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

Romain Frelat[a,b], Santiago Lopez-Ridaura[b], Ken E. Giller[c], Mario Herrero[d], Sabine Douxchamps[a], Agnes Andersson Djurfeldt[e], Olaf Erenstein[b], Ben Henderson[d], Menale Kassie[b], Birthe K. Paul[f], Cyrille Rigolot[d,g], Randall S. Ritzema[a], Daniel Rodriguez[h], Piet J. A. van Asten[i], and Mark T. van Wijk[a,1]

[a]International Livestock Research Institute, Livestock Systems and the Environment, Nairobi 00100, Kenya; [b]International Maize and Wheat Improvement Center, Sustainable Intensification and Socioeconomics programs, 06600 Mexico City, Mexico; [c]Plant Production Systems, Wageningen University, 6700 AK Wageningen, The Netherlands; [d]Commonwealth Scientific and Industrial Research Organisation, Agriculture Flagship, St. Lucia, QLD 4067, Australia; [e]Department of Human Geography, Lund University, S-223 62, Lund, Sweden; [f]International Center for Tropical Agriculture, Tropical Forages Program, International Centre of Insect Physiology and Ecology Duduville Campus, Nairobi, Kenya; [g]French National Institute for Agricultural Research, Unité Mixte de Recherche 1273 Metafort, 63122 Saint Genès-Champanelle, France; [h]University of Queensland, Queensland Alliance for Agriculture and Food Innovation, Toowoomba, QLD 4350, Australia; and [i]International Institute of Tropical Agriculture, IITA–Uganda, Kampala, Uganda

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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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[1]To whom correspondence should be addressed. Email: m.vanwijk@cgiar.org.

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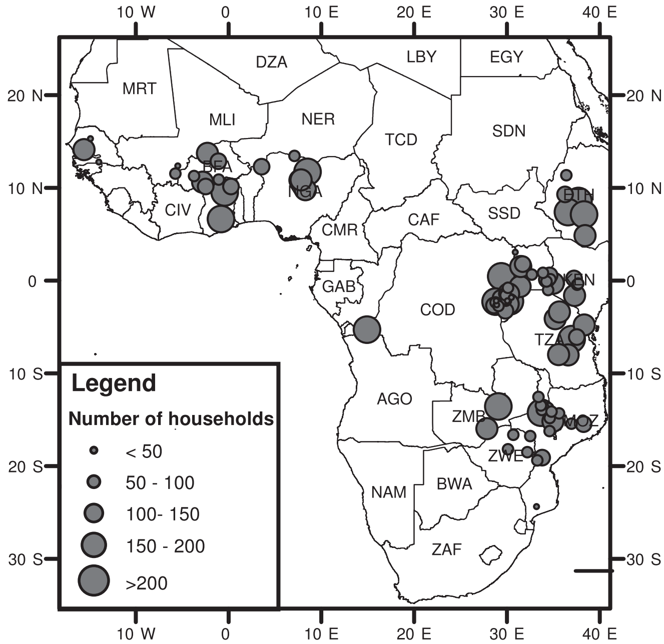

Fig. 1. Map of the study sites in SSA. The size of points represents the number of households surveyed. International borders of countries are shown and labels of the countries are written following the ISO three-letter codes.

consumption of food crops produced on-farm. By contrast, households with more adequate food availability (FA) depended more on cash-generating activities, although consumption of self-produced food crops still provided the base supply of energy. Consumption of self-produced food crops did not cover the food need for almost 80% of the households. Crop and livestock product sales were a substantial part of the FA indicator [expressed in potential food equivalent (PFE) energy (kcal) per capita per day] for these households, suggesting that the majority of households do not aim for full food self-sufficiency. Most households have a PFE value larger than the household's daily energy requirement (Fig. 3*A*), but it is important to note that the FA indicator is an indicator of potential supply (i.e., it overestimates actual FA). However, despite all of the assumptions, the FA indicator is a meaningful indicator for food security: the indicator is strongly correlated with self-scoring of food security status of food security status (Fig. S1), household level diet diversity, and the USAID Hunger and Food Insecurity Status indicator.

