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Suitability of root, tuber, and banana crops in Central Africa can be favoured under future climates

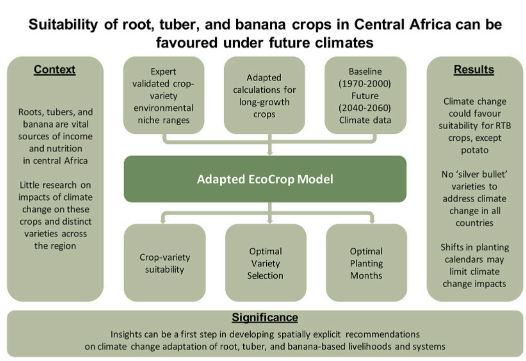
Rhys Manners[a,*], Elke Vandamme[b], Julius Adewopo[a], Philip Thornton[c], Michael Friedmann[d], Sebastien Carpentier[e], Kodjovi Senam Ezui[f], Graham Thiele[d]

[a] International Institute of Tropical Agriculture (IITA), Kigali, Rwanda
[b] International Potato Center (CIP), Kigali, Rwanda
[c] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), International Livestock Research Institute (ILRI), Nairobi, Kenya
[d] CGIAR Research Program on Roots, Tubers and Bananas, International Potato Center (CIP), Lima, Peru
[e] Bioversity International, Leuven, Belgium
[f] African Plant Nutrition Institute, Nairobi, Kenya

HIGHLIGHTS

- Root, tuber and banana (RT&B) systems are prevalent in Central Africa, yet there is limited knowledge of climate change impacts on these systems.
- Adapted version of EcoCrop model generated insights on how future climates may affect the suitability of Central African RT&B systems.
- Study analysed RT&B crop and variety suitability, shifts in planting date, and identified implications for future research.
- Climate change will marginally favour RT&B crops, except potato. Planting date shifts and variety selection could ensure future suitability.
- Data-driven insights generated from this work can be a first step in developing spatially explicit recommendations across distinct timeframes.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Climate change is projected to negatively impact food systems in Sub-Saharan Africa. The magnitude of these impacts is expected to be amplified by the extensive reliance on rainfed agriculture and the prevalence of subsistence farming. In the Great Lakes Region of Central Africa, smallholder farming households are largely dependent on root, tuber and banana crops. However, the potential impacts of various climate change scenarios on these crops are not well reported. Yet, data-rich insights about the future impacts of climate change on these crops and the adaptive capacity of food systems in the Great Lakes Region is critical to inform research and development investments towards regional climate change adaptation.

* Corresponding author at: Kigali KG 563, Rwanda.
E-mail address: r.manners@cgiar.org (R. Manners).

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Objectives: We aimed to gain insights of potential impacts of climate change on root, tuber, and banana crops in the Great Lakes Region, specifically investigating changes to localised crop suitability, planting dates, and identifying potential 'climate-proof' variety types of each crop for specific geographies.

Methods: We developed a modified version of the EcoCrop model to analyse the suitability of future climates for four key root, tuber, and banana crops (banana, cassava, potato, and sweetpotato) and a suite of varieties for each (typical, heat-tolerant, drought-tolerant, and early maturing). The model considers only the direct impacts of climate change on crop suitability. It does not consider how climate change impacts crop suitability by affecting the occurrence of extreme weather events or indirect effects on incidence and severity of pest and disease outbreaks.

Results and conclusions: Our results demonstrate that climate change will be somewhat favourable to root, tuber, and banana-based systems, with only widespread negative impacts seen for potato. These changes should be qualified by the observation that in most cases the environmental suitability for banana, cassava, and sweetpotato will remain constant or improve if farmers shift planting schedules. Location- and crop-dependent shifts to different variety types were found to be effective in improving suitability under future climates.

Significance: Data driven insights generated from this work can be used as a first step in developing spatially explicit recommendations for both farmers and decision-makers on how to adapt to climate change and plan investment in the research needed to adapt root, tuber, and banana-based livelihoods and systems to those long-term changes.

1. Introduction

Global temperatures are expected to increase between 1.5° and 5.6 °C by 2100, compared to pre-industrial levels (~1750), depending on the trajectory of greenhouse gas emissions (IPCC, 2014; Raftery et al., 2017; Zelinka et al., 2020). For high-emission scenarios, even greater localised temperature increases are expected in Sub-Saharan Africa (SSA; James and Washington, 2013; Niang et al., 2015). Since 2001, Africa-wide annual temperatures have been observed to be at least 0.5 °C warmer than a 1910–2000 baseline (NOAA, 2018). In East Africa, most regions are projected to become wetter, with localised drying (Niang et al., 2015), contrasting with historical trends of long-term drying (Hartmann et al., 2013; Williams and Funk, 2011), although there is some uncertainty with respect to regional rainfall changes.

Rainfed and low-input agricultural production systems, both prevalent in SSA, are thought to be particularly vulnerable to climate change (Girvetz et al., 2019). This vulnerability is driven by direct (e.g. changes in weather patterns) and indirect (e.g. increased severity and incidence of pests and diseases) factors linked to climate change (Musana et al., 2013; Okonya et al., 2019). Individually and in combination, these factors represent severe threats to food systems (IPCC, 2019, 2018). Climate change-induced latitudinal shifts in temperature ranges and seasonal rainfall onset may also drive changes in the environmental suitability of agroecologies for crop production (Calberto et al., 2015; Cho and Mccarl, 2017; Di Paola et al., 2018; Rhiney et al., 2018). Shifts in rainfall patterns and changes in temperature, coupled with increased risk and frequency of extreme weather events may require adaptations to planting dates and variety selection as traditional planting calendars reliant on consistent seasonal conditions (e.g. wet-season onset) become unreliable and conditions more extreme (Girvetz et al., 2019). Yegbemey et al. (2013) have already observed changes in cropping calendars in response to increased climate variability. Data-driven evidence about potential changes in environmental suitability and shifts in planting dates of crops are critical to develop local adaptation strategies for smallholder farmers and production systems in SSA.

Root, tuber, and banana (RT&B) production systems are particularly prevalent across SSA (Kamira et al., 2016; Gambart et al., 2020; Thiele et al., 2021). A growing body of literature has described the potential impacts of climate change on RT&B crops (e.g. Rippke et al., 2016; Serdeczny et al., 2017; Taylor et al., 2019; Chapman et al., 2020: Varma and Bebber, 2019; Jennings et al., 2020). Understanding the impacts on RT&B crops is particularly relevant in SSA due to their importance in contributing to food security, livelihoods, and household income (Thiele et al., 2017; Thiele and Friedmann, 2020). In the Great Lakes Region (GLR) of Central Africa, RT&B-based foodstuffs contribute up to 47% of daily caloric intake and are notable sources of micro- and macronutrients (Thiele and Friedmann, 2020; Scott, 2021). In general, bananas and potatoes are grown for consumption and to generate income, while cassava and sweetpotato are cultivated primarily for home consumption (Okonya et al., 2019), emphasising the multi-faceted role of RT&Bs in central African households.

Reinforcing their importance, RT&B crops may also provide a mechanism for household and livelihood resilience to climate change (Prain and Naziri, 2020; Thiele and Friedmann, 2020). RT&B crops are noted for their resilient traits (Calberto et al., 2015; Heider et al., 2020; Prain and Naziri, 2020), including: (i) high energy and nutrient output per day of growing period and unit area, combined with high drought stress tolerance (as in sweetpotato - Heider et al., 2020); (ii) capacity to survive under dry conditions by extracting water from deep soil layers, controlling stomata closure and shedding leaves during dry periods (as in cassava – Alves, 2002); and (iii) an ability to thrive under high temperatures and survive with little inputs for extended periods (Ndabamenye et al., 2012; Kamira et al., 2016).

Despite their potential resilience to climate change and their critical role for farming households, limited knowledge exists regarding overall effects of climate change on RT&B crops in SSA, compared to other crop groups (Manners and van Etten, 2018; Petsakos et al., 2019). Improving this understanding could inform breeding programmes and encourage breeding for future conditions, with varieties selected to keep pace with future changes in environmental conditions (Challinor et al., 2016; Whitfield et al., 2021). Furthermore, while crop varieties often differ in terms of their requirements for growth and degree of tolerance or resilience under varying environmental conditions, there is rarely any effort directed towards targeting/re-matching varieties of RT&B crops with future climate scenarios to position farmers for sustained production in the region (Balié et al., 2019). These gaps demonstrate there is need to support RT&B farmers in formulating climate change adaptation strategies in the GLR, while guiding decision-makers to target research activities and funds towards improving the resilience of agricultural systems.

