Report on the observed climate, projected climate, and projected biodiversity changes for *Ragain?s vingis* under differing levels of warming

Jeff Price[1], Nicole Forstenhäusler[1], Erin Graham[2],
Timothy J. Osborn[3], and Rachel Warren[1]

Report of the Wallace Initiative, July 3, 2024

[1]Tyndall Centre for Climate Change Research,
School of Environmental Sciences, University of East Anglia, Norwich, UK.
[2]eResearch Centre, James Cook University, Townsville, Australia.
[3]Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, UK.

Contents

Acknowledgements

This work draws on nearly a decade of collaborative research between the Tyndall Centre for Climate Change Research, University of East Anglia, United Kingdom, and the eResearch Centre at James Cook University, Australia. We wish to thank those who played a major role in producing the original underlying models, data, and webpages used in the Wallace Initiative - J. VanDerWal, I. Atkinson, D. Baird, and P. Lawrey. We would also like to acknowledge the High Performance Computing Team at the University of East Anglia. Portions of this work have been funded from the MacArthur Foundation funding to World Wildlife Fund-US and IUCN (Ecosystems and Livelihoods Adaptation Network), WWF-UK (Wildlife in a Warming World), UK Natural Environment Research Council (NERC) grant no. NE/P014992/1 (IMPALA).

The climate projections were produced using the ClimGen system funded by NERC (QUEST-GSI; NE/E001831/1) and EU (HELIX; 603864) and we thank Ian Harris and Craig Wallace for producing the underlying data. We acknowledge the climate modelling groups, the Program for Climate Model Diagnosis and Intercomparison and the World Climate Research Programme's Working Group on Coupled Modelling for producing and making available the CMIP5 model output.

Parts of this work was funded with support from the European Union's Horizon 2020 research and innovation programmes under grant agreement No 101003687 (PROVIDE).

University of East Anglia
HIGH PERFORMANCE COMPUTING

Executive Summary

Climate change threatens the world's major centres of biodiversity, jeopardising many of the collective conservation and development efforts and investments to date. Observed changes, and the amount of climate change that society and ecosystems are already committed to, indicate that climate change is already damaging ecosystems and livelihoods, and that the amount of damage is increasing over time.

Protected Areas have long played a role in the maintenance and conservation of biodiversity. They appear as Target 3 in the Convention on Biological Diversity's 2030 Kunming-Montreal Global Biodiversity Framework with a recommendation of setting aside 30% of each country's land for biodiversity. However, many protected areas were not specifically set aside for biodiversity and many conservation strategies have largely been developed under the assumption that the world's climate will stay static (i.e., not change). A changing climate in tandem with other existing and future human pressures means there is a high risk that these strategies will fail in their goals.

Outside of a few areas, and/or specific protected areas, access to protected area specific information on observed climate changes, projected climate changes, and how biodiversity is projected to change, have not been readily available. Extraordinary outside pressures (e.g., resource extraction) can drastically limit the ability of an area to persist under the additional pressures from climate change – or to act as a refugium for species under increasing levels of climate change.

Reducing biodiversity's vulnerability to climate change requires an understanding of the projected magnitude of the risks. These can be estimated from models of the climatic range relationships of more than 135 000 species of terrestrial fungi, plants, vertebrates, and invertebrates as we have done in the Wallace Initiative. In areas where future climate change is projected to exceed the modelled climatic tolerance of many species, the species currently present may not be able to persist into the future. On the other hand, there are places where the climatic tolerance of most species is not exceeded by projected climate change, and we classify these as refugia (areas remaining climatically suitable for >75% of the terrestrial biodiversity in that area). **These may be the best places to protect to conserve biodiversity (also known as no-regrets action) in the future despite climate change (i.e., arks).**

It is not just the species that are being conserved, but also the ecosystem services they provide. For example, acting as seed banks, providing natural food resources, nurseries for wild species, and homes for pollinators, as well as performing important processes that have large scale benefits such as carbon storage, air purification, water collection and purification, flood mitigation and soil conservation (Price et al., 2024b).

The Wallace Initiative classifies *Ragain?s vingis* in the Republic of Lithuania as being in the bottom 13% of all non-marine protected areas in the World for projected overall biodiversity resilience to climate change at 4 °C warming above pre-industrial.

Between 2000 and 2010, the area surrounding the *Ragain?s vingis* (within 15 km of the border) has seen an decrease in human population of close to 2229 and this is predicted to decrease to 37 258 by 2050 and to 32 451 by 2100 (SSP2).

Satellite data show that, between 1992 and 2020, the area within the boundaries has seen changes in land cover, with main changes in land cover types *Cropland, rainfed*(-1.1%) and *Tree cover, broadleaved, deciduous, closed to open (>15%)*(+1.1%) (Table ES1). Overall, the biodiversity (see report for a breakdown of taxa) is projected to see species richness remaining to drop to 70.6% at 1.5 °C, 60.4% at 2 °C, 39.4% at 3 °C, and 30.4% at 4 °C (Figure ES1).