Overall, off-farm income was more important for households with higher FA: its importance as source of PFE energy increased from 12% for households with insufficient food to 27% for households with potentially more than enough food (Fig. 3*B*). The main intensification pathway was cash crop production, with an increasing relative importance from 4% for the households with insufficient food available to 11% in the sufficient food-available households. Across the three FA classes, the contribution of livestock to PFE was relatively conservative with a total contribution of about 20% (Fig. 3*B*). Within this overall contribution of livestock, though, there was a clear shift away from poultry to cattle as the level of FA increased. The contribution of food crop consumption decreased from 45% for the households with insufficient food available to 22% in the more than sufficient food-available households. The sale of food crops was stable at roughly 20%. Crop production was the major source of PFE energy, providing from 67% for the insufficient food-available households to only 55% for the households with more than sufficient food available.

Food-Availability Thresholds and Constraints. Land, livestock, and household size explained a substantial part of FA variation (R^2 of 0.33; Fig. 4*D*). The response curves identified by the artificial neural networks (ANNs) (these were used because they do not use a predefined response relationship and can fit highly nonlinear relationships) were robust (i.e., they had a small uncertainty). The relation between land used for cropping and FA was a nonlinear saturation curve, with a threshold at around 3 ha (Fig. 4*A*). This finding suggests that land productivity decreased in households with more land. FA without off-farm income increased gradually with increasing livestock ownership (Fig. 4*B*), although two rates of change in the response were visible: at tropical livestock unit (TLU) values below 0.2 (two goats or 20 chickens), there was a strong increase in FA per unit of increase in TLU, whereas for TLU values larger than 0.2 the slope was less steep. The FA—household size response was as expected (i.e., FA decreased as family size increased, but the overall response was flatter than the expected reciprocal relationship which is used in the calculations).

The ANN response model with the three primary household resources was used to predict the FA "frontier" (Fig. 5). Based on the resources of the household and its size (crop land, livestock, and family size), the model predicted correctly the FA status (can a household, yes or no, produce and/or purchase enough food to feed the family?) of 72% of the households (with a PFE energy threshold set at 2,500 kcal per capita per day). We considered model performance to be satisfactory, given the fact that the FA status indicator is a binary variable with high levels of associated noise (with many farm households, close to the threshold value; Fig. 3*A*). Increasing family size shifted the livestock—land threshold curve upwards, so more land and livestock were needed to feed the family (Fig. 5). This simple model had a relatively good prediction power with an α error of 0.25 (probability erroneously to predict a household to have enough food available to feed the family) and a β error of 0.35 (probability erroneously to predict a household as having insufficient food available).

The frontier curves shifted substantially when the environmental factors were taken into account (Fig. 6). In land but not market constrained systems (densely populated and more land intensive Africa, "L"), the land threshold was smaller (i.e., farmers were food secure with less land than predicted by the overall model of Fig. 5). With around 0.4 ha, a family of 4.4 male adult equivalents (MAEs) was predicted to be able to produce enough food and cash to feed the family. Households in market-constrained environments ("M," "LM") needed more land to achieve sufficient FA values, with

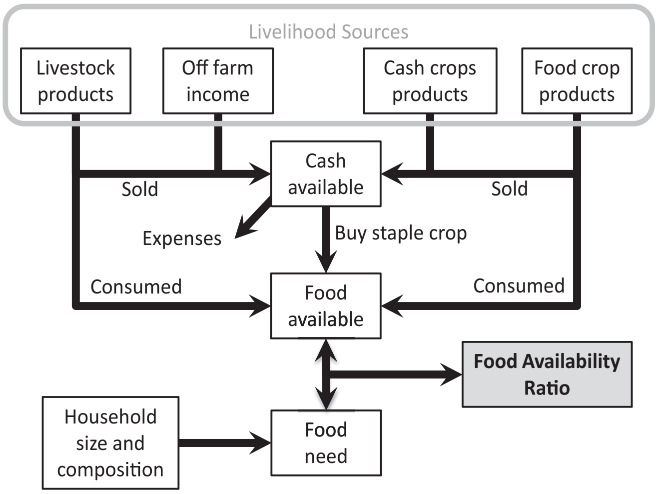

Fig. 2. Schematic representation of the calculation of the FA at household level in energy (kcal) per capita and per day.