To support both farmers and decision-makers, crop suitability models can generate information that provides a coarse understanding of how future climates might affect agroecological systems (e.g. Jarvis et al., 2012; Zabel et al., 2014). EcoCrop is one such modelling tool (Hijmans, 2017), by comparing crop-specific environmental niche ranges of temperature and precipitation with climatic data of the environment, it analyses the suitability of a given environment for a crop (FAO, 2016). EcoCrop has been extensively applied across crops and locations to generate insights into how crops may be affected by future climates (e.g. Chapman et al., 2020; Piikki et al., 2017; Vermeulen et al., 2013). Despite this, EcoCrop has some limitations including: the use of potentially outdated parameters; no consideration of crop varieties;

potential under-estimation of suitability for longer growing crops (e.g. cassava and banana); and a lack of consideration of environmental conditions of key growth periods for longer growing crops.

In this context, the specific objectives of this study were to: (i) validate crop-specific environmental niche ranges for different root, tuber and banana crops; (ii) generate values for different variety types; (iii) test an adapted version of EcoCrop to improve crop suitability estimates for long duration crops; (iv) analyse crop (and variety type) suitability and assess suitability changes under future climates for RT&B crops in the GLR of Central Africa; (v) map any shifts in planting date; and (vi) identify implications for future research and scaling investments in RT&B crops.

2. Methodology

2.1. Crops and regions

The study was conducted in the Great Lakes Region of Central-East Africa, which consists of seven countries (Burundi, the Democratic Republic of the Congo, Kenya, Malawi, Rwanda, Tanzania, and Uganda) that border the African Great Lakes.

We focus this analysis on four RT&B crops: banana (*Musa* spp), cassava (*Manihot esculenta*), potato (*Solanum tuberosum*), and sweetpotato (*Ipomoea batatas*).

For banana, most farmers in the GLR grow this crop as a perennial, where the crop is initially established by planting a mother plant, and later maintained by selecting ratoons from the same plant mat and continuing for successive generations. The growth duration for the mother plant and ratoon is different, which has implications for crop suitability modelling. As banana is more frequently harvested from ratoons than mother plants, we calculated crop suitability considering the average growth duration of a ratoon. Within-year variation in climate should ideally be considered for determining the optimal time of selecting ratoons, avoiding poor climatic conditions (mainly too little rainfall) during key growth periods. Hence, the subsequent dates of selecting ratoons (sucker selection management) can be considered as equivalent to ideal planting date in the other crops.

Cassava is a perennial shrub that is generally propagated vegetatively through woody stem cuttings. Although young fresh leaves are widely consumed as a vegetable in the GLR, we focus on the storage root, which smallholder farmers increasingly harvest 11–12 months after planting.

Like banana and cassava, potato and sweetpotato are vegetatively propagated. The common method of crop establishment for potato is through planting sprouted tubers while sweetpotato is commonly established by planting cuttings from the vines. Before sprouting, potato tubers will go through a stage of dormancy of one to several months depending on variety. When well sprouted potato tubers are used at planting time, plants will start emerging from the soil after 2–3 weeks, and the crop will mature in 3 to 4 months for most varieties.

For sweetpotato, many varieties possess the trait of continuous storage root formation which allows farmers to harvest mature storage roots from around three months after planting while other roots continue to mature. Not all varieties are as suitable for piecemeal harvesting, and storage roots of early maturing varieties usually mature around the same time at 4 to 5 months after planting.

2.2. Crop suitability modelling

2.2.1. Climate data

Crop suitability modelling was performed for two time periods: baseline (1970–2000) and future (2040–2060).

Baseline climate data were sourced from WorldClim2, with monthly precipitation and temperature (minimum and mean) data collected (Fick and Hijmans, 2017). Data layers were assembled at a spatial resolution of 30 arc *sec* (~1 km^2 at the equator). These data are averages of conditions from 1970 to 2000. Unfortunately, more recent high resolution and aggregated precipitation and temperature data are not currently available. The Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) and the Climate Hazards Group InfraRed Temperature with Station Data (CHIRTS) datasets provide more recent data (1981–2016), but these data are only available at ~4.5km^2 resolution (Funk et al., 2015; Funk et al., 2019). To maintain a high-resolution analysis, we chose the WorldClim2 climate data.

Future downscaled climate data were taken from the database of the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS; Ramirez and Jarvis, 2010). We collected monthly data layers (precipitation, minimum and mean temperature) at a spatial resolution of 30 arc sec (~1 km^2 at the equator) for 2050. These data are estimates of average climate conditions for the period 2040–2060. We collected future data for the representative concentration pathway (RCP) 6.0. Emissions by 2100 are projected to range between the pathways of RCP4.5 and RCP6.0 (Raftery et al., 2017). We selected RCP 6.0 as this represents the upper bound of this range and a potential worse-case scenario. Under the conditions of this scenario, emissions peak in 2080 and average global temperatures increase by 1.4 °C–3.1 °C by 2100, relative to 1986–2005 averages (IPCC, 2013). Data layers were assembled for the 15 available global circulation models (GCMs).

All climate data (baseline and future) were cropped to an area of 5.4°N to 17.1°S and from 12.2°E to 41.9°E, bounding the GLR. Climate layers were then cropped to areas defined as cropland within the region as of 2015 (Xiong et al., 2017). Although a number of studies suggest (e.g. Smith et al., 2010; Porfirio et al., 2017) future expansion in global cropland areas (largely in Boreal and arid regions), we were unable to find high resolution projections of future cropland area for the study region. Therefore, future suitability analyses were performed using current cropland areas. We recognise that population pressures, governance issues, and other socio-economic forces may drive future regional expansion in cropland area.

2.2.2. EcoCrop

The EcoCrop model of the R package *dismo* (Hijmans, 2017; Hijmans et al., 2001) can provide an informative approximation of the impacts of climate change on environmental suitability of crops. EcoCrop analyses the suitability of an environment for a crop by comparing crop-specific optimum and absolute ranges for minimum temperature, average temperature, and precipitation with climatic data. EcoCrop provides a suitability value (ranging from 0 = no suitability to 1 = perfect suitability) based upon how suited climatic conditions are relative to the crop-specific ranges. A detailed description of the EcoCrop model is provided in S1 and by Ramirez-Villegas et al. (2013) and Hijmans (2017). Due to its simplicity, the model does have some limitations (Ramirez-Villegas et al., 2013), such as no consideration of biotic pressures (e.g. incidence or severity of pests and diseases) and no consideration of weather variability between years and within months. More specific limitations are noted below. However, EcoCrop is applied in this study to derive a general indicator of climate change impacts (i.e. whether climate change improves or reduces environmental suitability for crops).

2.2.3. Expert-validated niche ranges

Previous studies using EcoCrop have relied upon the crop-specific environmental niche ranges and growth duration data assigned by the FAO (2016: See S2). We validated these niche ranges to check whether they are consistent with typical varieties of the studied crops cultivated within the GLR. To do this, we combined a literature search with expert knowledge. Absolute and optimal ranges of average temperature and minimum temperature for each crop were derived from recognised literature sources (Alves, 2002; Erpen et al., 2013; A. J. Haverkort et al., 2015; Machovina and Feeley, 2013). Experts in crop physiology then validated these ranges. The consulted experts are active within the CGIAR Roots, Tubers and Bananas Research Program and have broad experience with respective crops in the GLR (names of experts provided in the Acknowledgements). We found no reliable sources for the precipitation ranges. Experts agreed that the FAO precipitation ranges remained valid. Further information on the interaction with experts is provided in S2.

We also note that the FAO (2016) do not distinguish between different variety types. To address this, we developed niche ranges for three other variety types that: (i) mature faster than typical genotypes (early maturing); ii) can tolerate higher temperatures (heat-tolerant); (iii) can tolerate a higher level of drought stress (drought-tolerant). A description of how these environmental niche ranges were determined is provided in S3. The resulting set of parameters per crop and crop variety is presented in Table 1.

