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Supplementary Information

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

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Supplementary Text S1: Definition of transformational adaptation

The analyses presented in this paper focus on identifying the extent and timing and scale of cropping systems transformations under climate change, for sub-Saharan Africa. Hence, in the following text the term `transformational adaptation` will be defined. We start by reviewing and discussing existing definitions of adaptation as well as of transformational adaptation and then describe the way we use the concept of transformational change in the context of the present study. This brief review of knowledge does not intend to be fully comprehensive, but rather to provide elements with which the work presented here can be understood. Supplementary Text S2 provides examples of transformational adaptation from existing literature

Adaptation is a multifaceted term that is used across a number of academic disciplines and as a result a broad range of definitions exist. This paper adopts the Intergovernmental Panel on Climate Change (IPCC) definition of adaptation, as follows, “*the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects*”¹. Depending on the timing, adaptation can be proactive or reactive. Adaptation takes place in various systems (natural, economic, social) and on a variety of scales that vary from short-term (coping) to longer-term (systemic or transformative) actions (see Figure below). Furthermore, adaptive processes can be initiated and implemented by individuals, groups and governments and do not necessarily have to follow as a consequence of environmental stresses²⁻⁴.

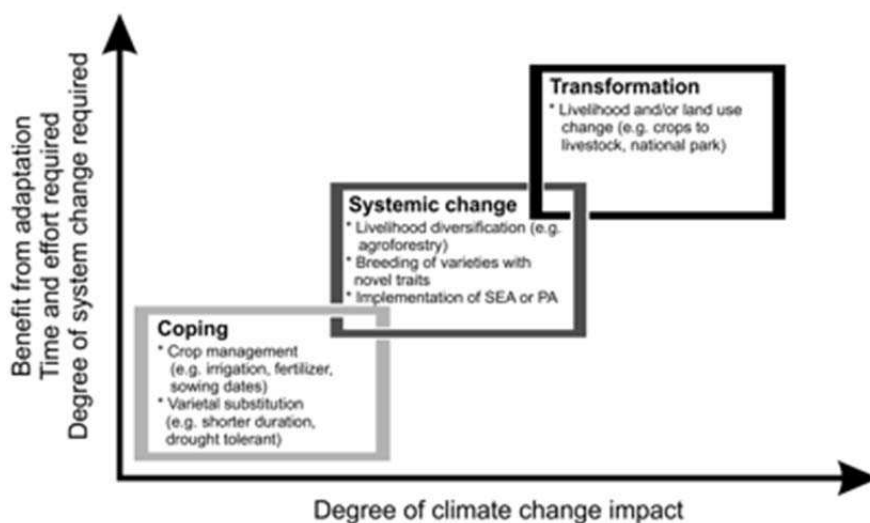


Figure Types of adaptations needed in a system as the degree of climate change impact increases. Three variables are provided in y-axis. SEA: site-specific agriculture, PA: precision agriculture. Taken from ref. ⁵, based on refs. ^{2,6,7}.

In recent years, an increasing body of literature focused on developing improved frameworks for the adaptation of agriculture to climate change. Within this process, the term adaptation has been diversified and was subdivided into different forms of adaptation, often referred to as incremental, systemic and transformational adaptation (see refs. ^{2,6}).

It is important to note that the terms and the concepts of incremental, systemic and transformational adaptation are in the process of clarification and still lack uniform and consistent definitions^{8,9}. However, they do provide a systematic and uniform approach that can be used to address the challenges that arise within the context of climate change adaptation. The term viability threshold, which we employ in this paper, in particular, has experienced widespread attention recently and is an overarching theme within the latest IPCC Fifth Assessment Report (AR5)^{1,9}.

Transformational adaptation represents the last and most significant level of adaptation. The initial conditions that make transformational adaptation necessary are high vulnerability in areas, populations or resource systems and severe changes in climatic conditions¹⁰. In contrast to incremental and systemic adaptation, transformational adaptation implies a major shift away from the current organizational objectives of a system^{8,11}.

In the words of the WGII of the IPCC AR5 transformational adaptation “(...) *changes the fundamental attributes of a system in response to climate and its effects*”^{1,12}. Hence, the existing system is less viable than alternatives and its objectives have to be replaced or newly defined. According to Park et al. (ref. ⁸) transformational adaptation can be described as a process that changes fundamentally the function, form or location of an existing system. Rickards and Howden (ref. ⁶) expand the definition to include the point at which radical alteration that includes deep and long-term transformations is required. Large spatial, organizational and temporal scales *can* but do not necessarily have to be a characteristic to define and identify transformational change. More specifically, Park et al. (ref. ⁸) state that transformational adaptation can happen at diverse scales, reaching from individual to collective as well as industry or regional levels. Therefore, the classification of adaptation strategies as transformation can be subjective and relative but nevertheless one important criterion is that the level of persistence of a system is lower than the introduced change⁶. Kates et al. (ref. ¹⁰), for example, list large scales and intensities as one criterion to distinguish transformational from incremental adaptation. Further criteria they include in their definition of transformational change are shifts in locations, types of adaptations that transform places, or adaptation forms that are completely novel to a region

or resource system^{10,13}. Other typical transformation strategies are a change in land use, or an increase in diversification of income streams¹⁴. Moreover, incremental or systemic adaptation forms can become transformational when they are applied at large scales or when they are combined and therefore have more powerful impacts¹⁰. Given the drastic character of the changes required, transformational adaptation requires a higher adaptive capacity than incremental or systemic adaptation strategies⁶.

