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1 **Title:** Timescales of transformational climate change adaptation in Sub-Saharan African
2 agriculture

3

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23 **Keywords:** transformational adaptation, livelihoods, crop suitability, staple crops

24 **Climate change is projected to constitute a significant threat to food security, if no**
25 **adaptation actions are taken^{1,2}. Transformation of agricultural systems, e.g. switching**
26 **crop types or moving out of agriculture, is projected to be necessary in some cases³⁻⁵.**
27 **However, little attention has been paid to the timing of these transformations. Here,**
28 **we develop a temporal uncertainty framework using the CMIP5 ensemble to assess**
29 **when and where cultivation of key crops in Sub-Saharan African becomes unviable.**
30 **We report potential transformational changes for all major crops during the 21st**
31 **century, as climates shift and areas become unsuitable. For most crops, however,**
32 **transformation is limited to small pockets (<15 % of area), and only for beans, maize**
33 **and banana is transformation more widespread (~30 % area for maize and banana,**
34 **60 % for beans). We envision three overlapping adaptation phases to enable projected**
35 **transformational changes: an incremental adaptation phase focused on improvements**
36 **to crops and management, a preparatory phase that establishes appropriate policies**
37 **and enabling environments, and a transformational adaptation phase in which**
38 **farmers substitute crops, explore alternative livelihoods strategies, or relocate. To best**
39 **align policies with production triggers for no-regret actions, monitoring capacities to**
40 **track farming systems as well as climate are needed.**

41

42 Agricultural activities are the main means to reduce poverty and improve food security
43 among 850 million undernourished people². Numerous studies have shown that climate
44 change can be a significant threat to food availability and stability by reducing agricultural
45 productivity and increasing inter-annual variations in yields^{1,2,6}. Adaptation will be
46 required if food production is to be increased in both quantity and stability in order to meet
47 food security needs during the 21st century. A recent global meta-analysis¹ reported that

48 decreases of ca. 5 % in crop productivity are expected for every degree of warming above
49 historical levels, and that adapted crops yield roughly 7 % greater than non-adapted crops.
50 Yield gains from adaptation through crop management and varietal substitution, however,
51 are highest with moderate or low (< +3 °C) levels of warming^{1,6}, suggesting that more
52 profound systemic and/or transformational changes may be required when and where
53 higher levels of warming occur⁵.

54

55 Transformational adaptation is defined by the IPCC⁷ as a response to the effects of climate
56 change that “*changes the fundamental attributes of a system*” (see Text S1 for definitions).

57 Transformational change implies shifts in locations for production of specific crops and
58 livestock, or shifting to farming systems new to a region or resource system^{3,5}. Here, we
59 consider one type of transformation: switching of staple crop type grown over a large
60 geographic area of 0.3 million ha (the grid cell size of our analysis) or more. We analyze
61 when and where major cropping systems transformations are likely to occur for important
62 crops in Sub-Saharan Africa, and identify key research and policy priorities to address these
63 changes as well as the timescales at which they should be put in place.

64

65 We use a crop suitability modeling approach together with CMIP5 climate model data for
66 RCPs 6.0 and 8.5 to simulate historical and future crop suitability for nine major crops in
67 Africa that constitute 50 % of African agricultural production quantity (45 % of value) and
68 60 % of the region’s produced protein supply⁸ (see Methods). The timing and character of
69 major changes is shown in terms of three stages using the frequency of crossing a viability
70 threshold (see Methods) and following a previous framework of adaptation across
71 timescales [see refs. ^{5,9} and Text S1]: incremental (i.e. coping), systemic, and

72 transformational adaptation (Table 1). We postulate a preparatory phase where threshold-
73 crossing frequency is relatively high (5 years out of 20 are unviable) preceding a
74 transformational phase. Results presented here focus on the timing of transformational
75 changes and their associated preparatory phase.