2.2.4. Adapted EcoCrop

On further inspection of the EcoCrop model, we identified two potential limitations that may impact the calculation of suitability for long-duration crops: (i) temperature suitability and (ii) the omission of key growth periods.

Regarding calculation of suitability, EcoCrop evaluates monthly values of mean temperatures during the growing period in a way that the model may only consider data from a single month in cases of extreme temperature. We note that this aspect may reduce suitability of a whole growing period to zero. This potential is problematic for long-duration crops (with crop cycles close to a year) where one month of extreme temperature may render the entire year unsuitable for a crop. Although this may not have such a dramatic effect on the suitability of shorter short-duration crops (potato and sweetpotato), it is still imperative to address this for the analysis of longer-duration crops (banana and cassava). Although for some crops such as rice, a few days of high temperatures around the time of flowering can result in significant yield loss due to heat stress-induced sterility (Wassmann et al., 2009). For RT&B crops, heat stress cannot induce sterility as RT&B crops are vegetatively propagated. Moreover, for long-duration crops such as cassava and banana, a short period of extreme temperature may depress growth relatively less compared to short duration crops. A detailed overview of this limitation and an example of its effect on crop suitability is provided in S4.

EcoCrop also does not consider specific environmental requirements of crops during key growth periods (e.g. during crop establishment and bunch initiation). These periods are a determining factor for planting dates and crop suitability for long-duration crops. Consultations with the same experts (described above) stressed that for long-duration crops, precipitation during key growth periods is as relevant to consider as cumulative precipitation during the entire growth period. These consultations revealed that for cassava sufficient precipitation during the first three months of the growth cycle is essential for good crop establishment, and, hence, farmers plant when there is a high likelihood of sufficient rain in subsequent months (usually at the start of the rainy season). For banana, precipitation during the time of bunch initiation and formation is a critical yield-determining factor, and farmers also choose planting dates (or date of selecting ratoons, see below) in response to this requirement.

To address these issues, we developed and tested two modifications: (i) addition of a new variable considering environmental conditions during key growth periods; and (ii) adaptation to how monthly values of temperature are compared to crop-specific environmental niche ranges and the calculation for minimum and mean temperature suitability. We believe these adaptations improve the original EcoCrop by addressing the limitations and generating more reliable suitability results for longer-duration crops, without affecting the suitability calculations for short-duration crops. A further functionally to extract the *ideal* month for planting (i.e. the month resulting in a growing period with the highest suitability) was derived as an output from the model.

A full description of these changes is available in S5 and S6.

2.2.5. Crop suitability

We calculated crop suitability using the adapted EcoCrop model for each 1km^2 cell currently defined as cropland (Xiong et al., 2017). For the baseline, the adapted EcoCrop model was run once per crop variety type. To estimate future crop suitability, the model was run once for each of the available GCM models. We calculated mean suitability per cell (1 km^2) across the GCM-specific results to derive an average future crop suitability per cell. To determine ideal planting month, we calculated the modal planting month across the GCMs. In cases where multiple (more than 6) months had the same suitability, we labelled these cells as 'mult' (multiple ideal planting dates).

The results developed under future climates were compared to the crop suitability values and ideal planting months calculated under baseline climates to evaluate climate change-induced changes. There are some caveats to bear in mind: (i) locations where crops were found to have multiple ideal planting dates in the present were automatically classified as having multiple ideal planting dates in the future; and (ii) locations where the baseline ideal month was a specific month – but where future multiple months were found to have the same suitability – were classified as having multiple ideal planting dates in the future. These assumptions were made to limit the computing required to quantify the change from a fixed month to multiple months and vice versa.

2.2.6. Comparison of baseline suitability with current crop distribution

To complement this work, we also compared spatially explicit crop suitability outputs with current crop distributions to assess whether environmental suitability is constraining geographic crop distributions. Following Manners et al. (2020), we expect an asymmetric relationship between cropped area and suitability, expecting crops to be either present or absent in regions of high suitability, but not present in regions of low suitability. To present this relationship, we plotted a hypothetical relationship line (not derived from statistical analyses) from the origin to the upper right of the figures (maximum harvested area). This line represents the relationship that could be expected if cropped area were to increase linearly with suitability. If environmental suitability is a limiting factor of harvested area, we would expect most points to be under this relationship line. We would not expect farmers to cultivate crops in areas of low suitability but crops also may not be highly cultivated in areas of high suitability. If most points were above this line, it suggests that environmental suitability does not limit areas of crop production.

To perform this analysis, we extracted harvest production area data (in hectares) for the year 2010 from the spatial production allocation model (SPAM) developed by IFPRI (2019). The data for the four analysed crops were collected at a 10km^2 resolution (4.5 arc minutes). To create a spatial match between the suitability and production area data, suitability data were aggregated from 30 arc *sec* to 4.5 arc minutes.

3. Results

3.1. Comparison of baseline suitability with current crop distributions

The relationships between environmental suitability and observed harvested land area for the four analysed crops (Fig. 1) show that all crops display an asymmetric pattern. A few examples exist where points are plotted above the hypothetical relationship line, suggesting that environmental suitability does not limit harvest area in these areas. However, most points are found under the lines, which supports the idea that environmental suitability limits areas of production.

Interestingly, except for potato, crops appear to be cultivated in regions of moderate (0.3–0.7) rather than perfect suitability. Banana, cassava, and sweetpotato cultivation peak in areas with suitability values between 0.4 and 0.9. These crops seem to be grown even at very low suitability values from 0 to 0.2. But this is not the case for potato, which is completely absent in areas with suitability values below 0.2,

Table 1
Expert-validated niche ranges for temperature, precipitation, and growth cycle duration for all genotypes of each crop, including the optimum range in which crop suitability is maximum (1), and the minimum and maximum temperature and precipitation thresholds beyond which crop suitability is between 0 and 1. The niche ranges of the new variable (Precipitation during the Key Growth Period) are also included.

Crop	Temperature					Precipitation				Growth duration	Precipitation during key growth period					
	Optimum min. (°C)	Optimum max. (°C)	Min. (°C)	Max. (°C)	Kill (°C)	Optimum min. (mm)	Optimum max. (mm)	Min. (mm)	Max. (mm)	Days	Optimum min. (mm)	Optimum max. (mm)	Min. (mm)	Max. (mm)	Start month[a]	End month[a]
Banana typical	23	29	12	38	5	1200	3600	650	5000	320[b]	315	945	171	1250	8	10
Banana heat-tolerant	23	32	12	42	5	1200	3600	650	5000	320	315	945	171	1250	8	10
Banana drought-tolerant	23	29	12	38	5	960	2880	520	5000	320	252	756	137	1250	8	10
Banana early maturing	23	29	12	38	5	1144	3431	620	4766	305	315	945	171	1250	7	9
Cassava typical	25	29	15	38	0	1000	1500	500	5000	365	250	375	125	1250	1	3
Cassava heat-tolerant	25	32	15	42	0	1000	1500	500	5000	365	250	375	125	1250	1	3
Cassava drought-tolerant	25	29	15	38	0	800	1200	400	5000	365	200	300	100	1250	1	3
Cassava early maturing	25	29	15	38	0	740	1110	370	3699	270	185	277	92	925	1	3
Sweetpotato typical	18	28	10	38	5	750	2000	350	5000	135	–	–	–	–	–	–
Sweetpotato heat-tolerant	18	31	10	42	5	750	2000	350	5000	135	–	–	–	–	–	–
Sweetpotato drought-tolerant	18	28	10	38	5	600	1600	280	5000	135	–	–	–	–	–	–
Sweetpotato early maturing	18	28	10	38	5	500	1333	233	3333	90	–	–	–	–	–	–
Potato typical	15	20	3	28	0	500	800	250	2000	120	–	–	–	–	–	–
Potato heat-tolerant	15	22	3	31	0	500	800	250	2000	120	–	–	–	–	–	–
Potato drought-tolerant	15	20	3	28	0	400	640	200	2000	120	–	–	–	–	–	–
Potato early maturing	15	20	3	28	0	375	600	188	1500	90	–	–	–	–	–	–

[a] Months after planting.
[b] Growth cycle duration of the ratoon.