Despite the increasing body of academic literature that deals with the importance of transformational adaptation in the context of climate change and agriculture¹³, the concept itself remains “*little studied and poorly understood*” (ref. ⁶, p247). Nevertheless, the WGII of the recent IPCC AR5 states “*that incremental adaptation may not be sufficient to avoid intolerable risks, and therefore transformational adaptation may be required to sustain some human and natural systems*” (ref. ⁹, p3). At the same time, WGII suggests that the existing ambiguous definitions and the complexity of transformational adaptation could prevent the successful and effective implementation of the concept by policy makers⁹.

Transformational adaptation in the context of this study

We adopt a general definition of transformation (IPCC WGII), but apply it to quantify a very specific but important transformation case: transformation out of cultivating a major staple crop (see main text). One of the objectives of the work presented here is the spatial and temporal determination of cropping system transformations across sub-Saharan Africa for major staple crops. The term cropping system refers usually to the crops and crop combination cultivated by a farmer as well as to the crop sequences and management techniques applied on a particular field over a period of years¹⁵. In this paper, cropping system transformations take place when one or several crops of a cropping system become unsuitable and transformational adaptation has to occur. Hence, cropping system transformation can occur when certain crops become unsuitable and cease to be cultivated without crop replacement and/or when unsuitable crops are substituted. The substitution of a crop represents a change in the crop combination and might also imply changes in crop sequences and management techniques. Moreover, the addition of new, formerly not cultivated crops to a cropping system is considered as transformation. This implies that shifts in suitable area, as outlined in the examples on transformational adaptation given in Supplementary Text S2 (wine and coffee cultivation), can also cause cropping system transformation.

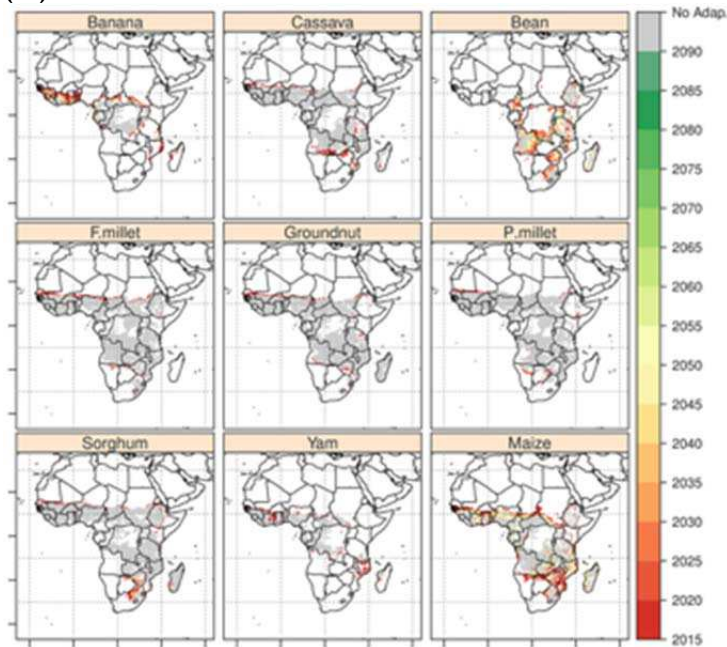
Supplementary Text S2: Examples of transformational change

The examples provided here are based on our literature review of transformational adaptation actions. The first two examples focus on commercial systems (Australian wine, Latin American coffee), but they serve an illustrative purpose. For the types of transformations associated with commercial systems to occur in Africa, a shift from subsistence to commercial farming would be needed. Park et al. (ref. ⁸) give examples of transformational changes in the context of climate change for the Australian wine industry. Transformational adaptation measures included for instance the purchase of additional vineyards in cooler regions in Australia (e.g. Tasmania) by wine making companies, grape growers that relocated to cooler grape growing regions or, in the case of small wine producers, the substitution of grape production by alternative activities like tourism or the cultivation of other crops.

Another example is given by Vermeulen et al. (ref. ⁷, also see ref. ¹⁶) illustrating the case of shifting suitability zones of coffee over altitudinal gradients in Central America. In this case, the transformation consists of crop substitution in low elevations from one high-value perennial cropping system to a different one, in this case from coffee to cocoa. This crop substitution was considered as transformation because, firstly, it implied the acceptance of fundamental changes in future crop suitability: current high suitability zones were projected with full agreement amongst different climate model projections to move to higher elevations. And, secondly, it implies the introduction of a new crop (cocoa), which is more suitable for the projected future conditions of this region. Recent empirical evidence suggests that transformation out of coffee-based livelihoods has been occurring in the last 20 years in Colombian coffee growing environments as a result of local warming and the incidence of pests and diseases¹⁷.

