

Drivers of household food availability in sub-Saharan Africa based on big data from small farms

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We calculated a simple indicator of food availability using data from 93 sites in 17 countries across contrasted agroecologies in sub-Saharan Africa (>13,000 farm households) and analyzed the drivers of variations in food availability. Crop production was the major source of energy, contributing 60% of food availability. The off-farm income contribution to food availability ranged from 12% for households without enough food available (18% of the total sample) to 27% for the 58% of households with sufficient food available. Using only three explanatory variables (household size, number of livestock, and land area), we were able to predict correctly the agricultural determined status of food availability for 72% of the households, but the relationships were strongly influenced by the degree of market access. Our analyses suggest that targeting poverty through improving market access and off-farm opportunities is a better strategy to increase food security than focusing on agricultural production and closing yield gaps. This calls for multisectoral policy harmonization, incentives, and diversification of employment sources rather than a singular focus on agricultural development. Recognizing and understanding diversity among smallholder farm households in sub-Saharan Africa is key for the design of policies that aim to improve food security.

food security | smallholder farmers | yield gap | resource scarcity | farm size

Achieving sustainable food security (i.e., the basic right of people to produce and/or purchase the food they need, without harming the social and biophysical environment) is a major challenge in a world of rapid human population growth and large-scale changes in economic development (1). In sub-Saharan Africa (SSA), production on smallholder farms is critical to the food security of the rural poor (2) and contributes the majority of food production at the national level. National policies and local interventions have profound impacts on the opportunities and constraints that affect smallholders (3). However, policy frameworks that aim to improve food security and rural livelihoods in the developing world face many uncertainties and often fail (4).

The formulation of effective policies needs adequate information on how different options affect the complex issues surrounding food security and sustainable development. A complication in generating such information is the large diversity within and among smallholder farming systems. Agroecological conditions, markets, and local cultures determine land use patterns and agricultural management across regions, whereas within a given region, farm households differ in many ways, including resource endowment, production orientation and objectives, ethnicity, education, past experience, management skills, and in the farm households' attitude toward risk. Policies by their nature have to be widely applicable, but recognizing this diversity in farm households is key to designing more effective policies to help poor farmers (5). Understanding the main drivers of

household diversity and their relationship with livelihood strategies can help to better codesign and target agricultural innovations (6).

In this study, we brought together cross-sectional farm household characterization data from 93 sites in 17 countries of SSA (Fig. 1). Such a large database provides an immensely rich resource to derive descriptions linking indicators of food security and land use to the socioeconomic and biophysical environment of the smallholder farmers. We use these data to develop a simple farm household performance indicator (Fig. 2) that is robust and can be calculated based on the household information collected in different surveys. We hypothesized that a few simple but important household characteristics can be used to tease apart the large diversity in farm households and farming systems, thereby leading to an improved understanding of the main drivers of the complexity in household functioning and that these characteristics can be used predictively to inform policy options.

Results

The Dynamics of Food Availability. The importance of different household activities changed from households with insufficient food available to those households with ample food available across the whole dataset (Fig. 3*A* and *B*). Households that had insufficient food available obtained their energy mainly from the

Significance

We collated a unique dataset covering land use and production data of more than 13,000 smallholder farm households in 93 sites in 17 countries across sub-Saharan Africa. The study quantifies the importance of off-farm income and market conditions across sites differing strongly in agroecology and derives generally applicable threshold values that determine whether farm households have enough food available to feed their families. These results show there is a strong need for multisectoral policy harmonization and incentives and improved interconnectedness of people to urban centers and diversification of employment sources, rather than a singular focus on agricultural development of smallholder farmers in sub-Saharan Africa.

