Potential Natural Vegetation of Eastern Africa(Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia). Volume 7

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FACULTY OF LIFE SCIENCES
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Introduction

This book represents **Volume 7** in a seven-volume series that documents the potential natural vegetation map that was developed by the VECEA (Vegetation and Climate change in East Africa) project. The VECEA map was developed as a collaborative effort that included partners from each of the seven VECEA countries (Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia).

- In **Volume 1**, we present the potential natural vegetation map that we developed for seven countries in eastern Africa. In Volume 1, we also introduce the concept of potential natural vegetation and give an overview of different application domains of the VECEA map.
- **Volumes 2** to **5** describe potential natural vegetation types, also including lists of the "useful tree species" that are expected to naturally occur in each vegetation type – and therefore also expected to be adapted to the environmental conditions where the vegetation types are depicted to occur on the map. **Volume 2** focuses on forest and scrub forest vegetation types. **Volume 3** focuses on woodland and wooded grassland vegetation types. **Volume 4** focuses on bushland and thicket vegetation types. In **Volume 5**, information is given for vegetation types that did not feature in Volumes 2 to 4.
- **Volume 6** gives details about the process that we followed in making the VECEA map.
- **Volume 7** shows the results of modelling the distribution of potential natural vegetation types for six potential future climates.

We are planning to submit one or several articles to peer-reviewed journals that are based on some of the results that are presented in this volume. As most scientific journals do not allow publishing results that are available elsewhere, we have deliberately summarized the results, limited the discussion section, only shown results for 2080 and limited the number of references. For the same reasons, we have not yet made the climate-change results available online where the VECEA map is provided (http://sl.life.ku.dk/English/outreach_publications/computerbased_tools/vegetation_climate_change_eastern_africa.aspx).

Acknowledgements

We are extremely grateful to the Rockefeller Foundation for having funded most of the work that has led to the development and publication of the VECEA map and its accompanying documentation.

We also greatly appreciate the comments and suggestions that were made by Paul Smith and Jonathan Timberlake (both of Royal Botanic Gardens Kew) when they reviewed early drafts of volumes 2, 3, 4 & 5.

Thanks to anybody in our institutions who contributed directly or indirectly to the completion of the VECEA vegetation map and its associated documentation. We especially appreciate the assistance by Nelly Mutio (as for organizing logistics for the regional workshop that we organized in 2009 and for assisting in administrative issues), Melita Jørgensen (for desktop publishing), and of Jeanette van der Steeg for helping with the final preparation of the maps for Volume 1.

Thanks to Ann Verdoodt and Eric Van Ranst (both from the University of Ghent) for compiling and sharing thematic soil maps that were derived from the soil of Rwanda (Birasa, E.C., Bizimana, I., Bouckaert, W., Gallez, A., Maesschalck, G., and Vercruysse, J. (1992). Carte Pédologique du Rwanda. Echelle: 1/250.000. Réalisée dans le cadre du projet "Carte Pédologique du Rwanda" (AGCD, CTB). AGCD (Belgique) et MINAGRI, Kigali).

Thanks to Eugene Kayijamahe, Center for Geographic Information System and Remote Sensing at National University of Rwanda for sharing the digital map "Vegetation of Volcanoes National Park" that allowed us to classify in greater detail this part of the VECEA map.

Thanks to UNEP-GEF for funding the Carbon Benefits Project (CBP) through which information was compiled on indicator and characteristic species for The Vegetation Map of Africa (White 1983). (This work led to the publication in 2011 of an Africa-wide tree species selection tool that is available from: *http://www.worldagroforestrycentre.org/our_products/databases/ useful-tree-species-africa)* Thanks to BMZ for funding the ReACCT project in Tanzania through which funding was made available for field verification of the VECEA map around Morogoro (this was essential in preparing the VECEA map as the base map for Tanzania was essentially a physiognomic map.

Abbreviations

Abbreviation	Full
A	Afroalpine vegetation
B	Afromontane bamboo
Bd	Somalia-Masai *Acacia-Commiphora* deciduous bushland and thicket
Be	Evergreen and semi-evergreen bushland and thicket
bi (no capital)	Itigi thicket (edaphic vegetation type)
br (no capital)	Riverine thicket (edaphic vegetation type, mapped together with riverine forest and woodland)
C	In species composition tables: we have information that this species is a characteristic (typical) species in a national manifestation of the vegetation type
D	Desert
DBH	diameter at breast height (1.3 m)
E	Montane *Ericaceous* belt (easily identifiable type)
f (no capital)	In species composition tables: since this species is present in the focal country and since it was documented to occur in the same vegetation type in some other VECEA countries, this species potentially occurs in the national manifestation of the vegetation type
Fa	Afromontane rain forest
Fb	Afromontane undifferentiated forest (Fbu) mapped together with Afromontane single-dominant *Juniperus procera* forest (Fbj)
Fc	Afromontane single-dominant *Widdringtonia whytei* forest
fc (no capital)	Zanzibar-Inhambane scrub forest on coral rag (fc, edaphic forest type)
Fd	Afromontane single-dominant *Hagenia abyssinica* forest
Fe	Afromontane moist transitional forest
fe (no capital)	Lake Victoria *Euphorbia dawei* scrub forest (fe, edaphic forest type mapped together with evergreen and semi-evergreen bushland and thicket)
FeE	distinct subtype of Afromontane moist transitional forest in Ethiopia
FeK	distinct subtype of Afromontane moist transitional forest in Kenya
Ff	Lake Victoria transitional rain forest
Fg	Zanzibar-Inhambane transitional rain forest
Fh	Afromontane dry transitional forest
Fi	Lake Victoria drier peripheral semi-evergreen Guineo-Congolian rain forest
FLD	Forest & Landscape (URL *http://sl.life.ku.dk/English.aspx)*
Fm	Zambezian dry evergreen forest
Fn	Zambezian dry deciduous forest and scrub forest
Fo	Zanzibar-Inhambane lowland rain forest
Fp	Zanzibar-Inhambane undifferentiated forest
Fq	Zanzibar-Inhambane scrub forest
fr (no capital)	Riverine forests (fr, edaphic forest type mapped together with riverine woodland and thicket)
Fs	Somalia-Masai scrub forest (Fs, mapped together with evergreen and semi-evergreen bushland and thicket)
fs (no capital)	Swamp forest (fs, edaphic forest type)
G	Grassland (excluding semi-desert grassland and edaphic grassland, G)
g (no capital)	Edaphic grassland on drainage-impeded or seasonally flooded soils (edaphic vegetation type, g)
GCM	General Circulation Models
GHG	greenhouse gas
gv	Edaphic grassland on volcanic soils (edaphic subtype, gv)
ICRAF	World Agroforestry Centre (URL *http://www.worldagroforestry.org/*)
IPCC	Intergovernmental Panel on Climate Change
L	Lowland bamboo
M	Mangrove

P	Palm wooded grassland (physiognomically easily recognized type)
PROTA	Plant Resources of Tropical Africa (URL *http://www.prota.org/*)
S	Somalia-Masai semi-desert grassland and shrubland
PNV	Potential Natural Vegetation
s (no capital)	Vegetation of sands (edaphic type)
SRES	Special Report on Emissions Scenarios
T	*Termitaria* vegetation (easily identifiable and edaphic type, including bush groups around *termitaria* within grassy drainage zones)
UNEP	United Nations Environment Programme (URL *http://www.unep.org/*)
VECEA	Vegetation and Climate Change in Eastern Africa project (funded by the Rockefeller Foundation)
Wb	*Vitellaria* wooded grassland
Wc	*Combretum* wooded grassland
Wcd	dry *Combretum* wooded grassland subtype
Wcm	moist *Combretum* wooded grassland subtype
WCMC	World Conservation Monitoring Centre (URL *http://www.unep-wcmc.org/*)
wd (no capital)	Edaphic wooded grassland on drainage-impeded or seasonally flooded soils (edaphic vegetation type)
We	Biotic *Acacia* wooded grassland
Wk	Kalahari woodland
Wm	Miombo woodland
Wmd	Drier miombo woodland subtype
Wmr	Miombo on hills and rocky outcrops subtype
Wmw	Wetter miombo woodland subtype
Wn	north Zambezian undifferentiated woodland and wooded grassland (abbreviation: undifferentiated woodland)
Wo	Mopane woodland and scrub woodland
wr (no capital)	Riverine woodland (edaphic vegetation type, mapped together with riverine forest and thicket)
Wt	*Terminalia sericea* woodland
Wvs	*Vitex - Phyllanthus - Shikariopsis (Sapium) - Terminalia* woodland (not described regionally)
Wvt	*Terminalia glaucescens* woodland (not described regionally)
Wy	Chipya woodland and wooded grassland
X	Fresh-water swamp
x (no capital)	In species composition tables: we have information that this species is present in a national manifestation of the vegetation type
Z	Halophytic vegetation
ZI	Zanzibar-Inhambane coastal mosaic (Kenya and Tanzania coast)

Contents

1. Background

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) shows that global mean surface temperature has increased in a linear trend of 0.74°C over the last 100 years (IPCC, 2007). Most of the observed increase in global average temperatures since the mid-20th century is very likely due to anthropogenic greenhouse gas (GHG) concentrations. Current global median projections predict an increase in mean temperature and a decrease in mean annual precipitation in many of the already marginal dry areas (IPCC, 2007). These changes will result in lower river flows, an increase in evapotranspiration, drier soils, and shorter growing seasons. Moreover, increase in extreme climatic events such as longer droughts, more intense storm events and even extreme low temperature spikes that could damage or destroy crops and vegetation, are projected.

The SRES (Special Report on Emissions Scenarios) scenarios of the IPCC were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The SRES team defined four narrative storylines, labelled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways (*http://sedac.ciesin.columbia.edu/ddc/sres/*): ..

- A1 storyline and scenario family: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- A2 storyline and scenario family: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
- B1 storyline and scenario family: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
- B2 storyline and scenario family: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

In the A1 family, three groups are differentiated:

- A1FI: Fossil Intensive
- A1T: Technology development of non-fossil sources
- A1B: Balance across energy sources

Uncertainties in climate projections make it harder to predict the impacts, making it even more difficult to develop appropriate and effective adaptation and mitigation strategies. More probable outcomes are obtained from a range of scenarios run through an ensemble of General Circulation Models (GCMs), so that the different results obtained from individual models (with different algorithms and structure) are 'averaged' (IPPC, 2007).

As Turral *et* al (2011) summarized, future projections of temperatures vary from significant to slight increases for different scenarios (Figure 1.1), but with a high likelihood of occurrence, and good consistency between models. By comparison, the predictions of precipitation are far less consistent, with some models predicting increases in precipitation where others predict decreases for the same scenario (IPPC, 2007). Most GCMs agree on projected decrease in precipitation over much of North Africa and the northern Arabian Peninsula. Projection of precipitation over the area immediately south of those areas carries large uncertainties (Kanamaru, 2011) and should therefore be considered with care.

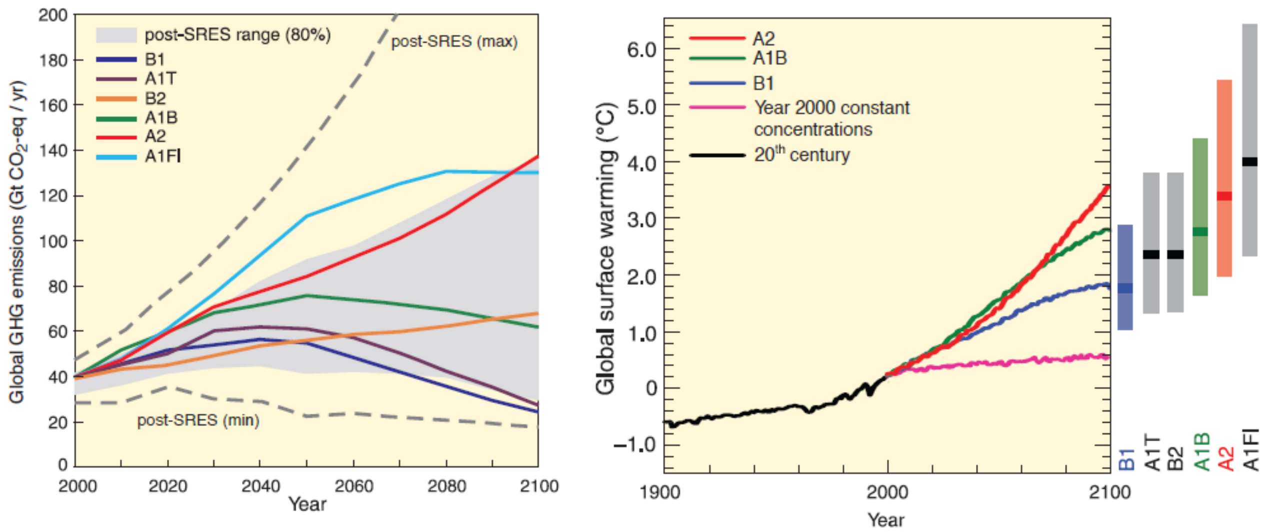


Figure 1.1: The range of scenario prediction for GHG emissions (left) and global warming (right) (IPCC, 2007)

2. Suitability distribution modelling of the VECEA potential natural vegetation map in current and possible future climates

In order to estimate the possible consequences of climate change on the distribution of potential natural vegetation (PNV) in eastern Africa, we calibrated vegetation distribution models based on the current distribution of climatic conditions. We compared these with vegetation distribution patterns under possible future climates for 2080.

2.1 Methods

2.1.1. Modelling the distribution of potential natural vegetation types under current conditions

We created suitability distribution models for each PNV type listed in Table 1. Note that Table 1 only includes potential natural vegetation types that we expect are mainly under climatic control. Edaphic PNV types that occur where particular soil and landscape conditions result in the occurrence of these PNV types instead of PNV types that are mainly under climatic control, were excluded from climate-change modelling. The respective areas of edaphic PNV types were masked from the VECEA map during modeling.

For each PNV (Table 1), we first generated 1000 random point locations within the mapped distribution of that PNV. Subsequently, we generated 10,000 random point locations outside its distribution area. For each sample point, we recorded the variables listed in Table 2 at the point location.

Next, we created distribution models for each of the PNVs using the maximum entropy suitability mapping method (Phillips *et al.* 2004; Phillips & Dudik 2008) as implemented in the MAXENT software (Phillips *et al.* 2010).

For PNVs that were mapped as compound vegetation types in some areas of the VECEA map (see Volumes 2 – 6), we created two distribution models: one where we included and another one where we excluded the areas with compound vegetation from the modelling. The final suitability distribution maps for these PNVs were created by averaging the suitability score of the two models.

As a final step in modelling the distribution of PNV under current conditions, we combined the modelled probability distribution layers for each PNV distribution model. The classification of each raster cell (*i.e.* the PNV type that was predicted to occur under the current climatic conditions) was determined by selecting the PNV with the highest probability score.

An evaluation of initial modelling results showed that the modelling of the Somalia-Masai semi-desert grassland and shrubland and deserts (Ethiopia and Kenya; mainly mapped as a compound vegetation type [VECEA mapping units "D" and "S", see Volume 5]) and *Acacia-Commiphora* stunted bushlands (VECEA mapping) were especially problematic:

1. In Ethiopia, deserts are mapped as compound vegetation types with semi-deserts. At the same time, some of the driest areas in Ethiopia are not mapped as desert or semi-desert but as Somalia-Masai *Acacia-Commiphora* deciduous bushland and thicket.
2. The distribution of deserts in Kenya seems to be influenced by edaphic rather than climatic conditions.
3. Models of the Somalia-Masai semi-desert grassland and shrubland in Kenya did not match very well with the mapped distribution of desert + semi-desert grassland and shrubland in Ethiopia.

Based on the above evaluation, we made the following adaptations to the original input vegetation map:

1. The desert areas in Kenya and the desert + semi-desert areas in Ethiopia were masked out. These areas were therefore ignored in the modelling of other PNVs (Table 1).
2. The areas with annual precipitation < 200 mm were reclassified as desert. These areas were subsequently used as input in the suitability distribution model for desert
3. All *Acacia-Commiphora* stunted bushlands and Somalia-Masai semi-desert grassland and shrubland in Kenya were reclassified as one compound type '*Acacia-Commiphora* stunted bushlands and semi-desert grassland and shrubland'. Next, we created a suitability distribution model of this compound type for the whole region (*i.e.*, we extrapolated the model results outside Kenya).

Table 1. Climatic PNVs for which we created suitability distribution models

Code	PNV
Forests and scrub forest types	
FaK	Afromontane rain forest in all countries except Ethiopia
FaE	Afromontane rain forest in Ethiopia
Fb	Afromontane undifferentiated forest (Fbu) mapped together with Afromontane single-dominant *Juniperus procera* forest (Fbj)
Fc	Afromontane single-dominant *Widdringtonia whytei* forest
Fd	Afromontane single-dominant *Hagenia abyssinica* forest
FeK	Afromontane moist transitional forest in Kenya
FeE	Afromontane moist transitional forest in Ethiopia
Ff	Lake Victoria transitional rain forest
Fg	Zanzibar-Inhambane transitional rain forest
Fh	Afromontane dry transitional forest
Fi	Lake Victoria drier peripheral semi-evergreen Guineo-Congolian rain forest
Fm	Zambezian dry evergreen forest
Fn	Zambezian dry deciduous forest and scrub forest
Fo	Zanzibar-Inhambane lowland rain forest
Fp	Zanzibar-Inhambane undifferentiated forest
Fq	Zanzibar-Inhambane scrub forest
Fs	Somalia-Masai scrub forest
Woodland and wooded grasslands and edaphic wooded grasslands	
Wb	*Vitellaria* wooded grassland
Wc	*Combretum* wooded grassland
Wcm	Moist *Combretum* wooded grassland (subtype of Wc)
Wcd	Dry *Combretum* wooded grassland (subtype of Wc)
Wd	*Acacia-Commiphora* deciduous wooded grassland
Wk	Kalahari woodland
Wm	Miombo woodland
Wmd	Drier miombo woodland (subtype of Wm)
Wmw	Wetter miombo woodland (subtype of Wm)
Wmr	Miombo on hills and rocky outcrops (subtype of Wm)
Wn	North Zambezian undifferentiated woodland and wooded grassland
Wo	Mopane woodland and scrub woodland
Wt	*Terminalia sericea* woodland
Wv	*Vitex - Phyllanthus - Shikariopsis (Sapium) - Terminalia* woodland (Wvs) and *Terminalia glaucescens* woodland (Wvt)
Wvt	*Terminalia glaucescens* woodland (subtype of Wv)
Wy	Chipya woodland and wooded grassland
Bushland and Thicket	
Bd	Somalia-Masai *Acacia-Commiphora* deciduous bushland and thicket (synonym: deciduous bushland
Be + We	Evergreen and semi-evergreen bushland and thicket and Biotic *Acacia* wooded grassland
Bds +S	*Acacia-Commiphora* stunted bushland + Somalia-Masai semi-desert grassland and shrub-land (only the areas in Kenya were considered, see text for more details)
E	Montane Ericaceous belt

Code	PNV
Other potential natural vegetation types	
A	Afroalpine vegetation
B	Afromontane bamboo
D	Desert (see text)
G	Grassland (excluding semi-desert grassland and edaphic grassland, also referred to as climatic grassland)
L	Lowland bamboo
Bds +S	*Acacia-Commiphora* stunted bushland + Somalia-Masai semi-desert grassland and shrubland

Table 2. Data sets used in the modelling of the suitability distribution models of the potential natural vegetation map for the VECEA region. All layers were resampled to 30 arc seconds (approx. 1 km at the equator).

