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# Forgotten food crops in sub-Saharan Africa for healthy diets in a changing climate

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**As climate changes in sub-Saharan Africa (SSA), Africa's "forgotten" food crops offer a wide range of options to diversify major staple production as a key measure toward achieving zero hunger and healthy diets. So far, however, these forgotten food crops have been neglected in SSA's climate-change adaptation strategies. Here, we quantified their capacity to adapt cropping systems of SSA's major staples of maize, rice, cassava, and yams to changing climates for the four subregions of West, Central, East, and Southern Africa. We used climate-niche modeling to explore their potential for crop diversification or the replacement of these major staples by 2070, and assessed the possible effects on micronutrient supply. Our results indicated that approximately 10% of the present production locations of these four major staples in SSA may experience novel climate conditions in 2070, ranging from a high of almost 18% in West Africa to a low of less than 1% in Southern Africa. From an initial candidate panel of 138 African forgotten food crops embracing leafy vegetables, other vegetables, fruits, cereals, pulses, seeds and nuts, and roots and tubers, we selected those that contributed most to covering projected future and contemporary climate conditions of the major staples' production locations. A prioritized shortlist of 58 forgotten food crops, able to complement each other in micronutrient provision, was determined, which covered over 95% of assessed production locations. The integration of these prioritized forgotten food crops in SSA's cropping systems will support the "double-win" of more climate-resilient and nutrient-sensitive food production in the region.**

neglected and underutilized plants | climate change adaptation | nutrition | crop diversification | niche modelling

## Significance

Africa's "forgotten" food crops could support more climate-resilient and healthful food systems in sub-Saharan Africa (SSA), but the promotion of these crops has received limited attention. Projecting forward to the year 2070, we show that a prioritized collection of these crops, differentiated by food groups, has high potential to diversify cropping systems of major staples to support climate-resilience and nutrition in the SSA region. Our analysis, contextualized by subregions within SSA as a whole, informs practitioners, researchers, and policymakers on the use of Africa's forgotten food crops in the diversification of food supply for healthy diets in a changing climate.

Climate change trends and extreme events exacerbate efforts to achieve zero hunger in sub-Saharan Africa (SSA), a region where it is already challenging to sufficiently increase food quantity and quality to provide healthy diets for a fast-growing population (1–4). Crop diversification at landscape, farm, and field scales is proposed to provide a portfolio of more climate-resilient food crops in the region to sustain food production under climate change (2, 5, 6), while addressing simultaneously micronutrient deficiencies because of poor and monotonous diets, and corresponding health problems (7, 8). A wide variety of traditional African food plants that have coevolved with human food systems over centuries or millennia (9, 10) could support crop diversification, but with a shift to "Western" diets and drastic land-use changes in recent decades, many of these plants have been neglected in mainstream food markets and supplies (11). This neglect means these "forgotten" food crops, which include many vegetables, fruits, cereals, pulses, seeds and nuts, and roots and tubers, have been little studied formally, which further inhibits their agricultural promotion and inclusion in cropping systems (12). They however already fill marginal bioclimatic niches where major food staples grow poorly, they are important off-season foods that are rich in nutrients, and they are connected strongly to local peoples' histories and identities, all of which are attributes that support healthy diets in a changing climate (13, 14). Although some studies have started to explore options for crop diversification to support climate resilience in SSA (5, 15), no systematic assessment so far has been undertaken on the extent to which forgotten food crops, from different food groups, could play a role. This limits the development of appropriate adaptation options for food systems, especially with reference to nutrient-dense food supply. Our aim in this paper is to begin to rectify this deficiency.

Our study of forgotten food crops in SSA focuses on four objectives. The first is to identify the needs for resilience-building crop diversification or possible replacement at present production locations for SSA's major food staples, through modeling still-suitable and novel climates for these production locations by the year 2070. The second is to assess the opportunities for crop diversification or replacement provided by a broad candidate panel of Africa's forgotten food crops, by modeling these crops' edaphic and climatic suitability to grow in the production locations of major staples today and in the future. The third is to select a subset

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The authors declare no competing interest.

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of prioritized forgotten food crops from different food groups that are best-bet options for nutrient-sensitive as well as climate-resilient crop diversification or staple replacement, by comparing climate-niche coverage of candidate crops per food group. The fourth is to understand the consequences of the selection of prioritized forgotten food crops for the provision of specific key dietary micronutrients, by analyzing crop-specific nutrient composition data extracted from specialized food composition databases.

The underlying logic to our analysis is that if a candidate forgotten food crop is able to grow at a location where one of the currently major staples can still grow under 2070 projected climate conditions, then it may diversify the staple's production to support future climate resilience. In addition, when a candidate crop is able to grow at a location where that currently major staple may no longer be able to grow under 2070 conditions – that is, a location where a novel climate for the major staple is predicted – then it offers opportunities for that staple's replacement and the design of new cropping systems. The last component of our logic is that by assessing the overlap between the bioclimatic range of a candidate crop and the contemporary climate of major staples' present production locations, we should gain an understanding of the present-day diversification opportunities. These opportunities should support not only current diversification, but also the development of the tools and protocols needed for diversification or replacement under future climates, such that current diversification is a step in driving future action. To help define climate-change adaptation strategies that are context relevant, we undertake our modeling for the four geographic subregions of SSA of West, Central, East, and Southern Africa, as defined by the African Union.

We discuss our findings in terms of the research and development needs for further designing climate-resilient and nutritious cropping systems in SSA, recognizing that the modeling presented in this paper is only one needed step among many to support appropriate future food systems.

## Methods

**Modeling Still-Suitable and Novel Climates for Major Staples' Present Production Locations by the Year 2070.** Based on contemporary baseline bioclimatic niches, we modeled the projected impact of climate change by the year 2070 under two emission scenarios (SSP 2-4.5 and 5-8.5) on the present production locations of four major staples in SSA: maize (*Zea mays*), rice (*Oryza glaberrima* and *O. sativa*), cassava (*Manihot esculenta*), and major yams (*Dioscorea alata* and *D. cayennensis*). Analysis was undertaken separately for each of these four major staples and for each of the four African Union subregions of SSA of West, Central, East (including Madagascar), and Southern Africa. In each subregion, we assessed where these staples will still be able to grow in 2070 among their present production locations, because climate conditions will still be suitable (within the staples' baseline bioclimatic niches), and at which locations it is uncertain that they will grow, because of novel climate conditions (outside the staples' baseline bioclimatic niches). The four major staples we assessed were chosen for modeling because they had the largest reported tonnage production of all food crops in SSA in 2020 (16). Adapting cropping systems of these major staples is therefore likely to be critical for future food security in the region. We considered projections from contemporary climate (1970 to 2000) to 2070 (2061 to 2080) as a suitable time interval for implementing adaptation strategies for food production. Bioclimatic niches were delineated as concave alpha hulls of environmental data points on the first two axes of a principal component analysis (PCA). Detailed information on the modeling and data input is presented in *SI Appendix*, Text S1. An example of the modeling approach is presented in Fig. 1*A*.

