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

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Climate change is projected to constitute a significant threat to food security, if no adaptation actions are taken[1,2]. Transformation of agricultural systems, e.g. switching crop types or moving out of agriculture, is projected to be necessary in some cases[3–5]. However, little attention has been paid to the timing of these transformations. Here, we develop a temporal uncertainty framework using the CMIP5 ensemble to assess when and where cultivation of key crops in Sub-Saharan African becomes unviable. We report potential transformational changes for all major crops during the 21st century, as climates shift and areas become unsuitable. For most crops, however, transformation is limited to small pockets (<15 % of area), and only for beans, maize and banana is transformation more widespread (~30 % area for maize and banana, 60 % for beans). We envision three overlapping adaptation phases to enable projected transformational changes: an incremental adaptation phase focused on improvements to crops and management, a preparatory phase that establishes appropriate policies and enabling environments, and a transformational adaptation phase in which farmers substitute crops, explore alternative livelihoods strategies, or relocate. To best align policies with production triggers for no-regret actions, monitoring capacities to track farming systems as well as climate are needed.

Agricultural activities are the main means to reduce poverty and improve food security among 850 million undernourished people[2]. Numerous studies have shown that climate change can be a significant threat to food availability and stability by reducing agricultural productivity and increasing inter-annual variations in yields[1,2,6]. Adaptation will be required if food production is to be increased in both quantity and stability in order to meet food security needs during the 21st century. A recent global meta-analysis[1] reported that decreases of ca. 5 % in crop productivity are expected for every degree of warming above historical levels, and that adapted crops yield roughly 7 % greater than non-adapted crops. Yield gains from adaptation through crop management and varietal substitution, however, are highest with moderate or low (< +3 ºC) levels of warming[1,6], suggesting that more profound systemic and/or transformational changes may be required when and where higher levels of warming occur[5].

Transformational adaptation is defined by the IPCC[7] as a response to the effects of climate change that "*changes the fundamental attributes of a system*" (see Text S1 for definitions). Transformational change implies shifts in locations for production of specific crops and livestock, or shifting to farming systems new to a region or resource system[3,5]. Here, we consider one type of transformation: switching of staple crop type grown over a large geographic area of 0.3 million ha (the grid cell size of our analysis) or more. We analyze when and where major cropping systems transformations are likely to occur for important crops in Sub-Saharan Africa, and identify key research and policy priorities to address these changes as well as the timescales at which they should be put in place.

We use a crop suitability modeling approach together with CMIP5 climate model data for RCPs 6.0 and 8.5 to simulate historical and future crop suitability for nine major crops in Africa that constitute 50 % of African agricultural production quantity (45 % of value) and 60 % of the region's produced protein supply[8] (see Methods). The timing and character of major changes is shown in terms of three stages using the frequency of crossing a viability threshold (see Methods) and following a previous framework of adaptation across timescales [see refs. [5,9] and Text S1]: incremental (i.e. coping), systemic, and transformational adaptation (Table 1). We postulate a preparatory phase where threshold-crossing frequency is relatively high (5 years out of 20 are unviable) preceding a transformational phase. Results presented here focus on the timing of transformational changes and their associated preparatory phase.

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

Proportions of area projected to need transformational adaptation across the 21st century indicate significant divergence in crop responses to future climate scenarios (Fig. 2) as well as in the biophysical driver of transformational change (Table S1). Common beans were projected to be the most impacted crop for both scenarios with 60 % of area crossing the transformational threshold by the end of the century under RCP 8.5 (RCP 6.0 reaches 30 % by the same period) (Fig. 2C, F). This represents 1.85 million ha (0.88 million ha for RCP 6.0) of current bean cropping systems across sub-Saharan Africa, where currently 41.4 % (18.8 % for RCP 6.0) of total sub-Saharan African bean production occurs. The largest contiguous areas of change will be nearly 350 million ha crossing Angola and DRC (beans, RCP 8.5). The extent of transformation was also large for maize, with ca. 35 % area transformed under RCP8.5 by the end of the century. Transformational change was also significant for banana (both RCPs) with transformed areas between 15-30 % by the 2090s (Fig. 2B, E). Root crops (yams, cassava) and drought-resistant cereals (millets, sorghum) underwent the least simulated change with less than 15 % of currently suitable area transformed by the 2090s. Analyses of percentage area transformed in major producing countries for each crop indicated geographically-specific investment priorities to enable adaptation, with important temporal nonlinearities (Figs. S4, S5). In the case of beans, Uganda and Tanzania both require transformation for about 10 % of their suitable areas by the 2050s, whereas by the 2090s this increases to more than 30 % (median RCP 8.5, Fig. S5B). Similarly, projected maize transformations represent 5% of Nigeria's current production by the 2050s and 25 % by 2100 (median RCP 8.5, Fig. S5F).

