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The role of crop diversity in climate change adaptation: insights from local observations to inform decision making in agriculture

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1 **Title**

2 **The role of crop diversity in climate change adaptation: insights from local observations**
3 **to inform decision making in agriculture**

4
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32 Data analysis: VL, DR, MD, ED, AM

33 Writing: VL, DR, VRG, YA, SC, SMC

34

35 **Keywords**

36 Crop diversity; Climate Change; Farming; Local Ecological Knowledge; Sustainability

37

38 **Highlights**

- 39 ● We review climate-driven changes in crop portfolios reported by farmers.
- 40 ● We discuss the implications for local calories and nutrient production.
- 41 ● We document increased cultivation of water-demanding horticultural crops.
- 42 ● These crops contain less energy but more vitamins than abandoned ones, mainly
43 cereals.
- 44 ● Farmers' knowledge is an untapped source of information for climate decision
45 making.

46

47 **Abstract**

48 Homogenization of crop portfolios from the field to the global scale is raising concerns about
49 agricultural adaptation to climate change. Assessing whether such trends threaten farmers'
50 long-term adaptive capacity requires a thorough understanding of changes in their crop
51 portfolios, identification of the drivers of change, and the implications such changes have for
52 local nutrition and food production. We reviewed the available literature on farmers' reports
53 of climate-driven crop changes. Small-scale farmers tend to adopt water-demanding crops,
54 even in areas where models predict that reduced rainfall will reduce yields. The adoption of
55 horticultural cash-crops combined with the abandonment of subsistence cereals modifies
56 farmers' nutritional inputs in terms of calories and nutrients, potentially undermining their

57 food security. Farmers' knowledge contributes to understand trends in crop diversity and
58 support the design of strategies for adaptation to climate change.

59 **1. Introduction**

60 Diversification and modification of crop species and variety portfolios are widespread
61 strategies used by farmers to cope with environmental and socio-economic variability and to
62 adapt to change [1] including climate change [2]. Despite the significance of crop diversity
63 for the ability of agroecosystems to adapt to climate change, existing public policies and
64 development interventions provide limited support for crop diversification [3]. Rather,
65 development policies combined with market demand over the last forty years have led to the
66 general homogenization of crop species and varieties across regions [4], as well as of national
67 and global food supplies [5]. Now, in the face of climate change, crop homogenization is
68 jeopardizing global food security [5] and weakening farmers' adaptive capacity [2]. The
69 impacts of climate change on agriculture are expected to be particularly strong in Africa,
70 Southeast Asia, Central America, the Pacific, and the Caribbean [6], where small-scale
71 farmers are already facing pressure due to increasing market globalization, urbanization, and
72 population shifts, all of which impact farmers' crop portfolios [7,8,9] and household nutrition
73 [10].

74 Several studies report a global reduction in crop diversity [4,5], but a thorough
75 understanding is needed of how changes in farmers' crop portfolios are linked to global trends
76 and of the combined effects of climatic and socio-economic factors on these changes.
77 Understanding changes in farmers' crop portfolios, the interplay between climate and other
78 drivers of change, and the implications for farmers' food security, nutrition, and income is
79 crucial to inform agricultural decision making, particularly to design viable strategies for
80 long-term adaptation in a rapidly changing world.

81 Local knowledge is a relatively untapped source of information on the impacts of climate
82 change on local communities and their adaptation strategies [11]. Here, drawing on farmers'
83 reports of observed changes in crop abundance and/or diversity at the level of the species or
84 variety, we describe patterns of climate-related changes in crop diversity and the potential
85 impacts of such changes on farmer's nutrition. Finally, we discuss how studies on local
86 farmers' knowledge contribute to crop diversity research and agricultural decision-making in
87 the face of climate change.

88

89 **2. Methods**

90 We searched scientific literature databases covering the semantic fields of local knowledge
91 and observations, crops, and climate change. We selected 95 articles published in English up
92 to and including 2019, that documented changes in crop diversity reported by farmers and
93 explicitly linked to medium- to long-term climate change (see SI 1 for details). For each
94 reported change, we (i) recorded the geographical location, the corresponding climate zone
95 according to the Köppen-Geiger classification [12,13], and the predominant farming system
96 (i.e., small- or large-scale system) in the area concerned, (ii) coded the trajectory of change at
97 the species or variety level as “an increase in abundance or adoption” (hereafter “adoption”)
98 or “a decrease in abundance or abandonment” (hereafter “abandonment”), (iii) coded climate-
99 related drivers of crop changes based on a classification proposed by [14], and (iv) recorded
100 additional non-climate related drivers of crop change, classifying them in economic,
101 ecological, institutional, and socio-cultural categories.

102 We then classified the documented crops in eight categories: cereals, legumes, tubers,
103 horticultural crops, oilseed, fruit and nuts, service crops (e.g., shade trees), and others (e.g.,
104 spices, fodder, and fibers; see SI 2 for details). We calculated the most frequent trajectories of
105 change in each crop category and species and the distribution of perceived drivers of change.
106 Finally, to explore the potential nutritional impacts of the documented crop changes (in terms
107 of total energy, macro- and micronutrients [see SI 1 for the complete list]), we performed
108 two-way ANOVA to compare the nutritional values of adopted and abandoned crop species,
109 using the crop-specific USDA Food and Nutrient database for raw crops [15].

