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Title page

Action needed for staple crops in the Andean-Amazon foothills because of climate change

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Action needed for staple crops in the Andean-Amazon foothills because of climate change

Abstract

The Andean-Amazon foothills region, shaped by Andean moist forests and Amazon forests in southwestern Colombia, Napo Province in Ecuador, and Ucayali Province and Napo Basin in Peru, provides local and global ecosystem services as food, water, world climate regulation, water purification, and carbon absorption. However, it faces major problems of land-use change that are exacerbated by climate change that affects these ecosystem services. For instance, conventional agriculture contribute to deforestation, soil degradation, and biodiversity loss, which might be further aggravated by climate change-induced droughts, thus reducing staple crop production and, consequently, food security. Cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.), and plantain (*Musa paradisiaca* L.) are major staple crops in the region. They play a key role for food security and local farmers' income but are highly exposed to climate risks. This article aims to quantify the level of exposure to climate change (measured as climatic suitability) of these crops in the Andean-Amazon foothills by using the EcoCrop model by the 2030s, 2050s, and 2080s under Representative Concentration Pathway 2.6, 4.5, and 8.5 scenarios. EcoCrop results showed that, whereas cassava will not lose climatic suitability, maize will lose more than half of its current suitable area and plantain will gain and lose area, which would affect local food security. Globally, these results are important in highlighting adaptive and cost-effective strategies in agriculture and suggest that agricultural crop diversification may improve resilience by promoting the use of local crops varieties.

Keywords

Exposure, cassava, maize, plantain, crop climatic suitability, EcoCrop

1. Introduction

The Andean-Amazon foothills (AAF) region, shaped by Andean moist forests and Amazon forests in the departments of Caquetá, Cauca, Nariño, and Putumayo in southwestern Colombia; Napo Province in Ecuador; and Ucayali Province and Napo Basin in Peru, has a vital role in world climate regulation and the provision of other ecosystem services such as water purification and carbon absorption. Also, people and indigenous communities living in the AAF directly depend on their resources to cover their necessities of water and food

(FAO, 2011). The AAF face major problems of land-use change that result in deforestation, soil degradation, and biodiversity loss (Armenteras et al. 2006; Dinerstein et al. 1995; Hernández and Naranjo 2007; Hoffmann et al. 2018; Miles et al. 2004) that are exacerbated by climate change (Laurance 1998; Nobre et al. 2016), thus negatively affecting food security (Beddington et al. 2012). For instance, conventional agriculture and cattle ranching contribute to reducing vegetation cover and increasing soil erosion (Smith et al. 2016), which might be further aggravated by climate change-induced droughts, thus affecting staple crop production and, consequently, food security.

The major staple crops in the AAF are cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.), and plantain (*Musa paradisiaca* L.). "*A staple crop dominates the major part of our diet and supplies a major proportion of our energy and nutrient needs. If staple crops are threatened by drought, pests or nutrient-poor soils, hunger and poverty can rise dramatically*" (FAO and IAEA, 2012). These crops play a key role in food security in the region, where they are central to the diet of local people and constitute a major source of income, particularly for smallholder farmers (Huamán Espino and Valladares 2006; ICBF and FAO 2015; Molina Recio et al. 2016; Ortiz et al. 2013). This is reflected in the fact that these crops occupy the first positions in cultivated area (for self-consumption and commercialization) and show high production rates. With regard to cultivated area, it was estimated that cassava, maize, and plantain encompassed (a) 9,195 ha, 9,000 ha, and 19,750 ha, respectively, in the AAF of Caquetá and Putumayo departments in Colombia in 2016 (Ministerio de Agricultura Colombia 2016a); (b) 5,700 ha, 19,600 ha, and 16,698 ha, respectively, in the Ecuadorian Amazon region in 2017 (INEC 2017); and (c) 54,500 ha, 86,800 ha, and 87,000 ha, respectively, in Amazonas, Loreto, Ucayali, and San Martín departments in Peru in 2012 (INEI 2012).

For crop production, the numbers estimated for 2016 were 71,500 tons of cassava, 10,000 tons of maize, and 120,000 tons of plantain, which represented 70% and 62% of the crop production in Caquetá and Putumayo departments, respectively (Ministerio de Agricultura Colombia 2016b). For the Amazon region in Ecuador in 2017, statistics showed 19,000 tons of cassava, 46,500 tons of maize, and 107,000 tons of plantain (INEC 2017). Finally, for the Peruvian AAF in 2011, the numbers were 53,697 tons of cassava, 92,256 tons of maize, and 87,041 tons of plantain, of which approximately 55% and 35% of the cassava and plantain production were for self-consumption (INEI 2012).

These major staple crops grow in alluvial zones significantly marked by the adverse effects of climate change and extreme events (Gratelly Silva 2011). In fact, flooding in Ucayali and Loreto (Peru) caused losses estimated at 2,450 ha of cassava, 820 ha of maize, and 2,980 ha of plantain from August 2018 to April 2019 (MINAGRI 2019). Climate model projections, under the Representative Concentration Pathway (RCP) scenarios, show that, in the Amazon, temperatures are projected to increase by approximately 0.6 °C and 2 °C under RCP 2.6 scenario and by 3.6 °C and 5.2 °C under RCP 8.5 scenario, and rainfall is projected to vary between +10% and –25% by the end of the 21st century (Magrin et al. 2014). As a result, river discharges are likely to increase, particularly for larger rivers draining from the Andes, which will cause flooding downstream in Peruvian floodplains and the Solimões River in the western and central Amazon. On the other hand, declines in river discharges are anticipated for the eastern basins, which will face increases in drought during dry seasons (Sorribas et al. 2016). These hydrological changes and increases in temperature might affect crop production due to crop physiological alterations, including shorter crop duration, usually associated with lower yields, declines in photosynthesis rate, plant damage, and increased pest and disease incidence (Lobell and Gourdji 2012).

In the case of cassava, although considered a robust crop that grows under diverse environments in areas with annual rainfall ranging from less than 500 mm to more than 3,000 mm, its growth is affected by high temperatures, inadequate soil drainage, and pests such as mite species. The most significant negative impact of climate change could be a decrease in root dry matter content, which is crucial for cassava consumption and commercialization (Ceballos et al. 2011, CIAT 2002). For maize, higher projected temperatures could have a critical negative impact on its crop production because higher temperatures lead to reductions in the crop life cycle, light interception, growing season, grain-filling period, and fertility (Tripathi et al. 2016). Similarly, high temperatures and water scarcity would negatively affect plantain production by reducing the rates of photosynthesis and leaf and bunch emergence (Ramirez-Villegas et al. 2011a). Consequently, these crops have a high risk of exposure to climate change, where exposure is defined by the IPCC

(Intergovernmental Panel on Climate Change) as "the presence of people’s livelihoods, environmental services, infrastructure, or socioeconomic or cultural assets in places that could be adversely affected by physical events" (Lavell et al. 2012).

To date, some studies have evaluated the exposure of cassava, maize, and plantain to climate change by modeling current and future climatic suitability. However, most of these studies have been conducted globally (Ceballos et al. 2011; Müller and Robertson 2014; Teixeira et al. 2013) or for the African continent (Adams et al. 2018; Ramirez-Villegas and Thornton 2015; Rippke et al. 2016; Tesfaye et al. 2015). For example, future scenarios project a loss of climatic suitability areas for maize in Sub-Saharan Africa, but an expansion in Europe (Ramirez-Cabral et al. 2017). In the case of South America, studies that evaluate the exposure of these staple crops to climate change are limited. For instance, one regional study modeled the changes in climatic suitability of these crops, among other important economic crops for the Andean region of Colombia, Ecuador, and Peru (CIAT 2014), but no known studies report a similar analysis for the AAF. This region is valuable because it provides local ecosystem services such as food, water, pollination, and pest control and global ecosystem services such as world climate regulation, water purification, and carbon absorption (FAO, 2011). Also, the AAF are important because of their natural diversity and cultural diversity as they are home to indigenous communities, "colonos," and "mestizos." Anticipating how projected climatic conditions could affect these staple crops’ climatic suitability and spatial distribution would be valuable to informing community-based climate change adaptation strategies for protecting local food security, the local economy, and the local and global ecosystem services provided by the AAF. Therefore, the objective of this study is to quantify the level of exposure to climate change of cassava, maize, and plantain in the AAF by using the EcoCrop model (Ramirez-Villegas et al. 2011b), thus laying the groundwork for future climate vulnerability studies.

2. Methods

2.1. Study area

The AAF, called Napo moist forest global ecoregion, are one of the richest biodiversity hotspots on the planet (Dinerstein et al., 2017). They comprise two ecoregions: the Napo moist forest ecoregion and the Ucayali moist forest ecoregion. The former includes the northwestern area of Peru, the Amazon district of Ecuador, and the southwestern border of the Colombian Amazon. It is delimited by the Andean foothills to the west, the Napo River in Peru to the east, the Caguán area in Colombia to the north, and the Marañón River in Peru to the south. Its altitude ranges from 100 m in the east to 400 m in the west. Mean annual temperature is 26 °C and precipitation is 2,500 to 3,000 mm in the east and 4,000 mm in the west. The Ucayali moist forest ecoregion is located in Peru, and it extends from the Andean foothills in the west to the Ucayali River in the east. It encompasses premontane moist forests at high elevations in the west and wet lowland rainforest in the east. Altitude ranges from 200 to 1,000 m and annual precipitation from 1,600 to 2,500 mm (Dinerstein et al., 2017).

The AAF have an extensive climatic and ecosystemic variability, including the eastern side of the Andean Range foothills, where a wide range of temperatures and different environmental conditions can be found (CEPAL and Patrimonio Natural 2013). The main productive activities in the region are small-scale and commercial agriculture, including the cultivation of staple and cash crops. The most common crops for local consumption are cassava, maize, plantain, beans, and rice, with the first three being the most important in terms of daily consumption, caloric intake, and cultivated area. Other important economic activities for locals are livestock and fishing (ICBF and FAO 2015; INEI 2012; Peña-Venegas et al. 2016).

2.2. Present-day climate data construction

Crop modeling of spatial niches requires, as a first step, characterizing the current climate for the study area. Accordingly, a monthly climatology (30-year average) through spatial interpolation and records of weather stations from 1981 to 2010 was developed. Subsequently, a set of monthly surfaces at a spatial resolution of 2.5 arc-min (~5-km) for accumulated precipitation and minimum and maximum temperature was generated. The method described by Hijmans et al. (2005) was followed, using data from the national meteorological services of Colombia (IDEAM), Peru (SENAMHI), Brazil (INMET), and Ecuador (INAMHI)[1] and data from global weather station networks, including the Global Historical Climatological Network (GHCN) (Menne et

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[1] Institute of Hydrology, Meteorology and Environmental Studies (IDEAM)-Colombia; National Meteorology and Hydrology Service of Peru (SENAMHI); National Institute of Meteorology (INMET)-Brazil; National Institute of Meteorology and Hydrology (INAMHI)-Ecuador.

al. 2012) and Global Surface Summary of the Day (GSOD) (NCDC 2011). This method interpolates these data using the thin-plate smoothing spline algorithm (Hutchinson and de Hoog, 1985) and performs a second-order interpolation with ANUSPLIN software version 4.3. The interpolation uses latitude, longitude, and elevation (CGIAR SRTM elevation model) (Jarvis et al. 2008) as co-variables.