For the regions projected to require transformation, two options exist: an alternative cropping system (including crops not analyzed here), or where no viable alternative exists, transformation out of crop-based livelihoods[4]. For maize under RCP8.5 (Fig. 3; see Fig S6 for other crops), 58.9 %, on average, of maize area remains suitable throughout this century, and 40.6 % of areas require transformation and have suitable substitution crops. The most viable substitution crops, not only for maize but also for other crops, were primarily millets and sorghum due to their drought and heat stress tolerance[10] (Fig. S6). However, 0.5 % of maize areas have no viable crop substitution option (dark grey areas in Fig. 3A), which given the broad range of crops analyzed here, we argue highly likely would need to move out of crop-based agriculture. These areas total 0.8 MHa and were located in the dry zones of South Africa,. Currently, 2.7 million tons of maize are produced in these affected regions.

The projected changes in crop suitability and resulting transformational adaptation suggest particular attention has to be paid to adaptation in banana-, maize- and bean-based cropping systems. Maize and beans are a critical part of livelihoods in large parts of East Africa[11]. Our results indicate that farmers in the maize-mixed farming system might, in the long run, shift to more drought-tolerant cereals like millet and sorghum, which we identify as viable substitutes in many locations, though these may experience yield reductions (Table S2). Furthermore, in some areas in the southern Sahel and in dry parts of Southern and Eastern Africa even these drought-resilient crops might become increasingly marginal (Fig. S6). For these areas, a more drastic transformation to livestock might be necessary since cropping might not be a viable livelihood strategy in the long run [cf. ref. [4]].

Food security of farmers and consumers will depend on how transformational change in staple crops is managed. Governments will need to prepare for possible large losses in national production potentials, and production areas, of up to 15% by 2050 and over 30% by 2100. We propose a framework for developing and implementing transformational changes in African cropping systems. We envision three overlapping phases of adaptation needed to support transformational change in areas where one or all crops become unsuitable: an incremental adaptation phase that focuses on improvements to existing crops and management practices, a preparatory phase that establishes enabling environments at multiple levels to support transformational change, and a transformation phase in which farmers substitute crops or explore alternative livelihoods strategies. Changes between different states of the crop systems analyzed here can be seen as continuous transitions in a cyclical framework[12], with different information and policy support needs[13].

Actions in the incremental adaptation phase include modifications to crops and to management practices including irrigation to prolong suitability in areas of decline. A key opportunity is crop improvement for traits such as increased heat or drought tolerance[14,15]. If successful, crop improvement and improved agronomy (e.g. for yield gap closure[16]) will delay transformations, maintaining cropping systems beyond the initial time threshold we project, and in exceptional cases avoid transformation. Crop improvement requires lead times of 15 years or more and hence investment should be prioritized immediately, well ahead of projected transformation thresholds 20-50 years from now[17]. In addition to crop improvement, changes in farm management practices, such as cropping calendars and water and nutrient regimes, and enhanced support, such as agro-climatic advisory services, can prolong the incremental adaptation phase[6]. The interacting nature of crop management, breeding and transformational adaptation strategies is a topic that merits future research, particularly given progress in national-level adaptation planning[18].