76

77 Transformational changes are likely for all crops under RCP 8.5 during the 21st century,
78 though with large variations in extent and location of affected areas across crops (Figs. 1,
79 S1). Later threshold-crossing times and smaller affected areas for RCP6.0 suggest benefits
80 from more aggressive mitigation (Figs. S2). For six out of the nine crops, the vast majority
81 of currently suitable area was projected to stay suitable. For beans, maize and banana,
82 transformations were found likely in large portions of their currently suitable areas (> 30 %
83 for maize and banana, 60 % for beans). In general, there was a trend for all crops to
84 undergo transformational change along the Sahel belt before 2050s, with maize being the
85 most affected crop (Fig. 1). Similar frontier movements were seen in the south west
86 (Namibia, Angola) and the south east (Botswana, Zimbabwe and Mozambique).
87 Particularly notable is the widespread transformation projected in bean areas in East Africa,
88 especially in Uganda and Tanzania, occurring mostly after 2050s (Fig. 1). In most of the
89 areas projected to undergo transformational change during the 21st century, preparatory
90 phases occur very early or should already be in place (Fig. S3).

91

92 Proportions of area projected to need transformational adaptation across the 21st century
93 indicate significant divergence in crop responses to future climate scenarios (Fig. 2) as well
94 as in the biophysical driver of transformational change (Table S1). Common beans were
95 projected to be the most impacted crop for both scenarios with 60 % of area crossing the

96 transformational threshold by the end of the century under RCP 8.5 (RCP 6.0 reaches 30 %
97 by the same period) (Fig. 2C, F). This represents 1.85 million ha (0.88 million ha for RCP
98 6.0) of current bean cropping systems across sub-Saharan Africa, where currently 41.4 %
99 (18.8 % for RCP 6.0) of total sub-Saharan African bean production occurs. The largest
100 contiguous areas of change will be nearly 350 million ha crossing Angola and DRC (beans,
101 RCP 8.5). The extent of transformation was also large for maize, with ca. 35 % area
102 transformed under RCP8.5 by the end of the century. Transformational change was also
103 significant for banana (both RCPs) with transformed areas between 15-30 % by the 2090s
104 (Fig. 2B, E). Root crops (yams, cassava) and drought-resistant cereals (millets, sorghum)
105 underwent the least simulated change with less than 15 % of currently suitable area
106 transformed by the 2090s. Analyses of percentage area transformed in major producing
107 countries for each crop indicated geographically-specific investment priorities to enable
108 adaptation, with important temporal nonlinearities (Figs. S4, S5). In the case of beans,
109 Uganda and Tanzania both require transformation for about 10 % of their suitable areas by
110 the 2050s, whereas by the 2090s this increases to more than 30 % (median RCP 8.5, Fig.
111 S5B). Similarly, projected maize transformations represent 5% of Nigeria's current
112 production by the 2050s and 25 % by 2100 (median RCP 8.5, Fig. S5F).

113

114 For the regions projected to require transformation, two options exist: an alternative
115 cropping system (including crops not analyzed here), or where no viable alternative exists,
116 transformation out of crop-based livelihoods⁴. For maize under RCP8.5 (Fig. 3; see Fig S6
117 for other crops), 58.9 %, on average, of maize area remains suitable throughout this
118 century, and 40.6 % of areas require transformation and have suitable substitution crops.
119 The most viable substitution crops, not only for maize but also for other crops, were

120 primarily millets and sorghum due to their drought and heat stress tolerance¹⁰ (Fig. S6).
121 However, 0.5 % of maize areas have no viable crop substitution option (dark grey areas in
122 Fig. 3A), which given the broad range of crops analyzed here, we argue highly likely would
123 need to move out of crop-based agriculture. These areas total 0.8 MHa and were located in
124 the dry zones of South Africa,. Currently, 2.7 million tons of maize are produced in these
125 affected regions.

126

127 The projected changes in crop suitability and resulting transformational adaptation suggest
128 particular attention has to be paid to adaptation in banana-, maize- and bean-based cropping
129 systems. Maize and beans are a critical part of livelihoods in large parts of East Africa¹¹.
130 Our results indicate that farmers in the maize-mixed farming system might, in the long run,
131 shift to more drought-tolerant cereals like millet and sorghum, which we identify as viable
132 substitutes in many locations, though these may experience yield reductions (Table S2).
133 Furthermore, in some areas in the southern Sahel and in dry parts of Southern and Eastern
134 Africa even these drought-resilient crops might become increasingly marginal (Fig. S6).
135 For these areas, a more drastic transformation to livestock might be necessary since
136 cropping might not be a viable livelihood strategy in the long run [cf. ref. ⁴].