110

111 **3. Results**

112 **3.1. Geographic and climatic distribution of observations**

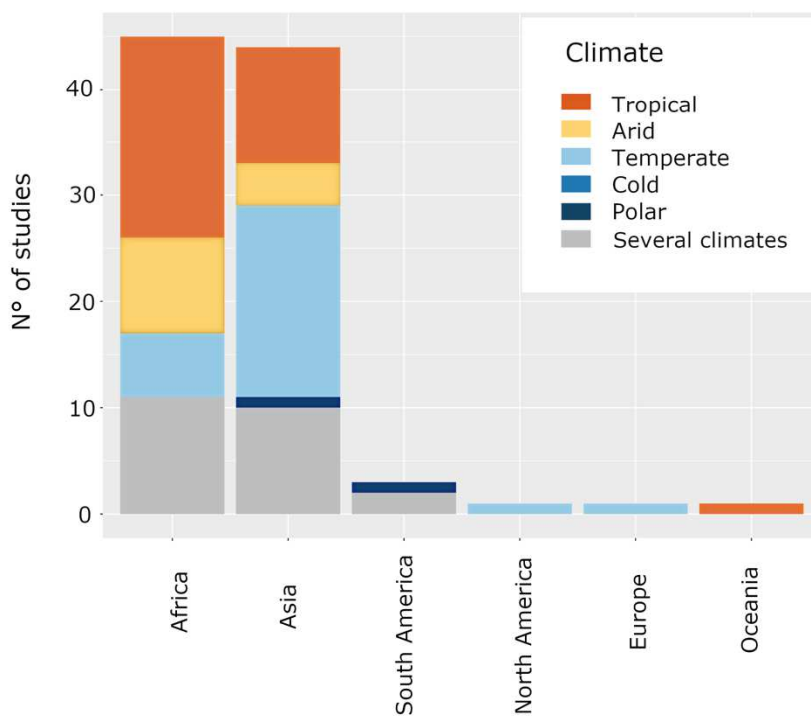
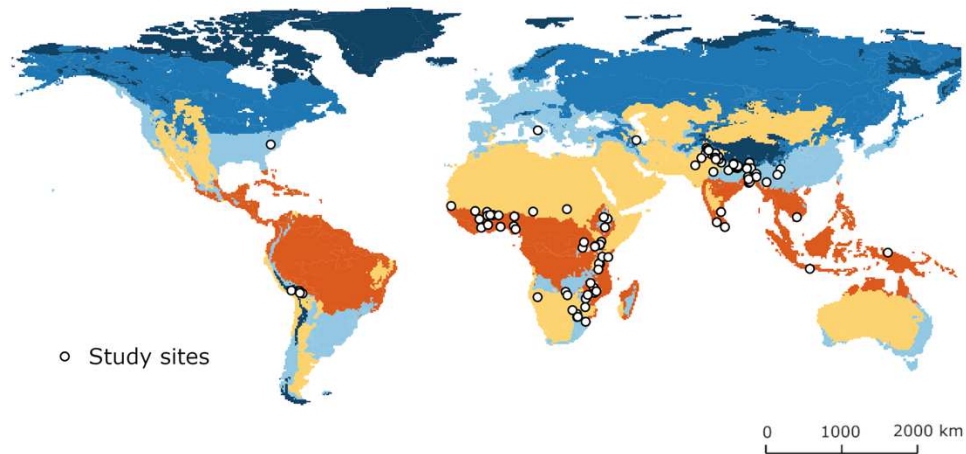
113 The 95 studies reporting farmers’ observations of climate-related changes in crops we
114 reviewed were conducted in 34 countries, 87% of which were in small-scale farming systems.
115 Only 14% of the studies focused specifically on the impacts of climate change on crops, while
116 the majority (86%) mentioned impacts on crops among other elements affected by climate
117 change (e.g., water availability, natural ecosystems, forests). Our results reveal very uneven
118 geographic and climatic distribution of research aimed at documenting climate-related local
119 observations of changes in crops (Figure 1). Forty-seven percent of the studies were
120 conducted in 20 African countries and 46 in 10 countries in Asia. Europe, North America,
121 Oceania, and Latin America were poorly represented (7%, 4 countries). Furthermore, studies

122 were clustered in specific areas, especially in Southern Asia, where most studies focused on
123 India and Nepal, and in southern, eastern, and western Africa. In terms of climate zones, 33%
124 of the studies were conducted in tropical climates, 27% in temperate climates, and 14% in
125 arid climates, and only two studies in polar climates, where agriculture is a minor activity.
126 Twenty-four percent (n=23) of the studies reported data from more than one site located in
127 different climate zones.

128

129 Figure 1. Top: Geographic and climatic distribution of the case studies analyzed. Bottom:
130 Number of studies per continent and climate zone according to the Köppen-Geiger
131 classification [12,13].

132 [FIGURE 1 HERE]



133

134

135 3.2. From local to global patterns of changes in crop diversity

136 Out of 428 observations of changes in crop abundance, reports of adoption of species
137 (54%) and varieties (18%) in response to climate change were more common than reports of

138 abandonment of species (23%) or of varieties (5%). Overall, we found reports of changes in
139 the abundance of 113 different species, although 16 species (6 horticultural, 5 cereal, 3 tuber,
140 1 oilseed, and 1 fruit species) accounted for half the observations that mentioned changes in
141 species.