The pre-processing stage included all the weather information and involved unifying formats (as each institution stores data differently), detecting outliers (e.g., values greater than the third quartile plus 5 times interquartile range), identifying and removing duplicate records, and identifying and filling in missing data. Data gap filling was based on a lineal regression model generated with data from CHIRPS[2] for rainfall (Funk et al. 2015) and data from AgMERRA[3] for temperature (Ruane et al. 2015).

Figure 1 shows the spatial distribution of available stations by climatic variable and Table 1 summarizes the number of stations selected for this study, by source. Because of the low density of weather stations in some areas, pseudo-stations for these areas were created using the information provided for those points by AgMERRA for temperature and CHIRPS for precipitation. The points within these areas were selected randomly based on the inverse of the density of the present stations.

[Fig. 1 near here]

[Table 1 near here]

2.3. Construction of future climate scenarios

Future climate scenarios at high spatial resolution are necessary to investigate the risk posed by projected climate change to local agricultural conditions and to inform climate change adaptation decisions. However, the current Global Circulation Models (GCMs) are not suitable to project impacts at subnational scales. GCMs can only model Earth processes in coarse grid cells, which are unsuitable for local agricultural studies (Baron et al. 2005; Challinor et al. 2009). Therefore, a statistical downscaling process was performed, based on the sum of the anomalies of GCMs, on the high-resolution baseline surfaces at monthly scale to overcome

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[2] Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS).

[3] Agriculture Modern-Era Retrospective Analysis for Research and Applications (AgMERRA).

this limitation. This method is called the *delta method* (Ramirez-Villegas and Jarvis 2010). The delta is the ratio between GCM simulations of future scenarios and current climate (anomalies) and is used as a multiplicative factor to obtain future regional scenarios. The anomalies are interpolated between cell centroids and then applied to a baseline climate given by a high-resolution surface. Downscaling of climate data produces data that allow simulating local climate change projections and investigating their likely impacts.

Sixteen GCMs were downscaled (Table 2). GCMs were available for three RCPs, RCP 2.6 (optimistic), RCP 4.5 (intermediate), and RCP 8.5 (pessimistic), and three 30-year future periods, 2020–2049 (2030s), 2040–2069 (2050s), and 2070–2099 (2080s). These GCMs belong to CMIP5[4] (IPCC 2013; Taylor et al. 2012) and were also used in Colombia's Third National Communication on climate change (IDEAM et al. 2015). The GCM outputs from the Earth System Grid Federation (ESGF) Peer-to-Peer (P2P) enterprise system were downloaded. The full range of models for the crop niche modeling was used and the ensemble mean (multi-model average) of the downscaled outputs by RCP and period was calculated to describe the average projected future climate conditions in the AAF. The three mentioned variables **(**accumulated precipitation and minimum and maximum temperature**)** of present-day climate and the same resolution (5-km) were used.

[Table 2 near here]

2.4. Current and plausible future impacts of climate change on the target staple crops

2.4.1. The EcoCrop model

Current and future exposure to climate change of cassava, maize, and plantain were evaluated using the EcoCrop model developed by Hijmans et al. (2001) and calibration and evaluation procedures further developed by Ramirez-Villegas et al. (2011b) were applied. EcoCrop is a simple but robust agroecological zonification model that calculates the potential suitable niche of a crop in a particular area, based on crop marginal and optimum climate parameters (temperature and rainfall) (Ramirez-Villegas et al. 2011b). EcoCrop works for rainfed systems and it has been widely used in different studies to evaluate future climatic impacts on crops (Eitzinger et al. 2014; Hunter and Crespo 2019; Jarvis et al. 2012; Semwal et al. 2016). EcoCrop calculates the probability of current and future climatic suitability (on a 0 to 100 scale) based on

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[4] Coupled Model Intercomparison Project Phase 5 (CMIP5)

temperature and rainfall independently as well as an overall probability given by the product of both temperature and precipitation probabilities. Future probability is the average of the EcoCrop runs over each of the 16 GCMs by scenario and period (equations and further details are outlined in Ramirez-Villegas et al. 2011a).

The parameters used by EcoCrop are the following:

- Growing season length (GS)
- Killing temperature (Ktmp)
- Minimum and maximum absolute temperature (Tmin and Tmax)
- Minimum and maximum optimum temperature (Topmin and Topmax)
- Minimum and maximum absolute rainfall (Rmin and Rmax)
- Minimum and maximum optimum rainfall (Ropmin and Ropmax)

Agro-climatic parameters for each of the three crops were defined based on available studies (see Table 3). EcoCrop was run for current climatic conditions, adjusting in some cases the parameters and securing a good representation of the current suitable areas according to the crop evidence data collected from the study area (Eitzinger et al. 2014; GBIF.org 2017; Ramankutty et al. 2008).

[Table 3 near here]

2.4.2. Change in crop climatic suitability

The overall climatic suitability change (OSC) was estimated by the difference between future and current probabilities for the AAF, and compared across climate change scenarios and time periods using analysis of variance (ANOVA) (Wobbrock et al. 2011). As the data were non-parametric, previous to the ANOVA, an Aligned Rank Transformation (ART) for non-parametric factorial data analysis was performed in ARTool version 0.10.4, in R-studio (RStudio Team 2015). ART is recommended for non-parametric data to compare multiple factors. Also, the ratio of positively to negatively impacted areas (PIA/NIA), which is the ratio of gained suitable areas to lost suitable areas for each crop and region (Napo and Ucayali), was estimated.

2.4.3. Uncertainty analysis

A “cascade” of uncertainties exists in producing crop suitability projections. This cascade ranges from the uncertainty in future greenhouse gas emissions through a range of GCM responses to given emissions (Hawkins et al. 2012). First, the associate uncertainty related to future climate was evaluated by calculating the standard deviation (SD) of annual mean temperature and total precipitation projections, considering the spread of RCPs and GCMs (over RCP 8.5, for which it is possible to see greater differences) at mid-century (2050s). Second, the uncertainty related to crop modeling was evaluated calculating the spread of the suitability areas modeled with EcoCrop (in terms of SD), considering the runs over all RCPs and GCMs (over RCP 8.5) at mid-century (2050s).

3. Results and discussion

3.1. Present-day climate in the AAF

Analysis reveals a strong spatial climate heterogeneity in the AAF. The developed climatic baseline shows a wide range of rainfall values, from 100 to 3,500 mm/quarter (Fig. 2). The highest rainfall is present in the lowlands, with values above 3,000 mm/year as reported in previous studies (Emck 2007; Espinoza-Villar et al. 2009; Laraque et al. 2007), and the lowest values are observed at higher elevations. Precipitation over the eastern slope of the Andes is extremely high due to flows of moist air coming from the Amazon basin (Garreaud 2009) as well as orographic rainfall and permanent drizzles from orographic clouds. Precipitation in the AAF decreases with altitude toward the tropics, reaching less than 1,500 mm/year in the Peruvian plains. It is clear that the highest and lowest annual rainfall values in the Amazon are registered within the AAF (Espinoza-Villar et al. 2009).

This climatic baseline shows a significant contrast in terms of precipitation between the northern (Colombia and Ecuador) and southern regions (Peru and Brazil) of the AAF, mainly during the DJF (December-January-February) and JJA (June-July-August) quarters (Fig. 2). For example, during JJA, rainfall in the Ucayali region remains below 500 mm, while in Napo it typically surpasses 800 mm. Moreover, bimodal and unimodal regimes of precipitation are present in the same area (Fig.2). For instance, a northern bimodal regime contrasts with a southern long dry season from June to September in the Peruvian Amazon.

[Fig. 2 near here]

Temperature in the AAF region shows homogeneity (Fig. 2). Some spatial fluctuations in temperature, however, are directly related to elevation, with the lowland plain zones having relatively higher values. In fact, the lowland plains exhibit values above 20/25 °C (minimum/maximum temperature) and can reach 35 °C in the lowest areas of the AAF, as previously reported in Lavado et al. (2012). In the highest areas, the temperature is about 25 °C. Moreover, seasonality is low. For example, the minimum and maximum temperature variations throughout the year are very low for the flatter zones (below 3 °C). In the foothills, the amplitude of the variations is higher, reaching 5 °C, but still having low seasonality.

The complexity of the AAF climate marks the need to consider comprehensive, highly reliable climate data. High-resolution and up-to-date climate-interpolated surfaces were developed from a wider collection of weather stations in comparison with previous studies in the Amazon (Espinoza-Villar et al. 2009; Prüssmann et al. 2016). Figure S1 shows the performance of an interpolation algorithm through cross-validation. Accumulated precipitation for the modeled and observed data shows a coefficient of determination (R^2) above 0.5 (red dotted line) in all months and above 0.75 (red solid line) in the drier months (May-September). The RMSE (root mean square error) remains under 75 mm. The R^2 coefficient across the months is higher for minimum temperature (>0.7) and the RMSE remains below 0.6 °C at the maximum and below 0.4 °C at the minimum temperature.

3.2. Climate projections in the AAF

Seasonal accumulated precipitation is projected to increase (compared with the present-day climate 1981–2010) toward the northwestern and western regions in the AAF, especially in the DJF and JJA quarters and for all RCP scenarios (with a remarkable increase over RCP 8.5) and periods. This increase is concentrated in the wet season. For eastern zones, rainfall would tend to decrease, particularly in the JJA and SON quarters (Fig. S2). Similar patterns of change are projected in other studies (Case 2006; Christensen et al. 2013; Gloor et al. 2015; Marengo et al. 2016; Sorribas et al. 2016), but here higher regional detail is provided.

The average changes in precipitation fluctuate between –22% and +40% and this trend of change is the same throughout all climate scenarios but with higher contrast (positive/negative) in the most pessimistic scenario in terms of emissions (i.e., RCP 8.5) and changes exceeding 40% after the 2050s (Fig. S2) in some zones and seasons in Colombia and Peru. There are also differences between the low- and high-emissions scenarios (Table 4). According to the downscaled global model projections, annual precipitation could increase by 136/349 mm by the 2030s/2080s, respectively, in the Napo region, and by 182/330 mm in the 2030s/2080s in Ucayali (Table 4). At the end of the 21st century, precipitation increases significantly in the wettest months, up to 120/73 mm in Napo/Ucayali, respectively.

[Table 4 near here]

According to the projections, the mean temperature could rise by 2.2 °C for the Napo region and by 2.3 °C for the Ucayali region by mid-century for the RCP 8.5 scenario (Table 4), and could increase up to ~4 °C in both regions by the 2080s. Similar values are found in other studies for the western Amazon (Christensen et al. 2007; Llopart et al. 2014). The projections also show higher increases for maximum temperature than for minimum temperature (Figs. S3–S4). Toward the 2080s, for example, the annual minimum temperature rises by 4.1/4.2 °C in Napo/Ucayali, while the annual maximum temperature increases by 4.3/4.5 °C in Napo/Ucayali under the RCP 8.5 scenario (Table 4). This discrepancy in which the maximum temperature increases at a higher rate than the minimum temperature in most of the climate change scenarios and seasons suggests higher degree days across the year and, as a consequence, higher evapotranspiration rates.

Warmer temperatures and lower precipitation, especially during the driest months, could indicate more severe droughts and marked changes in seasonality. These changes could have devastating impacts, including increased erosion, degradation of freshwater systems, loss of ecologically and agriculturally valuable soils, loss of biodiversity, decreased agricultural yields, increased insect infestation, spread of infectious diseases, environmental stress, and collapse of the Amazon forest biome (Case 2006; Marengo et al. 2016).

