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1 **Increased mineral fertilizer use on maize can improve both household food security and**
2 **regional food production in East Africa**

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28 **Abstract:**

29 *Context*

30 Despite recent improvements in living standards, a substantial proportion of farm households
31 in sub-Saharan Africa (SSA) is food insecure, and increasing crop productivity could help
32 address this problem.

33 *Objective*

34 We estimated the effect of increasing maize yields with mineral fertilizer on household food
35 security and on regional and national maize supply in two East African countries - Uganda and
36 Tanzania.

37 *Methods*

38 We estimated maize yield response to nitrogen (N) fertilization with a machine learning model
39 trained on 15 952 observations of maize responses to fertilizer across SSA. Together with
40 spatial price data, we used this model to quantify the profit-maximizing N fertilizer input for a
41 nationally-representative sample of 4188 agricultural households in the two countries. We
42 computed a food availability indicator for all households.

43 *Results and conclusions*

44 The mean profit-maximizing N input was 82 kg ha⁻¹ in Tanzania, but it was much lower in
45 Uganda (24 kg ha⁻¹) mostly because of less favorable prices. The profit-maximizing N input
46 was above the reported N input for 95% of the households in Tanzania and for 43% of the
47 households in Uganda. It was predicted to increase the food availability ratio of food insecure
48 maize growers by 95% in Tanzania, and by 25% in Uganda. The administrative regions where
49 maize supply could increase most were not the same as the regions where the increase in
50 household-level food security was largest. With increased fertilization, food insecure maize

51 growing households (35% in Tanzania and 42% in Uganda) could only contribute about 20%
52 of the overall increase in maize supply, whereas the 20 to 30% food secure households that
53 have a larger area planted with maize could contribute more than 60%.

54 *Significance*

55 Our study makes two key contributions: i) a substantial increase in national maize supply is
56 more likely to come from already food secure households with relatively large farms, while
57 food insecure households with small farms may nevertheless increase their household-level
58 food security through maize intensification, and ii) high potential areas to increase maize
59 domestic production do not necessarily match with areas where there is immediate scope to
60 improve household-level food security

61 *Keywords: random forest, LSMS-ISA household surveys, sub-Saharan Africa*

62 **1. Introduction**

63 Over the past decade, living standards have improved substantially in some countries of sub-
64 Saharan Africa (SSA). This has been associated with high growth in agricultural gross domestic
65 product (GDP) (Jayne et al., 2018a), improved health (Masters et al., 2018) and better nutrition
66 (Beal et al., 2017). Despite these positive trends, food security remains a critical issue, and more
67 than a third of rural households across 17 countries in SSA was found to be food insecure (Frelat
68 et al., 2016). Food production has not kept pace with population growth (FAO et al., 2022; Luan
69 et al., 2013) and the majority of countries in SSA are net food importers (Mendez del Villar and
70 Lançon, 2015; Rakotoarisoa et al., 2011; van Ittersum et al., 2016),

71 Increasing staple food production on current agricultural land is necessary to improve
72 household and national food security, while limiting biodiversity loss and carbon dioxide
73 emissions associated with agricultural land expansion (van Loon et al., 2019; van Ittersum et
74 al., 2016). Yet, crop yields in SSA are much lower than yields that are attainable with good
75 agronomic management practices. A major reason for the low crop yields in SSA is that the
76 average fertilizer use in SSA is low, that is 12, 2 and 3 kg/ha for nitrogen (N), phosphorus (P)
77 and potassium (K), respectively (FAOSTAT, 2018). It has, however, rapidly increased in some
78 countries over the past decades (for example, N fertilizer use was 39 kg/ha in Zambia and 23
79 kg/ha in Ethiopia in 2018). The limited use of mineral fertilizer leads to widespread nutrient
80 mining (Cobo et al., 2010). Therefore, a significant increase in nutrient inputs in the form of
81 mineral fertilizer is required to sustainably increase crop productivity (ten Berge et al., 2019,
82 Jayne et al., 2019). In combination with mineral fertilizer, the integration of legumes in crop
83 rotations (Franke et al., 2018), the implementation of agroforestry practices (Kuyah et al.,
84 2019), and the better use of organic resources such as manure (Vanlauwe et al., 2014) are key
85 to improve nutrient use efficiency and avoid detrimental nutrient losses to the environment.

86 The biophysical environment can constrain the effectiveness of mineral fertilizer inputs. For
87 example, fields that are already fertile, or, in contrast, lack secondary nutrients and
88 micronutrients, can be unresponsive to NPK fertilizers (Nziguheba et al., 2021; Vanlauwe et
89 al., 2010). Drought stress or excessive rainfall events can also lead to low fertilizer use
90 efficiency (Affholder, 1997; Mapanda et al., 2012), which may discourage farmers to invest in
91 fertilizer. These biophysical constraints vary spatially, owing to a combination of natural
92 environmental variability and soil fertility heterogeneity associated with previous field
93 management by farmers (Njoroge et al., 2017). Economic constraints also act as a barrier for
94 investment in fertilizer to increase crop productivity. High prices of fertilizer and low prices of
95 agricultural products can lead to unfavourable cost:benefit ratios (see Jayne et al., 2018 and
96 Bonilla Cedrez et al., 2021 for recent estimates of cost:benefit ratios across SSA). These
97 economic constraints vary spatially, as fertilizer price is usually higher in remote – poorly
98 accessible – areas (Bonilla Cedrez et al., 2020a). In addition, farm household characteristics
99 can constrain intensification of crop production to improve household-level food availability
100 (Tittonell et al., 2010). For example, rural households with limited crop land do not directly
101 benefit from an increase in crop productivity (Giller et al., 2021; Ritzema et al., 2017), and poor
102 households may not have the cash to buy fertilizer, even if it would be profitable to do so.
103 Farmers resource endowment also varies spatially, with local variations as important as
104 country-wide variations (Wichern et al., 2018). The current literature falls short in determining
105 the spatial interaction between biophysical, economic and household-level factors that drive the
106 contribution of maize intensification to food security in the diverse contexts of SSA. In their
107 most optimistic scenario, Ritzema et al. (2017) investigated how a 100% increase in cereal yield
108 would impact household food security of 1700 households in seven countries of East and West
109 Africa. But the increase in cereal yield could be much stronger, e.g. maize yield can be
110 quadrupled in some areas with favorable soil and climate in SSA

111 (<https://www.yieldgap.org/gygaviewer/index.html>). Moreover, the authors relied on site-
112 specific household surveys that possibly did not cover the full span of existing biophysical
113 conditions and farmers' context. Palmas and Chamberlin (2020) investigated the biophysical
114 and economic constraints to the use of mineral fertilizer on maize in Tanzania. Their study
115 brought crucial insights into the spatial determinants of fertilizer profitability, but did not
116 consider the household dimension. Yet, household characteristics (e.g. land per capita) can
117 strongly influence the contribution of intensification of cereal production to improved food
118 security.

119 Maize is the most important staple food crop in SSA, especially in Eastern Africa (OCDE and
120 FAO, 2016). Tanzania and Uganda are ideal case study countries for several reasons. Firstly,
121 Tanzania and Uganda are in the top-ten maize producing countries in SSA, with 6.2 and 2.7 Mt
122 yr⁻¹ (2017-2018 average), respectively (FAOSTAT, 2018). Secondly, both countries have
123 diverse agro-ecological conditions allowing the analysis of a wide range of maize growing
124 conditions that also prevail elsewhere across SSA: there are six "maize mega-environments"
125 (Hartkamp et al., 2000) in Tanzania: dry lowland, dry mid-altitude, highland, wet lower mid-
126 altitude, wet upper mid-altitude and wet lowland, and five of these also prevail in Uganda (no
127 wet lowlands). Thirdly, maize yield and fertilizer use in the two countries is low, as it is the case
128 in most countries in SSA: the average maize yield in 2018 was 2.6 t ha⁻¹ in Uganda, and 1.7 t
129 ha⁻¹ in Tanzania (FAOSTAT, 2018); Nitrogen fertilizer use on cropland was 1.2 kg (N) ha⁻¹
130 year⁻¹ in Uganda and 9.1 (N) kg ha⁻¹ year⁻¹ in Tanzania in 2018 (FAOSTAT, 2018). Fourthly,
131 arable land per capita, a crucial indicator of how agricultural intensification can contribute to
132 improve food security (Giller et al., 2021), is more constrained in Uganda than in Tanzania:
133 land per capita is 0.16 ha in Uganda, close to the first quartile of 0.15 ha for SSA countries, and
134 0.24 ha in Tanzania, close to the third quartile of 0.25 ha per capita for SSA countries (World

135 Bank, 2021a). Lastly, the two countries allow to explore the impact of variable mineral N
136 fertilizer costs, as these are greater in Uganda than in Tanzania (Bonilla Cedrez et al., 2020a).

137 In this study we estimate the potential contribution of maize intensification with mineral
138 fertilizer to increase maize production and household food security in Uganda and Tanzania.
139 Using existing datasets across SSA on maize fertilizer trials (Bonilla Cedrez et al., 2021; Kihara
140 et al., 2017, 2016), fertilizer and maize price (Bonilla Cedrez et al., 2020a, 2020b), and
141 nationally representative household surveys in Uganda and Tanzania (Kilic et al., 2015), we
142 explore the spatial variation in maize response to nutrient inputs, maize prices and fertilizer
143 costs, and household characteristics. We estimate the contribution to national food security, that
144 is, the amount of surplus production that farm households can produce, to be sold and consumed
145 by others. We explore the three following research questions: i) What is the potential increase
146 in household-level food security by intensification of maize production? ii) What is the relative
147 importance of increasing maize production in already food secure and currently food insecure
148 maize growers for national maize production? and iii) Are the regions where household-level
149 food security would benefit most, also the regions where national-level production would
150 increase most? In line with the recent finding that small farms contribute only marginally to
151 global food production (Lowder et al., 2021; Ricciardi et al., 2018), our leading hypothesis was
152 that an increase in national maize production will be achieved mostly by large farms that are
153 already food secure, while food insecure small farms will contribute less to this increase. We
154 also hypothesized that despite their low contribution to national food security, food insecure
155 small farms benefit from maize intensification to improve their food security.

