

Supplementary Material

Supplement to: *“Need for shared internal mound conditions by fungus-growing Macrotermes does not predict their species distributions, in current or future climates”*

*Colleen L. Seymour^{1,2}, Judith Korb³, Grant S. Joseph², Richard Hassall⁴, Bernard W.T. Coetzee⁵

*to whom correspondence should be addressed: c.seymour@sanbi.org.za

¹*South African National Biodiversity Institute, Kirstenbosch Research Centre, Private Bag X7, Claremont, 7735, South Africa*

²*FitzPatrick Institute of African Ornithology, University of Cape Town, Rondebosch, 7701, South Africa*

³*Faculty of Biology, Evolutionary Biology & Ecology, University of Freiburg, Germany*

⁴*UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford Wallingford, Oxfordshire, OX10 8BB*

⁵*Department of Zoology and Entomology, University of Pretoria, South Africa*

Contents

Supplementary Material 1	3
Species information for the <i>Macrotermes</i> assessed	3
Supplementary Material 2	4
See Supp_Mat_2.xls	4
Supplementary Material 3	4
Climatic variables used	4
Supplementary Material 4	5
Biome Descriptions	5
Supplementary Material 5	7
Pearson correlation coefficient between pairs of predictor variables.....	7
Supplementary Figure S1.....	8
Raster showing log of number of insects recorded in each site in Africa	8
Supplementary Fig S2	9
Supplementary Figure S2 (i). Distribution of <i>Macrotermes bellicosus</i>	9
Supplementary Figure S2 (ii). Distribution of <i>Macrotermes falciger</i>	9
Supplementary Figure S2 (iii). Distribution of <i>Macrotermes muelleri</i>	10
Supplementary Figure S1 (iv). Distribution of <i>Macrotermes natalensis</i>	10
Supplementary Figure S2 (v). Distribution of <i>Macrotermes subhyalinus</i>	11
Supplementary Figure S2 (vi). Distribution of <i>Macrotermes vitrialatus</i>	11
Supplementary Figure S3	12
Köppen–Geiger climate-vegetation models, comparing current and future vegetation trends for Africa.....	12
References.....	12

Supplementary Material 1

Species information for the *Macrotermes* assessed.

M. bellicosus: tolerates relatively dry conditions (400 mm to 800 mm annual rainfall) from Sahel savanna to forest edge, West Africa. Abundant from Senegal, across to Uganda and the Congo basin, but not found further south. Found in forest clearings in Congo forest. Mounds can be to 7 m tall (Collins 1977). May have the most elaborate architecture of all *Macrotermes* (Ruelle 1970). Live mound density variable, from almost 23/ha in scrub savanna to 6.5/ha in gallery forest (Korb and Linsenmair 1998). Feeds on woodfall and tree leaf litter (Collins 1977).

M. falciger: found mostly in eastern and southern Africa, predominantly in woodland, particularly miombo in Zambia and Zimbabwe, and savanna, rainfall range ca. 500 – 1270 mm/year (Meyer et al. 1999, Erens et al. 2015). Mounds often > 5 m in height, 20 m in diameter, occur in densities 3 – 5 mounds/ha in Congo (Erens et al. 2015; MAP = ca. 1200 mm.year⁻¹), 2 mounds/ha in Chizarira, Zimbabwe (Joseph et al. 2011; annual rainfall ca. 600 - 800 mm.year⁻¹), less than 0.03 in Northern Kruger Park, South Africa (Meyer 1999; annual rainfall ca. 495 mm.year⁻¹). Requires well-drained soils (Ruelle 1970).

M. muelleri: Most abundant of the forest *Macrotermes* in Africa, restricted to sheltered forest habitats (Ruelle 1970). Does not occur in many riverine or low-canopied, secondary forest habitats. Mounds recorded to be between 2.5 and 3 m high in Congo (Ruelle 1970). Feeds on leaf cuttings from woody species.

M. natalensis: Mainly in eastern and southern Africa, has lower humidity requirements than *M. falciger* (Ruelle 1970). Average mound densities in northern Kruger Park, South Africa, of 0.73/ha (Meyer 1999). In higher densities in undulating areas with good drainage; mound density increases with rainfall within its distribution (Meyer et al. 2001). Feed on woody plant species matter (Ferrar 1982).

M. subhyalinus: Most widely dispersed of the species under consideration – tolerates drier conditions than does *M. bellicosus*, but has also been reported to be able to thrive in equatorial forest. Mounds to 2.5 m in height in dryland ecosystems of Ethiopia (MAP = 350 – 900 mm), at densities of 10–14 ha⁻¹ (Tilahun et al. 2012). Seem to prefer C3 (i.e., Woody species) in their diets (Phillips et al. 2021), possibly because woody vegetation has higher N content than grass, but diets of individual termite mounds mostly dictated by local vegetation, with the proportion of woody matter correlating with that of canopy cover of trees and shrubs in the mound's surrounds (Vesala et al. 2022).