3.3. Current and plausible future impacts of climate change on staple crops

Spatial analyses showed that, for current climate conditions, cassava plantations have a high percentage (97%) of climatic suitability in the ecoregion, based on temperature and precipitation parameters, but their growth diminishes toward the Andes (70%), where altitude increases (Fig. 3). Maize plantations grow with more limitations toward the south of the AAF (60%). As well as cassava, plantain systems grow with more constraints toward the Andes in the north of the AAF (Fig.3).

[Fig. 3 near here]

The results of the cassava EcoCrop model (Fig. 3) agree with previous global models using EcoCrop, which show that the AAF is suitable in terms of climatic variables for the crop’s growth (Ceballos et al. 2011). In contrast with previous studies executed in CLIMEX, the maize EcoCrop model showed adequate climatic suitability for the north area of Peru (Fig. 3). Modeling in CLIMEX was performed at a global scale, which could explain the differences with the results with EcoCrop (Ramirez-Cabral et al. 2017). Plantain showed a low climatic suitability in the north area of the AAF in comparison with previous crop modeling exercises using EcoCrop, also at a global scale (Ramirez-Villegas et al. 2011a).

The spatial analyses of cassava show that, for optimistic and intermediate climate change scenarios in the 2080s, very few areas would lose up to 30% of their climatic suitability (orange areas), and most areas would remain invariable (yellow areas) (Fig. 4). For intermediate and pessimistic scenarios, the spatial analyses reveal that some areas would gain up to 30% in suitability in the 2080s, but a considerable area might lose up to 30% in suitability for the pessimistic scenario in the 2080s (Figs. 4 and 5). These results coincide with cassava plasticity and capability of growing in a wide range of conditions, from semiarid zones to rainy areas with 500 to 3,000 mm of annual precipitation, respectively. These qualities make cassava a crop with a high potential for adaptation to climate change, especially in the foothills, where soils are more fertile than in the plains; however, nowadays in Colombia, foothills are mainly used more for cattle ranching than for crop production (SINCHI 2016). Existent cassava global adaptation models agree that cassava is a crop that will be adapted in the tropics, subtropics, and highlands in the Andes in the face of climate change (Ceballos et al. 2011; Fernandes et al. 2017).

The spatial analyses for maize reveal that, for the optimistic scenario toward the 2080s, half of Napo and Ucayali will lose up to 30% of their climatic suitability, and a small area toward the Andes will gain less than 30% in it. Also, although there is a gain in climatic suitability for a few areas in Napo and Ucayali (green areas), most areas will lose up to 30% for the intermediate scenario and other areas will lose more than 30% for the intermediate and pessimistic scenario in the 2080s (Figs. 4 and 5). These results suggest that maize is highly exposed to the climate change projected for the ecoregion, and this may be exacerbated as the crop is susceptible to drought in the eastern zones, where precipitation is projected to decline. Figures S5-S6 show that both temperature and precipitation are limiting factors for growing maize in areas of low suitability (Fig. 4). The results are in line with previous analyses in CLIMEX that predicted a decrease of 43% in maize climatic suitability for South America in 2100 and with other spatial analyses in EcoCrop that suggested a decrease of more than 50% in climatic suitability of maize under the pessimistic climate change scenario in the 2080s (Ramirez-Cabral et al. 2017).

The spatial analyses for plantain illustrate that a considerable area in the north of the AAF could gain up to 30% in climatic suitability (green areas), while a similar area might lose this amount (orange areas) under the optimistic and intermediate climate change scenarios toward the 2080s (Fig. 4). On the other hand, most of the ecoregion will lose suitability under the pessimistic scenario in the 2080s (Fig. 5). These losses in suitability are due to predicted increases in precipitation and temperature, as plantain is susceptible to saturated soils. The major constraint for plantain seems to be temperature (Figs. S5 and S6). These results coincide with plantain global models that predict that the Amazon region and most parts of Peru will be some of the zones negatively affected by losses in suitability (Ramirez-Villegas et al. 2011a). These models also predict a reduction in climatic suitability in lowlands and increasing suitability in highlands, which explain areas of suitability gain (green areas) toward the Andean mountains in the west (Figs. 4 and 5).

[Fig. 4 near here]

[Fig. 5 near here]

3.3.1. Change in climatic suitability

ANOVA results support spatial analyses by showing significant differences in the overall climatic suitability change (OSC) of the three crops across climate change scenarios, periods, and regions (Table 5). During the three time periods, cassava will tend to gain suitable climatic areas (except for the pessimistic scenario), maize will tend to lose them, and plantain will tend to gain as well as lose them (Figs. 4 and 5). The Ucayali region seems to lose more suitable areas for maize than Napo and gain more suitable areas for cassava and plantain (Fig. 5). The ratio of positively to negatively impacted areas (PIA/NIA) also agrees with the spatial analyses (Fig. 5).

3.3.2. Uncertainties

Uncertainties for downscaled future climate showed a SD for the projected values ranging from 0 to 15% and from 1.5 to 3.0 °C in rainfall and temperature across GCMs, respectively, and below 5% and 1 °C across RCPs, respectively, which suggests that the projections are acceptable (Fig. 6). There is a higher discrepancy for the GCM spread than for the RCPs. However, despite the greenhouse gas concentrations being similar for all RCPs in the 2030s or 2050s, after mid-century, the differences among scenarios are more pronounced and the uncertainty is higher. The same happened when more distant periods in time were considered. Spatially, rainfall data showed more confidence in the eastern plains than in the mountains, contrary to data for temperature. Finally, the uncertainty related to the suitability results remains very low (SD <5%, with few exceptions) for both GCMs and RCPs. For maize and plantain, the confidence in the suitability projections is lesser than for cassava, but acceptable (SD <20%, with few exceptions).

[Fig. 6 near here]

3.4. Implications for the AAF

EcoCrop results based on temperature and rainfall parameters showed that, whereas cassava will not lose climatic suitability in the AAF with future climate change, maize will lose more than half of its area and plantain will gain area in Napo and lose area in Ucayali. The results of this study have major implications for food security of the AAF as cassava, maize, and plantain are consumed on a daily basis and are main sources of energy for indigenous people, "mestizos," and "colonos" (Peña-Venegas et al. 2016). Regarding cassava, it has a great potential to continue providing food and income to local communities in the AAF in the face of climate change as it is biologically adaptable to stressful climatic conditions projected into the future. By contrast, the effects of climate change will be unfavorable to maize and plantain production, which may intensify food insecurity in the AAF. Therefore, local communities in the AAF may need to cultivate adapted varieties of maize and plantain in the future under climate change that could be represented by local varieties (see below: EcoCrop and farmers' adaptation strategies).

The effects of climate change on maize and plantain crops may be detrimental in the Peruvian Amazon, given that one-third of the population living here was categorized as medium to seriously food insecure (Ortiz et al. 2013). In fact, Amazonas, Loreto, and Ucayali departments occupy the second (8.2%), third (7.3%), and fourth (6.6%) places in percentage of malnutrition in Peru (INEI 2014). Likewise, the departments located in Ecuador's Amazon Province have the highest number of food-insecure households in relation to provinces in Costa and Sierra regions (Calero 2011). Furthermore, Amazonas Department in Colombia also faces food insecurity, being second with higher amounts of chronic malnutrition in infants under five years (MinSalud Colombia et al. 2014). Also, major percentages of indigenous communities are more dependent on external markets, thus being more vulnerable to losing food self-sufficiency (Ortiz et al. 2013). Therefore, these food insecurity conditions that face the region might be intensified if the climatic suitability for daily-consumed crops such as maize and plantain diminishes (Fig. 4).

Instead, results showed that cassava seems to respond well to the projected climate and could be an option to adapt to future climate scenarios not only in the AAF, but in Africa; where it is also considered a staple crop and where increases in temperature from 1.2 to 2.0 ºC and a variation in rainfall from –39 to 64 mm/year are being projected (Jarvis et al. 2012; Hunter and Crespo 2019). This is the first study that models climatic suitability for cassava in the AAF, which is remarkable not only because it is a staple crop, important in the diet of locals, but is also the food base of the indigenous people of the Amazon, and is used as a ritual element of cultural and commercial exchange. In fact, the center of origin of cassava is the western Amazon and at least 39 varieties of cassava, cultivated by native communities, have been reported (Arias et al. 2005).

3.5. EcoCrop and farmers’ adaptation strategies

The EcoCrop model has many advantages as it is a simple but robust niche-based model, it is reasonably easy to parameterize, and it generates predictions that are comparable with those of more complex models (Ramirez-Villegas and Thornton 2015). However, as every model, EcoCrop has some constraints as it does not include information on soil data and crop management nor does it incorporate crop stress periods (Eitzinger et al. 2013). In spite of the disadvantages, many crops have been modeled using EcoCrop such as rice, bean, guava, mango, orange, tomato, and coffee, among others, because it is a robust model that can be used to predict climatic suitability when no prior knowledge or data are available (Jarvis et al. 2012).

Nevertheless, studies that have used EcoCrop have focused on common varieties, although several varieties identified by local farmers have the potential to adapt well in extreme climatic conditions and would be worth being modeled. For example, farmers from Caquetá Department in Colombia and Yurimaguas in Peru have reported varieties of maize and plantain that adapt well to drought and extreme rainfall (Beltrán et al. 2019; Vicaría Sur 2018). For plantain, they named *“pelipita,” “píldoro,”* and *“popocho”* in Caquetá, and *“manzano,” “sapino,”* and *“felipino”* in Yurimaguas. Farmers referred to them as varieties tolerant of high temperature, flooding, and pests, as well as being highly nutritious (Campanera Reig 2010; Sherman et al. 2016). For maize, farmers mentioned *“maiz shishaco”* and *“canchita”* in Yurimaguas, with these currently being less cultivated because of the introduction of improved varieties such as Marginal 28 (Beltrán et al. 2019).

These non-commercial varieties, cultivated on local farms for family consumption, could have great potential to offset the effects of climate change and help to avoid food insecurity in times of climatic crises. It has been reported that maintaining local diversity of crops provides benefits such as adaptation to specific agroecological conditions and risks (Di Falco and Chavas 2009). Crop varieties respond differently to (and might withstand) various climatic hazards; thus, diversification reduces the effects of extreme climate events (Altieri et al. 2015). In fact, the IPCC has among its recommendations of mitigation and adaptation to climate change, the incorporation of diverse crop varieties and the transformation of monocultures to crop diversification (Mbow et al 2019). Local varieties are the result of farmer selection for adaptation to specific environments; they are considered environmentally friendly as they are usually grown with very few capital inputs such as fertilizer, pesticide, or irrigation (Cavatassi et al 2011). Therefore, it is important to promote the rescue and cultivation of local varieties as an adaptation strategy to climate change and to raise resilience into agricultural systems. It is worthwhile to learn the current and future climatic suitability of different crop varieties, not only in the AAF, but in different regions of the world, and assess their potential to adapt to extreme climatic conditions and incorporate them in national plans for adaptation to climate change.

4. Conclusions

This study assesses the effects of climate change on three staple crops in the AAF. Results show that future climatic projections will not affect cassava climatic suitability, but maize will lose more than half of its suitable climatic area and plantain will gain, in Napo ecoregion, and will lose, in Ucayali ecoregion, suitable climatic area. In conclusion, these findings for maize and plantain might have negative implications for local food security and household income for smallholder farmers. Instead, cassava plasticity and the capability of growing in a wide range of conditions might represent one of the crucial crops in building resilient agricultural systems.