For Africa, evidence for dietary shifts across many parts of Africa indicates that changes in both the consumption and production of crops can happen, with varied factors driving the changes^{18,19}, thus leading to crop and food systems transformations. The shifts in consumption of traditional cereals (sorghum and millets) to maize, wheat and rice, mainly driven by international market prices and heavy research investment^{19,20}, suggest that opportunities to influence both the supply (what is grown) and the demand (what is consumed) end of the supply chains are plausible entry points for cropping and food systems transformations. As is more broadly discussed in the main text, we argue that both incentives for growing better adapted crops as well as policies and strategies to foster their use and consumption will be critical to facilitating transformational changes.

(A) Earliest



(B) Latest

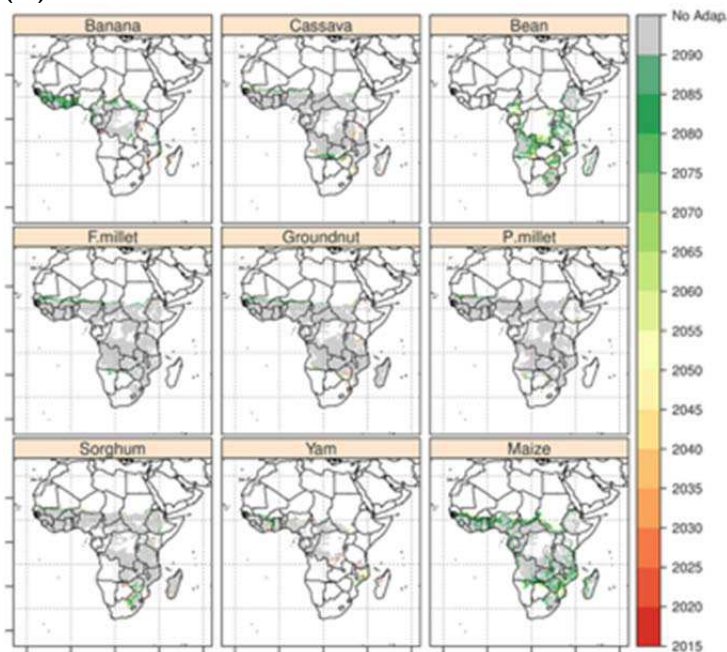


Figure S1 Earliest (i.e. multi-GCM minimum) (A) and latest (i.e. multi-GCM maximum) (B) time at which transformational adaptation is projected to occur for all crops analyzed in this study for RCP8.5. Light grey areas indicate areas where suitability of each crop is still above the respective viability threshold in more than 50 % of years in a 20-year period, i.e. where transformational adaptation is not needed during the 21st century. Dark grey areas indicate areas where transformation should be undergoing at present.