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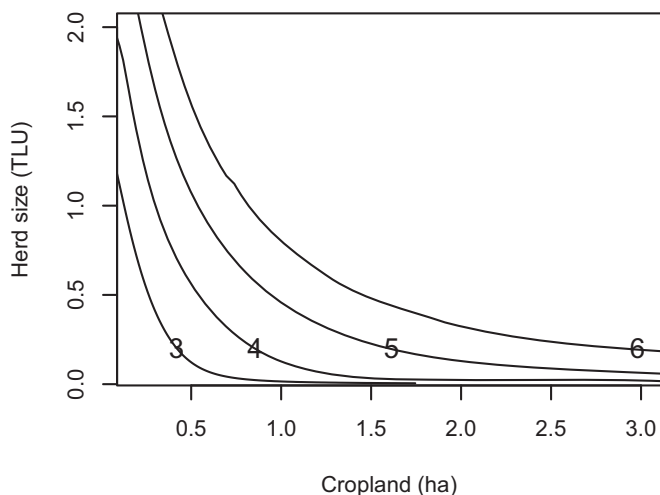


Fig. 5. Predicted FA threshold curves using the ANN with cropland, livestock (in TLU), and family size (in MAE) as inputs. Different curves are the threshold values at different family sizes from 3–6 MAE. Households with productive resources larger than the values determining the curve corresponding to their size in MAE equivalents are predicted to have enough food available to feed the family.

income has been shown to be a more important part of the livelihood of the poorest farmers (13), but our analyses, in which consumption of self-produced crop and livestock products is valued highly in calorie intake terms, show the opposite. A wide body of literature (e.g., refs. 14–16) showed that off-farm activities are a key source of social and economic stratification in rural areas (i.e., the better-off households tend to have access to the “better paid” nonfarm incomes, whereas the poorer farmers can only work as seasonal laborers on other farms in the region). Separate analyses based on the AFRINT (Africa Intensification) surveys showed that half of the farm households had no access to nonfarm income (16), so nonfarm income is not a pathway to food security available to all.

Simple Models and Indicators Needed for Targeting and Upscaling Policy and Development. We developed a simple response model that explained 33% of the calculated variation in the agriculture based FA indicator (so excluding off-farm income). Based on the number of livestock and the size of the household, a threshold value of land size could be defined, above which a smallholder farm is likely to be able to produce enough food and cash to feed the family. This is a powerful minimodel, because all three variables can be easily and rapidly collected for large numbers of households, in contrast to variables like productivity, consumption, and sales, which need detailed survey instruments and often display high variability and imprecision. Despite all of the approximations (hypotheses of the model, problem of merging datasets, simplicity of the analysis, limited number of predicting variables) and noise in the data, our model predicted correctly the FA status of 72% of the households (Fig. 5). The relationships in Fig. 5 were strongly affected by market access. When farmers have good market access, the size of the farm needed to produce and/or purchase enough food to feed the family secure can be small (Fig. 6). With good market access, farmers are able to generate cash through the production of high-value crops alongside a base supply of food crops, and buy the food they need. This observation confirms earlier findings (17) on farmers intensifying with cash crops as a result of higher relative factor prices in densely-populated areas with good market access and suggests that indeed Boserup’s endogenous intensification of farming systems in response to mounting land constraints can be found in our data (18, 19).

Our results show that, when focusing on FA (a key indicator of food security), a substantial part of the smallholder farmer population in Africa will face large difficulties in reaching a sufficient level of FA given their small farm sizes. This is a critically important finding given that around 80% of the smallholder farms in SSA are now smaller than 2 ha (20, 21). However, we also show that many could potentially increase FA sufficiently to feed the family on relatively small parcels of land through intensification practices involving cash crops and the use of livestock (e.g., ref. 22). This scenario is only possible if market access is ensured and overproduction does not depress prices of the farmers’ produce. Most of the farm households in our database do not have good market access, and therefore their farm size and livestock-holding thresholds are still very important, as shown in the average response threshold of Fig. 5. Current trends in farm size development in SSA are strongly negative in many countries (22, 23), making the future of smallholder farming bleak in many places unless market access can be ensured (24).