137

138 Food security of farmers and consumers will depend on how transformational change in
139 staple crops is managed. Governments will need to prepare for possible large losses in
140 national production potentials, and production areas, of up to 15% by 2050 and over 30%
141 by 2100. We propose a framework for developing and implementing transformational
142 changes in African cropping systems. We envision three overlapping phases of adaptation
143 needed to support transformational change in areas where one or all crops become

144 unsuitable: an incremental adaptation phase that focuses on improvements to existing crops
145 and management practices, a preparatory phase that establishes enabling environments at
146 multiple levels to support transformational change, and a transformation phase in which
147 farmers substitute crops or explore alternative livelihoods strategies. Changes between
148 different states of the crop systems analyzed here can be seen as continuous transitions in a
149 cyclical framework¹², with different information and policy support needs¹³.

150

151 Actions in the incremental adaptation phase include modifications to crops and to
152 management practices including irrigation to prolong suitability in areas of decline. A key
153 opportunity is crop improvement for traits such as increased heat or drought tolerance^{14,15}.
154 If successful, crop improvement and improved agronomy (e.g. for yield gap closure¹⁶) will
155 delay transformations, maintaining cropping systems beyond the initial time threshold we
156 project, and in exceptional cases avoid transformation. Crop improvement requires lead
157 times of 15 years or more and hence investment should be prioritized immediately, well
158 ahead of projected transformation thresholds 20-50 years from now¹⁷. In addition to crop
159 improvement, changes in farm management practices, such as cropping calendars and water
160 and nutrient regimes, and enhanced support, such as agro-climatic advisory services, can
161 prolong the incremental adaptation phase⁶. The interacting nature of crop management,
162 breeding and transformational adaptation strategies is a topic that merits future research,
163 particularly given progress in national-level adaptation planning¹⁸.

164

165 For this analysis, a preparatory phase is triggered when 5 years out of 20 are unviable, and
166 generally occurs up to 15-20 years ahead of the transformational phase (Fig. S3). From a
167 policy and planning perspective, the preparatory phase could signal a likely

168 transformational change of a key crop across large geographic areas. At the national level
169 this may entail re-assessment of major agricultural development and food security policies
170 including research, development and extension. A shift away from an established staple
171 crop may also require transitions in food storage, transport, processing, trade or dietary
172 patterns. Transformation of staple crop systems is, however, hardly unprecedented (see
173 Text S2). It is only one century since the transition from small grains (millets and sorghum)
174 to maize as Africa's dominant crop¹⁹. Moreover, evidence suggests that prevailing
175 preferences for maize are not immutable, with both farmers and government officials in
176 Kenya preferring re-diversification to small grains over, for example, improved maize
177 varieties²⁰. Furthermore, in some countries, farmers are already undertaking
178 transformational climate adaptation even at the early stages of climate change^{5,12,21}.

179

180 What kinds of public policy actions enable transformational shifts of cropping systems
181 among large numbers of farmers? Large-scale empirical evidence on barriers to adaptation
182 emphasizes the importance of tailored extension, information and financial services^{13,22}.
183 Shifts in staple crops will require transformation not only among farming communities but
184 also along value chains and among consumers; a preparatory phase could usefully provide
185 incentives for development of new processing and storage facilities, food and nutrition
186 standards, consumer education and recipes, government procurement strategies, and
187 piloting of markets for by-products. While policy options are myriad (e.g. refs. ^{13,22-25}), the
188 key to the preparatory phase will be to create a flexible enabling environment for self-
189 directed change among farmers, consumers and value chain participants in response to
190 climatic changes, situated within the wider context of rapid demographic and economic
191 change^{3,5,9}.

192

193 This analysis, like many others, operates in a context of high uncertainty⁹. Our estimates of
194 transformational adaptation are based on simulations of a single crop suitability model and
195 are probably conservative owing to projected changes in climate extremes, pests and
196 diseases, soil, trade and socio-economic constraints not considered here, and the fact that
197 threshold exceedance may happen after 2100. Despite these limitations, many studies
198 support our findings of decline in agricultural potential in sub-Saharan Africa under climate
199 change as well as on the mechanisms for such decline^{1,4,11,26–28}. Additionally, policies and
200 strategies are fairly easy to identify, but they must be applied when the appropriate triggers
201 for action occur taking into account risks, costs and benefits. This study contributes new
202 insights to the possible timings of such actions. Such changes heighten the need for
203 monitoring capacities to track farming systems as well as climate, to provide policy-makers
204 with early signals of when shifts in crop suitability are likely to occur and thus trigger a
205 proactive preparatory phase to facilitate the required food system transformation.