M. vitrialatus: Range very similar to that of *M. falciger*, but *M. vitrialatus* extends further northwest than *falciger*, and seems to be absent from Tanzania. May be more abundant than it appears from mapping. Nests are inconspicuous, often completely subterranean, although does have harder hummocks on soils with high clay content (Ruelle 1970). Cut leaves in a similar way to *M. muelleri*, although *M. vitrialatus* is not a forest species (Ruelle 1970). Seems not to swarm at onset of rainy season, unlike other *Macrotermes* species (Ruelle 1970).

Supplementary Material 2

[See Supp_Mat_2.xls](#)

Supplementary Material 3

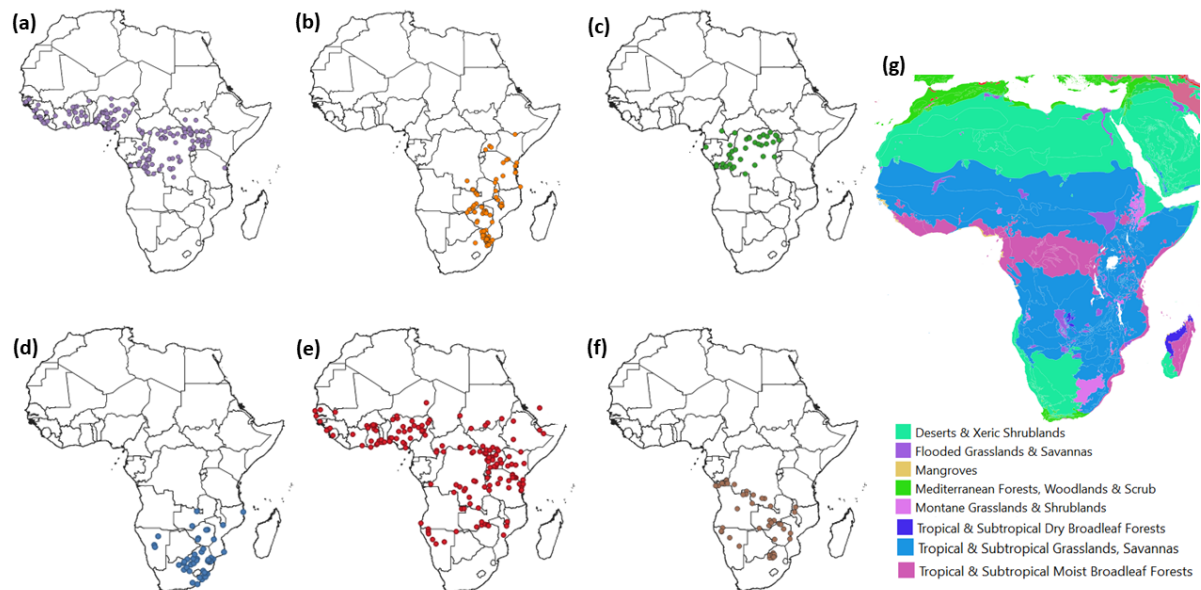
Climatic variables used

All data are from WorldClim 2 (Fick and Hijmans 2017) at a resolution of 2.5 arcminutes (approx. 5kmx5km), based on data from the years 1970 – 2000. These are based primarily on data from weather stations, but supplemented with satellite data collected using the MODIS platform

Variable	Description
Mean Annual Temperature	Mean of monthly maximum and minimum temperatures over a year. Measured in degrees Celsius
Minimum Temperature	Measured as the lowest monthly temperature occurrence over a given year; measured in degrees Celsius
Maximum Temperature	Measured as the highest monthly temperature occurrence over a given year; measured in degrees Celsius
Diurnal Temperature Range	Greatest value of difference between daily maximum and minimum temperatures, to capture range of temperatures dealt with by species within a day; measured in degrees Celsius
Difference in Annual Maximum and Minimum temperature	Greatest value of difference between maximum and minimum temperatures over a year to capture the range of temperatures that species have to cope with within a year; measured in degrees Celsius
Mean Annual Precipitation	Mean of annual precipitation over 1970 – 2000, calculated as the sum of all total monthly precipitation values, in milliliters
Precipitation seasonality	Variation in monthly precipitation totals within a year; the ratio of the standard deviation of the monthly total precipitation to the mean monthly precipitation (i.e., CV). Expressed as a percentage.

Supplementary Material 4

Biome Descriptions



The following biome summaries are based on the WWF Ecoregions summaries (Olson et al. 2001).

Deserts and Xeric Shrublands – Areas usually receiving < 250 mm/year, and where evaporation usually exceeds rainfall. Temperatures tend to be extreme. Vegetation usually characterized by woody-stemmed shrubs and ephemeral components, almost all evolved to deal with erratic rainfall and/or water loss. Fauna also well adapted to challenging environmental conditions.