**Assessing Crop Diversification or Replacement Opportunities to Build Resilience at Major Staples' Present Production Locations Provided by a Broad Candidate Panel of Africa's Forgotten Food Crops.** We examined the edaphic and contemporary bioclimatic niches of each entry of a candidate panel of 138 African forgotten food crops (candidate crops are listed in Dataset S1). The candidate forgotten food crops were chosen from inventories of African food crops that are relatively underresearched, underutilized, or underpromoted in an African context, and yet have the potential to support healthful human diets and local economies in the SSA region (choice of candidate crops is explained in *SI Appendix*, Text S1).

First, we estimated how the ranges of selected soil properties of the candidate crops calculated as concave hulls overlapped with the edaphic conditions at major staples' present production locations. Candidate crops' locations with soil properties within the edaphic concave hulls of the major staples were retained for further analysis. These retained locations were used to estimate how the contemporary climate ranges of the candidate crops – calculated as bioclimatic concave hulls with candidate crops' locations within the major staples' ranges for the selected soil properties – overlapped with the contemporary and projected 2070 climates at the present production locations of these staples. We applied this two-step modeling approach (first soil, then climate) to ensure that the detected novel and still-suitable environmental conditions could be explained by climate variables only, while assuming that edaphic conditions remain stable under climate change. For each major staple–subregion combination, we quantified for the year 2070 how many of the major staple's present production locations of still-suitable and novel climate fell within the concave hull of each of the candidate forgotten food crops. Similarly, we quantified for the contemporary climate how many of each major staple's present production locations fell within the concave hull of each of the candidate crops. As well as determining overlaps for individual candidate crops, we made comparisons between crops divided into the seven food group categories of leafy vegetables, other vegetables, fruits, cereals, pulses, seeds and nuts, and roots and tubers. Detailed information on the categorization of candidate crops into food groups is presented in Dataset S1. Further information on the modeling, the selected soil and bioclimatic variables, and analysis is presented in *SI Appendix*, Text S1. An example of the modeling approach for a candidate crop is presented in Fig. 1*B*. The R Script for the niche modeling of our four major staples and the candidate crops and the corresponding datasets are available at https://doi.org/10.6084/m9.figshare.21936801.v1.

**Selecting a Subset of Prioritized Forgotten Food Crops from Different Food Groups That Are Best-Bet Options for Major Staples' Diversification or Replacement.** We determined a subset of prioritized forgotten food crops from different food groups that are most likely to support nutrient-sensitive as well as climate-resilient crop diversification or replacement of major staples in SSA. To this end, we prioritized crops through a two-step protocol from each of the seven food groups. In the first step, for each food group, we selected all candidate crops that exclusively covered one or more major staples' present production locations having a novel climate. This was under one or both of our applied 2070 emissions scenarios, for one or more of our chosen Global Circulation Models (GCMs), and in one or more subregions. With the use of jackknife resampling, we identified for each food group which candidate crops provided this exclusive coverage by comparing the coverage of the aggregated concave hull of each selected candidate and the other candidate crops from its food group with the aggregated concave hull of the same candidate crops except the selected candidate. This was done for our four major staples, the two 2070 emission scenarios, the four subregions, and the nine GCMs. In the second step, the remaining candidate crops were filtered for a minimum of 70% coverage of the major staples' production locations under contemporary climate conditions, when averaged across subregions and our four major staples. The resulting list of prioritized forgotten food crops, which should be of value for supporting future and present cropping systems, was taken forward for nutritional composition assessment, as detailed below.

**Understanding the Consequences of the Selection of Prioritized Forgotten Food Crops for the Provision of Specific Key Dietary Micronutrients.** To understand the potential impacts of the selection of prioritized forgotten food crops on the provision of specific key dietary micronutrients, crop-specific nutrient composition data were extracted from three specialized food composition data sources that are the most comprehensive available for Africa's forgotten foods. These sources were the World Agroforestry Priority Food Tree and Crop Food Composition Database (17), the FAO/INFOODS West African Food Composition Table (18), and the World Vegetable Center Nutrition Database (http://nutrition.worldveg.org/). We extracted all information available on levels of iron, zinc, folate,