156 **2. Material and methods**

157 **2.1. Overall approach**

158 Our study assessed the contribution of the intensification of maize production to food security
159 in three main steps. First, we trained a statistical model with fertilizer trial data to predict maize

160 grain yield responses to N, P and K fertilizer application for the soil and climate conditions
161 prevailing across SSA, and predicted the spatial variation in maize grain yield response to N, P
162 and K fertilizer in Uganda and Tanzania. Then, we computed a simple food security indicator
163 at household level (the food availability ratio, FA, see below) for a nationally representative set
164 of farm households in Uganda and Tanzania. In a last step, we used the predicted maize yield
165 responses to N, and spatial data on fertilizer and maize prices, to estimate i) the profit-
166 maximizing N fertilizer input for each household, ii) the additional maize production from using
167 this amount of fertilizer, and its effect on the household food availability ratio, and iii) the
168 increase in the overall regional and national maize grain supply. We also performed a sensitivity
169 analysis to evaluate the impact of changes in maize prices, N fertilizer costs, and maize yield
170 responses to N on our estimates.

171 **2.2. Maize yield response to mineral fertilizer**

172 **2.2.1. Experimental data from maize fertilizer trials**

173 We combined data from 15,952 maize fertilizer trials conducted at 1352 locations in SSA from
174 1969 to 2017 (see Appendix 1 in Supplementary materials for details on the composition of the
175 dataset). The dataset included information on trial location (longitude, latitude), maize grain
176 yield, N, P and K fertilizer application rates, topsoil (0-30 cm) characteristics such as soil
177 organic carbon, sand, available P, exchangeable K, Ca and Mg contents and pH, and climate
178 variables such as growing-season rainfall, rainfall intensity and temperature, and number of
179 consecutive dry days over the maize growing season. The trials were rainfed, implying that
180 there may have been water stress in some growing seasons and/or in some locations.
181 Environmental variables that were not reported with the trial data were estimated from spatial
182 data bases (see Appendix 1 in Supplementary materials for details). Soil characteristics varied
183 greatly, allowing the analysis of a wide range of maize growth conditions (Figure S1). The trial

184 locations spanned all maize-mega-environments (Figure S2A), and covered a large range of
185 seasonal rainfalls and temperatures (Figure S2B).

186 **2.2.2. Spatial prediction of maize response to N, P and K fertilizer**

187 We used a Random Forest (RF) algorithm to predict maize grain yield as a function of nutrient
188 inputs (N, P, K), soil properties (soil organic carbon, sand, available P, exchangeable K, Ca and
189 Mg content and pH), and climatic factors (seasonal rainfall, average growing season
190 temperature, number of consecutive dry spell during the season and daily rainfall intensity
191 during the season). We tuned three hyperparameters (parameters that are calibrated during the
192 learning process of the RF algorithm, i.e. the number of trees, the number of candidate predictor
193 variables at each node and the minimum number of samples necessary to split a nonterminal
194 node) based on 70% of the dataset (randomly selected) and an 8-fold cross validation with two
195 replicates. We explored 30 combinations of the hyperparameters obtained by maximizing the
196 coverage of the parameter space. The criterion maximized during the training procedure was
197 the cross-validated proportion of the explained maize yield variance (R^2) averaged over the two
198 replicates. The performance of the best RF model (with optimal combination of hyper-
199 parameters) was then evaluated on the 30% hold-out test dataset. Feature analysis (i.e. partial
200 dependence plot and variable importance) was performed on the model fit with the full dataset.
201 Variable importance values were calculated based on a metric that captures the increase in mean
202 squared error (MSE), calculated from out-of-sample predictions, after randomly permuting the
203 values of the respective predictors (Breiman, 2001), using the R package *vip* (Greenwell et al.,
204 2020). Functional relationships between predictors and maize yield were analyzed through
205 partial dependence plots using the *pdp* R package (Greenwell, 2017). A partial dependence plot
206 shows the marginal effect of one input on the model prediction, averaged across the values
207 taken by the other inputs. In order to test the contribution of climate factors, we built one model

208 that included climate variables, and another model that did not include these, and compared the
209 predictive capacity of the two models.

210 The RF model was then used to predict maize control yield (0 N, 0 P, 0 K) in Uganda and
211 Tanzania at a spatial resolution of 250m using soil data (topsoil organic carbon, sand, available
212 P, exchangeable K, Ca and Mg content and pH) from Africa SoilGrid (Hengl et al., 2015; Hengl
213 et al., 2017). Effects on yield of incremental additions of N (i.e. 20, 40, 60, 80, 100, 120, 160,
214 180 and 200 kg/ha) were then investigated. Though the model was built to deal with the
215 interactions between N, P and K inputs, for this spatial exploration we focused on the impact
216 of N and assumed for all N additions an input of 20kg/ha of both P and K, i.e. the P and K
217 amounts that a compound basal fertilizer application would bring.

218 **2.3. Food security analysis**

219 **2.3.1. Farm household survey data**

220 We used the Living Standard Measurement Study – Integrated Surveys on Agriculture (LSMS-
221 ISA) of 2010-2011 for Uganda and Tanzania (Kilic et al., 2015). These household surveys are
222 nationally representative and cover the main regions of Uganda (World Bank, 2021b) and
223 Tanzania (World Bank, 2021a). These surveys included 2716 households in Uganda and 3440
224 in Tanzania. Households reporting no crop production and households with missing location
225 coordinates were excluded from the analysis, leading to a reduced sample of 1753 farm
226 households in Uganda and 2435 in Tanzania. We used the following variables: household
227 location (with a 10-km offset), household composition, farmer-reported total cropped land and
228 area for the different crops, farmer-reported total crop production and sales of crop production,
229 mineral fertilizer use on crops, total livestock production (meat and milk), sales of livestock
230 products, and off-farm income.

231 **2.3.2. Food security indicator: the household-level food availability ratio**

232 We adopted the food security indicator described in Frelat et al. (2016), also used in Ritzema
233 et al. (2017), Wichern et al. (2017) and Wichern et al. (2019): the ratio of household-level food
234 availability (expressed in potential food equivalent energy, kcal per day) to household energy
235 need (in kcal per day). Household-level food availability was computed as the sum of (i) the
236 energy from crop and livestock products consumed by the household and (ii) the energy that
237 could be obtained from food purchases with the income earned with the sales of on-farm
238 products (crop and livestock) and off-farm activities. Consumption of on-farm grown crop and
239 livestock products was computed by subtracting the reported sold quantities from the reported
240 produced quantities. Energy in consumed crop and livestock products was then computed using
241 product-specific energy content. In order to compute (potential) household-level food
242 availability, the income from the sales of on-farm products and from off-farm activities was
243 converted into energy (assuming that all of it was used to purchase maize) and added to calories
244 in consumed crop and livestock products produced on-farm. Household energy need was
245 obtained by multiplying household size (expressed in adult male equivalent) with the assumed
246 2500 kcal d⁻¹ energy need of a male adult (FAO, 2001). The food availability ratio was
247 computed as the ratio of household-level food availability to household energy need. A food
248 availability ratio of one indicates that potential calorie availability at household level (on-farm
249 production plus the calories that could be obtained with the income from off-farm activities and
250 sales of farm products) matches household needs. The food availability ratio corresponds to
251 potential food availability, i.e. in reality households do not entirely use their on- and off-farm
252 income to purchase the staple food (maize in our case), because of other consumptive needs
253 and also dysfunctional markets (Dillon and Barrett, 2017). It therefore quantifies the *potential*
254 of a household to be food secure. Under land, market and/or production constraints, the food
255 availability ratio has been shown to be well correlated to other food security indicators
256 (Hammond et al., 2017), namely the Household Dietary Diversity Score (HDDS), the

257 Household Food Insecurity Access Scale (HFIAS) (Coates et al., 2007) and the number of
258 months in which households experience food insecurity (Van Wijk et al., 2020). The food
259 availability ratio increased with HFIAS and HDDS, up to a food availability ratio of two
260 (Hammond et al., 2017). A food availability ratio of two indicates that potential calorie
261 availability at household level is twice household needs. We considered households with a food
262 availability ratio below two as “food insecure”, and those with a food availability ratio above
263 two as “food secure”. We further classified households with a food availability ratio below one
264 as “food deficient households”, and those with a food availability ratio between one and two as
265 “food fragile households”. Depending on whether households cultivated maize (i.e. maize area
266 on the farm above zero) or not, they were subsequently classified into “food insecure maize
267 growers” and “food insecure non-maize growers”.

268 In previous studies, farmer-reported maize yield was used to quantify the food availability
269 indicator in Uganda and Tanzania (e.g. Wichern et al., 2017; Fraval et al. 2019). For our analysis
270 we used the maize yields predicted by the model for the N, P, K application reported by the
271 farmer in the survey. Fields with missing information on N, P and K inputs, that is, for 99 fields
272 in Uganda (out of 3603 surveyed fields) and 844 fields in Tanzania (out of 2125 surveyed
273 fields), were assumed to have received median mineral fertilizer application (of all informed
274 fields per country), which was zero in Tanzania and Uganda. Wichern et al. (2017) and Fraval
275 et al. (2019) used the median of the reported maize prices per region to calculate the income
276 from sold maize. In this study, we used the spatially interpolated maize price as in Bonilla
277 Cedrez et al. (2020b). Similar to the farmer-reported prices in the LSMS surveys, they were
278 higher in Tanzania than in Uganda (Figure S3A, Figure S4).

