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Crop diversity buffers the impact of droughts and high temperatures on food production

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30 **Introduction**

31 Weather extremes, including heat waves and droughts, are major determinants of food
32 production shocks at the global scale (Ray *et al* 2015, Lesk *et al* 2016, Anderson *et al* 2019,
33 Cottrell *et al* 2019). Effects of these shocks are particularly severe in developing countries
34 where a high proportion of people rely on local, mainly rain-fed agriculture for consumption
35 and livelihoods, where political unrest and chronic poverty reign, and where financial
36 insurance mechanisms are inexistent or inaccessible (Morton 2007, Maxwell and Fitzpatrick
37 2012, Harvey *et al* 2014, Carleton 2017). More intense and frequent extreme weather events
38 are expected in the future (Pörtner *et al* 2022), fueling concerns about the vulnerability of
39 food systems (Thiault *et al* 2019) and humanity's ability to combat hunger (Sustainable
40 Development Goals 2, [UN General Assembly 2015]). In this context, international
41 organizations are calling for bold actions to evaluate risk-adverse solutions that can help
42 maintain food security under conditions of more unpredictable weather (FAO, IFAD,
43 UNICEF 2021).

44 Agricultural adaptation strategies to cope with climate change have so far mainly focused on
45 technological fixes. But on the ground, greater use of fertilizers and modern varieties have not
46 shown clear success in reducing the sensitivity of crops to climate extremes (Schlenker and
47 Lobell 2010, Zaveri and Lobell 2019). Moreover, increased reliance on fertilizers and
48 irrigation has generated numerous negative consequences (Foley *et al* 2011, Poore and
49 Nemecek 2018). These include greenhouse gas emissions (Crippa *et al* 2021), groundwater
50 depletion and pollution (Dubois 2011), that compromise efforts towards climate change
51 mitigation and sustainability (Sayre and Taraz 2019, Blakeslee *et al* 2020, Ryan and
52 Sudarshan 2022). Finally, these solutions tend to be expensive and their adoption may be slow
53 in the developing world, where farmers are poor and limited liquidity constrains agricultural
54 decisions (Tittonell and Giller 2013, Karlan *et al* 2014).

55 Attention to technological solutions may mirror a tendency of research to focus on a few
56 number of globally dominant crops, i.e maize, wheat, rice and soybeans (Lobell and Field
57 2007, Schlenker and Lobell 2010, Lobell *et al* 2011, Osborne and Wheeler 2013, Iizumi *et al*
58 2014, Ray *et al* 2015, Iizumi and Ramankutty 2016, Lesk *et al* 2016, Anderson *et al* 2019, Li
59 *et al* 2022), whose management facilitates the implementation of technology. These crop-
60 specific approaches have led to a better evaluation of the fine-scale spatial variability of the
61 effects of temperature and precipitation on the yield of major crops. However, this approach

62 may hide the way a wider diversity of crops influences responses to weather variability. It
63 remains unknown whether accounting for the diversity of crops and their responses changes
64 the relative balance of the effects of temperature and rainfall variability on the aggregated
65 response of a crop portfolio.

66 Plant diversity is considered to be a promising “nature-based” solution to meet multiple ends
67 in agriculture (Beillouin *et al* 2019, Dainese *et al* 2019), including the reduction of climate-
68 driven risks of crop failure (Renard and Tilman 2019). Decades of ecological research have
69 shown that increasing plant taxonomic, genetic or functional diversity in natural ecosystems
70 confers greater ecological stability (Donohue *et al* 2016) through increased resistance to
71 climate stresses (Isbell *et al* 2015) and lower year-to-year variability of biomass production
72 (Tilman and Downing 1994, Gross *et al* 2014, García-palacios *et al* 2018, Schnabel *et al*
73 2021). Comparatively, research on agricultural systems critically lags behind (Beillouin *et al*
74 2019, 2021). The few existing studies do support the notion that increasing crop diversity
75 leads to lower year-to-year variability in both yield (Smith *et al* 2008, Gaudin *et al* 2015,
76 Prieto *et al* 2015, Raseduzzaman and Jensen 2017, Renard and Tilman 2019) and incomes
77 (Falco and Chavas 2008, Chavas and Di Falco 2012, Auffhammer and Carleton 2018, Noack
78 *et al* 2019) from fields to countries. However, the potential of crop diversity to buffer crop
79 production and revenues against extreme weather events, and thus increase resistance, needs
80 to be evaluated.