For this analysis, a preparatory phase is triggered when 5 years out of 20 are unviable, and generally occurs up to 15-20 years ahead of the transformational phase (Fig. S3). From a policy and planning perspective, the preparatory phase could signal a likely transformational change of a key crop across large geographic areas. At the national level this may entail re-assessment of major agricultural development and food security policies including research, development and extension. A shift away from an established staple crop may also require transitions in food storage, transport, processing, trade or dietary patterns. Transformation of staple crop systems is, however, hardly unprecedented (see Text S2). It is only one century since the transition from small grains (millets and sorghum) to maize as Africa's dominant crop[19]. Moreover, evidence suggests that prevailing preferences for maize are not immutable, with both farmers and government officials in Kenya preferring re-diversification to small grains over, for example, improved maize varieties[20]. Furthermore, in some countries, farmers are already undertaking transformational climate adaptation even at the early stages of climate change[5,12,21].

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

This analysis, like many others, operates in a context of high uncertainty[9]. Our estimates of transformational adaptation are based on simulations of a single crop suitability model and are probably conservative owing to projected changes in climate extremes, pests and diseases, soil, trade and socio-economic constraints not considered here, and the fact that threshold exceedance may happen after 2100. Despite these limitations, many studies support our findings of decline in agricultural potential in sub-Saharan Africa under climate change as well as on the mechanisms for such decline[1,4,11,26–28]. Additionally, policies and strategies are fairly easy to identify, but they must be applied when the appropriate triggers for action occur taking into account risks, costs and benefits. This study contributes new insights to the possible timings of such actions. Such changes heighten the need for monitoring capacities to track farming systems as well as climate, to provide policy-makers with early signals of when shifts in crop suitability are likely to occur and thus trigger a proactive preparatory phase to facilitate the required food system transformation.

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Author contributions

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

Additional information

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

References

1. Challinor, A. J. *et al.* A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Chang.* **4,** 287–291 (2014).

2. Wheeler, T. & von Braun, J. Climate change impacts on global food security. *Science (80-.).* **341,** 508–513 (2013).

3. Kates, R. W., Travis, W. R. & Wilbanks, T. J. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proc. Natl. Acad. Sci.* (2012). doi:10.1073/pnas.1115521109

4. Jones, P. G. & Thornton, P. K. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environ. Sci. Policy* **12,** 427–437 (2009).

5. Rickards, L. & Howden, S. M. Transformational adaptation: agriculture and climate change. *Crop Pasture Sci.* **63,** 240–250 (2012).

6. Porter, J. R. *et al. Chapter 7. Food Security and Food Production Systems. Climate Change 2014: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the IPCC 5th Assessment Report*. (2014).

7. IPCC. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds. Barros, V. R. et al.) 688 (Cambridge University Press, 2014).

8. FAO. FAOSTAT. (2013). at <http://faostat.fao.org>

9. Vermeulen, S. J. *et al.* Addressing uncertainty in adaptation planning for agriculture. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 8357–62 (2013).

10. Mohamed, H. A., Clark, J. A. & Ong, C. K. Genotypic Differences in the Temperature Responses of Tropical Crops. *J. Exp. Bot.* **39,** 1121–1128 (1988).

11. Thornton, P. K., Jones, P. G., Alagarswamy, G. & Andresen, J. Spatial variation of crop yield response to climate change in East Africa. *Glob. Environ. Chang.* **19,** 54–65 (2009).

12. Park, S. E. *et al.* Informing adaptation responses to climate change through theories of transformation. *Glob. Environ. Chang.* **22,** 115–126 (2012).

13. Dowd, A.-M. *et al.* The role of networks in transforming Australian agriculture. *Nat. Clim. Chang.* **4,** 558–563 (2014).

14. Araújo, S. S. *et al.* Abiotic Stress Responses in Legumes : Strategies Used to Cope with Environmental Challenges. *CRC. Crit. Rev. Plant Sci.* **34,** 237–280 (2015).