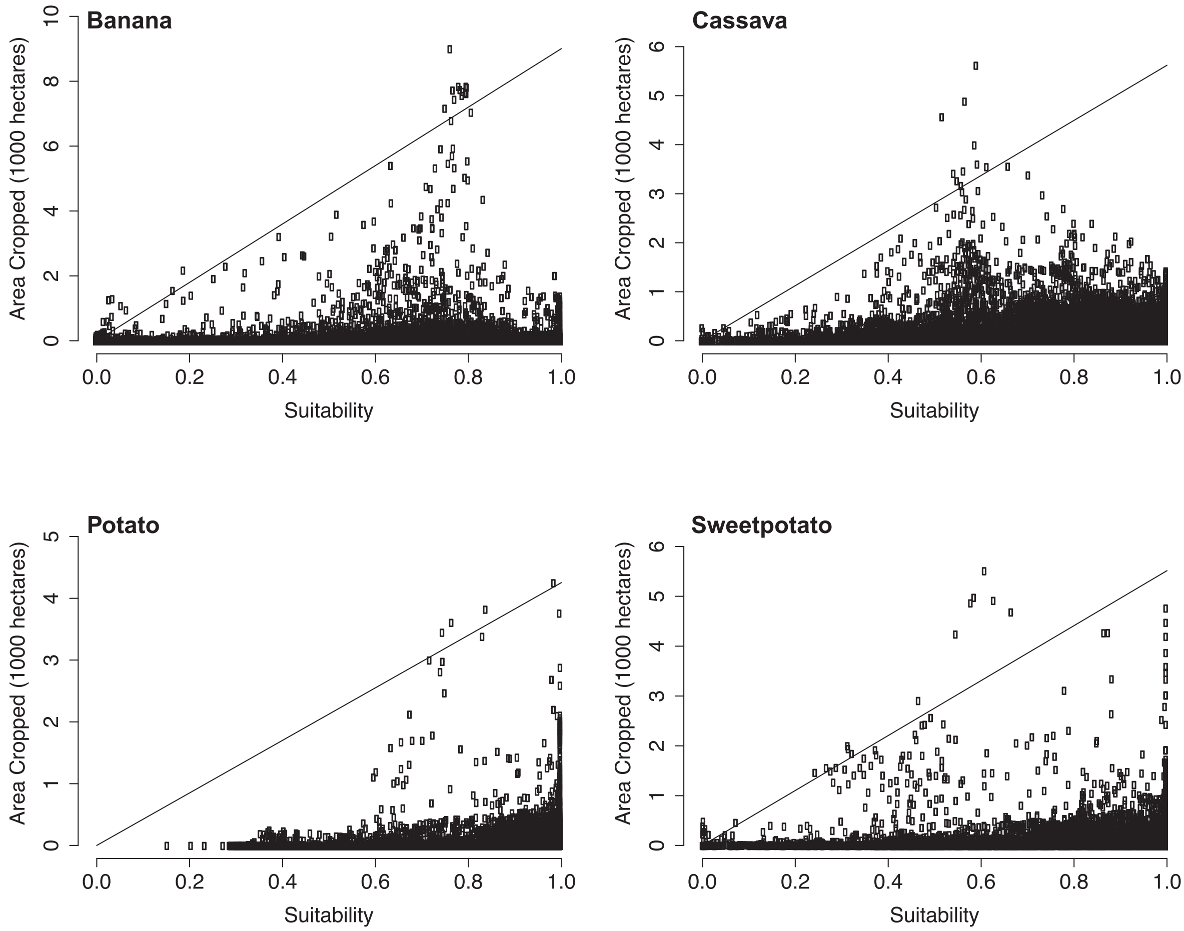

Fig. 1. Relationship between current crop distribution and baseline suitability. Line represents a non-statistically supported theoretical linear relationship between harvested area and suitability.

and mostly cultivated in areas with suitability values above 0.8.

3.2. Future climates in the GLR

A basic overview of projected future (2040–2060) climatic conditions within the GLR, compared to baseline climates (1970–2000) are presented in Fig. 2. The GLR is projected to be predominantly characterised by warmer and wetter conditions. Minimum temperatures in the GLR will increase on average 1.89 °C (±0.45 °C) with mean temperatures increasing 1.81 °C (±0.42 °C). Regions of western Tanzania were modelled to experience mean and minimum temperature increases of more than 8 °C (±0.5 °C). In central Kenya, minimum temperatures may reduce by 1 °C (±0.3 °C). Future precipitation patterns will be less uniform, ranging from reductions of up to −492 mm to increases of 1332 mm, with both extremes observed in Tanzania. On average, annual precipitation will increase 53 mm (±97 mm) with 80% of the GLR seeing precipitation increases. Pockets of southern Tanzania, central Malawi, southern DR Congo, and northern Uganda can expect

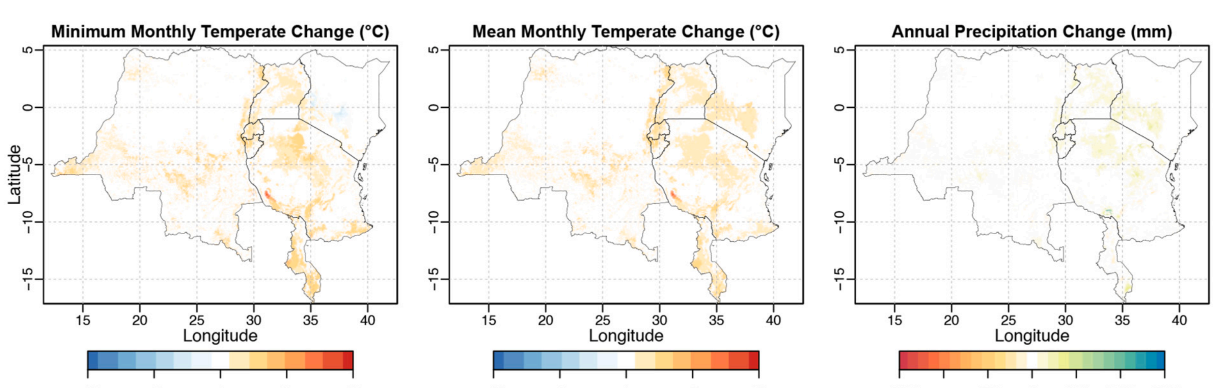

Fig. 2. Changes in temperature and precipitation from baseline (1970–2000) to future (2040–2060) conditions.

future climates to be drier.

3.3. Baseline crop suitability and crop suitability change under future climates

In general, future climates are favourable to the analysed crops (Fig. 3) and variety types (Fig. 4). Spatially explicit maps of crop suitability and suitability changes for the typical variety (Fig. 3) reveal contrasting impacts of climate change across crops and locations. In Fig. 4, we present histograms considering four scenarios for each crop: (i) typical variety type is still grown under future climates; (ii) shifts made from typical to drought-tolerant varieties; (iii) shifts made from typical to early maturing varieties; and (iv) shifts made from typical to heat-tolerant varieties. The bins of the histograms represent the frequency of cells that see suitability changes across the GLR. Similar maps to Fig. 3 (per variety type) are presented in Fig. S2.

Baseline cassava suitability was high across much of the GLR. Only parts of central Kenya, southern Tanzania, eastern DR Congo, regions of Rwanda, and areas of Burundi were modelled to have low suitability (Fig. 3). Future suitability increases of up to 0.2 were found across the four cassava variety types, with observed localised suitability increases of 0.5 (Fig. 4). Adoption of heat-tolerant varieties would generate almost identical suitability as the typical variety, whereas shifts to drought-tolerant or early maturing varieties would result in localised suitability declines.

The findings for banana largely reflect those for cassava with widespread suitability across the GLR under baseline climates. However, large areas of Kenya and Tanzania were modelled with suitability values less than 0.3 (Fig. 3). Under future climates, banana suitability improves almost universally, except for areas in northwestern Uganda and southern Malawi. Cultivation of typical and heat tolerant varieties generated suitability increases of up to 0.2 across an extensive area of the GLR (Fig. 4). Adoption of drought-tolerant varieties could produce localised increases beyond 0.5. Only the early maturing variety was observed to reduce suitability (up to 0.3) in localised areas.