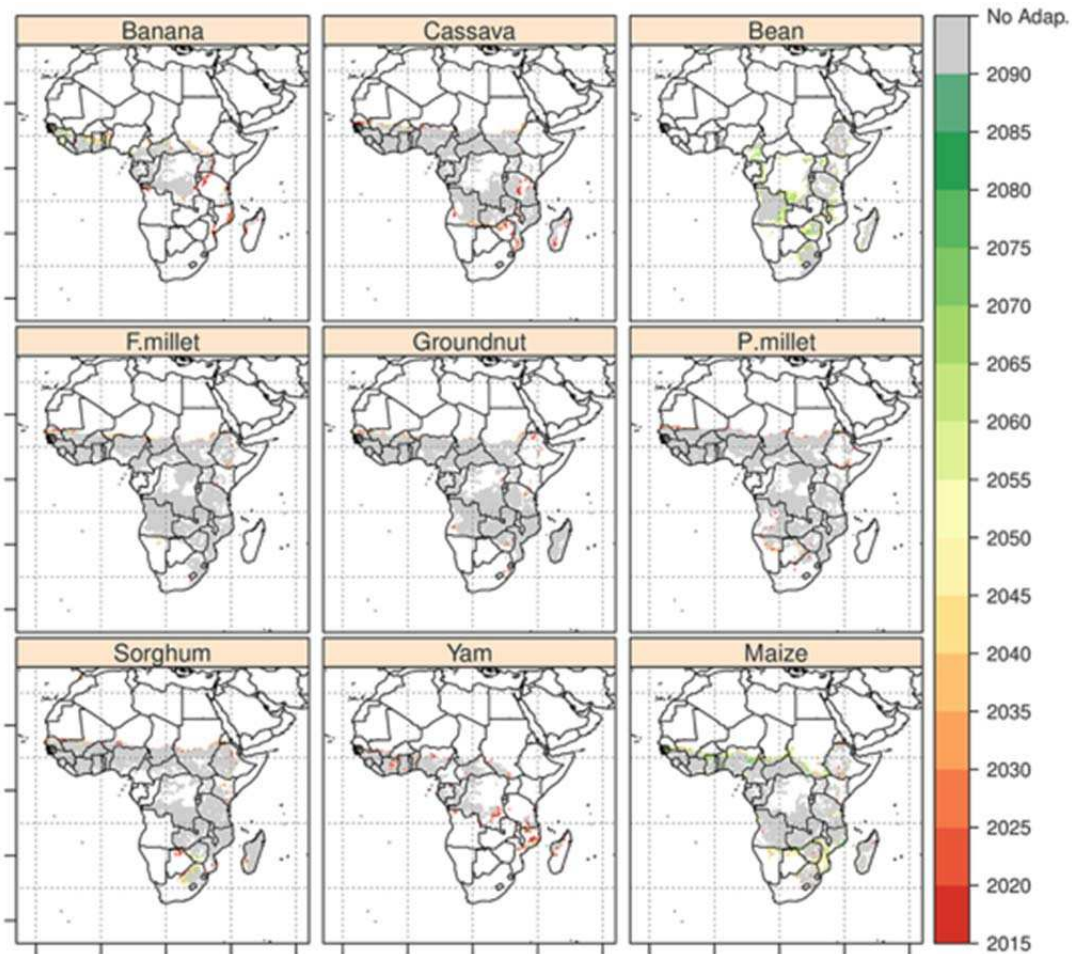
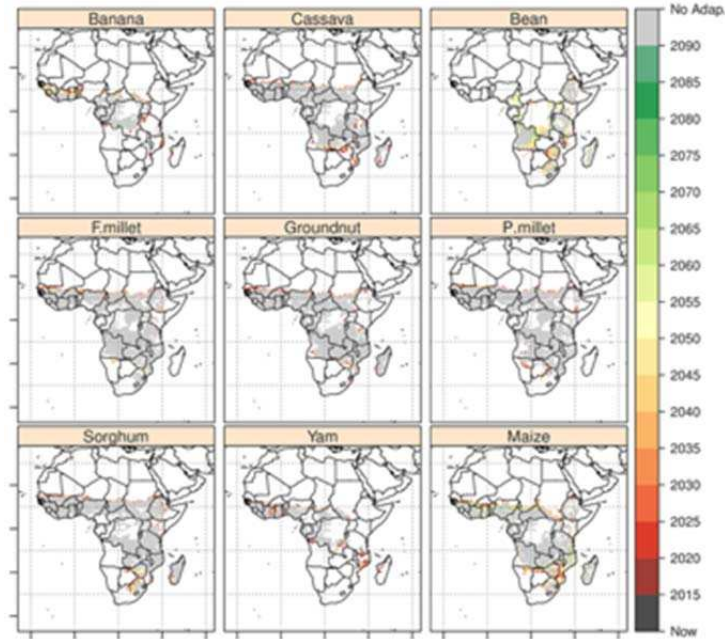


Figure S2 Mean time at which transformational adaptation is projected to occur for all staple crops analyzed in this study for RCP6.0. Grey areas indicate areas where suitability of each crop is still above the respective viability threshold in more than 50 % of years in a 20-year period, i.e. where transformational adaptation is not needed during the 21st century.

(A) RCP 6.0



(B) RCP 8.5

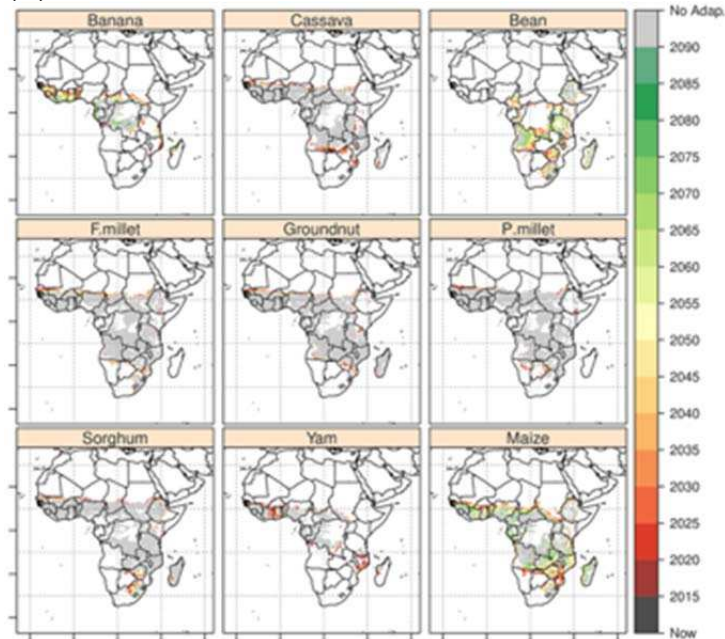
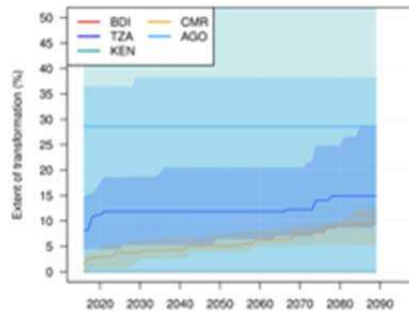
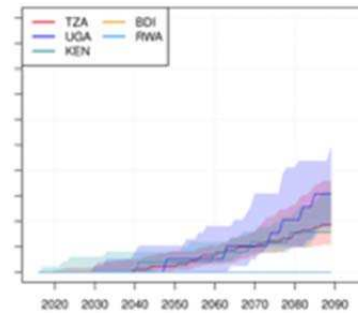


Figure S3 Mean time at which the preparatory phase is projected to occur for all staple crops analyzed in this study for (A) RCP6.0 and (B) RCP8.5. Light grey areas indicate areas where no preparatory phase is needed during the 21st century, whereas dark grey areas depict areas projected to undergo early transformation and hence should be in preparatory phase at present time.