Data	Description	Scale / resolution	Source
Bioclim 01	Annual Mean Temperature	30 arc seconds	(Hijmans *et al.* 2005; Worldclim 2011)
Bioclim 02	Mean Diurnal Range (Mean of monthly (max temp - min temp))	idem	idem
Bioclim 03	Isothermality (bioclim2/bioclim7)	idem	idem
Bioclim 04	Temperature Seasonality (standard deviation *100)	idem	idem
Bioclim 05	Max Temperature of Warmest Month	idem	idem
Bioclim 06	Min Temperature of Coldest Month	idem	idem
Bioclim 07	Temperature Annual Range (bioclim5-bioclim6)	idem	idem
Bioclim 08	Mean Temperature of Wettest Quarter	idem	idem
Bioclim 09	Mean Temperature of Driest Quarter	idem	idem
Bioclim 10	Mean Temperature of Warmest Quarter	idem	idem
Bioclim 11	Mean Temperature of Coldest Quarter	idem	idem
Bioclim 12	Annual Precipitation	idem	idem
Bioclim 13	Precipitation of Wettest Month	idem	idem
Bioclim 14	Precipitation of Driest Month	idem	idem
Bioclim 15	Precipitation Seasonality (Coefficient of Variation)	idem	idem
Bioclim 16	Precipitation of Wettest Quarter	idem	idem
Bioclim 17	Precipitation of Driest Quarter	idem	idem
Bioclim 18	Precipitation of Warmest Quarter	idem	idem
Bioclim 19	Precipitation of Coldest Quarter	idem	idem
HWSD	Percentage clay of the upper soil layer Percentage sand of the upper soil layer pH Drainage Lithology	idem	Harmonized World Soil Database, a raster database with soil mapping units linked to harmonized soil property data; http://www.fao.org/geonetwork/
Calculated for this study	Terrain wetness index Landscape morphology	3 arc-second	Calculated in GRASS GIS (GRASS Development Team. 2010), using the DEM (CGIAR-CSI 2008) as input

2.1.2. Modelling the distribution of potential natural vegetation types for possible future climatic conditions

We subsequently ran the models developed for each potential natural vegetation (PNV) type by using projected climate distribution layers for 2080 (statistical downscaled climate data from available from CIAT [2011] as listed in Table 2.3) as input. We assumed that the non-climatic variables would not change. We again combined predictions for each PNV by using the maximum probability to select the PNV that was most likely to become established at each raster position.

Table 3. Future climate layers based on the marked GDM models and scenarios for 2080 used in this study. Data was downloaded from *http://futureclim.info/* * footnote

Models		**Scenarios**	
	A1B	A2	B2
CCCMA-CGCM31	X	-	-
UKMO-HADCM3	X	-	-
CCCMA-CGCM2	-	X	X
HCCPR-HADCM3	-	X	X

Footnote: these data are also available from: *http://www.ccafs-climate.org/download_a1.html; http://www.ccafs-climate.org/download_a2.html* and *http://www.ccafs-climate.org/download_b2.html*

Please check in Appendix 1 for some details on statistical downscaling methods that are used for future climate distribution layers.

2.2 Results

Figure 2.1 shows that our methodology resulted in reliable calibration of the environment – PNV models. Note, however, that we did not model the distribution of PNV types that are mainly under edaphic control. Our methodology was based only on modeling of PNV types that were mainly under climatic control (see Figure 2.2), whereas we added PNV types that were mainly under edaphic control afterwards (as in Figure 2.1 on the right).

Figures 2.3 – 2.8 give the projected distribution of these PNVs based on the climate change projections by the models and under the scenarios listed in Table 3.

Table 4 shows the relative changes for each of the PNVs and the models (and scenarios). Changes are in general large. The results differ considerably between climate change scenarios and models. For example, Lake Victoria drier peripheral semi-evergreen Guineo-Congolian rain forest (Fi) shows a strong increase under the A1B scenario (model CCCMA-CGCM31) but a reduction under scenario A2 (model CCCMA-CGCM2).

However, some general trends (not dependent on a specific scenario or model) are that:

- Suitable areas for Afromontane forests (Fa and Fb) are reducing, especially in Ethiopia.
- Areas with Zambezian Kalahari woodland (Wk) become relatively more suitable for Zambezian dry deciduous forest and scrub forest (Fn).

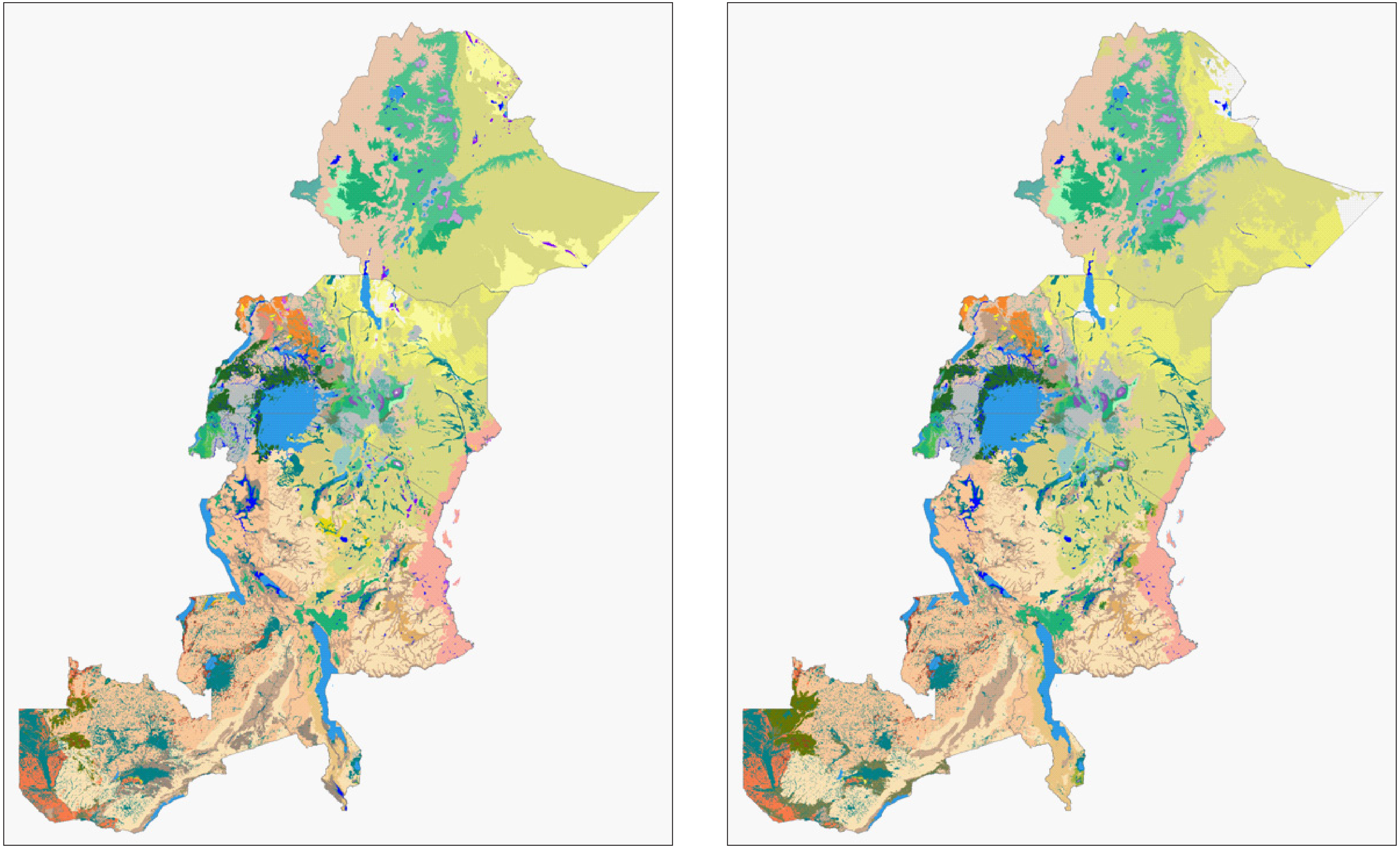


Figure 2.1. A visual comparison between the VECEA potential natural vegetation map (left) and the predicted VECEA map based on climate – vegetation modelling (right). Note that edaphic vegetation types were not modelled (and there is thus a perfect match between the distributions of edaphic vegetation types in both maps).

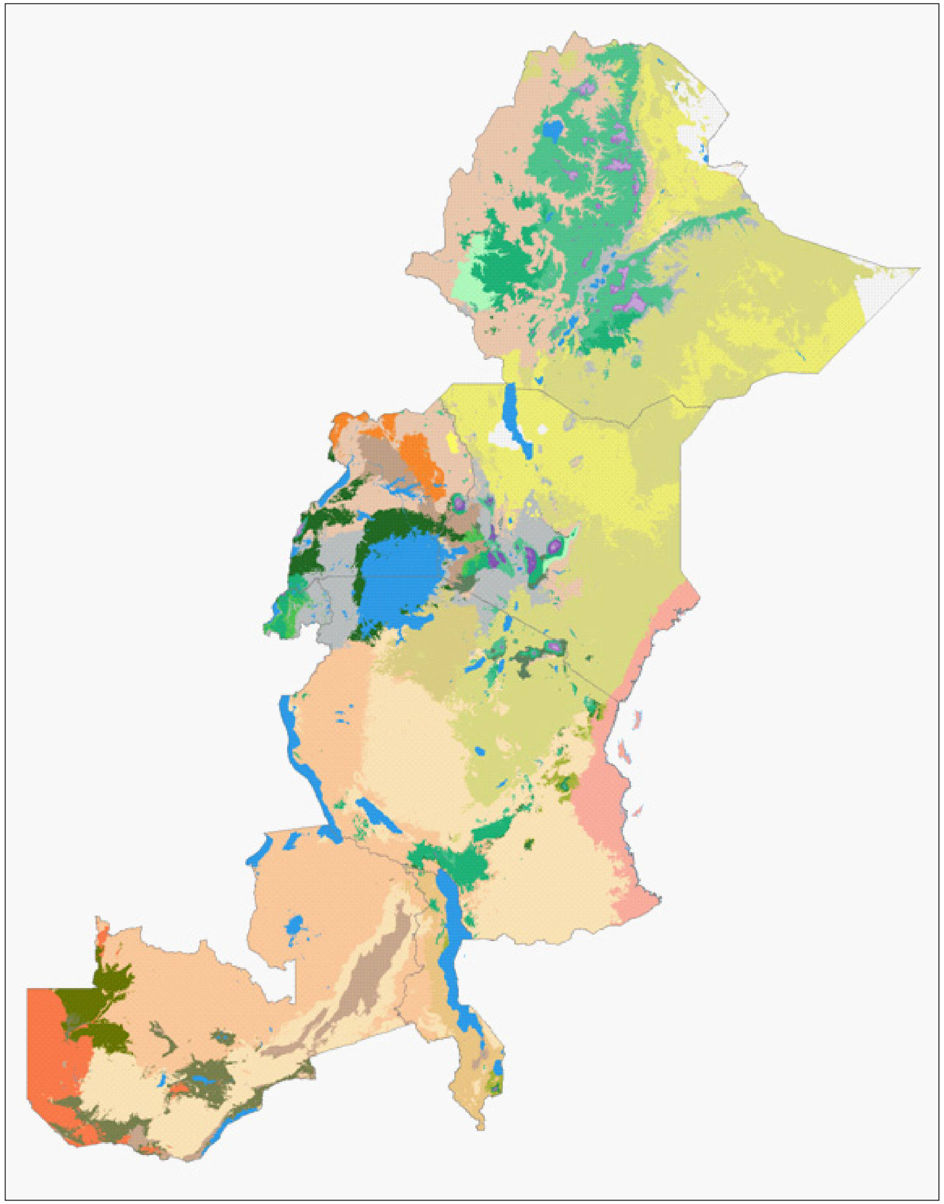


Figure 2.2. We modelled the VECEA potential natural vegetation (PNV) map based on maximum entropy modelling for each PNV type that was mainly under climatic control. Edaphic PNV types were excluded from modelling. The map shown here shows the predicted distribution of PNV under current conditions when only PNVs that are under climatic control are considered.

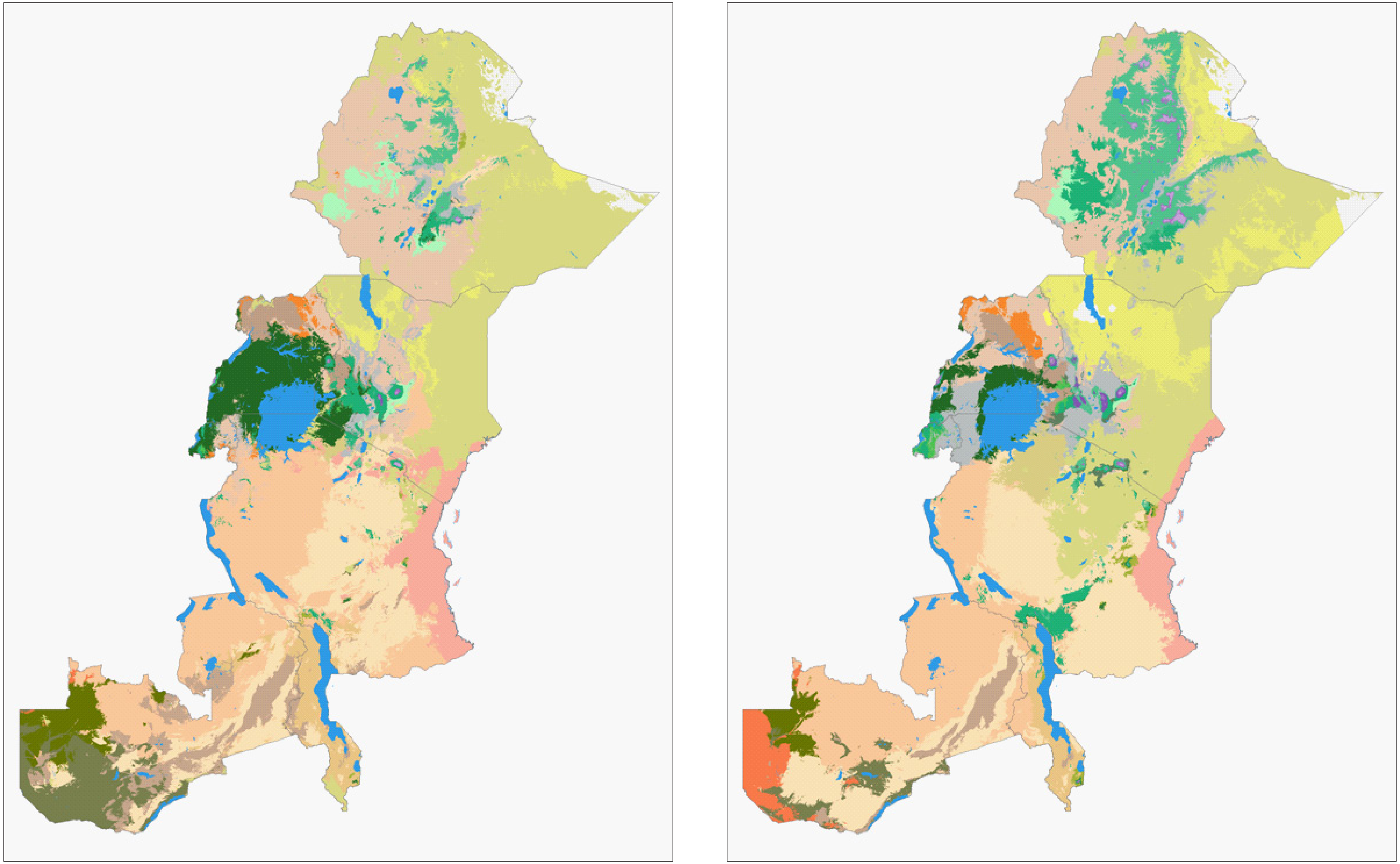


Figure 2.3. Left: projected changes in the distribution of potential natural vegetation (PNV) under scenario A1B (model CCCMA-CGCM31). Right: Modelled distribution of the PNVs under current climate conditions

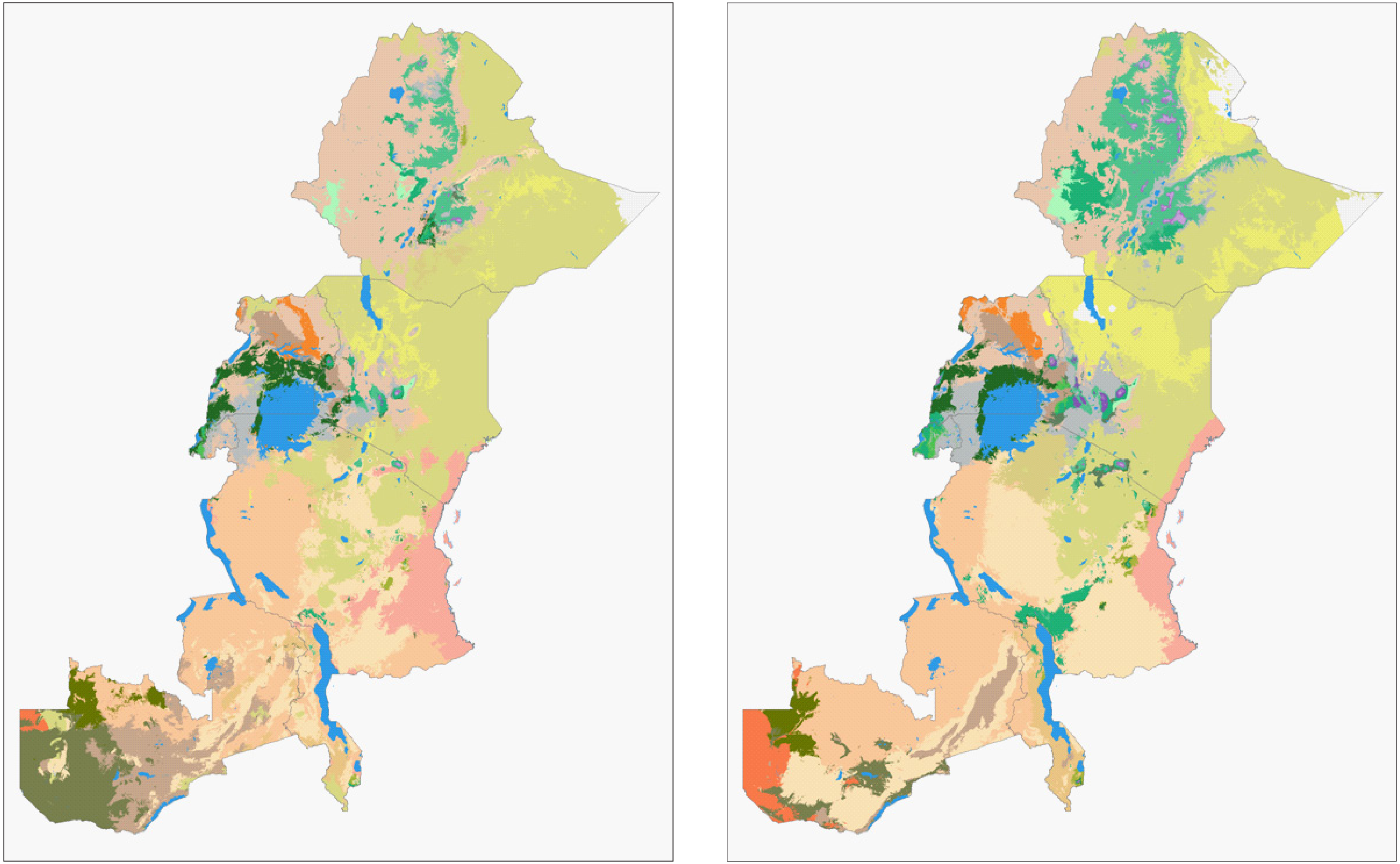
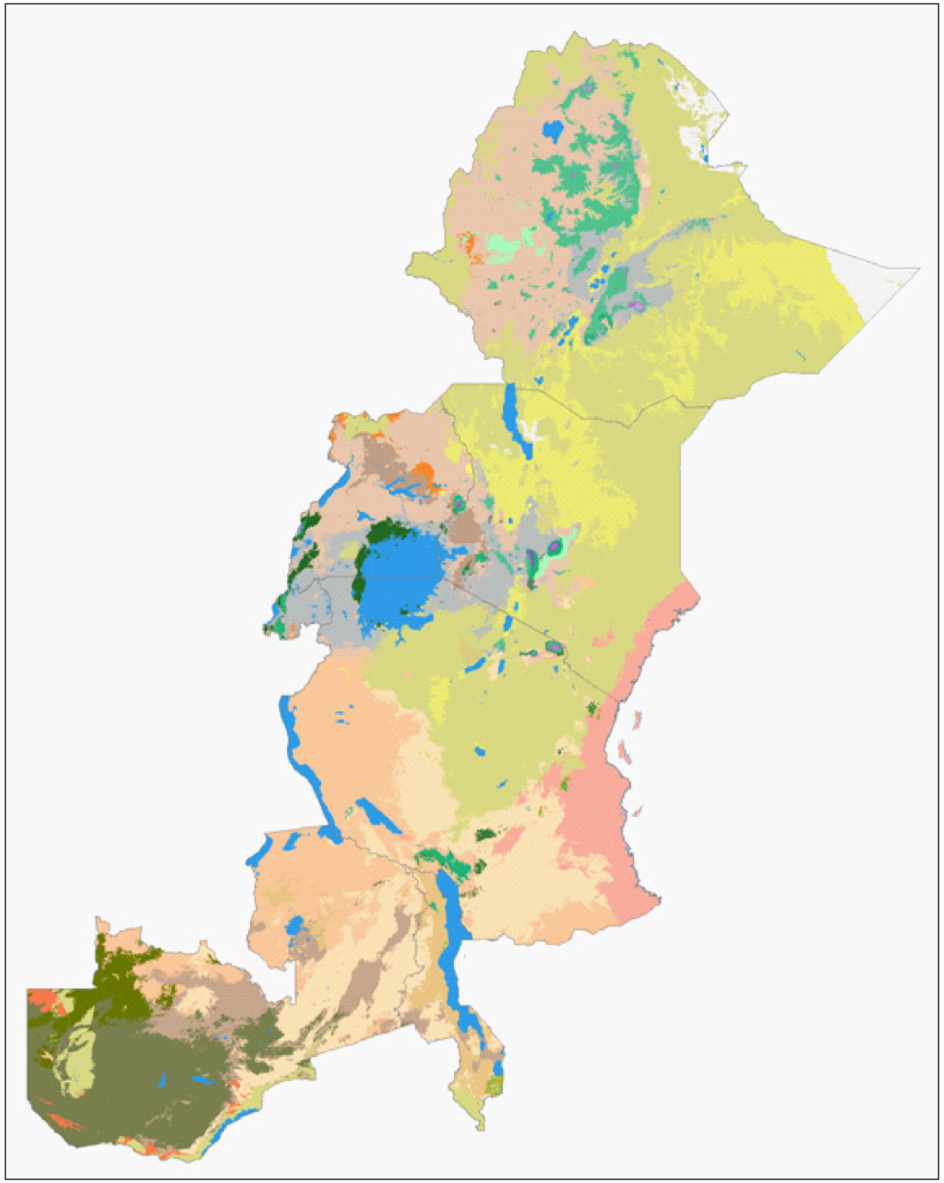