206

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223 development of software infrastructure in partnership with the Global Organization for
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225 insightful feedback.

226

227 **Author contributions**

228 JRV and AJ conceived the study. UR, JRV and AJ designed the research. UR and JRV
229 performed the analyses and analyzed the results. FM and LP parameterized some of the
230 crops used in the model. UR, JRV, AJ and SJV interpreted the results. UR, JRV, AJ and
231 SJV wrote the manuscript. All authors discussed results and commented on the manuscript.

232

233 **Additional information**

234 The authors declare no competing financial interests. Supplementary information
235 accompanies this paper on www.nature.com/natureclimatechange. Reprints and
236 permissions information is available online at www.nature.com/reprints. Correspondence
237 and requests for materials should be addressed to JRV.

238

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337 **Figure captions**

338 **Figure 1.** Timing of transformational adaptation. Mean time at which transformational
339 adaptation is projected to occur for all staple crops analysed in this study for RCP8.5. Grey
340 areas indicate areas where suitability of each crop is still above the respective viability
341 threshold in more than 50 % of years in a 20-year period, i.e. where transformational
342 adaptation is not needed during the 21st century.

343 **Figure 2.** Extent of transformational adaptation. Cumulative percentage of suitable area in
344 Sub-Saharan Africa projected to require transformational change for RCP 6.0 (A, B, C) and
345 RCP 8.5 (D, E, F) during the 21st century for (A, D) cereals, (B, E) roots and banana, and
346 (C, F) grain legumes. Thick lines represent the mean and shading corresponds to
347 interquartile range. Dashed lines at the beginning of each time series indicate no
348 simulations were carried out during that period.

349 **Figure 3.** Best substitute crops at mean time of crossing for maize for RCP 8.5. A
350 substitute is defined in a given pixel as a crop that by 2100 does not require transformation.
351 (A) Map of best substitutes. Green areas indicate that 2 crops or more can be potential
352 substitutes on a continuous scale. Dark grey areas indicate that no substitution is possible,
353 whereas light grey areas indicate no substitution needed. (B) Bar plot of percentage area
354 (from total area requiring transformation) that can be adapted through substitution. Note
355 that overlaps occur (green areas in panel A) and hence the sum of individual crops is not
356 100 %. Crop names as follows: PM (pearl millet), SO (sorghum), YM (yam), FM (finger
357 millet), GN (groundnut), CA (cassava), BA (banana), and BE (bean). “No Avail” refers to
358 the percentage area for which no substitutes are available. Error bars in panel (B) extend
359 one standard deviation across the GCM ensemble.

360

361 **Methods**

362 The EcoCrop model²⁹ was used for producing spatially-explicit suitability simulations of
363 nine major staple crops in Sub-Saharan Africa. EcoCrop has been used to assess the
364 impacts of climate change on a variety of crops including sorghum, cassava, common
365 beans, potatoes, and groundnut [cf. refs. ^{9,30}, and references therein]. We choose EcoCrop
366 over more complex process-based mostly because process-based modelling capabilities for
367 crops such as banana, yams and finger millets are limited. Moreover, recent research has
368 shown that current process-based cassava models do not simulate well the spill-over
369 mechanism that is typical of cassava root carbohydrate storage³¹. Furthermore,
370 comprehensive evaluations of process-based models across many environments in sub-
371 Saharan Africa are generally lacking. In addition to this, the scale and extent at which we
372 conduct our modelling would necessarily bring a number of additional limitations into play,
373 most notably the difficulty to constrain model parameters and initial conditions in data
374 scarce regions^{32,33}. Finally, previous studies have reported substantial agreement between
375 climate change impacts projections from EcoCrop and those of other models ^{9,29}. As a
376 robustness check, we compare our results with those of previous studies (see Table S2).

