcal over 60 years of age. Energy requirements for male and female infants during the first year of life, and for boys and girls up to 18 years of age, were based on FAO/WHO/UNU standards [85]. Daily recommended requirements for iron and zinc were calculated assuming low (5 %) bioavailability for iron and low (15 %) bioavailability for zinc. These bioavailability levels were based on consumption data from the same households indicating a largely vegetable-sourced diet [74]. Minimal presence of iron-rich animal source foods does not support adopting a higher bioavailability [86–88]. Recommended requirement levels of iron and zinc by gender and age group were based on FAO/WHO standards [86].

Nutrition balance

The difference between on-farm production (=output) and household demand (=input) for each individual household resulted in the nutrition balance for energy, iron and zinc. In turn, this balance is an indicator of the carrying capacity of the farming system in terms of its ability to provision sufficient energy, iron and zinc. The total output potentially available for each individual household follows a few assumptions. First, the output was considered to be readily available for consumption by households, without accounting for possible processing or post-harvest losses and produce sold. Second, production output as determined at the harvest and survey time was considered to be the only moment of food production for the household. This is generally true for rainfed agriculture in Huancavelica, yet some households also obtain modest off-season harvests. Third, nutrition balances are solely based on total production output and household requirement without considering food handouts from aid programs or foodstuffs acquired through barter or monetary purchase. The assumptions are simplifications of the reality, but necessary and reasonable to answer the main research question: (i) whether (or not) household-level crop–livestock production output is able to cover the minimal household-level nutrition requirements and (ii) whether commonly promoted agricultural interventions potentially make a difference.

Statistical analyses

After screening for missing and incomplete data, 165 household surveys remained as final dataset. Crop and livestock production data, household composition, nutritional demand, energy and micronutrient balances were firstly analyzed through descriptive statistics and by correlation analysis of all the continuous independent variables measured (35 in total) in the study. R package FactomineR [89] was used to perform principal component analysis (PCA) in order to identify variables that contribute the most to the variation in the dataset and to detect relationships between them. Multiple and logistic regressions were performed in RStudio (version 0.99.902) to identify variables that significantly influence energy, iron and zinc balances. R Package LEAPS [90] was used to assist in the variable selection process for model building purposes for multiple regressions. Three different regression models (wherein energy, iron and zinc were treated as dependent variable individually) that consisted of variables selected by the "regsubsets" approach in the LEAPS package (variables with a high R^2 and low Mallow's Cp score) and from the PCA were developed and chosen after being statistically tested against the full model. Logistic regression was used to identify variables that significantly contribute to the odds of a household meeting coverage for all nutritional parameters simultaneously (energy, iron and zinc) as a binary dependent variable (1 = household passes three parameters; 0 = household fails three parameters). A total of 119 households that passed ($n = 98$) or failed ($n = 21$) this criterion were used for logistic regression. A balancing methodology employed by ROSE package [91] in R was adopted for this analysis, since the number of responses classified under each category (pass all parameters/fail all parameters) was skewed and imbalanced. Model building, selection and significance testing for logistic regression was performed on the dataset that was balanced using the ROSE algorithm. A model that was not statistically different from a full model, and which had a lower AIC score, in addition to obtaining a high area under ROC (receiver operating characteristic) curve of 0.96 (Additional file 1), with an accurate prediction rate of 93 % during validation, was chosen for further interpretation.

Agricultural intervention scenarios

Four agricultural (food-based) intervention scenarios were analyzed by following the same procedure to calculate the energy, iron and zinc output from household-level crop–livestock production, household-level requirements (=input) and consequent output/input balances. We assumed successful adoption of practices or technologies across all 165 households resulting in: (1) a 30 % yield increase of landrace and bred potatoes; (2) a 20 % areal adoption of biofortified potato varieties with iron and zinc fresh-weight concentrations[1] twice as high as currently grown cultivars; (3) an addition of 1 male and 9 female guinea pigs in livestock production output; and (4) the combination of interventions 1, 2 and 3. For intervention 1, the 30 % yield increase was applied separately for household's landrace and bred potato areas, as these cultivar groups have different yield levels. For intervention 2, 10 % of landrace and 10 % of bred potato household-level areas were assumed to be planted with biofortified varieties. For intervention 3, an ideal male-to-female ratio of 1:9 was chosen for guinea pigs to reproduce and generate offspring of which 50 % would be destined for household consumption.

Results

Household and crop–livestock system characteristics

Table 2 summarizes household characteristics, and Fig. 2 shows household member distribution. Standard deviation values in total average cropping area elude to ample differences among households (Fig. 3). One extreme concerned two households that did not cultivate any crops, yet raised livestock and reported commerce and transportation as off-farm activities. On the other extreme, two households by far exceeded the average total cropping areas (2.4 and 2.8 ha). Households from the community of Ccasapata had the lowest average total cropping area out of the four communities: 5901 (±3460) m² compared to 7342 (±5662) m² in Chopccapampa, 7718 (±3851) m² in Sotopampa and 8399 (±4045) m² in Ccollpaccasa.

Production features by crop species are summarized in Table 3. The landrace potatoes were the most diverse

Table 2 Main household and crop–livestock system characteristics

Sample characteristics	
Number of households	165
Total number of household members	952
Demographic and socioeconomic characteristics	
Household size[a]	5.8 (±2.0)
Percentage of female household members (%)	51.2
Percentage of members 0–4 years old (%)	26.1
Percentage of members 5–10 years old (%)	20.4
Percentage of members 11–18 years old (%)	15.8
Percentage of members 19–35 years old (%)	27.4
Percentage of members > 35 years old (%)	10.3
Percentage of households with at least 1 migrant (%)	73.9
Number of months off-farm for migrating members[a]	1.6 (±1.7)
Percentage of households with local commerce as main activity (%)	17.6
Percentage of households with handicrafts as main activity (%)	32.1
Percentage of households with livestock as main activity (%)	63.6
Agricultural characteristics[a]	
Cultivated fields	9.1 (±3.3)
Crop species	6.0 (±1.5)
Animal species	3.9 (±1.5)
Tubers area (m²)	3605 (±2681)
Cereals area (m²)	2111 (±1496)
Legumes area (m²)	1523 (±1172)
Total cropped area (m²)	7239 (±4253)