81 Hypotheses about the mechanisms governing the diversity-stability relationships involve
82 mainly two processes (Thibaut and Connolly 2013, Xu *et al* 2021). The first one is based on a
83 selection effect: the more species there are in an ecosystem, the more likely it is that at least
84 one species is less sensitive to a given climate condition. The second process is based on a
85 complementarity effect. Complementarity arises from species differences in their ecological
86 niche (Barry *et al* 2019), a principle that underpins the concept of the insurance effect of
87 biodiversity (Tilman *et al* 1998, Ives and Carpenter 2007, Loreau and Mazancourt 2008,
88 Gross *et al* 2014). Accordingly, in a diversified system, one crop may fail, but multiple
89 failures are less likely. Because different crop genotypes, varieties or species exhibit different
90 responses to temperature and precipitation (i.e contrasting ecological niches), fluctuations in
91 productivity among plants can compensate each other and lead to greater resistance in a given
92 year or greater stability through time. At the country level, Mahaut *et al* (2021) showed that
93 fluctuations in the yield of crops that cover large proportions of harvested area (i.e., selection
94 effect), and the asynchronic dynamics that occur between crops (i.e., insurance effect), both

95 modulate climate-induced temporal variability of total yield of countries. However, only a
96 few studies so far tested for processes underlying the crop diversity-stability relationship at
97 large scale.

98 Here, our aim is to fill important gaps in the research linking biodiversity and stability in
99 agricultural systems. We test whether crop diversity within countries increases the resistance
100 of total caloric yield and economic revenues (all crops included) to weather extremes using 58
101 years (1961–2018) of annual data. We focused our study on droughts and high temperatures,
102 two types of extremes that are recognized as major threats to food supply (Pörtner *et al* 2022).
103 Agricultural data were matched with weather data based on the specific spatial extent of
104 individual crops. We further test whether the selection and/or the complementarity (through
105 the insurance) effects can explain the increased resistance to weather extremes conferred by
106 greater crop diversity at the country level.

107

108 **Material and Methods**

109 **Agricultural data.** The FAOSTAT database provided data on annual cropland and harvested
110 area (in ha), production (in tonnes) and agricultural revenues (in 2015 equivalent US dollars)
111 for an initial set of 246 countries and 176 crop commodities. From the initial list of crops, we
112 discarded aggregated crop categories (e.g. citrus or other cereals) and crops grown in fewer
113 than ten countries. Because agricultural yields and revenues, and their response to weather
114 extremes, are likely to be influenced by conditions linked to agricultural management, we
115 used annual total application of nitrogen and total cropland equipped with irrigation at the
116 country level from the FAOSTAT database as covariates. Quality of FAOSTAT data varies
117 among countries, depending on whether they have been estimated by the FAO or
118 communicated directly by countries. We accounted for this difference by removing 33
119 countries for which at least 20% of data on area harvested or production over the entire time
120 period had to be estimated (following Renard and Tilman 2019). We also discarded Ireland,
121 New Zealand and Netherlands, all of which use much of their fertilizer on pastures rather than
122 for croplands, and Egypt, which has 100% of its cropland equipped with irrigation for the
123 entire time period. For each of the remaining countries ($n = 127$) and for each year, we
124 calculated the total annual caloric yield (millions of kcal/ha) by (1) multiplying the production
125 of each of its crops by commodity-specific kcal conversion factors from the USDA's Nutrient

126 Database (2013); (2) summing these kcal harvests across all crops; and (3) dividing this sum
127 by the sum of all harvested land for all these crops. Similarly, for each country and each year,
128 we calculated the total annual agricultural revenues per hectare by dividing the total revenues
129 by the total harvested area (in constant 2015 USD \$/ha). We quantified crop diversity using
130 the Shannon-Wiener diversity index (H') based on the proportion of total area harvested
131 represented by each crop grown annually by each country studied. We calculated the annual
132 rate of application of nitrogen and irrigation per hectare by dividing their use by the total
133 cropland area in each country and each year. Sources of all the data are summarized in
134 Supplementary table 1.

135 **Weather data.** We obtained global 0.5° gridded temperature (in degrees Celsius) data from
136 the Climate Research Unit of the University of Anglia (CRU TS v.3.23, Harris *et al* 2014) for
137 the 1961 to 2018 period. We used these data to identify years with high growing season
138 temperatures (we provide details of the calculation below). In years with high growing season
139 temperatures, crops are expected to experience heat stress that affect their metabolic processes
140 and biomass production. Droughts are mostly related to a reduction in the amount of
141 precipitation, but they are also influenced by other variables including temperature and
142 evapotranspiration (Vicente-Serrano *et al* 2010). To quantify wet and dry annual weather
143 events, we used the global 0.5° gridded Standardized Precipitation-Evapotranspiration Index
144 (SPEI) from Vicente-Serrano *et al* (2010), an index that is based on both precipitation and
145 potential evapotranspiration (PET) data. The SPEI12 index was calculated for a period of one
146 year using the monthly climatic water balance (i.e., precipitation minus PET) from the CRU
147 database. SPEI index values are centered around zero to allow comparison of drought severity
148 through time and space (Vicente-Serrano *et al* 2010a). In order to simplify interpretation, we
149 used the negative of the SPEI index so that water deficits, hereafter referred to as droughts,
150 have positive values.