15. Beyene, Y. *et al.* Genetic Gains in Grain Yield Through Genomic Selection in Eight Bi-parental Maize Populations under Drought Stress. *Crop Sci.* **55,** 154 (2015).

16. Tittonell, P. & Giller, K. E. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *F. Crop. Res.* **143,** 76–90 (2013).

17. Chapman, S. C., Chakraborty, S., Dreccer, M. F. & Howden, S. M. Plant adaptation to climate change—opportunities and priorities in breeding. *Crop Pasture Sci.* **63,** 251 (2012).

18. Lesnikowski, A., Ford, J., Biesbroek, R., Berrang-Ford, L. & Heymann, S. J. National-level progress on adaptation. *Nat. Clim. Chang.* (2015). doi:10.1038/nclimate2863

19. Byerlee, D. & Heisey, P. W. in *Africa's Emerging Maize Revolution* 9–22 (Lynne Rienner Publishers, Inc., 1997).

20. Ely, A., Van Zwanenberg, P. & Stirling, A. Broadening out and opening up technology assessment: Approaches to enhance international development, co-ordination and democratisation. *Res. Policy* **43,** 505–518 (2014).

21. Mapfumo, P. *et al.* Pathways to transformational change in the face of climate impacts: an analytical framework. *Clim. Dev.* 1–13 (2015). doi:10.1080/17565529.2015.1040365

22. Hassan, R. M. Implications of climate change for agricultural sector performance in Africa: Policy challenges and research agenda. *J. Afr. Econ.* **19,** (2010).

23. Cock, J. *et al.* Crop management based on field observations: Case studies in sugarcane and coffee. *Agric. Syst.* **104,** 755–769 (2011).

24. Eakin, H. C., Lemos, M. C. & Nelson, D. R. Differentiating capacities as a means to sustainable climate change adaptation. *Glob. Environ. Chang.* **27,** 1–8 (2014).

25. Shackleton, S., Ziervogel, G., Sallu, S., Gill, T. & Tschakert, P. Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdiscip. Rev. Clim. Chang.* **6,** 321–344 (2015).

26. Knox, J., Hess, T., Daccache, A. & Wheeler, T. Climate change impacts on crop productivity in Africa and South Asia. *Environ. Res. Lett.* **7,** 34032 (2012).

27. Lobell, D. B., Banziger, M., Magorokosho, C. & Vivek, B. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nat. Clim. Chang.* **1,** 42–45 (2011).

28. Liu, J. *et al.* A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. *Glob. Planet. Change* **64,** 222–235 (2008).

Figure captions

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

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

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

Methods

The EcoCrop model[29] was used for producing spatially-explicit suitability simulations of nine major staple crops in Sub-Saharan Africa. EcoCrop has been used to assess the impacts of climate change on a variety of crops including sorghum, cassava, common beans, potatoes, and groundnut [cf. refs. [9,30], and references therein]. We choose EcoCrop over more complex process-based mostly because process-based modelling capabilities for crops such as banana, yams and finger millets are limited. Moreover, recent research has shown that current process-based cassava models do not simulate well the spill-over mechanism that is typical of cassava root carbohydrate storage[31]. Furthermore, comprehensive evaluations of process-based models across many environments in sub-Saharan Africa are generally lacking. In addition to this, the scale and extent at which we conduct our modelling would necessarily bring a number of additional limitations into play, most notably the difficulty to constrain model parameters and initial conditions in data scarce regions[32,33]. Finally, previous studies have reported substantial agreement between climate change impacts projections from EcoCrop and those of other models [9,29]. As a robustness check, we compare our results with those of previous studies (see Table S2).