[a] Mean (±SD)

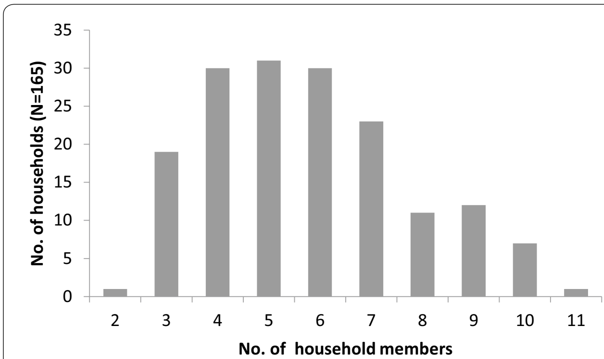

Fig. 2 Distribution of the total number of household members per household ($N = 165$)

[1] Fresh-weight, as opposed to dry-weight, iron and zinc concentrations were used because potato outputs were weighed in their raw, post-harvest state. No significant differences have been found between the iron and zinc concentrations of raw versus cooked potatoes [117, 118].

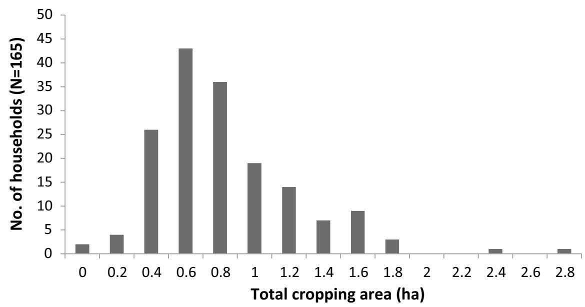

Fig. 3 Distribution of the total cropping area per household for the predominant agricultural season ($N = 165$)

Table 4 Species-based characteristics of livestock production ($N = 165$)

Livestock	Households raising (%)	Total no. of animals	
		Ave.	SD±
Cattle	78.2	2.6	1.6
Horse	49.7	1.4	0.6
Llama	12.7	5.8	4.3
Sheep	67.3	9.3	8.1
Pig	37.6	2.0	1.9
Poultry	80.6	4.3	3.5
Guinea Pig	63.0	7.0	5.5

crop in terms of the number of cultivars being grown, with one household growing as many as 160 different cultivars. Indeed high infraspecific diversity of the potato crop is a distinctive feature of Huancavelica region [75, 83, 92]. Olluco, mashua and oca cultivars—up to a maximum of 12, 14 and 10 per household, respectively—are frequently grown in close proximity to potato. Most households only plant a single variety of barley and oats. Among the legumes, one variety of lupine is commonly cultivated. Faba, with up to a maximum of 17 distinct cultivars grown at the household level, is common.

Households in the study site rise up to seven livestock species that serve multiple purposes (Table 4). Livestock species, except horses, are a source of food but are also used as mode of transport and for fertilizer, fuel, fiber, milk and cheese production. Yet households typically only slaughter animals on special occasions. Livestock is generally kept free-range, and herding is a common task of women and children. Use for home consumption in Huancavelica is occasional. Bigger livestock such as cattle and sheep represent an important asset that can be turned into cash.

Energy, iron and zinc balances under *status quo* management

Figure 4 shows household-level energy, iron and zinc balances. We excluded one outlier for compact visualization (164 total bars). The average energy, iron and zinc balances across all households were +10,826 kcal, +41 mg and +37 mg per day over the average basal household-level requirements. While the majority of households obtained sufficient energy from their crop–livestock systems to meet their requirements, the gap was wider for iron and zinc. In 13.9, 36.6 and 23.6 % of households, production output did not meet the household-level energy, iron and zinc requirements, respectively, under current crop–livestock management. We found household-level energy balances were highly correlated with iron ($r = 0.79$) and zinc ($r = 0.92$) balances ($p < 0.001$). Ninety-eight (out of 99) households who met both their iron and zinc requirements also met their energy requirements. Conversely, out of 142 households who met their energy requirements 98 (69 %) also met their iron and zinc requirements. Clearly, meeting

Table 3 Crop species production indicators at the household level ($N = 165$)

Crops	Households planting (%)	No. of fields		Field size (m^2)		Yield[a] (ton/ha)		No. of cultivars	
		Ave.	SD ±	Ave.	SD ±	Ave.	SD ±	Ave.	SD ±
Landrace potato	96.4	1.8	1.0	1323.1	983.8	14.7	5.3	5.7	4.0
Bred potato	85.5	1.2	0.4	885.6	614.4	23.1	11.3	1.1	0.8
Olluco	79.4	1.0	0.2	260.6	229.8	6.3	5.7	1.6	0.9
Mashua	71.5	1.0	0.1	241.5	240.7	9.1	8.5	1.2	0.6
Oca	23.6	1.0	0.2	220.1	197.7	7.6	7.0	1.8	1.2
Faba	90.3	1.4	1.1	571.1	469.2	1.7	1.3	2.5	1.5
Lupine	73.9	1.3	0.6	918.8	641.7	0.8	1.9	1.0	0.2
Barley	95.2	1.6	0.7	1066.7	667.3	2.3	1.9	1.0	0.2
Oats	68.5	1.2	1.1	724.7	579.7	1.7	1.9	1.0	0.0