151 **Combining weather and crop data.** To match the weather data to the agricultural data, we
152 first calculated temperature and SPEI for each country across all cropland areas (i.e all crops
153 included). We derived monthly temperature and SPEI values for the cropland area in each
154 country by taking the monthly values of each grid cell in a country, weighted by the
155 proportion of cropland in each gridcell (Monfreda *et al* 2008). Then, we calculated
156 temperature and SPEI for each country across annual growing seasons by averaging monthly
157 weather values over months of country-specific crop-growing-season calendars (Sacks *et al*
158 2010). Second, we derived annual temperature and SPEI conditions for the 154 individual

159 crop commodities for which the global harvested area at 5 min resolution was mapped by
 160 Monfreda *et al* (2018). We derived monthly temperature and SPEI values for each crop in
 161 each country by taking the monthly values of each grid cell in a country, weighted by the
 162 proportion of harvested area each crop occupied. Then, we calculated crop-specific
 163 temperature and SPEI across countries and annual growing seasons by averaging monthly
 164 weather values over months of country-specific growing-season calendars. Finally, we tested
 165 for the role of extreme temperatures by identifying years with a growing season temperature
 166 one standard deviation above the 1961-2018 growing season temperature average. This was
 167 made for both the cropland and the crop-specific analysis.

168 **Statistical analyses.** After the data cleaning process and homogenization between agricultural
 169 and weather data, the database comprised 127 countries (see Supplementary table 2 for the
 170 complete list) and 109 crop commodities. We first tested whether the response of total crop
 171 caloric yield and revenues to weather conditions depended on the diversity of crops grown
 172 within countries. We built models that account for management conditions (irrigation and
 173 nitrogen use) and other confounding factors. Using ordinary least squares (OLS) regression
 174 we estimated:

$$\begin{aligned}
 175 \quad & Y_{jt} = \\
 176 \quad & \beta_1 Weather_{jt} + \beta_2 Diversity_{jt} + \beta_3 Nitrogen_{jt} + \beta_4 Irrigation_{jt} + \beta_5 Diversity_{jt} \times \\
 177 \quad & Diversity_{jt} + \beta_6 Weather_{jt} \times Nitrogen_{jt} + \beta_7 Weather_{jt} \times Irrigation_{jt} + \gamma_j + \\
 178 \quad & \delta_t + \varepsilon_{jt} \quad (1)
 \end{aligned}$$

179 where Y_{jt} was the log transformed total output measured either in caloric yield or in revenues,
 180 aggregated across all crop species, in country j in year t . *Weather* is the weather during the
 181 growing season and cropland area of country j in year t . We ran separate regression models
 182 with high growing season temperatures and SPEI. We did not include both weather variables
 183 simultaneously since SPEI uses temperatures to calculate the PET. The three remaining
 184 variables of interest, crop diversity (*Diversity*), nitrogen fertilizer use (*Nitrogen*) and irrigation
 185 (*Irrigation*) have been calculated for each country j and year t . Here, we paid particular
 186 attention to the coefficients of the interaction terms. These measure the impact of crop
 187 diversity, fertilizer and irrigation on the responses of total caloric yield and revenues (Y),
 188 respectively, to weather extremes. We expected β_1 to be negative, reflecting a detrimental
 189 impact of droughts or high temperatures on Y , and the interaction term $\beta_5 Weather_{jt} \times$
 190 $Diversity_{jt}$ to be positive. A positive interaction would reflect the potential for increases in
 191

192 crop diversity to reduce or buffer the impact of droughts or high temperatures on Y . Because
193 *Diversity, Fertilizer and Irrigation* could respond to weather extremes and capture a direct
194 effect of these events on yield and revenues, we ran separate models where these variables
195 were lagged by one year. We expected that fertilizer use, irrigation and crop diversity in the
196 previous year were good predictors of the same variables in the current year and served as
197 tests of robustness for our results.

198 The last three terms were country fixed effects (country dummies), year fixed effects (year
199 dummies) and the error term. These fixed effects capture the cross-country differences
200 (including pedoclimatic conditions) and general changes in our variables over time due to
201 technological progress (for example). We therefore only used deviations of diversity and
202 output from country means and global trends to estimate our parameters. Given that variables
203 in our models were measured in different units and showed heterogeneous value ranges, we
204 normalized each predictor across all countries and over the full 58-year time period to enable
205 the quantitative comparisons of the model coefficients (Schielzeth 2010). To evaluate whether
206 crop diversity increased the resistance to weather extremes differently in different parts of the
207 world, we ran separate models for each of seven world regions (as classified by the World
208 Bank), excluding two regions with fewer than 10 countries (i.e., North America and South
209 Asia).