Most nations have stated their aim to meet the Paris Accord climate change targets of the United Nations – limit global warming to 2 °C and make efforts to limit warming to 1.5 °C. However, the

reality is far different. Country's current pledges for reducing greenhouse gas emissions would lead to a world that is approximately 2.7 °C - 3.5 °C warmer than pre-industrial. If countries do not meet their pledges then greater warming may occur, so it is still very important to consider how to conserve biodiversity in a 4 °C warmer world.

Table ES1: Percent land cover in 1992 and 2020, and change in land cover at 300 m resolution (ESA CCI) within *Ragain?s vingis*.

Land cover class	% in 1992	% in 2020	change (%)
Cropland, rainfed	13.90	12.83	-1.07
Herbaceous cover	1.07	1.60	0.53
Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (< 50%)	15.51	14.97	-0.54
Tree cover, broadleaved, deciduous, closed to open (>15%)	3.21	4.28	1.07
Tree cover, needleleaved, evergreen, closed to open (>15%)	0.53	0.00	-0.53
Tree cover, mixed leaf type (broadleaved and needleleaved)	0.00	0.53	0.53
Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	2.14	2.14	0.00
Grassland	44.92	44.92	0.00
Shrub or herbaceous cover, flooded, fresh/saline/brakish water	1.07	1.07	0.00
Water bodies	17.65	17.65	0.00

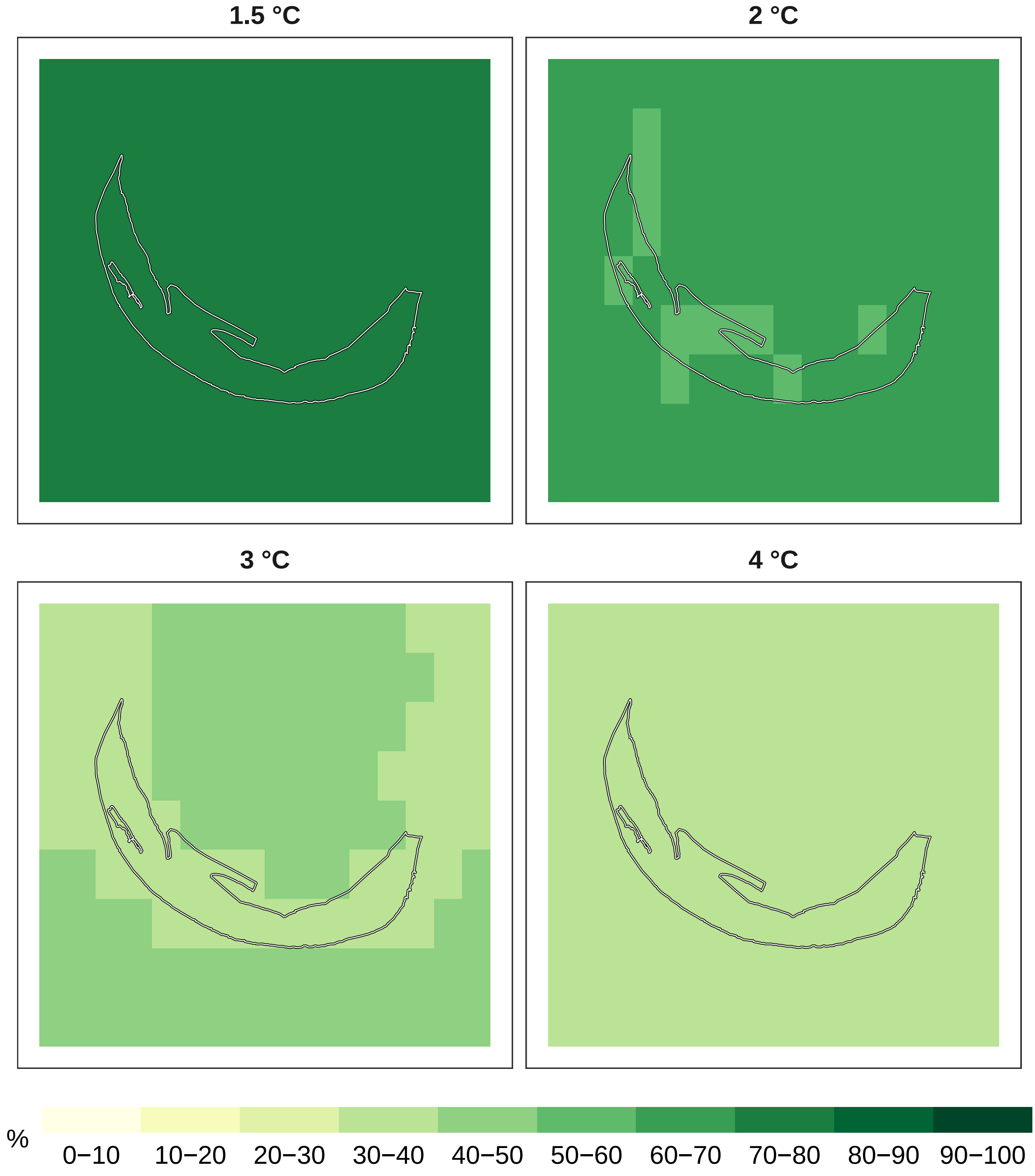

Figure ES1: Percent overall biodiversity remaining at 1 km resolution.