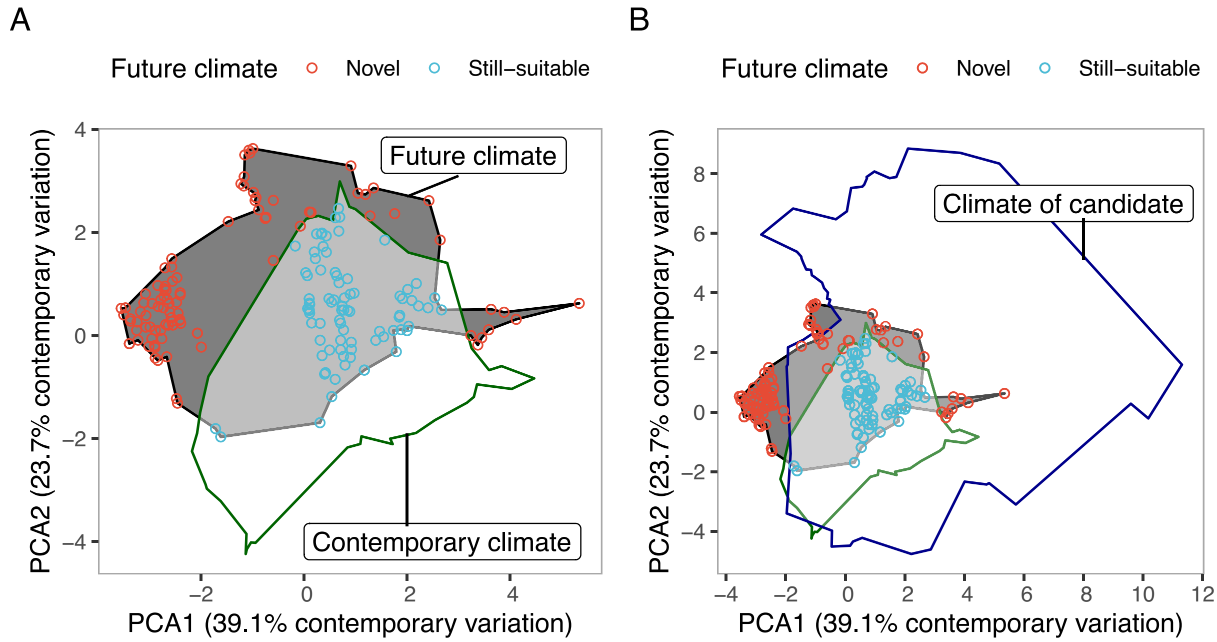


**Fig. 1.** Illustration of the overlap of bioclimatic niches for the major staple of maize and the candidate forgotten food crop *Amaranthus cruentus* (an amaranth) for the Central African subregion of sub-Saharan Africa (SSA). The illustration is based on General Circulation Model EC.Earth3.Veg and emission scenario 5.8-5 for the projected climate in 2070 (2061 to 2080). Panel *A* shows concave hulls for the contemporary bioclimatic niche of maize in Central Africa (baseline) and the projected future bioclimatic niche of maize, and how they cover the projected 2070 climate at maize's present production locations in Central Africa. Only data points for the future climates at these production locations are shown; they are colored based on whether their climates are indicated to be still suitable for maize (within the contemporary bioclimatic niche) or are novel for maize (outside the contemporary bioclimatic niche and uncertain for future growth). Panel *B* adds the concave hull for the contemporary bioclimatic niche of the candidate crop amaranth (indicated by the blue outline) to the maize hulls already shown in panel *A*. The bioclimatic niche of the candidate crop is constructed with location data from tropical and subtropical areas globally, following the Köppen–Trewartha climate classification to capture its broad bioclimatic potential, while only location data are considered that fall within the ranges of the edaphic conditions of the maize production locations; the latter being the subject sites for climate change adaptation by diversification or replacement of the staple with the candidate crops. In the case of amaranth, its bioclimatic concave hull covers a large proportion of the two maize hulls (it covers almost all of the hull for maize's present production locations with still-suitable climate, and a large proportion of the production locations with novel climates). The analysis thus creates four classifications of major staples' present production locations: *i*) those with novel climates in 2070 that are within the candidate crop's bioclimatic niche; *ii*) those with novel climates in 2070 that are outside the candidate crop's bioclimatic niche; *iii*) those with still-suitable climates in 2070 that are within the candidate crop's bioclimatic niche; and *iv*) those with still-suitable climates in 2070 that are outside the candidate crop's bioclimatic niche. These classifications, applied to our four major staples, four subregions of SSA, and our 138 candidate forgotten food crops, form the basis of the staple–forgotten food crop comparisons in the current study. Detailed information on the climate-niche modeling and the selected climate variables is provided in *SI Appendix*, Text S1.

vitamin A, and vitamin C in the foods identified for our prioritized crops (Dataset S2). We collected data on these micronutrients because of their widespread deficiencies that have negative impacts on public health in SSA, and because they are markers for overall micronutrient intake (19). These micronutrients are also difficult to obtain in diets heavily reliant on our four major staples. Micronutrient values obtained from databases were standardized to 100 g edible portions (EP). These values were then converted into percentages of daily Reference Nutrient Intakes (RNI), based on World Health Organization-averaged adult intake recommendations (17, 19). This approach allowed comparisons in micronutrient provision across prioritized crops and the food groups to which they belonged.

## Results

**Most Novel Climates Are Predicted in Central and West Africa and Are Greatest for Maize Followed by Yams.** The modeling of still-suitable and novel climates at major staples' production locations in 2070 revealed that locations with still-suitable climates declined most overall in West Africa (17.7%) and then Central Africa (14.5%), indicating these subregions to be priorities for intervention, and least in Southern Africa (0.7%) and then East Africa (6.5%) (mean percentages in decline across emission scenarios and major staples for still-suitable climates given in parentheses; *SI Appendix*, Table S1). Novel climate conditions were particularly evident for maize and yams in the two highly affected subregions of West and Central Africa, suggesting priority should be given here to diversifying or replacing these two staples. Overall, modeling predicted maize's present production locations to have the most novel climate conditions: More than a quarter and a third of all its locations in West Africa and Central Africa, respectively, considering means across the two 2070 emission scenarios. Modeling also predicted novel climate conditions for a large proportion of yams' present production locations – in more than a fifth and a sixth of its locations in West Africa and East Africa, respectively. Proportionally, cassava and rice were less affected in our modeling, with mean losses of the production locations with still-suitable climate of less than 4% and 8%, respectively, across emission scenarios and subregions. A still substantial proportion of West African locations was however predicted to be affected by novel climates. In Southern Africa, none of our modeled major staples (yams being excluded from modeling because of insufficient data) had unique climates exceeding 2% of their present production locations. Considering the number of GCMs that individually indicated novel climates at major staples' present production locations, sites with strong consensus were found at the highest density in West Africa, as would be expected from summarized novel climate findings; substantial parts of Central and East Africa also had strong consensus among GCMs in revealing localized novel climates (Fig. 2 and *SI Appendix*, Fig. S1).

**Candidate Forgotten Food Crops in the "Other Vegetables" Food Group Provide Particular Opportunities to Diversify or Replace Major Staples Today and by the Year 2070.** East Africa had the greatest overlap in candidate crops' coverage of major staples' present production locations (94.0 = the mean number of candidate forgotten food crops with overlap across major staples