210 To disentangle how the selection of more resistant crops and complementarity
211 between them underlined the effects of crop diversity on the resistance of agricultural
212 production and revenues, we first evaluated the individual response of each crop to SPEI and
213 high temperature. To do this, we used OLS regressions for each individual crop with the
214 following form:

$$Y_{ijt} = \beta_1 \text{Weather}_{ijt} + \gamma_i + \delta_t + \varepsilon_{ijt} \quad (2)$$

215
216 Where y_{ijt} was the total caloric yield of the crop i , in country j in year t . For *weather*, we ran
217 separate models with high growing season temperatures and SPEI over cropland area specific
218 to the crop i . The resulting coefficient β_1 provided information about the direction and
219 strength of the response of crop i to either droughts or high temperatures. Because we didn't
220 have crop-specific data on irrigation and fertilizer use, we did not include these variables in
221 our model (2). Using simple regression models, we tested the relationship between individual

222 crop responses to weather and total harvested areas or average revenues, respectively. Total
223 global area and revenues were calculated across the 127 countries in our dataset. We
224 hypothesized that main crops worldwide were also the most sensitive to weather extremes.
225 Second, for each country, we computed the weighted mean (W_{mean}) and the weighted
226 variance (W_{var}) of individual crop responses to droughts and high temperatures to
227 approximate the roles of selection and complementarity effects, respectively. To do this, we
228 weighted individual crop responses by crop-specific area harvested measured at the country
229 level. High W_{mean} values of the crop portfolio correspond to countries where the most
230 abundant crops (in terms of harvested areas) showed low sensitivity to weather extremes,
231 either high temperatures or droughts. High W_{var} values indicate that the most abundant crops
232 grown in a country display a great diversity of responses to weather extremes. We replaced
233 crop diversity in our model (1) by values of W_{mean} and W_{var} to test which of these two
234 facets of the sensitivity of crop portfolio of countries drove the responses of caloric yield and
235 revenues to weather extremes. All interactions among variables were included.

236 Statistical analyses were conducted using the R software v.1.4.1717, packages lfe (Gaure
237 2013) and Weighted.Desc.Stat (Parchami 2019).

238 **Results**

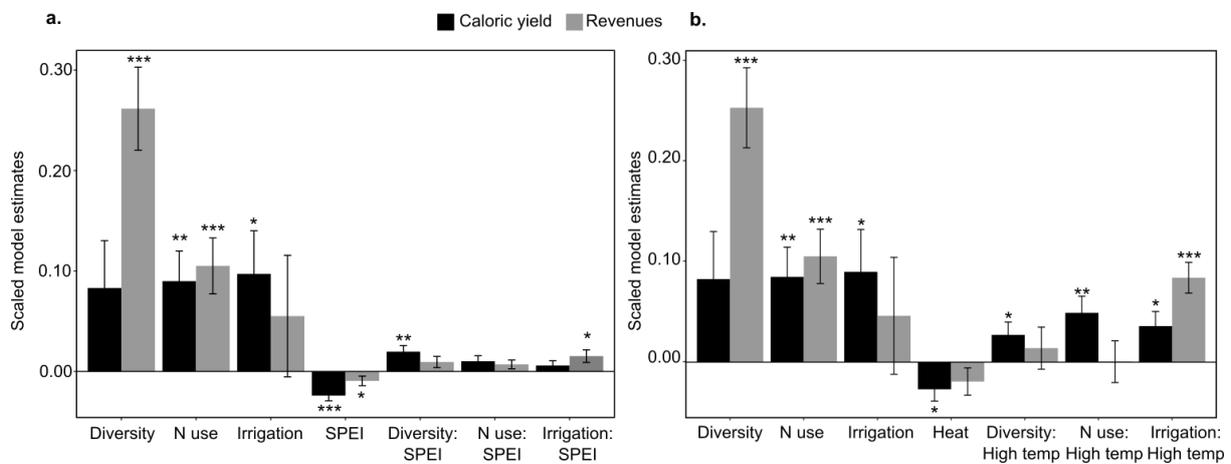
239 Total caloric yield significantly declined with droughts (figure 1(a)) and high temperatures
240 (figure 1(b)) while total economic revenues significantly declined only with droughts.
241 Consistently between models (using either drought or high temperatures), we found a stronger
242 impact of weather on yield than on revenues. We also found that total caloric yield
243 significantly increased with nitrogen and irrigation use and that total revenues strongly
244 increased with crop diversity and nitrogen use at the country level (figure 1) (model results
245 are detailed in the Supplementary table 3).