[a] Yields for faba, lupine, barley and oats were calculated in their dry state

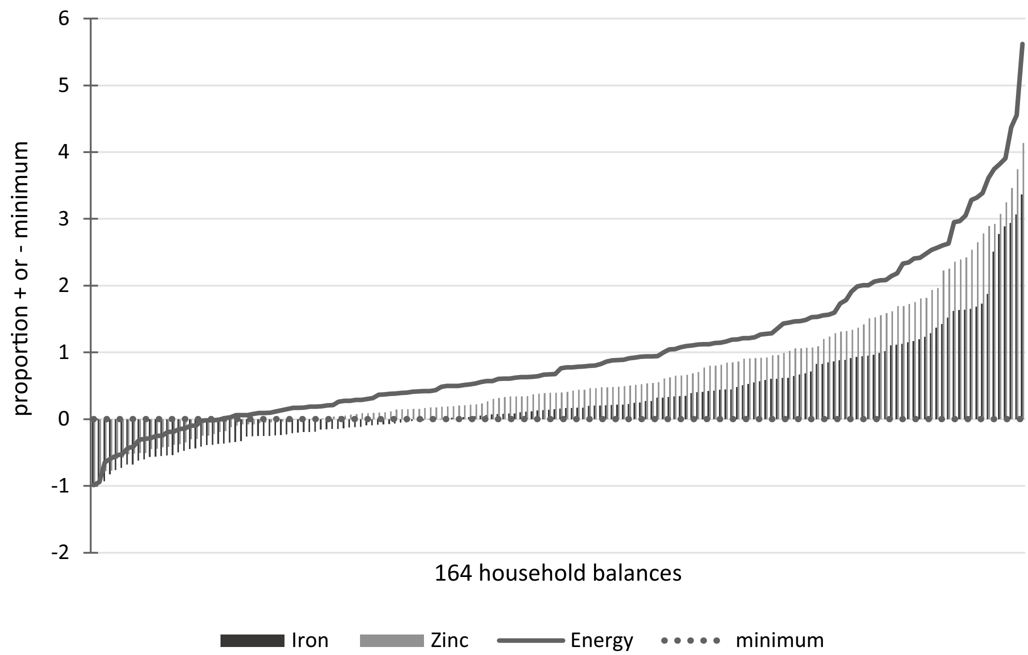

Fig. 4 Household-level energy, iron and zinc balances in ascending order and as proportions (+) or (−) of actual household requirements ($n = 164$). The *x-axis* ($y = 0$) represents basal household-level demand for full coverage

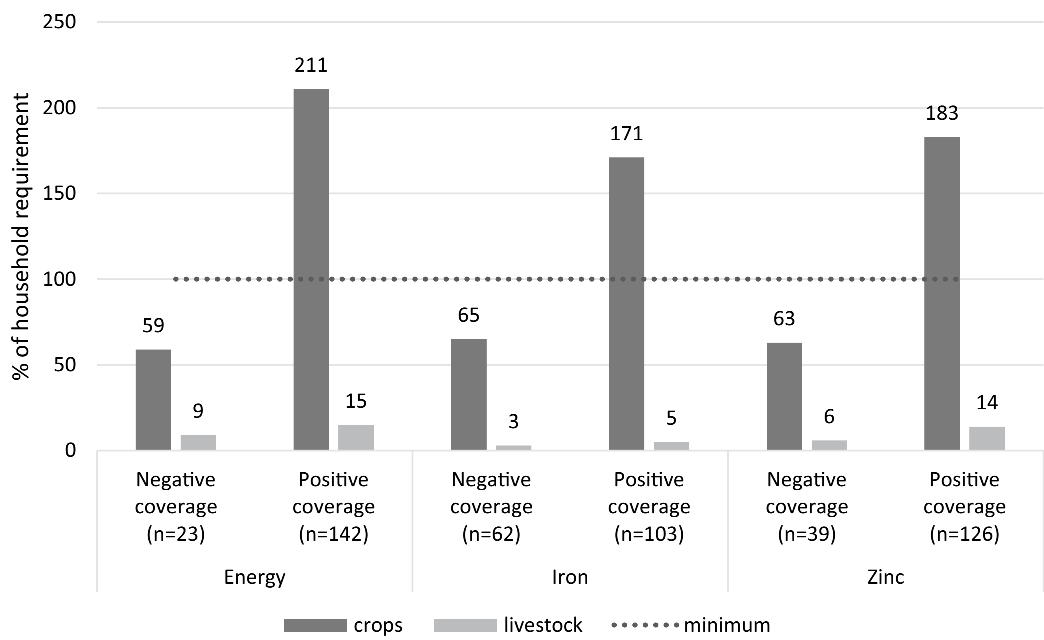

Fig. 5 Contribution of crop and livestock production to the actual energy, iron and zinc balance for households with a positive and negative coverage for each nutritional parameter. *Dotted line* ($y = 100$ %) represents basal household-level demand for full coverage

energy demands is more attainable than meeting essential micronutrients under current crop–livestock production systems.

Crop and livestock contribution to energy, iron and zinc requirements is presented as a proportion of household-level requirements (Fig. 5) for those households whose production systems did not meet minimum requirements (so-called negative coverage) and households whose production systems met or surpassed minimum requirements (so-called positive coverage). Livestock production contributed modestly to household energy, iron and zinc coverage. Overall, crops as compared to livestock accounted for 179, 122 and 144 % versus 13, 4 and 12 % of the energy, iron and zinc production output from agriculture, respectively, based on the average household-level balances. The PCA (Fig. 6) further indicated that individual crop outputs and per capita cropping areas for main staples (tubers, legumes, cereals) were strongly and positively correlated with the investigated parameter balances and together accounted for most of the variation observed in the dataset, in comparison with other variables such as those related to livestock and household that were also measured in this study.