142 At the species level, 38% of the reports of species adoption (n=231) referred to
143 horticultural crops, followed by cereals (14%), legumes (12%) and fruit and nuts (12%). Most
144 reports of species abandonment (n=97) referred to cereals (47%). While studies in Africa
145 reported more cereal adoption than abandonment, the opposite was observed in Asia (Figure
146 2). In Africa, both species abandonment (56%) and adoption (24%) mainly concerned cereals
147 (especially sorghum, maize and pearl millet). Horticultural crops (especially watermelon) also
148 represented a large share of species adoption in Africa (21%), followed by tubers (16%,
149 mainly cassava and sweet potato), and legumes (16 %, especially cowpea). In Asia,
150 abandonment mainly concerned cereals (45%, mainly rice, wheat and maize), and adoption
151 mainly concerned horticultural crops (43%, mainly tomato, cabbage and cauliflower).

152

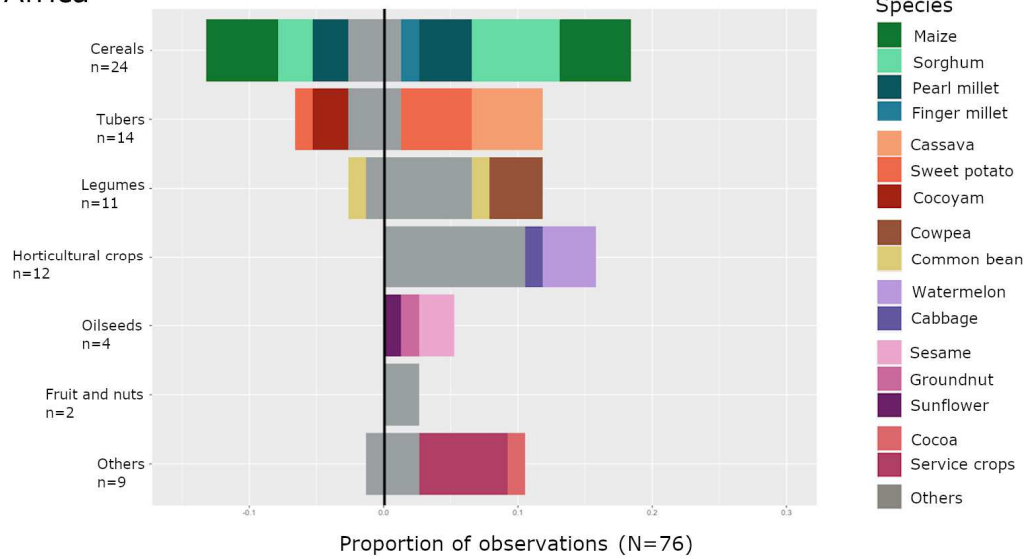
153 Figure 2. Relative proportion of crop species adopted (right) and abandoned (left) per
154 continent. The x axis shows the number of observations of change in a given species out of
155 the total number of observations for that continent. The main species are displayed in color
156 (i.e., representing more than 3% of the observations at the continent level) and the remaining
157 species are grouped as ‘others’.

158

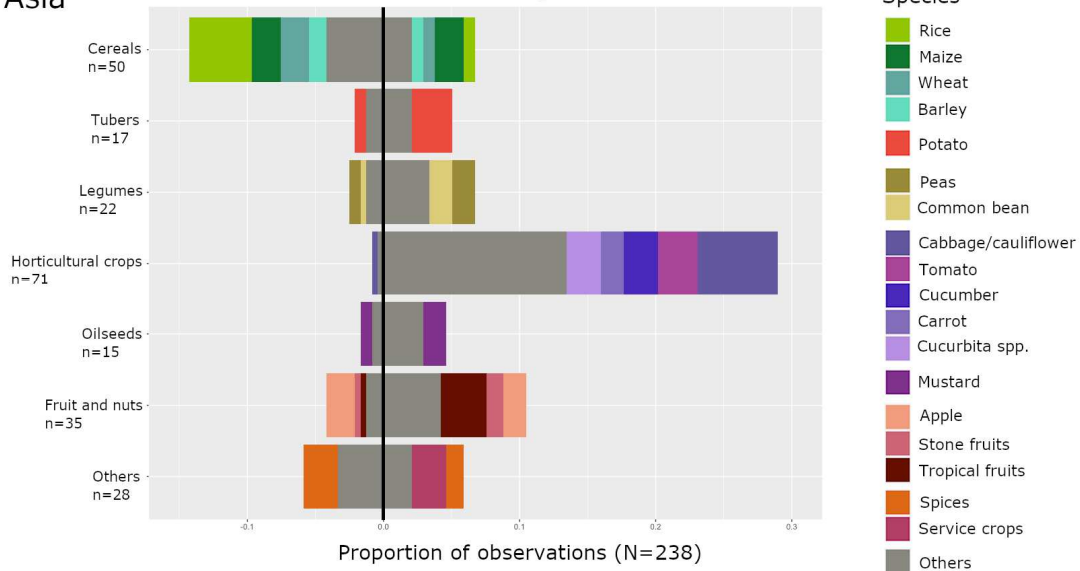
[FIGURE 2 HERE]