246 We found significant positive interaction effects affecting total caloric yield; between
247 droughts and crop diversity and between high temperatures and crop diversity. The
248 interactions mean that the negative impacts of the two weather extremes on total caloric yield
249 were significantly reduced as crop species diversity within countries increased (figure 1,
250 Supplementary table 3). Standardized estimates of our models suggested that increasing crop
251 diversity by one standard deviation at the country level canceled out the global impact of high
252 temperatures ($\text{Estimate}_{\text{High temp}} = -0.027$, $\text{Estimate}_{\text{High temp:Diversity}} = 0.028$), and almost canceled

253 out the impact of droughts on caloric yield ($\text{Estimate}_{\text{Drought}} = -0.024$, $\text{Estimate}_{\text{Drought:Diversity}} =$
 254 0.020).

255 We found that nitrogen or irrigation use have comparably buffered the impacts of high
 256 temperatures on total caloric yield. Finally, model results suggested that increasing irrigation
 257 use significantly reduced the negative impact of droughts and high temperatures on total
 258 revenues of countries (Supplementary table 3). Our results were robust to changes in the
 259 specifications of our statistical models (Supplementary table 4).

260



261
 262 **Figure 1:** Main determinants of total caloric yield (in black) and economic revenues (in grey)
 263 calculated at the country level. Figure (a) shows results for the model including droughts
 264 (SPEI) and figure (b) a similar regression, but using an indicator of growing season high
 265 temperatures. Stars indicate the significance level of each predictor (* P<0.05; **P<0.01;
 266 ***P<0.001).

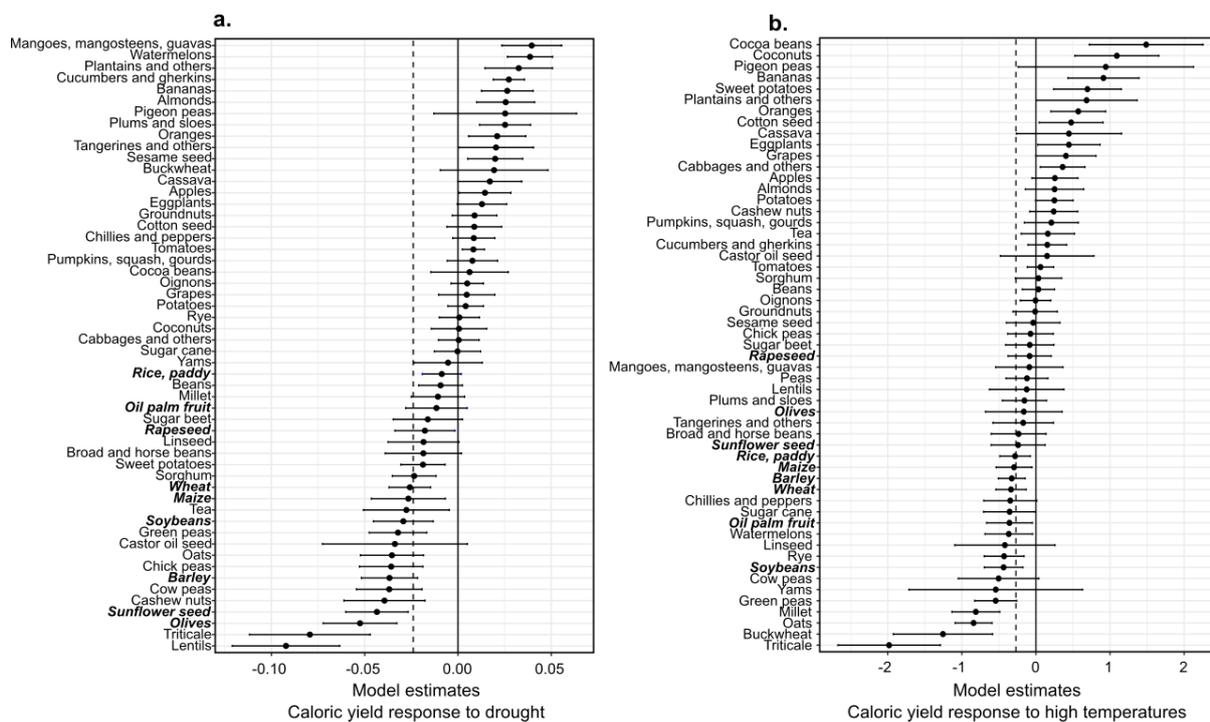
267

268 At the regional level, total caloric yield in countries of East Asia & Pacific (n = 24), Middle
 269 East and North Africa (n = 20) and Sub-Saharan Africa (n = 35) were the most negatively
 270 impacted by droughts. In countries of Sub-Saharan Africa, crop diversity had the largest
 271 positive impact on total caloric yield. Increased crop diversity also significantly buffered the
 272 negative impact of droughts on yield in this region, as shown by the significant positive
 273 interaction terms. A comparable result was found for countries of East Asia & Pacific. As for
 274 the general models, regional agricultural revenues showed less impacts from droughts in
 275 comparison with yield. Only revenues of Sub-Saharan Africa were significantly affected and

276 again, we found that crop diversity had a buffering effect. Countries of Sub-Saharan Africa
277 were also the ones where total caloric yield and total revenues declined the most with high
278 temperatures. Consistent with the models including drought, crop diversity had the largest
279 positive impact on both outputs and buffered the effects of high temperatures in this region.
280 Results from the regional analyses are detailed in Supplementary table 5.