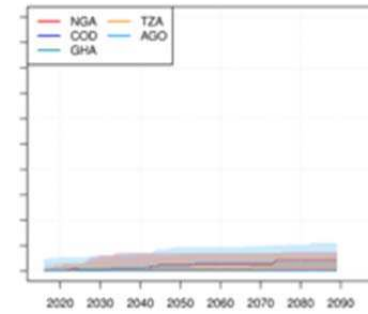
A. Bananas



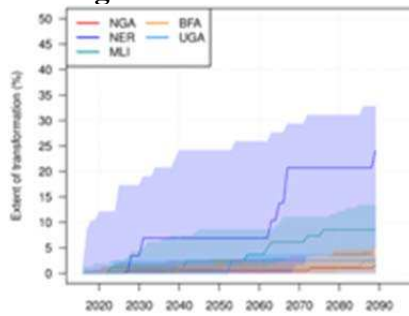
B. Bean



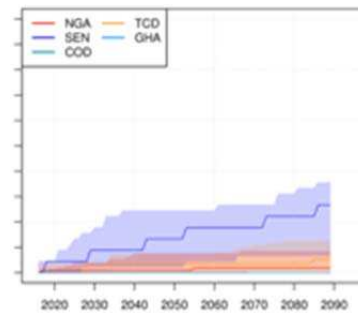
C. Cassava



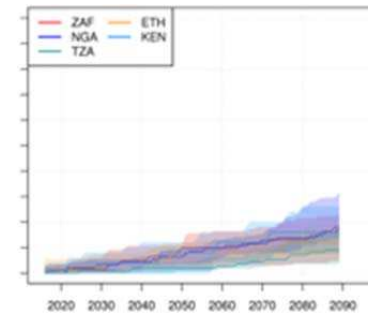
D. Finger millet



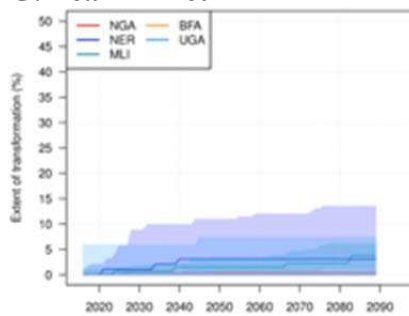
E. Groundnut



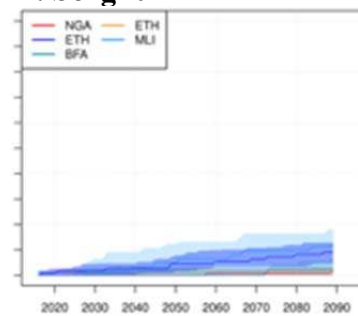
F. Maize



G. Pearl millet



H. Sorghum



I. Yam

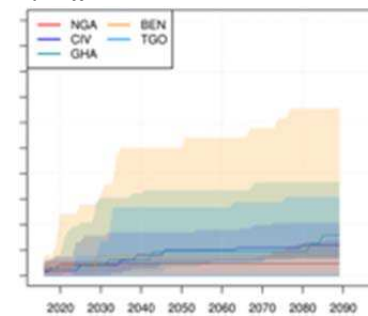
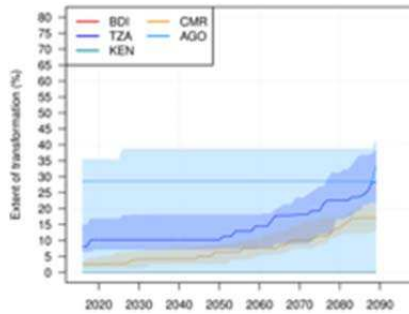
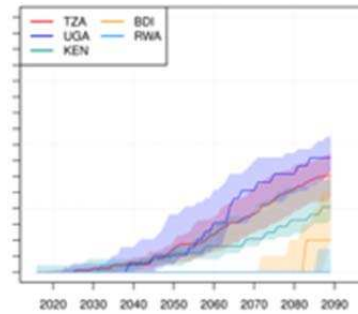


Figure S4 Cumulative percentage of suitable area in the top-5 producing countries of each crop projected to require transformational change for RCP6.0 during the 21st century. Thick lines represent the mean and shading the interquartile range. Country codes as follows: AGO (Angola), BDI (Burundi), BFA (Burkina Faso), CIV (Ivory Coast), COD (Democratic Republic of Congo), CMR (Cameroon), ETH (Ethiopia), GHA (Ghana), KEN (Kenya), MLI (Mali), NER (Niger), NGA (Nigeria), RWA (Rwanda), TZA (Tanzania), and TGO (Togo).