Flooded grasslands and savannas - large expanses or complexes of flooded grassland containing numerous flora and fauna adapted to the hydrologic regimes and soils. Often support large concentrations of migratory and resident waterbirds. Notable areas in Africa include the Lake Chad flooded savanna, the Sudd and the Zambebian flooded grasslands.

Mangroves – occurs in the intertidal zone, characterised by specialised, salt-tolerant trees and shrubs (also referred to as mangroves). Tend to be found on coasts between latitudes 25° N and 25° S – much has been destroyed by human activities, with implications for flood control.

Mediterranean Forests, Woodlands and Scrub - characterized by dry summers and rainy winters, with uniform rainfall in some areas. Summers are typically hot, winters typically mild to cool in low-lying locations but can be cold in inland and higher locations. Contain high levels of plant diversity characterised by high endemism.

Montane Grasslands and Shrublands – high elevation grassland and shrublands. Includes subalpine heath in East Africa ((e.g., Mount Kilimanjaro, Mount Kenya, Rwenzori Mountains), and drier subtropical montane grasslands, savannas and woodlands (e.g. Ethiopian Highlands, Zambezian montane grasslands and woodlands, and montane habitats of southeastern Africa). Flora and fauna adapted to cool, wet conditions and intense sunlight.

Tropical and subtropical Dry Broadleaf forests – Climate is warm year round and may receive relatively high rainfall, but have long dry seasons spanning months. Dominated by deciduous trees, which are leafless during the dry season. Contains some areas of evergreen trees, where trees have access to moisture, e.g. along rivers. Also known as the **tropical and subtropical dry forest** biome or the **tropical and subtropical deciduous forest** biome.

Tropical and subtropical grasslands, savannas – Areas in the tropics that receive insufficient rainfall to support extensive tree cover, rainfall typically between 900 – 1500 mm/year. Dominated by grasses with scattered, but sometimes common, trees. The African savannas and grasslands found in East Africa and Central and southern Africa comprise mosaics of miombo, mopane and other habitats. Large and diverse mammal faunas are found in areas that are still relatively intact, with large scale migration of savanna herbivores.

Tropical and subtropical moist broadleaf forests – Typically centred on the equatorial belt between the Tropics of Cancer and Capricorn. High rainfall (>2000 mm/year), dominated by evergreen and semi-deciduous species, temperatures relatively constant and warm, making for high productivity. High floral and faunal diversity. In Africa, these forests are found in the Congo Basin and Madagascar.

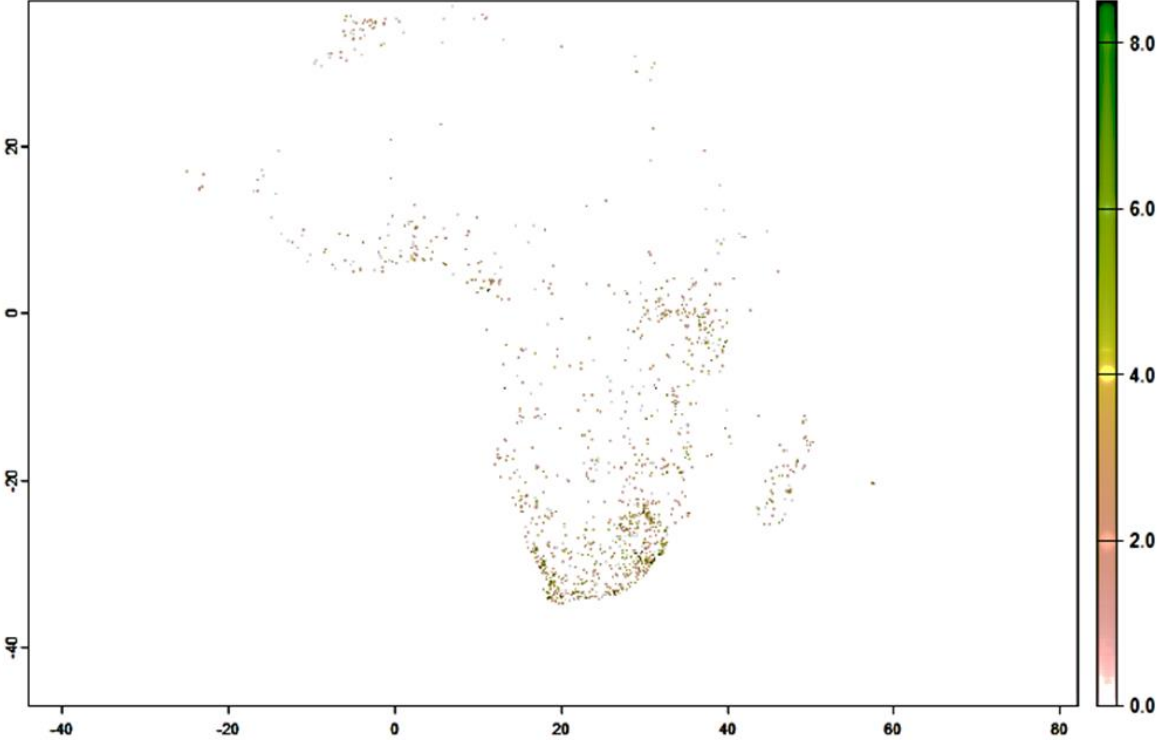
Supplementary Material 5

Pearson correlation coefficient between pairs of predictor variables.