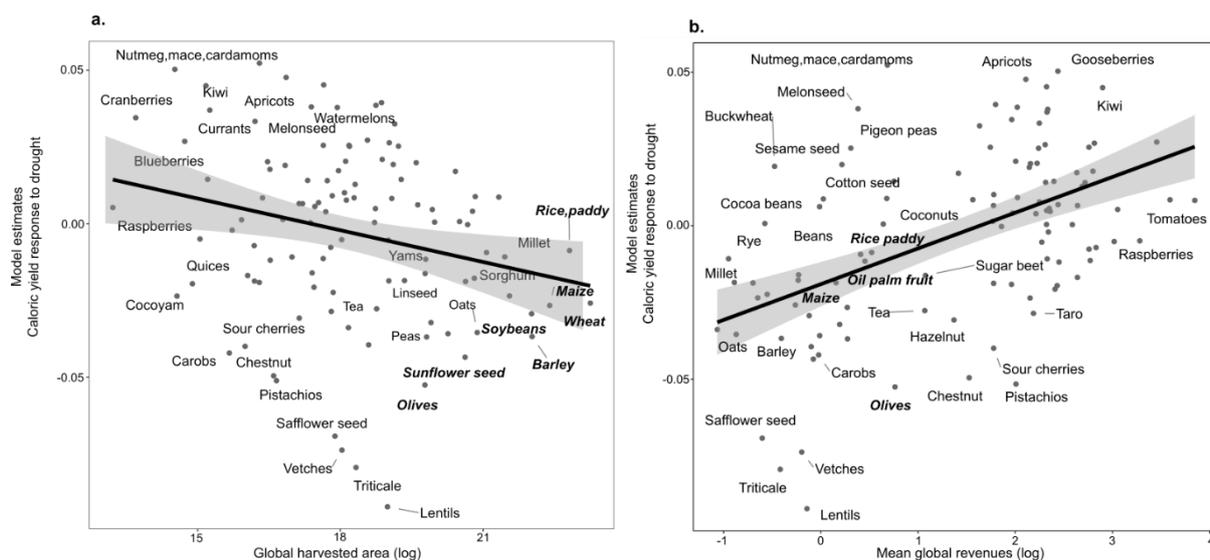
281

282 Caloric yield responses of individual crops to weather extremes showed substantial variation
283 (figure 2). With few exceptions, caloric yield of main cereals (wheat, maize, barley) and oil
284 crops (oil palm fruits, olive, sunflower, soybean) showed a negative response to droughts
285 (figure 2(a)) and high temperatures (figure 2(b)) that was greater or equal to the average
286 aggregated response across all crops. These results were supported by a significant and
287 negative relationship between the global harvested area of crops and their yield response to
288 droughts ($F_{(1,107)} = 6.63$, $P = 0.011$, figure 3(a)). This result showed that crops occupying the
289 largest harvested areas worldwide were also the most sensitive to droughts. Because these
290 dominant crops were also the ones with the least average global economic value ($F_{(1,107)} =$
291 39.62 , $P < 0.0001$) high-value crops were also less sensitive to drought ($F_{(1,107)} = 34.62$, $P <$
292 0.0001 , figure 3(b)). Only a few crops, mostly tropical horticultural ones (e.g., banana,
293 mango, coconuts, plantains, watermelons), experienced increasing yield related to location-
294 specific drought events (figure 2(a)). However, we found no significant relationship between
295 the global harvested area of crops and their crop yield response to high temperatures ($F_{(1,107)} =$
296 2.33 , $P = 0.13$).



297

298 **Figure 2.** Individual response of crop yield to (a) droughts and (b) high temperatures. We
 299 showed only the 50 most abundant crops in terms of global cropland area. The dashed line
 300 represents the mean effect of droughts on crop diversity (derived from the global model) in (a)
 301 and mean effect of high temperatures on crop diversity in (b). Crop names in bold and italic
 302 highlight the main cereals and oil crops (sunflower, rapeseed, soybean, wheat, maize, rice,
 303 barley, oil palm fruits) worldwide.



304

305 **Figure 3.** Linear relationship between responses of individual crops to droughts and (a) global
 306 harvested area (log-transformed) and (b) global average revenues (log-transformed). Crop

307 names in bold and italic highlight the main cereals and oil crops (sunflower, rapeseed,
308 soybean, wheat, maize, rice, barley, oil palm fruits).