Multiple regression analysis revealed that household size, landrace potato area (m^2), bred potato area (m^2), barley, faba and oats outputs (kg) significantly influence each of the balances (Table 5; Added-variable plots provided as Additional file 2). As expected, household size was a negatively correlated predictor across all models. This anti-correlation was also evident in the PCA, where the variable household size is placed in opposition to (all the) balances in the data space (Fig. 6). Household-level landrace and bred potato areas (m^2) and outputs (kg) were significantly correlated ($p < 0.001$) with respective household energy ($r = 0.78/0.65$) and zinc balances ($r = 0.58/0.55$), and less so with iron balances ($r = 0.38/r = 0.50$). Household-level barley output (kg) was significantly correlated ($p < 0.001$) with the iron ($r = 0.75$) and zinc balance ($r = 0.62$) of the households growing these crops, and less so with the household-level energy balance ($r = 0.48$). Faba was modestly correlated ($p < 0.001$) with iron ($r = 0.51$) and zinc balance ($r = 0.41$). Oats and lupine, although still important in terms of proportion of households who grow them and area coverage per household (Table 3), were not significantly correlated with energy, iron and zinc balance ($r < 0.35$). Mashua was moderately correlated

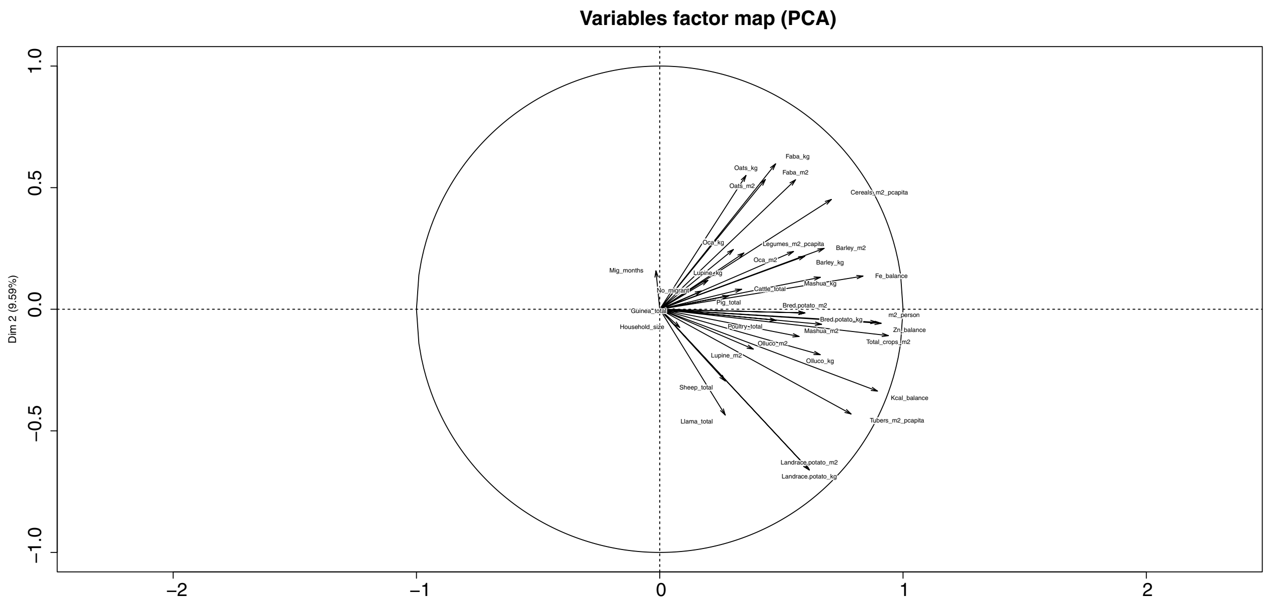

Fig. 6 PCA plot consisting of all the variables (35) measured in this study, showing their relative influence on the variation observed in the dataset, which is indicated as % on the first dimension (Dim 1) and the second dimension (Dim 2). This PCA also gives an indication of the grouping between all the variables measured. Variable labels: "Kcal_balance" = energy balance; "Fe_balance" = iron balance; "Zn_balance" = zinc balance; "Total_crops_m2" = total cropping area; "m2_person" = total cropping area per capita; "Tubers_m2_pcapita" = per capita area cultivated with tubers; "Cereals_m2_pcapita" = per capita area cultivated with cereals; "Legumes_m2_pcapita" = per capita area cultivated with legumes; "No_migrant" = number of household members migrating; "Mig_months" = number of months off-farm for migrating members. Livestock labels refer to total number of animals. Crop labels refer to total surface area in square meters (m2) and total outputs in kilograms (kg). Arrow length is proportionate to the contribution made by an individual variable to the variation in the dataset. Directionality relative to other variables illustrates the nature of correlations (positive or negative) among variables. Crop outputs and per capita cropping areas (tubers, cereals, legumes) are shown to not only be largely driving variation in the data space (*long arrows*) but to also be positively correlated to energy, iron and zinc balances (same direction). The fact that livestock and household (size, migration) parameters are placed relatively far from the remaining variables further suggests that crop parameters have the strongest and most influential relations to household balance outcomes

Table 5 Regression coefficients, standard errors (SE), *p* values and significance under three models for energy, iron and zinc balance ($N = 165$)

Predictor	Coefficient	SE	*p* value	Sig.
Energy balance				
Intercept	519,107.16	105,978.64	0.000	***
Household size	−809,849.58	18,288.05	<2e−16	***
Landrace potato (m^2)	1720.79	18.92	<2e−16	***
Bred potato (m^2)	2311.17	38.56	<2e−16	***
Barley (kg)	3957.88	168.97	<2e−16	***
Faba (kg)	2708.56	357.95	0.000	***
Lupine (kg)	2430.56	311.17	0.000	***
Oats (kg)	2992.72	413.65	0.000	***
Cattle[a]	173,366.37	20,712.54	0.000	***
Adjusted R^2	0.992			
Iron balance				
Intercept	6100.00	2600.00	0.018	*
Household size	−11,000.00	440.00	<2e−16	***
Landrace potato (m^2)	5.80	0.48	<2e−16	***
Bred potato (m^2)	13.00	0.93	<2e−16	***
Barley (m^2)	3.10	1.10	0.004	**
Mashua (kg)	19.00	7.70	0.017	*
Barley (kg)	98.00	5.10	<2e−16	***
Faba (kg)	66.00	8.70	0.000	***
Oats (kg)	31.00	10.00	0.003	**
Adjusted R^2	0.943			
Zinc balance				
Intercept	4677.76	604.52	0.000	***
Household size	−5028.19	104.29	<2e−16	***
Landrace potato (m^2)	5.45	0.11	<2e−16	***
Bred potato (m^2)	7.07	0.22	<2e−16	***
Barley (kg)	31.85	0.96	<2e−16	***
Faba (kg)	27.37	2.03	<2e−16	***
Lupine (kg)	45.66	1.76	<2e−16	***
Oats (kg)	39.62	2.35	<2e−16	***
Sheep[a]	255.16	25.70	<2e−16	***
Adjusted R^2	0.987			

[a] Livestock output is in number of animals

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

($p < 0.001$) with iron balance ($r = 0.59$). Our regression models showed that cattle and sheep made a positive and significant contribution to energy and zinc balances, respectively. In terms of iron, livestock sources were not detected as significant.