Globally, these results are important in highlighting adaptive and cost-effective strategies in agriculture and suggest that agricultural crop diversification may improve resilience by promoting the use of local crops varieties. Governments, therefore, should promote crop diversification in national plans for adaptation to climate change to improve food security and provided economic benefits to smallholder farmers.

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Table 1. Sources of available weather station information in the study zone

Source	**Institution**	**Number of Stations**		
		Precipitation	**Maximum Temperature**	**Minimum Temperature**
Global Summary of the Day (GSOD)	National Climatic Data Center (NCDC)	20	46	46
Global Historical Climatological Network (GHCN)	National Climatic Data Center (NCDC)	191	33	38
IDEAM (Colombia)	Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM)	782	198	203
INAMHI (Ecuador)	Servicio Meteorológico e Hidrológico Nacional del Ecuador	323	116	115

	(INAMHI)			
SENAMHI (Peru)	Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI)	54	7	8
INMET (Brazil)	Instituto Nacional de Meteorología (INMET)	6	6	6
AgMERRA (climate forcing dataset)	Goddard Institute for Space Studies (NASA)	NA	115	112
CHIRPS (satellite product)	Climate Hazards Group (CHG)	263	NA	NA
Total	--	1,639	521	528

Table 2. GCMs available for the three Representative Concentration Pathways, RCP 2.6 (optimistic), RCP 4.5 (intermediate), and RCP 8.5 (pesimistic), and three 30-year future periods, 2020–2049 (2030s), 2040–2069 (2050s), and 2070–2099 (2080s)

Model	**Country**	**Institute**	**References**
BCC-CSM1.1 **BCC-CSM1.1(m)**	China	Beijing Climate Center, China Meteorological Administration	Wu (2012) Xin et al. (2012, 2013)
CSIRO-Mk3.6.0	Australia	Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organisation	Rotstayn et al. (2012)
CESM1-CAM5	United States	National Science Foundation, Department of Energy, National Center for Atmospheric Research	Hurrell et al. (2013)
FIO-ESM	China	The First Institute of Oceanography, State Oceanic Administration	Qiao et al. (2013)
GFDL-CM3	United States	NOAA Geophysical Fluid Dynamics Laboratory	Delworth et al. (2006) Donner et al. (2011)
GISS-E2R	United States	NASA Goddard Institute for Space Studies	Schmidt et al. (2006, 2014)
IPSL-CM5A-LR	France	Institut Pierre Simon Laplace	Dufresne et al. (2013)
MIROC-ESM **MIROC-ESM-CHEM**	Japan	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Watanabe et al. (2011)
MIROC-MIROC5	Japan	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Watanabe et al. (2010)
MOHC-HadGEM2-ES	United Kingdom	UK Met Office Hadley Centre	Collins et al. (2011) Martin et al. (2011)
MRI-CGCM3	Japan	Meteorological Research Institute	Yukimoto et al. (2011, 2012)
NCAR-CCSM4	United States	US National Center for Atmospheric Research	Gent et al. (2011)
NCC-NorESM1-M	Norway	Norwegian Climate Centre	Bentsen et al. (2013) Iversen et al. (2013)
NIMR-HADGEM2-AO	Korea	National Institute of Meteorological Research and Korea Meteorological Administration	Collins et al. (2011) Martin et al. (2011)

Table 3. Selected agro-climatic parameters set for calculating suitability

Crop	**Scientific Name**	**GS (days)**	**K_{tmp} (°C)**	**T_{min} (°C)**	**T_{opmin} (°C)**	**T_{opmax} (°C)**	**T_{max} (mm)**	**R_{min} (mm)**	**R_{opmin} (mm)**	**R_{opmax} (mm)**	**R_{max} (mm)**	**Reference**
Cassava	*Manihot esculenta* C.	240	0	15	22	32	450	300	800	2,200	2,800	Ceballos et al. (2011)
Maize	*Zea mays* L.	130*	0	16.7	19.5	25.1	30*	541	974	1,840	2,273	Eitzinger et al. (2014)*

Plantain	*Musa paradisiaca* L.	365	80*	16	25*	28*	38*	1,000 *	1,300 *	3,000*	5,000	Ramirez-Villegas et al. (2011a)

* Some of these parameters were slightly modified by expert criteria

Table 4. Current and projected changes in climatic variables in Napo and Ucayali regions

Region	Variable	Current	2030s			2050s			2080s		
			RCP 2.6	**RCP 4.5**	**RCP 8.5**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**
Napo	Annual minimum temperature (ºC)	18.9	1.0	1.2	1.3	1.1	1.6	2.1	1.4	2.4	4.1
	Annual mean temperature (ºC)	23.1	1.1	1.3	1.3	1.2	1.7	2.2	1.4	2.4	4.2
	Annual maximum temperature (ºC)	27.2	1.1	1.3	1.4	1.2	1.8	2.2	1.5	2.5	4.3
	Maximun temperature of warmest month (ºC)	28.3	1.9	2.1	2.4	2.2	2.1	3.5	2.3	3.3	5.6
	Minimum temperature of coldest month (ºC)	17.9	0.8	0.9	1.1	1.0	0.9	2.1	1.0	1.8	3.8
	Annual precipitation (mm)	2,761	90	136	89	71	136	146	51	131	349
	Precipitation of wettest month (mm)	312	38	50	35	39	50	50	38	53	120
	Precipitation of driest month (mm)	155	0	4	1	-3	4	0	-5	0	1
Ucayali	Annual minimum temperature (ºC)	18.1	1.1	1.3	1.3	1.2	1.7	2.2	1.4	2.5	4.2
	Annual mean temperature (ºC)	24.0	1.1	1.4	1.4	1.2	1.8	2.3	1.5	2.6	4.4
	Annual maximum temperature (ºC)	39.8	1.2	1.5	1.5	1.2	1.9	2.4	1.6	2.7	4.5
	Maximun temperature of warmest month (ºC)	30.5	0.4	0.5	0.9	0.7	1.2	0.9	0.8	1.8	4.3
	Minimum temperature of coldest month (ºC)	17.9	-0.2	-0.1	0.2	0	0.6	0.2	0.1	1.0	3.1
	Annual precipitation (mm)	1,894	188	221	182	188	239	182	190	215	330
	Precipitation of wettest month (mm)	252	27	31	31	28	36	31	32	33	73
	Precipitation of driest month (mm)	66	3	6	1	1	5	1	2	4	4

Table 5. ANOVA results that compare the average of change in climatic suitablility of cassava, plantain, and maize by scenario, period, and region

Variables	Cassava		Plantain		Maize	
	F	**p**	**F**	**p**	**F**	**p**
RCP	8.4	0.0003 *	53.98	<2.22e-16 *	127.24064	<2e-16 *
Period	11.15	2.23e-05 *	50.65	<2.22e-16 *	110.48499	<2e-16 *
Region	88.45	< 2.22e-16 *	85.45	<2.22e-16 *	264.16095	<2e-16 *
RCP x Period	2.02	0.092	37.75	<2.22e-16 *	34.60085	<2e-16 *

*Significant differences

Figures captions

Fig. 1 Weather stations collected from different sources: (a) precipitation stations (left) and (b) temperature stations (right). Andean-Amazon foothills (AAF) region highlighted in red (Dinerstein 2017). ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

Fig. 2 Present-day climate characterized through spatial interpolation and records of weather stations from 1981 to 2010 at 2.5 arc-min (~5-km) for (a) accumulated precipitation, (b) mean temperature, and (c) maximum temperature, aggregated by quarters. DJF (December-January-February), MAM (March-April-

May), JJA (June-July-August), SON (September, October, November) quarters. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

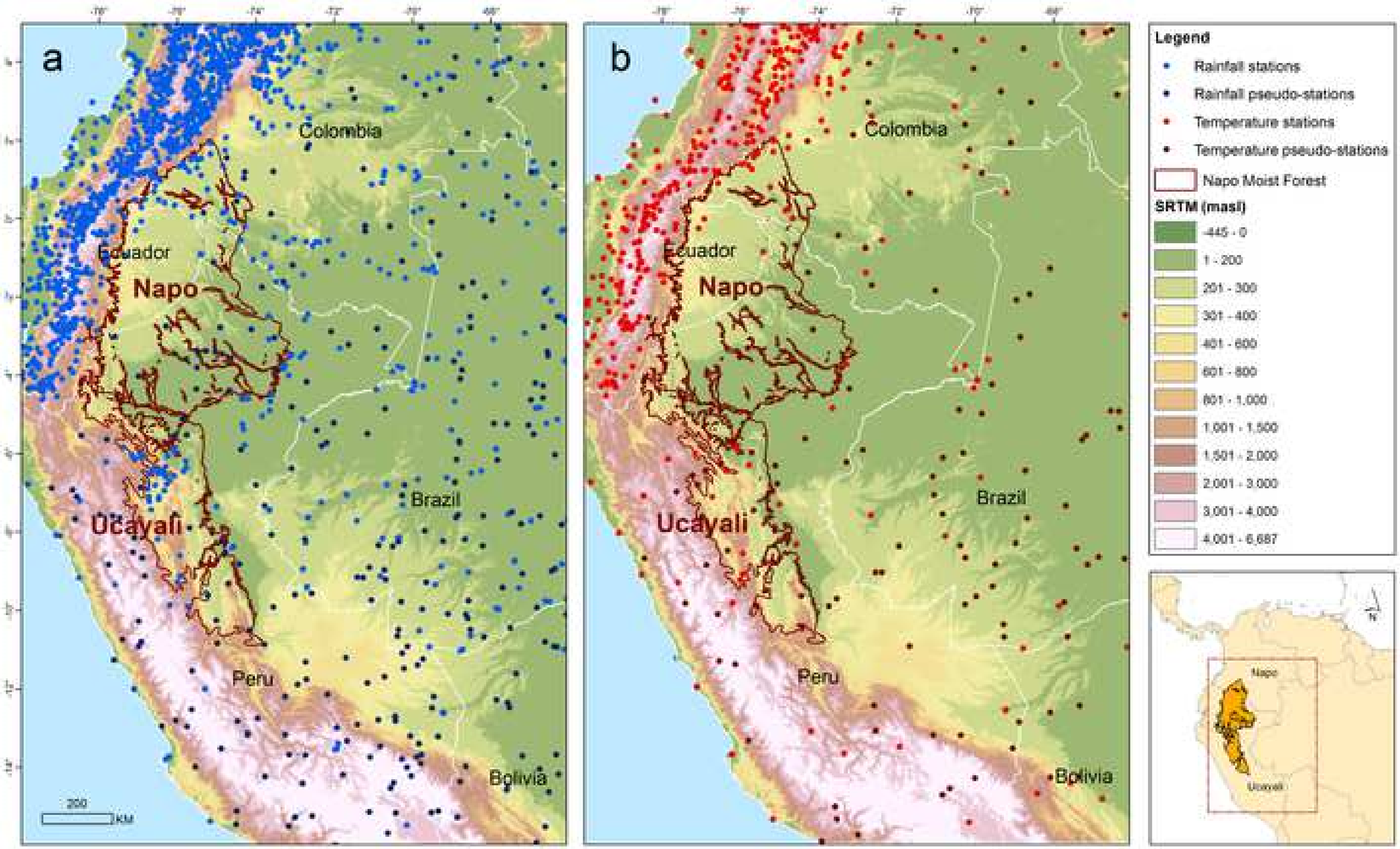
Fig. 2 Current climatic suitability of the three selected crops: (a) cassava, (b) maize, and (c) plantain in the Andean-Amazon foothills (AAF) region, modeled in EcoCrop. Red represents low suitability and green represents high suitability. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