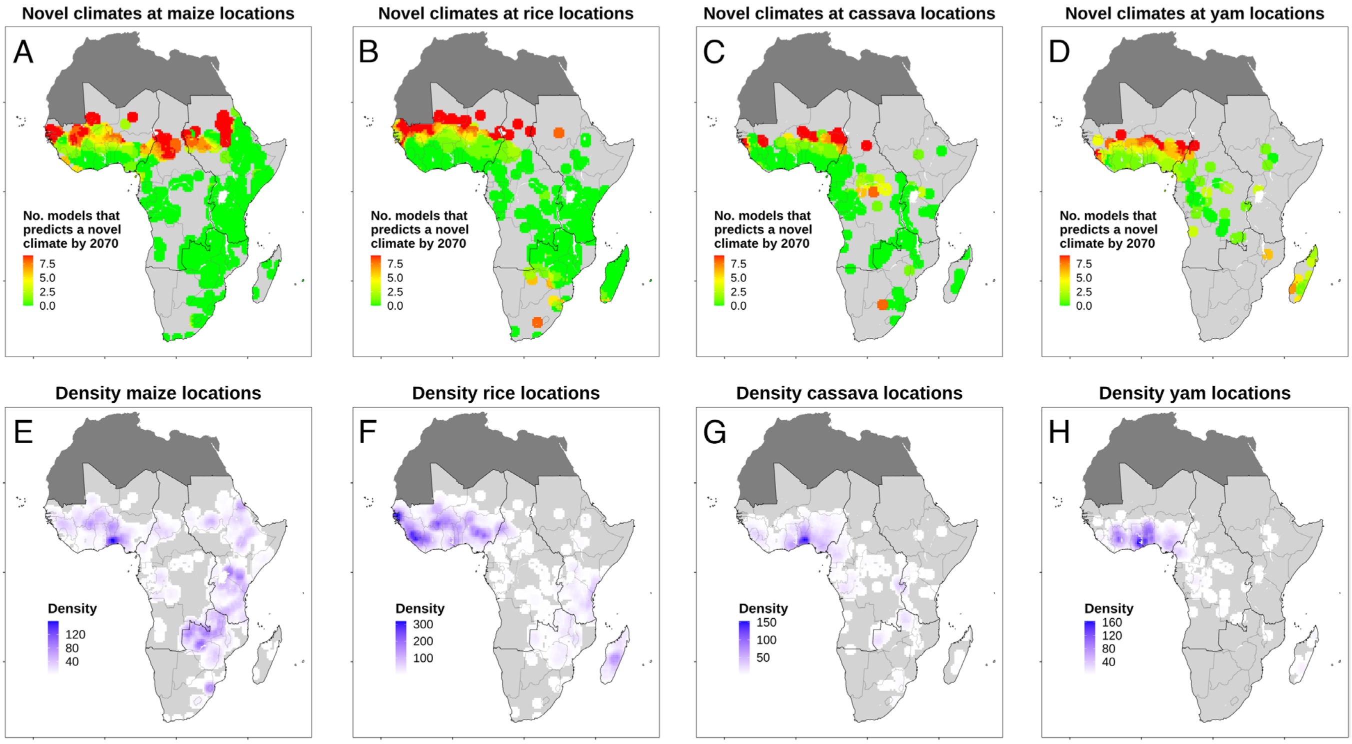


**Fig. 2.** Heat maps showing novel climates by the year 2070 under emission scenario SSP5-8.5 predicted with concave hull modeling for the present production locations of the four major staples of maize, rice, cassava, and yams. Panels *A* and *E* refer to maize; panels *B* and *F* refer to rice; panels *C* and *G* refer to cassava; and panels *D* and *H* refer to yams. Panels *A* to *D* show the level of consensus among nine General Circulation Models used in the modeling. Panels *E* to *H* show the density of major staples' present location data used in the modeling. For further information on analysis, refer to *SI Appendix*, Text S1. Thicker outlines on maps reveal the four subregions of the African Union that were considered separately in our analyses: West, Central, East (including Madagascar), and Southern Africa. For heat maps showing predicted novel climates by 2070 under emission scenario SSP2-4.5, see *SI Appendix*, Fig. S1.

and the two future emission scenarios) and then Southern Africa (84.5 candidate crops). Central Africa had the second least coverage (78.2 candidate crops), and West Africa the least (59.8 candidate crops) (*SI Appendix*, Table S2; $P < 0.001$). East Africa and then Southern Africa are therefore indicated to be the subregions where the potential for the complete panel of the 138 candidate crops to diversify or replace our four major staples in 2070 is greatest (but see also crop prioritization below). The same pattern of coverage across subregions was detected for each of our four chosen major staples, although the number of candidate crops that covered the projected 2070 climate at rice's present production locations was particularly poor for West Africa (mean of 31.2 candidate crops across the two future emissions scenarios).

Considering the projected 2070 climate conditions for all major staples' present production locations (those with still-suitable and novel climates in the year 2070 together), the average coverage by candidate crops' concave hulls was 57.3% (mean percentage cover for all 138 candidate crops averaged across emission scenarios, subregions, major staples, and GCMs; *SI Appendix*, Table S3). When considering still-suitable and novel climate conditions at major staples' present production locations separately, the coverage by candidate forgotten food crops overall was greater for still-suitable climates (68.0% of all production locations with still-suitable climates) than it was for novel climates (44.0% of all production locations with novel climates) (mean values in parentheses; *SI Appendix*, Table S3). These data suggest that options for crop diversification of major staples under future climate are important as well as are options for replacement. The figures on 2070 coverage of still-suitable climates are similar to the average coverage by candidate forgotten food crops of 68.5% of contemporary climates at major staples' present production locations, averaged across emission scenarios, subregions, major staples, and GCMs. These last data reveal important opportunities for the current-day crop diversification of major staples with forgotten food crops that can then support future cropping system adaptation.

The assignment of the individual 138 candidate crops to food groups (Dataset S1) resulted in a maximum number of 60 candidate crops in the fruit group, including many perennial fruits as well as annuals, and a minimum number of seven crops in the roots and tubers group (Table 1). The leafy vegetables food group also had a large number of entries, with 47 candidate crops, while the other vegetables category followed with 24 entries.

For all major staples, other vegetables showed on average greatest overlap of the projected 2070 climate at major staples' present production locations (i.e., those locations with still-suitable and novel climates in the year 2070 together) ($P < 0.001$ for all the four major staples; Fig. 3 and *SI Appendix*, Figs. S2, S3, S4, and S5 for results by subregion). This result came from the Friedman ANOVAs that compared the coverage by single concave hulls for candidate crops that were grouped following their specific food groups; in this analysis, coverage was averaged across the four subregions, the two emission scenarios, and the nine GCMs. The overlap by other vegetables significantly differed from the overlap by fruits, and seeds and nuts, for all major staples, and from the overlap by candidate roots and tubers in the specific cases of maize, rice, and yams [*SI Appendix*, Tables S4 and S5 for grouping and multiple comparisons with Tukey's honestly significant difference (HSD) tests]. Other vegetables' overlap did not however significantly differ from the overlap by candidate cereals, leafy vegetables, or pulses, for all major staples; or from the overlap by candidate roots and tubers, in the specific case of cassava.

**Table 1. Numbers of candidate and prioritized forgotten food crops by food group**

| Food group | No. of candidate forgotten food crops | No. of prioritized forgotten food crops | Percentage of prioritized forgotten food crops from food group |
|---|---|---|---|
| Total | 138 | 58 | 42 |
| Food group | | | |
| Cereals | 12 | 9 | 75 |
| Fruits | 60 | 17 | 28 |
| Leafy vegetables | 47 | 23 | 49 |
| Other vegetables | 24 | 15 | 63 |
| Pulses | 11 | 7 | 64 |
| Roots and tubers | 7 | 3 | 43 |
| Seeds and nuts | 18 | 6 | 33 |

Candidate crops, listed in Dataset S1, were chosen from inventories of African food crops that are relatively underresearched, underutilized, or underpromoted in an African context. Some crops were assigned to more than one food group. See *SI Appendix*, Text S1 for details on the choice of forgotten food crops and food group assignments.

Other vegetables also had the greatest overlap for each of the four major staples when considering only still-suitable or only novel climate conditions at major staples' present production locations as projected for 2070 ($P < 0.001$ for all the four major staples in each of the climates). Under still-suitable conditions, the overlap by other vegetables was larger compared to the overlap by fruits, and seeds and nuts, for all major staples, and larger compared to the overlap by pulses in the specific cases of maize, rice, and yams. Other vegetables' overlap did not however significantly differ from the overlap by candidate cereals, leafy vegetables, or roots and tubers, for all major staples; or from the overlap by pulses in the specific case of cassava. Under novel conditions, the overlap by other vegetables differed again significantly from that of fruits, seeds and nuts, and roots and tubers, for all the four major staples. Other vegetables' overlap did not however significantly differ from the overlap by leafy vegetables, candidate cereals, or pulses. When considering the contemporary climate conditions, other vegetables also had the greatest overlap and differed significantly from fruits, and seeds and nuts, for all the four major staples; and from overlaps by candidate roots and tubers, in the specific cases of maize and rice ($P < 0.001$ for all comparisons).