Figure 2.4. Left: projected changes in the distribution of potential natural vegetation (PNV) under scenario A1B (model UKMO-HADCM3). Right: Modelled distribution of the PNVs under current climate conditions



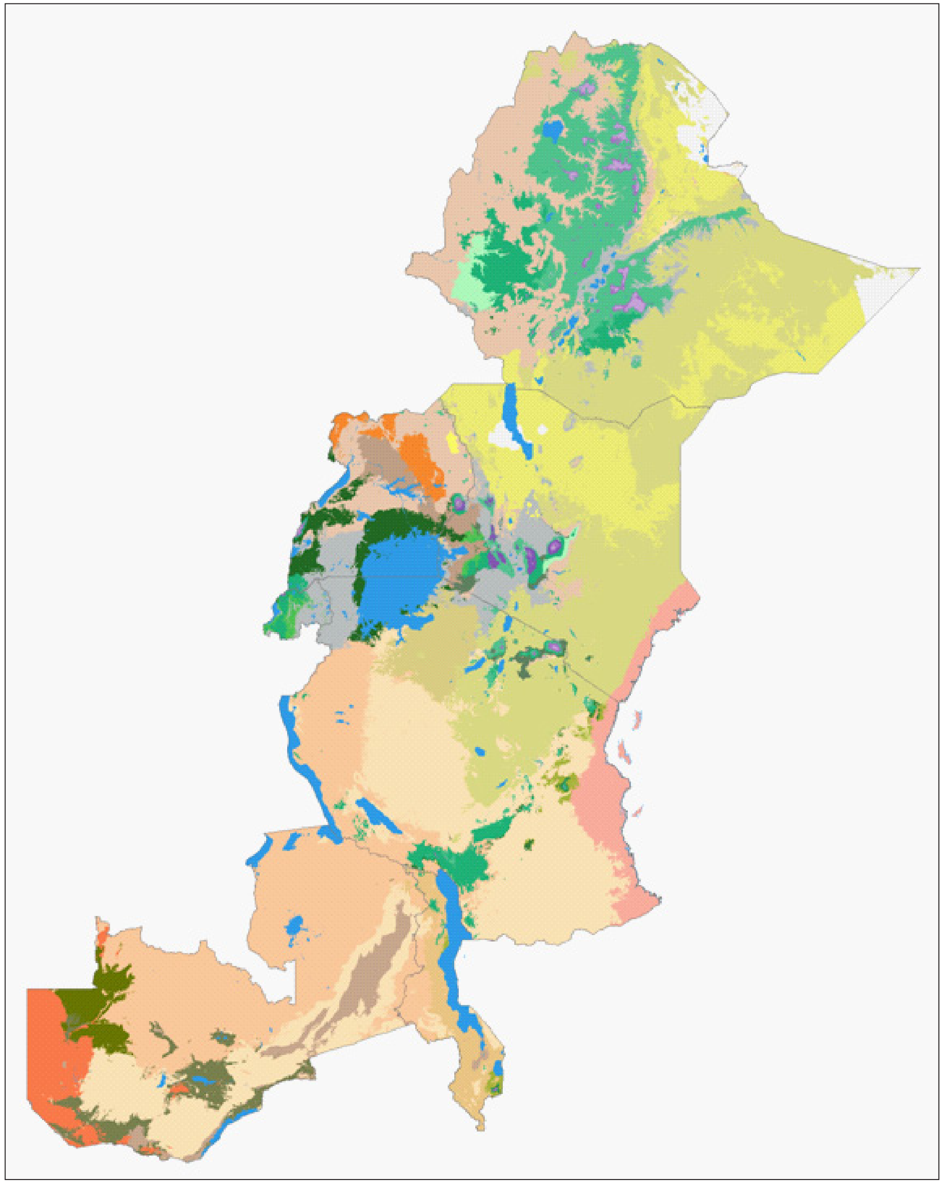


Figure 2.5. Left: projected changes in the distribution of potential natural vegetation (PNV) under scenario A2 (model CCCMA-CGCM2). Right: Modelled distribution of the PNVs under current climate conditions.

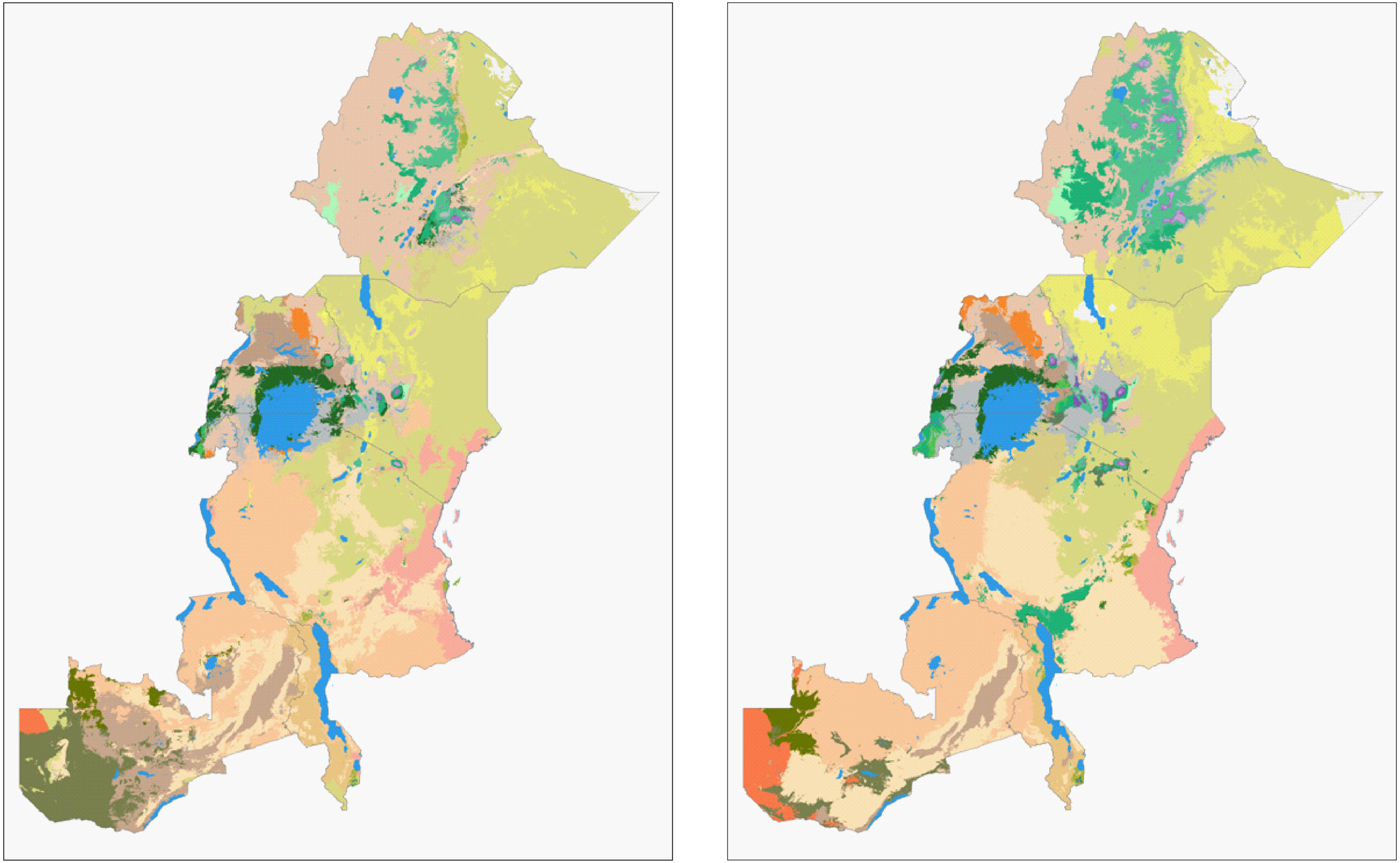


Figure 2.6. Left: projected changes in the distribution of potential natural vegetation (PNV) under scenario A2 (model HCCPR-HADCM3). Right: cModelled distribution of the PNVs under current climate conditions.

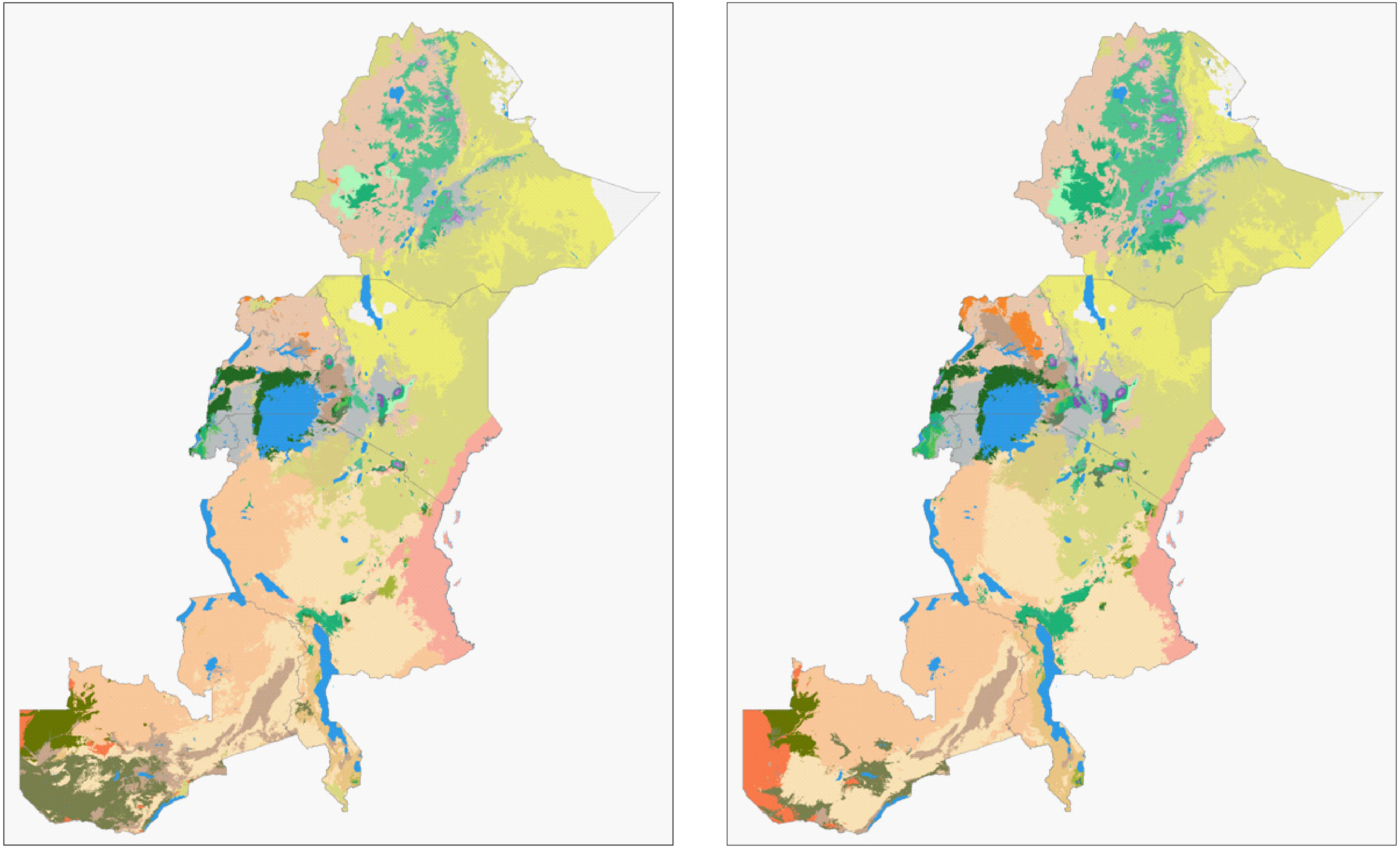


Figure 2.7. Left: projected changes in the distribution of potential natural vegetation (PNV) under scenario B2 (model CCCMA-CGCM2). Right: Modelled distribution of the PNVs under current climate conditions.

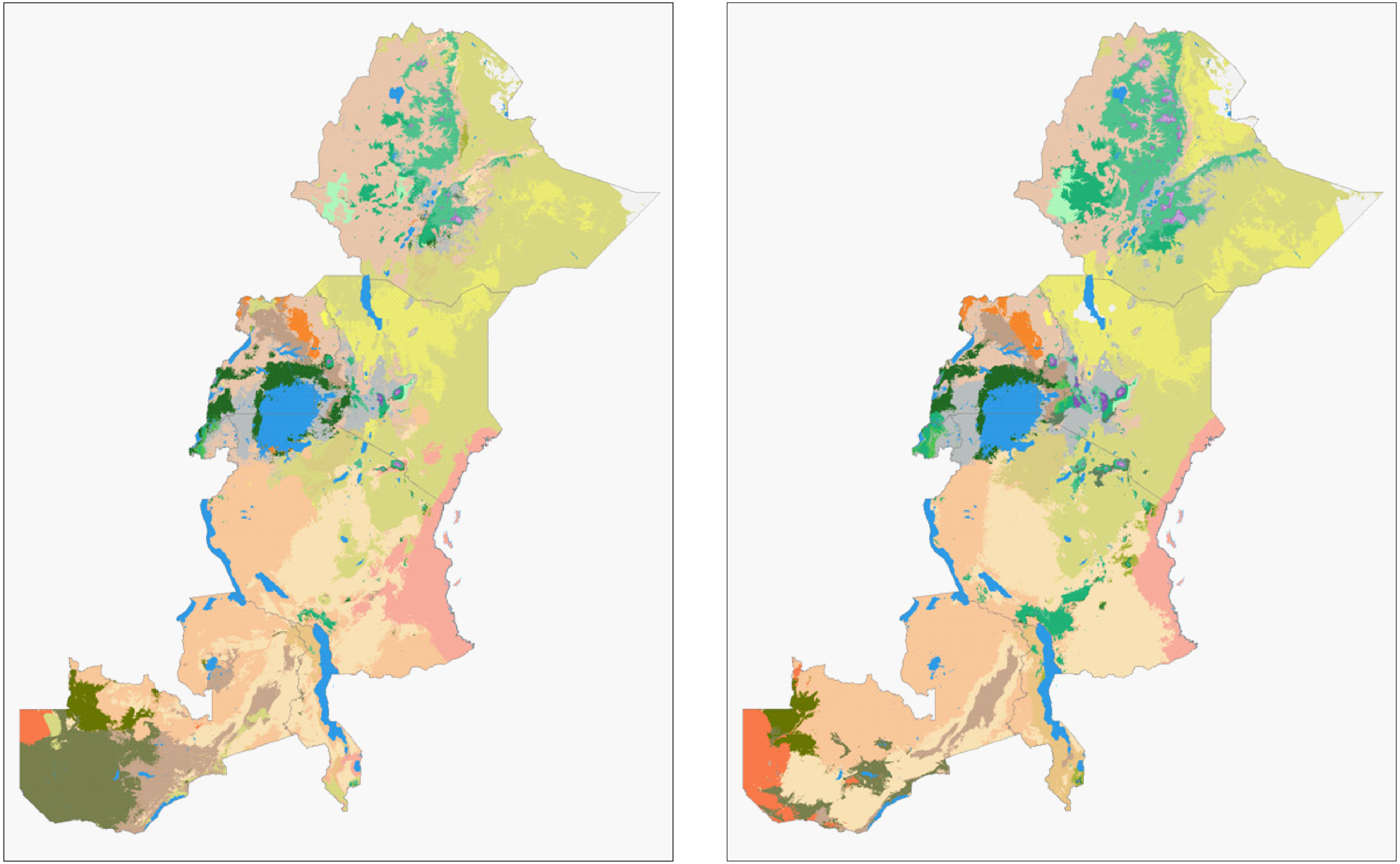


Figure 2.8. Left: projected changes in the distribution of potential natural vegetation (PNV) under scenario B2 (model HCCPR-HADCM3). Right: Modelled distribution of the PNVs under current climate conditions.

Table 4. The percentage change in surface areas with the highest suitability score for the given Potential Natural Vegetation type (PNV) for different GCM models and scenarios. See Table 1 for full names of PNVs. ZI = Zanzibar-Inhambane coastal mosaic (see Volume 6).

PNV	**CCCMA CGCM31 A1B**	**UKMO HADCM3 A1B**	**CCCMA CGCM2 A2**	**HCCPR HADCM3 A2**	**CCCMA CGCM2 B2**	**HCCPR HADCM3 B2**
Fa	-45%	-71%	-82%	-68%	-60%	-51%
Fb	-77%	-64%	-58%	-74%	-36%	-59%
Fe	**+144%**	-7%	-25%	-25%	+23%	+7%
Ff	-79%	-70%	-94%	-72%	-46%	-56%
Fg	-58%	-82%	-6%	-87%	-15%	-60%
Fh	-82%	-71%	-76%	-69%	-50%	-77%
Fi	**+212%**	+31%	-59%	+29%	-11%	+27%
Fm	**+109%**	-4%	+37%	-29%	33%	+8%
Fn	**+180%**	**+229%**	**+338%**	**+232%**	**+164%**	**+292%**
Fo	-63%	-39%	-62%	-10%	-25%	-50%
Bdd	+15%	+43%	+51%	+38%	+2%	+16%
Bds	-78%	-75%	-12%	-71%	+7%	-42%
Be	-58%	-33%	+19%	-44%	+1%	-20%
Wb	-39%	-21%	-59%	-47%	-82%	-27%
Wcm	+27%	-8%	-6%	+70%	-19%	+12%
Wcd	+51%	+67%	+22%	+75%	+23%	+56%
Wd	-82%	-36%	-88%	-40%	-30%	-16%
Wk	-97%	-90%	-84%	-83%	-84%	-75%
Wmw	12%	6%	-31%	-3%	-4%	-4%
Wmd	-18%	-37%	-31%	-31%	-2%	-18%
Wmr	+72%	-20%	+7%	+42%	-18%	-57%
Wo	**+203%**	**+222%**	**+122%**	**+294%**	**+108%**	**+141%**
A	-87%	-92%	-87%	-93%	-73%	-86%
B	-88%	-96%	-83%	-89%	-69%	-85%
D	-20%	-66%	+7%	-68%	+25%	-43%
E	-86%	-78%	-74%	-74%	-54%	-60%
G	**-100%**	-84%	-73%	-45%	-37%	-44%
ZI	+82%	+88%	+61%	+40%	+56%	+91%

The results shown in figures 2.3 – 2.8 and table 4 need to be interpreted with much care. Notwithstanding the uncertainties in predicting future climates, the highest suitability score for a grid cell can be very low (even below 0.1 – corresponding to a probability of less than 10%) as illustrated in Figures 2.9 – 2.14.