279 **2.3.3. Computing profit-maximizing N input**

280 Using the N response predicted by the RF model at the household locations, we computed the
281 partial gross margin (i.e. not including the cost of other inputs that are left unchanged) for
282 incremental additions of fertilizer N: 20, 40, 60, 80, 100, 120, 160, 180 and 200 kg/ha:

$$283 \quad gm_i = (Y_{0N} + NAE_i \times i) \times maize\ price - i \times N\ cost \quad (1)$$

284 where gm_i is the gross margin for N input rate i , Y_{0N} is maize grain yield with no N fertilizer
285 input predicted by the model at a given household location, $N-AE_i$ is the agronomic efficiency
286 of N predicted by the model at a given household location, i is the N input rate, *maize price* is
287 the predicted maize price at a given household location, and *N cost* is N fertilizer cost at a given
288 household location. Profit-maximizing N input was the N input rate with the highest gross
289 margin at a given household location. Additional labor cost for increased fertilizer application
290 was not considered because of lack of reliable data.

291 N-AE was computed as follows (Vanlauwe et al., 2011):

$$292 \quad N-AE_i = \frac{(Y_i - Y_{0N})}{i} \quad (2)$$

293 where Y_i is the maize grain yield with N input rate i and Y_{0N} is the maize grain yield with no
294 N fertilizer input.

295 The market maize price and N fertilizer cost at a given household location was extracted from
296 the spatial dataset of Bonilla Cedrez et al. (2020a, 2020b) (Appendix 2 in Supplementary
297 materials describes the model development procedure of these two studies).

298 **2.3.4. Change in food availability ratio and increase in regional and national** 299 **maize supply**

300 When profit-maximizing N fertilizer input was above the currently reported N fertilizer input
301 by farmers, we computed the corresponding potential additional maize production ΔP :

$$\Delta P = (Y_{new1} - Y_{current1}) \times \text{area}_{s1} + (Y_{new2} - Y_{current2}) \times \text{area}_{s2} \quad (3)$$

302 where Y_{new1} and Y_{new2} are the predicted maize yields with profit-maximizing N input for the
 303 short and long growing seasons, respectively, $Y_{current1}$ and $Y_{current2}$ are the corresponding
 304 predicted maize yields with the N input as reported by the farmer in the survey, and area_{s1} and
 305 area_{s2} are the maize areas in, respectively, short and long season, as reported by the household
 306 head in the survey (depending on household location, there may be only one growing season
 307 and area_{s2} was therefore equal to 0). We assumed equal maize responses to N for the two seasons
 308 at a given household location. When profit-maximizing N fertilizer input was equal or below
 309 the currently reported N fertilizer input, ΔP was set to 0. ΔP was converted to energy and used
 310 to compute the household food availability ratio adjusted for the use of profit-maximizing N
 311 input (FAprofmax). A relative change in the household food availability ratio (ΔFA) was then
 312 computed as follows:
 313

$$\Delta FA = \text{FAprofmax} / \text{FAbaseline} \quad (4)$$

314 Where FAprofmax is the food availability ratio with profit-maximizing N input and FAbaseline
 315 is the food availability ratio with current reported N input on maize.

316 The impact of N-AE and farm characteristics (per-capita maize area, total cropland, livestock
 317 and off-farm income) on ΔFA was explored by classifying farms in three classes with regard to
 318 these variables: class one below the 33th percentile of all farms for the considered variable,
 319 class two between the 33th and 66th percentile, and class three above the 66th percentile.

320 Then ΔP was aggregated for all surveyed household at the level of the administrative region
 321 and country, to compute the relative increase in maize grain supply, assumed to be a proxy for
 322 the relative increase in regional/national maize production. The contribution of food insecure
 323 and food secure households (further disaggregated by classes of per-capita maize area) to this
 324 potential increase in maize grain supply was also calculated.

326 **2.3.5. Sensitivity analysis**

327 The impact of variations in N-AE, maize price and N cost on i) the profit-maximizing N input,
328 ii) the share of food insecure maize growers who would increase their food availability ratio
329 with the use of profit-maximizing N input, iii) the median Δ FA of food insecure maize growers,
330 and iv) the relative potential increase in national maize grain supply, was explored through
331 sensitivity analysis. N-AE, maize price and N fertilizer cost varied between 0.25 to 2 times their
332 baseline value.

333 **3. Results**

334 **3.1. Maize grain yield predictions**

335 The inclusion of climate-related predictors (seasonal rainfall and mean temperature over the
336 maize growing season, number of consecutive dry days over the season, and daily rainfall
337 intensity over the season) only marginally improved the predictive capacity of the model; R^2
338 increased from 0.82 to 0.87. For this reason, we used the RF model without climate variables.
339 The model predicted maize grain yield (for hold-out data) with a Root Mean Square Error
340 (RMSE) of 919 kg grain yield ha^{-1} (corresponding to a relative RMSE of 27%), and a Mean
341 Absolute Error (MAE) of 657 kg grain yield ha^{-1} (Figure 1). Uncertainty in model predictions
342 increased with higher values of observed maize yield (Figure 1). N and P fertilizer inputs
343 contributed most to predict maize yield, followed by the soil sand content (Figure S5). In
344 contrast, the contribution of K fertilizer and that of the other soil properties (available P,
345 exchangeable K, Mg, Ca, organic carbon and pH) was marginal (Figure S5). Predicted maize
346 yield increased with N applied in the range 0-150 kg N ha^{-1} and with P up to 50 kg P ha^{-1} , but
347 decreased with coarser soil texture (higher soil sand content, Figure S6).

348 **3.2. Predicted maize yield in response to fertilizer in Uganda and Tanzania**

349 Predicted maize grain yields with no fertilizer input (“control yield”) ranged from 500 to more
350 than 2500 kg ha⁻¹ (Figure 2A). Predicted control yield was generally smaller in sandy areas
351 such as the coastal areas in Tanzania and somewhat higher in areas with high soil available P
352 such as the volcanic soils in Eastern Uganda near Mount Elgon and in the northern highlands
353 of Tanzania near Kilimanjaro (Figures S7, S8). With the maximum fertilizer use considered
354 (200 kg N ha⁻¹, 20 kg P ha⁻¹, 20 kg K ha⁻¹), predicted yield increased by up to five times the
355 control yield (Figure 2B). The largest predicted yield increase was in areas with the smallest
356 control yields (for example, in the southwest Tanzanian highlands, south-eastern Tanzania, and
357 the area around Lake Victoria in Uganda). Median N-AE (across locations) was 20 kg (grain)
358 kg (N)⁻¹ with N inputs of 40 kg ha⁻¹, and decreased gradually with higher N fertilizer inputs
359 (Figure S9B). N-AE also significantly (P-value <0.001) decreased with higher control yields,
360 lower sand content, and higher soil organic carbon (Figure S10). As a consequence, the areas
361 with the lowest control yields were generally areas of highest N-AE (Figure 2A and Figure
362 S11).

363 **3.3. Food security analysis with current fertilizer use**

364 Fertilizer use reported by farmers in the 2011 survey was very low. In Tanzania, only 12% of
365 the 3212 surveyed maize plots had received N, 3% had received P and 0.3% had received K,
366 with a median application (for fields receiving mineral fertilizer) of 38 (N), 12 (P) and 7 (K)
367 kg/ha. In Uganda, less than 1% of the 3553 surveyed maize plots had received mineral fertilizer,
368 with median application of 1.0 (N), 1.4 (P) and 2.5 (K) kg/ha. Overall, predicted maize grain
369 yield (with N use reported by farmers) was greater (median=1207 kg/ha) than farmer-reported
370 maize yield (median=482 kg/ha), possibly because of weed/disease/pest stresses not accounted
371 for by the RF model. Yet, in some cases, especially in Uganda, farmer-reported yield was
372 greater than the predicted yield with the reported N use – possibly because of the uncertainty
373 related to farmers’ estimates of their maize production and area.

374 We found that a large share of the surveyed farm households was food insecure when using the
375 maize yield predicted with their reported N use: 44% of the households in Tanzania and 46%
376 in Uganda had a food availability ratio of less than two, and 25% of household in Tanzania and
377 Uganda had a food availability ratio of less than one (Figure 3). When using farmer-reported
378 maize yield, these percentages were greater in Tanzania, and similar in Uganda: 74% of the
379 households in Tanzania and 45% in Uganda had a food availability ratio of less than two. In
380 what follows we report results that used predicted maize yields. Crops produced and consumed
381 on-farm were the largest contributors to household food availability for food insecure (FA<2)
382 households in Tanzania (Figure 3a). Off-farm income and sales of livestock and crop products
383 contributed more to the food security status of farm households in Uganda than in Tanzania
384 (Figure 3b). The majority of food insecure (FA<2) households produced maize: 64% in
385 Tanzania and 51% in Uganda. The majority of food secure (FA>2) households also grew maize,
386 87% in Tanzania and 58% in Uganda. There were no obvious spatial patterns in the locations
387 of food insecure maize growers; Households were sampled and surveyed in the eastern,
388 western, northern and southern parts of Uganda and Tanzania (Figure S12A), and food insecure
389 maize households could be found in almost all regions where the survey was conducted (Figure
390 S12B). The scope for intensifying maize production (that is, the maximum relative increase in
391 maize yield, Figure 2B) varied greatly across the locations where food insecure households
392 were found, in both countries (Figure S12B).