Fig. 3 Change in climatic suitability between future and current scenarios for cassava, plantain, and maize in the Andean-Amazon foothills (AAF) region. Results are shown by RCP and period. Spatial analysis reveals the difference between future (average of 16 GCMs) and current climates. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

Fig. 4 Impacts of climate change on cassava, maize, and plantain in the Napo moist forest global ecoregion. OSC: overall suitability change; PIA/NIA: ratio of positively to negatively impacted areas (values above 1, dotted line, indicate that positively impacted areas are larger than negatively impacted areas). Thick black vertical lines are the median; boxes show the first and third quartile. The distributions of boxplots are combinations of crop-by-region predictions and by period considering all RCPs. White boxplots belong to Napo regions and gray boxplots belong to Ucayali regions (RStudio Team 2015)

Fig. 5 Uncertainties in predicted climate change and crop modeling expressed as SD across GCMs/RCPs for (a) total annual rainfall, (b) temperature, and (c) the suitability results over three studied crops. For GCM spread calculation, RCP 8.5 and the 2050s period were used. For RCP calculation, the 2050s period was used. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

colour figure



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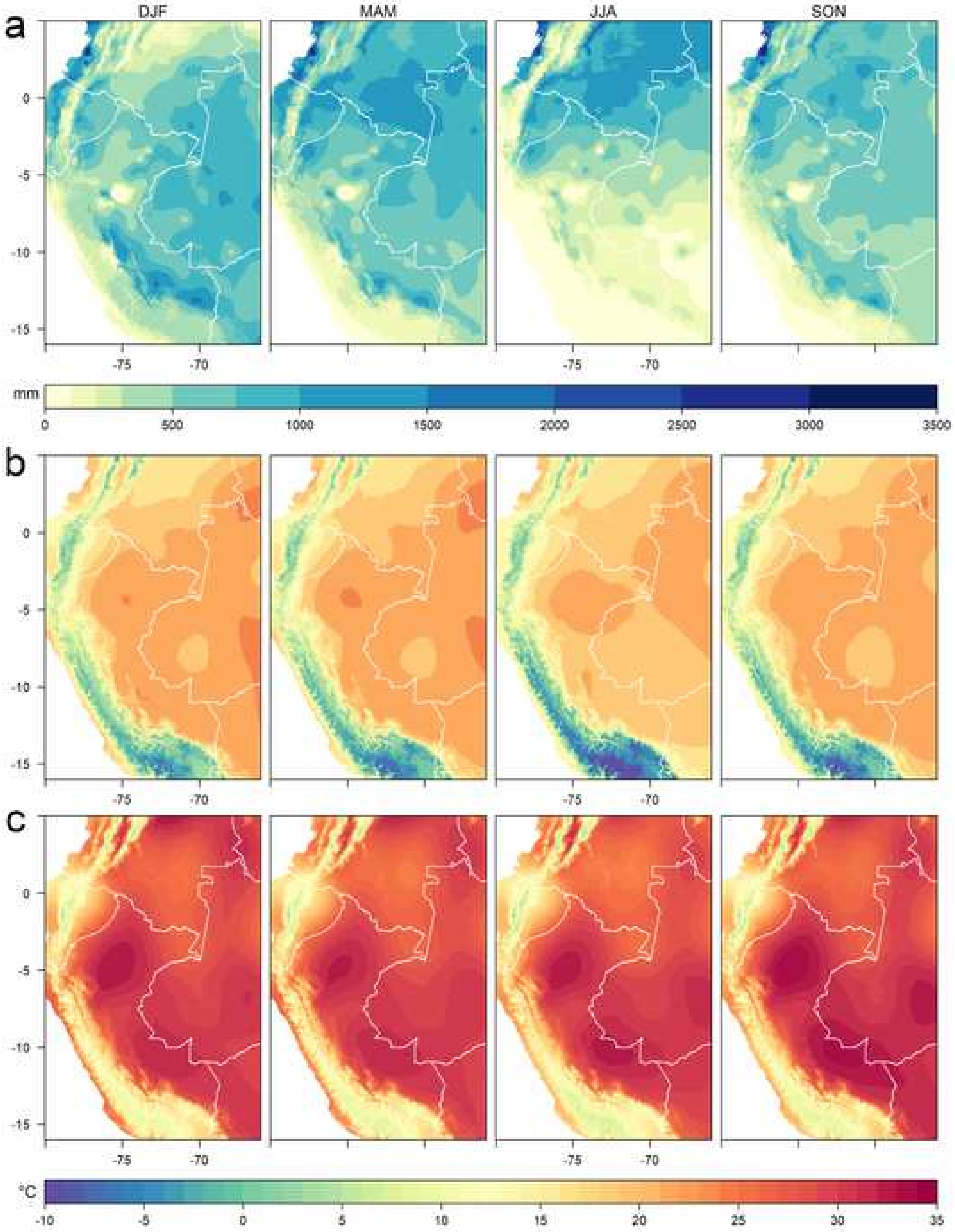

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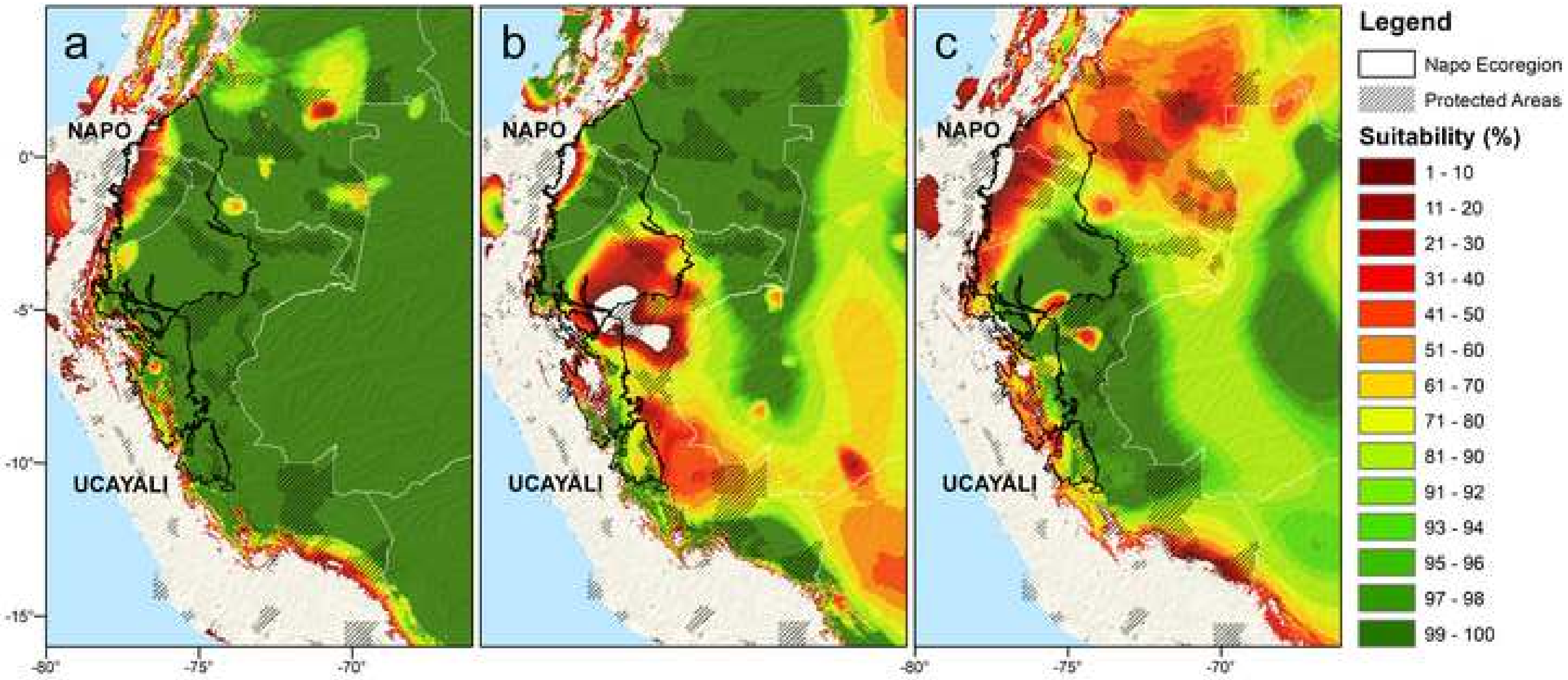

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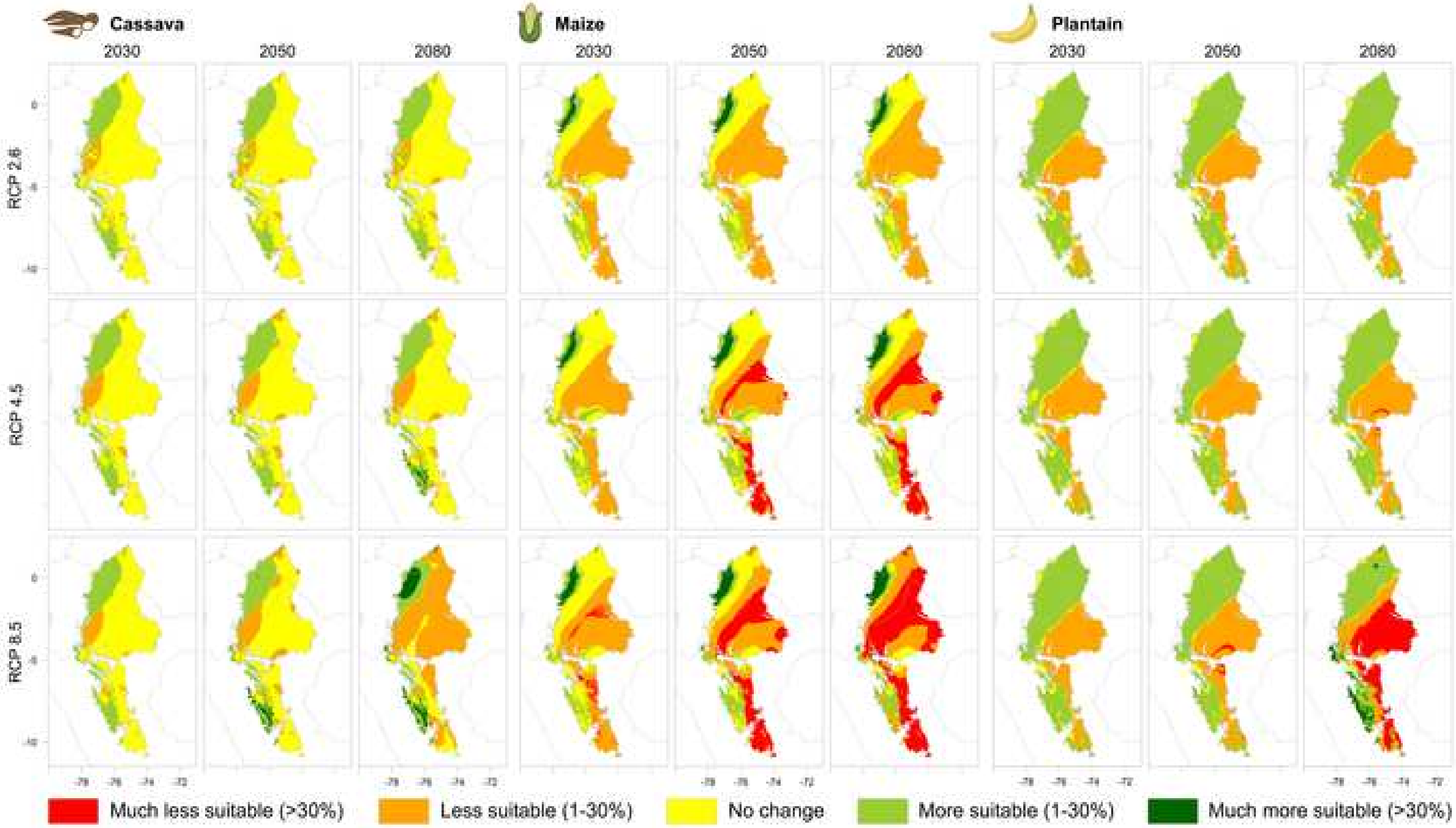