377

378 Crops included in the analyses were maize, common beans, finger millet, pearl millet,
379 cassava, banana, groundnut, sorghum and yam, which together contribute to 50 % of total
380 production quantity (45 % of value) and 60 % of produced protein supply in the region.
381 Rice (1.95 % of production, 11.2 % of protein supply) and wheat (no significant
382 production, 11.9 % protein supply) were excluded from the analyses because both crops are
383 largely imported and, additionally, rice is mainly cultivated in irrigated paddies that cannot
384 be modeled with the EcoCrop model.

385

386 EcoCrop parameter sets were derived from previous studies for beans, cassava, banana and
387 sorghum (Table S3). For finger millet, pearl millet, groundnut and yam, crop presence data
388 were gathered from the Genesys portal (<http://www.genesys-pgr.org>), the Global
389 Biodiversity Information Facility (GBIF, available at <http://www.gbif.org>), and existing
390 literature (Table S3). Potential parameter sets were then derived following ref. ²⁹, whereby
391 a set of ecological parameters is derived based on the known distribution of the crop. This
392 implies that the model parameters take into account a wide range of genotypic variation²⁹,
393 though without providing the detailed variety-level information that would be needed for
394 sub-national and local-level adaptation planning. For the scale of our analysis we believe
395 crop-level parameters provide enough detail to support our conclusions. Use of objective
396 skill metrics (i.e. root mean squared error, omission rate), and careful examination of crop
397 suitability simulations against the MapSPAM crop distribution dataset³⁴ helped ensuring
398 consistency with observational data. For maize, the same method was followed, though it
399 was applied separately for each of the 6 maize mega-environments of Africa ³⁵. As a further
400 consistency check, model parameters were carefully assessed against literature, and
401 adjusted where necessary. Finally, suitability simulations for Africa as well as model
402 parameters of finger millet, pearl millet, groundnut and yam and maize were sent for review
403 to crop-specific experts (1-2 per crop) via e-mail and parameters adjusted until suitability
404 simulations fully agreed with expert knowledge (see Table S3).

405

406 To analyze transformational adaptation, a crop-specific suitability threshold below which
407 the crop in question is considered not agriculturally viable in a particular location, was
408 determined. Using the MapSPAM dataset as a reference, the fractions of true positives

409 (TP), true negatives (TN) and false positives (FP) were calculated. Sensitivity [$SE=TP/(TP$
410 $+ TN)-1$] and specificity [$SP=TN/(TN+FP)-1$] were calculated for all integer suitability
411 values in the range [0, 100]. For each crop, the suitability threshold at which the maximum
412 value of $SE+SP$ occurred was chosen (maximum specificity and sensitivity, MSS). This
413 threshold is hereafter named ‘viability’ threshold. This method was chosen because it
414 provides a complete consideration of presences and absences in the model and the data,
415 which is critical for establishing agronomic viability. Additionally, the MSS has been
416 previously identified as a well suited method for threshold selection in the context of
417 presence-absence analyses [see ref. ³⁶]. Further analysis showed that threshold values at
418 maximum Cohen’s Kappa did not differ significantly from those of MSS (see Table S4). As
419 an indication of agreement between MapSPAM and EcoCrop (though not of crop model
420 skill) the Area Under the Receiving Operating Characteristic (ROC) curve (AUC) was also
421 calculated.

422

423 Future climate data were downloaded from the CMIP5 data portal³⁷ for two Representative
424 Concentration Pathways (RCPs): RCP6.0 and RCP8.5. The larger climate change signal
425 associated with these two RCPs^{38,39} is a priori more likely to trigger transformational
426 changes in cropping systems. Table S5 presents the full list of GCMs used in this study (19
427 GCMs in total). CMIP5 GCM outputs were bias-corrected using the observed
428 climatological means using CRU data and the change factor method, which is
429 mathematically equivalent to ‘nudging’ the GCM output [see ref. ⁴⁰]. No consideration of
430 sub-monthly variability was done since EcoCrop uses only monthly-level data²⁹.

431

432 Crop suitability simulations were carried out for the historical period (1961-1990) and for
433 93 years in the 21st century (2006-2098), for each GCM and RCP. From yearly suitability
434 simulations, on a grid cell basis, and only for grid cells reported as cultivated for each crop,
435 20-year running timeframes were used to determine the timing of transformational
436 adaptation interventions as follows:

- 437 1. Preparatory phase: when suitability is above the viability threshold in only 10-15
438 years out of the 20 year running period, preceding a transformation phase.
- 439 2. Transformation phase: when suitability is above the viability threshold in less than
440 10 years out of the 20-year running period. We assume a 50 % level as a
441 compromise between the levels of crop failure often experienced across farming
442 systems in Sub-Saharan Africa (see ref. ⁴¹).