Supporting Information

This report is one of thousands prepared as part of the Wallace's pARCs (protected area refugia to climate change) project — identifying climate change refugia in countries and protected areas. It is hoped that providing information on what the projected impacts are to a protected area can be a first step for the park managers to assist them in preparing for a climate changed world.

The data and methods underpinning these reports have been published in the peer reviewed literature (Price et al., 2024a; Warren et al., 2018a,b) and are similar to the approach originally developed for analyses prepared for World Wildlife Fund to underpin their publication 'Wildlife in a Warming World' (WWF, 2018). Each of our reports provides information on the observed changes in the climate, the projected changes in climate, the refugia potential, and the 'adaptation effort'(that is, the size of the climate change challenge faced by professionals in trying to preserve existing biodiversity) for biodiversity within the boundaries of the protected area (as defined by the World Database on ProtectedAreas; UNEP-WCMC and IUCN, 2024). The report is accompanied by highly detailed information about interpreting the report.

Overview

The tables and figures below provide data extracted for the area listed in the title of the report. Brief interpretive information is provided in the headings and the captions, including the spatial resolution of the data. More detailed information can be found at the end of the tables and figures and this has been hyperlinked back to the appropriate place in the document if you are reading it online.

Climate

The climate data below are averaged over 30-year time periods. The spatial resolution is 0.5° latitude x 0.5° longitude.

Average Monthly High Temperature (usually the temperature of mid- to late-afternoon)

Table 1: Observed Average Monthly High Temperature (°C) with a comparison of the amount of change occurring between 1961-1990 and 1991-2020. Warmest refers to the warmest year in the 30-year period, coolest to the coolest year. In the warmest column, yellow shading indicates a temperature equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates a temperature equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990. One way of looking at this is these years could be seen as "proxies" for what an average year in the future looks like.

	1961-1990			1991-2020			Difference 91-20 to 61-90
Month	Coolest	Average	Warmest	Coolest	Average	Warmest	Average
Jan	-9.5	-2.2	3.3	-7.1	-0.7	3.1	1.5
Feb	-8.0	-1.3	5.4	-4.7	0.2	4.3	1.4
Mar	-0.4	3.4	8.1	-0.1	4.9	9.3	1.4
Apr	8.6	10.7	14.2	8.8	12.5	16.3	1.8
May	13.3	17.6	20.7	15.1	18.2	22.8	0.6
Jun	18.2	20.9	24.0	18.3	21.3	25.4	0.4
Jul	18.0	21.8	24.6	20.1	23.4	26.4	1.6
Aug	19.1	21.4	24.1	19.3	23.0	26.5	1.6
Sep	13.7	16.7	20.9	13.5	17.6	20.2	0.9
Oct	7.7	11.0	14.0	7.4	11.1	14.6	0.0
Nov	0.3	4.5	7.6	-0.6	5.0	7.6	0.5
Dec	-5.1	0.0	3.0	-4.7	1.0	5.6	1.0

Table 2: Projected Changes in Average Monthly High Temperature (°C) - Yellow shading indicates when the new average is equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates when the new average is equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990.

	Scenario					
Month	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
Jan	1.7	2.5	3.3	4.0	4.8	5.5
Feb	1.7	2.4	3.1	3.8	4.6	5.3
Mar	1.7	2.4	3.1	3.8	4.5	5.2
Apr	1.4	2.0	2.7	3.3	3.9	4.5
May	1.2	1.8	2.3	2.8	3.4	3.9
Jun	1.4	2.0	2.6	3.2	3.8	4.5
Jul	1.8	2.5	3.3	4.0	4.8	5.6
Aug	1.8	2.7	3.5	4.3	5.1	5.9
Sep	1.7	2.5	3.2	4.0	4.7	5.5
Oct	1.6	2.3	3.0	3.7	4.4	5.1
Nov	1.6	2.2	2.9	3.6	4.3	5.0
Dec	1.7	2.4	3.1	3.9	4.6	5.3

Average Monthly Temperature

Table 3: Observed Average Monthly Temperature (°C) with a comparison of the amount of change occurring between 1961-1990 and 1991-2020. Warmest refers to the warmest year in the 30-year period, coolest to the coolest year. In the warmest column, yellow shading indicates a temperature equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates a temperature equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990. One way of looking at this is these years could be seen as "proxies" for what an average year in the future looks like.