159

Africa



Asia



160

161

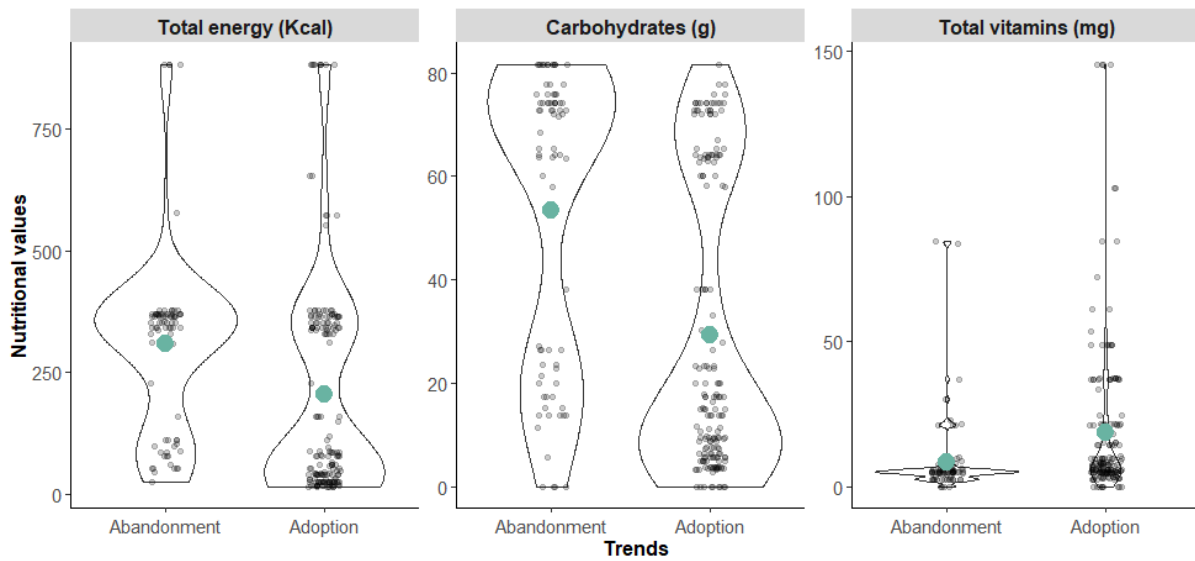
162 The crops that have been adopted have, on average, fewer calories ($F = 12.1$; $P =$
 163 0.001) and carbohydrates ($F = 39.4$; $P < 0.001$) and higher total vitamin ($F = 9.8$; $P = 0.02$)
 164 contents than crops that have been abandoned (Figure 3, see SI 3 for details).

165

166 Figure 3. Caloric and nutritional content of abandoned crop species (left) and adopted species
 167 (right). The violin plot and the dots show the distribution of the crop-specific caloric values,
 168 macronutrients, total vitamin and mineral contents, while the green dots represent the average
 169 value per trend of crop change.

170
171

[FIGURE 3 HERE]



172
173

174 At the infraspecific level, 150 observations reporting changes in the abundance of
175 varieties were found in 66 studies. More adoptions (79%) than abandonment (21%) of
176 varieties were reported. Cereals were the most frequently reported category (65% of
177 adoptions and 58% of abandonments). The adoption of varieties mainly concerned rice in
178 Asia and maize in Africa. Most of the varieties that were adopted were modern varieties (74%
179 of the observations), whereas most of the varieties that were abandoned were landraces, i.e.,
180 local “heirloom” varieties (74%).

181 **3.3. The relative role of climate change as a driver of changes in farmers’ crop**
182 **portfolios**

183 The literature refers to climate change as a driver of changes in crop portfolios both in
184 broad and specific terms. In 43% (n=185) of all the observations, researchers broadly reported
185 that farmers attribute changes in their crop portfolio to “climate change” (Figure 4). Among
186 the observations in which climate was mentioned as a specific driver (n=251), changes in
187 precipitation, particularly increased variability, was the most frequently cited climate driver,
188 and appeared in 86% of the reports. Changes in precipitation itself (mean and variability)
189 were reported to drive 36% of the cases in which horticultural crops were adopted, 67% of the
190 cases in which cereals were abandoned, and 50% of the adoption of cereals. Changing
191 temperatures were also reported to drive the adoption of horticultural crops (22%). Cascading