309

310 The response of revenues from individual crops to weather extremes also showed variation
311 (Supplementary figure 1). We found no significant relationship of the individual response of
312 revenues to droughts ($F_{(1,107)} = 1.66, P = 0.20$) and to high temperatures ($F_{(1,107)} = 0.14, P =$
313 0.71) with global harvested area.

314 We then investigated how two facets of the sensitivity of crop portfolios to weather extremes
315 can confer greater agricultural outputs and greater resistance to these events at the country
316 level. First, regression models showed that countries growing crop portfolios with high
317 W_{mean} (abundant crops were also less drought-sensitive) and W_{var} (abundant crops
318 displayed various responses to drought) values had significantly greater total caloric yield and
319 agricultural revenues. Although the effect of W_{mean} on caloric yield was smaller than that of
320 W_{var} , crop portfolios with high W_{mean} values contributed to buffer drought impact on
321 caloric yield (W_{mean} response \times drought, Supplementary table 6). We further found that crop
322 portfolios with greater crop diversity also had a greater diversity of responses to droughts
323 (W_{var}) ($t = 3.67, P = 0.0004$). However, we found no significant relationship between crop
324 diversity and W_{mean} values ($t = 1.18, P = 0.24$). The weak effect of droughts on revenues
325 found in our general model was no longer significant in the regressions including W_{mean} and
326 W_{var} (Supplementary table 6). Finally, models considering high temperatures revealed no
327 significant impact of either W_{mean} or W_{var} on total caloric yield and no significant buffering
328 effect (Supplementary table 6). We only found a significant, positive effect of W_{mean} on total
329 revenues. Only nitrogen and irrigation use significantly impacted total caloric yield and its
330 response to high temperatures. Irrigation also enhanced total revenues in the model
331 considering high temperatures.

332 **Discussion**

333 Our research shows that increases in crop diversity within countries have the potential to
334 buffer yield losses caused by droughts and high temperatures without compromising overall
335 total yield (i.e., from all crops), and to generate higher revenues. Our findings indicate that
336 encouraging greater crop diversity can be an adaptive strategy and warrants more attention,
337 specifically in poorer developing countries that are likely to suffer disproportionately from

338 climate change impacts (Smith *et al* 2001, Mertz *et al* 2009). Finally, our work contributes to
339 scale-up the research on the benefits of crop diversity (Gonzalez *et al* 2020), and provides a
340 better understanding of the characteristics of crop portfolios within countries that can support
341 higher yield and yield stability in the face of climate change.

342 Consistent with previous research, we showed that droughts and high temperatures have a
343 strong negative impact on agricultural production (Cottrell *et al* 2019). We found the impact
344 of droughts on total caloric yield to be about equal in magnitude compared to the effect of
345 high temperatures at the country level. This result differs from previous research on climate
346 change impacts showing a stronger impact of high temperatures compared to that of
347 precipitation (Lobell and Field 2007, Lobell *et al* 2011, Iizumi and Ramankutty 2016). This
348 can be partly explained by the fact that weather and the relative importance of temperature
349 and precipitation may differ across different crop growing areas of large countries. Although
350 we could measure the spatial heterogeneity of extreme weather events, our analyses were
351 limited by the coarse resolution of our crop output data. Moreover, differences between our
352 results and those of previous research may come from differences in approach. Our results
353 suggest that the aggregated response of crop portfolio to weather extremes at the country level
354 might not reflect the response of a subset of crops assessed individually. Within the wide
355 variation in responses of individual crop to weather extremes, major cereals and oil crops
356 showed among the greatest sensitivity to droughts and temperatures. Although global major
357 crops constitute the majority of calories produced on a global basis, focusing research on
358 these crops may provide a partial picture of the effect of extreme weather events on food
359 production and the future of food security.

360
361 Accounting for both caloric yield and economic revenues allowed us to compare the effect of
362 weather extremes on these two measures of agricultural output. We found that revenues were
363 consistently less impacted by droughts and high temperatures than was yield in all of our
364 models. A possible explanation is that increased prices in response to reduced supply partially
365 offset drought-related losses in caloric yield. If so, this compensatory mechanism benefits
366 producers, it hurts consumers, who may face higher food prices.

367
368 We found large negative impacts of past drought events on total caloric yield in countries of
369 Sub-Saharan Africa, the Middle East & North Africa region and in the East Asia & Pacific
370 region. Although floods, hailstorms and crop pests/diseases are sources of risk in these

371 regions, drought is predominant (Miyan 2015, Ayanlade *et al* 2018, Trambly *et al* 2020,
372 Rahut *et al* 2021). These three regions contain a large share of current arid and semi-arid
373 zones that are expected to expand in size and to experience more frequent and intense
374 droughts in the future (Pörtner *et al* 2022). Additional research efforts will be needed to build
375 climate change resilience in these “hot spots” (De Souza *et al* 2015), especially in Sub-
376 Saharan Africa where we found that agriculture was also severely impacted by high
377 temperatures.