	mean_temp	max_temp	min_temp	diurnal_range	diff_mean_max	precip_ann
mean_temp						
max_temp	0.66					
min_temp	0.66	0.06				
diurnal_range	0.01	0.53	0.61			
diff_mean_max	0.07	0.69	0.72	0.70		
precip_ann	0.33	0.62	0.08	0.37	0.5	
precip_season	0.43	0.25	0.21	0.26	0.07	0.1

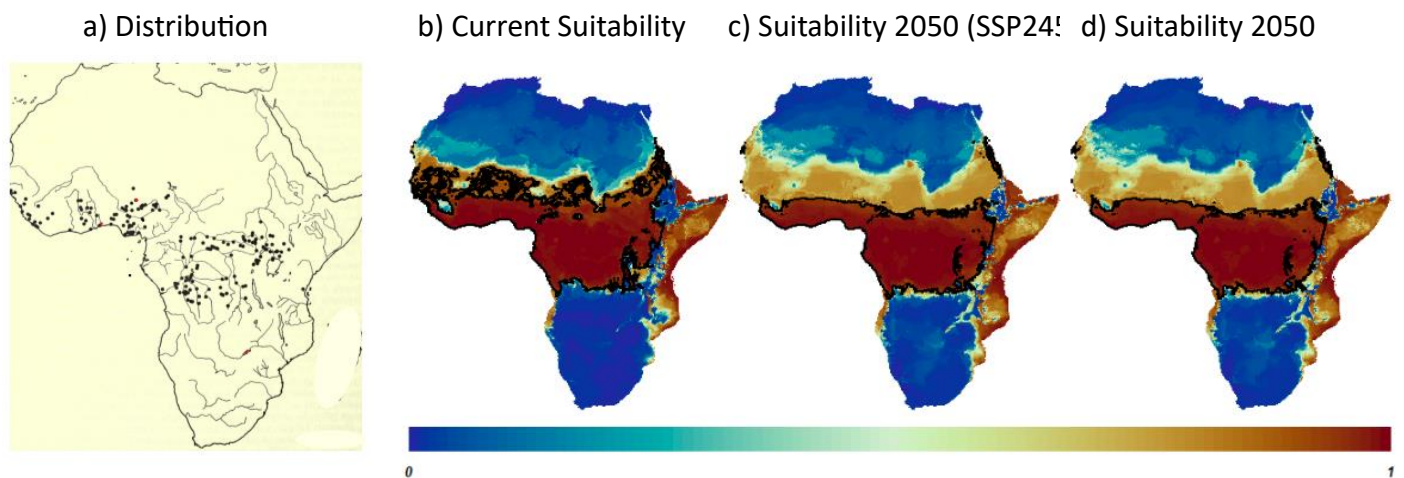
Supplementary Figure S1.