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

EcoCrop parameter sets were derived from previous studies for beans, cassava, banana and sorghum (Table S3). For finger millet, pearl millet, groundnut and yam, crop presence data were gathered from the Genesys portal (http://www.genesys-pgr.org), the Global Biodiversity Information Facility (GBIF, available at http://www.gbif.org), and existing literature (Table S3). Potential parameter sets were then derived following ref. [29], whereby a set of ecological parameters is derived based on the known distribution of the crop. This implies that the model parameters take into account a wide range of genotypic variation[29], though without providing the detailed variety-level information that would be needed for sub-national and local-level adaptation planning. For the scale of our analysis we believe crop-level parameters provide enough detail to support our conclusions. Use of objective skill metrics (i.e. root mean squared error, omission rate), and careful examination of crop suitability simulations against the MapSPAM crop distribution dataset[34] helped ensuring consistency with observational data. For maize, the same method was followed, though it was applied separately for each of the 6 maize mega-environments of Africa [35]. As a further consistency check, model parameters were carefully assessed against literature, and adjusted where necessary. Finally, suitability simulations for Africa as well as model parameters of finger millet, pearl millet, groundnut and yam and maize were sent for review to crop-specific experts (1-2 per crop) via e-mail and parameters adjusted until suitability simulations fully agreed with expert knowledge (see Table S3).

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

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

Future climate data were downloaded from the CMIP5 data portal[37] for two Representative Concentration Pathways (RCPs): RCP6.0 and RCP8.5. The larger climate change signal associated with these two RCPs[38,39] is a priori more likely to trigger transformational changes in cropping systems. Table S5 presents the full list of GCMs used in this study (19 GCMs in total). CMIP5 GCM outputs were bias-corrected using the observed climatological means using CRU data and the change factor method, which is mathematically equivalent to 'nudging' the GCM output [see ref. [40]]. No consideration of sub-monthly variability was done since EcoCrop uses only monthly-level data[29].

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

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

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

Threshold-crossing approaches have been widely used in climate impacts research[42,43]. The selected length of 20 years reflects most adequately the development of mean suitability conditions in the models (from a mean climate state), and hence reflects well progressive changes in climates. In addition, using shorter 10-year running periods as opposed to 20-year ones resulted in the same qualitative conclusions for our study. We concentrate only in currently cropped areas under the assumption that new land will not become available for a crop except if it is for the replacement of another crop[44]. Identified timeframes and the uncertainty associated with the ‘when’ each action should be taken are mapped out and analyzed for each crop. Finally, for each crop and location where transformational adaptation is projected to occur, suitability of the other crops is analyzed to determine a set of potential substitute crops.

Methods references

29. Ramirez-Villegas, J., Jarvis, A. & Läderach, P. Empirical approaches for assessing impacts of climate change on agriculture: The EcoCrop model and a case study with grain sorghum. *Agric. For. Meteorol.* **170,** 67–78 (2013).

30. Jarvis, A., Ramirez-Villegas, J., Herrera Campo, B. V. & Navarro-Racines, C. Is Cassava the Answer to African Climate Change Adaptation? *Trop. Plant Biol.* **5,** 9–29 (2012).

31. Gabriel, L. F. *et al.* Simulating Cassava Growth and Yield under Potential Conditions in Southern Brazil. *Agron. J.* **106,** 1119 (2014).

32. Iizumi, T., Tanaka, Y., Sakurai, G., Ishigooka, Y. & Yokozawa, M. Dependency of parameter values of a crop model on the spatial scale of simulation. *J. Adv. Model. Earth Syst.* **6,** 527–540 (2014).

33. Ramirez-Villegas, J., Watson, J. & Challinor, A. J. Identifying traits for genotypic adaptation using crop models. *J. Exp. Bot.* **66,** 3451–3462 (2015).

34. You, L., Wood, S. & Wood-Sichra, U. Generating plausible crop distribution maps for Sub-Saharan Africa using a spatially disaggregated data fusion and optimization approach. *Agric. Syst.* **99,** 126–140 (2009).

35. Hodson, D. P., Martinez-Romero, E., White, J. W., Corbett, J. D. & Bänzinger, M. *Africa Maize Research Atlas version 3.0*. (2002). at <http://intranet.cimmyt.org/en/services/geographic-information-systems/resources/maize-research-atlas>

36. Liu, C., White, M. & Newell, G. Selecting thresholds for the prediction of species occurrence with presence-only data. *J. Biogeogr.* **40,** 778–789 (2013).

37. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An overview of CMIP5 and the Experiment Design. *Bull. Am. Meteorol. Soc.* 1–39 (2012). doi:10.1175/BAMS-D-11-00094.1

38. Kirtman, B. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Stocker, T. F. et al.) (Cambridge University Press, 2013).

39. Collins, M. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Stocker, T. F. et al.) (Cambridge University Press, 2013).

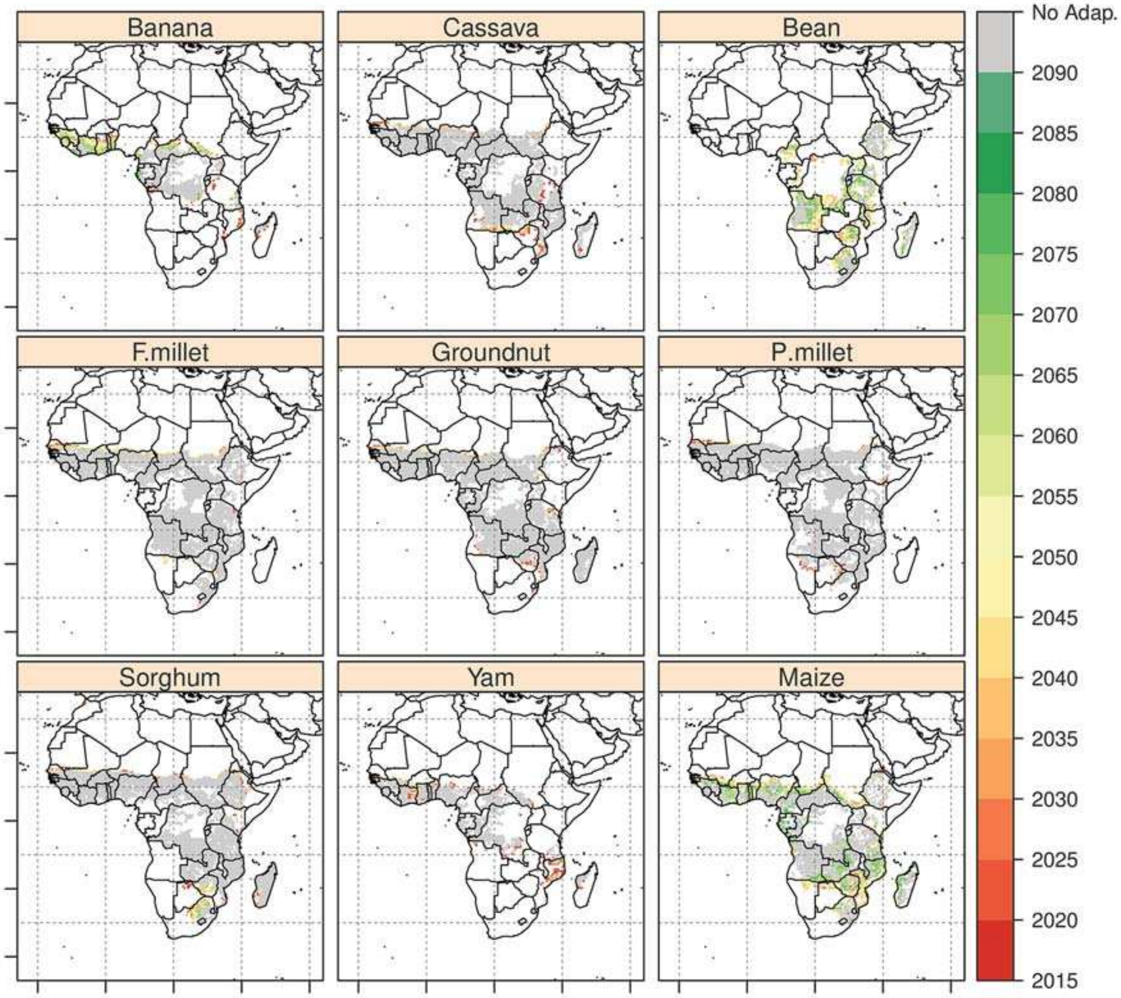
40. Hawkins, E., Osborne, T. M., Ho, C. K. & Challinor, A. J. Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. *Agric. For. Meteorol.* **170,** 19–31 (2013).