393 **3.4. Impact of additional N input on household food security**

394 Based on model prediction and spatial price data, the mean profit-maximizing N input was 82
395 kg (N) ha⁻¹ in Tanzania, and only 24 kg (N) ha⁻¹ in Uganda (Figure S13). The difference between
396 countries was mostly attributed to lower maize price and higher N cost in Uganda (Figure S4).
397 For 90% of maize growers in Tanzania (95% of the food insecure maize growers), profit-
398 maximizing N input was above the current reported N use, and their food availability ratio was

399 predicted to increase when using the profit-maximizing N input. In Uganda, this was the case
400 for only 41% of the maize growers (43% of the food insecure maize growers). Households for
401 which profit-maximising N input was above current reported use were spread all over Tanzania,
402 and in Uganda around Lake Victoria (Figure S13B), i.e. in areas with higher maize prices, lower
403 fertiliser costs, and thus with a maize price : N fertilizer cost ratio compatible with profitable
404 use of more fertiliser (Figure S3).

405 The relative increase in the food availability ratio (with additional N input) decreased with the
406 baseline food availability ratio: food insecure ($FA > 2$) households benefited much more in
407 relative terms, than food secure ($FA > 2$) households (Figure 4A). In addition, household with
408 greater N-AE, larger per-capita maize area, and larger cropped land benefited most from the
409 use of profit-maximizing N inputs (Figure 4B, 4C and 4D). Off-farm and livestock income had
410 only a marginal impact on the relative increase in food availability ratio (Figure 4E and 5F).

411 With the additional - profit-maximizing - N input, the share of food insecure maize growers
412 was predicted to drop from 28% to 13% of the total household population in Tanzania (Figure
413 5A). In Uganda, the change was marginal, i.e. from 23% to 21% (Figure 5A). The farm
414 households who could reach food security had medium to large per-capita maize area (above
415 0.17 ha in Tanzania, and 0.03 ha in Uganda) (Figure 5B). None of the households with small
416 per-capita maize area could achieve food security with the additional profit-maximizing N input
417 (data not shown).

418 **3.5. Regional-level vs household-level food security**

419 Though food insecure ($FA < 2$) households benefited more from profit-maximising N input for
420 their food security than food secure ($FA > 2$) households, they contributed only marginally to
421 the overall increase in national maize supply. Food insecure households contributed less than
422 20% to the overall increase in maize supply in Tanzania and Uganda, though they represented

423 around 40% of the total farm population in both countries (Figure 6). In contrast, food secure
424 households with large per-capita maize area, , contributed more than 60% to the overall increase
425 in maize supply in both countries, though they represented only 20 to 30% of total household
426 population (Figure 6).

427 The relative increase in regional maize supply with N fertilizer use was predicted to vary
428 between one (i.e. no increase) and three, across administrative regions in Tanzania and Uganda
429 (Figure 7A). In some regions, this increase in total maize production concurred with an increase
430 in the household-level food availability ratio for food insecure maize growers. For example, in
431 the Mtwara Region in southern Tanzania (#23 in Figure 7), regional maize supply was predicted
432 to increase three times, and the food availability ratio for food insecure households by almost
433 2.5 times. However, there were regions where despite a small predicted increase in total maize
434 supply, the predicted increase in household-level food availability for food insecure maize
435 growers was substantial. For example, in the Iringa Region in central Tanzania (#8 in Figure
436 7), total maize supply was predicted to increase 1.8 times, while the household-level food
437 availability ratio for food insecure maize growers was predicted to increase 2.3 times. Regions
438 where the potential for increasing total maize supply was highest did not necessarily match with
439 regions with the largest potential for improving household-level food security.

440 **3.1. Impact of changes in N-AE, maize price and N fertilizer cost**

441 The profit-maximizing N input, the share of beneficiaries (i.e. food insecure maize growers who
442 increased their food availability ratio with additional N fertilizer use on maize), and the relative
443 national increase in maize supply were all sensitive to changes in maize prices, N-AE and N
444 fertilizer costs (Figure 8). Changes in N-AE had the same effect as changes in maize prices on
445 the output variables of Figure 7, which is not surprising as both variables play a similar role in
446 the equation that determines profitability of N fertilizer use (see Section 2.3.3). On the other
447 hand, the median relative change in food availability ratio for food insecure maize growers was

448 not sensitive to changes in maize prices, N-AE and N fertilizer costs, because it was also
449 influenced by the share of beneficiaries (i.e. this share fluctuated in the different scenarios on
450 maize prices and N fertilizer costs) (Figure 8C).

451 **4. Discussion**

452 *4.1 Potential and obstacles of maize intensification to improve household food security*

453 Our analysis showed that a substantial share of food insecure maize growers in Tanzania and
454 Uganda could increase their household food availability in the short term with additional N
455 fertilizer use on maize. This finding matches the results of an analysis in East, West and
456 Southern Africa (comprising 1024 households in total) of Giller et al. (2021), who estimated
457 that closing the yield gap of major crops would allow more than 50% of farm households to
458 become food secure.

459 Soil properties influence the opportunity for farm households to improve their food security.
460 Largest benefits were obtained in areas with large N-AE values, that is, on sandy soils with low
461 soil organic matter and therefore low maize yields when no fertilizer was used. On the other
462 hand, smaller N-AE values were achieved on clayey soils on which maize yields in the absence
463 of fertilizer were relatively high because these soils tend to have more organic matter that can
464 mineralize and provide substantial amounts of N to the crop in the absence of fertilizer. Some
465 characteristics of the farm households were also important in enhancing food security at
466 household level. We found that the opportunity to achieve food security through intensified
467 fertilizer use increased with farm size and maize area per capita, similar to the findings of Giller
468 et al. (2021) for small farms sizes in Ethiopia, Ghana and Malawi. However, in addition to
469 intensification of crop production, off-farm income is key for enhanced food security at
470 household level. Agricultural intensification may, however, help spur a thriving rural non-farm
471 economy that can generate alternative income sources for households (Haggblade et al., 2010).

472 In this context, rural to urban migration, the so-called “natural Malthusian population control”
473 (Demont et al., 2007) can restrain further farm fragmentation in rural areas and provide at the
474 same time key remittances for the development of the rural economy.

475 Although additional N fertilizer use could substantially contribute to improved household food
476 security, this strategy was not profitable for farm households in locations where the maize price
477 and N fertilizer cost were unfavorable; the estimated profit-maximizing N input was null in
478 Western, Northern and Eastern Uganda in particular, corroborating the low current use of
479 mineral fertilizer by farmers. An increase in the price:cost ratio could be achieved with input
480 subsidy programs for maize growers for whom fertilizer is currently not profitable. Input
481 subsidy programs through which farmers can access fertilizer at below-market prices have been
482 on the rise again since 2010 in several countries of SSA (Jayne et al., 2018b). Despite failing
483 to target the poorer farmers in a number of instances (Pan and Christiaensen., 2012, Jayne et
484 al., 2013), these programs have had a measurable impact on maize productivity. For example,
485 the Farm Input Subsidy Program (FISP) in Malawi brought a 17% increase in farmers’ gross
486 margin (Karamba and Winters, 2015). Reducing transport costs (with e.g. improvements in road
487 conditions) could also contribute to lower fertilizer cost and improve the profitability of
488 fertilizer use (Guo et al., 2009). For example, the average N fertilizer price of 0.39 USD kg⁻¹ in
489 Illinois (USA) during 2001-2013 (Beckman and Riche, 2015) is about 17% of the estimated
490 price across Tanzania and Uganda in this study (2.34 USD kg⁻¹). The much lower N cost
491 reported by Beckman and Riche (2015) corresponds to the lower limit of N cost explored in the
492 sensitivity analysis of this study; this boundary is therefore not unrealistic for prices elsewhere
493 in the world. On the other hand, with a 75% increase in N fertilizer price, profit-maximising N
494 input in Tanzania was predicted to drop to zero, highlighting the drastic impact that the current
495 rise in fossil fuel prices, and thus N fertilizer prices, is likely to have on food security in SSA.
496 Seasonal variations in maize grain prices (Bonilla Cedrez et al., 2020b) can also impact fertilizer

497 profitability. Poor households usually sell their production soon after harvest when prices are
498 usually low, because they have no storage facilities and/or need cash. In our study, we
499 considered annualized maize grain prices, while farmers who are equipped with adequate
500 storage facilities and well connected to markets, may want to sell their extra produce during the
501 lean season when maize prices are higher (Burke et al., 2020).

502 Profit-maximizing N input rates increase with improved N use efficiency by maize (higher N-
503 AE values), which can enlarge the share of beneficiaries from intensification of maize
504 production, especially in Uganda. The average predicted N-AE for maize in our study was 20
505 kg grain yield kg⁻¹ N added (for a N input of 40 kg N ha⁻¹), which is well below the 32 kg kg
506 N⁻¹ or more that can be achieved in well-managed maize fields (ten Berge et al., 2019;
507 Vanlauwe et al., 2011). Our model was trained with mostly on-farm data, with possibly sub-
508 optimal weed, pest and disease management affecting N-AE. More generally, improving the
509 synchrony between crop demand and N supply following the “4R” nutrient management
510 framework (“using the right N source at the right rate, right time and in the right place”,
511 Udvardi et al., 2021) is also key to achieve greater N-AE.