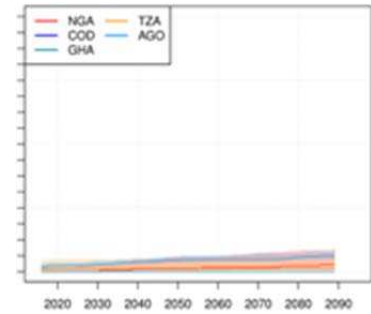
A. Bananas



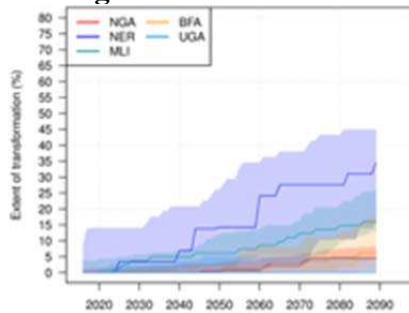
B. Bean



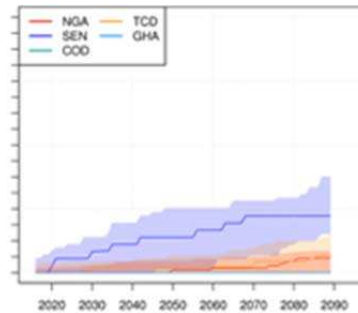
C. Cassava



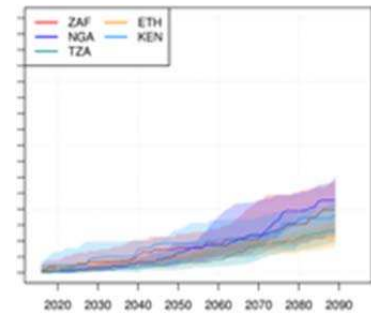
D. Finger millet



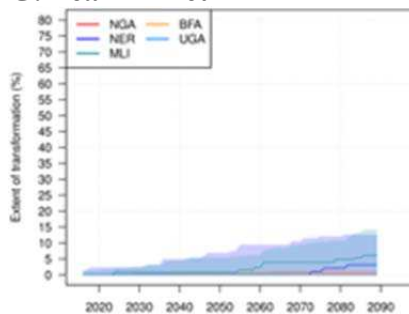
E. Groundnut



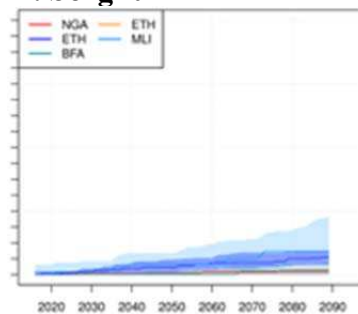
F. Maize



G. Pearl millet



H. Sorghum



I. Yam

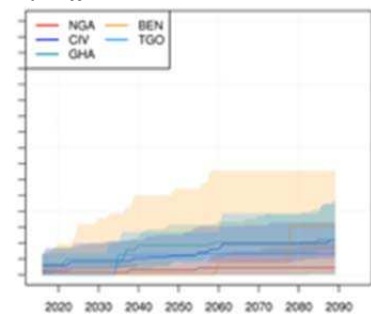


Figure S5 Cumulative percentage of suitable area in the top-5 producing countries of each crop projected to require transformational change for RCP8.5 during the 21st century. Thick lines represent the mean and shading the interquartile range. Country codes as follows: AGO (Angola), BDI (Burundi), BFA (Burkina Faso), CIV (Ivory Coast), COD (Democratic Republic of Congo), CMR (Cameroon), ETH (Ethiopia), GHA (Ghana), KEN (Kenya), MLI (Mali), NER (Niger), NGA (Nigeria), RWA (Rwanda), TZA (Tanzania), and TGO (Togo).