Raster showing log of number of insects recorded in each site in Africa

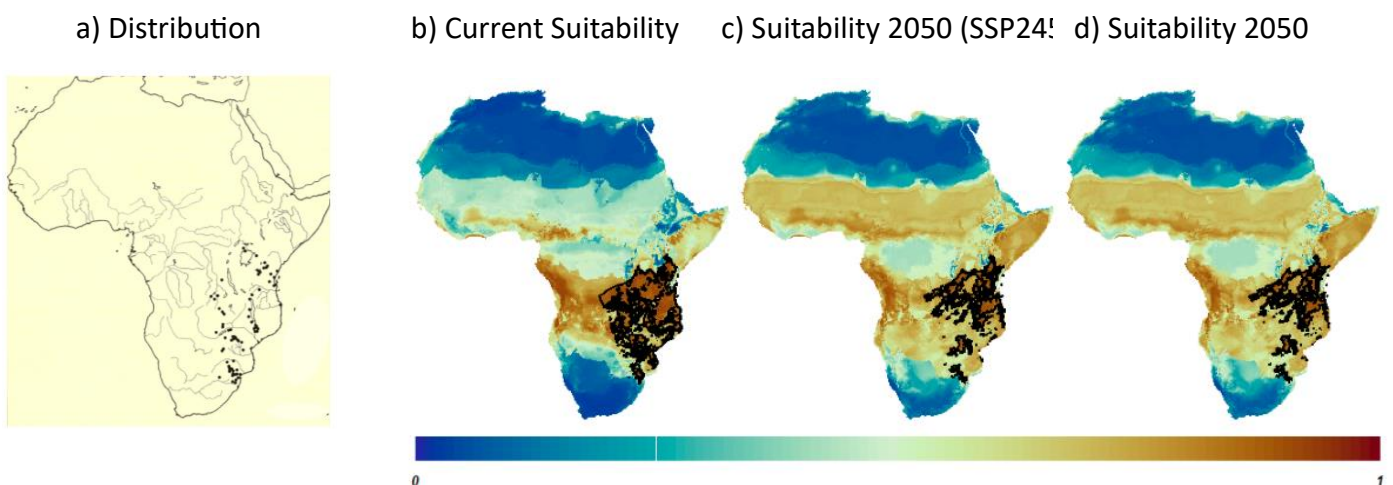


Supplementary Fig S2

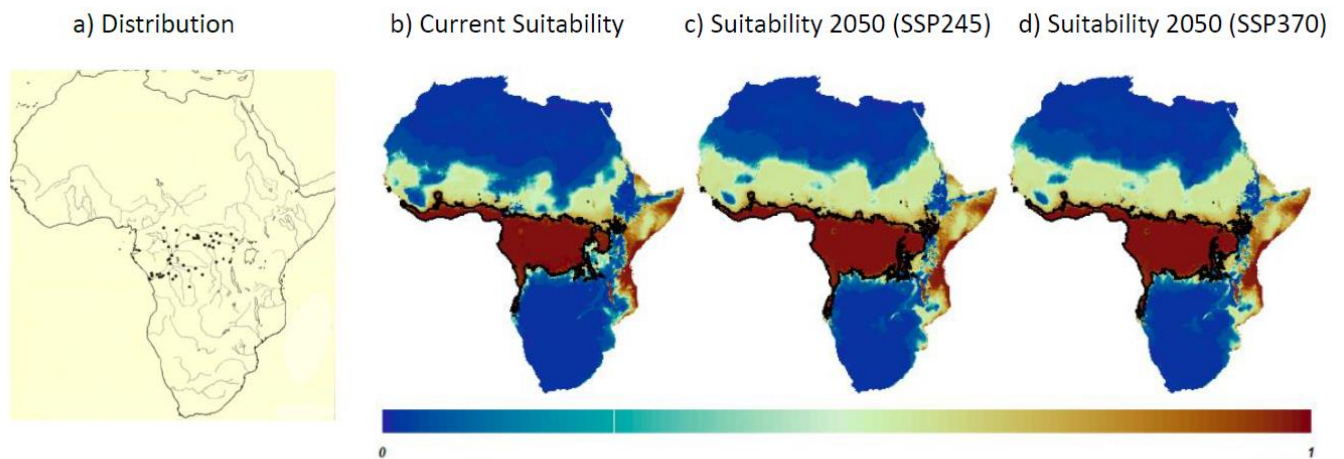
Supplementary Figure S2 (i). Distribution of *Macrotermes bellicosus* (a), relative to the model outputs of current high suitability for distribution (b). By 2050 under scenario SSP245, the area encircled in black will decrease in high suitability by 1874997km² (22.2%). (C). By 2050 under scenario SSP370, the area encircled in black will decrease in high suitability by 1870180 km² (22.1%) (c). Areas of high suitability outside of black polygons represent areas where colonisation is unlikely for ecological and geographic regions. Barriers for *M. Bellicosus* include the Ethiopian highlands, and termination of habitat (savanna woodland and forest), which are not projected for this area in future vegetation scenarios (Beck et al. 2018).



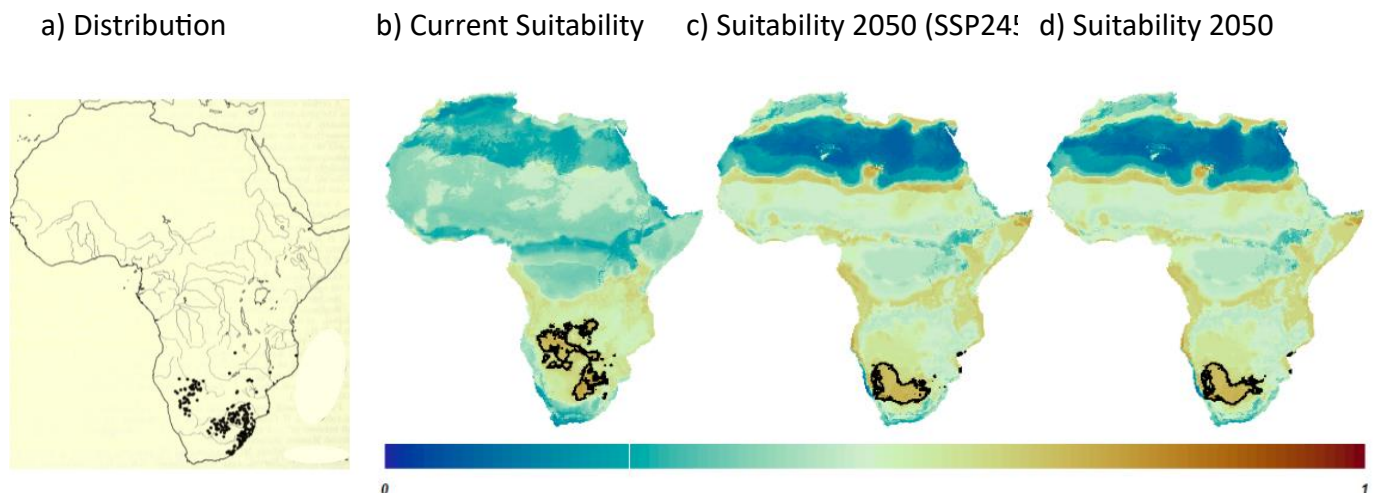
Supplementary Figure S2 (ii). Distribution of *Macrotermes falciger* (a), relative to the model outputs of current high suitability for distribution (b). By 2050 under scenario SSP245, the area encircled in black will decrease in high suitability by 1,000,007km² (51.08%). (c). By 2050 under scenario SSP370, the area encircled in black will decrease in high suitability by 1,086,892 km² (55.52%) (d). Barriers for *M. falciger* include the Ethiopian highlands and Congo basin.