512 Our analysis showed that for most farm households in Tanzania, the use of additional N
513 fertilizer was profitable. Yet, the question remains why these farmers do not actually use (more)
514 fertilizer. One reason could be that farmers lack capital to buy fertilizer, possibly also because
515 credit options to finance its purchase at the start of the season are scarce or do not exist. Another
516 explanation could be the usual risk averse nature of farmers, associated with e.g. exposure to
517 drought (Assefa et al., 2021; Jourdain et al., 2020). While fertilizer use might be profitable on
518 average, in years with, for example, drought stress leading to poor yields, farmers would not
519 break even (e.g. Bielders and Gérard, 2015). In addition, in our study we assumed that farmers
520 would apply the profit-maximizing N fertilizer input. However, in reality farmers might only
521 go for more N fertilizer if the increment in gross margin exceeds the extra N cost by a safety

522 margin. A value:cost ratio of two is typically used as a basis for adoption of a technology (e.g.
523 Jayne et al., 2018b). Lastly, the extra cost of labour for fertilizer application was not considered
524 in our study; including it would also lower the estimated profitability of fertilizer use.

525 *4.2 National food security vs household-level food security*

526 The use of additional N fertilizer was predicted to substantially increase overall regional and
527 national maize production. The food riots of 2008, the COVID-19 outbreak, and the recent war
528 in Ukraine have emphasized the vulnerability of relying heavily on food imports to national
529 governments and revived the idea of national and regional food self-sufficiency (d'Amour et
530 al., 2016; Fontan Sers and Mughal, 2020). Building resilience in SSA's states to the
531 consequences of such events, while meeting a growing food demand with population growth
532 and avoiding further cropland expansion, requires drastic increases in cereal yields. Van
533 Ittersum et al. (2016) calculated that cereal yields have to increase to close to 80% of their
534 water-limited yield potential to feed the population in SSA by 2050, and this will require a 15-
535 fold increase in nutrient inputs (ten Berge et al., 2019). Our study helps identify regions where
536 the scope to increase maize production is greatest (see Figure 7C). However, these priority
537 regions in terms of national food security do not necessarily match with the regions where the
538 scope to improve household-level food security is the strongest (see Figure 7B). Policy
539 interventions that prioritize national food security will require specific attention to this, ensuring
540 that "no one is left behind" (United Nations, 2015).

541 *4.3 Long-term sustainability of cropping systems*

542 Although relatively small profit-maximizing N fertilizer inputs (80 kg N ha⁻¹ in Tanzania, and
543 20 kg N ha⁻¹ in Uganda) may yield immediate benefits for household food security, these inputs
544 are unlikely to be sufficient to avoid soil mining and to guarantee long-term sustainability of
545 maize-based systems. Ten Berge et al. (2019) calculated that on average a minimum of 140-

546 150 kg N ha⁻¹ must be available to maize crop to sustain yields compatible with SSA food self-
547 sufficiency by 2050, i.e. far more than the profit-maximizing N fertilizer inputs computed in
548 our study. Recycling of biomass, use of farmyard manure, rotating with grain legumes and use
549 of leguminous trees in agroforestry systems can complement mineral fertilizer to provide the N
550 required to sustain high maize yields in future. The increased N fertilizer input required to
551 achieve household and national food security, while preserving long-term soil fertility, comes,
552 however, at a cost for the environment in the form of N leaching losses and gaseous emissions.
553 Narrowing the maize yield gap in SSA will undoubtedly increase N₂O emissions (Leitner et al.,
554 2020). Yet, van Loon et al. (2019) estimated that meeting the food demand in SSA by 2050
555 through intensification of cereal production with mineral fertilizer, assuming good agronomy
556 and using the '4R' principles of nutrient management, would emit less greenhouse gases than
557 through cropland expansion from deforestation. Large fertilizer inputs, if not retained in soils,
558 can also contribute to eutrophication in lakes, inland and coastal waters, with direct threats to
559 biodiversity and human health. The '4R' approach to nutrient management that is crucial for
560 increasing nutrient use efficiency and profitability, will at the same time reduce leaching and
561 run-off of nutrients causing eutrophication.

562 *4.4 Opportunities to use and improve the proposed framework*

563 Extending our analysis to other countries or regions with larger land holdings and possibly
564 larger maize area per capita would be necessary to fully grasp the potential of maize
565 intensification to contribute to improved food security throughout SSA, e.g. in the cotton basin
566 in Mali the median cultivated land area per capita is 0.84 ha compared with 0.13 ha in central
567 Malawi and 0.14 ha in the Ethiopian highlands (Giller et al., 2021). Besides, other crops than
568 maize, e.g. traditional grains like sorghum and millet, rice, legumes (e.g. groundnut and
569 cowpea), highland banana, root and tuber crops and vegetables, have to be considered to
570 quantify the full potential of intensification and diversification of crop production to reduce

571 food insecurity. It will however, be challenging to do this with an empirical model as there is
572 less data available for these types of crops than for maize.

573 The accuracy of the RF model of our study ($R^2 = 0.82$) was better than that of a model trained
574 on yields measured in 601 field trials in Tanzania [$R^2=0.24$, Palmas and Chamberlin, (2020)],
575 highlighting the importance of training the model on a large dataset. The main features of our
576 model were in line with the findings of a meta-analysis of 71 studies across SSA that showed
577 that soil texture, pH and exchangeable K were the main factors explaining variability in N-AE
578 (Ichami et al., 2019). Soils can vary substantially in macro and micro-nutrient content at short
579 distances – owing to past crop management by farmers (Falconnier et al., 2016). The variations
580 of crop responses to nutrient inputs depending on rainfall season (short vs long in area with two
581 growing seasons per year) would also deserve further analysis. With the current data, total
582 rainfall, and other indicators related to its distribution, only marginally improved the ability of
583 the RF model to explain maize yield variability. Process-based crop models could be used to
584 simulate crop responses to fertilizer inputs. This type of models can be calibrated with data
585 from a limited set of trials spread across representative locations and then used to make
586 predictions at any location (see Deng et al., 2019 for an example). More specifically, process-
587 based crop models can account for the impact of drought or excessive rainfall on fertilizer use
588 efficiency, and are useful to determine the probability of yield failure and the risk of not
589 breaking-even when using fertilizer (e.g. Ricome et al., 2017). Risk assessment will help to
590 further distinguish areas where fertilizer use is a low-risk opportunity for farmers and those
591 where its use is too risky and must be complemented with specific interventions [e.g. index-
592 based insurance (Benami et al., 2021)].

593 Lastly, local variations in prices of maize and costs of fertilizer, due to e.g. transportation costs
594 that are not included in the spatial price predictions, and uncertainty of farmer-reported crop
595 areas are substantial sources of uncertainty in our analysis, as pointed out in our sensitivity

596 analysis. Our study and the proposed framework could therefore guide national and regional
597 priority settings of interventions around intensification of maize production with fertilizer, but
598 should be complemented with place-based assessments of the local relevance of proposed
599 interventions.

600

601 **Conclusions**

602 Intensification of maize production with mineral fertilizer can substantially improve the food
603 security of food insecure households in Uganda and Tanzania. Households with relatively large
604 per-capita maize area benefit most, as well as those located in areas where maize yields are low
605 in the absence of fertilizer use and where yield responses to nutrients are high. In some areas,
606 particularly in Uganda, profit-maximizing N fertilizer input is low, and the potential of maize
607 intensification through fertilizers to reduce food insecurity is thus limited. Institutional
608 commitment to smart input subsidies and investments in road networks could lower fertilizer
609 price, and broader investments in agricultural research, development and extension to
610 operationalize best-practices (better seed quality, timely planting, optimal plant density, and
611 proper weed, pest and disease management) could help to improve nutrient use efficiency by
612 crops. Our study brings important insights for priority setting as high potential areas for
613 increased maize domestic production do not necessarily match with areas where there is
614 immediate scope for improving household-level food security. These two impact levels should
615 be coherently considered when articulating policy and research priorities that aim at improving
616 food security at household level and regionally.

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624

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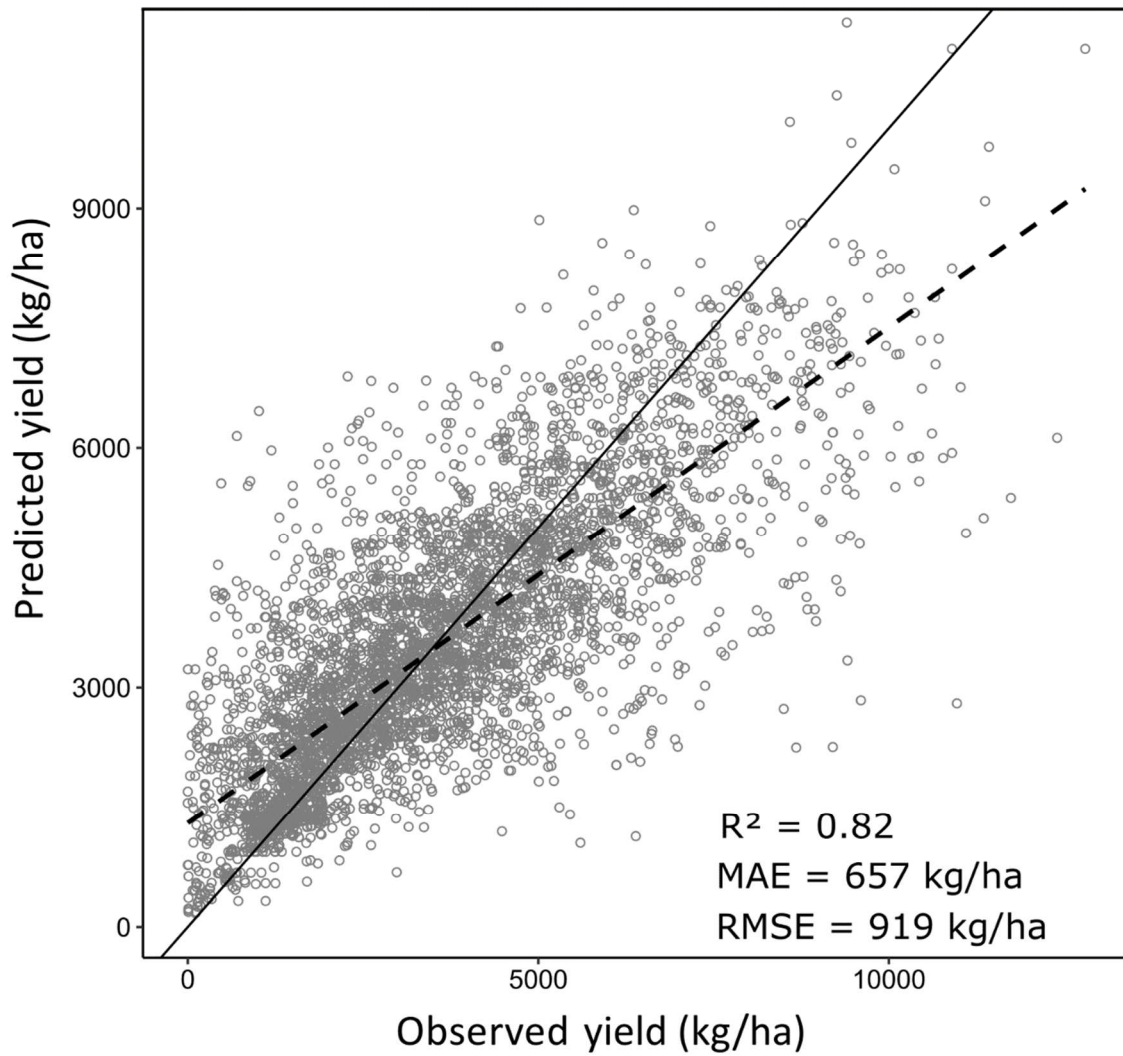