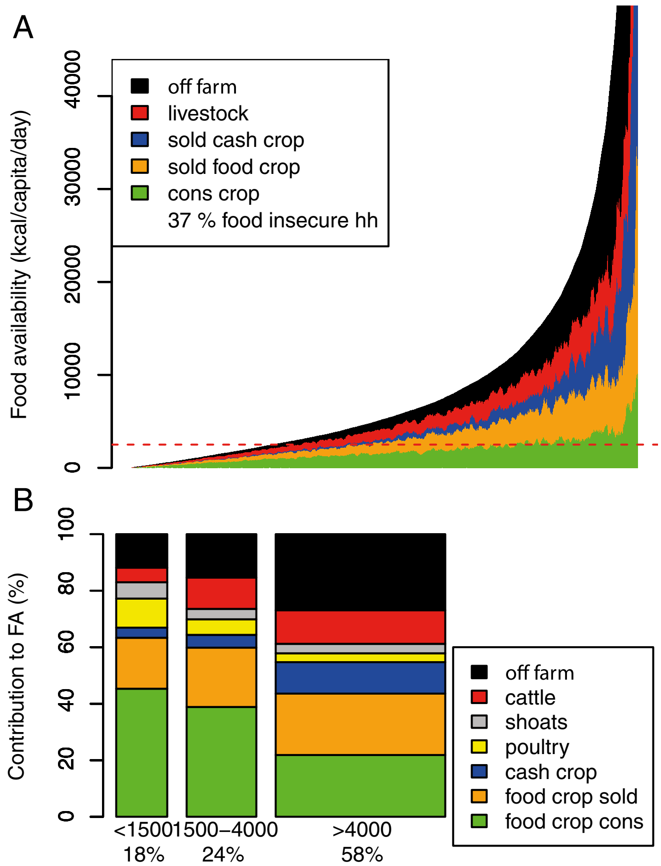

Fig. 3. (*A*) Overall distribution of food available (FA) in energy per capita per day for the 13,567 households. Households are ordered on the *x* axis based on increasing FA. Each vertical bar represents one household, the colors represent its sources of energy, and the height represents the degree of FA. The red dashed line is a PFE of 2,500 kcal per capita per day, the daily energy need of a male adult (36). For the ease of interpretation, a moving average has been applied with a window length of 100 households (to smooth the curves). (*B*) Relative contribution of household activities to FA per FA class (not enough food available <1,500 kcal per capita per day, roughly enough food available between 1,500 and 4,000 kcal per capita per day and more than enough food available >4,000 kcal per capita per day).

livestock being important ("LM") or necessary ("M"). There was only a small increase in the predictive power of the threshold model (75% correctly predicted status of FA) when environmental factors were included. This limited increase in predictive power is likely to be caused by the noisy nature of this binary dependent variable.

Discussion

Bridging Yield Gaps Is Important, but Improving Market Access Is Essential. Consumption of food crops produced on the farm forms the base level of energy supply in all smallholder farms, but most farm households start selling food crops before the households' consumption reaches food self-sufficiency. Farm households sell produce even when they do not produce enough food to be self-sufficient: 83% of the farm household sell part of their crop produce, and only 4% of the farmers do not sell anything of their crop or livestock produce. Thus, market access is crucial to ensure or improve the livelihoods of these families. Simply increasing production by closing the yield gaps of important food crops does not necessarily lead to improved food security because many of these food crops (e.g., maize) typically have low market prices (7). Closing yield gaps might allow families to buy more food at cheaper prices, thereby helping the food security of the poorest families. However, our results show that the majority of smallholder farmers rely on the sale of food crops to generate cash. Decreasing food prices might be attractive for the poorest families but would have adverse consequences for market-orientated smallholder families. A more logical entry point for the poorest families is therefore to stimulate the labor market for off-farm activities. Unless farmers are able to use improved production levels of food crops to reach the base level of food consumption on less land, thereby freeing up land to produce cash crops and to market these in return for good prices, our analyses indicate that increased food crop production is not necessarily an attractive entry point for improving the livelihood of these smallholder farmers. However, the success of this depends on market access.