Low probability scores indicate that the (combination of) conditions in the respective raster cells are either outside or at the extreme of the ranges of environmental conditions that are currently found in the region. In areas with low maximum suitability scores, it may be more likely that new vegetation types will develop, containing new combinations of species and possibly changes in physiognomy.

In general, the large areas with low probability scores (Figures 2.9 – 2.14) show that there are large uncertainties how vegetation will develop under possible future climates.

Another point to consider is the increasing distances between the current distribution area of a PNV type (and its species) and areas that will become more suitable for the same vegetation type under changing climates. With larger distances, it becomes more difficult for natural shifts to new areas to occur. In these situations, establishment at present of sources of tree seeds across the environmental range of (important) tree species may become essential to enable human-assisted migration.

3. Suitability distribution modelling of two important agroforestry species (*Prunus africana* and *Warburgia ugandensis*) in current and possible future climates based on the VECEA map

3.1 Methods

In volumes 2-5 of the VECEA documentation, each potential natural vegetation (PNV) type is linked to species composition tables. These tables provide a list of species that typically occur in each of the vegetation types, including characteristic and indicator species.

Information on species composition enables us to use the distribution of vegetation types as a proxy for the distribution of listed woody species. This is achieved by approximating the distribution of a species with the distribution of all the PNVs in which this species is known to occur. In many situations, this remains the best model that we currently have for most African tree species. This is a consequence of the situation that, although sophisticated approaches are currently available (such as the maximum entropy modelling in combination with statistically downscaled geospatial data sets that was used in section 2), comprehensive and high-resolution point-location data sets are not available for most of these species at present.

To illustrate the methodology of using the VECEA map to predict the possible future distribution of tree species, we selected two important tree species: *Prunus africana* and *Warburgia ugandensis*.

Prunus africana is a characteristic or indicator species in the following PNVs: Afromontane rain forest (VECEA mapping unit Fa; for descriptions of PNVs, refer to VECEA volumes 2 to 5), Afromontane undifferentiated forest (Fb) and Lake Victoria transitional rain forest (Ff). This species was also recorded to be present in Afromontane single-dominant *Widdringtonia whytei* forest (Fc), Afromontane moist transitional forest (Fe), Lake Victoria drier peripheral semi-evergreen Guineo-Congolian rain forest (Fi), Zanzibar-Inhambane transitional rain forest (Fg), Riverine forests (fr, an edaphic forest type that was excluded from modelling), swamp forest (fs, an edaphic forest type that was excluded from modelling), Afromontane bamboo (B) and the Montane Ericaceous belt (E).

Warburgia ugandensis was listed as a characteristic or indicator species for only one VECEA vegetation type: Afromontane dry transitional forest (VECEA mapping unit Fh). This species was recorded to further occur in Afromontane undifferentiated forest (Fb), Afromontane moist transitional forest (Fe), Lake Victoria transitional rain forest (Ff), Lake Victoria drier peripher-

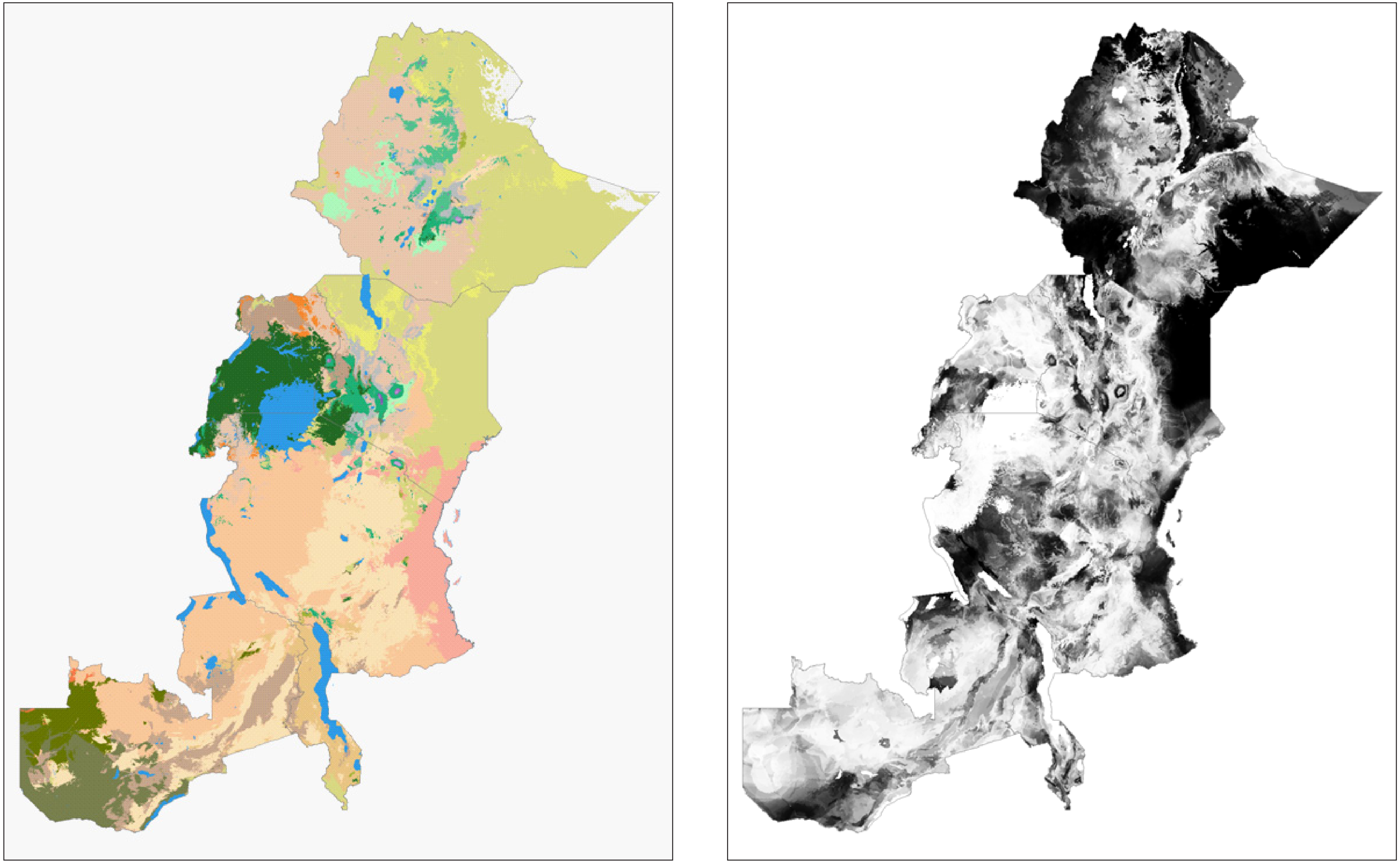


Figure 2.9. Projected changes in the distribution of potential natural vegetation (PNV) under scenario A1B (model CCCMA-CGCM31). Left: projected distribution of PNV based on maximum probabilities of occurrence. Right: maximum probabilities of occurrence (darker areas have higher probabilities).

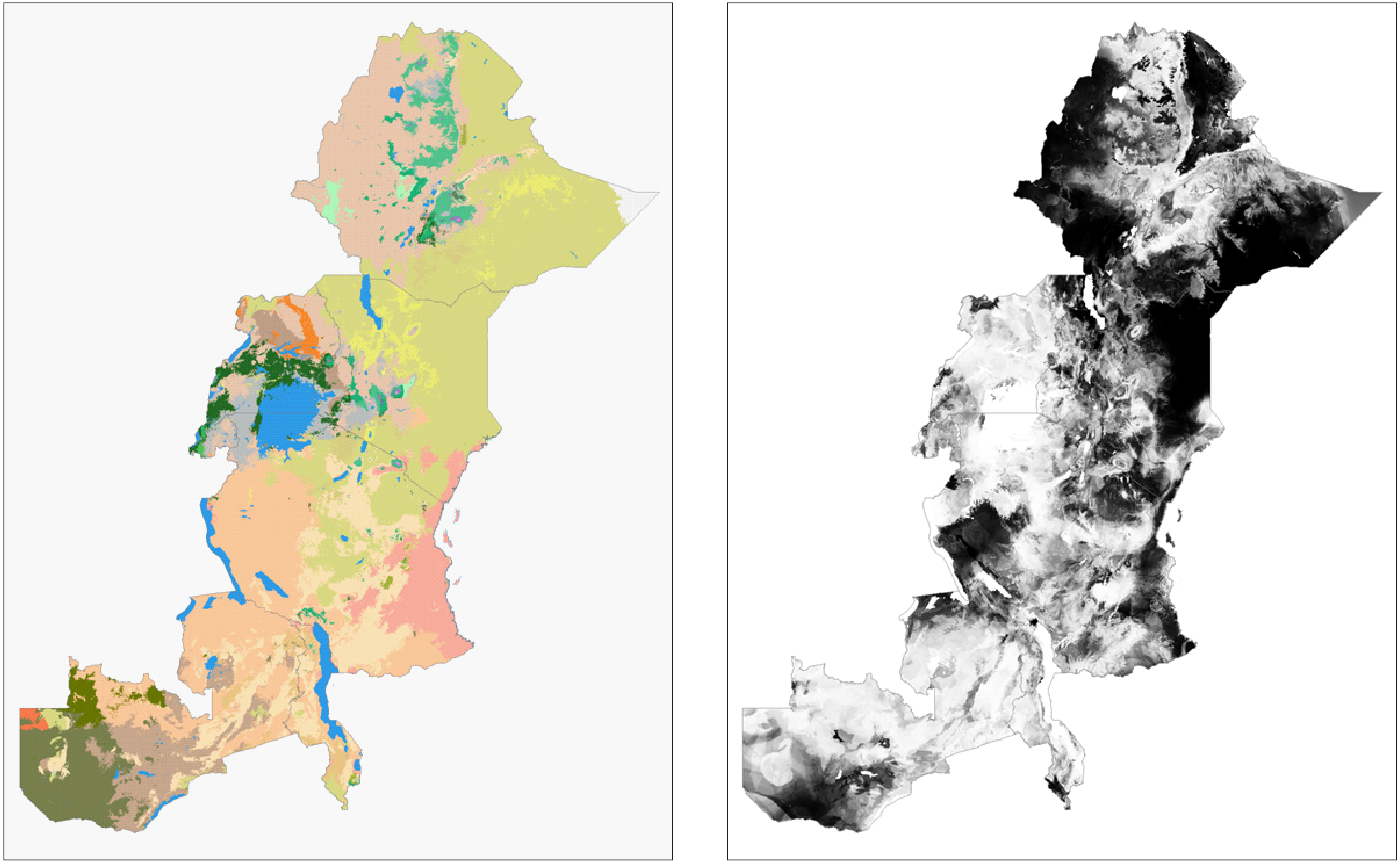


Figure 2.10. Projected changes in the distribution of potential natural vegetation (PNV) under scenario A1B (model UKMO-HADCM3). Left: projected distribution of PNV based on maximum probabilities of occurrence. Right: maximum probabilities of occurrence (darker areas have higher probabilities).

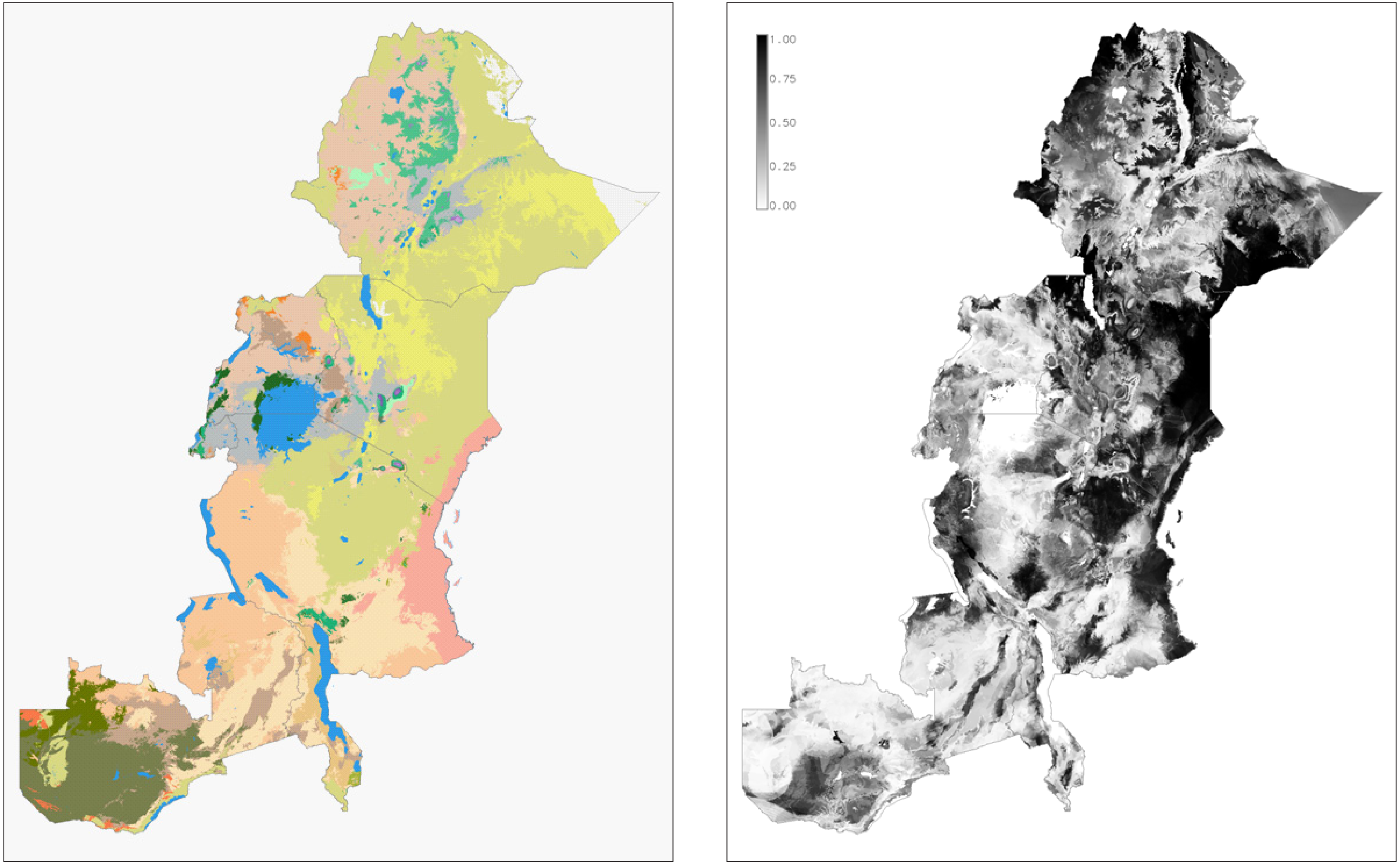


Figure 2.11. Projected changes in the distribution of potential natural vegetation (PNV) under scenario A2 (model CCCMA-CGCM2). Left: projected distribution of PNV based on maximum probabilities of occurrence. Right: maximum probabilities of occurrence (darker areas have higher probabilities).

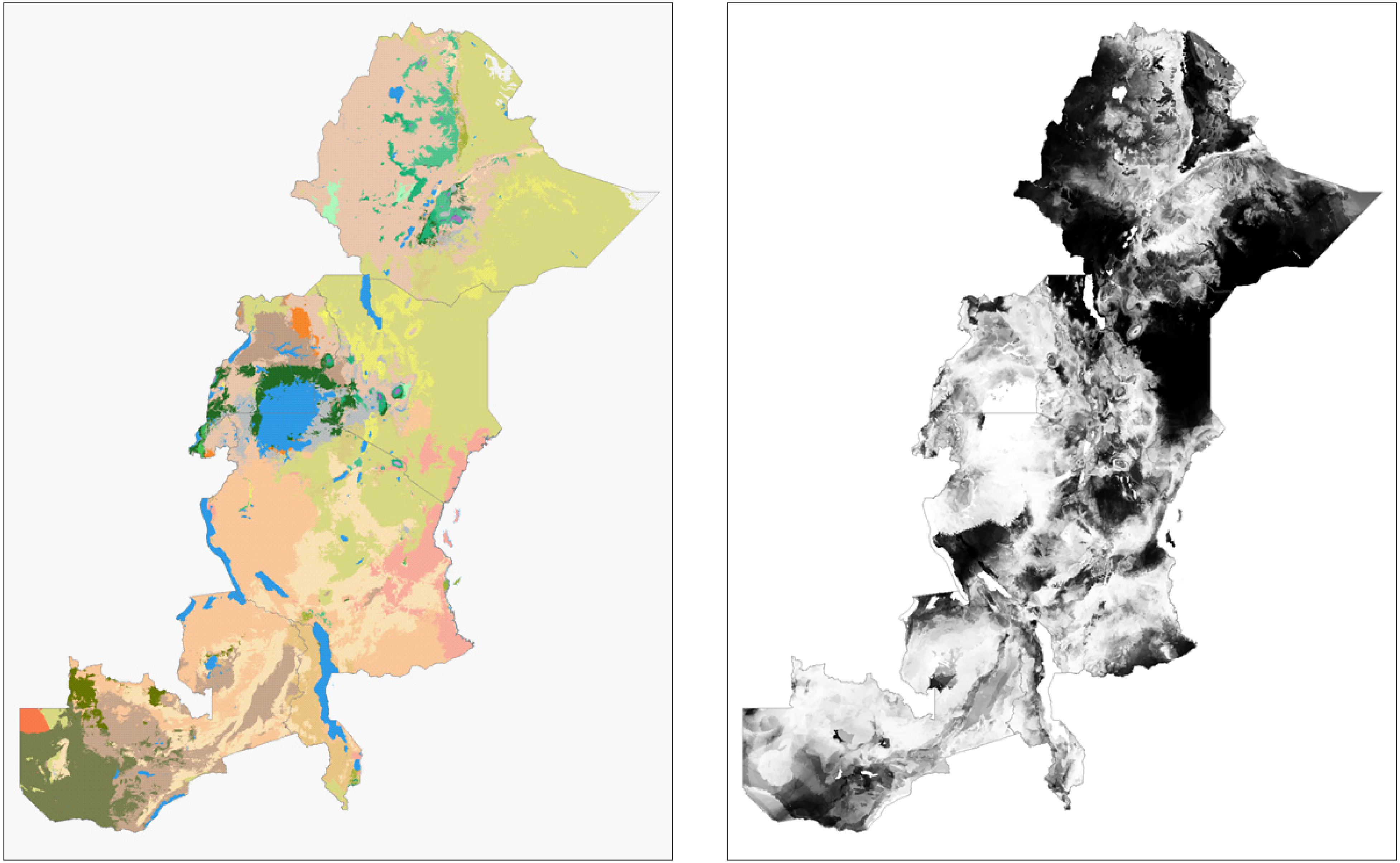


Figure 2.12. Projected changes in the distribution of potential natural vegetation (PNV) under scenario A2 (model HCCPR-HADCM3). Left: projected distribution of PNV based on maximum probabilities of occurrence. Right: maximum probabilities of occurrence (darker areas have higher probabilities).