	1961-1990			1991-2020			Difference 91-20 to 61-90
Month	Coolest	Average	Warmest	Coolest	Average	Warmest	Average
Jan	-13.7	-4.8	1.5	-10.1	-2.9	1.5	1.9
Feb	-11.6	-4.1	2.9	-7.8	-2.3	1.9	1.8
Mar	-4.4	0.1	4.8	-3.7	1.5	5.5	1.4
Apr	4.4	6.2	8.4	4.7	7.7	10.8	1.4
May	8.6	12.2	15.1	10.3	12.7	16.7	0.5
Jun	13.4	15.6	17.9	13.4	16.0	19.2	0.4
Jul	14.1	16.9	20.0	15.4	18.3	21.1	1.4
Aug	14.8	16.5	18.3	15.1	17.9	20.1	1.4
Sep	10.1	12.4	15.3	9.8	13.2	15.1	0.8
Oct	4.1	7.7	10.5	4.5	7.8	10.6	0.1
Nov	-2.2	2.2	5.6	-2.9	2.9	5.5	0.6
Dec	-8.2	-2.3	1.1	-7.5	-1.0	3.8	1.3

Table 4: Projected Changes in Average Monthly Temperature (°C) - Yellow shading indicates when the new average is equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates when the new average is equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990.

	Scenario					
Month	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
Jan	2.0	2.8	3.7	4.5	5.4	6.2
Feb	1.9	2.6	3.4	4.2	5.1	5.9
Mar	1.7	2.4	3.1	3.9	4.6	5.3
Apr	1.4	2.0	2.7	3.3	3.9	4.5
May	1.3	1.8	2.3	2.9	3.4	4.0
Jun	1.4	1.9	2.5	3.1	3.7	4.3
Jul	1.6	2.3	3.1	3.8	4.5	5.2
Aug	1.7	2.5	3.2	3.9	4.7	5.4
Sep	1.6	2.3	3.0	3.7	4.4	5.1
Oct	1.5	2.2	2.8	3.5	4.1	4.8
Nov	1.6	2.3	3.0	3.7	4.4	5.1
Dec	1.8	2.6	3.4	4.2	5.0	5.8

Average Monthly Low Temperature (usually the temperature just before dawn)

Table 5: Observed Average Monthly Low Temperature (°C) with a comparison of the amount of change occurring between 1961-1990 and 1991-2020. Warmest refers to the warmest year in the 30-year period, coolest to the coolest year. In the warmest column, yellow shading indicates a temperature equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates a temperature equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990. One way of looking at this is these years could be seen as "proxies" for what an average year in the future looks like.

	1961-1990			1991-2020			Difference 91-20 to 61-90
Month	Coolest	Average	Warmest	Coolest	Average	Warmest	Average
Jan	-17.9	-7.4	-0.3	-13.2	-5.1	0.0	2.3
Feb	-15.2	-7.0	0.5	-11.0	-4.8	-0.1	2.2
Mar	-8.8	-3.3	1.6	-7.4	-1.8	1.7	1.5
Apr	-0.4	1.8	3.8	0.7	2.9	5.3	1.0
May	3.9	6.9	9.5	4.8	7.2	10.6	0.4
Jun	8.4	10.4	12.7	8.5	10.8	13.1	0.4
Jul	10.3	12.1	15.5	10.8	13.3	16.0	1.2
Aug	10.2	11.6	13.5	10.7	12.8	14.9	1.2
Sep	6.3	8.2	10.3	6.2	8.9	10.4	0.7
Oct	0.5	4.4	7.0	1.6	4.6	8.2	0.2
Nov	-4.7	0.0	3.6	-5.2	0.8	3.5	0.8
Dec	-11.3	-4.7	-0.8	-10.3	-3.0	2.1	1.7

Table 6: Projected Changes in Average Monthly Low Temperature (°C) - Yellow shading indicates when the new average is equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates when the new average is equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990.

	Scenario					
Month	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
Jan	2.3	3.3	4.3	5.3	6.3	7.3
Feb	2.2	3.1	4.1	5.1	6.0	7.0
Mar	1.9	2.7	3.5	4.4	5.2	6.0
Apr	1.4	2.1	2.7	3.3	3.9	4.6
May	1.3	1.8	2.4	2.9	3.5	4.0
Jun	1.3	1.9	2.5	3.1	3.7	4.3
Jul	1.5	2.2	2.9	3.5	4.2	4.9
Aug	1.6	2.3	3.0	3.6	4.3	5.0
Sep	1.5	2.2	2.9	3.5	4.2	4.9
Oct	1.5	2.2	2.8	3.5	4.1	4.8
Nov	1.7	2.5	3.2	4.0	4.8	5.5
Dec	2.1	3.0	3.9	4.8	5.8	6.7

Precipitation

Table 7: Observed Average Monthly Precipitation (mm/month) with a comparison of the amount of change occurring between 1961-1990 and 1991-2020. Wettest refers to the wettest year in the 30-year period, driest to the driest year. In the wettest and driest columns, yellow shading indicates precipitation amounts that exceed 1 SD above (wettest year) or below (driest year) the 1961-1990 average, i.e. amounts comparable to those that occur approximately one in every three years during 1961-1990; red shading indicates precipitation amounts occurring one in every twenty years compared to 1961-1990 (> 2 SD for wettest year, < 2 SD for driest). One way of looking at this is these years could be seen as "proxies" for what an average year in the future looks like.