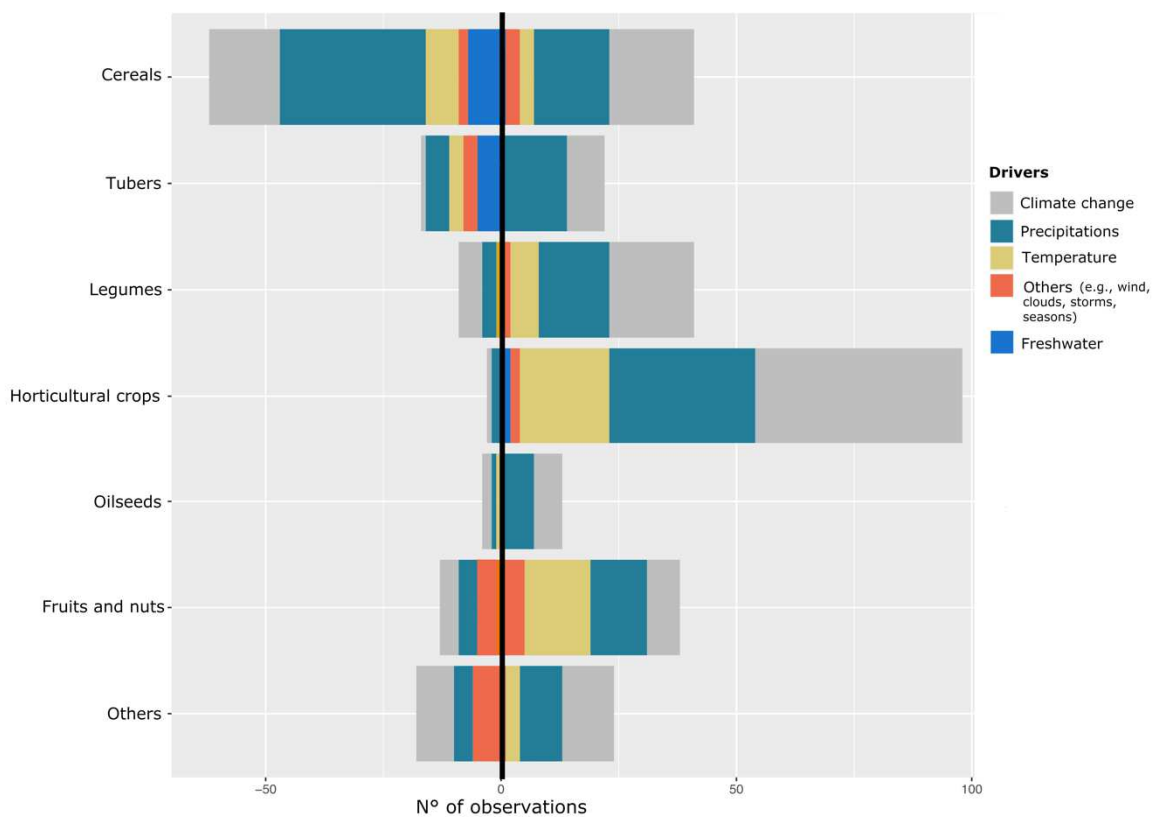
192 effects of climate changes affecting freshwater availability were only reported as a driver in
193 5% of the observations of changes in crop portfolios reported.

194

195 Figure 3: Share of observations of changes in crop portfolios at the species level per crop
196 category and climate-related indicators of change. The x axis represents the number of
197 observations of change in crop species associated with each category of climate-related
198 drivers. Positive and negative values along the x axis indicate crop adoption and
199 abandonment, respectively.

200

[FIGURE 4 HERE]



201

202

203 While our search focused on the role of climate as a driver of changes in crop
204 portfolios, we noted that climate change was often interlinked with other important drivers of
205 change, sometimes acting in synergetic and sometimes in antagonistic ways. Thus, 32%
206 (n=139) of the reports of changes in crop portfolios were also associated with non-climatic
207 drivers. Economic drivers (55%), and particularly increased access to market opportunities,
208 were the most frequently cited co-drivers of changes in crop portfolios. For example, farmers
209 reported that adopting cash crops (e.g., vegetables) helped offset the lower yields of food

210 crops (e.g., cereals), with the pressure of the two drivers acting to change cropping systems
211 (see SI 4 for further details). Some studies also reported that farmers mentioned other
212 environmental changes, such as declining soil fertility and increasing cases of disease,
213 increasing damage caused by pests or predators as co-drivers of changes in crop portfolios
214 (32%). In a few cases (8%) development programs or NGO projects were also mentioned as
215 drivers of changes in crop portfolios.

216

217 **4. Discussion**

218 Our findings suggest that farmers' observations are a valuable source of information
219 on climate-related changes in local crop diversity. However, to understand global trends,
220 research should aim to fill two important gaps, namely the strong geographical clustering of
221 studies and the strong focus on small-scale farming systems. Our review showed that
222 available literature is focused on a small number of regions in Asia and Africa where climate
223 change is particularly obvious (e.g., in the Himalayas), and that research on farmers'
224 knowledge is circumstantial in regions where large-scale farming predominates (e.g. Europe,
225 USA, Australia). Further, our results suggest that in some regions (e.g. Latin America or
226 North Africa), studies focused on local knowledge are probably published in other languages
227 than English. The body of knowledge on climate-related changes in crop diversity would
228 benefit from including areas that are particularly threatened by climate change and where a
229 drastic decrease in crop yield is expected [16] (including arid regions: the Sahel, North Africa
230 and the Middle East), and those where climate change may open up new farming
231 opportunities (Northern Europe) [17,18].

232 Our results also suggest that an approach based on farmers' knowledge could provide
233 a complementary perspective to current agricultural research on adaptation to climate change
234 in two important ways. First, current research largely neglects the Southern Hemisphere [19,
235 20]. Second, our review reports on changes to a wide range of crop species, including
236 neglected ones, i.e., species that have been the subject of less research despite their potential
237 for adaptation to climate change [21]. Further study of farmers' knowledge would
238 complement the limited scope of current agricultural research on the impacts of climate
239 change that is focused on a small number of crops, maize, wheat, rice and soy [19].