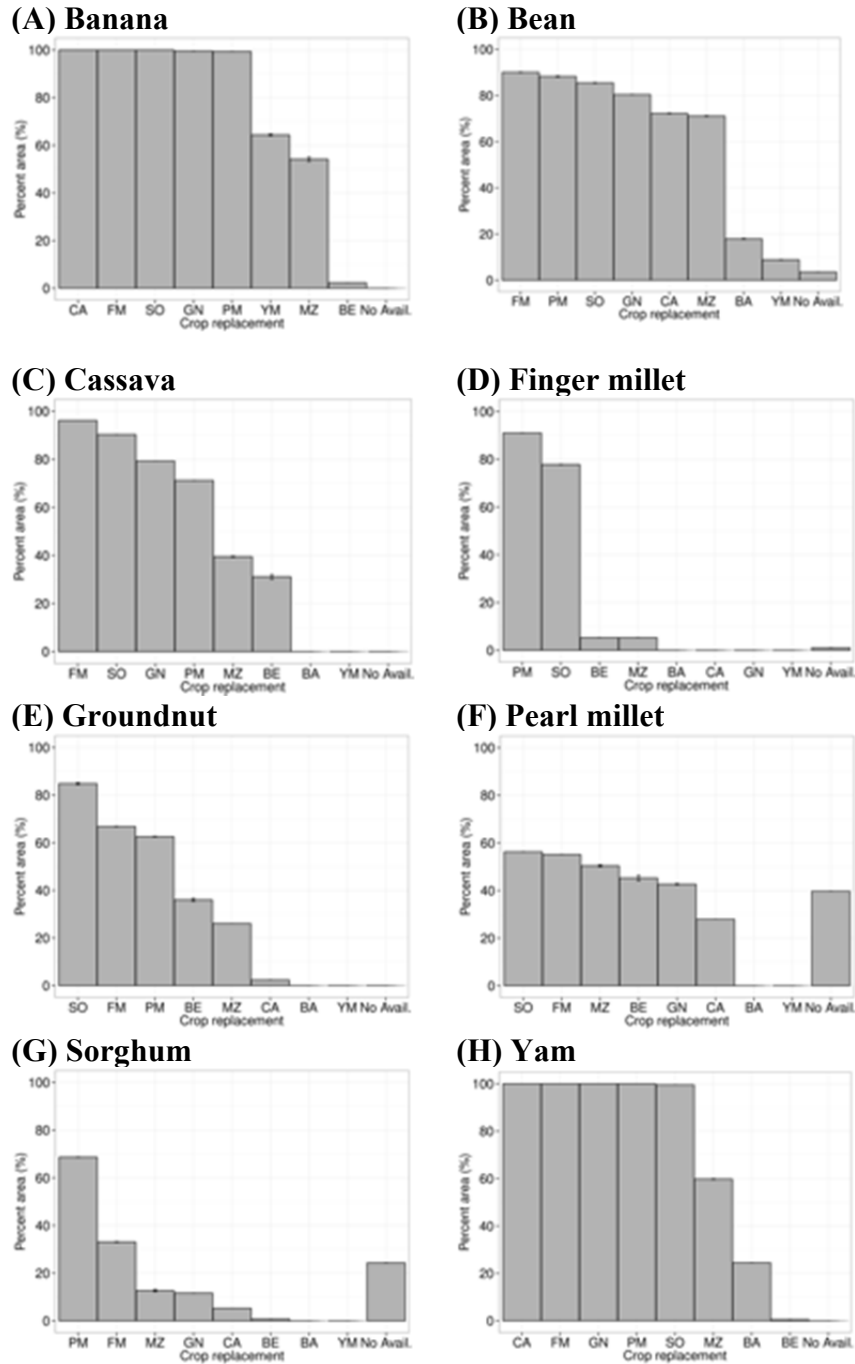


Figure S6 Bar plot of percentage area (from total area requiring transformation) that can be adapted through substitution for RCP8.5. A substitute is defined in a given pixel as a crop that by 2100 does not require transformation. Note that overlaps occur and hence the sum of individual crops is not 100 %. Crop names as follows: PM (pearl millet), SO (sorghum), YM (yam), FM (finger millet), GN (groundnut), BA (banana), BE (bean), CA (cassava), and MZ (maize). “No Avail” refers to the percentage area for which no substitutes are available. Note that the x-axis of each panel is different (except for the position of “No Avail”). Vertical error bars show the variation (1 s.d.) across the GCM ensemble.

Table S1. The projected driving biophysical constraints shown as the percentage of total area that requires transformational change for each region for RCP 6.0 and 8.5. Only areas where transformational adaptation is required are considered, hence precipitation and temperature constraints add up to 100%, but only the percentage of the prevailing constraint is shown. Red/blue coloring indicates that temperature/precipitation is the driving constraint, respectively. The presented numbers are GCM averages (μ) plus or minus the corresponding standard deviations (σ). Regions: East Africa = EAF, Humid West Africa = WAF, South Africa = SAF, Central Africa = CAF and Sahel = SAH.

Regions	CAF		EAF		SAF		SAH		WAF	
	6	8.5	6	8.5	6	8.5	6	8.5	6	8.5
Crop	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$
Banana	80 15	80 15	71 17	75 13	77 14	73 17	87 12	93 6	82 9	85 9
Cassava	70 43	87 33	63 29	84 18	68 15	86 9	100 0	97 7	100 0	100 1
Bean	98 2	98 2	64 16	78 10	72 7	75 6	89 19	95 9	NA NA	NA NA
F. Millet	100 0	69 46	93 8	92 15	98 4	98 2	92 16	69 29	97 7	81 26
Groundnut	54 44	77 39	82 16	86 23	80 14	89 13	100 1	93 14	100 0	91 23
P. Millet	100 0	73 43	66 27	76 24	51 23	68 21	97 12	100 0	96 12	100 0
Sorghum	61 46	57 49	62 22	51 21	59 13	61 14	84 28	84 27	84 29	86 32
Yam	51 9	67 28	63 26	59 41	63 18	70 16	96 6	97 4	92 12	98 2
Maize	65 21	78 18	78 14	66 17	83 8	74 12	67 21	78 14	61 24	75 17

Table S2 Projected yield changes of crops in Africa as reported by various studies. References noted as super-indices in each box.