	1961-1990			1991-2020			Difference 91-20 to 61-90
Month	Wettest	Average	Driest	Wettest	Average	Driest	Average
Jan	108.9	50.9	17.6	132.9	62.7	22.4	11.8
Feb	64.9	34.8	5.5	77.8	47.5	15.9	12.7
Mar	85.8	41.0	9.9	78.8	43.9	9.6	2.9
Apr	90.0	41.5	5.8	66.9	37.8	3.0	-3.7
May	96.0	50.1	15.4	99.8	50.0	21.0	0.0
Jun	118.0	70.2	29.3	108.8	67.4	13.0	-2.8
Jul	181.6	89.2	35.2	181.0	94.1	7.9	5.0
Aug	162.7	82.2	23.2	140.6	84.1	8.2	1.9
Sep	145.1	78.1	18.4	150.8	68.5	26.2	-9.6
Oct	227.5	68.1	10.4	148.0	77.2	19.8	9.1
Nov	163.3	83.8	35.0	113.8	71.4	25.9	-12.4
Dec	114.0	64.8	14.4	94.3	65.5	35.1	0.7

Table 8: Projected Average Monthly Precipitation Change (mm) - Yellow shading indicates when the new average is equal to that occurring approximately one in every three years (> 1 SD) compared to 1961-1990; red shading indicates when the new average is equal to or greater than that occurring one in every twenty years (>2 SD) compared to 1961-1990.

	Scenario					
Month	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
Jan	4.3	6.1	8.0	9.8	11.7	13.5
Feb	2.4	3.5	4.5	5.6	6.7	7.7
Mar	3.3	4.7	6.1	7.6	9.0	10.4
Apr	2.3	3.3	4.3	5.2	6.2	7.2
May	2.6	3.7	4.9	6.0	7.1	8.3
Jun	1.8	2.5	3.3	4.0	4.8	5.6
Jul	-2.4	-3.5	-4.5	-5.5	-6.5	-7.5
Aug	-3.4	-4.8	-6.2	-7.6	-8.9	-10.2
Sep	-0.6	-0.9	-1.1	-1.4	-1.6	-1.9
Oct	3.3	4.8	6.2	7.7	9.1	10.6
Nov	5.0	7.2	9.4	11.5	13.7	15.9
Dec	5.0	7.2	9.3	11.5	13.7	15.8

Drought/Waterlogging

The drought metric used here measures severe meteorological drought (SPEI12, -1.5). It is the metric often used when looking at potential drought issues for agricultural and natural lands. The metric looks at droughts developing over the preceding 12 months before the 'counting' begins. Thus, an area identified as having a maximum drought duration of 12 months has been in drought for up to 24 months. The values in the table are calculated for the 30-year period for the observed or warming level given. Waterlogging is the reverse of the drought metric (SPEI12, +1.5) and is an indication of areas having excess moisture for extended periods, potentially leading to waterlogged soils.

Table 9: Observed number of months in severe drought or waterlogged in a 30-year period with a comparison of the amount of change occurring between 1961-1990 and 1986-2015.

	1961-1990	1986-2015	Difference 86-15 to 61-90
In drought	25	11.6	-13.4
Waterlogged	18	24.2	6.2

Table 10: Observed maximum number of consecutive months in severe drought or waterlogged in a 30-year period with a comparison of the amount of change occurring between 1961-1990 and 1986-2015.

	1961-1990	1986-2015	Difference 86-15 to 61-90
In drought	14	3	-11
Waterlogged	17	8	-9

Table 11: Changes in number of months in severe drought or waterlogged in a 30-year period.

	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
In drought	16.1	25.4	38.5	54	73.2	90.8
Waterlogged	1.7	1.5	1.1	0	0.0	-0.2

Table 12: Changes in maximum number of consecutive months in severe drought or waterlogged in a 30-year period.

	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
In drought	4.2	4.9	5.7	7.4	9.4	20.9
Waterlogged	-1.4	-3.2	-4.2	-5.0	-5.3	-6.2

Population

Table 13: Projected population for the years 2010 through 2100 at a 1 km^2 spatial resolution. These data are provided both in terms of the population within the protected area boundary, and those within an area including a 15 km wide buffer zone around the boundary. The data from 2000 and 2010 are interpolations of observed population sizes, the other periods are projections of future change in a 'middle-of-the-road' scenario with historical patterns of development continued through te 21st century.

Area	2000	2010	2030	2050	2070	2090	2100
Within region	303	232	199	169	145	126	118
Region plus buffer	42,654	40,425	38,843	37,258	35,689	33,655	32,451

Landcover changes

Table 14: Percent landcover in 1992 and 2020, and change in landcover (300 m resolution). These figures are provided to assist in understanding how landcover has changed over time as this may have had immediate biodiversity implications in the area.