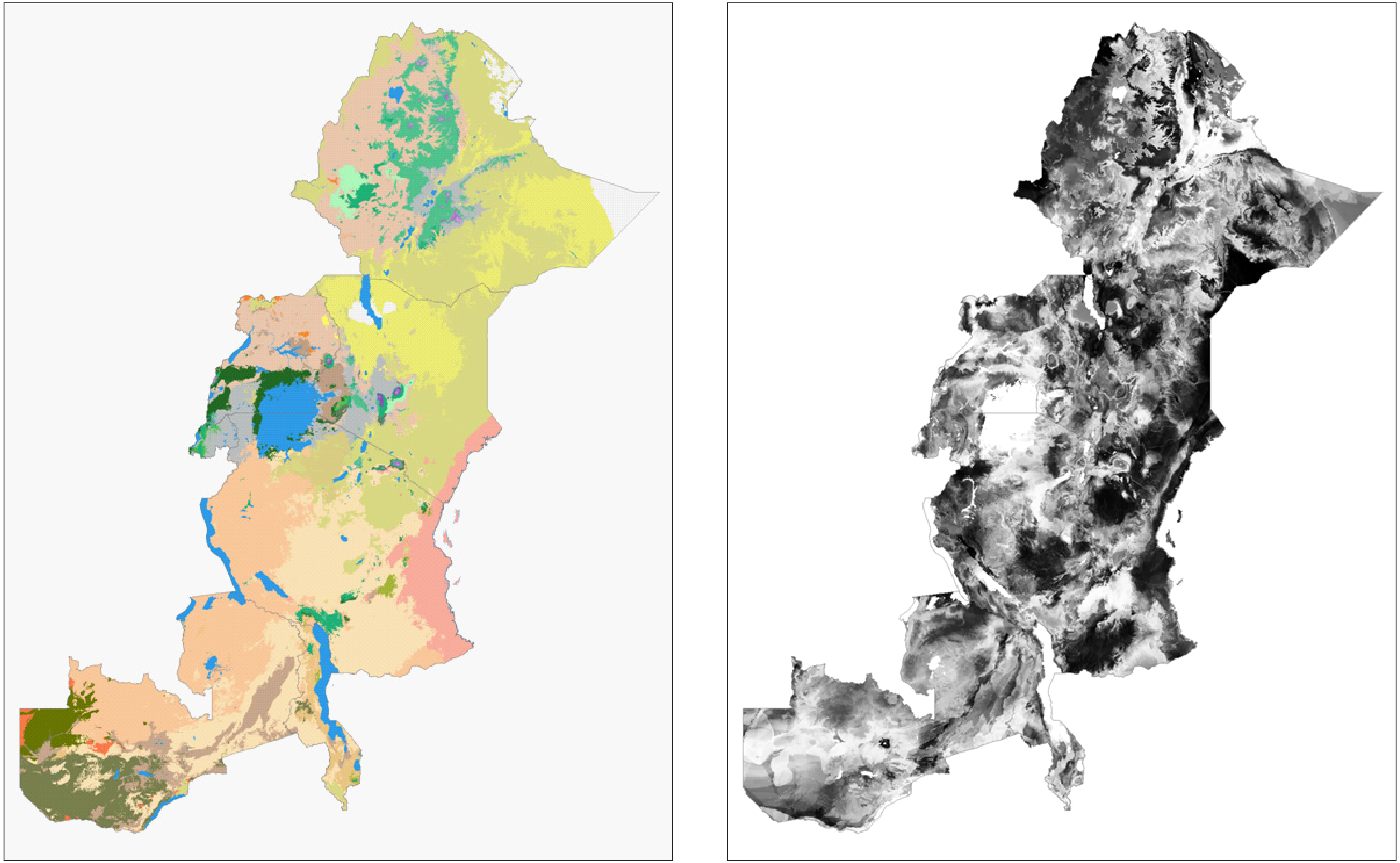


Figure 2.13. Projected changes in the distribution of potential natural vegetation (PNV) under scenario B2 (model CCCMA-CGCM2). Left: projected distribution of PNV based on maximum probabilities of occurrence. Right: maximum probabilities of occurrence (darker areas have higher probabilities).

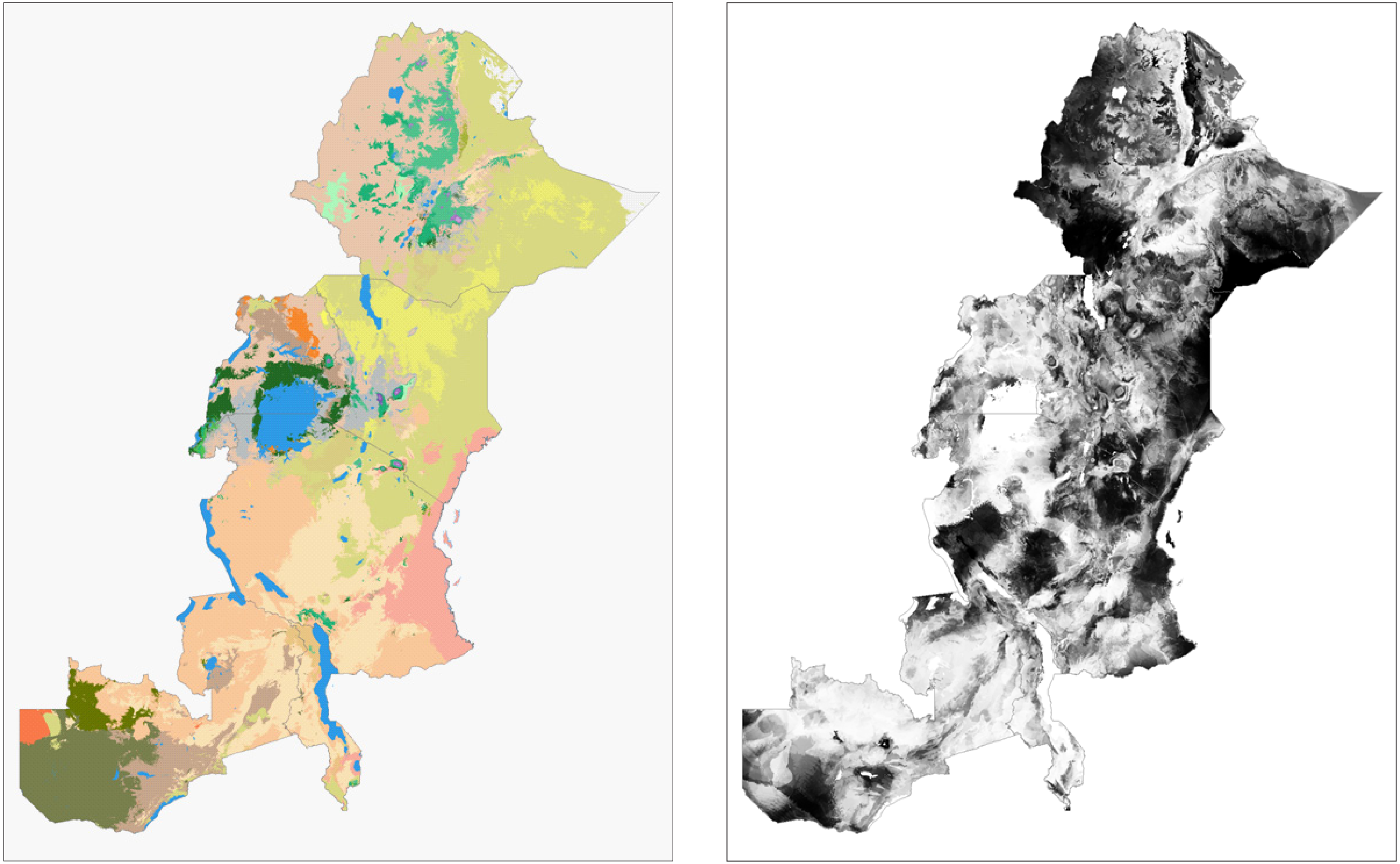


Figure 2.14. Projected changes in the distribution of potential natural vegetation (PNV) under scenario B2 (model HCCPR-HADCM3). Left: projected distribution of PNV based on maximum probabilities of occurrence. Right: maximum probabilities of occurrence (darker areas have higher probabilities).

al semi-evergreen Guineo-Congolian rain forest (Fi), Riverine forests (fr, an edaphic forest type that was excluded from modelling), Swamp forest (fs, an edaphic forest type that was excluded from modelling) and Evergreen and semi-evergreen bushland and thicket (Be).

We combined the suitability distribution models of the PNVs listed for each species, using the maximum score of the models of the selected PNVs to create a suitability distribution map of. The implicit assumption that we made with this approach is that the probability of encountering the focal species (*Prunus africana* or *Warburgia ugandensis*) within each vegetation type does not differ between PNVs. This may not be a realistic assumption for each vegetation type (for example, we expect that the probability of encountering *Prunus africana* within the montane Ericaceous belt is considerably lower than encountering this species within Afromontane rain forest). Another assumption that was made in the species composition tables of Volumes 2 – 5 is that floristic information (information that a species occurred in a country) could be interpreted (as done here for *Prunus africana* or *Warburgia ugandensis*) as evidence that a species occurred within each country where a particular PNV occurs **based only on evidence from some of the countries where the vegetation type occurs.** This may be a particularly "dangerous" assumption and we therefore encourage anybody who uses the VECEA map and its documentation not to use the map as a "decision making tool", but rather as a "decision support tool" that is used together with other sources of information (such as the experience of foresters, botanists and ecologists in particular countries).

We used the same method of combining PNV-specific probability models (based on the highest probability score amongst them) in creating habitat suitability maps of *Prunus africana* and *Warburgia ugandensis* under projected future climates. For projections in future climates, we used the same downscaled models and scenarios that were used for the modelling of the VECEA map in future climates (see Table 3).

3.2 Predicted distribution of *Prunus africana* and *Warburgia ugandensis* in current climates

Figures 3.1 and 3.2 show the estimated suitability distribution range of the two species.

Maps as shown here offer a view on the distribution of these species complementary to maps based on point location data. Ideally we should include point location data to these probability maps as these provide an independent method to verify the accuracy of these maps.

3.3 Predicted distribution of *Prunus africana* and *Warburgia ugandensis* in possible future climates

The possible distribution of the vegetation types under projected future climate conditions give an indication of the impact of climate change on the species (Figures 3.3 – 3.8).

Tables 5 show the average scores of respectively the *Prunus africana* and *Warburgia ugandensis* suitability maps under current and possible future (2080) climates within the PNVs in which these species are reported to occur.

It shows that the areas where *Prunus africana* and *Warburgia ugandensis* are currently expected to occur (*i.e.* under the assumptions that we listed above) will generally become less suitable. Perhaps unsurprisingly, effects are strongest under the climate change scenario's A1 and A2, but also note the differences between the different models.

Table 3.1 Average suitability scores of the *Prunus africana* probability maps under current and future climates within the PNV's in which these species are reported to occur. Projected future climates are all for 2080.

Climate model / scenario	Average suitability score for *Prunus africana*	Average suitability score for *Warburgia ugandensis*
current conditions	0.56	0.48
cccma_cgcm2_A2a	0.19	0.23
cccma_cgcm2_B2a	0.33	0.34
cccma_cgcm31_A1b	0.23	0.20
hccpr_hadcm3_A2a	0.16	0.14
hccpr_hadcm3_B2a	0.26	0.22
ukmo_hadcm3_A1b	0.19	0.17

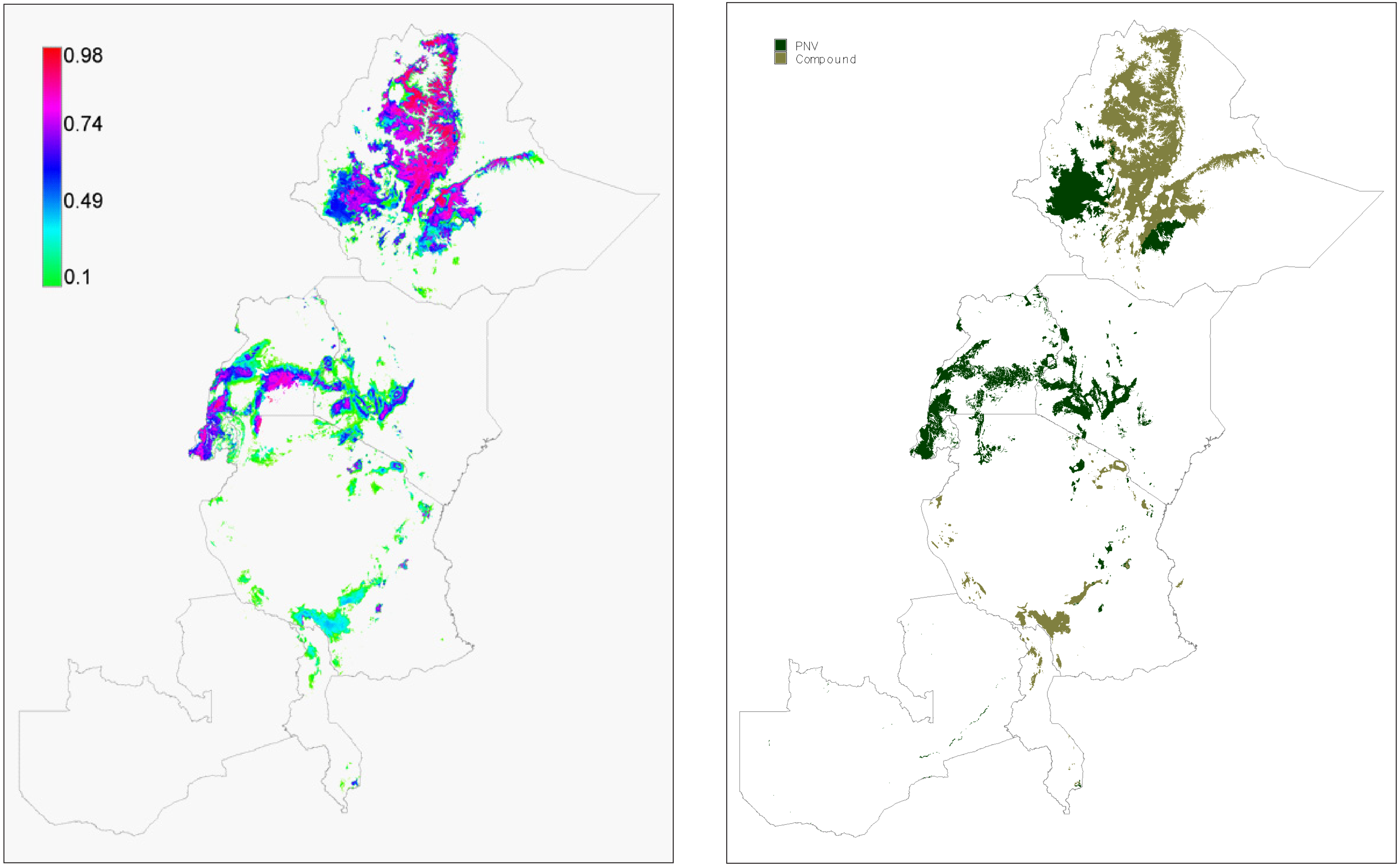


Figure 3.1. Left: Modelled distribution of *Prunus africana* under present conditions. Right: Distribution of potential natural vegetation in the VECEA map in which *Prunus africana* is reported to occur (see text).

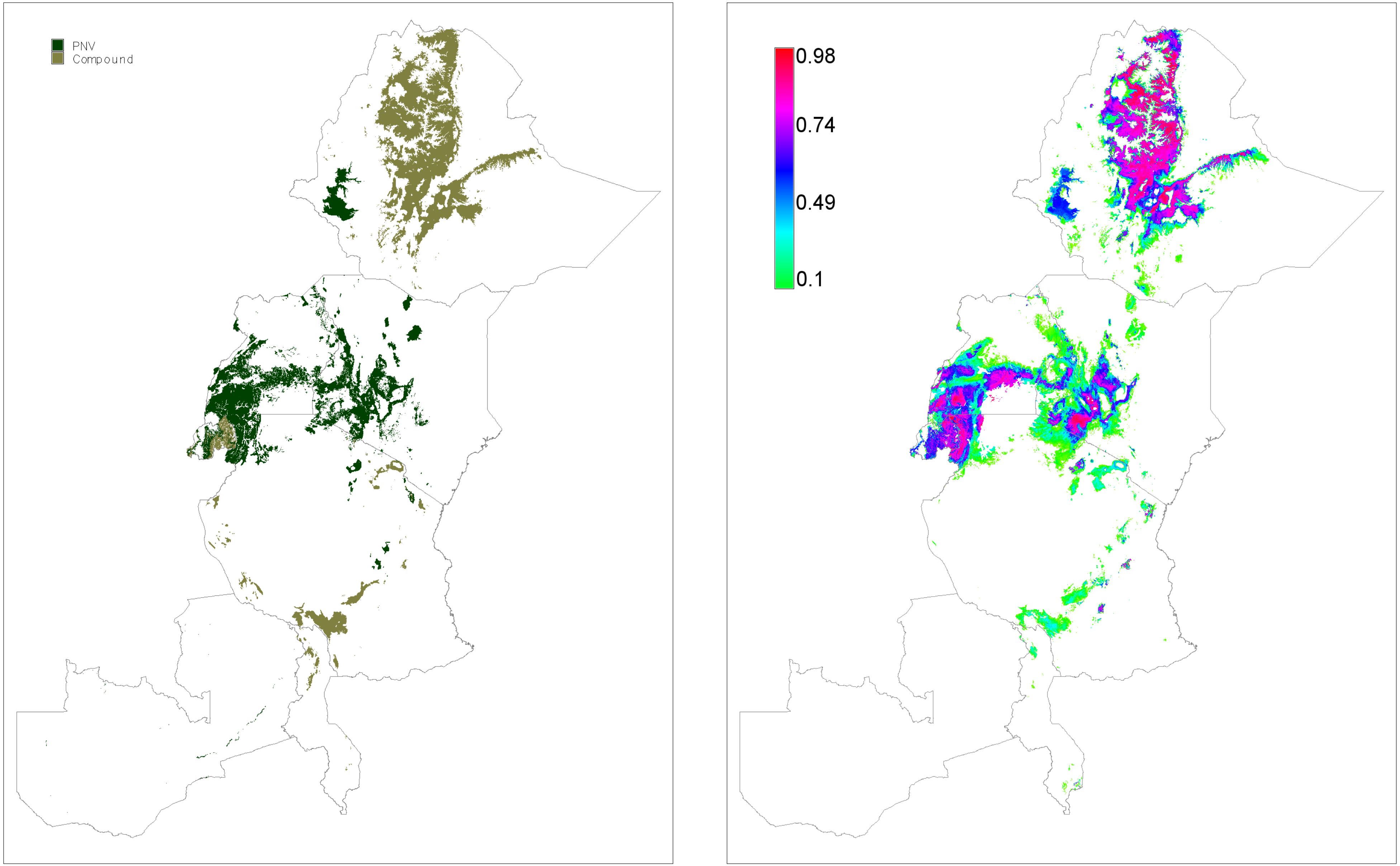
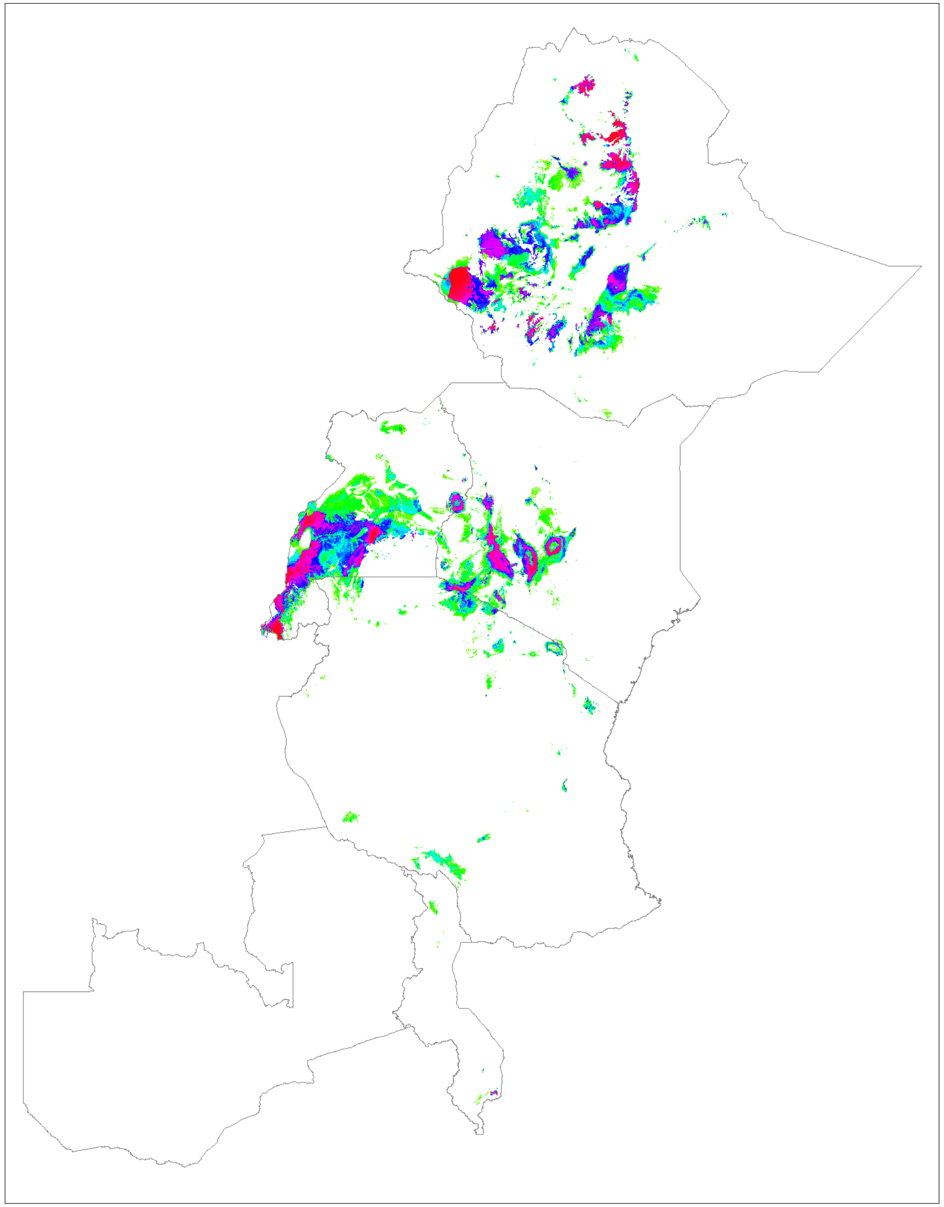


Figure 3.2. Left: Distribution of potential natural vegetation in the VECEA map in which *Warburgia ugandensis* is reported to occur. Right: Modelled distribution of *Warburgia ugandensis* under present conditions.