In Table 6, we show results for the logistic regression model where the binary dependent variable was the odds of a household meeting energy, iron and zinc requirements given a set of predictor variables. Surprisingly, household size was not a significant predictor of the odds ratio of a household meeting its energy, iron and zinc requirements through family farming. The odds of a household meeting its energy, iron and zinc basal requirements decreases by a factor of 0.945 (not significant) for every additional family member, whereas it significantly increases by a factor of 1.014 ($p < 0.001$) for every square meter of tubers grown, a factor of 1.010 ($p < 0.01$) for every square meter of legumes and a factor of 1.004 ($p < 0.05$) for every square meter of cereals. The highest contribution to tubers area comes from landrace potato, bred potato and mashua. Legumes area is mostly represented by lupine and faba, while cereals area is mainly attributed to barley. This analysis suggests that the likelihood of a household achieving all its basal balance requirements is positively influenced by increasing its per capita cultivated areas for tubers, legumes and cereals. Furthermore, these results are in agreement with the PCA, which indicates that per capita cropping areas ("Tubers_m2_pcapita," "Cereals_m2_pcapita," "Legumes_m2_pcapita" in Fig. 6) make a larger relative contribution to variation and are positively correlated with energy, iron and zinc balances ("Kcal_balance," "Fe_balance," "Zn_balance" in Fig. 6).

Table 6 Balanced (optimal) model of logistic regression with coefficients (odds ratio), standard errors (SE), *p* values and significance levels ($N = 119$)

Predictor	Coefficient[a]	SE	*p* value	Sig.
Intercept	0.001	2.398	0.005	**
Household size	0.945	0.164	0.732	
Tubers area per capita (m^2)	1.014	0.004	0.001	***
Cereals area per capita (m^2)	1.004	0.002	0.036	*
Legumes area per capita (m^2)	1.010	0.003	0.001	**

[a] Odds ratio of household meeting all nutritional parameters (energy, iron, zinc)

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Household differences behind the nutrition balances

In the previous sections, we presented the factors that were most strongly associated with balances in terms of a household´s crop–livestock production system meeting its energy, iron and zinc requirements. In light of those findings, we summarize the main differences between households with a negative coverage whose production system did not provide sufficient output ($n = 21$), and households with a positive coverage whose production system met demand or provided a surplus ($n = 98$) for energy, iron and zinc (Table 7). Why did certain households cover their needs, while others didn't? Landrace and bred potato outputs, followed by cereals like barley and legumes like faba, represent the bulk of households'

Table 7 Summary of differences for households with a positive and negative coverage from family farming for all three parameters (energy, iron and zinc)

Variables	Households with positive coverage for energy, iron and zinc ($n = 98$)				Households with negative coverage for energy, iron and zinc ($n = 21$)				Mean diff.
	Ave.	SD±	Min.	Max.	Ave.	SD±	Min.	Max.	*p* value
Household size	5	2	3	10	6	3	2	11	0.175
Landrace potato (kg)	3968	3157	0	20,213	1370	1353	0	3675	0.000
Bred potato (kg)	2519	2557	0	20,213	750	997	0	3609	0.000
Mashua (kg)	133	151	0	900	47	60	0	180	0.000
Olluco (kg)	127	148	0	900	32	26	0	60	0.000
Oca (kg)	32	67	0	360	5	22	0	100	0.002
Barley (kg)	394	249	0	1320	103	118	0	360	0.000
Oats (kg)	80	97	0	480	33	53	0	210	0.003
Faba (kg)	132	133	0	630	37	50	0	160	0.000
Lupine (kg)	64	136	0	1200	20	25	0	84	0.003
Tubers area per capita (ha)	0.08	0.06	0.02	0.38	0.02	0.01	0	0.04	0.000
Cereals area per capita (ha)	0.05	0.03	0.004	0.16	0.01	0.01	0	0.05	0.000
Legumes area per capita (ha)	0.04	0.03	0	0.17	0.01	0.01	0	0.05	0.000
Total crop area (ha)	0.88	0.44	0.24	2.78	0.31	0.21	0	0.78	0.000
Total area per capita (ha)	0.17	0.08	0.05	0.56	0.05	0.02	0.01[a]	0.10	0.000
People per ha	7	3	2	20	29	37	10[a]	182	0.000
Cattle no.	2	2	0	9	1	1	0	5	0.021
Sheep no.	7	8	0	41	2	3	0	12	0.000
Llama no.	1	3	0	18	0	1	0	5	0.050
Pig no.	1	2	0	13	0	1	0	2	0.001
Poultry no.	4	4	0	30	2	2	0	5	0.000
Guinea pig no.	5	5	0	29	3	3	0	10	0.035
Migrants per household	1	1	0	3	1	1	0	3	0.602
Months migrating	1.23	1.56	0	12	0.81	0.93	0	3	0.110
Local commerce main act[b]	(%)	15.3			(%)	23.8			
Handicrafts main act[b]	(%)	34.7			(%)	19.0			
Livestock main act[b]	(%)	63.3			(%)	42.9			

[a] Does not include 2 households without cropping areas

[b] Categorical variables calculated as percentage of households in each group (positive/negative coverage)

production and source of energy, iron and zinc. This is a consequence of cropping areas and yield levels. Households with a positive coverage, or those whose production systems met minimum parameter requirements, had significantly higher cropping areas by individual species and as grand total. Household size was not significantly different between households with positive and negative coverage ($p = 0.175$). The opposite was true for cultivated surface area per household member (area per capita) which was significantly different ($p < 0.001$). Household size was generally large across both groups, but households with a negative coverage for energy, iron and zinc from family farming were constrained by small cropping areas and consequent limited production outputs per household member. In that context—unavailable land—adding one more mouth to feed to household-level crop–livestock production will result in a negative nutrition balance, as should be expected and was previously made evident through the relations of variables in the PCA and regressions.