443 Implicitly this approach assumes that farmers are ‘smart’ in the sense that they make
444 rational decisions based on the relative suitability of different crops.

445

446 Threshold-crossing approaches have been widely used in climate impacts research^{42,43}. The
447 selected length of 20 years reflects most adequately the development of mean suitability
448 conditions in the models (from a mean climate state), and hence reflects well progressive
449 changes in climates. In addition, using shorter 10-year running periods as opposed to 20-
450 year ones resulted in the same qualitative conclusions for our study. We concentrate only in
451 currently cropped areas under the assumption that new land will not become available for a
452 crop except if it is for the replacement of another crop⁴⁴. Identified timeframes and the
453 uncertainty associated with the ‘when’ each action should be taken are mapped out and
454 analyzed for each crop. Finally, for each crop and location where transformational

455 adaptation is projected to occur, suitability of the other crops is analyzed to determine a set
456 of potential substitute crops.

457

458 **Methods references**

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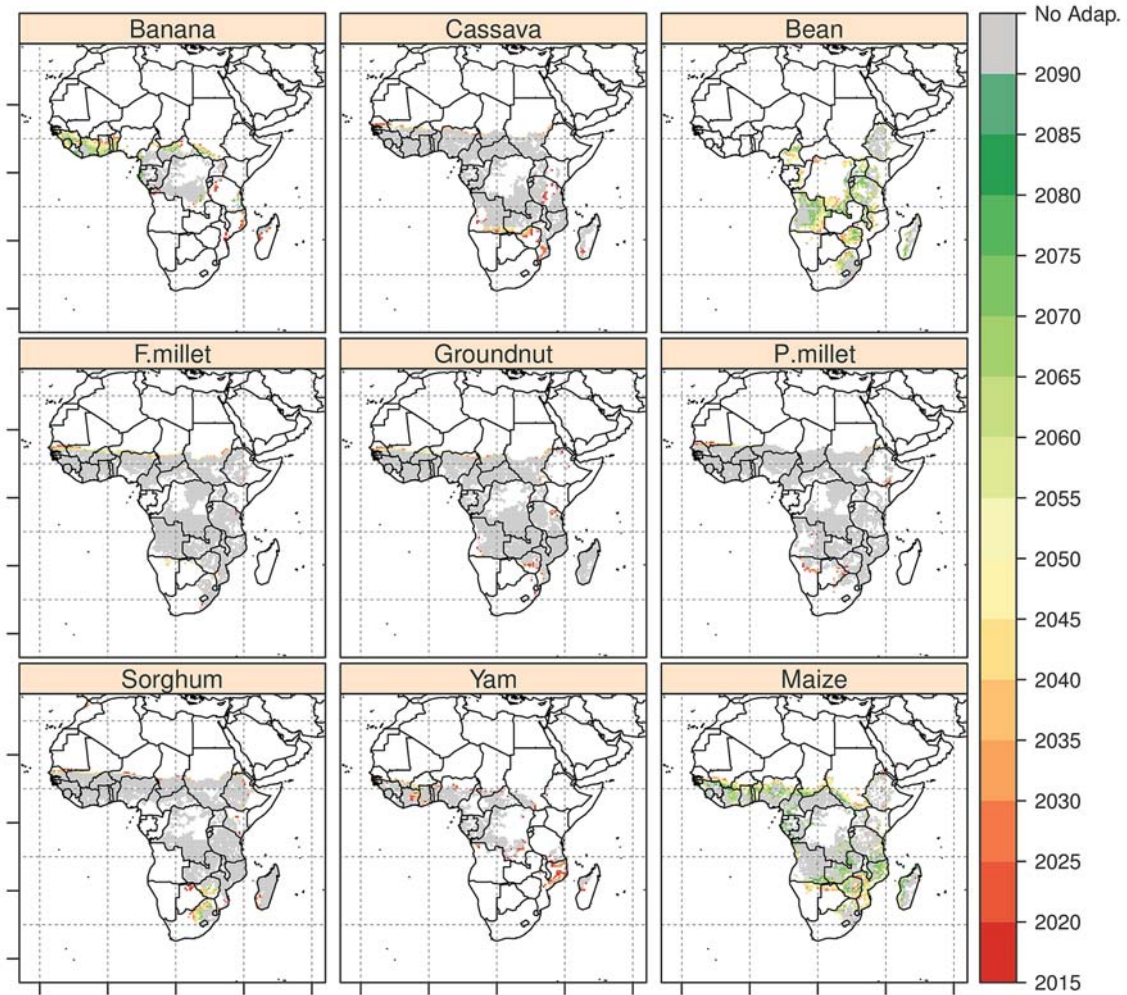
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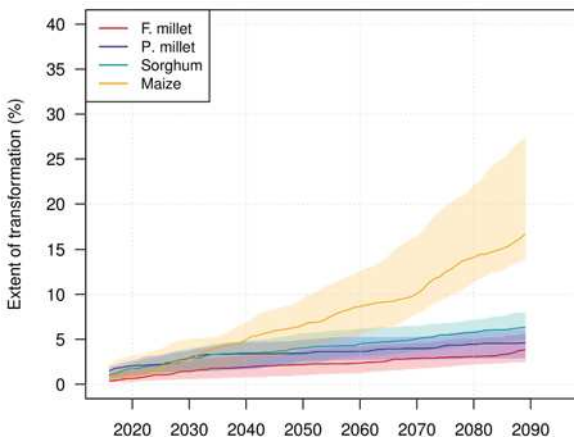
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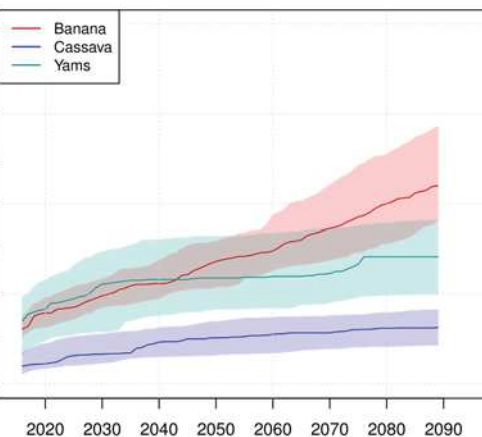
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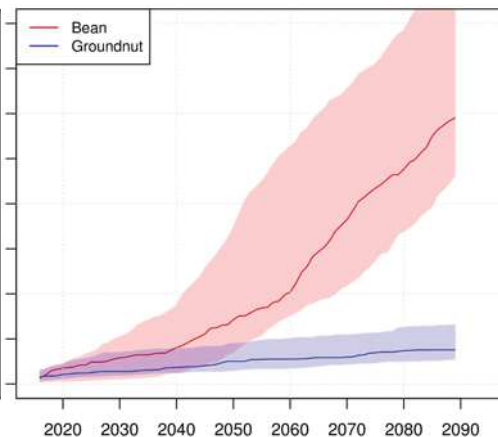
A. Cereals (RCP6.0)