240 The patterns of changes in crop portfolios reviewed here raise concerns for small-scale
241 farmers' capacity for adaptation to climate change in the long term. We documented the

242 adoption of water-demanding crops (e.g., maize, tomato, watermelon), even in areas where
243 models based on IPCC scenarios predict a decrease in their yield, driven by reduced rainfall
244 [22]. This is particularly the case in Africa [6,23]. The high proportion of reports on non-
245 climate drivers of crop change (i.e., market incentives, development programs) in our search
246 (that itself focused on climate change) suggests that other factors also drive shifts in crop
247 portfolios. In particular, several articles reported that farmers consider the adoption of high-
248 value cash crops, mainly irrigated horticultural crops, as an opportunity to cope with the
249 impacts of climate change on rainfed food crops (e.g. [24,25]). Strategies to cope with the
250 impacts of climate change are supported by technological improvements in local agricultural
251 systems (e.g., access to irrigation) and better access to markets. However, they may also
252 threaten farmers' adaptive capacity in the long term, as opportunities to cultivate more water-
253 demanding and high-market value crops are likely to shrink under future climatic conditions
254 [26,27].

255 Our review revealed that species' adoption concerns a wide range of crop species and
256 categories (i.e., horticultural crops, tubers, legumes). However, these results call for further
257 investigation to assess if changes to local crop portfolios would lead to homogenization at the
258 regional or global scale that would also pose a threat to the resilience of food systems [4,5].
259 Furthermore, despite this apparent gain in diversity at the species level, we also noted that
260 most of the crops that are adopted are modern varieties and that abandoned crops are local
261 landraces. This trend could reduce intraspecific diversity and shrink the diversity reservoir
262 that is critical for adaptation to climate change [28].

263 The cropping trends we identified also raise concerns for food security. The crop
264 species that have been adopted (i.e., fruit and vegetables) have lower energy and carbohydrate
265 contents than abandoned crop species (i.e., cereals), but are richer in vitamins that are
266 essential for human health. On the other hand, the fruit and vegetables that are being adopted
267 are often geared towards markets, and these new sources of vitamins may not necessarily
268 benefit smallholders' nutrition [29]. Conversely, the decline in the cultivation of staple
269 cereals, widely reported for major African cereals like millet or sorghum, could increase
270 farmers' food and nutrition insecurity by increasing their dependence on imported crops (e.g.,
271 rice) of low nutritional quality [30] and that are also subject to market fluctuations [31]. The
272 benefits of commercial horticulture and associated global food trade for smallholder remains
273 highly controversial, and is strongly scale-dependent and context-based [32,33,34].

274 Our review identified important issues for agricultural decision making, especially for
275 development initiatives aimed at strengthening the capacity of small-scale farmers to adapt to
276 climate change. Rural development actors including national and international development
277 agencies and NGOs promote the development of horticulture in small-scale agriculture (e.g.,
278 [35]), but we argue that such recommendations should not be made without prior evaluation
279 of their medium to long term consequences for small-scale farmers food security and adaptive
280 capacity. The dramatic expansion of horticulture is already causing groundwater depletion in
281 some places (e.g., [36]). Rural development actors should consider supporting agricultural
282 water uses that are suited to predicted climate change, and need to be sure that expanding
283 commercial horticulture will benefit smallholders' livelihoods without jeopardizing their
284 capacity to adapt in the long term.

285

286 **5. Conclusion**

287 Farmers across the world are reacting to the combined effects of climate and non-
288 climate drivers of change by adjusting their crop portfolios. While such adjustments involve
289 both the adoption and the abandonment of certain crops or landraces, we identified a general
290 trend involving the adoption of water-demanding horticultural crops with little energy
291 content. We argue that this trend may threaten the resilience of local cultivation systems and
292 livelihoods. Our review calls for coordinated interdisciplinary research to fill methodological
293 and geographical gaps that currently limit a thorough understanding of farmers' responses to
294 climate change [37]. Such collective efforts are urgent, and could represent a unique
295 opportunity to monitor the dynamics of under-researched crops and trends in regions where
296 long-term research is a challenge. Information concerning climate-related changes in crop
297 diversity at the local scale and their co-drivers could help reorient agricultural policies and
298 development programs toward long-term adaptation to climate change.

299

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313

314 7. References

315

316 1. Lin BB: **Resilience in agriculture through crop diversification: adaptive**
317 **management for environmental change.** *BioScience* 2011, **61**:183–193.

318 <http://dx.doi.org/10.1525/bio.2011.61.3.4>

319

320 2. Altieri MA, Nicholls, CI: **The adaptation and mitigation potential of traditional**
321 **agriculture in a changing climate.** *Clim Change* 2017, **140**:33–45.

322 <http://dx.doi.org/10.1007/s10584-013-0909-y>

323

324 3. Pimbert MP, Moeller NI: **Absent agroecology aid: on UK agricultural development**
325 **assistance since 2010.** *Sustainability* 2018, **10**:505. <http://dx.doi:10.3390/su10020505>

326

327 4. Martin AR, Cadotte MW, Isaac ME, Milla R, Vile D, Violle C: **Regional and global**
328 **shifts in crop diversity through the Anthropocene.** *PloS one* 2019, **14**:2, e0209788.

329 <http://dx.doi.org/10.1371/journal.pone.0209788>

330 * Using national scale agricultural data (FAO), the authors found a global trend toward crop
331 diversification during the 1970s-80s period. Although timing and duration of major changes
332 in crop diversity vary across regions, authors found evidence of increased similarity in crop
333 pool grown globally.

334

335 5. Khoury CK, Bjorkman AD, Dempewolf H, Ramirez-Villegas J, Guarino L, Jarvis A,
336 Rieseberg LH, Struik PC: **Increasing homogeneity in global food supplies and the**
337 **implications for food security.** *Proc Natl Acad Sci* 2014, **111**:4001–4006.