Livestock Matters for the Poor and the Rich. Livestock provided roughly 20% of the energy of the households. A clear shift in livestock species was observed: the poorest farmers rely on poultry, and those with better FA own cattle. This shift follows what has been described as the "livestock ladder" across different farms (8, 9). The livestock ladder depicts a system that poor smallholders can use to ascend from keeping small-stock to acquiring larger animals, so a dynamic change over time within the same smallholder farm. Our results show that the upper rungs of the ladder are associated with better FA. However, the ladder does not show whether limiting resources, for example, fodder availability, will limit the ability of farmers to climb the ladder (10).

Off-Farm Income: The Stabilizer in the Equation. Off-farm income was strongly related to the degree of FA: its importance as a source of energy increased from 12% for the insufficient food-available households to 27% for the more than sufficient food-available households. Off-farm income is one of the key options for achieving food security (11, 12). In previous work, off-farm

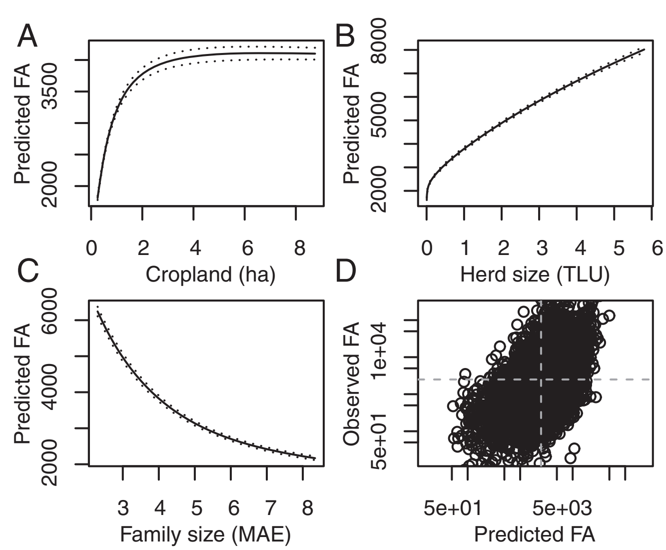

Fig. 4. (*A*–*C*) The response curves of the ANN model using cropland (*A*), TLUs (*B*), and family size (in MAE) (*C*) as inputs (on the *x* axes) and the predicted FA response (in kcal per capita per day) on the *y* axes. The curves were calculated from the controlled variation of one variable, whereas the other two were set to their median values: crop land, 1.33 ha; TLU, 0.75; and household size, 4.4 MAE. The bold line shows the average response curve, and the dashed line is the average ± SD. (*D*) Model performance, with the observed FA (in kcal per capita per day; calculated using measured data) on the *y* axis and predicted FA (in kcal per capita per day) using the three earlier-mentioned variables as input of the ANN on the *x* axis. Both axes are in log scale. The dashed gray lines are the daily requirement thresholds of 2,500 kcal per capita per day (35).

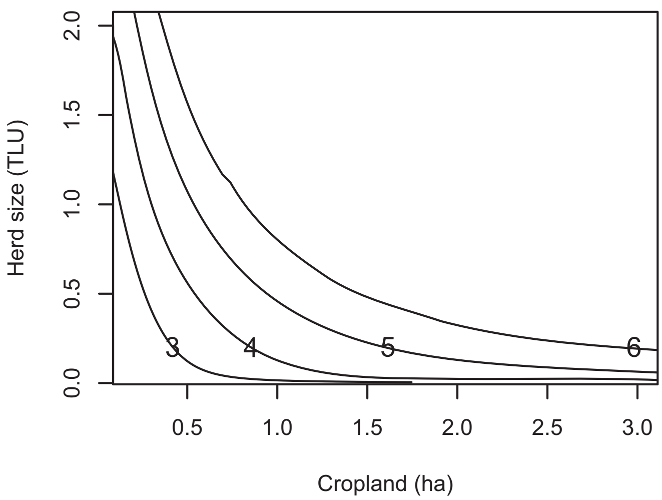

Fig. 5. Predicted FA threshold curves using the ANN with cropland, livestock (in TLU), and family size (in MAE) as inputs. Different curves are the threshold values at different family sizes from 3–6 MAE. Households with productive resources larger than the values determining the curve corresponding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