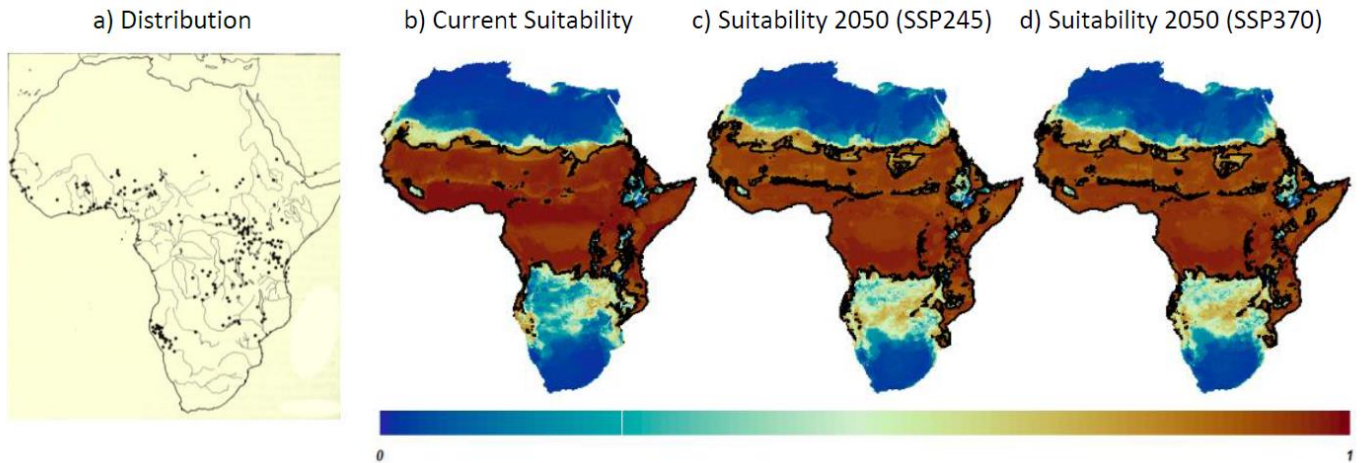
Supplementary Figure S2 (iii). Distribution of *Macrotermes muelleri* (a), relative to the model outputs of current high suitability for distribution (b). By 2050 under scenario SSP245, the area encircled in black will increase in high suitability by 374,147 km² (9.78 %). (c). By 2050 under scenario SSP370, the area encircled in black will increase in high suitability by 365,292 km² (9.55 %) (d). Barriers for *M. muelleri* include the Ethiopian highlands and termination of habitat (closed-canopy forest), which are not projected for these areas in future vegetation scenarios (Beck et al. 2018).