Finally, when the 138 candidate forgotten food crops were broken down into native and indigenized statuses (Dataset S1), the indigenized candidate crops covered more of the major staples' present production locations than native candidate crops ($P < 0.001$ for all the four major staples under contemporary climate as well as still-suitable and novel climates in 2070 together and separately).

**A Subset of 58 Prioritized Forgotten Food Crops Selected from across All Food Groups Together Covers over 95% of Major Staples' Novel Climate Conditions in the Year 2070.** A prioritized list of 58 forgotten food crops covering the seven food groups was identified by applying our two-step selection approach based on novel 2070 and contemporary climate coverage of major staples crops' present production locations. Aggregating the single concave hulls for these prioritized crops into one aggregated concave hull, 98.1% of all 2070 climate points at major staples' present production locations was covered, with 100% of all still-suitable climate points covered and 96.7% of all novel climate points, averaged across emission scenarios, subregions, major staples, and GCMs (*SI Appendix*, Table S6). The values of coverage were similar to when one aggregated concave hull was modeled with the hulls of all 138 initial candidate crops together. The overlap values for the aggregated concave hull for the 58 prioritized forgotten food crops were slightly higher than the aggregated concave hulls for candidate crops per food group. When candidate crops were aggregated in hulls according to their food group, they covered 96.1% of all 2070 climate points, 99.4% of the still-suitable climate points, and 92.7% of the novel climate points, averaged across food groups, emission scenarios, subregions, major staples, and GCMs (*SI Appendix*, Table S7). These findings show that for most major staples' present production locations, it is possible to choose one or more forgotten food crop(s) from each food group that will be suitable for cultivation under 2070 climate conditions.

Cereals (75%), pulses (64%), and other vegetables (63%) were most overrepresented in our list of prioritized forgotten food crops (percentages in parentheses are for entries in the list of 58 prioritized crops compared to entries in the initial list of 138 candidate crops, by food group) (Table 1). Fruits (28%), and seeds and nuts (33%), were the most underrepresented food groups. Because of the greater numbers of entries initially, however, leafy vegetables (23 crops), fruits (17 crops), and other vegetables (15 crops) contributed most crops to the prioritized list. Crops from these three food groups may therefore have particular use in diversification, especially other vegetables, considering also their high representation. However, the high representation of cereals and pulses is also of note, and indicates that a widening of the initial panel of candidate forgotten food crops is merited for these food groups.

**Prioritized Forgotten Food Crops from Different Food Groups Provide Complementary Micronutrients for Diets.** The extraction of crop- and food group-specific nutrient composition data for the 58 prioritized forgotten food crops from our three data sources revealed 51 crops (and 61 crop–food group combinations from a possible 80 combinations) for which data were available. The illustrative intakes for our five key dietary micronutrients from the prioritized crops categorized by six food groups (the seeds and nuts group was excluded due to only limited nutrient composition data being available for this group) revealed the value of a diversity of food groups and specific crops in providing key micronutrients to reach RNI (Fig. 4 and *SI Appendix*, Fig. S6). The prioritized leafy vegetables, for example, were observed on average to be high in iron, folate, and Vitamin A, while prioritized pulses also contained on average high folate concentrations compared to prioritized crops from other food groups and to our four major staples (Fig. 4). Prioritized fruits showed on average high vitamin C levels compared to crops from other food groups and to our four major staples. *SI Appendix*, Fig. S6 also reveals, however, that while broad differences in micronutrient levels can be seen between prioritized crops partitioned by food groups, variation in database-tabulated levels of particular micronutrients can often be large within food groups, emphasizing the need for specific crop choices (and possible retesting and confirmation of micronutrient levels).

A selection of our prioritized leafy vegetables, fruits, one nut, and one pulse crop, provided particularly high values for one or more of the five micronutrients we assessed (Dataset S2). The three prioritized forgotten food crops with the highest reported concentrations for iron were two leafy vegetables (*Amaranthus hybridus* and *Cleome gynandra*), and one nut (*Anacardium occidentale*); for zinc were one nut (again, *A. occidentale*) and two leafy vegetables (*Amaranthus graecizans* and *A. cruentus*); for folate were two leafy vegetables (*Celosia argentea* and, again, *A. graecizans*) and one pulse (*Vigna radiata*); for vitamin A were three leafy vegetables (*Moringa oleifera*, again