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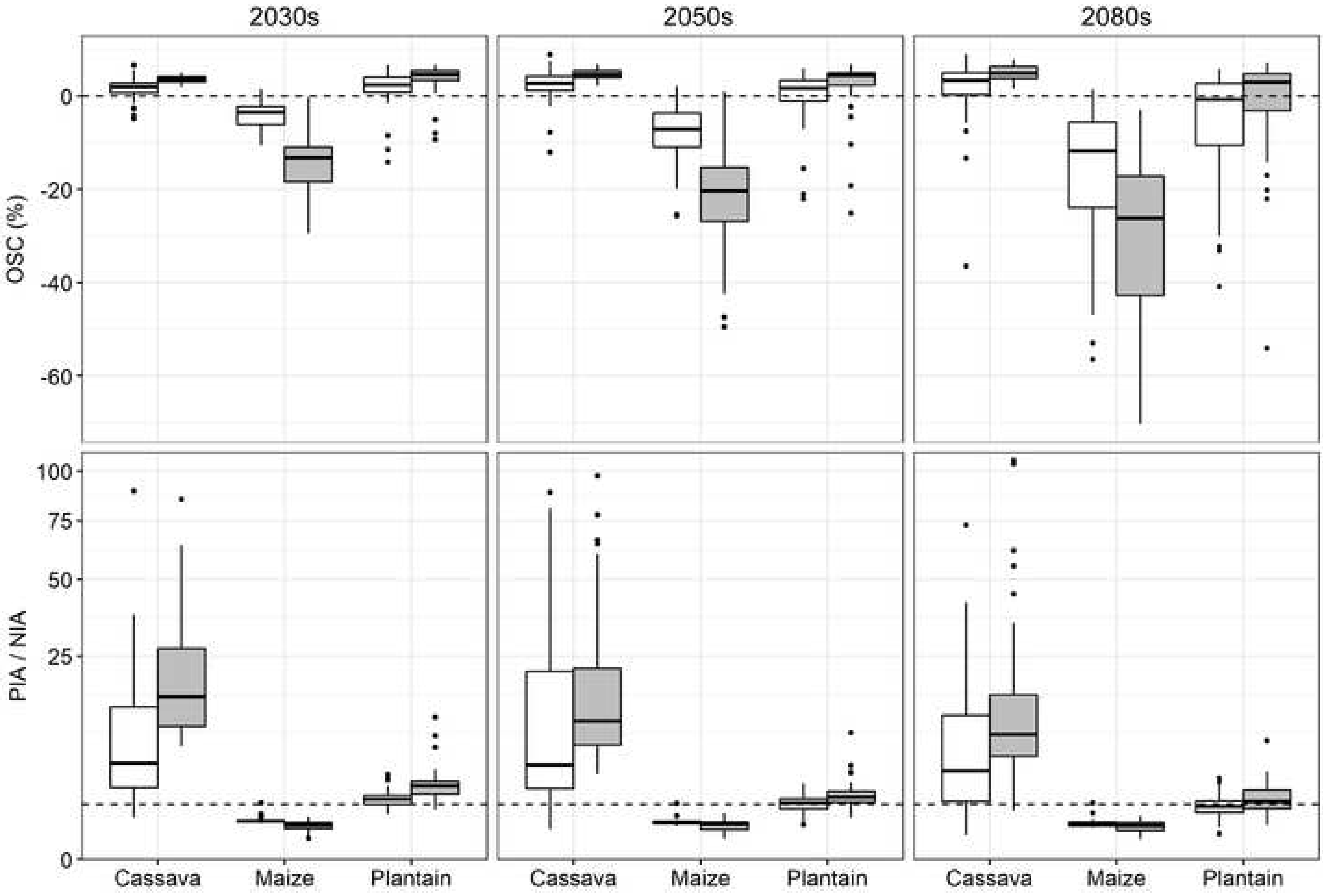
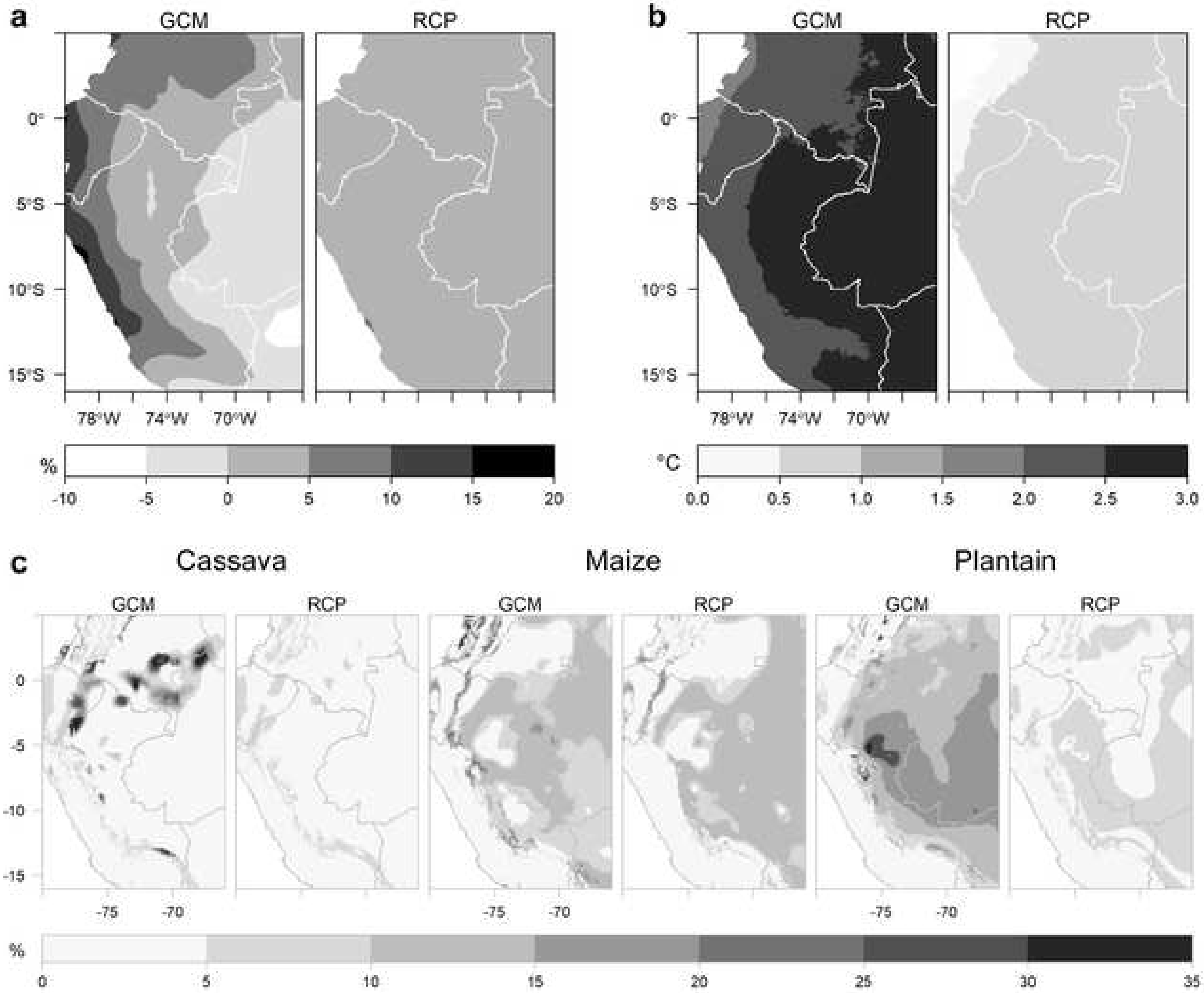

2030s
2050s
2080s
OSC (%)
0
-20
-40
-60
PIA / NIA
100
75
50
25
0
Cassava
Maize
Plantain
Cassava
Maize
Plantain
Cassava
Maize
Plantain

colour figure



Supplementary material captions

Action needed for staple crops in the Andean-Amazon foothills because of climate change

Mitigation and Adaptation Strategies for Global Change

Fig. S 1 Cross-validation of the interpolated monthly surfaces for accumulated precipitation (a and d), maximum temperature (b and e), and minimum temperature (c and f). A-D shows the variation in the coefficient of determination (R^2) and d-f the root mean square error (RMSE). Dotted red line represents 50% of the data and the red continuous line 75% of the measurement (RStudio Team 2015)

Fig. S 2 Projected changes in seasonal rainfall for the Andean-Amazon foothills (AAF) region, toward the 2030s (top), 2050s (middle), and 2080s (bottom) for RCP 8.5. DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), SON (September, October, November) quarters. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