Crop	Projected yield changes					
Maize	-23% (Median) by 2055 ²¹	-12% by 2030 in Mali ²²	+ 3 to +4% by the 2030s ²³	+7 to +16% by 2020 for Cameroon ²⁴	-5 by 2050 for all regions across Africa ²⁵	-24 ± 19 by 2090 +5°C in all regions ²⁶
Millet	+6 to +12% increase ²³	-20 to -40 in the Sahel under +2/+3°C ²⁷	-10 by 2050 all regions across Africa ²⁵			
Sorghum	-11 to -17% by 2030 Mali ²²	No change by the 2030s ²³	-7 to +8% found for Cameroon by 2020 ²⁴	-15 by 2050 all regions across Africa ²⁵		

Table S3 Overview of the nine target crops and the consulted literature and experts.

Crop	Scientific name	Expert(s)	References
Banana	<i>Musa acuminata</i>	Prof. David Turner (University of Western Australia); Dr. Charles Staver (Bioversity International)	28–30
Cassava	<i>Manihot esculenta</i>	Dr. Hernan Ceballos (International Center for Tropical Agriculture, CIAT)	31,32
Beans	<i>Phaseolus vulgaris</i>	Dr. Steve Beebe and Dr. Idupulapati M. Rao (International Center for Tropical Agriculture, CIAT)	33
Finger millet	<i>Eleusine coracana</i>	Dr. Tom Hash (International Crops Research Institute, ICRISAT), Henry Ojulong, (ICRISAT- Nairobi), Eric Manyasa (ICRISAT-Nairobi); Dr. Prem Mathur (Bioversity International)	34,35
Groundnut	<i>Arachis hypogaea</i>	Authors of this study (AJC, JRV)	7,34,36–38
Maize	<i>Zea mays</i>	Dr. Kai Sonder (International Maize and Wheat Improvement Center, CIMMYT)	39–41
Pearl millet	<i>Pennisetum glaucum</i>	Dr. Ousmane Sy (Institut Senegalaise de Recherches Agricoles, ISRA); Dr. Prem Mathur (Bioversity International)	34,35
Sorghum	<i>Sorghum bicolor</i>	Dr. Myles Fisher (CIAT), and authors of this study (JRV).	37,42
Yam	<i>Dioscorea rotundata</i>	Dr. Antonio Lopez-Montes (International Institute of Tropical Agriculture, IITA), Dr. Alexandre Dansi (University of Abomey-Calavi, Benin)	43

Table S4 Overview of the suggested threshold values (0-1) according to two applied indices MSS (max. sensitivity + specificity) and maximum value of Cohen's Kappa (max. Kappa). The shown thresholds (MSS values) were assessed using only areas with less than 80% tree cover density as reported by ref. ⁴⁴. Also shown are the AUC values as indicators of agreement between the simulated suitability maps and the reference crop distribution reported by SPAM. The AUC was assessed using all area (AUC all area) and using only areas with less than 80% tree cover density (AUC FEX) as reported by ref. ⁴⁴.

Crop	MSS	Max. Kappa	AUC FEX	AUC all area
Banana	0.18	0.20	0.73	0.71
Cassava	0.55	0.49	0.76	0.71
Beans	0.38	0.37	0.62	0.60
Finger millet	0.48	0.37	0.71 ¹	0.64
Groundnut	0.80	0.63	0.78	0.73
Maize	0.40	0.28	0.65	0.60
Pearl millet	0.54	0.50	0.68	0.68
Sorghum	0.59	0.56	0.52	0.50
Yam	0.37	0.33	0.79 ²	0.60

¹ value was assessed using only the area of East and South Africa

² value was assessed using only the area of West Africa.

Table S5. Overview of the used CMIP5 models for RCP 6.0 and 8.5 and the corresponding modeling center and institution.

Model	Modeling Center	Institution
bcc_csm1_1	BCC	Beijing Climate Center, China Meteorological Administration
bcc_csm1_1_m	BCC	Beijing Climate Center, China Meteorological Administration
cesm1_cam5	NCAR	National Center for Atmospheric Research
csiro_mk3_6_0	CSIRO-QCCCCE	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence
fio_esm	FIO	The First Institute of Oceanography, SOA, China
gfdl_cm3	NOAA GFDL	Geophysical Fluid Dynamics Laboratory
gfdl_esm2g	NOAA GFDL	Geophysical Fluid Dynamics Laboratory
gfdl_esm2m	NOAA GFDL	Geophysical Fluid Dynamics Laboratory
giss_e2_h	NASA GISS	NASA Goddard Institute for Space Studies
giss_e2_r	NASA GISS	NASA Goddard Institute for Space Studies
ipsl_cm5a_lr	IPSL	Institut Pierre-Simon Laplace
miroc_esm	MIROC	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute
miroc_esm_chem	MIROC	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute
miroc_miroc5	MIROC	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
ukmo_hadgem2_es	UKMO	UK Met Office
mri_cgcm3	MRI	Meteorological Research Institute
ncar_ccsm4	NCAR	National Center for Atmospheric Research
ncc_noresm1_m	NCC	Norwegian Climate Centre
nimr_hadgem2_ao	NIMR/KMA	National Institute of Meteorological Research/Korea Meteorological Administration

Supplementary references

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