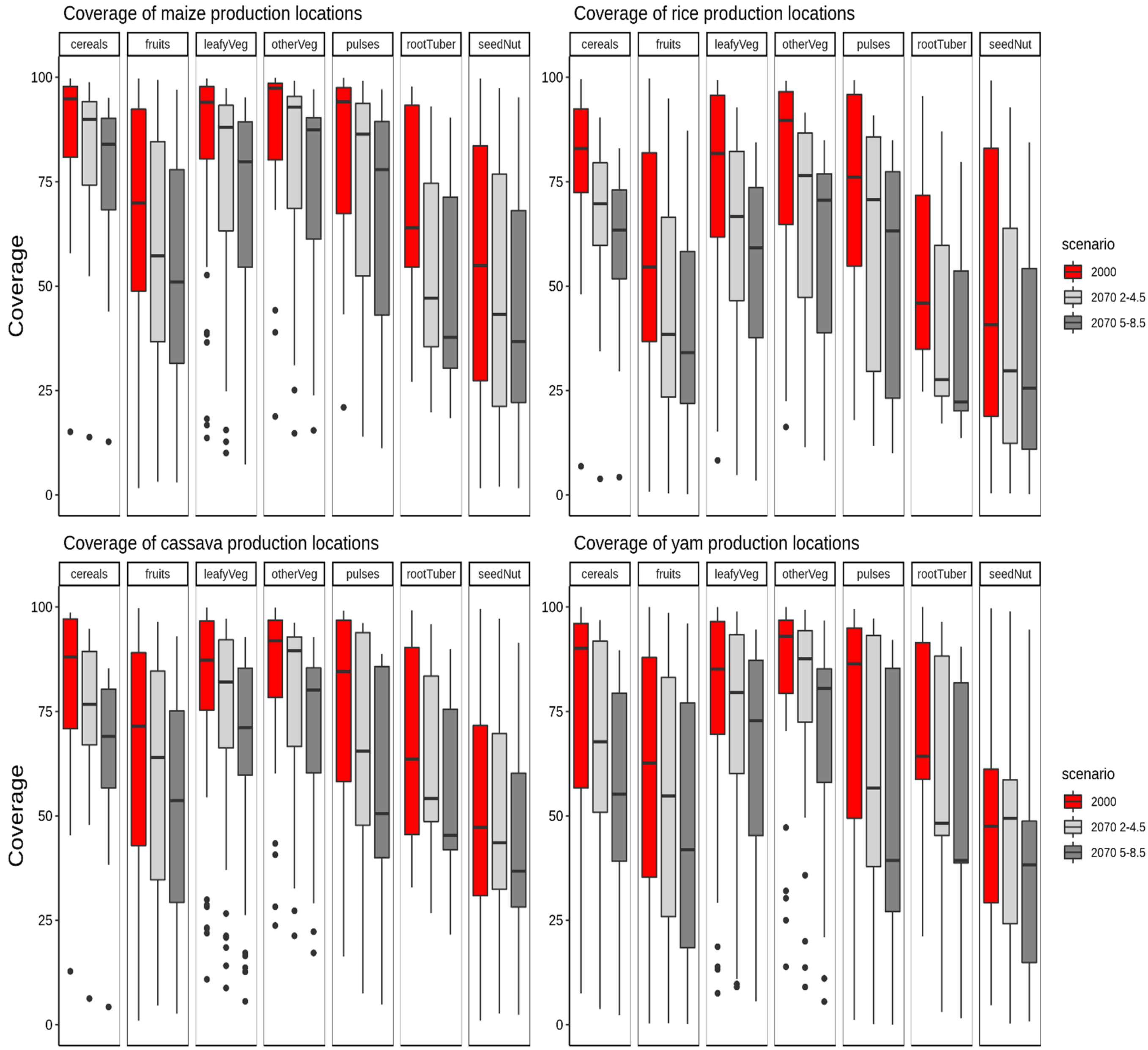


**Fig. 3.** Coverage of contemporary and projected 2070 climate at major staples' present production locations in sub-Saharan Africa (SSA) by 138 candidate forgotten food crops categorized by seven food groups. The seven food groups are cereals, fruits, leafy vegetables (leafyVeg), other vegetables (otherVeg), pulses, roots and tubers (rootTuber), and seeds and nuts (seedNut). Findings are shown for each of the four major staples of maize, rice, cassava, and yams. Values shown are based on averages from the four SSA subregions of West, Central, East, and Southern Africa. Separate subregional values for each major staple are provided in *SI Appendix*, Figs. S2, S3, S4, and S5. For the projected 2070 climate, coverage is shown separately for emission scenarios SSP2-4.5 and SSP5-8.5; these values are for the entirety of major staples' present production locations (i.e., locations with still-suitable and novel climate in 2070, together) compared to candidate forgotten food crops' contemporary bioclimatic niches. Within the box plots shown, the top three candidate crops for each food group in terms of coverage of the major staples, averaged across subregions, climate periods, emission scenarios, and the General Circulation Models used in the modeling, are: cereals, *Sorghum bicolor* (93.8% coverage), *Paspalum scrobiculatum* (91.7%), and *Amaranthus hybridus* (88.9%); fruits, *Mangifera indica* (96.2%), *Psidium guajava* (94.8%), and *Carica papaya* (94.4%); leafy vegetables, *Portulaca oleracea* (96.0%), *Celosia argentea* (95.3%), and *Momordica charantia* (93.4%); other vegetables, again *C. argentea* (95.3%; note that some crops belong to more than one food group), *Vigna unguiculata* (94.8%), and *Solanum lycopersicum* (94.8%); pulses, again *V. unguiculata* (94.8 %), *Phaseolus vulgaris* (93.3%), and *Senna obtusifolia* (93.0%); roots and tubers, *Ipomoea batatas* (93.0%), *Colocasia esculenta* (91.3%), and *Xanthosoma sagittifolium* (62.7%); and seeds and nuts, again *P. oleracea* (96.0%), *Anacardium occidentale* (89.2%), and *Lagenaria siceraria* (88.6%) (species authorities are provided in Dataset S1).

*C. gynandra* and *Xanthosoma sagittifolium*); and for Vitamin C were three fruits (*Psidium guajava*, *Sclerocarya birrea*, and *Carissa spinarum*) (species authorities are mentioned in Dataset S1).

## Discussion

Responding to climate change requires multiple interventions in SSA's crop production. The adaptation of major staples to new conditions through breeding is essential, but achieving this adaptation is generally not straightforward when factoring in both broad climatic trends and the extreme weather events caused by climate change (20). The diversification of cropping systems of major staples and their replacement with other crops is an alternative response to promote greater resilience, with the current study indicating the opportunities that Africa's forgotten food crops provide if following this intervention pathway. In practice, a full