Landcover class	% in 1992	% in 2020	change (%)
Cropland, rainfed	13.90	12.83	-1.07
Herbaceous cover	1.07	1.60	0.53
Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (< 50%)	15.51	14.97	-0.54
Tree cover, broadleaved, deciduous, closed to open (>15%)	3.21	4.28	1.07
Tree cover, needleleaved, evergreen, closed to open (>15%)	0.53	0.00	-0.53
Tree cover, mixed leaf type (broadleaved and needleleaved)	0.00	0.53	0.53
Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	2.14	2.14	0.00
Grassland	44.92	44.92	0.00
Shrub or herbaceous cover, flooded, fresh/saline/brakish water	1.07	1.07	0.00
Water bodies	17.65	17.65	0.00

Biodiversity

The biodiversity information presented comes from models projecting climate suitability for ∼135 000 terrestrial fungi, plants, invertebrates, and vertebrates. Resolution ∼1 km^2.

Local Extinction Risk

Table 15: Percentage of species in different taxonomic groups projected to be at risk of local extinction owing to changes in climate alone. Yellow shading indicates areas projected to become climatically unsuitable for >25% of the species studied (by group); orange shading indicates areas projected to become climatically unsuitable for >50% of the species studied; and red shading indicates areas projected to become climatically unsuitable for >75% of the species studied. NA means there is insufficient data for that group in that area.

Taxa	1.5 °C	2 °C	3 °C	4 °C
Biodiversity	29.4	39.6	60.6	69.6
Plants	21.4	26.4	43.2	53.1
Ferns	10.4	17.2	35.0	47.9
Mosses	29.8	36.2	56.1	71.3
Pines	14.0	20.0	40.4	51.2
Flowering plants	18.6	22.4	36.4	46.2
Magnoliopsida	18.3	22.0	35.6	45.6
Liliopsida	20.3	23.6	37.8	47.6
Grasses	22.2	25.0	36.7	47.6
Lilies	44.2	46.4	73.4	85.2
Orchids	17.2	20.4	36.4	45.9
Palms	NA	NA	NA	NA
Vines	NA	NA	NA	NA
Timber species	9.6	13.2	24.7	41.0
Animals	40.9	54.6	76.5	82.7
Arthropoda	42.7	57.0	79.5	85.7
Arachnida	32.1	43.5	73.4	84.0
Spiders	31.6	43.5	74.9	85.7
Insecta	43.3	57.7	79.8	85.8
Bees	21.2	29.0	59.9	71.3
Beetles	49.4	65.8	86.7	90.9
True Bugs	33.5	53.2	75.2	82.6
Flies	53.0	63.4	80.0	88.4
Lepidoptera	50.6	59.3	78.4	84.2
Butterflies	12.8	19.0	46.4	59.0
Moths	53.9	62.7	81.7	86.6
Dragonflies	25.8	39.1	80.9	88.9
Pollinators	58.1	67.6	83.9	87.8
Chordata	11.3	14.2	23.4	30.2
Amphibia	27.1	32.0	54.5	54.5
Aves	10.9	12.7	19.9	24.2
Mammals	13.1	17.0	36.1	54.9
Reptiles	16.6	16.7	30.0	38.9

Species Richness Remaining

Figures 1 to 9 show the average percent of the species (species richness) *remaining* within the boundaries of the area (also depicted on the map as a solid black line) for selected groups. This shows the spatial variability in the potential patterns of loss.