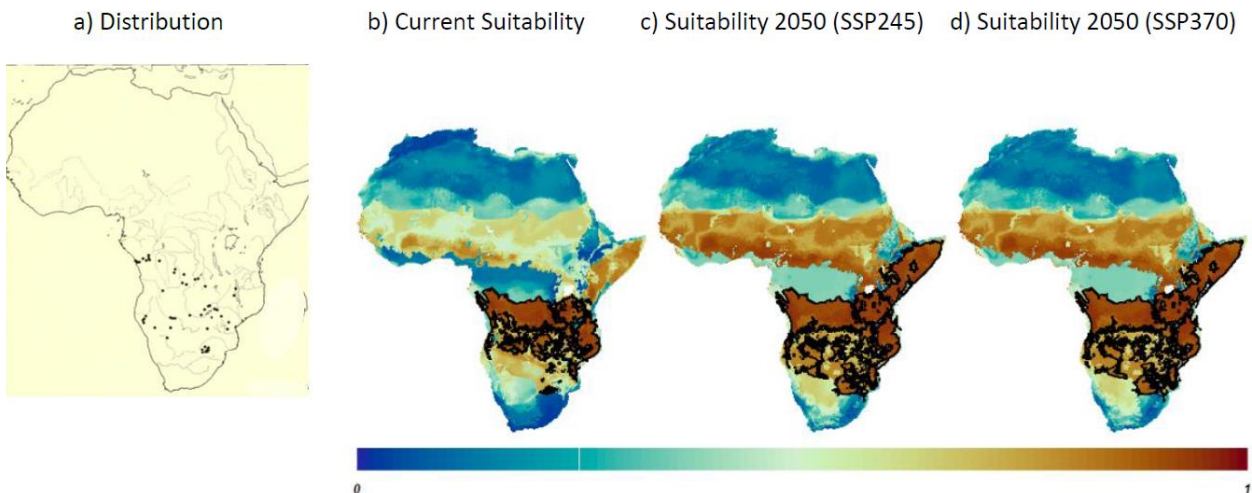
Supplementary Figure S1 (iv). Distribution of *Macrotermes natalensis* (a), relative to the model outputs of current high suitability for distribution (b). By 2050, the area encircled in black is predicted to decrease in high suitability by circa 70%; (c). Barriers for *M. natalensis* include areas of increasingly unsuitable habitat between current distributions and potential distributions, and the Congo basin, and Ethiopian highlands.



Supplementary Figure S2 (v). Distribution of *Macrotermes subhyalinus* (a), relative to the model outputs of current high suitability for distribution (b). By 2050 under scenario SSP245, the area encircled in black will increase in high suitability by 307,567 km² (2.12 %). (c). By 2050 under scenario SSP370, the area encircled in black will increase in high suitability by 214,618 km² (1.48 %). *M. subhyalinus* will experience marginal shifts, with loss of northern distributions offset by expansion in the south east.

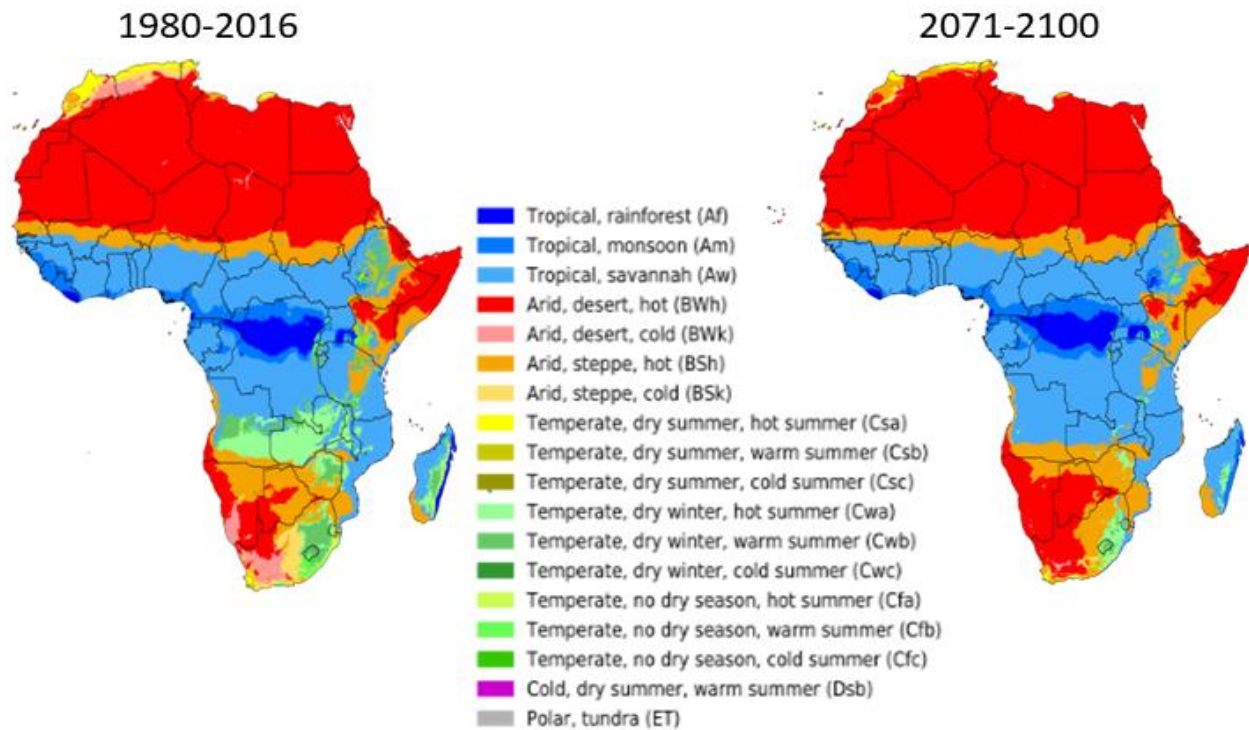


Supplementary Figure S2 (vi). Distribution of *Macrotermes vitrialatus* (a), relative to the model outputs of current high suitability for distribution (b). By 2050 under scenario SSP245, the area encircled in black will increase in high suitability by 1,802,405 km² (63.78 %). (c). By 2050 under scenario SSP370, the area encircled in black will increase in high suitability by 1,819,174 km² (64.37 %). The expansion into the Horn of Africa will likely be limited by biome mismatch, as biome is the strongest driver of distribution for this species (c), which relies on savanna woodland and savanna. The Horn will become less arid than today, but future vegetation predictions still support a relatively xeric future (Beck et al. 2018).