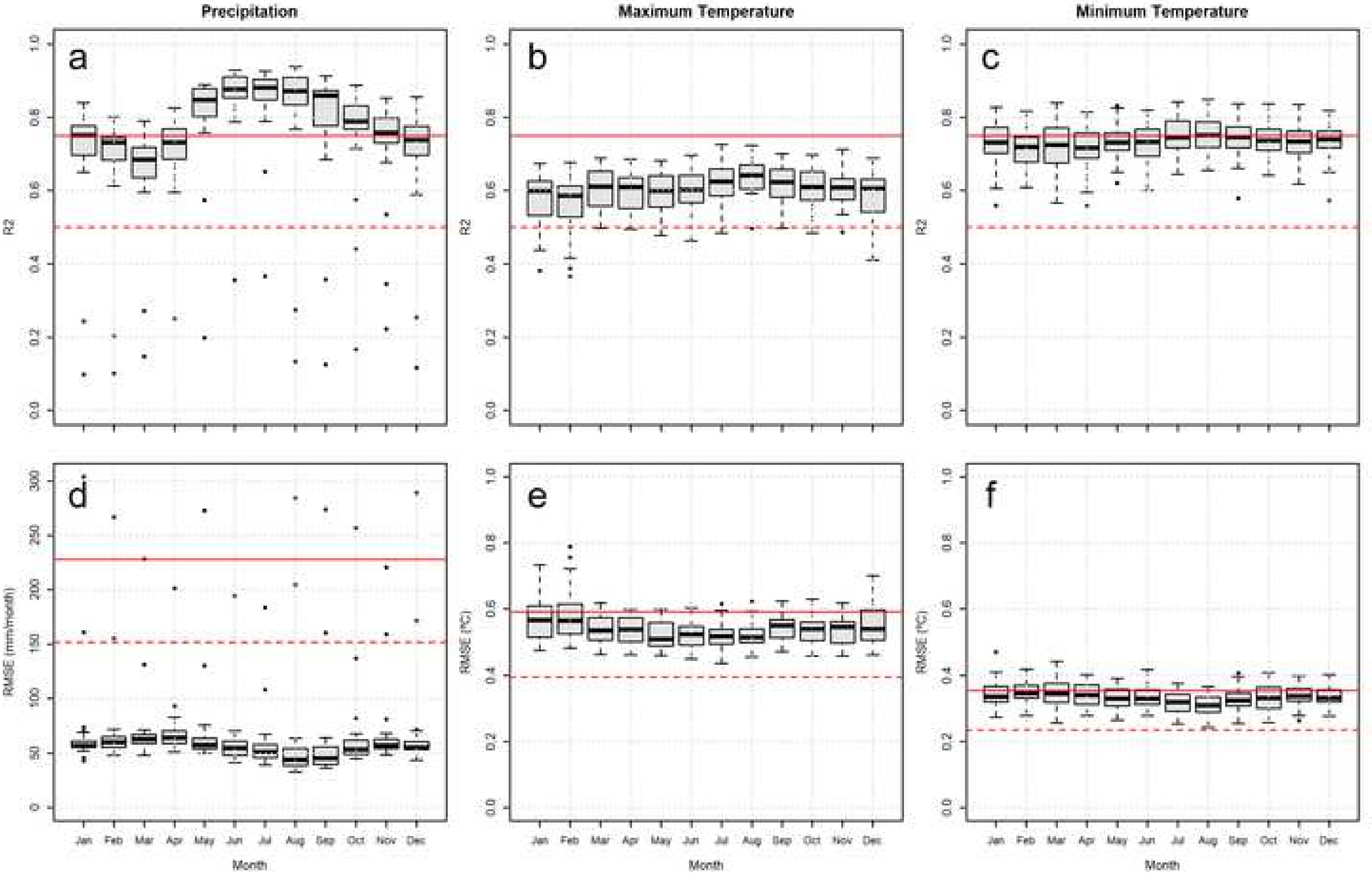
Fig. S 3. Projected changes in seasonal minimum temperature for the Andean-Amazon foothills toward the 2030s (top), 2050s (middle), and 2080s (bottom) for RCP 8.5. DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), SON (September, October, November) quarters. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

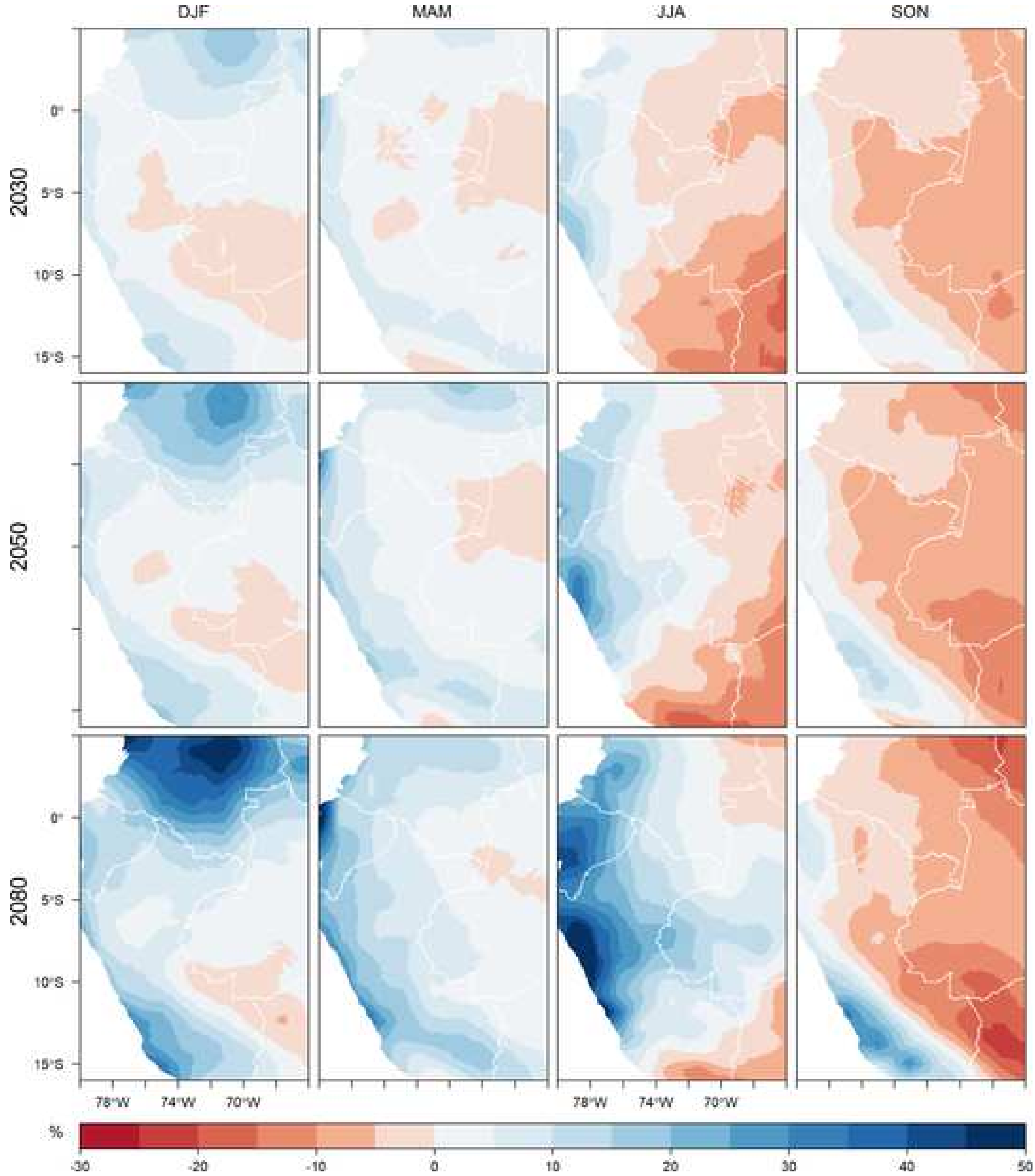
Fig. S 4 Projected changes in seasonal maximum temperature for the Andean-Amazon foothills toward the 2030s (top), 2050s (middle), and 2080s (bottom) for RCP 8.5. DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), SON (September, October, November) quarters. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

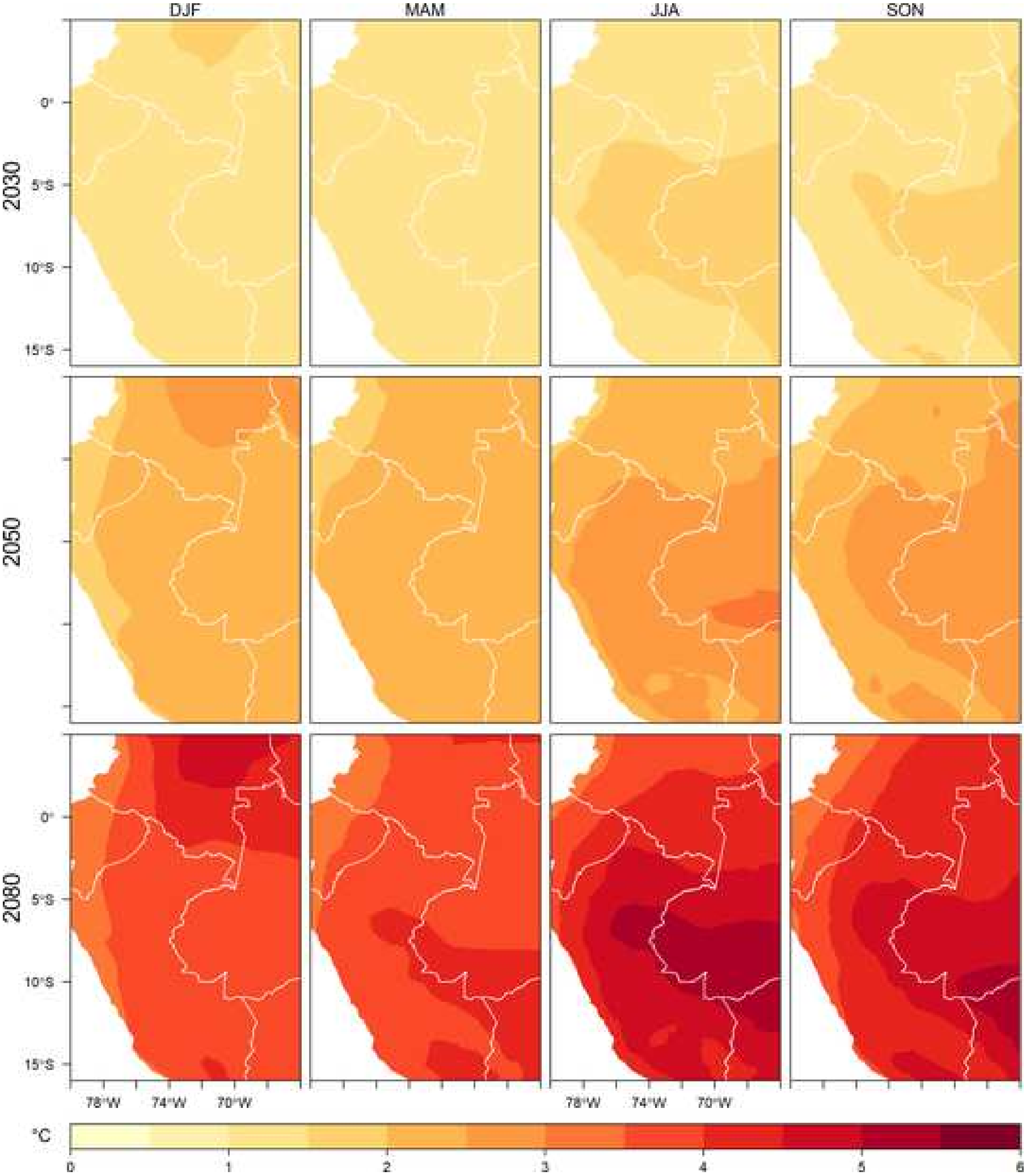
Fig. S 5 Current and future climate suitability based only on precipitation of the three selected crops, cassava, maize, and plantain, in the Andean-Amazon foothills (AAF) region, modeled in EcoCrop. Red represents low suitability and green represents high suitability. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