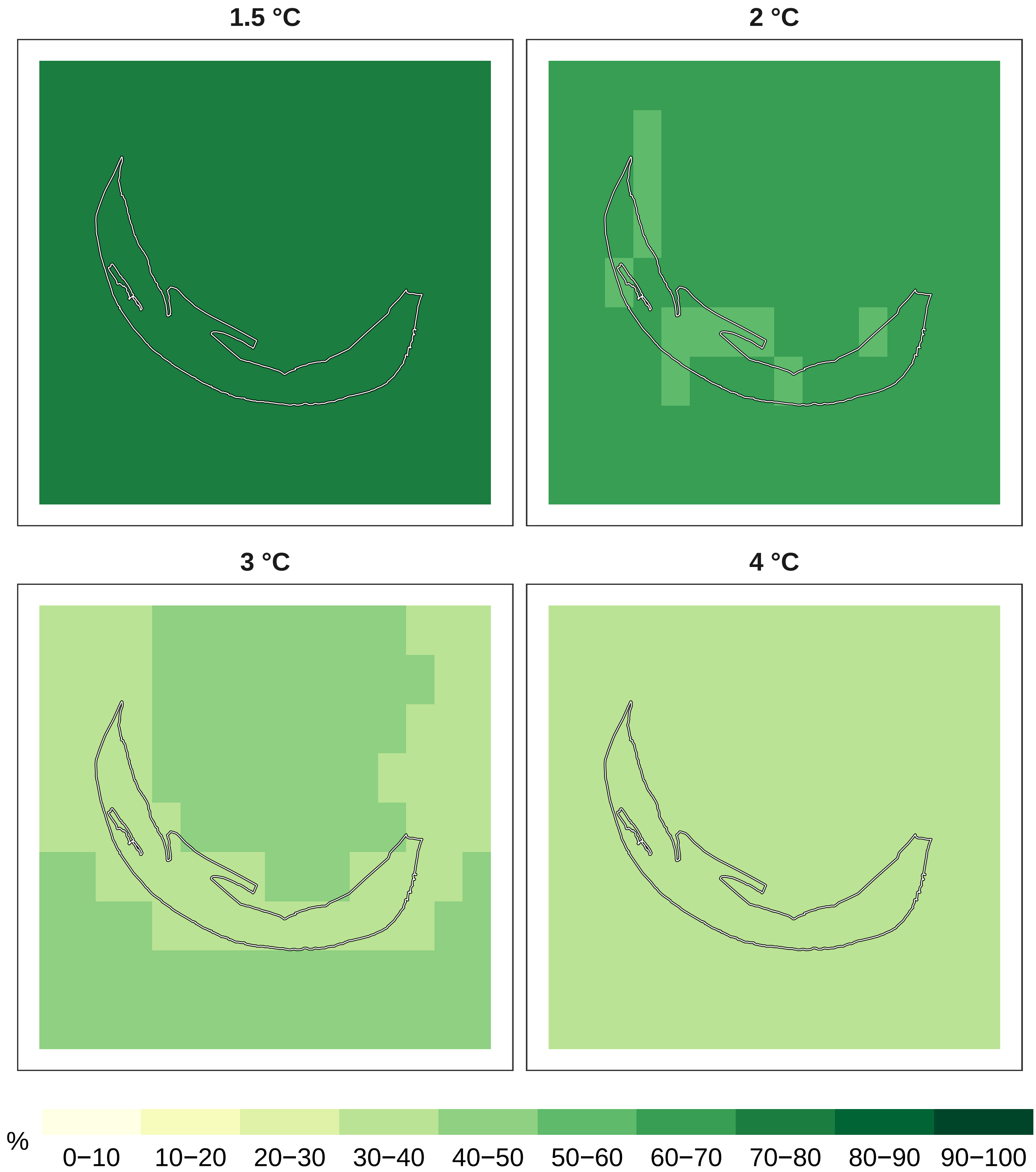

Figure 1: Percent overall biodiversity remaining at 1 km resolution.