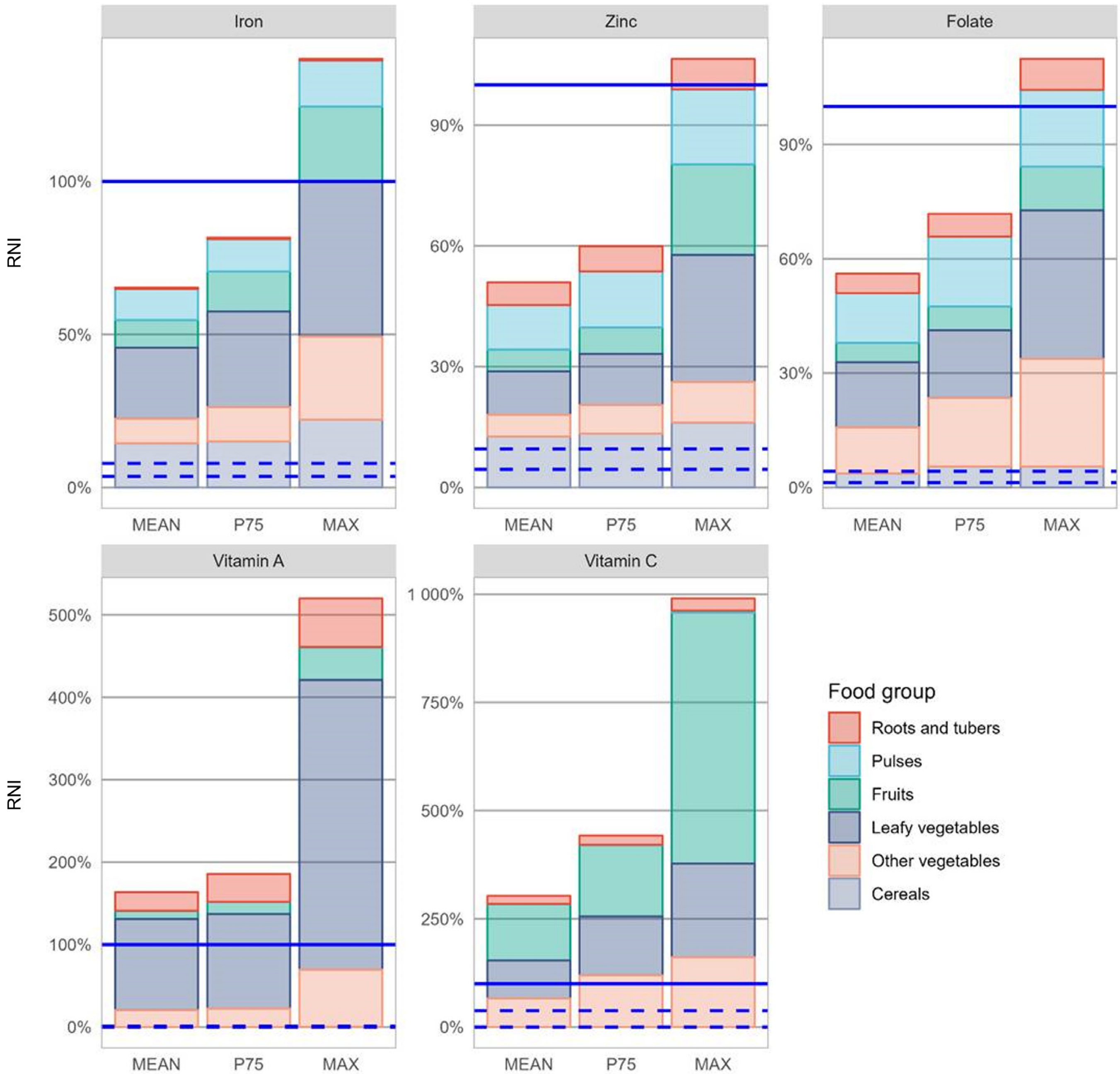


**Fig. 4.** Stacked bar charts showing illustrative intakes for five key dietary micronutrients from prioritized African forgotten food crops categorized by six food groups. 58 prioritized crops of particular value for supporting cropping systems of major staples today and by the year 2070 were assigned to food groups and nutrient composition data for crop foods, where available, were converted into adult daily reference nutrient intake (RNI) values for 100 g edible portions (EPs). Bar charts are based on nutrient composition data available for 51 of the prioritized crops. The food group of seeds and nuts was excluded from the charts, as composition data were only available for two prioritized seeds and nuts. Charts show the mean, third quartile (75% = P75), and maximum values of RNI fulfilled by the foods of the prioritized crops within each food group for each selected micronutrient, and the culminative hypothetical total intakes from consuming an EP daily of each food group (i.e., 100 g of each of the six food groups). Full horizontal lines indicate the RNI for each micronutrient and dashed lines the upper and lower limits for each micronutrient provided by an EP of the four chosen major staples in the study. Charts show the value of a diversity of specific crops, food groups, and food group combinations, in providing key micronutrients to reach RNI. Micronutrient compositions for the prioritized crops and our four major staples are shown in Dataset S2. Further information on micronutrient provision by prioritized crops categorized by food group is provided in *SI Appendix*, Fig. S6.

response to ensure sufficient food supply in both quantity and quality will require breeding interventions for major staples, diversification of cropping systems of major staples or their replacement, and the breeding of the forgotten food crops that can complement existing major staples so that they better fit in cropping systems (12).

Our current study, based on niche modeling, quantifies the opportunities for climate-smart agriculture in SSA through the diversification or replacement of cropping systems of four major food staples with Africa's forgotten food crops under a changing climate. The replacement of major staples with these forgotten food crops will not normally in itself address food security needs *sensu* calorie provision, because forgotten food crops are generally lower yielding than our four major staples. It may do so though in marginal areas and other specific circumstances where forgotten food crops are locally grown widely, or where product sales of particularly fruits and vegetables result in incomes used for staple food purchase and for enhancing livelihoods more generally (21, 22). Diversification or replacement of major staple food intake with micronutrient-rich forgotten foods however has particular potential for combatting micronutrient deficiences and corresponding health issues, which has been seen as a more prominent challenge than food security per se in SSA over the last decade (23). The addressing of nutritional security in SSA with these forgotten food crops is culturally relevant as the crops have long histories in local and regional food systems (24). Moreover, the value of diversifying the cropping systems of major staples with a broader range of crops of different food groups to reach climate resilience and nutritional security has been recognized globally as an important strategy (25–27).

Our study provides indications of the extent to which interventions are required for the diversification or replacement of cropping systems of the major staples of maize, rice, cassava, and yams, in the SSA region and its four subregions, and the capacity of forgotten food crops for these purposes. An initial candidate panel of 138 African forgotten food crops, embracing multiple food groups, provided significant opportunities, while a more manageable subset of 58 prioritized crops of this panel, for which micronutrient compositions were compared among food groups and with our four major staples, still covered most options for "double-wins" in supporting climate-resilient and nutrient-sensitive food production simultaneously. Nutrient composition data revealed the value of devising portfolios of specific crops, food groups, and food group combinations among our prioritized crops, to support nutrient provision, although the absence of composition data for a number of foods limits comparisons and indicates gaps in information that need to be filled for more complete assessment. The absence of compositional data for seeds and nuts, where specific micronutrient levels (when known) are sometimes observed to be high, and where some crops play an important role in regional food systems (e.g., "egusi" seed crops in West Africa) (28), particularly needs addressing.

Through our modeling of the distribution of novel climates at major staples' present production locations, we indicate the particular need to diversify and replace major staple production in the SSA subregions of West and Central Africa, which is in line with previous modeling (4, 5), especially for maize and yams. Although East and Southern Africa are the subregions of SSA where we have shown that the potential for forgotten food crops covering all food groups to diversify cropping systems of major staples or to replace them in 2070 is greatest, we have also shown that for Central and West Africa, multiple options exist in most examined production locations of our four major staples. Contextualized choices of forgotten food crops are revealed to be required by subregion, with this contextualization being further dependent on farmers' specific choices and food cultures.

Overall, the food group of other vegetables, including fruit vegetables and legume pods, appears to represent particular opportunities to diversify or replace cropping systems of major staples in SSA under changing climates. This is based on niche modeling and because experiences with cultivation have proven these forgotten food crops grow well in the relevant climatic and edaphic conditions. Our subset of 58 prioritized crops also included large numbers of leafy vegetables and fruits, which provide important sources particularly for Vitamins A and C, respectively, and in the case of leafy vegetables also for iron, folate, and zinc. Cereal and pulse forgotten food crops, though smaller in number in our assessment, were overrepresented in our final list of prioritized crops compared to the initial list of candidate crops. These cereals and pulses may be good choices for crop diversification or replacement, and support calorie and protein supply as well micronutrient provision. Appropriately combining forgotten food crops from different food groups for diversification or replacement of cropping systems of major staples will increase micronutrient concentrations in food production that otherwise remain low in the production of major staples, while providing alternatives for macronutrients too.