378 According to our findings, Sub-Saharan Africa is the region that could benefit the most from
379 promoting crop diversity to buffer the strong impacts of weather extremes on caloric yield and
380 economic revenues. This finding resonates with ecological theories stating that biodiversity
381 has its greatest moderating effect on ecosystem functioning in contexts of limited resources,
382 including poor soil fertility (Lal 2009). We believe that our results have important
383 implications considering not only the higher risks of climate shocks, but also the high level of
384 vulnerability of African populations to climate change (Funk *et al* 2008, Thornton *et al* 2014).
385 Agriculture supports the livelihoods of over 60% of the African population (FAO 2021a) and
386 the continent is home to 37% of all malnourished people (FAO 2021b). In this context, studies
387 assessing the benefit of biodiversification of agriculture still remain underrepresented in this
388 region (Beillouin *et al* 2019). Our findings add urgency to the need to address this issue. The
389 lack of emphasis on crop diversity as a form of climate insurance seems surprising
390 considering that crop diversity is already a pillar of smallholder farming systems (Ricciardi *et al*
391 *et al* 2018) and a lever of adaptation to climate risks (Koffi *et al* 2017, Mango *et al* 2018, Bellon
392 *et al* 2020, Makate *et al* 2022). Evidence from local ethnobiological research suggests that
393 societies farming in areas prone to high precipitation variability and/or to extreme weather
394 events tend to make use of a wider range of crop varieties to secure their livelihoods (Kassie
395 *et al* 2013, Matsuda 2013, Coomes *et al* 2015). Similarly, Baumgärtner and Quaas (2010)
396 found that farmers diversified their crop portfolio in the face of uncertain climatic conditions
397 and when financial insurance was not available or was too expensive for farmers to afford. A
398 promising line of research consists of finding how to leverage the crop diversity that
399 smallholding farmers in Sub-Saharan Africa make use of in order to secure better yields, limit
400 yield stability and/or enhance revenues (though not all crops grown by smallholders are
401 grown for sale). It is critical that research and policy efforts in this area catch up with the pace
402 and scale of climate change.

403 Beyond trends, processes involved in the relationship between crop diversity and stability
404 have mainly been evaluated at the local scale, within or between cultivated fields, where crops
405 interact. However, mechanisms governing the diversity-stability relationship can be scale-
406 dependent and the role of biotic interactions is expected to decline with spatial grain size
407 (Gonzalez *et al* 2020). At the country level, our results suggest that processes close to the
408 selection and complementarity effects promote total caloric yield, with the latter having the
409 strongest effect. But to buffer drought impact on yield, crops occupying large shares of
410 cropland within countries have to be drought-resistant, conferring high W_{mean} values to the
411 crop portfolio. However, we found no relationship between W_{mean} and higher crop diversity
412 and no effect of our metrics in models including high temperatures, meaning that there is still
413 an additional way by which crop diversity buffered weather extreme impacts that we could
414 not account for, and that merits further research.

415 Our results, however, could indicate how to appropriately constitute, or diversify, crop
416 portfolios within countries. More specifically, we showed that relatively minor, high-value
417 crops, were more stress-tolerant than major commodity crops. Although these minor crops
418 represent a still untapped source of diversity to meet multiple challenges in agriculture (Zhang
419 *et al* 2018), planting more rare crops may offer little stabilizing benefits. Instead, our results
420 suggest that a diversification strategy based on promoting drought-resistant, high-value crops
421 could help increase the W_{mean} value of the portfolio while increasing the diversity of
422 responses to weather (W_{var}) and thus leading to greater annual caloric yield and revenues.

423 Finally, we found that increasing irrigation and nitrogen use contributed to reducing the
424 impact on of high temperatures but not of droughts on caloric yield. Here, only irrigation use
425 was found to increase resistance of revenues to the impact of both weather extremes. The lack
426 of crop-specific data on management practices prevents us from going any further into the
427 understanding of the buffering role of inputs. It is important to note, however, that there is in
428 general terms a very limited degree to which increased irrigation can be used as a buffer
429 against climate shocks in agriculture. Increasing yield and revenues through a more
430 sustainable use of inputs could contribute to enhancing food security in other ways, for
431 example by enabling farmers to constitute grain reserves and economic savings to compensate
432 for crop and income losses in bad years.

433

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439

440 **Data availability**

441 The data that support the findings of this study are all publicly available following the links
442 listed in the Supplementary Table 1 available from the corresponding author on reasonable
443 request.

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