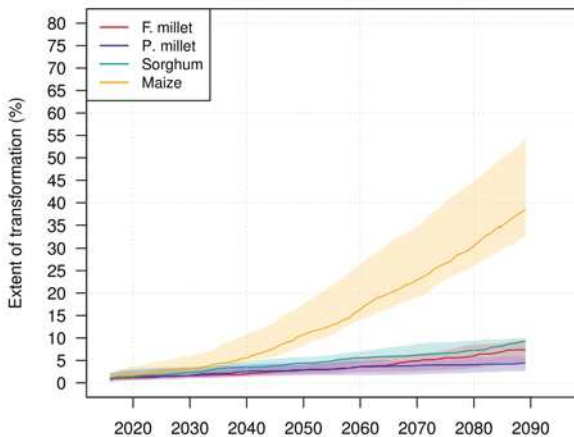
B. Roots and banana (RCP6.0)



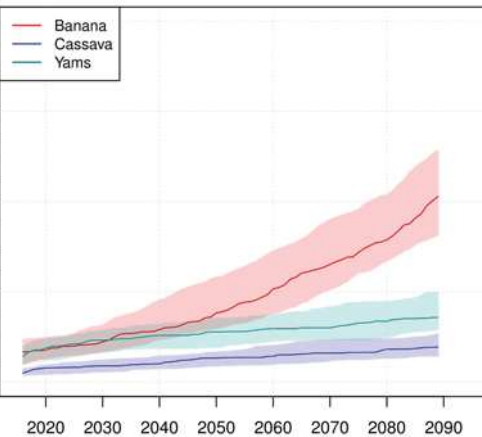
C. Grain legumes (RCP6.0)



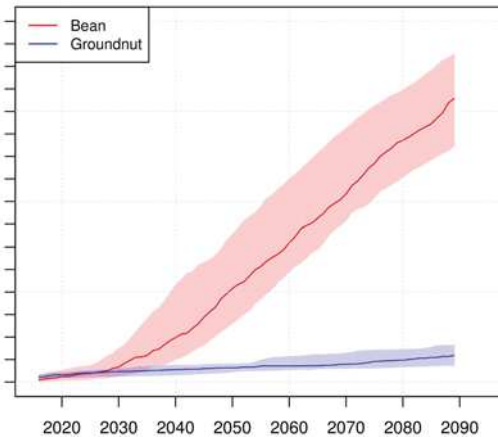
D. Cereals (RCP8.5)



E. Roots and banana (RCP8.5)



F. Grain legumes (RCP8.5)



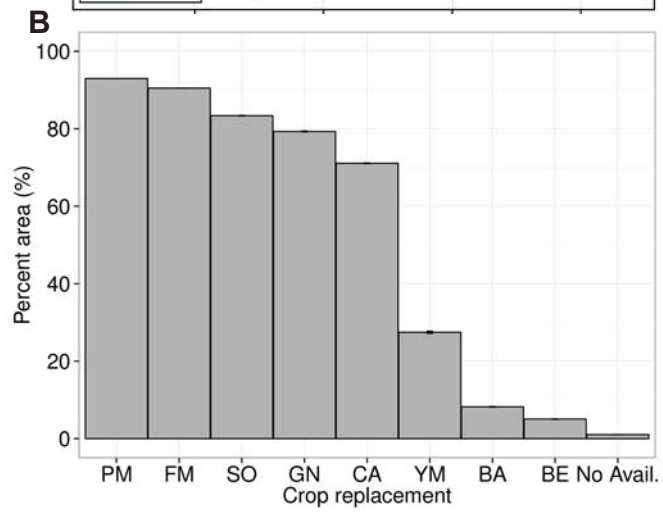
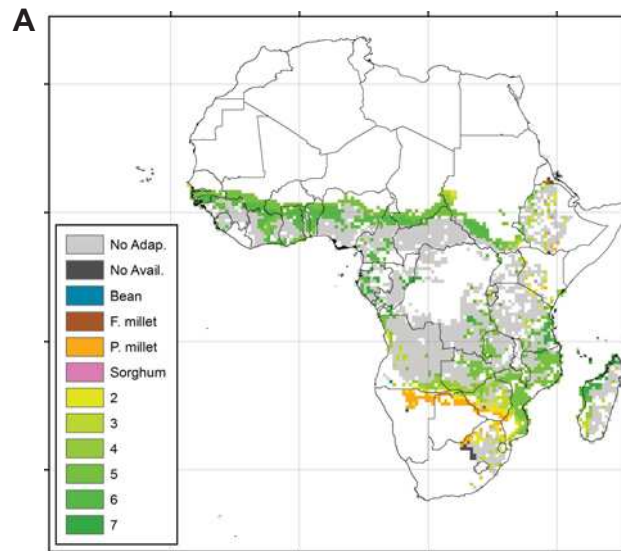


Table 1. Definition of adaptation across timescales and its relationship with viability threshold crossing

Adaptation type	Biophysical behaviour at time of crossing¹
Coping phase	Crossing frequency is low ($Y_{BT} \leq 5$) in all periods
Systemic adaptation	Crossing frequency is intermediate ($Y_{BT} \geq 5$), but no transformation is projected later in the century ($Y_{BT} < 10$)
Preparatory phase	Crossing frequency is intermediate ($Y_{BT} \geq 5$) and transformation occurs at some point afterwards
Transformational change	Crossing frequency is high ($Y_{BT} \geq 10$)

¹ Y_{BT} refers to the number of years (over a 20-year period) in which crop suitability is below the viability threshold