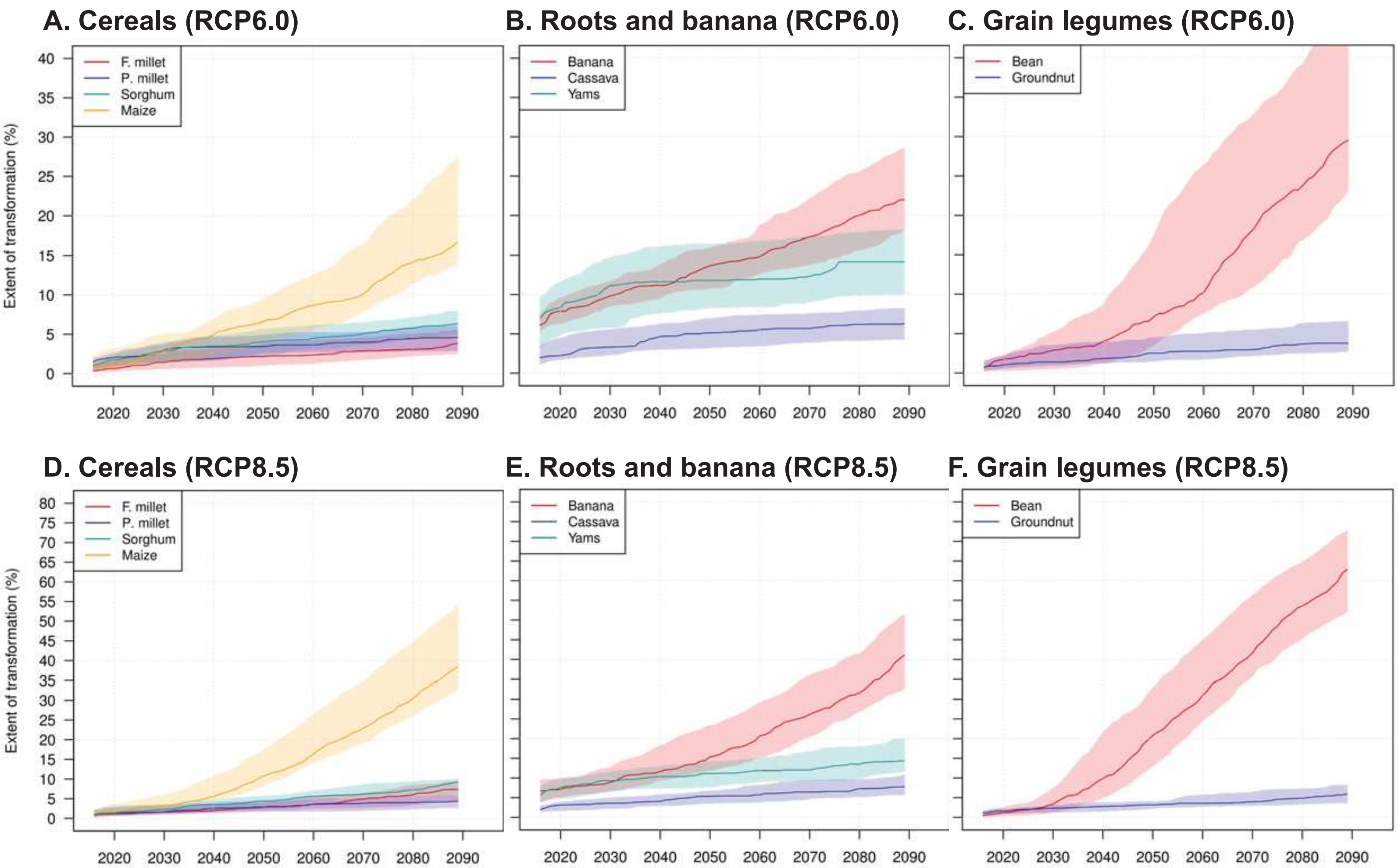
41. Hyman, G. *et al.* Strategic approaches to targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production. *Agric. Syst.* **98,** 50–61 (2008).