338 <http://dx.doi.org/10.1073/pnas.1313490111>

339

340 6. Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, Lobell DB,
341 Travasso MI: **Food security and food production systems. In: Climate Change 2014:**
342 **Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution**
343 **of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on**
344 **Climate Change.** Edited by Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD,
345 Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN,
346 MacCracken S, Mastrandrea PR, White LL. Cambridge University Press; 2014:485-533.

347

348 7. Van Vliet N, et al.: **Trends, drivers and impacts of changes in swidden cultivation**
349 **in tropical forest-agriculture frontiers: a global assessment.** *Glob Environ Change* 2012,

350 **22**: 418-429. <http://dx.doi.org/10.1016/j.gloenvcha.2011.10.009>

- 351
352 8. Zimmerer KS: **Biological diversity in agriculture and global change.** *Annu Rev*
353 *Environ Resour* 2010, **35**:137–166. <http://dx.doi.org/10.1146/annurev-environ-040309->
354 113840
355
356 9. Aguiar S, Texeira M, Garibaldi LA, Jobbágy EG: **Global changes in crop diversity:**
357 **Trade rather than production enriches supply.** *Glob Food Secur* 2020, **26**:100385.
358 <http://dx.doi.org/10.1016/j.gfs.2020.100385>
359
360 10. Tilman D, Clark M: **Global diets link environmental sustainability and human**
361 **health.** *Nature* 2014, **515**:518–522. <http://dx.doi.org/10.1038/nature13959>
362
363 11. Reyes-García V, Fernández-Llamazares Á, Guèze M, Garcés A, Mallo M, Vila-
364 Gómez M, and Vilaseca M: **Local indicators of climate change: The potential**
365 **contribution of local knowledge to climate research.** *Clim Change* 2016, **2**:109-124.
366 <http://dx.doi.org/10.1002/wcc.374>
367 * This analysis highlights the complementarity of fine-grained local knowledge and scientific
368 knowledge on climate change, pleading for bridging both knowledge systems to develop
369 effective adaptation strategies.
370
371 12. Peel MC, Finlayson BL, McMahon TA: **Updated world map of the Köppen-Geiger**
372 **climate classification.** *Hydrol Earth Syst Sci Discuss* 2007, 11:1633-1644.
373 <http://dx.doi.org/10.5194/hess-11-1633-2007>
374
375 13. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F: **World map of the Köppen-Geiger**
376 **climate classification updated.** *Meteorologische Zeitschrift* 2006, **15**:259–263.
377 <http://dx.doi.org/10.1127/0941-2948/2006/0130>
378
379 14. Reyes-García, V. *et al.* Local Indicators of Climate Change Impacts. Data collection
380 protocol. *Figshare* 2020, <http://dx.doi.org/10.6084/m9.figshare.11513511.v3>
381
382 15. United States Department of Agriculture. **National Nutrient Database.** [https://](https://ndb.nal.usda.gov/)
383 ndb.nal.usda.gov/ 2013.
384
385 16. World Bank: **World Bank development report 2010: Development and climate**
386 **change.** 2010
387
388 17. Bindi M, Olesen JE: **The responses of agriculture in Europe to climate change.**
389 *Reg Environ Change* 2011, **11**:151–158. <http://dx.doi.org/10.1007/s10113-010-0173-x>
390
391 18. Ergon Å, Seddaiu G, Korhonen P, Virkajärvi P, Bellocchi G, Jørgensen M, Østrem L,
392 Reheul D, Volaire F: **How can forage production in Nordic and Mediterranean Europe**
393 **adapt to the challenges and opportunities arising from climate change?** *Eur J Agron*
394 2018, **92**:97–106. <http://dx.doi.org/10.1016/j.eja.2017.09.016>
395
396 19. White JW, Hoogenboom G, Kimball BA, Wall GW: **Methodologies for simulating**
397 **impacts of climate change on crop production.** *Field Crops Res* 2011, **124**:357–368.
398 <http://dx.doi.org/10.1016/j.fcr.2011.07.001>
399