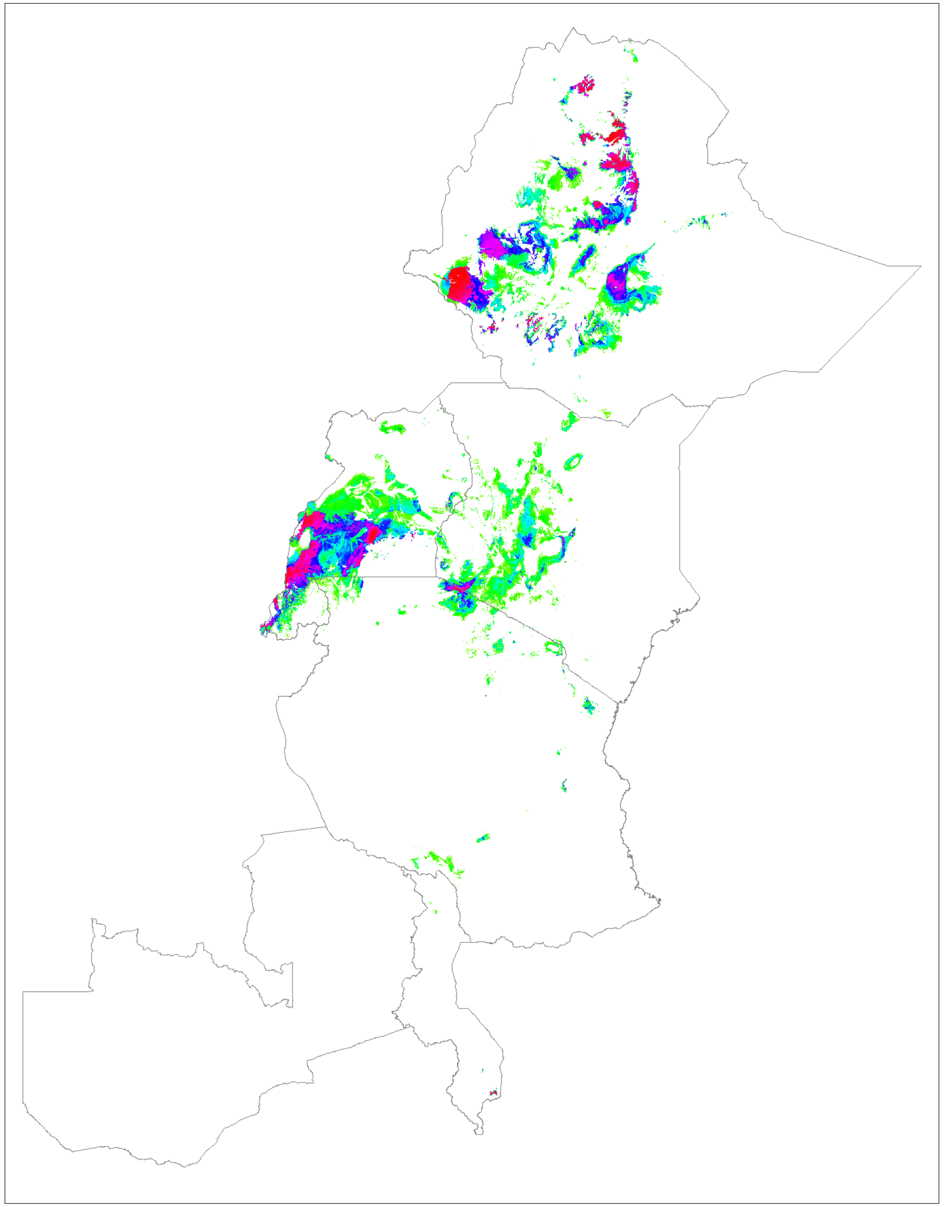


Figure 3.3. Projected changes in the distribution of two important agroforestry species under scenario A1B (model CCCMA-CGCM31). Left: possible future distribution of *Prunus africana*. Right: possible future distribution of *Warburgia ugandensis*.

Figures 3.9 to 3.14 give for the different future climate change scenarios the changes in areas suitable for the PNVs in which *Prunus africana* and *Warburgia ugandensis* occur, including: (i) areas that are suitable under current conditions (baseline) and will remain so under future climates (*i.e.* remaining habitat); (ii) areas that are suitable under current conditions but not under future climates (possible declining habitat); (iii) areas that are unsuitable under current conditions and suitable under future climates (possible new habitat); and (iv) areas that are unsuitable now and under future climates. In these figures, we used a suitability threshold of 0.2 below which we assumed that areas would not be suitable for the species. This threshold gave a good balance between false positives and false negatives in the predictions of areas where the species occur and do not occur.

Using future projections of vegetation probability distribution models, we make some important, and largely untested assumptions about how the climate influences the distribution of vegetation and species in a similar manner. However, in lieu of more species specific information, the results do give an indication of the potential impact of climate change on the species. For all models and scenarios, the possible impact of climate change is largely negative for these species, with climate conditions in the current distribution area getting less suitable for both *Prunus africana* and *Warburgia ugandensis*. Differences between models and scenario's are considerable though, making it difficult to predict where the changes are largest.

It should be noted that both species are typical forest species (although *Warburgia ugandensis* is also a species that is confirmed as a constituent of the evergreen and semi-evergreen bushland and thicket type), and that results might therefore look different for the more typical dryland species.

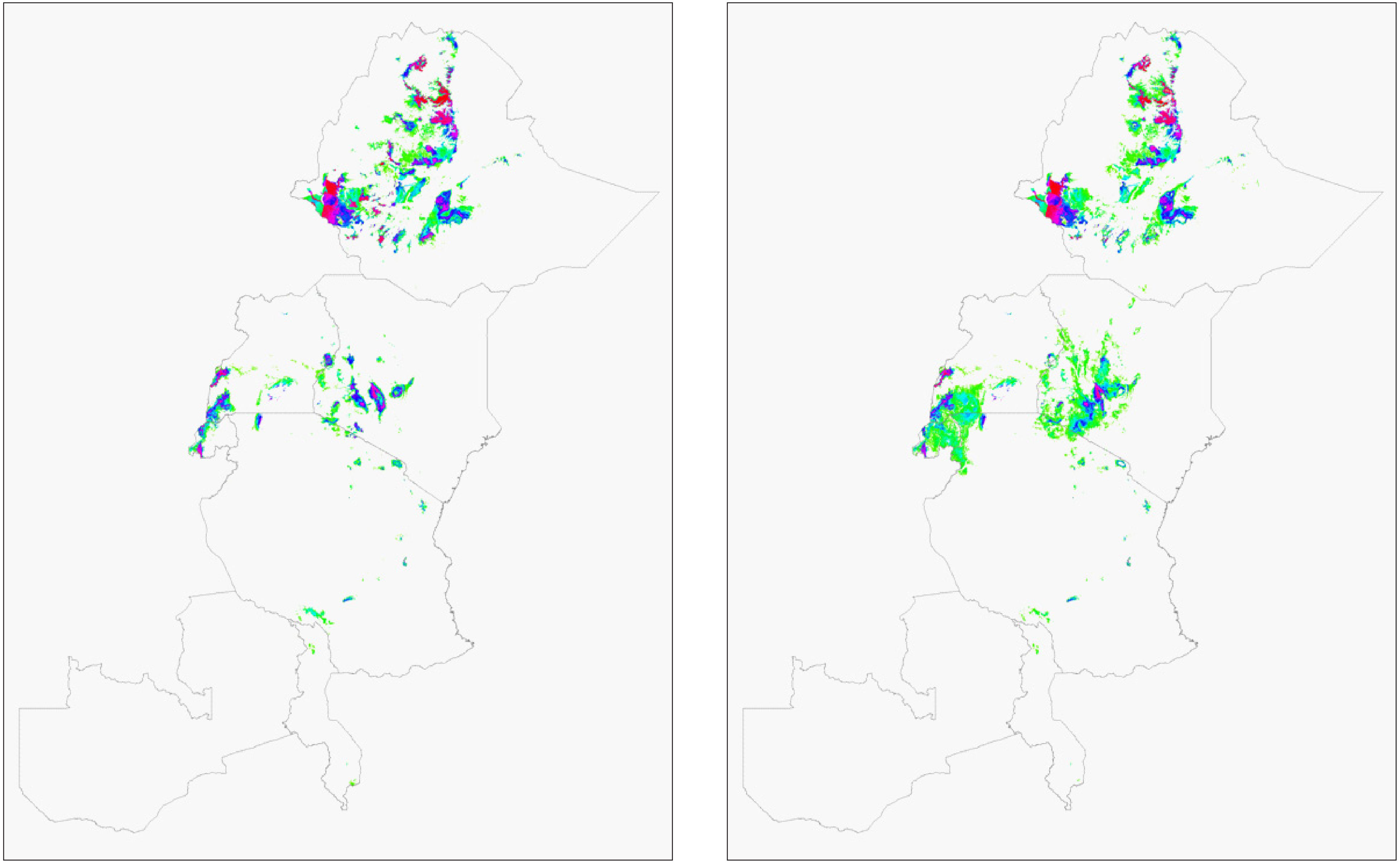


Figure 3.4. Projected changes in the distribution of two important agroforestry species under scenario A1B (model UKMO-HADCM3). Left: possible future distribution of Prunus africana. Right: possible future distribution of *Warburgia ugandensis*.

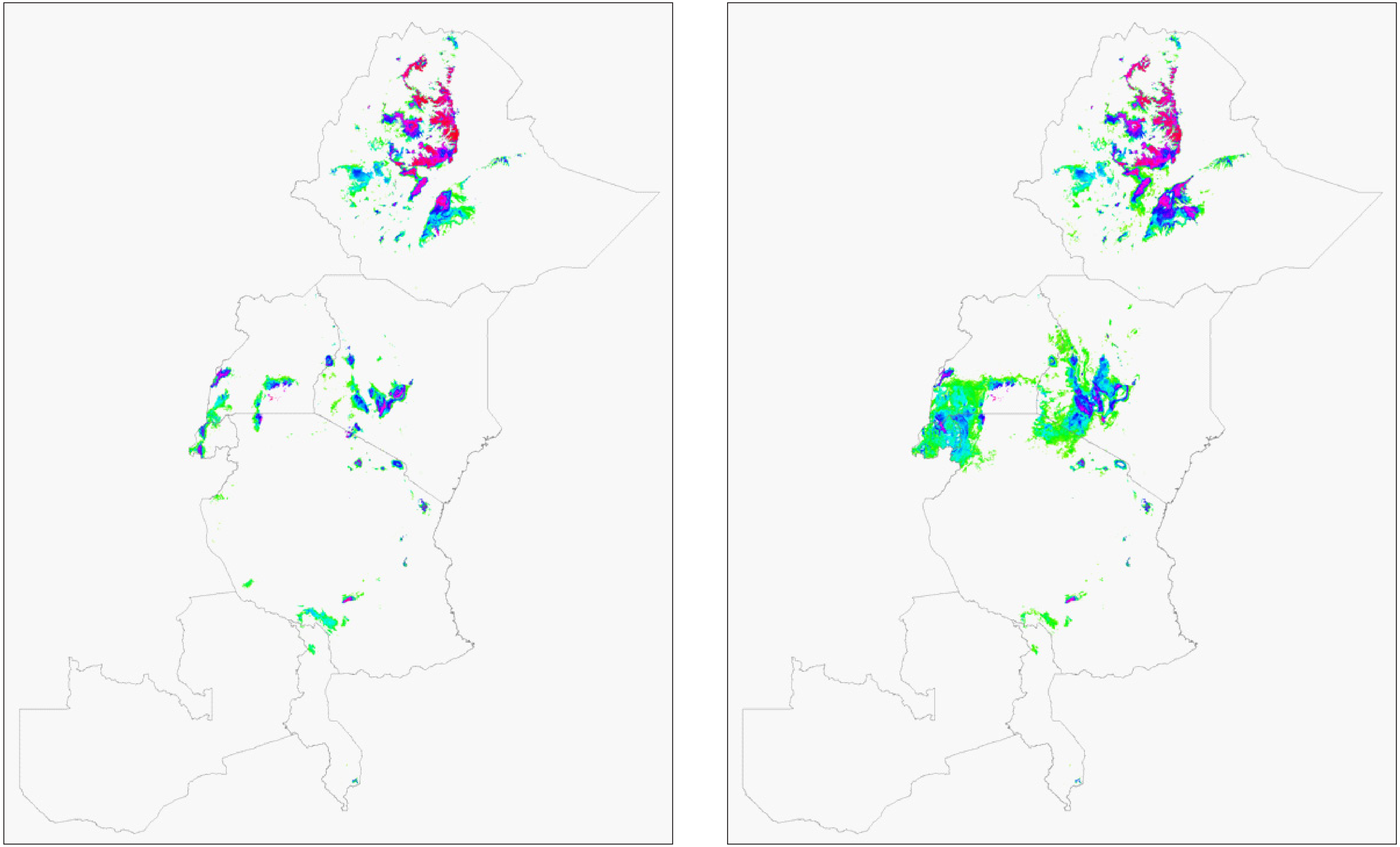


Figure 3.5. Projected changes in the distribution of two important agroforestry species under scenario A2 (model CCCMA-CGCM2). Left: possible future distribution of Prunus africana. Right: possible future distribution of *Warburgia ugandensis*.

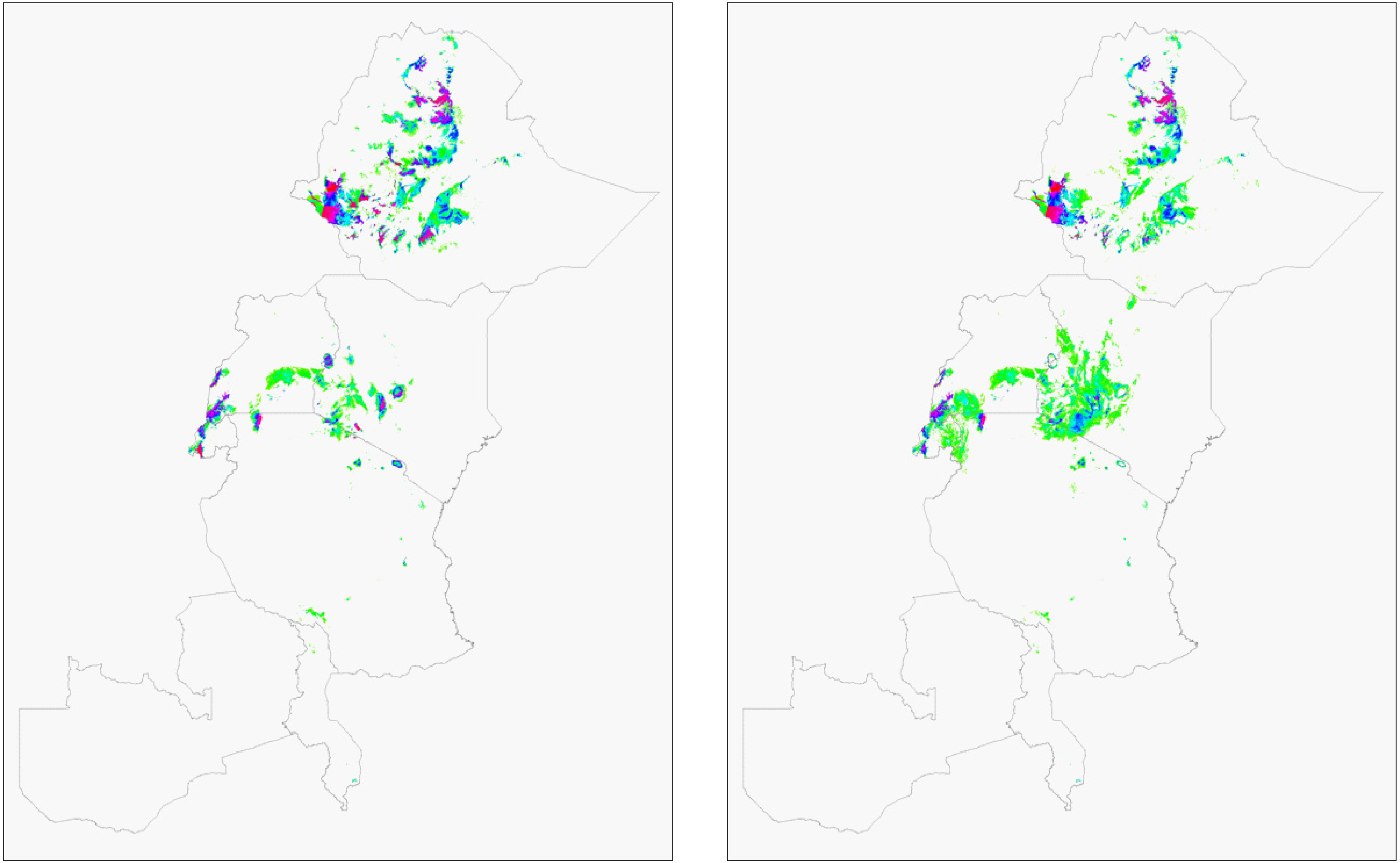


Figure 3.6. Projected changes in the distribution of two important agroforestry species under scenario A2 (model HCCPR-HADCM3). Left: possible future distribution of Prunus africana. Right: possible future distribution of *Warburgia ugandensis*.