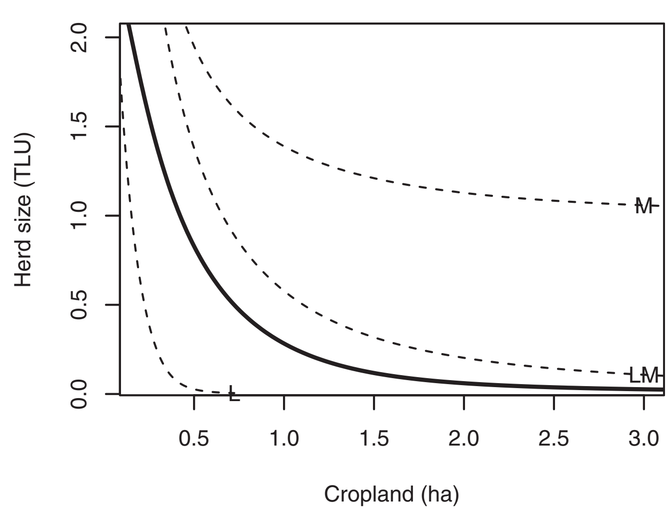

Fig. 6. The predicted FA threshold curves of the ANN model with cropland, livestock (in TLU), and family size expressed in MAE as inputs, together with the environmental constraint variables (for an explanation, see *Methods*). The bold line shows the average response and threshold curves (as in Fig. 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 methodology (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_c 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 $USD{\cdot}kg^{-1}$, 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 $USD{\cdot}kg^{-1}$ 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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1. Foley JA, et al. (2011) Solutions for a cultivated planet. *Nature* 478(7369):337–342.
2. Herrero M, et al. (2010) Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science* 327(5967):822–825.
3. Dorward AR (2003) *Modelling Poor Farm Household Livelihoods in Malawi: Lessons for Pro-Poor Policy.* Working Paper: Institutions and Economic Policies for Pro-Poor Agricultural Growth, June 2003 (Imperial College, Wye Campus, London).
4. Ericksen PJ, Ingram JSI, Liverman DM (2009) Food security and global environmental change: Emerging challenges. *Environ Sci Policy* 12(4):373–377.
5. Giller KE (2013) Can we define the term' farming systems'? A question of scale. *Outlook Agric* 42(3):149–153.
6. Klapwijk L, van Wijk MT, van Asten P, Thornton PK, Giller KE (2014) Trade-off analysis in (tropical) agricultural systems. *COSUST* 6:110–115.
7. Harris D, Orr A (2014) Is rainfed agriculture really a pathway from poverty? *Agric Syst* 123:84–96.
8. Todd H (1998) Women climbing out of poverty through credit; or what do cows have to do with it? *Livest Res Rural Dev* 10(3):1–9.
9. Udo HMJ, et al. (2011) Impact of intensification of different types of livestock production in smallholder crop-livestock systems. *Livest Sci* 139(1-2):22–29.
10. Klapwijk L, et al. (2014) The 'One cow per poor family' programme: Current and potential fodder availability within smallholder farming systems in southwest Rwanda. *Agric Syst* 131:11–22.
11. Otsuka K, Yamano T (2006) Introduction to the special issue on the role of nonfarm income in poverty reduction: Evidence from Asia and East Africa. *Agric Econ* 35(S3): 393–397.
12. Kristjanson P, Mango N, Krishna A, Radeny M, Johnson N (2010) Understanding poverty dynamics in Kenya. *J Int Dev* 22(7):978–996.
13. Jayne TS, Chamberlin J, Headey DD (2014) Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy* 48:1–17.
14. Bezu S, Barrett CB, Holden ST (2012) Does the nonfarm economy offer pathways for upward mobility? Evidence from a panel data study in Ethiopia. *World Dev* 40(8): 1634–1646.
15. Haggblade S, Hazell P, Reardon T (2010) The rural non-farm economy: Prospects for growth and poverty reduction. *World Dev* 38(10):1429–1441.
16. Andersson Djurfeldt A, Djurfeldt G (2013) Structural transformation and African smallholders: Drivers of mobility within and between the farm and non-farm sectors for eight countries. *Oxf Dev Stud* 41(3):281–306.
17. Baltenweck I, et al. (2003) *Crop–Livestock Intensification and Interaction Across Three Continents. Main Report CGIAR System-Wide Livestock Programme* (ILRI, Addis Ababa, Ethiopia), pp 1–124.
18. Boserup E (1965) *Conditions of Agricultural Growth* (Aldine Publications, Chicago).
19. Herrero M, et al. (2014) Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. *Glob Environ Change* 24:165–182.