Supplementary Figure S3.

Köppen–Geiger climate-vegetation models, comparing current and future vegetation trends for Africa.



References

Beck H, Zimmermann NE, McVicar TR, Vergopolan N, Berg, Wood EF. 2018. Data Descriptor: Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data volume 5, Article number: 180214

Collins, N. M. 1977. The population ecology and energetics of *Macrotermes bellicosus* Smeathman (Isoptera). Imperial College, London.

Erens, H., M. Boudin, F. Mees, B. B. Mujinya, G. Baert, M. Van Strydonck, P. Boeckx, and E. Van Ranst. 2015. The age of large termite mounds – radiocarbon dating of *Macrotermes falciger* mounds of the miombo woodland of Katanga, DR Congo. Palaeogeography, Palaeoclimatology, Palaeoecology 435:265–271.

Ferrar, P. 1982. Termites of a South African savanna - I. List of species and subhabitat preferences. Oecologia 52:125–132.

Fick, S. E., and R. J. Hijmans. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37:4302–4315.

https://commons.wikimedia.org/wiki/Category:Present_and_future_K%C3%B6ppen-Geiger_climate_classification_maps_at_1-km_resolution#/media/File:Koppen-Geiger_Map_Africa_present.svg

https://commons.wikimedia.org/wiki/Category:Present_and_future_K%C3%B6ppen-Geiger_climate_classification_maps_at_1-km_resolution#/media/File:Koppen-Geiger_Map_Africa_future.svg

Joseph, G. S., G. S. Cumming, D. H. M. Cumming, Z. Mahlangu, R. Altwegg, and C. L. Seymour. 2011. Large termitaria act as refugia for tall trees, deadwood and cavity-using birds in a miombo woodland. *Landscape Ecology* 26:439–448.

Korb, J., and K. E. Linsenmair. 1998. The effects of temperature on the architecture and distribution of *Macrotermes bellicosus* (Isoptera, Macrotermitinae) mounds in different habitats of a West African Guinea savanna. *Insectes Sociaux* 45:51–65.

Meyer, V. W. 1999. Distribution and density of termite mounds in the northern Kruger National Park , with specific reference to those constructed by *Macrotermes Holmgren* (Isoptera : 7:123–130.

Meyer, V. W., L. E. O. Braack, H. C. Biggs, and C. Ebersohn. 1999. Distribution and density of termite mounds in the northern Kruger National Park, with specific reference to those constructed by *Macrotermes Holmgren* (Isoptera: Termitidae). *African Entomology* 7:123–130.

Meyer, V. W., R. M. Crewe, L. E. O. Braack, H. T. Groeneveld, and M. J. van der Linde. 2001. Biomass of *Macrotermes natalensis* in the northern Kruger National Park , South Africa – the effects of land characteristics. *Sociobiology* 38:431–448.

Olson, D. M., E. Dinerstein, N. D. Wikramanayake, E. D. Burgess, G. V. N. Powell, J. A. Underwood, E. C. D’Amico, I. Itoua, H. E. Strand, J. C. Morrison, C. J. Loucks, T. F. Allnutt, T. H. Ricketts, Y. Kura, J. F. Lamoreux, W. W. Wettengel, P. Hedao, and K. R. Kassem. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. *BioScience* 51:933–938.

Phillips, S., R. H. Scheffrahn, A. Piel, F. Stewart, A. Agbor, G. Brazzola, A. Tickle, V. Sommer, P. Dieguez, E. G. Wessling, M. Arandjelovic, H. Kuhl, C. Boesch, and V. M. Oelze. 2021. Limited evidence of C₄ plant consumption in mound building *Macrotermes* termites from savanna woodland chimpanzee sites. *PLoS ONE* 16:1–20.

- Ruelle, J.-E. 1970. A revision of the termites of the genus *Macrotermes* from the Ethiopian region (Isoptera : Termitidae). London, The Museum, 1950-1977.
- Tilahun, A., F. Kebede, C. Yamoah, H. Erens, B. B. Mujinya, A. Verdoodt, and E. Van Ranst. 2012. Quantifying the masses of *Macrotermes subhyalinus* mounds and evaluating their use as a soil amendment. *Agriculture, Ecosystems and Environment* 157:54–59.
- Vesala, R., A. Rikkinen, P. Pellikka, J. Rikkinen, and L. Arppe. 2022. You eat what you find – Local patterns in vegetation structure control diets of African fungus-growing termites. *Ecology and Evolution* 12:1–15.