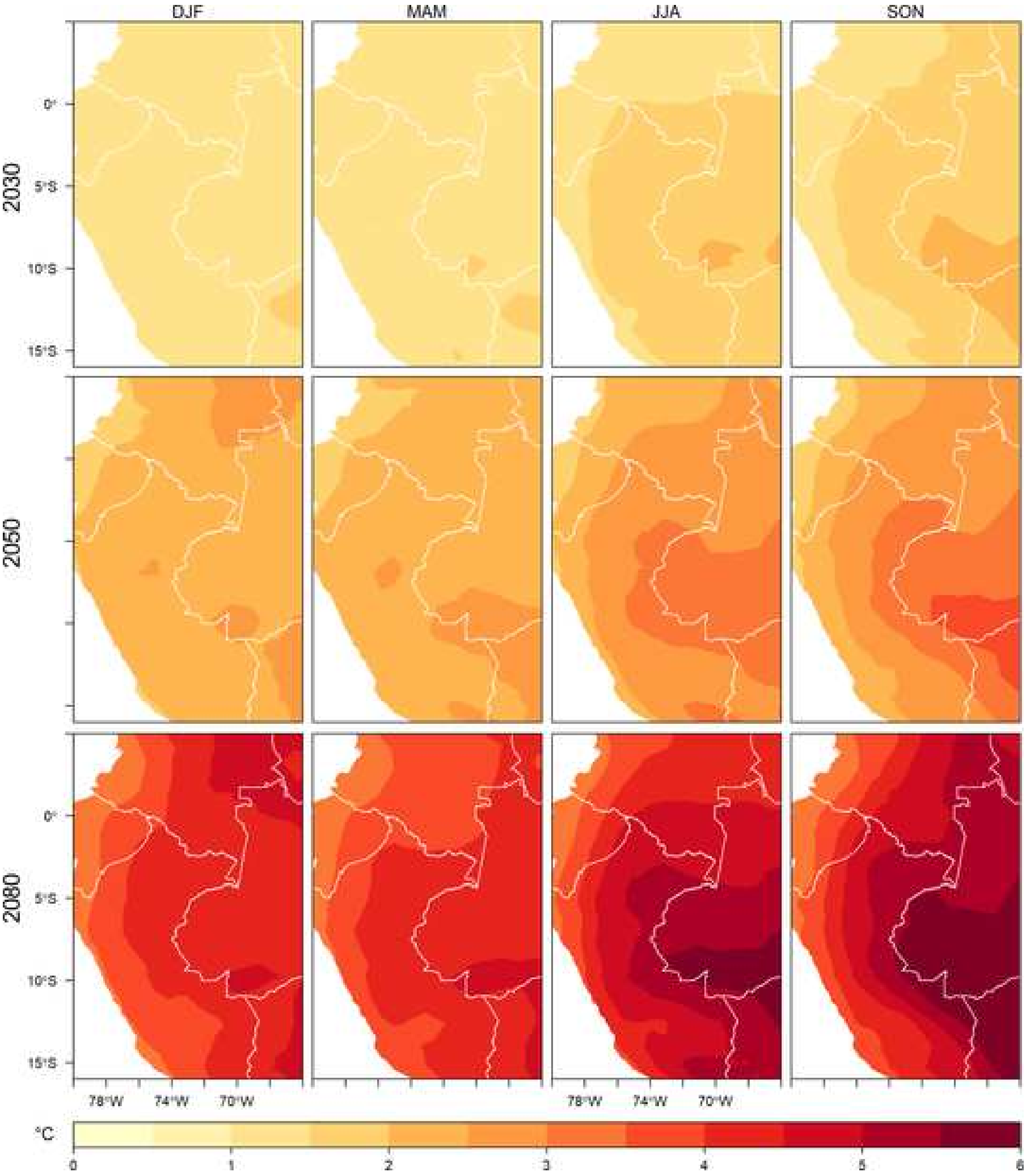
Fig. S 6 Current and future climate suitability based only on temperature of the three selected crops, cassava, maize, and plantain, in the Andean-Amazon foothills (AAF) region, modeled in EcoCrop. Red represents low suitability and green represents high suitability. ArcMap 10.5 (http://desktop.arcgis.com/en/arcmap)

Supplementary material




DJF
MAM
JJA
SON
2030
2050
2080
0°
5°S
10°S
15°S
78°W
74°W
70°W
%
-30
-20
-10
0
10
20
30
40
50


DJF
MAM
JJA
SON
2030
2050
2080
0°
5°S
10°S
15°S
78°W
74°W
70°W
°C
0
1
2
3
4
5
6


DJF
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2030
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0°
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78°W
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0
1
2
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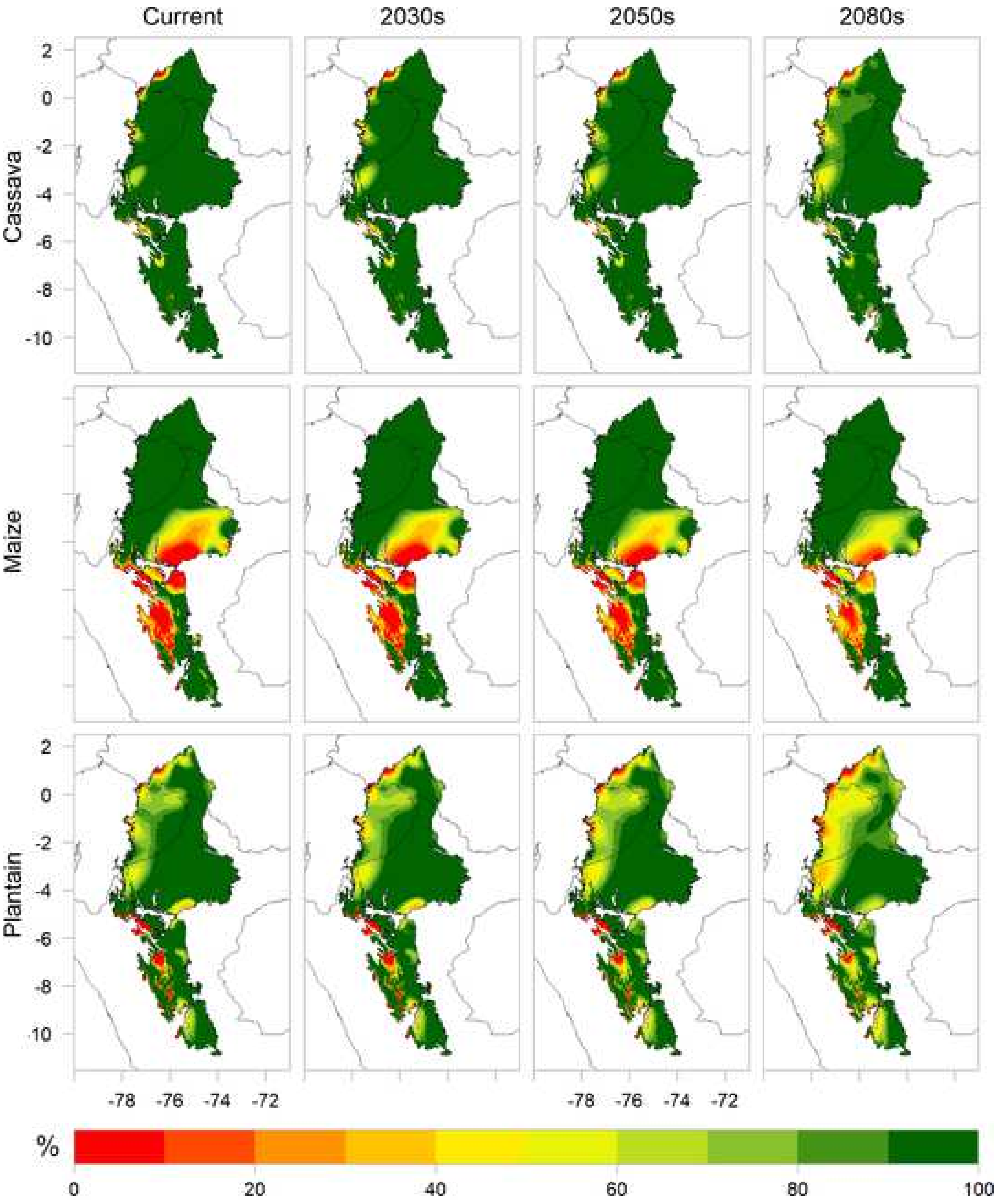
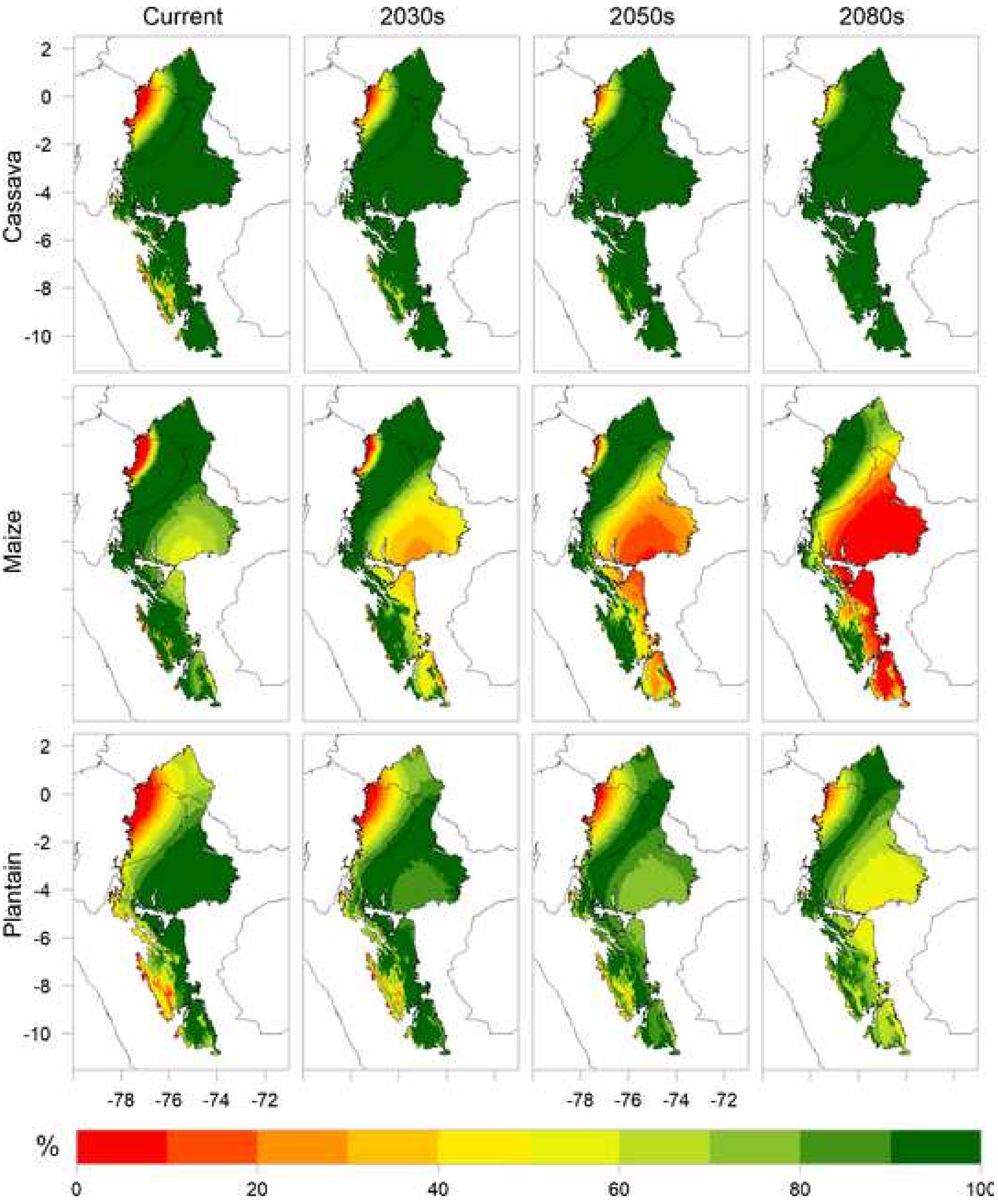
6


Current
2030s
2050s
2080s
Cassava
Maize
Plantain
2
0
-2
-4
-6
-8
-10
-78
-76
-74
-72
%
0
20
40
60
80
100


Current
2030s
2050s
2080s
Cassava
Maize
Plantain
2
0
-2
-4
-6
-8
-10
-78
-76
-74
-72
%
0
20
40
60
80
100