Baseline crop suitability for potato is above 0.8 for much of Rwanda, Burundi, Kenya, Malawi, and southern Tanzania, most likely due to the short growing period of this crop, combined with relatively low minimum precipitation requirements (i.e. one short period of intense rainfall is sufficient to meet the crop water requirements). Under future conditions, potato suitability declines universally across the GLR. However, shifts to heat-tolerant varieties could compensate, with future suitability observed to remain largely unchanged under future climates and, in some regions, increase compared to observed suitability under baseline conditions.

Baseline climatic conditions are mostly suitable for sweetpotato across the GLR, with the exceptions of southern Uganda, eastern Kenya, central Tanzania, and under future climates. Under future climates suitability remained stable across most regions. Western Kenya and western DR Congo were modelled with slight reductions, while southwestern and central Tanzania, southern Uganda, northern Rwanda, and eastern DR Congo were projected with suitability increases. A shift to drought-tolerant or early maturing varieties could result in suitability increases beyond 0.5 in some areas.

These results demonstrate the spatially explicit nature of climate changes impacts. In general terms, RT&B crop suitability is favoured by climate change with a few spatial and crop-specific exceptions. The results also illustrate how variety shifting could, in some cases, help farmers to adapt to climate-induced negative changes when crop switching is not an adaptation option. To complement this finding, in Fig. 5, we map the spatial distribution of future best-performing variety types (variety types with highest suitability) across the GLR under future climates.

In general, early maturing varieties of cassava, drought-tolerant varieties of potato, typical varieties of sweetpotato, and drought-tolerant banana exhibit the highest suitability under future climates. The results highlight that different geographies require adaptive and diverse crop-variety portfolios to align with modelled future climates. For example, to achieve maximum suitability certain regions of Kenya would require three variety types of banana, sweetpotato, and potato, but only one variety of cassava. In other cases, the same locality of Rwanda may need heat-tolerant varieties of potato and drought-tolerant varieties of banana. This finding reinforces the need for spatially explicit and tailored interventions to respond to future climates and ensure resilience of RT&B farming systems under future climates.

3.4. Changes in ideal planting month under future climates

The previous sections outline how crop suitability may change under the assumption that farmers are aware of the ideal planting month and flexible enough to change their planting dates. Understanding how planting dates may change, combined with crop suitability changes, provides further insights to empower farmers to change their practices and to make crop-specific recommendations for future planting calendar adaptations. We quantify these changes as the difference between the ideal planting month in the baseline, compared to the future. For example, in the case of the ideal planting month being May under baseline climates, and July under future climates, we map this as $+2$ shift, in contrast a future ideal planting month of March would be denoted as -2 shift. The predicted changes in planting dates (Fig. 6) illustrate that long-duration crops, in some cases, exhibit the same suitability across multiple planting months. In cases where more than six months were found to have the same suitability either in the baseline or future climates, cells were classified as 'mult' (multiple potential planting months) and coloured dark grey. Across the analysed crops it is evident that in almost all regions of the GLR, at least one of the analysed crops will undergo extensive changes in ideal planting period.

Under baseline climates, cassava was observed to be the most flexible crop as much of the GLR shows more than 6 months of the year with the same suitability. Cassava contrasts with banana, which only shows such flexibility in parts of DR Congo and northern Uganda. Extensive planting date flexibility is noted for potato across Rwanda and in pockets of Kenya. We also observed such pockets of flexibility for sweetpotato in Kenya and DR Congo.

Climate change was found to induce extensive shifts in ideal planting months. Due to the flexibility of cassava, it is difficult to extensively quantify the scale of any shifts, but in eastern Kenya, shifts of up to five months were observed, with lesser changes seen in Tanzania and DR Congo. Shifts of between 3 and 6 months were observed for banana in parts of Rwanda, eastern DR Congo, western Uganda, and southern Tanzania. Shifts for potato are, in general, less than 3 months and were noted in eastern Kenya, central and eastern DR Congo, western DR Congo, and eastern Rwanda. For a four-month growing season crop, these shifts infer that considerable adaptations will be necessary for farmers to maintain optimal suitability. For sweetpotato, shifts are minimal, except in regions of Uganda, Kenya, and eastern DR Congo, where 5-month shifts were observed. Changes in planting date for different variety types are presented in Fig. S3.

4. Discussion

4.1. Current cultivated area versus crop suitability

We examined the relationship between cultivated area and crop suitability and found cassava, banana, and sweetpotato to be cultivated across areas of diverse suitability. This may be attributed to the common practice among smallholder farmers to grow these crops for household consumption (Okonya et al., 2019). The cultural and culinary importance of these crops (Thiele et al., 2017) may suggest opportunistic cultivation of the crops by farmers, even in less than ideal conditions (Marimo et al., 2020). However, we acknowledge that the results may also present a limitation of suitability-based approaches, as variables

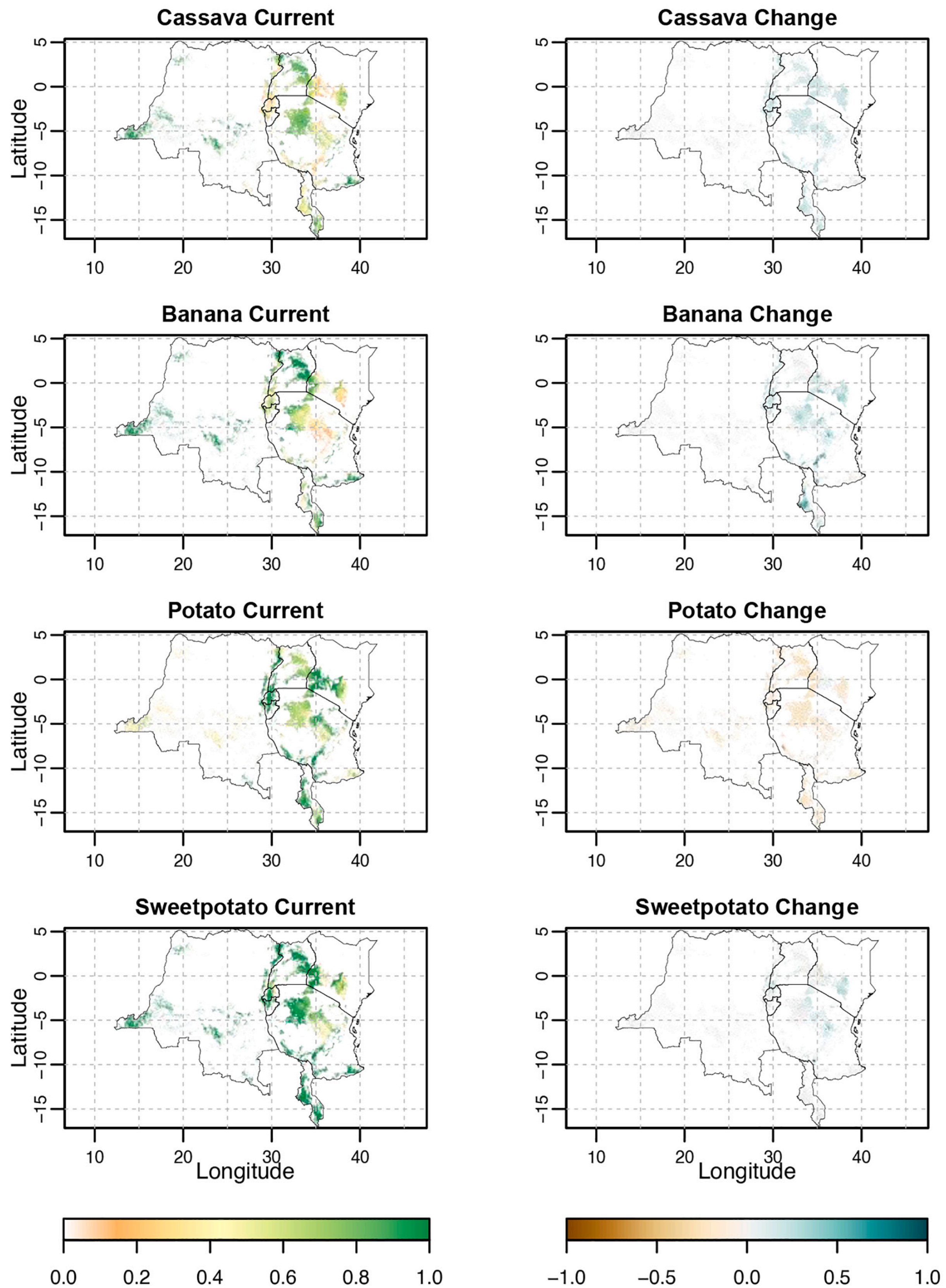

Fig. 3. Crop suitability under baseline climates and suitability changes under future climates for selected RT&B crops across the GLR of Africa.