More Land Does Not Automatically Mean More Food Is Available Throughout SSA. The saturated FA—land size curve of Fig. 5 is caused by a decline in productivity per unit land (expressed in kcal per ha) when land sizes increase in the overall dataset. More detailed analyses presented in Fig. S3 show that this decline in land productivity with increased land holdings per farm was visible across all datasets available from SSA but also occurred within regions with contrasting agroecological and socioeconomic conditions. Per region, the range of cropland holdings was different, but across these different ranges, land productivity systematically declined with an increase in cropland holding. This finding supports the inverse land size productivity relation that has been found in many studies for smallholder farmers (25, 26). Recent studies qualify this relationship (27), showing that medium size farms are most efficient per unit area. The results in Fig. 5 change when the environmental constraints are taken into account (Fig. 6), and these results indicate that the inverse land size productivity relation is less severe in land-constrained sites with market access. The relationship between our FA indicator and cropland size is almost flat in sites where there is no land

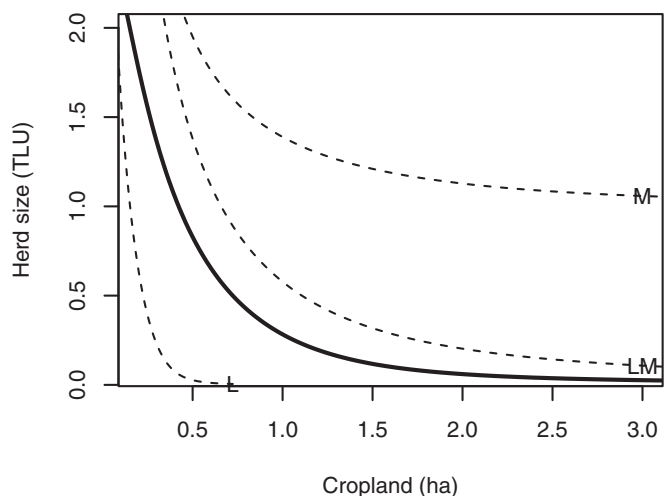


Fig. 6. The predicted FA threshold curves of the ANN model with cropland, livestock (in TLU), and family size expressed in MAE as inputs, together with the environmental constraint variables (for an explanation, see *Methods*). The bold line shows the average response and threshold curves (as in Fig. 5 but now for a family size of 4.4 MAE). The dashed lines show thresholds for some contrasting constrained environments: land and market constrained environment (LM) (18% of households), land constrained (L) (11% of households), and market constrained (M) (10% of households).

constraint and where there is no market access (e.g., in semiarid regions with low population densities), illustrating that the only way to become food secure in those sites is through livestock holdings in the face of an extremely severe inverse land size productivity relation (Fig. 6; also see Figs. S3 and S4).

Targeting More Than Agricultural Development Is a Necessity. The results of these analyses can help with the targeting of food policies because the results quantify the importance of different on and off-farm activities to FA, and the importance of market access on the potential of farming systems to intensify. The role of off-farm income and market access clearly shows that rural development in SSA has to be more than closing yield gaps and agricultural development per se. Connecting people to urban centers and generating other employment sources will directly affect food security in a manner that boosting production cannot (see also 12, 15). As discussed earlier, farmers start selling produce at levels below fulfilling food self-sufficiency, and increasing productivity of food crops will only lead to substantial improvement in food security if cash crops and intensified livestock production can take place, both needing good market access (17, 28, 29).

Our approach is based on farmer-reported data, with all of its constraints and limitations (30, 31). Except for the off-farm income estimates, which were biased by the survey of the project in which they were collected, the overall results were consistent across surveys. The analyses presented in this study show how big datasets can be used to identify generic patterns that can be used to prioritize policies, despite the huge diversity in smallholder farming systems in SSA.