There is some overlap in the range of total cropping areas of households with a positive and negative coverage of energy, iron and zinc demands from family farming. However, their total areas and per capita areas by staple group (tubers, cereals, legumes) point to significantly different means. The variable "people per hectare" also reveals a striking difference for households with a positive and negative coverage. Factors such as differences in yield and available household labor can affect the household-level production output per area unit to sustain more people.

Although livestock sources of energy, iron and zinc contributed modestly to households' overall balance, differences between households with positive and negative coverage were nonetheless significant for stocks of sheep, poultry and pig. This suggests that in addition to land as a household asset, households with a positive coverage had access to other forms of assets allowing them to sustain more livestock, such as time, labor, grazing area, feed or monetary resources. Compared to households with negative coverage, a greater proportion of households with positive coverage reported livestock raising as a main activity. Some households with a positive coverage compensated the absence of one crop (min. values of 0 in Table 7) with another, thus maintaining an overall positive balance. For instance, one family did not cultivate landrace potatoes but allocated large areas to bred potato (3750 m^2) and barley (3125 m^2). On the other hand, two households with a negative coverage did not cultivate any crops but reported employment in commerce (local store) and transportation (inter-provincial driver). Thirty-five percent (35 %) of households with a positive coverage were involved in artisanal (woven) crafts as source of income, compared to 19 % of households with negative coverage. When non-agricultural activities are able to complement households' maintenance of their crop–livestock portfolios, nutrition balances can shift positively through food access. Number of household migrants and months off-farm were not significantly different between households with a positive or negative coverage (p values of 0.602 and 0.110 in Table 7), nor did they correlate significantly to households' balance outcomes ($r < 0.11$ and $p > 0.15$ across all balances). This may suggest a lack of reinvestment of migration-based income in production and on-farm nutrient provision. However, our limited sample, lack of precise income data and of dietary measurements of energy, iron and zinc coverage via other, off-farm routes of food access do not allow us to further pursue such potential associations.

Nutrition balances under intervention scenarios

Current practices (=*status quo*) and development intervention scenario outcomes on household-level energy, iron and zinc balanced are compared in Table 8. A 30 % yield increase of potato reduced the total proportion of households with a negative coverage for energy, iron and zinc from family farming by 4.8, 7.9 and 7.2 %, respectively. While the balance deficit decreased across the three nutrition parameters, they remained negative, being insufficient to overcome the overall nutrition gap. A 20 % areal adoption of biofortified potatoes did not modify average energy balance, as it solely involved iron and zinc. It resulted, however, in a 3.7 and 3.6 % reduction of the total proportion of households with a negative coverage for iron and zinc, while their balances only modestly increased. The introduction of 10 additional guinea pigs (and offspring during one season) for each household has minimal effect on nutrition outcomes. Only an additional 1.8 and 1.2 % of households will shift to basal iron and zinc coverage, while average balances remain negative at nearly the same level as *status quo*.

Considering energy, iron and zinc (all at once), the combined strategy is the most effective. However, negative household balances are still not overcome. Of the first three scenarios seen in isolation, a 30 % yield increase of potato was most impactful in terms of reducing the energy, iron and zinc deficit. Nevertheless, the combined scenario is probably a best case scenario of what development agencies can achieve even though it is still far from eradicating deficits.

Table 8 Energy, iron and zinc balance outcomes in *status quo* and intervention scenarios

Scenario	% Households with negative coverage ($n = 165$)			Average household balance per day[a] ($n = 21$)		
	Energy	Iron	Zinc	Energy (kcal)	Iron (mg)	Zinc (mg)
Status quo	13.9	37.6	23.6	−3903	−90	−34
1. Potato yield increase[b]	9.1	29.7	16.4	−1999	−77	−27
2. Biofortified potatoes[c]	13.9	33.9	20.0	−3903	−87	−32
3. Microlivestock[d]	13.9	35.8	22.4	−3858	−89	−33
4. Combined (1 + 2 + 3)	9.1	26.1	15.2	−1954	−77	−25

[a] Calculations based on households with negative coverage targeted by interventions. Minus 484 (−) sign indicates deficit

[b] 30 % yield increase in bred and landrace potatoes

[c] Biofortified potatoes adopted on 20 % of potato cropping area

[d] Introduction and adoption of guinea pigs: 1 male and 9 females

Discussion

Nutrient balances under current crop–livestock systems

Food security encompasses four essential dimensions: availability, access, utilization and stability [93, 94]. Fundamental in the availability dimension is not only the quantity but also the nutritional quality of foods [95]. We have conducted an in-depth analysis of the availability pillar of food security rather than the access, utilization and stability dimensions. Particularly, we have focused on the capacity of contemporary high-altitude smallholder production systems to cover the energy, iron and zinc requirements at the household level. Our results show that 86 % of households were able to cover basal energy requirements through on-farm production. Yet, the farming system's iron and zinc output would not meet basal household-level demand for 37 and 24 % of households. Considering energy, iron and zinc simultaneously, only 59 % of households in the study site would be able to cover their requirements based on agricultural output.