20. Nagayets O (2005) *Small Farms: Current Status and Key Trends.* Information Brief prepared for the Future of Small Farms Research Workshop, Wye College, June 26–29.
21. Bélières J-F, et al. (2013) *Les Agricultures Familiales du Monde. Définitions, Contributions et Politiques Publiques* (le Cirad et l'Agence Française de Développement, Montpellier, Paris).
22. Jayne TS, et al. (2003) Smallholder income and land distribution in Africa: Implications for poverty reduction strategies. *Food Policy* 28:253–275.
23. Jayne TS, Mather D, Mghenyi E (2010) Principal challenges confronting smallholder agriculture in Sub-Saharan Africa. *World Dev* 38(10):1384–1398.
24. Hazell PBR (2005) Is there a future for small farms? *Agric Econ* 32(S1):93–101.
25. Ali DA, Deininger K (2014) *Is there a farm-size productivity relationship in African agriculture? Evidence from Rwanda.* World Bank Policy Research Paper 6770 (World Bank, Washington, DC).
26. Larson D, Otsuka K, Matsumoto T, Kilic T (2013) Should African rural development strategies depend on smallholder farms? An exploration of the inverse productivity hypothesis. *Agric Econ* 45(3):1–13.
27. Muyanga M, Jayne TS (2014) *Is small still beautiful? The farm size-productivity relationship Revisited.* Paper prepared for presentation at the 2014 conference on land policy in Africa African Union Conference Center, Addis Ababa, Ethiopia November 11- 14, www.afdb.org/en/aec-2015/papers/paper/is-small-still-beautiful-the-farm-size-productivity-relationship-revisited-4736/.
28. McIntire J, Bourzat D, Pingali P (1992) *Crop–Livestock interaction in Sub-Saharan Africa* (World Bank, Washington, DC), 246 pp.
29. Jones Govereh, T.S Jayne (2003) Cash cropping and food crop productivity: Synergies or trade-offs? *Agric Econ* 28(1):39–50.
30. Carletto C, Zezza A, Banerjee R (2013) Towards better measurement of household food security: Harmonizing indicators and the role of household surveys. *Glob Food Secur* 2(1):30–40.
31. Carletto C, Savastano S, Zezza A (2013) Fact or artifact: The impact of measurement errors on the farm size–productivity relationship. *J Dev Econ* 103:254–261.
32. Hengsdijk H, Franke AC, van Wijk MT, Giller KE (2014) *How Small is Beautiful? Food Self-sufficiency and Land Gap Analysis of Smallholders in Humid and Semi-arid sub Saharan Africa* (Wageningen UR, Wageningen).
33. Coates J (2013) Build it back better: Deconstructing food security for improved measurement and action. *Glob Food Secur* 2(3):188–194.
34. Headey D, Ecker O (2013) Rethinking the measurement of food security: From first principles to best practice. *Food Security* 5:327–343.
35. Food and Agricultural Organization of the United Nations (2001) *Human Energy Requirements. Food and Nutrition Technical Report Series 1* (Food and Agricultural Organization of the United Nations, Rome), pp 1–103.
36. Holden ST, Shiferaw B, Pender J (2001) Market imperfections and profitability of land use in the Ethiopian highlands: A comparison of selection models with heteroskedasticity. *J Agric Econ* 52(3):53–70.
37. Ehui S, Li-Pun H, Mares V, Shapiro B (1998) The role of livestock in food security and environmental protection. *Outlook Agric* 27(2):81–87.
38. Staal SJ, Baltenweck I, Waithaka MM, DeWolff T (2002) Location and uptake: Integrated household and GIS analysis of technology adoption and land use, with application to smallholder dairy farms in Kenya. *Agric Econ* 27(3):295–315.
39. Headey D, Jayne TS (2014) Adaptation to land constraints: Is Africa different? *Food Policy* 48:18–33.