Of course, the niches of forgotten food crops are not solely shaped by climatic (and edaphic) factors; people also modify these niches with management interventions such as weeding, irrigation, and fertilization. The niche hulls of several of our candidate panel of forgotten food crops were based on relatively few occurrence points, and several are still partly harvested from the wild or are grown in low-input systems. These factors may result in our underestimation of the potential of these foods, with appropriate agronomic interventions, for diversifying or replacing cropping systems of major staples. This is particularly the case for forgotten food crops that are native to sub-Saharan Africa, as unlike for many of the indigenized crops also included in the current study, they often have not been tested in broader bioclimatic niches outside the region.

**Mainstreaming' Forgotten Food Crops in Sub-Saharan Africa's Food Systems.** The niche modeling presented in this paper is only one part of a much larger decision-making and implementation framework for diversifying food systems to respond to climate change (25). From our own experiences as practitioners in SSA, we know that food system diversification requires a nuanced understanding of the factors that drive the successful mainstreaming of forgotten food crops (23, 29). One principle is that promotion should be done in a participatory way, to ensure it is connected to the existing knowledge and practices of farmers in crop production, and consumers in food preparation (25). It is thus rooted in the complex food systems and many cultures in the four subregions of SSA (30). The way forgotten fruits and vegetables and other neglected and underpromoted food crops can be combined with major staples varies greatly, and many annual and perennial crops are grown for different purposes in different locations (25) (Fig. 5 provides several examples). Lack of access to appropriate planting material is one well-known major hindrance to diversifying food production with forgotten food crops in SSA, while the lack of markets for the foods produced is another well-recognized constraint (23). Tackling these two major constraints will boost the adoption of forgotten food crops, while issues such as farmers' capacity building in how to integrate crops into their cropping systems also need to be addressed. The speed of crop adoption at the individual household level depends on the appetite of the farmer to innovate and the effectiveness of communication and awareness raising about new crop options (31).

Successful existing examples to support the mainstreaming of forgotten food crops in the SSA region include for fruits and vegetables. Work partnering researchers with rural communities in East Africa has resulted in the design and implementation of locally tailored "food tree portfolios" in over 15 locations (23). These portfolios are collections of food tree species that, combined with other plant foods, are able to supply peoples' nutrient needs over the entire year, including during major staples' off-seasons. Taking Kenya as an example, these portfolios include food trees such as *A. occidentale* (cashew) and *Tamarindus indica* (tamarind) that were among the 58 prioritized forgotten food crops in the current study. The seedlings of the portfolio trees are distributed through community nurseries to support planting, while dietary education in schools, combined with the influence of school pupils on their parents, guides their consumption.

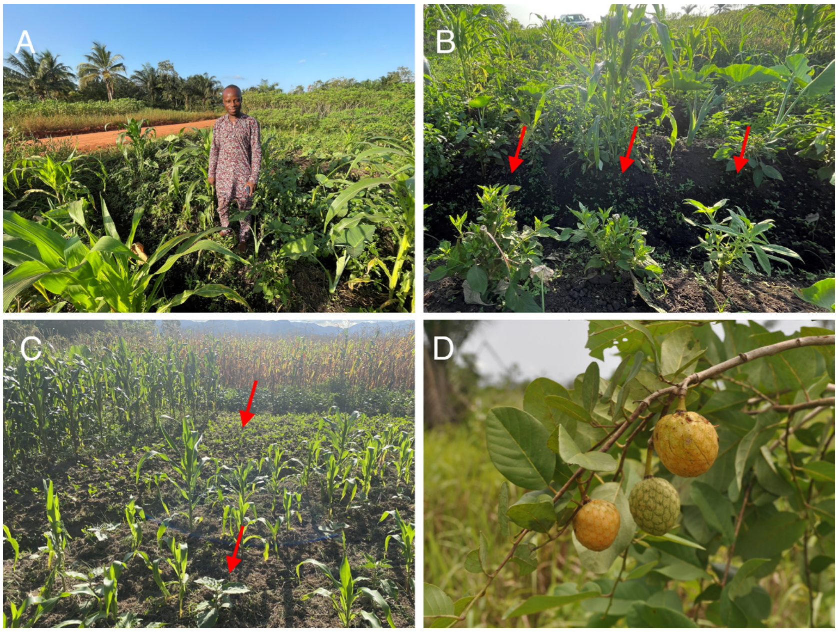


**Fig. 5.** Examples of diversified cropping systems in sub-Saharan Africa that include forgotten food crops. Panel *A*: A Beninese farmer stands in his diversified farm field that includes *Colocasia esculenta* (taroyam), maize, *Amaranthus* spp. (amaranth), and *Celosia argentea* (celosia) within an agricultural landscape dominated by cassava. Panel *B*: Three different amaranth varieties in the forefront of the picture (arrowed) are being evaluated by the same farmer as part of a participatory variety evaluation experiment in Benin; Panel *C*: Maize cropping system diversified with leafy and fruit vegetables in Eswatini. In the front of the picture, maize is intercropped with *Solanum aethiopicum* (African eggplant, arrowed). At the back of the picture, amaranth has been sown between maize fields (arrowed). Panel *D*: The fruit crop *Annona senegalensis* (wild custard apple) is widely used in Benin. Photo credits: Sognigbé N'Danikou, World Vegetable Center (panels *A* and *B*); Maarten van Zonneveld, World Vegetable Center (panel *C*); Enoch G. Achigan-Dako, University of Abomey-Calavi (panel *D*) (species authorities are mentioned in Dataset S1).



In the case of traditional vegetables, researchers and development partners evaluate varieties with farmers in a participatory way in West and East African countries (Benin, Mali, and Tanzania) as a tool to increase the adoption of locally adapted and preferred types. The chosen crops for this work include *A. cruentus* (amaranth), *C. gynandra* (spider plant), and *Abelmoschus esculentus* (okra), all of which were among the 58 prioritized crops in our study.

To further scale the supply of suitable varieties of forgotten food crops in SSA, major partnership initiatives such as the Africa Vegetable Breeding Consortium and the African Orphan Crop Consortium have been established to help address delivery constraints (32, 33). Improvements in biodiversity-related policies that provide for crop variety exchange, genetic resources' access-and-benefit sharing, and crop commercialization are also needed in SSA and at global level, as current policies do not generally pay sufficient attention to forgotten food crops (34, 35). To better encourage market development, shorter and more diversified value chains are required for many of the vegetables and fruits shortlisted in the current study (34, 36). Greater understandings of dietary preferences and behaviors, and of how food environments can enable consumer access and acceptability, are also needed to mainstream forgotten food crops in the SSA region (37). Exploring these gaps in knowledge will make possible viable intervention pathways for the diversification of Africa's food systems with Africa's forgotten food crops.

**Data, Materials, and Software Availability.** Climate data have been deposited in [figshare] (https://doi.org/10.6084/m9.figshare.21936801.v1). All study data are included in the article, Dataset S1, Dataset S2, and/or *SI Appendix*.

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