- 400 20. Beillouin D, Ben-Ari T, Makowski D: **Evidence map of crop diversification**
401 **strategies at the global scale.** *Environ Res Lett* 2019, **14**:123001.
402 <http://dx.doi.org/10.1088/1748-9326/ab4449>
403
- 404 21. Chivenge P, Mabhaudhi T, Modi A, Mafongoya P. **The Potential Role of Neglected**
405 **and Underutilised Crop Species as Future Crops under Water Scarce Conditions in**
406 **Sub-Saharan Africa.** *Int J Environ Res Public Health* 2015, **12**:5685–5711.
407 <http://dx.doi.org/10.3390/ijerph120605685>
408
- 409 22. Tripathi A, Tripathi DK, Chauhan DK, Kumar N, Singh GS: **Paradigms of climate**
410 **change impacts on some major food sources of the world: a review on current**
411 **knowledge and future prospects.** *Agric Ecosyst Environ* 2016, **216**:356–373.
412 <http://dx.doi.org/10.1016/j.agee.2015.09.034>
413
- 414 23. Pironon S, Etherington TR, Borrell JS, Kühn N, Macias-Fauria M, Ondo I, Tovar C,
415 Wilkin P, Willis KJ: **Potential adaptive strategies for 29 sub-Saharan crops under future**
416 **climate change.** *Nat Clim Change* 2019, **9**:758–763. [http://dx.doi.org/10.1038/s41558-019-](http://dx.doi.org/10.1038/s41558-019-0585-7)
417 [0585-7](http://dx.doi.org/10.1038/s41558-019-0585-7)
418
- 419 24. Akinyemi FO: **Climate change and variability in Semiarid Palapye, Eastern**
420 **Botswana: An assessment from smallholder farmers’ perspective.** *Weather, Clim, and Soc*
421 2017, **9**:349-365. <http://dx.doi.org/10.1175/WCAS-D-16-0040.1>
422
- 423 25. Shrestha RP, Nepal N: **An assessment by subsistence farmers of the risks to food**
424 **security attributable to climate change in Makwanpur, Nepal.** *Food Sec* 2016, **8**:415-425.
425 <http://dx.doi.org/10.1007/s12571-016-0554-1>
426
- 427 26. Schewe J et al.: **Multimodel assessment of water scarcity under climate change.**
428 *Proc Natl Acad Sci* 2014, **111**:3245-3250. <http://dx.doi.org/10.1073/pnas.1222460110>
429
430
- 431 27. Guodaar L, Asante F, Eshun G, Abass K, Afriyie K, Appiah DO, Gyasi R, Atampugre
432 G, Addai P, Kpenekuu F: **How do climate change adaptation strategies result in**
433 **unintended maladaptive outcomes? Perspectives of tomato farmers.** *Int J Veg Sci* 2020,
434 **26**:15-31. <http://dx.doi.org/10.1080/19315260.2019.1573393>
435 * An ethnographic approach with tomato farmers in Ghana shows that farmers (i) perceive
436 maladaptive impacts of climate variability on tomato production and (ii) report negative
437 outcomes of irrigation as an adaptive strategy. This study interestingly highlights the need to
438 check not only positive but also negative outcomes of adaptation strategies.
439
- 440 28. Gepts P: **Plant genetic resources conservation and utilization.** *Crop Sci* 2006, **46**:
441 2278–2292.
442
- 443 29. Sibhatu KT, Qaim M: **Meta-analysis of the association between production**
444 **diversity, diets, and nutrition in smallholder farm households.** *Food Policy* 2018, **77**:1–
445 18. <http://dx.doi.org/10.1016/j.foodpol.2018.04.013>
446 * This meta-analysis revealed that only 20% of studies reviewed showed a consistent positive
447 association between farm-level production diversity and household and individual level
448 dietary diversity. This study interestingly questions the assumption that farm diversification is
449 an effective strategy to improve diets and nutrition for smallholder farmers.

- 450
451 30. Ka A, Boëtsch G, Macia E: **L'alimentation des pasteurs peuls du Sahel. Entre**
452 **globalisation, désir de «modernité» et risques sanitaires.** *Cah Nutr Diététique* 2020, **55**:
453 47–52. <http://dx.doi.org/10.1016/j.cnd.2019.11.001>
454
- 455 31. D'Amour CB, Anderson W: **International trade and the stability of food supplies**
456 **in the Global South.** *Environ Res Lett* 2020, **15**:074005. doi:10.1088/1748-9326/ab832f
457
- 458 32. Fader M, Gerten D, Krause M, Lucht W, and Cramer W: **Spatial decoupling of**
459 **agricultural production and consumption: quantifying dependences of countries on food**
460 **imports due to domestic land and water constraints.** *Environ Res Lett* 2013, **8**:014046.
461 <http://dx.doi.org/10.1088/1748-9326/8/1/014046>
462
- 463 33. Clapp J: **Food self-sufficiency: Making sense of it, and when it makes sense.** *Food*
464 *policy* 2017, **66**:88-96. <http://dx.doi.org/10.1016/j.foodpol.2016.12.001>
465
- 466 34. Kummu M, Kinnunen P, Lehtikoinen E, Porkka M, Queiroz C, Rööös E, Troell M, Weil
467 **C: Interplay of trade and food system resilience: Gains on supply diversity over time at**
468 **the cost of trade independency.** *Glob Food Sec* 2020, **24**:100360.
469 <http://dx.doi.org/10.1016/j.gfs.2020.100360>
470
- 471
- 472 35. Talukder A, Kiess L, Huq N, de Pee S, Darnton-Hill I, Bloem MW: **Increasing the**
473 **production and consumption of vitamin A-rich fruits and vegetables: Lessons learned in**
474 **taking the Bangladesh homestead gardening programme to a national scale.** *Food and*
475 *Nutr Bull* 2000, **21**:165-172. <http://dx.doi.org/10.1177/156482650002100210>
476
- 477
- 478 36. Shiferaw B, Reddy VR, Wani SP: **Watershed externalities, shifting cropping**
479 **patterns and groundwater depletion in Indian semi-arid villages: The effect of**
480 **alternative water pricing policies.** *Ecol Econ* 2008, **67**:327-340.
481 <http://dx.doi.org/10.1016/j.ecolecon.2008.05.011>
482
- 483
- 484 37. Labeyrie V, Renard D, Benyei P, Junqueira AB, Li X, Porcher V, Porcuna-Ferrer A,
485 Schlingmann A, Soleymani-Fard R, Reyes-García V: **Monitoring crop diversity trends**
486 **based on local knowledge: a protocol for data collection.** Figshare 2020,
487 <http://dx.doi.org/10.6084/m9.figshare.11842566.v4>