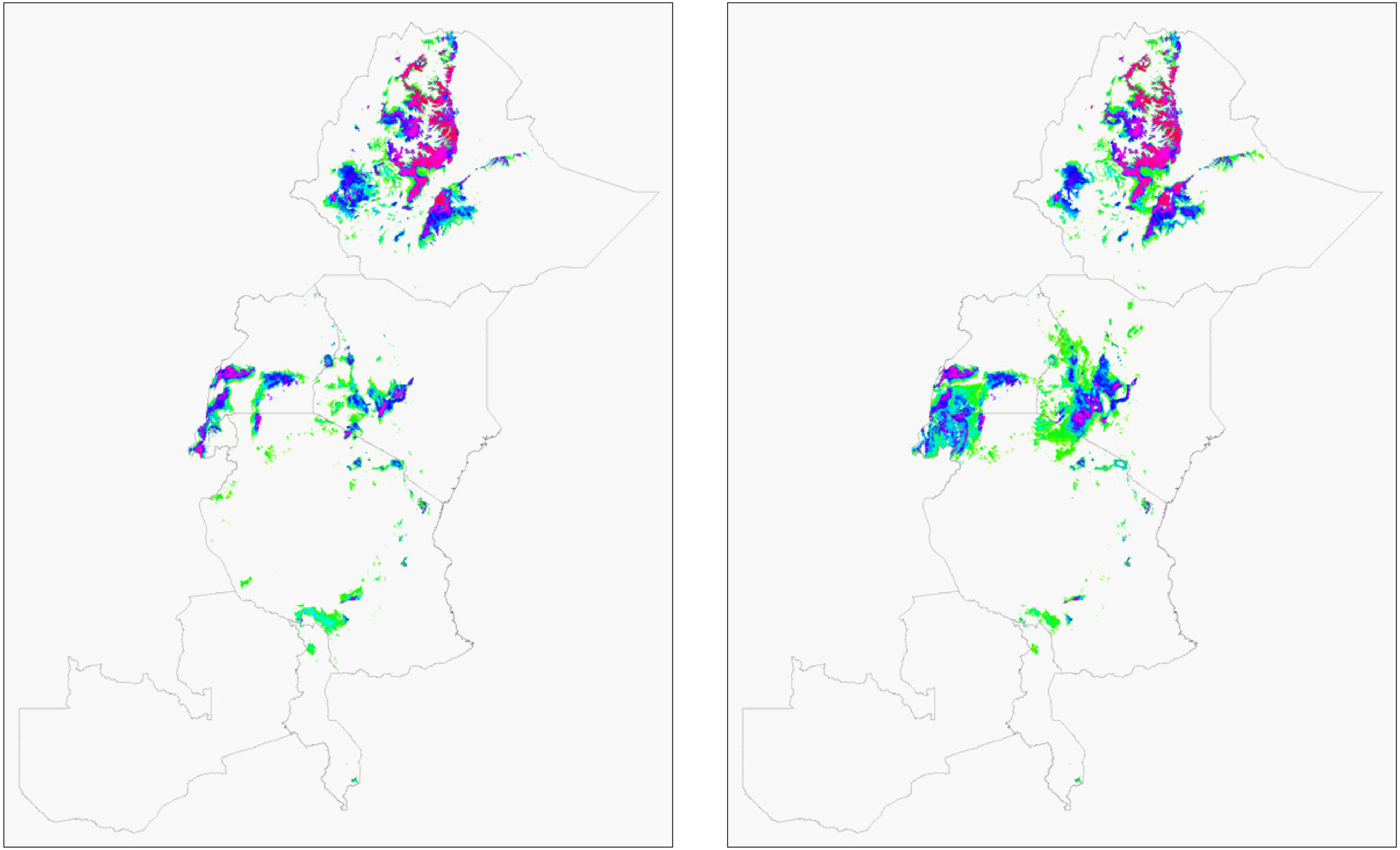


Figure 3.7. Projected changes in the distribution of two important agroforestry species under scenario B2 (model CCCMA-CGCM2). Left: possible future distribution of Prunus africana. Right: possible future distribution of *Warburgia ugandensis*.

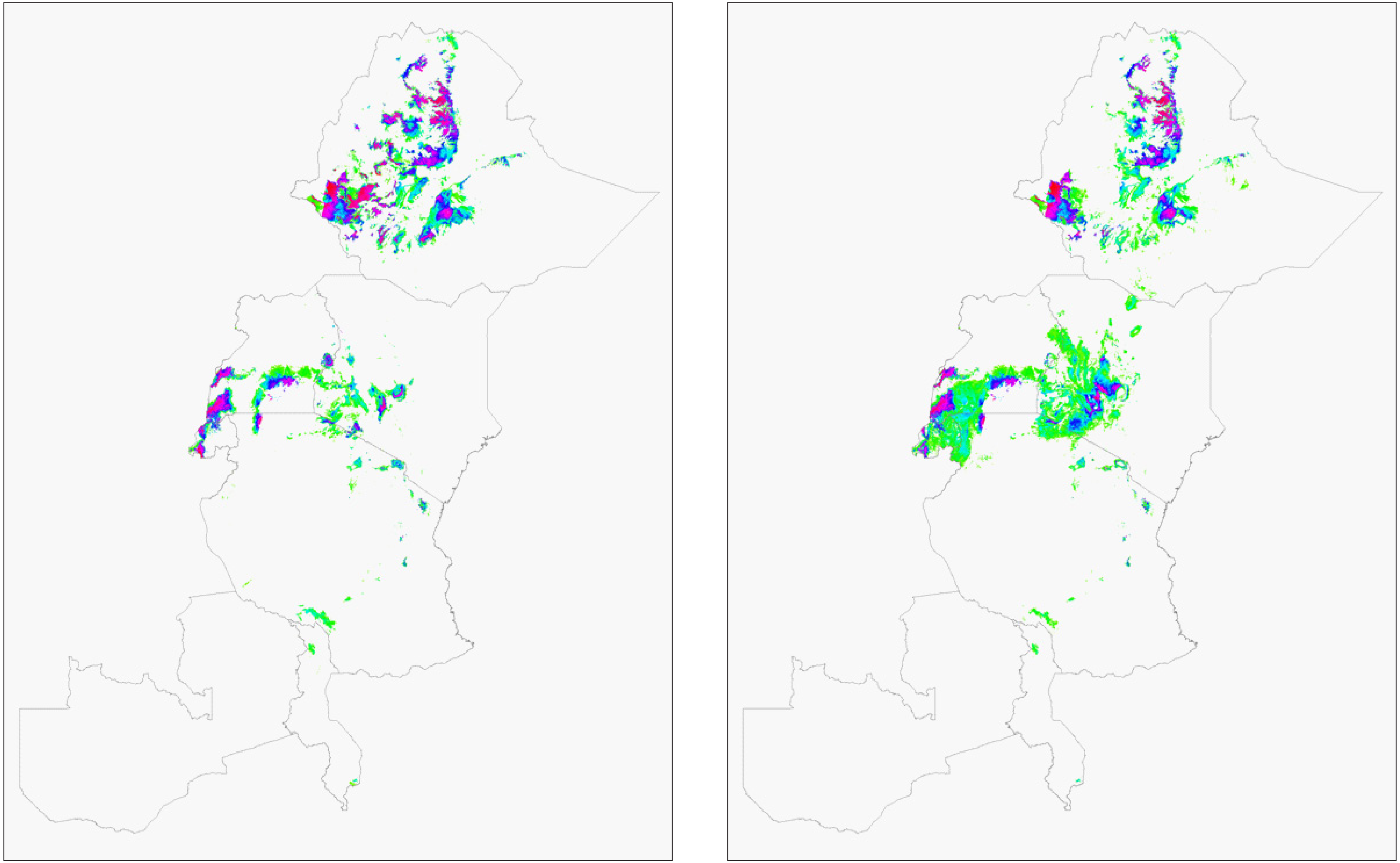


Figure 3.8. Projected changes in the distribution of two important agroforestry species under scenario B2 (model HCCPR-HADCM3). Left: possible future distribution of Prunus africana. Right: possible future distribution of *Warburgia ugandensis*.

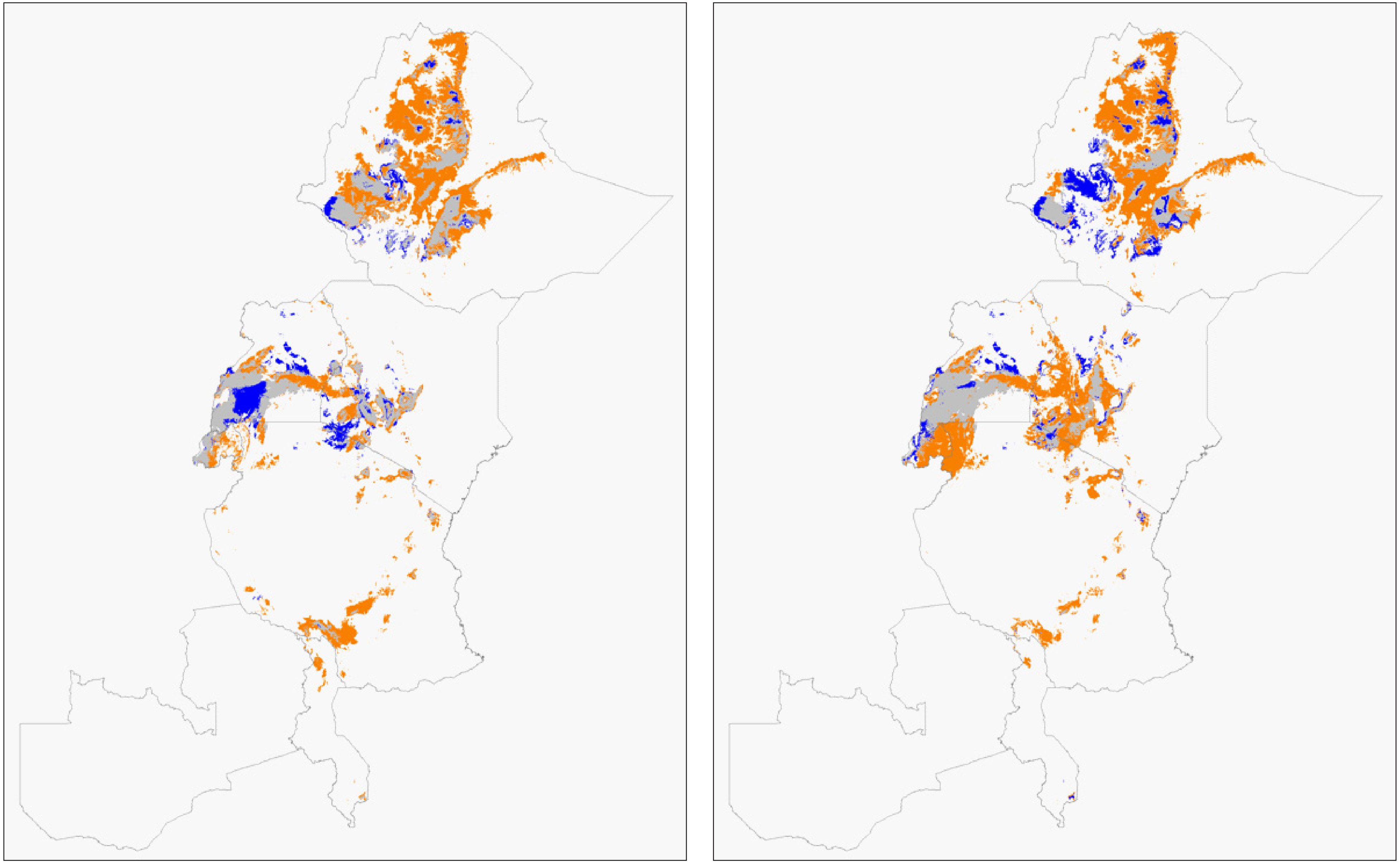
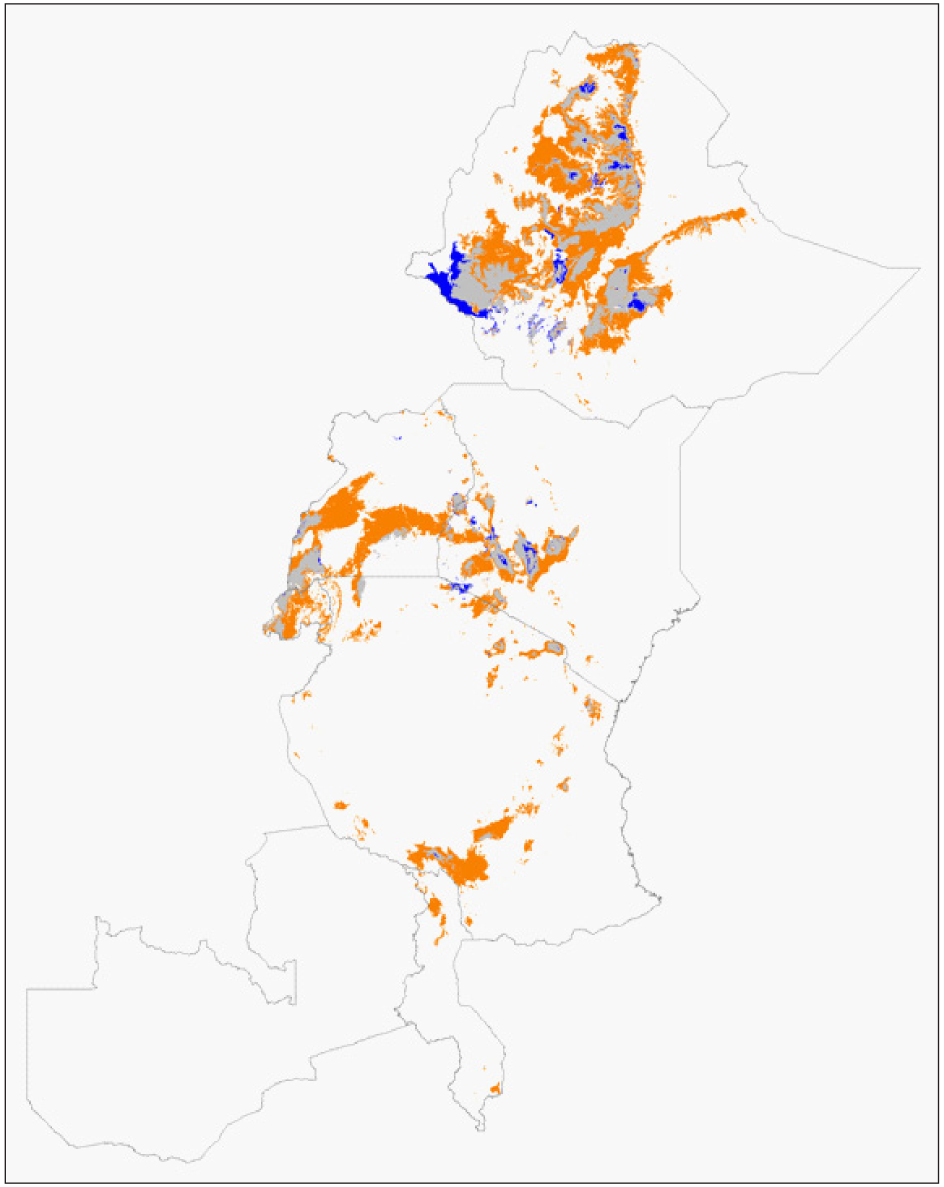


Figure 3.9. Projected changes in the distribution of two important agroforestry species under scenario A1B (model CCCMA-CGCM31). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Left: possible changes in distribution of *Prunus africana*. Right: possible changes in distribution of *Warburgia ugandensis*.



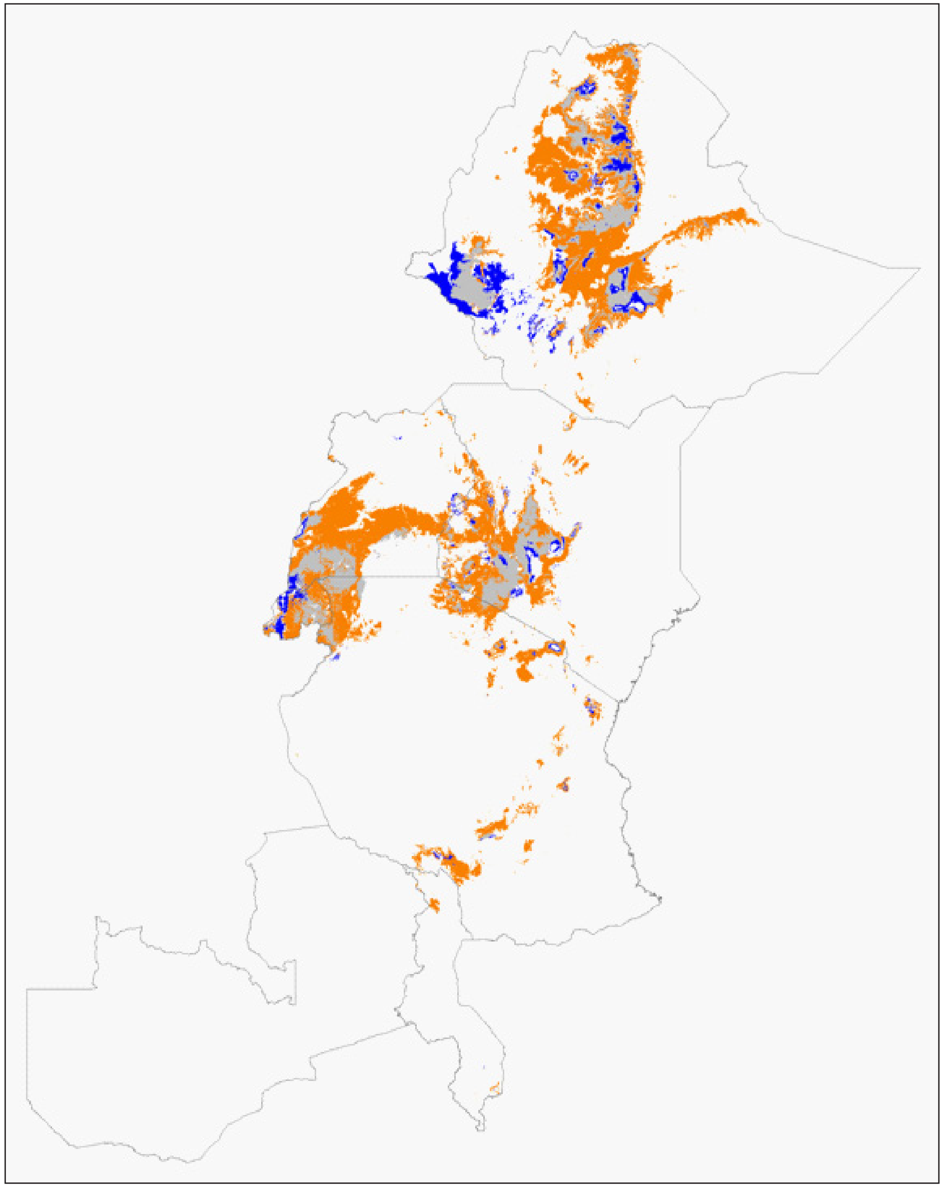
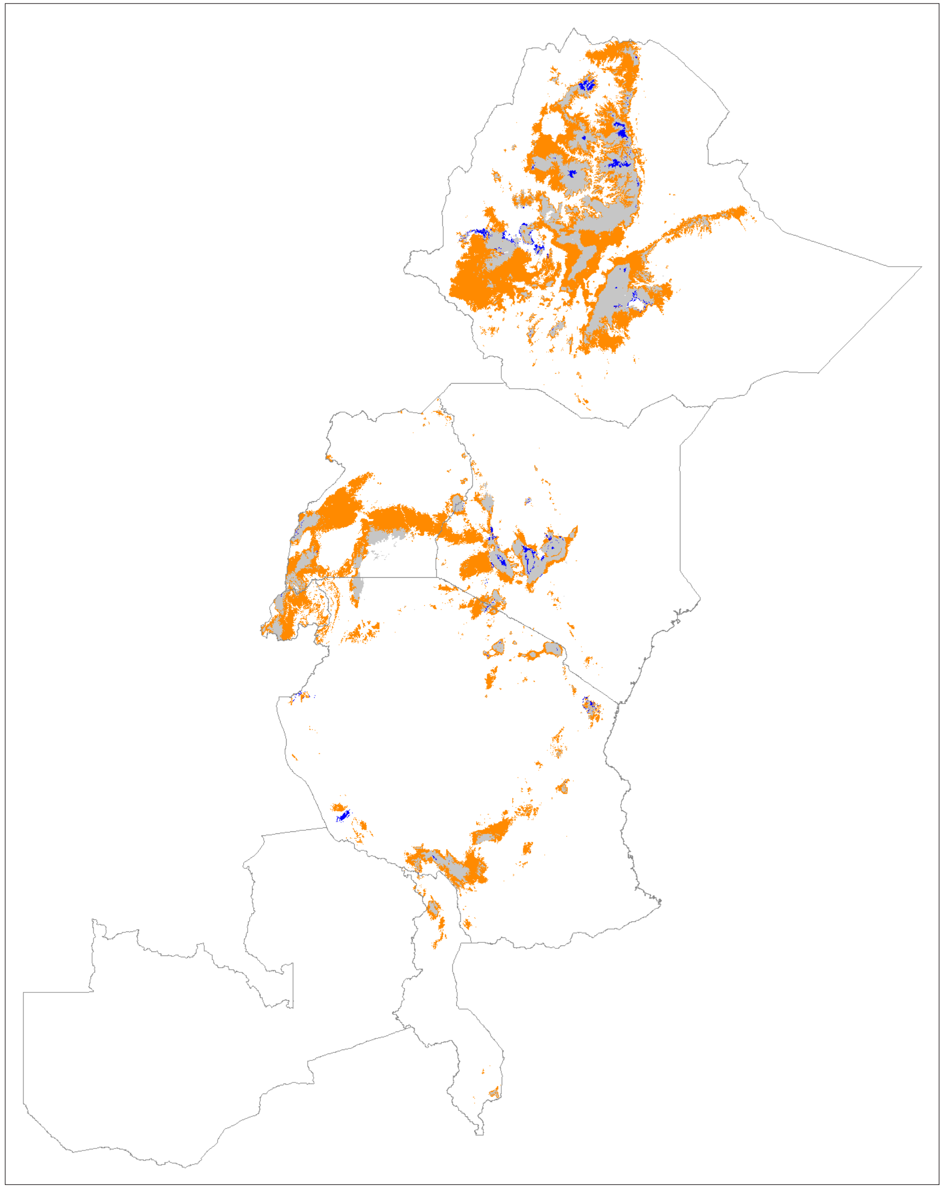


Figure 3.10. Projected changes in the distribution of two important agroforestry species under scenario A1B (model UKMO-HADCM3). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Left: possible changes in distribution of *Prunus africana*. Right: possible changes in distribution of *Warburgia ugandensis*.