Figure 1: Observed and Random Forest predictions of maize yield for the maize trials across sub-Saharan Africa used for model validation. The solid line is the 1:1 line, the dotted line is the regression line of predicted vs observed values.

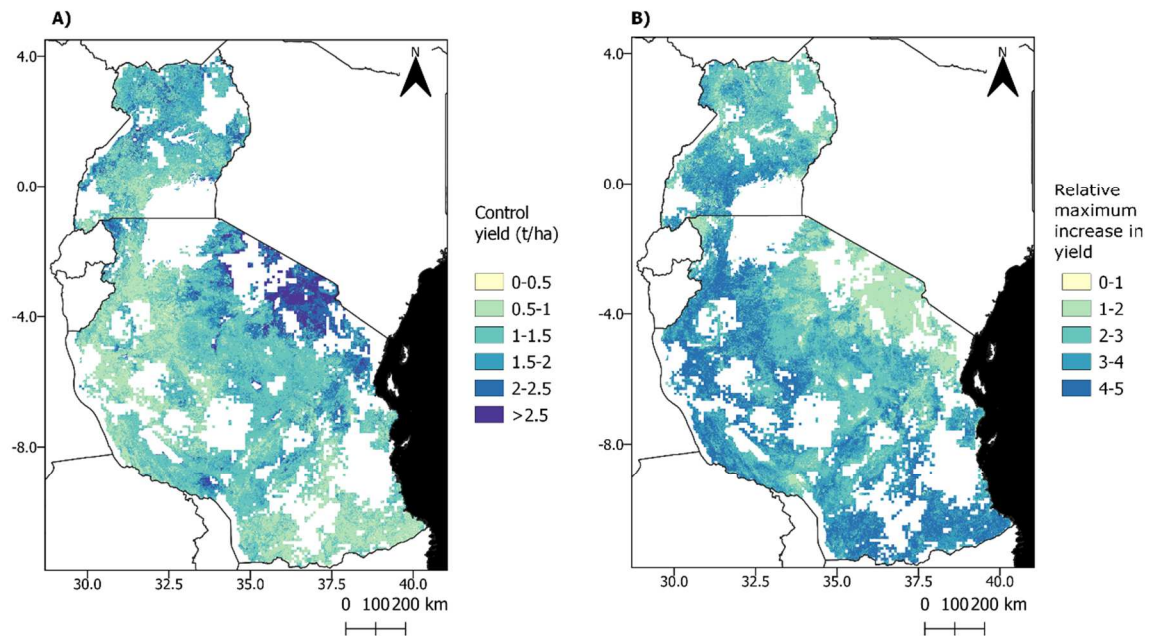


Figure 2: A) Control maize yield (no fertilizer input) predicted by the Random Forest model and B) maximum relative increase in yield (i.e. yield with maximum (200N/20P/20K) fertilizer application divided by control yield). Areas in Uganda and Tanzania where maize is not grown (according to IFPRI, 2020) appear in white. In areas with two (short and long) cropping seasons per year, the model predicted the same yield because weather-related variables were not used as input to the Random Forest model.

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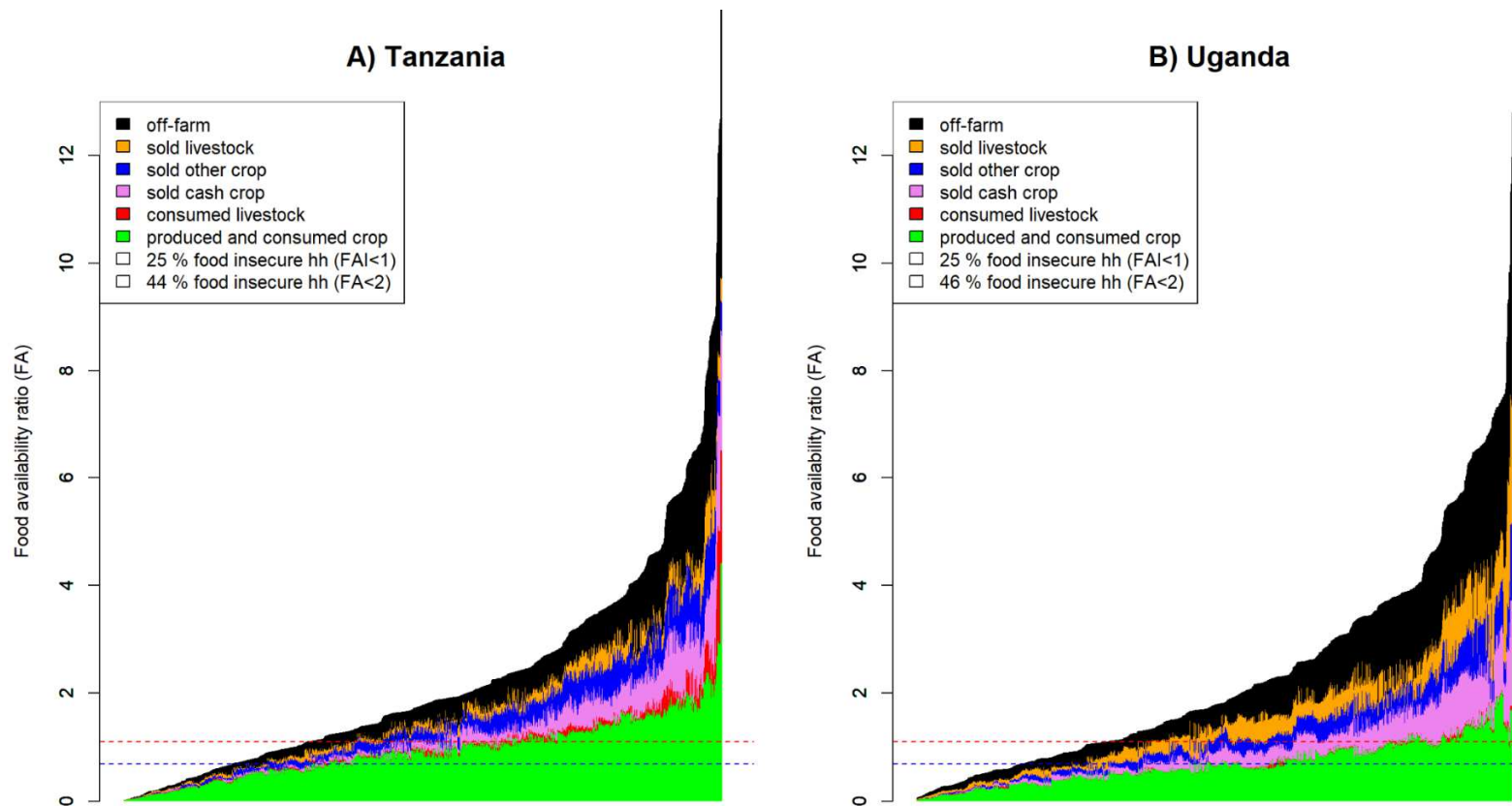


Figure 3: Household (hh) food availability ratio (FA) for 2435 households in Tanzania (A) and 1753 households in Uganda (B). The y-axis was log-transformed so that $y = \log(FA + 1)$. Households were ordered by increasing food availability ratio (i.e. the ratio of available food to the required food) along the x-axis. A bar is one household. The red dashed line is the 5000 kcal cap⁻¹ day⁻¹ food security threshold (i.e. food availability ratio =2), and the blue dashed line is the 2500 kcal cap⁻¹ day⁻¹ food security threshold (i.e. food availability ratio =1). A rolling average was applied with subsets of 30 households to smooth the curves for easier interpretation. Different colours indicate the source of the food, be it produced on-farm or purchased. Crops were considered as cash crops when more than 90% of the annual production was sold. Large values of sold and consumed crop on the right side of the plots correspond to potential bias in survey data rather than to real consumption values.