The capacity of family farming to provide households with their basic nutritional needs varies widely among households. Contrasting positive and negative nutrition balances at the household-level offer valuable lessons. Firstly, differences in household-level cropping area ultimately determined production outputs. Households with fewer fields and smaller size fields are less likely to meet basal energy, iron and zinc requirements. This clearly indicates the limits to the carrying capacity of farming systems to potentially cover the nutrient demands of the households who depend on family farming as a means of (partial) self-sufficiency. Also, the cultivated area available to households and production outputs are a consequence of land access and the intensive on-farm labor implicit and fundamental in these systems, which is not equally available to households [96, 97]. Secondly, household size, although not directly correlated to energy, iron and zinc balances, influences the capacity of crop–livestock systems to cover requirements among households already strained by limited land availability. We demonstrated this association in our multiple regression models where household size was a significant predictor of the household-level energy, iron and zinc balance. In the logistic regression model, although not significant, the odds of a household meeting its energy, iron and zinc requirements also decreased with increasing household size.

Diversity in agricultural production has been associated with nutritional diversity and improved dietary quality, especially in the context of smallholder farming systems [98–102]. While overall crop and livestock production diversity is high in the study area, many households would not be able to cover the basal micronutrient (iron and zinc) demand through self-production. On-farm species richness does not, according to several studies, linearly translate into food security, dietary diversity and improved nutrition [103–105]. In addition to the effects of landholding and household size, the actual energy and micronutrient composition of foods determined household balance outcomes. Importantly, landrace and bred potatoes, faba and barley were highly influential in the context of the cropping portfolios we have examined, in terms of their energy, iron and zinc provisioning capabilities across all households. The opposite is true of animal-based foods, which are encouraged as part of a diverse and nutrient-dense diet that makes essential micronutrients like iron and zinc readily available to people [106–109]. In this study, we have shown that, even for households with positive coverage, the contribution of livestock to energy, iron and zinc demands is modest compared to crop-based energy, iron and zinc. Nevertheless, the significant differences between households with positive and negative coverage in terms of animal stocks underscore assets other than food that are likely available to households with a positive coverage, such as labor, grazing areas, feed or cash once they are sold (i.e., cattle, sheep).

Nutrient balances under intervention scenarios

Keeping cropping areas and household sizes the same, even the most commonly promoted intervention scenarios were not sufficient to close the gap in energy, iron and zinc provision from family farming. The mixed intervention strategy that combined yield increase and biofortification of potatoes with the introduction of microlivestock (i.e., guinea pig) reduced the percentage of households with a negative coverage from family farming to a minimum of 9.1 % for energy, 26.1 % for iron and 15.2 % for zinc. On its own, a bred and landrace potato yield increase of 30 % led to results that were comparatively low (9.1, 29.7, 16.4 %, respectively). Promoting management options for a higher production output per area unit for the main staple crops has a higher probable impact on raising the energy, iron and zinc output from the system compared to biofortification or promotion of microlivestock given the intervention options we have examined. Nonetheless, nutrient provision from agricultural interventions underlying food-based approaches to nutrition will ultimately depend on actual land availability, which is already strained in the region of Huancavelica where the research was conducted. It is precisely due to limited production capacity, particularly small and fragmented land holdings, that common interventions aimed at yield increases, biofortification and/or microlivestock promotion do not significantly shift realities. Households with a negative coverage of energy, iron and zinc from their farm have fewer production assets (land, livestock). Proportionally, the limited scale of new technologies or interventions they adopt as compared to those households with more sizeable assets and surplus production will only contribute marginally toward improving their nutrition situation. In addition to the assumption that smallholder households targeted by agricultural interventions toward food-based approaches to nutrition have the land capacity to attain a positive coverage from family farming, another factor that may be overlooked is labor scarcity and the increasing shift of labor responsibilities on women, who are also primary caregivers for infants [20, 26, 100]. In the context of migratory patterns and intensifying agricultural workloads for women, interventions may actually undermine household nutrition. From the standpoint of land and on-farm labor availability and capacity, the gap in energy, iron and zinc provision from agriculture among the most resource-poor households is likely to persist, unless development organizations seek complementary ways of improving food security and nutritional outcomes, for example, through combining agricultural interventions with off-farm employment opportunities.

Study limitations

In order to pursue the analysis that we have presented in this study, assumptions were necessary. Crop production outputs were calculated without considering potential post-harvest losses, sales or additional, off-season production. Livestock were deemed available for consumption assuming that households would not sell or save their animal stocks as reserves. In the context of Chopcca crop–livestock systems, households generally raise their animals for uses other than consumption or prefer to sell them for cash thereby increasing their purchasing power to access other goods. Thus, even under the conservative reproductive rates that we derived, our approximations of livestock production to nutrient output reflect an ideal consumption scenario. The energy, iron and zinc content of crop and livestock output was assumed to remain stable and available to households without taking into account preparation, cooking or processing losses that could affect the actual micronutrients available for consumption.

Our study limited itself to the detailed analysis of energy, iron and zinc output from family farming and its contribution to meeting household-level demands. It thus does not deal with actual food intake, which is beyond the scope of the research here reported.[2] We used DRI assuming low bioavailability for iron and zinc, considering the local dietary patterns. This may have been an underestimation in some cases, although the presence of animal source foods (medium and high iron and zinc bioavailability) in the diet was infrequent and minimal. How the production of energy and micronutrients is actually allocated at the intra-household level, and whether or not they reach the most vulnerable household members (i.e., infants) is beyond the scope of this study.

Other factors that we have not explored, such as off-farm foods, accessible markets, labor migration and increasingly non-agricultural and diversified incomes, are important drivers of changing food systems and smallholder diets [23, 103, 105]. In particular, household-level information about off-farm food purchases and on-farm produce sold would have allowed us to quantify households' energy and micronutrient availability from on- and off-farm sources more accurately. Considering that the primary research objective was to determine crop–livestock systems' energy and micronutrient coverage solely based on household-level production, our study has been able to make a significant advance to inform agricultural strategies underlying food-based approaches to nutrition. As an important next step, we recommend investigating an additional model to characterize the nutrition inputs available to smallholder households as off-farm contributions via agricultural income generation and off-farm employment.