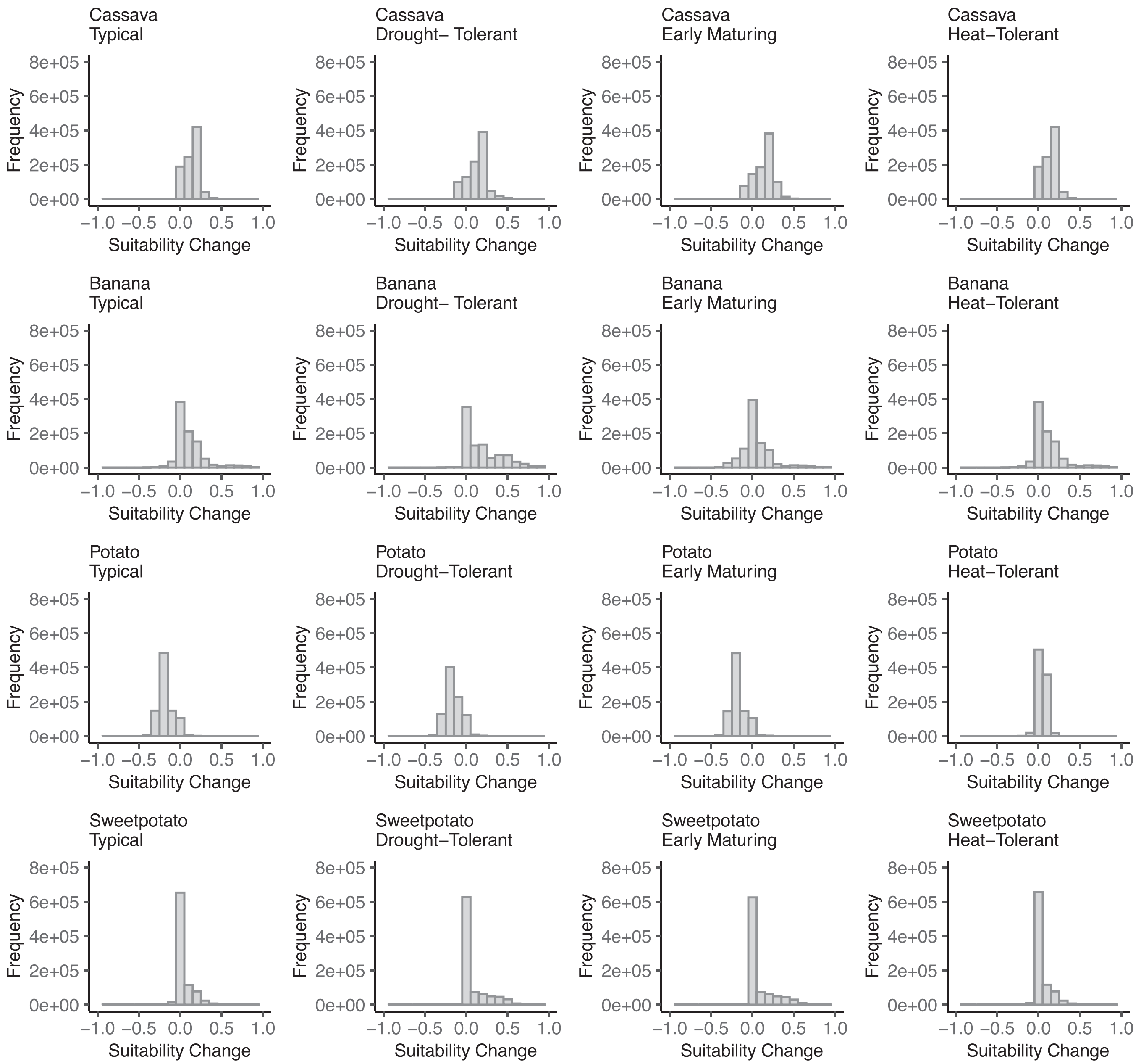

Fig. 4. Change in crop suitability under future climates for different crop variety types. Changes represent the difference between suitability and future suitability for four variety types and baseline climate conditions for typical varieties. Bars represent the number of cells within each category of suitability changes.

that may better explain crop distribution may be missing (e.g. socio-cultural, and nutritional).

In the case of potato, factors related to market access and local demand also often inform farmers' decisions regarding land allocation for cultivation of RT&B crops (Bagamba, 2007), which may help to explain the distribution of potato. Potato is a high value crop but also requires comparatively more investment in inputs such as seeds and pesticides (Schulte-Geldermann, 2012) and this may dissuade farmers who live in areas that are too hot or dry for good potato harvests. However, areas with near-perfect suitability for potato (i.e. wet, cold, and high-altitude) are common in the GLR. In these areas, potato has a comparative advantage over crops that are favoured by higher temperatures, such as banana and cassava.

4.2. Projected climate change impacts in the GLR and agronomic and breeding implications

We found that future climates are generally favourable to RT&B crops in the GLR, which aligns with previous analyses (Calberto et al., 2015; Jarvis et al., 2012; Raymundo et al., 2018). Consistent with Jarvis et al. (2012), cassava was projected to undergo widespread improvements in suitability to 2050. Chapman et al. (2020) recently projected that such improvements could continue to the end of the century, even under the extreme conditions of RCP8.5. Climate change does not universally benefit cassava as we found southern parts of the GLR characterised by marginally reduced suitability, conforming with the findings of Whitfield et al. (2021). Despite this exception, the results reinforce the notion that cassava is a resilient crop, adaptable to changing climates (Rippke et al., 2016).