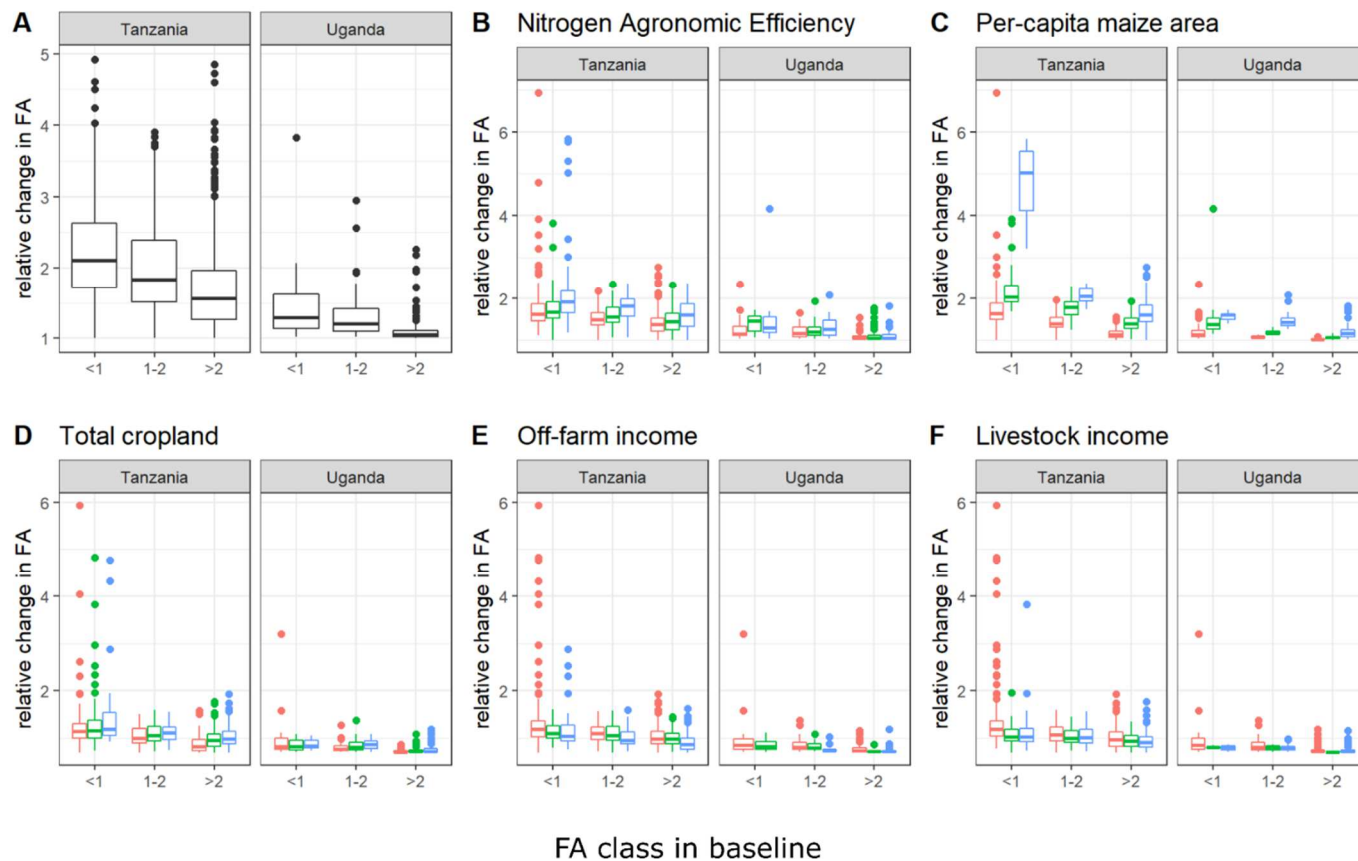


Figure 4: Boxplots of relative change in Food availability ratio (FA) per FA class in baseline (i.e. with current reported N input on maize) in Tanzania and Uganda (A), and for three classes of nitrogen agronomic efficiency (N-AE) (B), per-capita maize area (C), total cropland (D), off-farm income (E) and livestock income (F). Red boxplot are households below the 33th percentile of the considered N-AE or farm characteristic, green boxplots are households between the 33th and 66th percentile, and blue boxplots are households above the 66th percentile. The y-axis was log-transformed so that $y = \log(\text{relative change in FA} + 1)$.

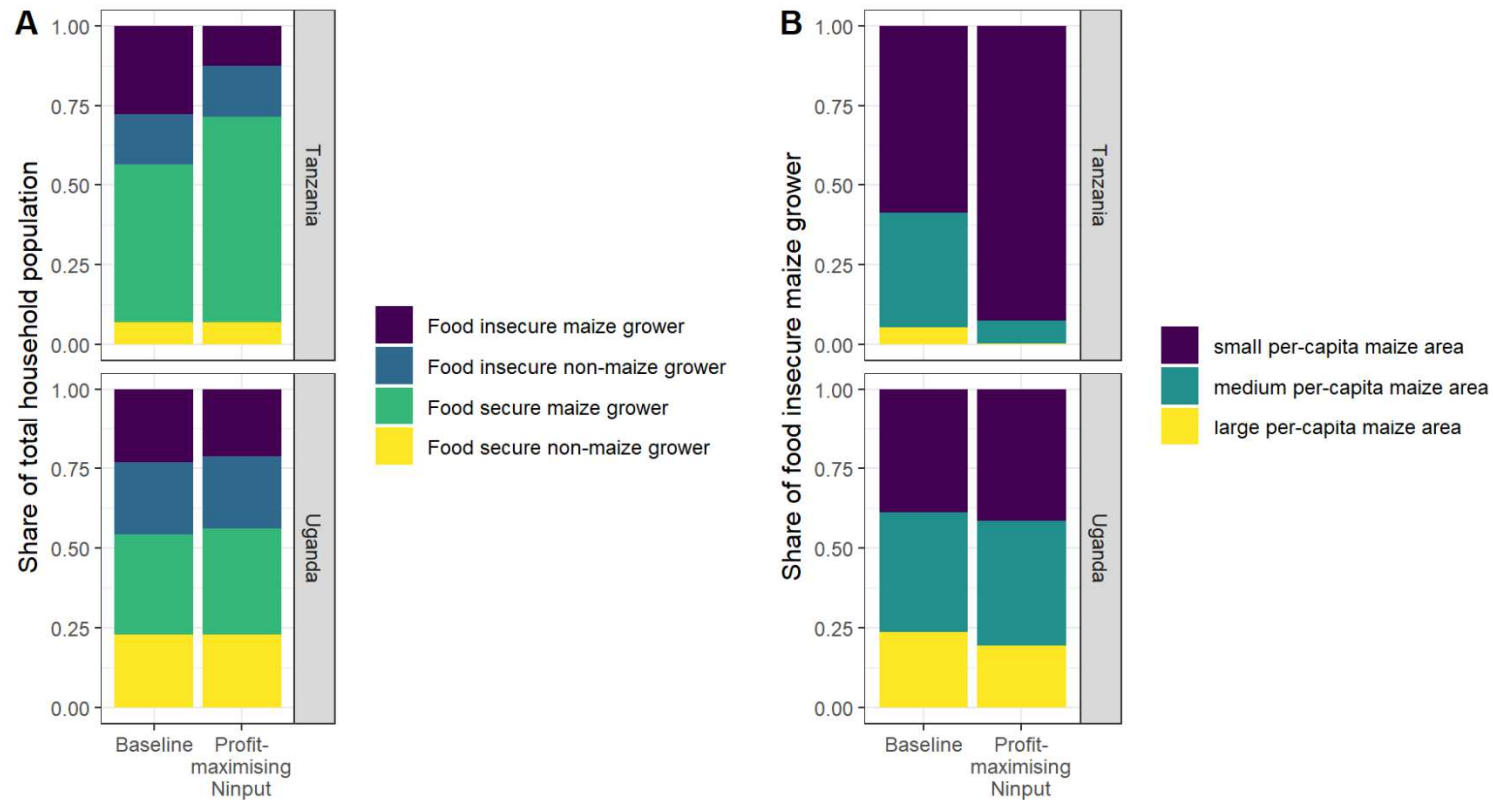


Figure 5: (A) Share of food insecure maize growers in total agricultural household population in baseline situation (current maize yield) and with profit-maximizing N input on maize in Uganda and Tanzania and (B) share of these food insecure maize growers who have small per-capita maize area (<0.17 ha in Tanzania and <0.03 in Uganda), medium per-capita maize area (0.17-0.38 ha in Tanzania and 0.03-0.07 in Uganda) and large per-capita maize area (>0.38 in Tanzania and >0.07 in Uganda)