Conclusion

Agricultural interventions supporting food-based approaches to nutrition are deployed in regions most affected by high rates of undernutrition, such as Huancavelica in the central Andes of Peru, under two underlying assumptions: (1) Smallholder agriculture has the capacity to provision household-level energy and micronutrient needs; (2) innovations can make a substantial difference among the most vulnerable households. In this study, we have demonstrated that both assumptions can either be positively reaffirmed or rejected, depending to a large extent on the size of land holdings and family size. While all households studied managed typical smallholder farming systems, not all family farms had the carrying capacity to supply sufficient energy, iron and/or zinc for the households that depend on them. We demonstrate that for poorer households, the current practices and even improvement in productive capacity do not satisfy household-level demand for energy, iron and zinc. Yet, the research also validates the sufficiency of the

[2] Assessment of daily food and nutrient intakes in the children of these families, using the 24-hour recall methodology, is addressed in a different study as part of the same McKnight Foundation project [74, 81].

nutrient and energy output conferred by agriculture and the strategy of enhancing local production for resource-sufficient households.

A negative coverage of iron and zinc from family farming is a reality for 21 % of the households studied. This level of undercoverage from farming is not significantly reduced by the most commonly promoted interventions, precisely because households with negative coverage do not have the assets (land, labor) to generate a big enough effect from the key innovations. Balances for production output *versus* household demand for energy, iron and zinc remain negative among the most resource-strained households across all intervention options. As has been assessed in previous studies, well-intentioned interventions aimed at enhancing agricultural production toward better food-based nutrition do not necessarily translate into positive outcomes [110–112].

For the most resource-poor households, current practices and an enhancement in productive capacity do not satisfy energy and essential micronutrient coverage from the family farm. Conversely, more resourceful households possess sufficient land to meet, if not surpass, their energy, iron and zinc requirements via self-production. Importantly, these households manage cropping areas that are on average 2.8-fold larger compared to households with negative coverage. Further, these households own more livestock which, if not directly consumed, they can maintain as capital and future liquid assets. Such sources of modest income, in addition to that provided through off-farm employment, could in turn be enhancing the crop productivity of the households with a positive coverage for energy, iron and zinc from family farming through purchases of agricultural inputs (i.e., fertilizer, seeds). Access to agricultural and mixed livelihood strategies that include the cultivation of key staples, modest livestock reserves and non-agricultural sources of household income are important conditions for smallholder farmers to meet household-level energy and micronutrient requirements.

Crop and livestock production systems are still an essential part of a dynamic and evolving Andean food system. As consumption patterns, sources of food, off-farm income strategies and markets are changing, the on-farm provisioning of energy and micronutrients from agriculture continue to be important [105, 113, 114]. Yet, non-traditional livelihood activities in the rural Andes, part-time farming and feminization of agriculture are also challenging perceptions of subsistence agriculture and smallholder reliance on agriculture-centered options alone [22, 23, 25, 26, 115, 116]. In order for future research and interventions to effectively target nutrition outcomes, we recommend a mixed approach and attention to support smallholders' food and nutrition security via the opportunities offered by other routes of income diversification and food acquisition.

Additional files

Additional file 1. ROC curve legend: Data from 75 % of the households that failed or passed the nutritional requirement criterion (see main text for further details) were used to develop and train the logistic regression model. The remaining 25 % was used for validation purposes. Red line corresponds to the area under ROC curve (0.96) obtained during validation on the dataset that was balanced using the ROSE algorithm (see Research methods section for details), while the black line corresponds to the area under ROC curve (0.98) obtained from the raw dataset. Notice the similarity between the area under ROC curve values, indicating that the variables selected in the selected logistic regression model are sufficient to significantly differentiate households into pass or fail subclasses.

Additional file 2. Multiple regression added-variable plots legend: Added-variable plots let us know the contribution of a particular regressor by taking into account the effect of the other independent variables (regressors) in the model. The residuals from the regression of the response on a subset of the regressors are plotted versus the residuals from the regression of the new regressor on the same subset of regressors. In our multiple regressions, our responses were energy balance (Kcal_balance); iron balance (Fe_balance); zinc balance (Zn_balance). Taking one of these response variables as an example, if we say that energy balance (Kcal_balance) is related to household size (Household_size), how does this relationship change when landrace potato area (Landrace_potato_m2) is added (second plot from top in A column), and then how does this relationship between household size (Household_size) + landrace potato area (Landrace_potato_m2) change when bred potato area (Bred_potato_m2) is added (third plot from top in A column), and so forth until all regressors studied in the model have been progressively added. The same procedure follows for iron balance (B column) and zinc balance (C column). The advantage of these added-variable plots is that they offer a tangible visualization of each model and the relationships between each of the balances (energy, iron, zinc) and their eight (8) predictors. For the slope coefficients corresponding to each of the subplots, please refer to Table 5 ("regression coefficients, standard errors (SE), *p* values and significance under three models for energy, zinc and iron balance ($N = 165$)") in the manuscript.

Abbreviations

AIC: Akaike information criterion; BMR: basal metabolic rate; DRI: daily recommended intake; FAO: Food and Agriculture Organization; IIN: Instituto de Investigacion Nutricional; KCAL: kilocalories; MG: milligrams; NGO: non-governmental organization; PCA: principal component analysis; ROC: receiver operating characteristic; SD: standard deviation; UNU: United Nations University; WHO: World Health Organization.

Authors' contributions

SDH conceived the study. AA led its development, performing the data analysis, interpretation and preparation of the manuscript. HCK provided guidelines on foods' energy and micronutrient contents and human requirements. MS, RC and EO designed the household surveys, coordinated implementation and collected field data. RC and EO supported with crop and livestock data interpretation. DB performed statistical analyses and revised results interpretation. SDH contributed to writing the manuscript. HCK and MS reviewed and made editorial comments of the manuscript draft. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and material
The data that support the findings of this study are available in the Open Science Framework repository "Chopcca agri-nutrition": https://osf.io/wgtqr/.

Ethics approval and consent to participate
The study received ethics approval from the Research Ethics Committee of the Instituto de Investigación Nutricional (IIN). Informed consent was given verbally by each research participant prior to the application of any research procedures (survey).

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