Our results for banana align with Calberto et al. (2015) who found

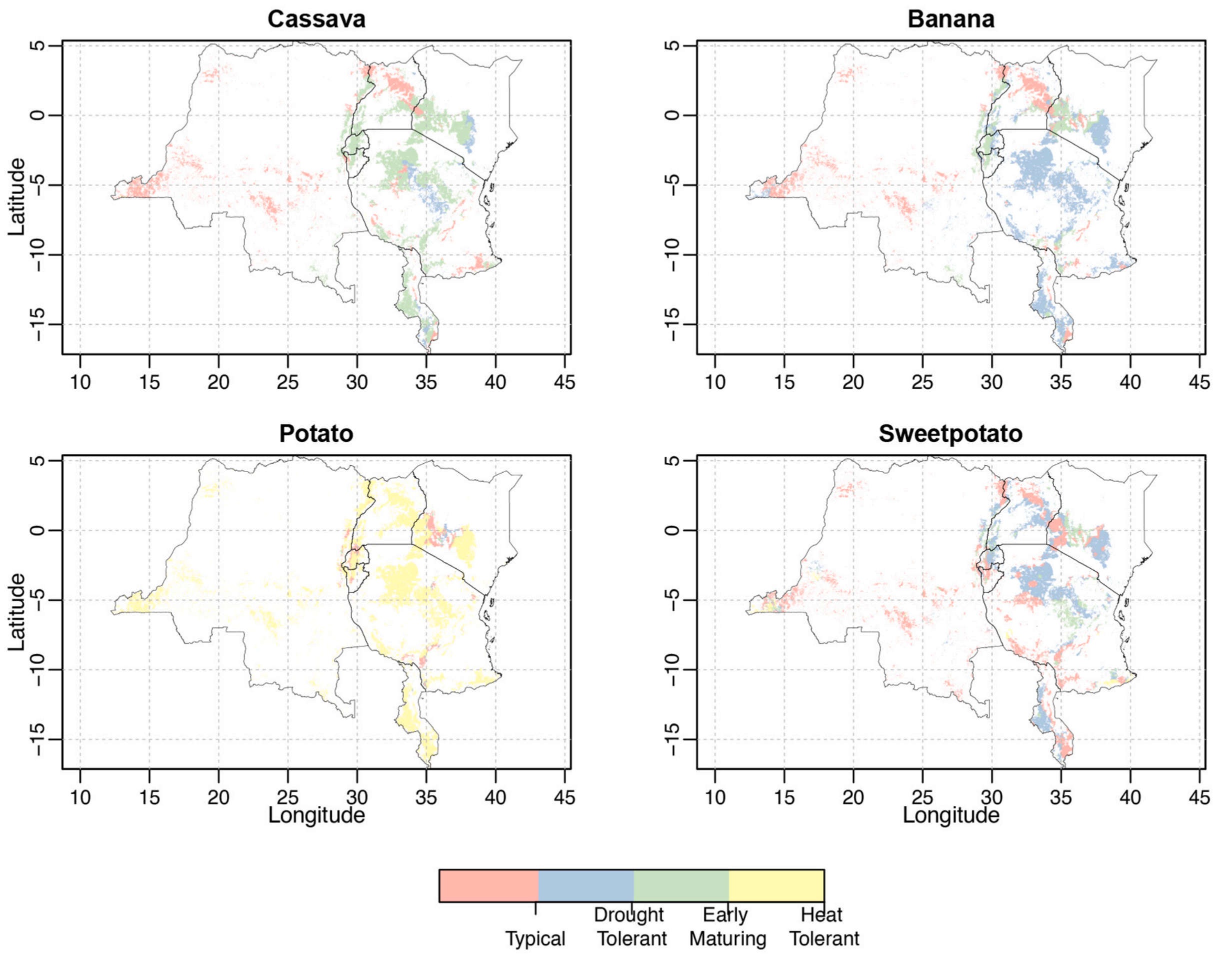

Fig. 5. Crop varieties with highest suitability values under future climates.

that areas suitable for its production would increase by mid-century. More recently, Varma and Bebber (2019) observed that African banana systems would be almost universally favoured by climate change. Although no direct comparison can be made between our results of environmental suitability and Varma and Bebber's, their projected increases in banana yield and the general directions of change in yield are consistent with the environmental suitability changes observed in this study and in Calberto et al. (2015). However, we warn that relying on a single global model to understand the climate sensitivity of banana productivity can result in considerable error (Varma and Bebber, 2019). Moreover, Rippke et al. (2016) observe that considerable adaptations (e.g. crop improvement and alterations to cropping calendars) may be required in banana systems to ensure continuity of productivity in certain areas of the GLR by mid-century. This reinforces the need for spatially disaggregated information to better understand changing dynamics of suitability. For an administrative aggregate, climate change may improve conditions, but pockets where conditions worsen will likely exist.

For potato, suitability will almost universally reduce across the GLR. These results are somewhat consistent with Raymundo et al. (2018) who found that future climates would inhibit potato production in Malawi, Tanzania, and Uganda, but would favour potato systems in Burundi and Rwanda, which runs contrary to our findings. These differences may be attributed to the inclusion of CO_2 fertilisation in their modelling, which has been found to offset temperature and precipitation-induced negative impacts on potato (Raymundo et al., 2014). Jennings et al. (2020) also report that potato yields in some pockets of the GLR could increase due to a combination of CO_2 fertilisation, variety selection, and planting shifts. We also note that changes in variety and planting shifts could address some negative impacts of climate change in the GLR.

Sweetpotato was found to be the most suitable RT&B crop to baseline climates across the GLR. Under future climates, suitability increased marginally with some small areas of decline. These results reinforce the adaptive quality of sweetpotato, which is cultivated across diverse environments in SSA, from the humid tropics to semi-arid regions (Low et al., 2020). These results also align with Manners and van Etten (2018), who concluded that sweetpotato is a nutrient dense crop, favoured by climate change in Central Africa.

It is good that the suitability of banana, cassava and sweetpotato will largely remain stable or improve in GLR, but it is important to note that an adaptation buffer has been built into the modelling framework. The model allows for changing planting dates and shifting the dates to the most ideal conditions. We found that planting dates would shift for most crops to some extent and, in many cases, quite dramatically (e.g. cassava in Rwanda), representing considerable alterations to traditional agricultural calendars. For future ideal planting dates, our results for potato were consistent for much of the GLR with those developed by Jennings et al. (2020). Unfortunately, similar analyses for banana, cassava, and sweetpotato were unavailable.

Planting shifts have been noted as a relatively 'low-hanging' adaptation strategy for farmers (inter alia Nouri et al., 2017; Turral et al., 2011). Nevertheless, farmers are often constrained by a lack of access to technology (Van Ittersum et al., 2016) and their adaptation potential is further hindered by a lack of information (Castells-Quintana et al., 2018). Extension infrastructure can address this information asymmetry, providing an information distribution channel to farmers (Tsan et al., 2019). Providing information on shifts in planting dates could become a technology-lite but information-heavy pathway to adaptation

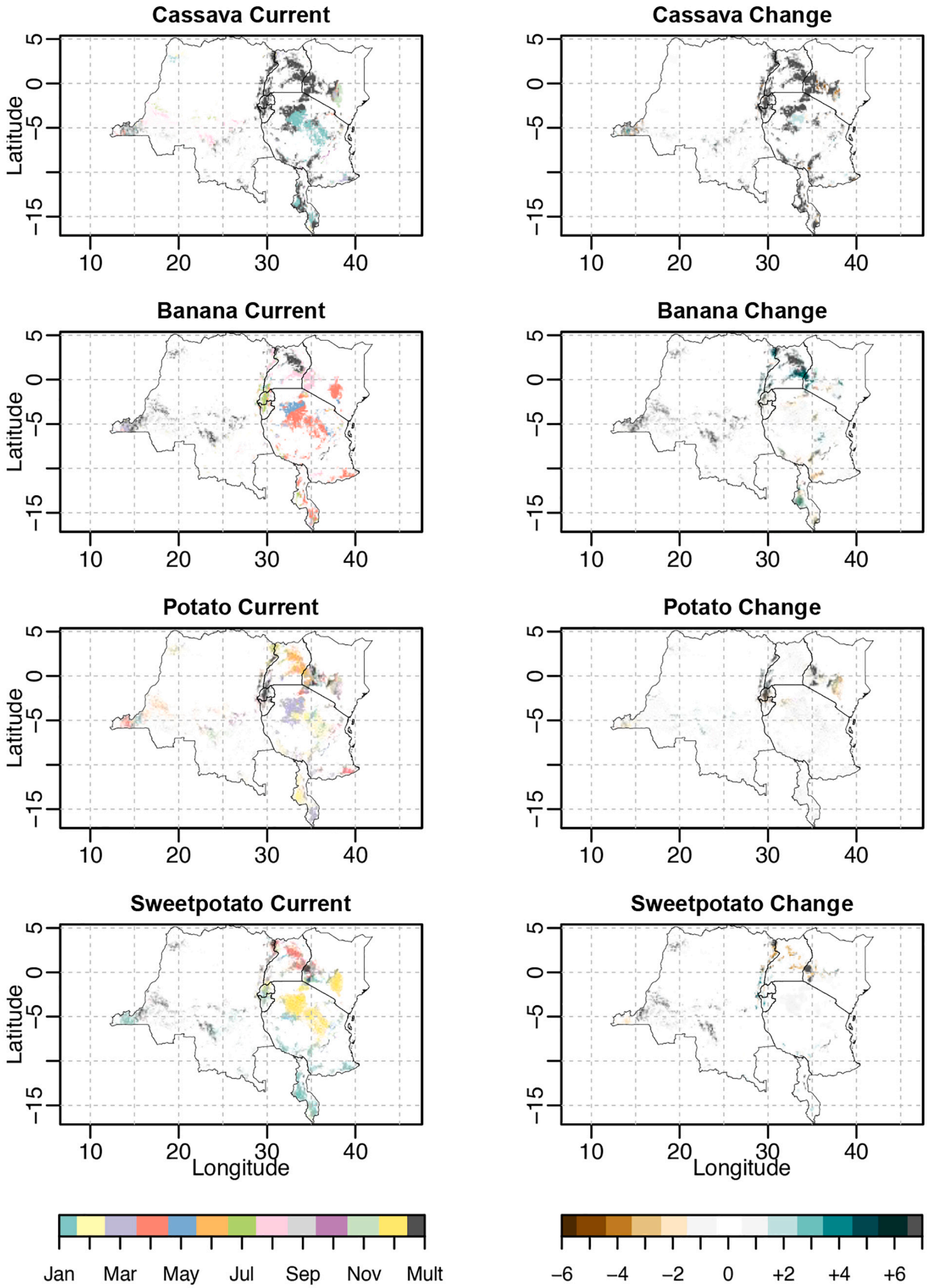

Fig. 6. Ideal planting month under baseline climates and changes in ideal planting months under future climates. Blank areas on the maps are areas that are either i) not agricultural lands; ii) agricultural lands with zero crop suitability; or iii) reflect no suitability change for a respective crop.

in SSA, using national agricultural research systems and private extension organisations as potential conduits of this information to farmers and other stakeholders. However, we still need a better understanding of farmers' capacity and willingness to adapt to new calendars to gauge the most effective modes and pathways of dissemination (e.g. Kilwinger et al., 2020). In spite of these concerns, calendar adaptation may be less disruptive than alternative adaptation strategies like crop-switching (Tessema et al., 2019). For these reasons, we suggest that more detailed investigation into planting-date shifts and about best channels for information sharing is needed.