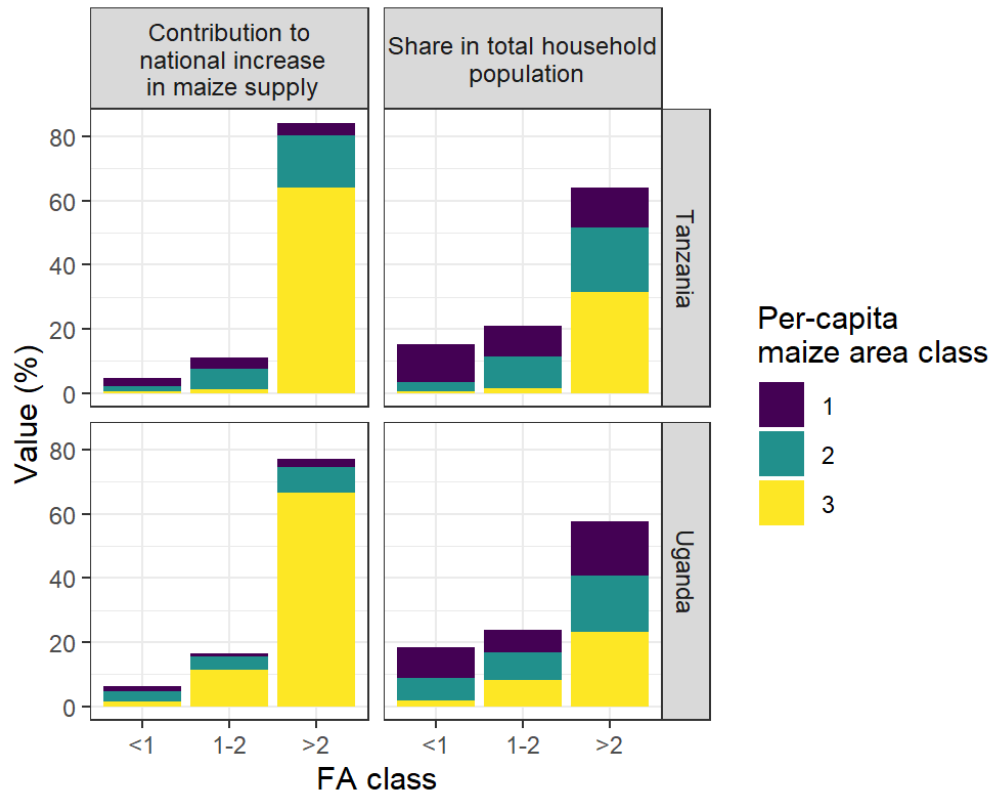


Figure 6: Comparison between the i) relative contribution to national increase in maize supply and ii) share in total household population, for household of contrasting food availability ratio (FA) and maize area per capita classes in Tanzania and Uganda. Class 1 for per-capita maize area is <0.17 ha in Tanzania and <0.03 in Uganda, class 2 for per-capita maize area is 0.17-0.38 ha in Tanzania and 0.03-0.07 in Uganda, and class 3 for per-capita maize area is >0.38 in Tanzania and >0.07 in Uganda.

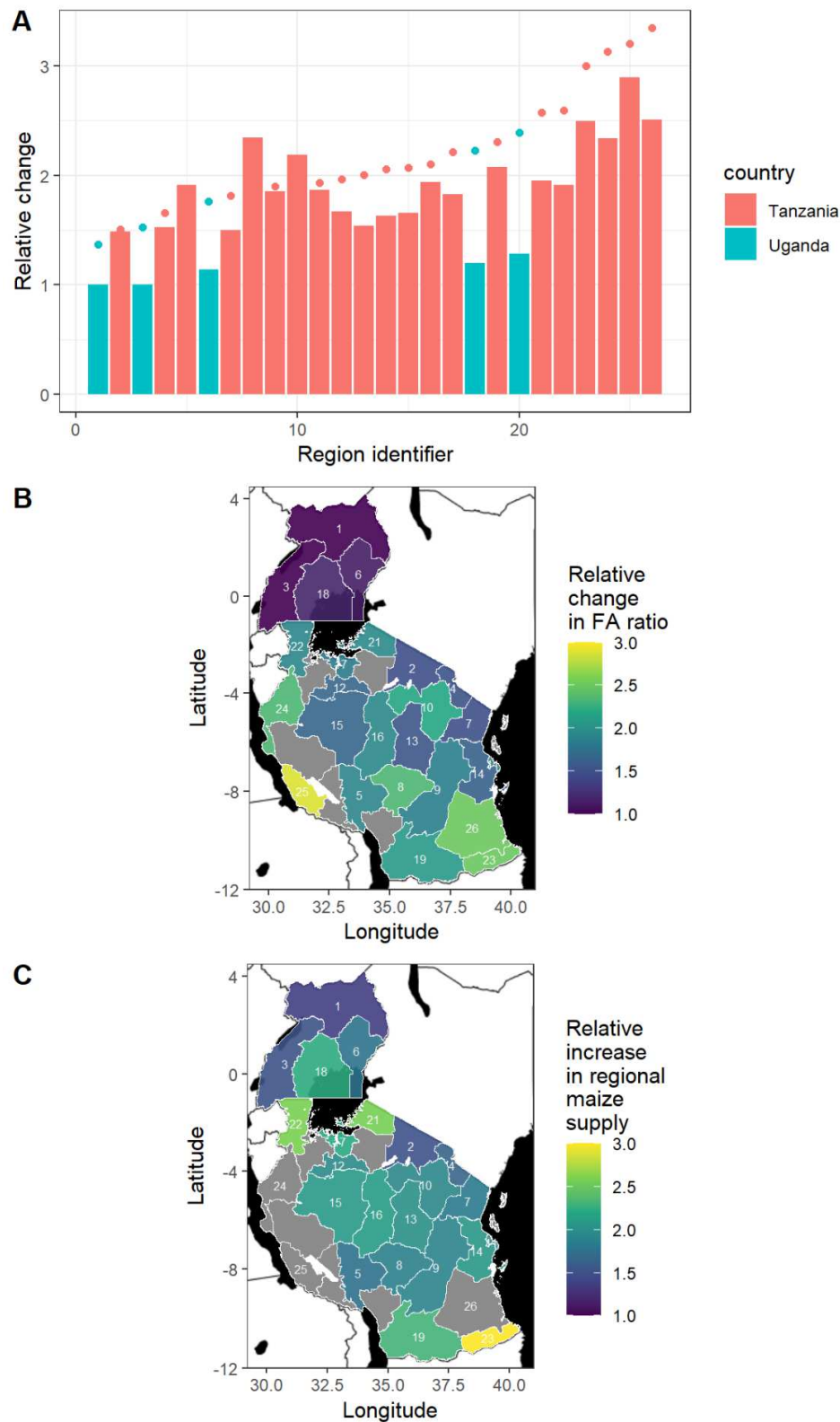


Figure 7: A) Relative change in regional maize supply (dots) and median relative change in household-level food availability (FA) ratio for food insecure maize-growers (with the use of additional, profit-maximizing N input), in regions of Uganda and Tanzania (bars), B) map of regional median relative change in food availability ratio for food insecure maize-growers, and C) map of relative increase in regional maize supply. Numbers in the map are number of regions that correspond with the Region identifier along the x-axis of figure A.

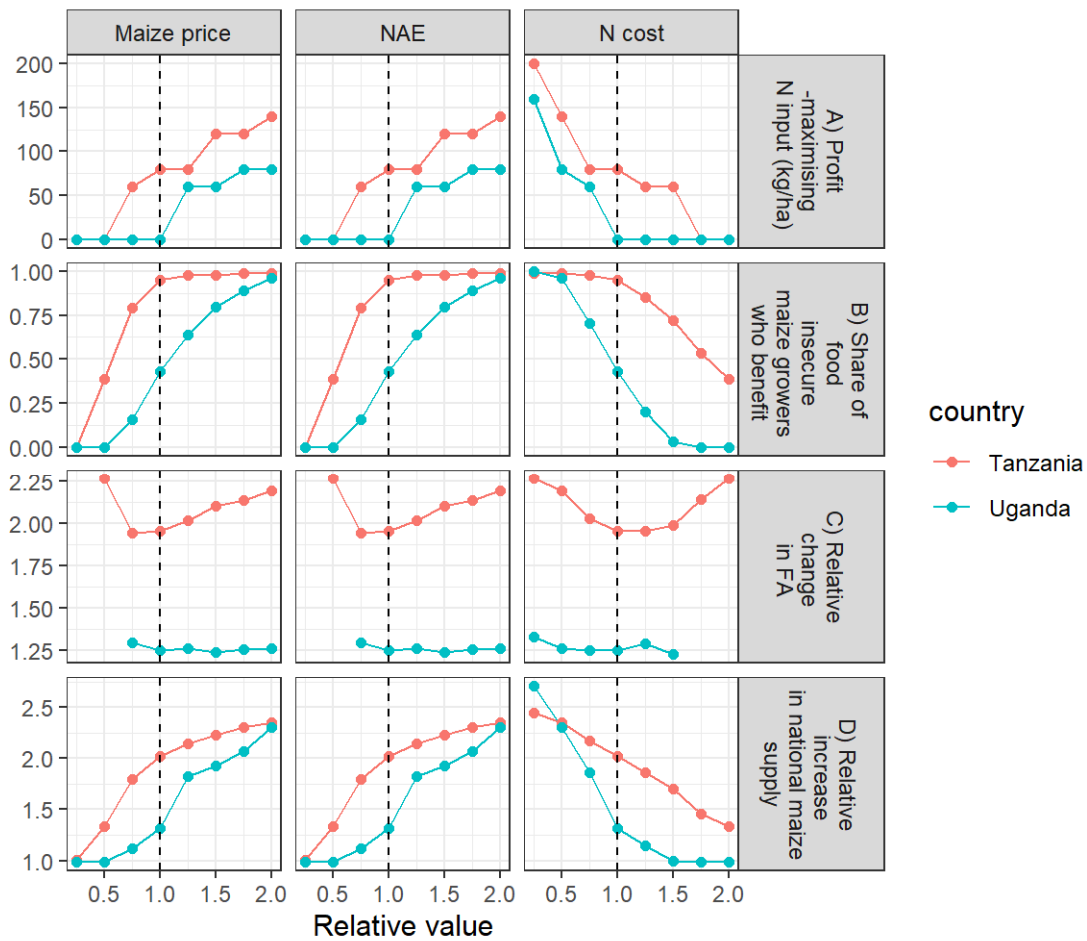


Figure 8: Sensitivity analysis of the impact of a change in maize price, nitrogen agronomic efficiency (N-AE) and N cost on A) profit-maximizing N input, B) share of food insecure maize growers who increase their food availability ratio with the use of additional profit-maximizing N input on maize, C) median relative change in food availability ratio (FA) for food insecure maize growers, and D) relative increase in national maize supply due to the use of additional N input on maize, in Tanzania and Uganda.