Methods

Household Data. We collated recent cross-sectional farm household characterization data from six different projects in countries of SSA. The projects were AFRINT (www.keg.lu.se/en/research/research-projects/current-research-projects/afrint), CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (<https://ccafs.cgiar.org>), Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA) (www.cialca.org), Conference des Responsables de Recherche Agronomique Africains–Australian Aid (CORAF-AUSAID) (www.coraf.org/csiroV2013), N2Africa (www.n2africa.org), and Sustainable Intensification of Maize and Legume Systems for Food Security in Eastern and Southern Africa (SIMLESA) (simlesa.cimmyt.org). These data sources were chosen for (i) their availability of recently collected information on crop production and livestock at household level; (ii) their random sampling of households within sites and a relatively high number of households per site; and (iii) their locations to cover different farming systems, agroecologies, and countries across SSA (Fig. 1 and Table S1). In total, 93 different survey sites were sampled in 17 countries across contrasting regions (Fig. 1), with between 35 and 400 randomly selected farm households per site (Table S1).

Calculation of the Food Availability Indicator. A simple food security indicator was developed building on earlier work by Hengsdijk et al. (32). FA was calculated from on-farm consumption of food crops, and food that could be purchased on the basis of money earned through on-farm and off-farm activities (Fig. 2). This indicator of food security does not cover all of the complexity contained in the concept of food (in)security (33, 34). Our indicator estimates the potential annual amount of energy available at household level, and we therefore refer to it as “food availability.” The indicator provides a continuous “food-availability scale” that allows us to quantify the contribution of key determinants of FA for individual households within and across sites.

FA was expressed in PFE energy (kcal) per capita per day and is calculated according to

$$PFE = \frac{E_{cons} + E_{income}}{365 \times n_{hh}} \quad [1]$$

where E_{cons} is the direct consumption of PFE energy from on farm food produce in kcal (calculated from Eq. 3), E_{income} is the indirect consumption of the PFE energy from income (farm sales, off-farm) in kcal (calculated from Eq. 4), and n_{hh} is the household size in MAE (calculated from Eq. 2).

Household members were disaggregated by sex and age brackets following Food and Agricultural Organization of the United Nations meth-

odology (35) to quantify household size n_{hh} in MAE, based on energy requirements for members of each age bracket (Eq. 2).

$$n_{hh} = \sum_i n_i \times \alpha_i \quad [2]$$

where n_i is number of person in class i , and α_i the percentage of energy requirement of class i [compare with the energy requirement of an adult male with average daily activity, 2,500 kcal/d (36)].

The PFE energy from direct consumption of on-farm produce was calculated as

$$E_{cons} = \sum_c E_c \times m_c \times \theta_c + \sum_l E_l \times m_l \times \theta_l \quad [3]$$

where E_c is the energy content of the yield of crop c , m_c is the yield of crop c in kg, and θ_c is the percentage of the yield of crop c consumed. For livestock, E_l is the energy content of livestock product l , m_l is the produced amount of product l in kg, and θ_l is the percentage of livestock produce l consumed. Energy contents were based on a standard product list developed by the US Department of Agriculture (source: ndb.nal.usda.gov/ndb/search/list).

The PFE energy from indirect consumption of income was calculated as

$$E_{income} = I_{USD} \times \frac{E_{staple}}{P_{staple}} \quad [4]$$

I_{USD} is the money earned by the household (by selling farm production and off-farm income) in US dollars (USD) (calculated from Eq. 5), E_{staple} is the PFE energy content of the staple crop (kcal/kg), and P_{staple} is the price per kg of the staple crop (USD/kg). Only the staple crop was purchased with the money earned because in most surveys, information was lacking on the actual purchase of food items or was only available for a limited period of the year. By only assuming purchase of the staple crop, the actual energy supply of food is likely to be overestimated, and the FA indicator is therefore only an indicator of the potential to generate enough energy to feed the family by the different livelihood activities.

The money earned by the household was calculated as

$$I_{USD} = \sum_c P_c \times m_c \times (1 - \theta_c) + \sum_l P_l \times m_l \times (1 - \theta_l) + \Phi \quad [5]$$

where P_c and P_l are the price of the crop yield c (or livestock product l) in USD·kg⁻¹, and Φ is the off-farm income (in USD).

Data Availability and Quality. We defined the following categories that contribute to FA: food crops consumed, food crops sold, cash crops sold, livestock and livestock products consumed or sold, and off-farm income. Cash crops were defined as crops of which more than 90% of the annual produce is sold. Prices were converted to USD·kg⁻¹ using the currency-conversion rate of the first of January of the year of the survey. To control for the large variability in reported price values for the farm products, we took the median value of these prices per kilogram per site.