The provision and targeting of improved or adapted cultivars could be a technology-based pathway to more adaptive RT&B farming systems. Bevan et al. (2017) and Rippke et al. (2016) both demonstrate how improved technology can stimulate productivity growth. Previous studies demonstrate that intraspecific crop diversity, coupled with locational and context-specific recommendations could ensure RT&B production stability under future climates (Heider et al., 2020; Pironon et al., 2019). The results from this study provide spatially explicit insights into how different crop variety types might be affected by climate change and how drought-tolerant, heat-tolerant, and early maturing varieties compare to typical varieties in terms of their suitability under future climates. Our analysis suggests that no 'silver-bullet' variety exists to alleviate negative impacts of future climates on crops across the GLR. This finding reminds us that blanket variety recommendations are not appropriate, even across small countries like Rwanda.

Recommendations for new RT&B varieties in SSA should be based upon a diverse suite of criteria (beyond climatic suitability) including palatability (Moyo et al., 2021), resistance to pests and diseases (Musana et al., 2013; Swennen et al., 2013), market potential (Lynam, 1996), yield (van Asten et al., 2011), and nutritional make- up (Whitfield et al., 2021). Breeding efforts will need to combine climate-smart variety traits with others valued by farmers and consumers. Insufficient priority given to consumer-preferred traits has previously contributed to limited uptake of newly-introduced RT&B varieties in SSA (Thiele et al., 2021). Novel participatory methods (e.g. van Etten et al., 2019) to measure variety preference across criteria and stakeholder groups are already being implemented to generate location-specific recommendations for RT&B crops in the GLR (Manners et al., forthcoming). Tailored and location-explicit recommendations for variety selection will be paramount to ensure stable production under future climates. In this way, our analysis can contribute to better understanding of where and how to target breeding investments or recommendations to improve RT&B crop suitability. Highly-resolved, spatially-explicit information is indispensable to improve the efficiency of research investments under the current reality of competing priorities and limited resources for RT&B crop research (Petsakos et al., 2019).

4.3. Limitations

We recognise that future precipitation and temperature seasonal patterns may further complicate climatic suitability of RT&B crops within the focal geographies of this study. We note that even if suitability of RT&B crops (other than potato) are, in general, not modelled to decline, it is highly likely that farmers will also face risks related to future inter- and intra-seasonal variation in precipitation (droughts/floods), increased frequency and intensity of heatwaves, and/or increases in pest and disease pressure (e.g. Okonya et al., 2019; Girvetz et al., 2019). There is consensus among climate models for future precipitation increases, but precipitation and weather patterns in general will likely become less predictable (IPCC, 2019, 2018; Kroschel et al., 2016). The impacts of this unpredictability may be worsened by increases in the severity and length of heat wave events and other climate extremes under future climates (Seneviratne et al., 2012). Musana et al. (2013) and Okonya et al. (2019) outline how future regional climates may be suitable to RT&B pest and diseases, potentially increasing the severity and incidences of outbreaks in the future. The interaction of the changes may increase the vulnerability of farming systems with severe consequences for regional or national food security. However, including seasonal variability and pests and diseases is beyond the current modelling framework applied. Although climate extremes may impact RT&B-based farming systems negatively, we note that RT&B crops have a number of traits that make them especially resilient to extreme stress and shocks, and may even contribute to post-disaster recovery (Prain and Naziri, 2020).

We also note that the effect of climatic variables, such as temperature and humidity on evapotranspiration (Allen et al., 1998), is not included in this model. Rather, our model considers crop-specific precipitation requirements and compares them with precipitation for each location. However, conditions such as higher temperatures and lower humidity lead to higher evapotranspiration and would change the amount of sufficient precipitation needed for a crop. Hence, the relatively small increases in precipitation projected for the region may be negated by increasing temperatures, which would increase evapotranspiration. Future improved versions of the model could compare actual precipitation with crop- and location-specific potential evapotranspiration instead of fixed crop-specific precipitation requirements. This adjustment would make computations considerably heavier but could improve the accuracy of crop suitability estimates as affected by spatial variation in climatic variables.

Detailed mechanistic crop growth models usually consider growing degree days instead of number of days to define the growth cycle duration (Ezui et al., 2018; Haverkort et al., 2015). This is another aspect that could be improved in future studies as it is largely accepted that growth duration is temperature sum-dependent instead of equivalent to a fixed number of days. The model used here could, in theory, consider a temperature sum-dependent growth duration (but that would also make the computations more complex).

4.4. Future directions

A future extension of this work would include contextualising the outputs of suitability analyses to guide local actions. The model implemented here provides general (though spatially explicit) insights into how crop suitability will be impacted under climate change. Despite previous attempts (Ramirez-Villegas et al., 2013), it remains difficult to directly relate suitability values with yield. Understanding how yields will change requires more advanced crop growth models and advanced parametrisation, which may not be available for use across RT&B crops (and varieties). While EcoCrop does not provide information on potential yield losses, it does provide outputs that make it possible to compare projected impacts across crops and locations, which can be informative for prioritisation and decision-making on targeting research investments (Thornton et al., 2018). For instance, the model outputs can help identify locations where investments for climate adaptation are most needed. Outputs can also be used to highlight where crop calendars will be most heavily affected and open the possibility for new cropping combinations and crop portfolios in RT&B farming systems. This information could be coupled with socio-economic factors to provide a detailed characterisation of potential climate-related impacts by combining factors that evidence the exposure of regions to climate change and the adaptive capacity of these regions to cope with the changes (IPCC, 2014). Therefore, a follow up study of this work will involve the development of a standardised approach for translating the outputs of the model into tangible and actionable recommendations on for targeting research and development investments towards climate-smart agriculture for RT&B crops in the GLR.

5. Conclusions

This study analysed the impacts of climate change on crop suitability of RT&B crops in the GLR of Africa. The study modified the EcoCrop suitability model to be more sensitive to longer-duration crops like some

RT&Bs and generated improved model outputs by validating environmental niche ranges for RT&B crops and crop variety types. Our model considered only the direct impacts of climate change on crop suitability, but not how climate change-driven alterations in extreme weather events or pest and diseases outbreaks will affect crops.

Application of the model revealed important ramifications of climate change for food security outlooks in the GLR by showing that suitability and planting calendars of important RT&B crops (and hypothetical variety genotypes) will undergo location-specific shifts. Our findings suggest that future rainfall and temperature shifts due to climate change will be somewhat favourable to RT&B-based systems in the region (with widespread negative impacts observed only for potato). Nevertheless, in most cases, RT&B crop suitability will remain constant or improve following shifts in planting calendars. Location and crop dependent shifts to different variety types also appeared to be effective in stabilising or improving suitability under future climates.

The data-driven insights generated from this work can be used as a first step in developing spatially explicit recommendations across distinct timeframes. These insights can help to facilitate farmers' decision making in the near future to mitigate impacts, while helping decision-makers who need to plan long-term for developing and implementing policy and investments needed to adapt RT&B-based livelihoods and systems.

Data availability

All outputs of this analysis can be requested from the authors and are available on the dashboard available here: http://www.rtbclimateportal.org/.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103246.

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