42. Piontek, F. *et al.* Multisectoral climate impact hotspots in a warming world. *Proc. Natl. Acad. Sci.* **111,** 3233–3238 (2014).

43. Joshi, M., Hawkins, E., Sutton, R., Lowe, J. & Frame, D. Projections of when temperature change will exceed 2^{o}C above pre-industrial levels. *Nat. Clim. Chang.* **1,** 407–412 (2011).

44. Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield Trends Are Insufficient to Double Global Crop Production by 2050. *PLoS One* **8,** e66428 (2013).


Banana
Cassava
Bean
F.millet
Groundnut
P.millet
Sorghum
Yam
Maize
No Adap.
2090
2085
2080
2075
2070
2065
2060
2055
2050
2045
2040
2035
2030
2025
2020
2015


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)
Extent of transformation (%)
F. millet
P. millet
Sorghum
Maize
Banana
Cassava
Yams
Bean
Groundnut
2020
2030
2040
2050
2060
2070
2080
2090

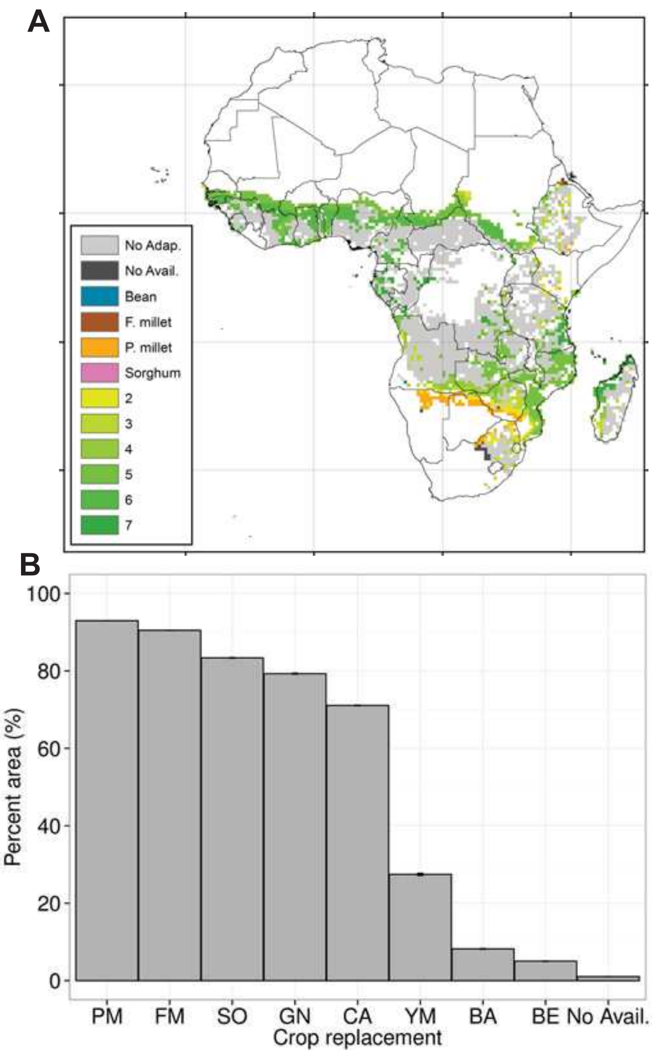

A
No Adap.
No Avail.
Bean
F. millet
P. millet
Sorghum
2
3
4
5
6
7
B
Percent area (%)
100
80
60
40
20
0
PM
FM
SO
GN
CA
YM
BA
BE
No Avail.
Crop replacement

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

Adaptation type	Biophysical behaviour at time of crossing[1]
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