Data Analysis. The FA analysis was applied to all 13,567 households in our database. We first quantified the energy contribution of different on and off-farm activities to FA for all households. We tested our FA indicator by comparing it to self-assessed food security status where available. In both the AFRINT and N2Africa surveys, information per household was available on the number of meals per day; in the CIALCA dataset, information on FA classes was available: each household classified itself in one of four food security classes. Statistically significant correlation coefficients between 0.18 and 0.37 were found between the reported class or level of food security (either expressed as number of meals per day or as a food security class scoring) and the (log-transformed) FA indicator (Fig. S1). Therefore, strong variations in the FA indicator were related to variations in the overall food security indicators used for comparison, and the FA indicator, despite its strong underlying assumptions, gave a reasonable insight in the overall food security status of individual farm households.

Preliminary analyses showed that the median value for the base level of food crop consumption (expressed as PFE energy) across all individual farm households was roughly 1,500 kcal per capita per day. The overall median value of FA was roughly 4,000 kcal per capita per day. These values were used as a proxy to define three FA classes: “insufficient food available” with less than 1,500 kcal per capita per day, “sufficient food available” with between 1,500 and 4,000 kcal per capita per day, and “more than sufficient food available” with more than 4,000 kcal per capita per day. These FA classes

were used to explore the relative contribution of different on-farm and off-farm household activities in detail.

After this data-exploration step, we tried to explain variations in the FA indicator. In this step, we focused on the drivers of the agriculture-related contribution to FA, thereby excluding off-farm activities. This exclusion of off-farm activities was for two reasons: first, we wanted an explanatory model of FA and off-farm activities are less related to on farm resources and therefore less predictable; and second, initial analyses showed that values in off-farm income were systematically influenced by the way information about this resource was collected in the surveys (a decision tree analysis showed that the name of the survey was one of the key determinants of variations in off-farm income).

To quantify the relationships between farm level resources and FA, we used three key farm household level variables to describe variation in FA among farm households: the crop land used by the farm household (in ha), the livestock herd size (expressed in TLU), and the family size (in MAE). These variables were also identified in other studies as important variables of household-level food security (2, 15, 36, 37).

Site-level variables were used as discrete variables, because initial test results showed that a functional interpretation of the relationships found between FA values and continuous site variables was extremely difficult. We characterized the sites based on key constraints identified in literature or in the survey data themselves. Three constraints were used: land, livestock, and market (19, 38, 39). Whether a site was defined as land-constrained or not was based on the country classification of Headey and Jayne (39). Whether market access was a constraint was based on the importance of cash crops in a site in the survey data: sites with less than 25% of the farm households growing cash crops were labeled as "market-constrained." "Livestock-constrained" sites were sites where less than 50% of the households owned 0.7 TLU [i.e., at least one cow (Fig. S2)]. Variables describing the agroecological environment of the sites (e.g., rainfall, soil) were included in initial analyses,

but either the variables did not result in balanced data divisions or the site-level GPS information was too coarse. Therefore, we did not include the biophysical site-level variables in this analysis.

Because the relationships between FA and the explanatory variables were expected to be nonlinear, with strong interactions present between the drivers, we used ANNs to quantify these relationships. ANNs produce the best possible empirical relationship between the input and output variables presented to the network. A standard three-layer, back-propagation network was used with, after testing different numbers, four hidden neurons. The networks were trained on 75% of the available data, whereas 25% was used for testing. The ANNs were cross-validated 500 times, and in each sampling, 50 initializations of the neural network architecture were used. At the end of the analysis, 500 different networks were available per combination of input variables, which were used to quantify the uncertainty in the network performance and the response curves that were generated with the networks. We checked the relationships found by the ANNs between FA values and changes in household size to make sure the ANN models were not simply identifying the inverse household-size relationship used in the FA calculations, resulting in circular reasoning.

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