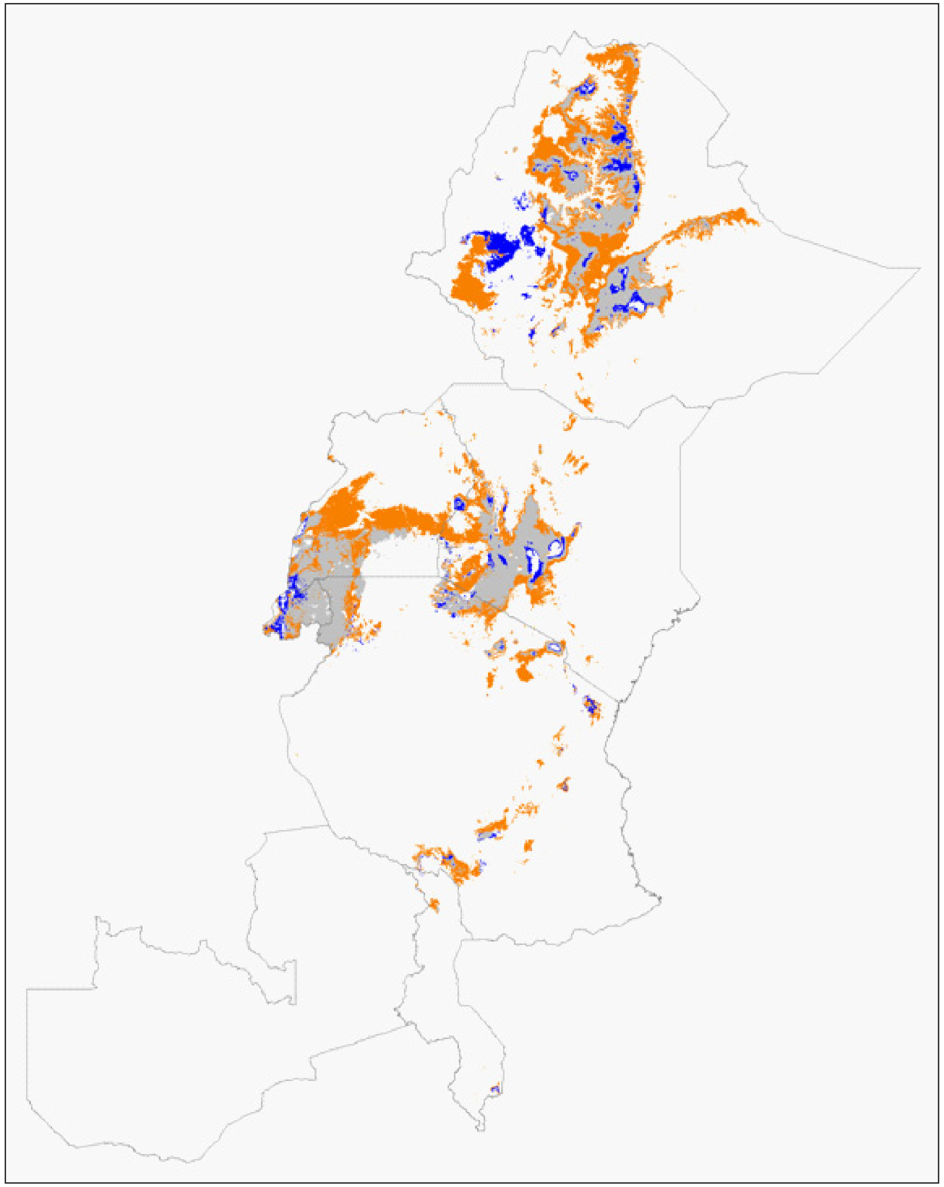


Figure 3.11. Projected changes in the distribution of two important agroforestry species under scenario A2 (model CCCMA-CGCM2). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Left: possible changes in distribution of *Prunus africana*. Right: possible changes in distribution of *Warburgia ugandensis*.

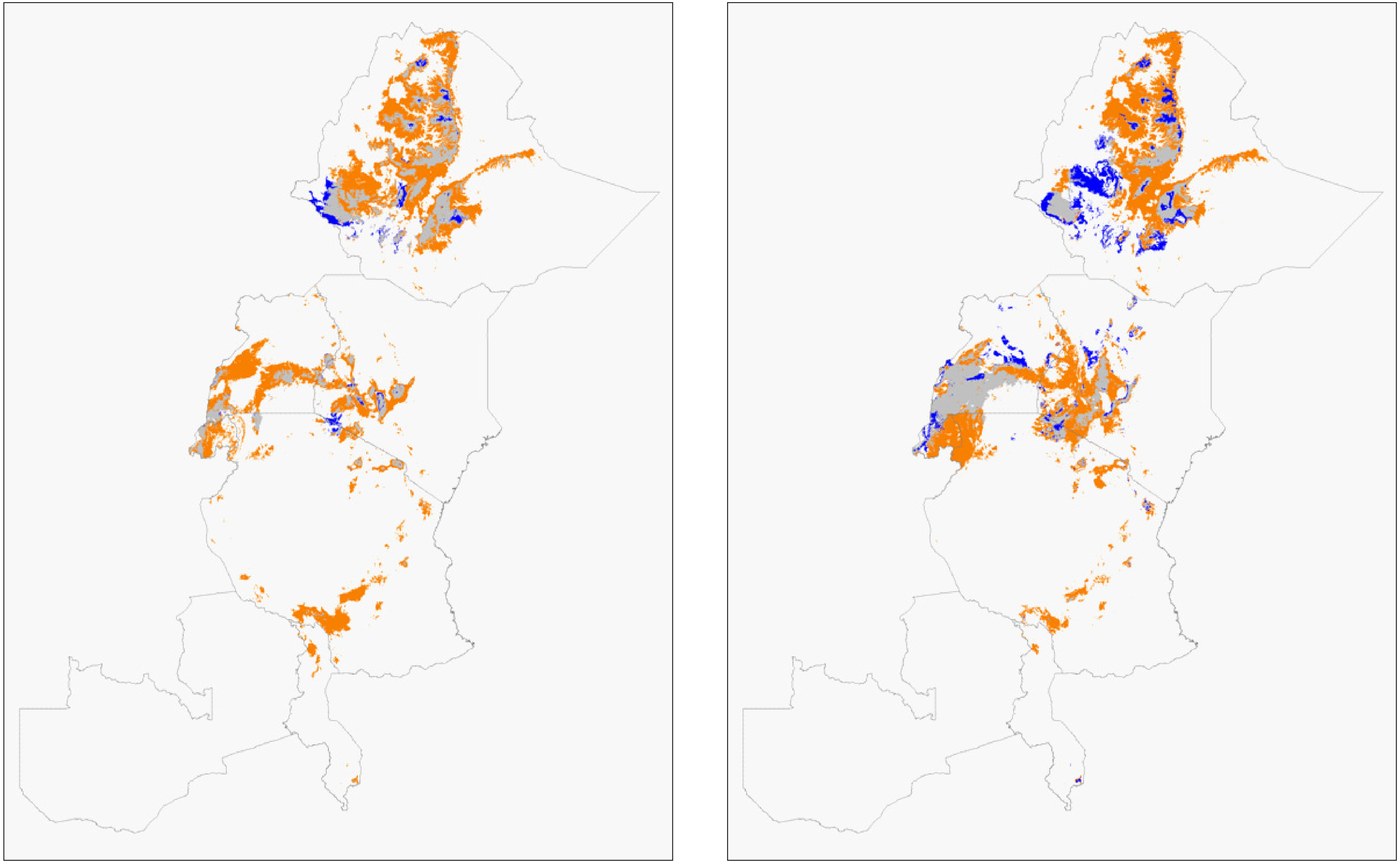


Figure 3.12. Projected changes in the distribution of two important agroforestry species under scenario A2 (model HCCPR-HADCM3). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Left: possible changes in distribution of *Prunus africana*. Right: possible changes in distribution of *Warburgia ugandensis*.

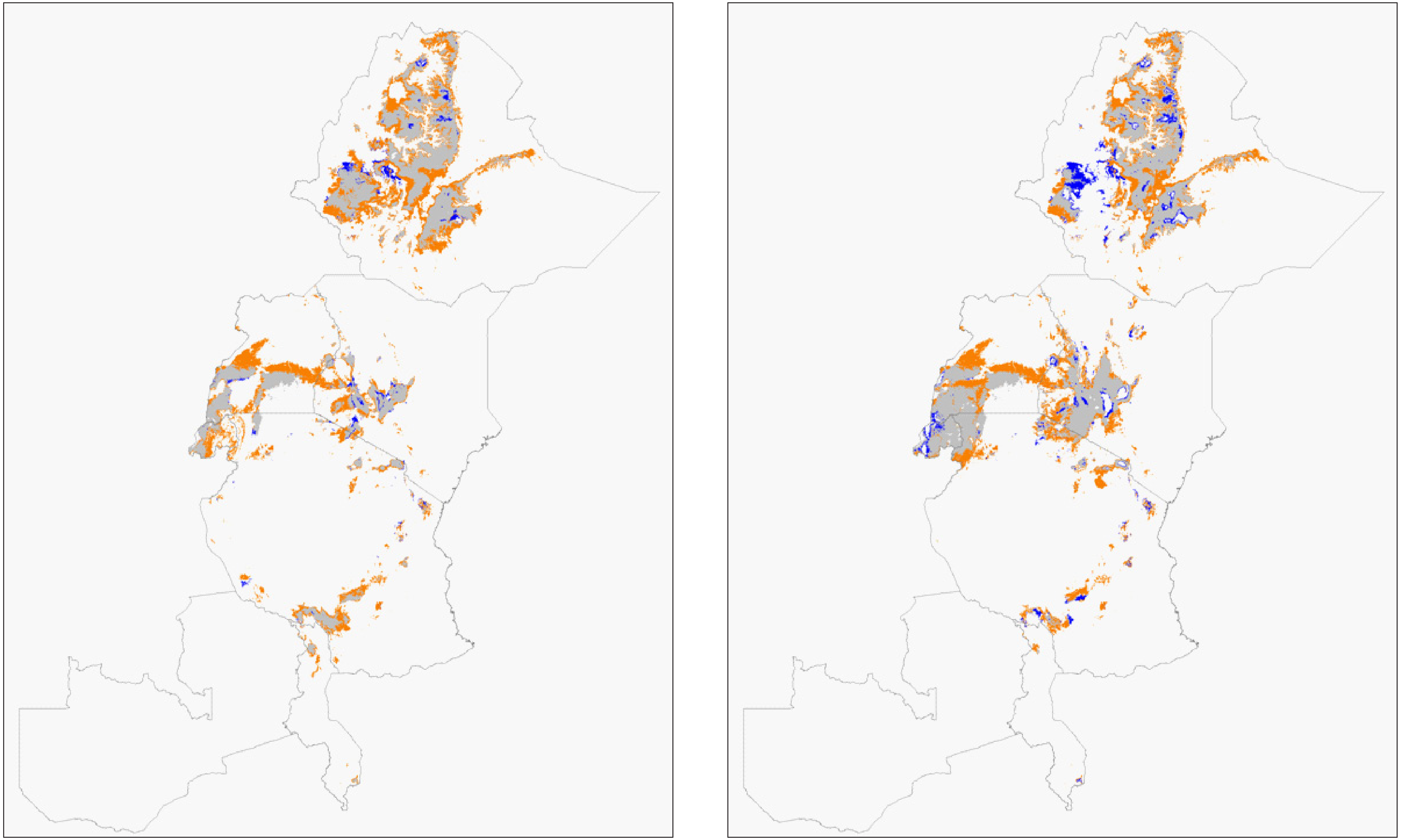


Figure 3.13. Projected changes in the distribution of two important agroforestry species under scenario B2 (model CCCMA-CGCM2). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Left: possible changes in distribution of *Prunus africana*. Right: possible changes in distribution of *Warburgia ugandensis*.

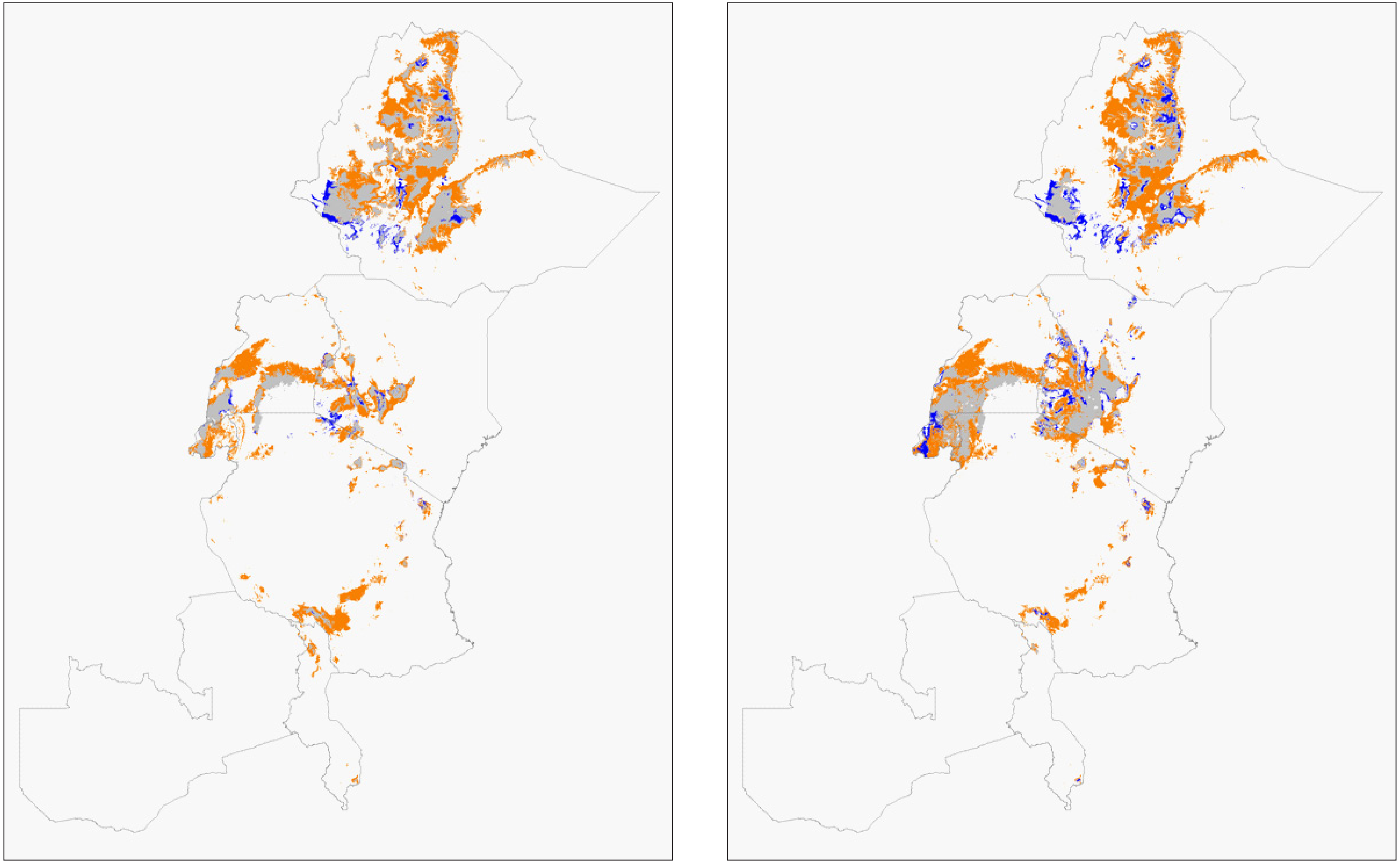


Figure 3.14. Projected changes in the distribution of two important agroforestry species under scenario B2 (model HCCPR-HADCM3). Areas in grey are suitable in current and the possible future climate, areas in blue are possible new habitat, and areas in orange are areas that are currently suitable but possibly not longer suitable in the future climate (i.e. possibly declining habitat). Left: possible changes in distribution of *Prunus africana*. Right: possible changes in distribution of *Warburgia ugandensis*.

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Appendix 1. Some notes on statistical downscaling of climate change results

Global Circulation Models (GCM) outputs are readily available, e.g., from amongst others the Earth System Grid (ESG) online platform (*https://esg.llnl.gov:8443/index.jsp*) and IPCC (*http://www.ipcc-data.org/*). These provide the most credible projections of changes in climates during this century. However, the created surfaces are very coarse in resolution (100 or 200km) and are therefore not practical for assessing agricultural landscapes, particularly in the tropics, where climatic conditions vary significantly across relatively small distances (Ramirez and Jarvis 2010).

Different downscaling techniques have been created to obtain regional predictions of climatic changes, ranging from smoothing and interpolation of GCM anomalies to neural networks, and regional climate modelling. They vary in terms of accuracy, output resolution and also on climatic science robustness (i.e. theoretical background). Because of the computational and time requirements, data based on many of these methods are not easy to create and therefore not readily available (Ramirez and Jarvis 2010).

Statistical downscaling provides a faster and easier method then most other methods, allowing the rapid development of high resolution climate change surfaces. CIAT has developed future climate surfaces for 24 GCMs and three different emission scenario's (SRES-A1B, A2 and B1), which are freely available from *http://gisweb.ciat.cgiar.org/dapablogs/dapa-climate/*. They were created using the delta method (Ramirez and Jarvis 2010), which is a downscaling method based on thin plate spline spatial interpolation of anomalies (deltas) of original (GCM) outputs. Anomalies are interpolated between GCM cell centroids and are then applied to a baseline climate given by a high resolution surface (Worldclim, Hijmans *et al.* 2005).

This method makes some important assumptions, i.e.,

1. Changes in climates vary only over large distances (i.e. as large as GCM side cell size
2. Relationships between variables in the baseline ('current climates') are likely to be maintained towards the future.

These assumptions might not hold true in highly heterogeneous landscapes, especially where topography could cause considerable variations in anomalies. Moreover, there are additional uncertainties involved in the downscaling processes, especially if going as far as 30 arc-seconds (Ramirez and Jarvis 2010). On the other hand, lower resolution data is less suitable for modelling of vegetation distribution at a landscape scale as this would require the upscaling of the vegetation data. The price of not downscaling to reduce GCM resolution to a finer scale could therefore be greater than the likely degradation of GCM data when statistical downscaling.