Plants

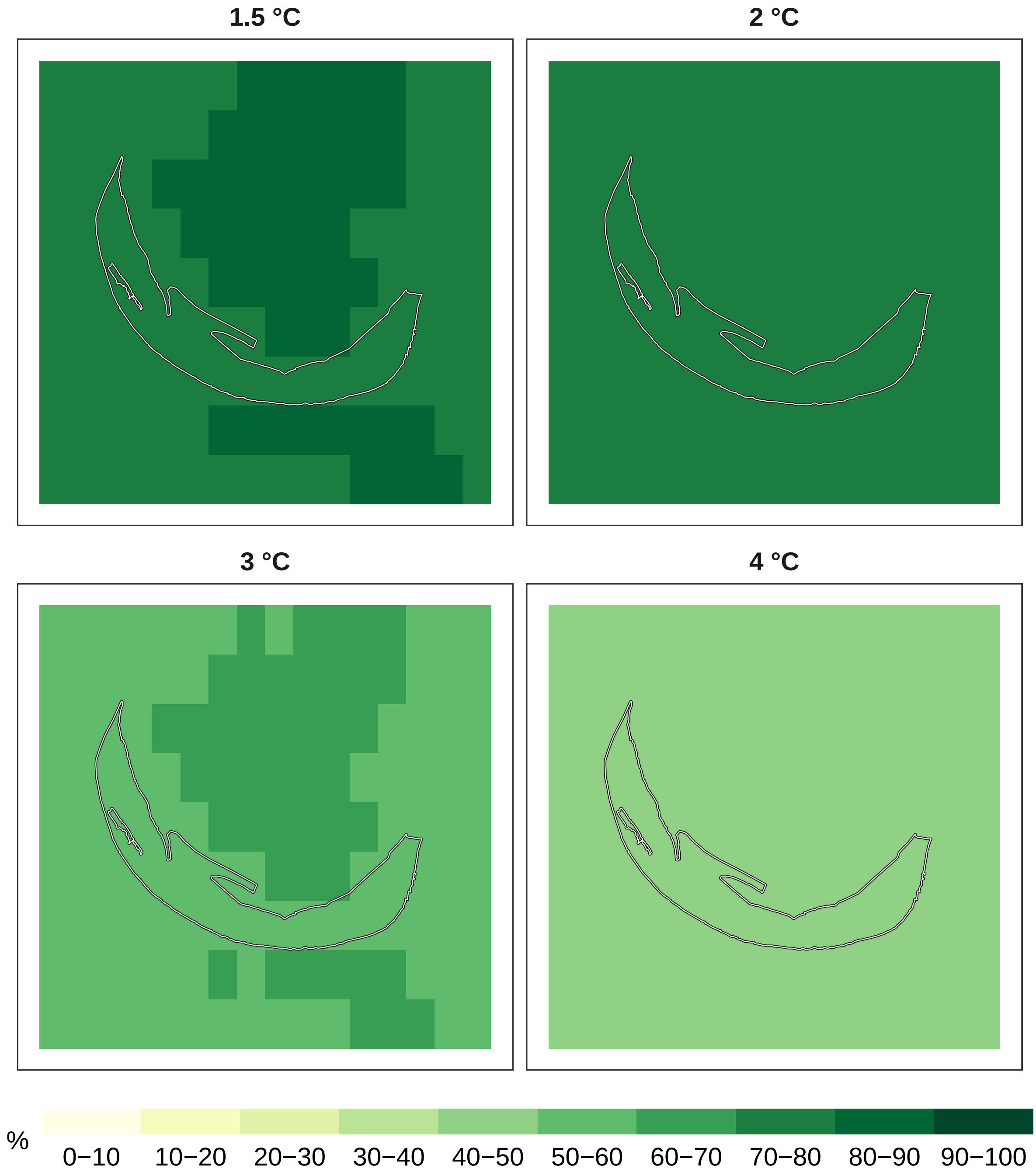

Figure 2: Percent plants remaining at 1 km resolution.

Amphibians

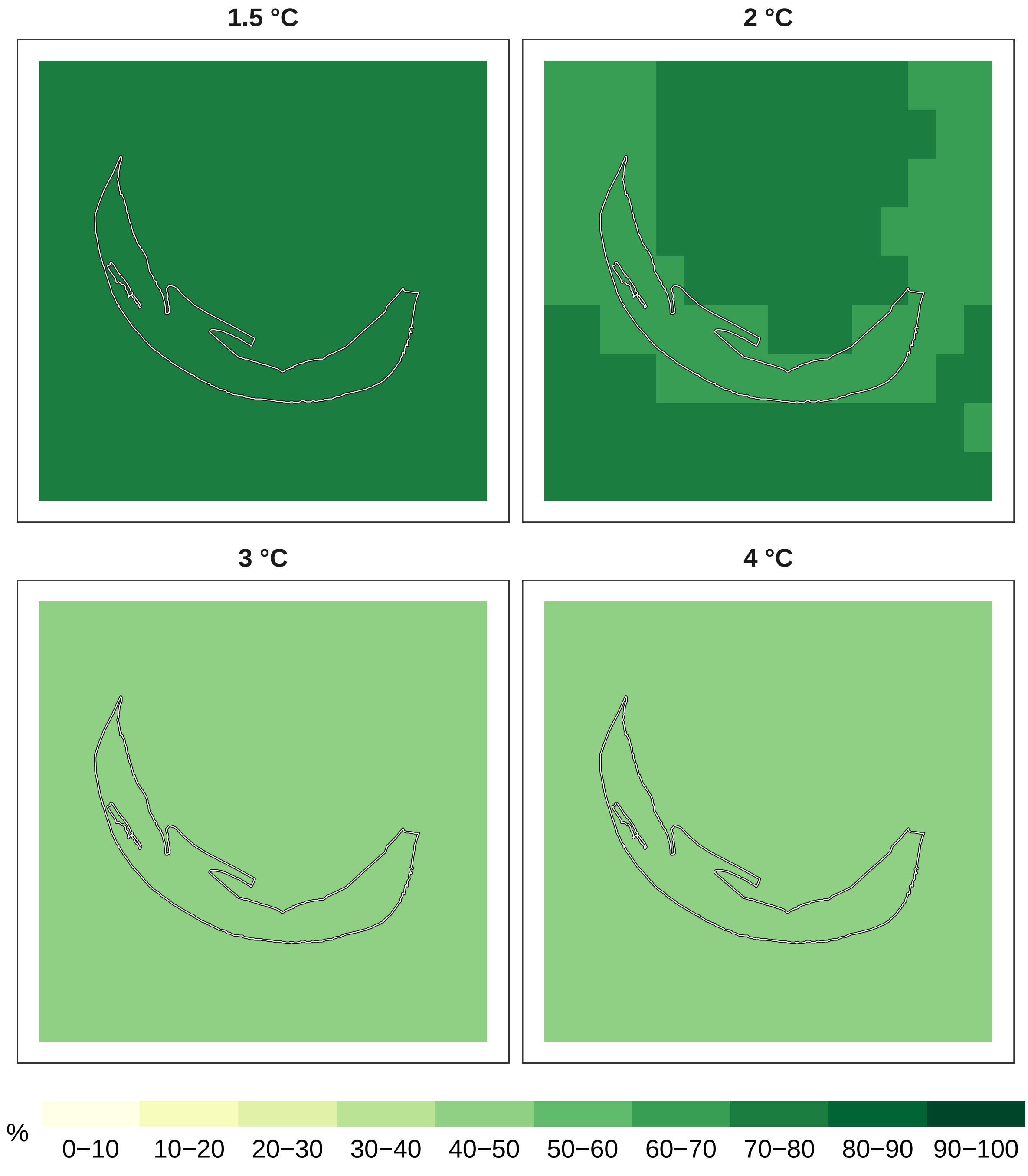

Figure 3: Percent amphibians remaining at 1 km resolution.

Birds

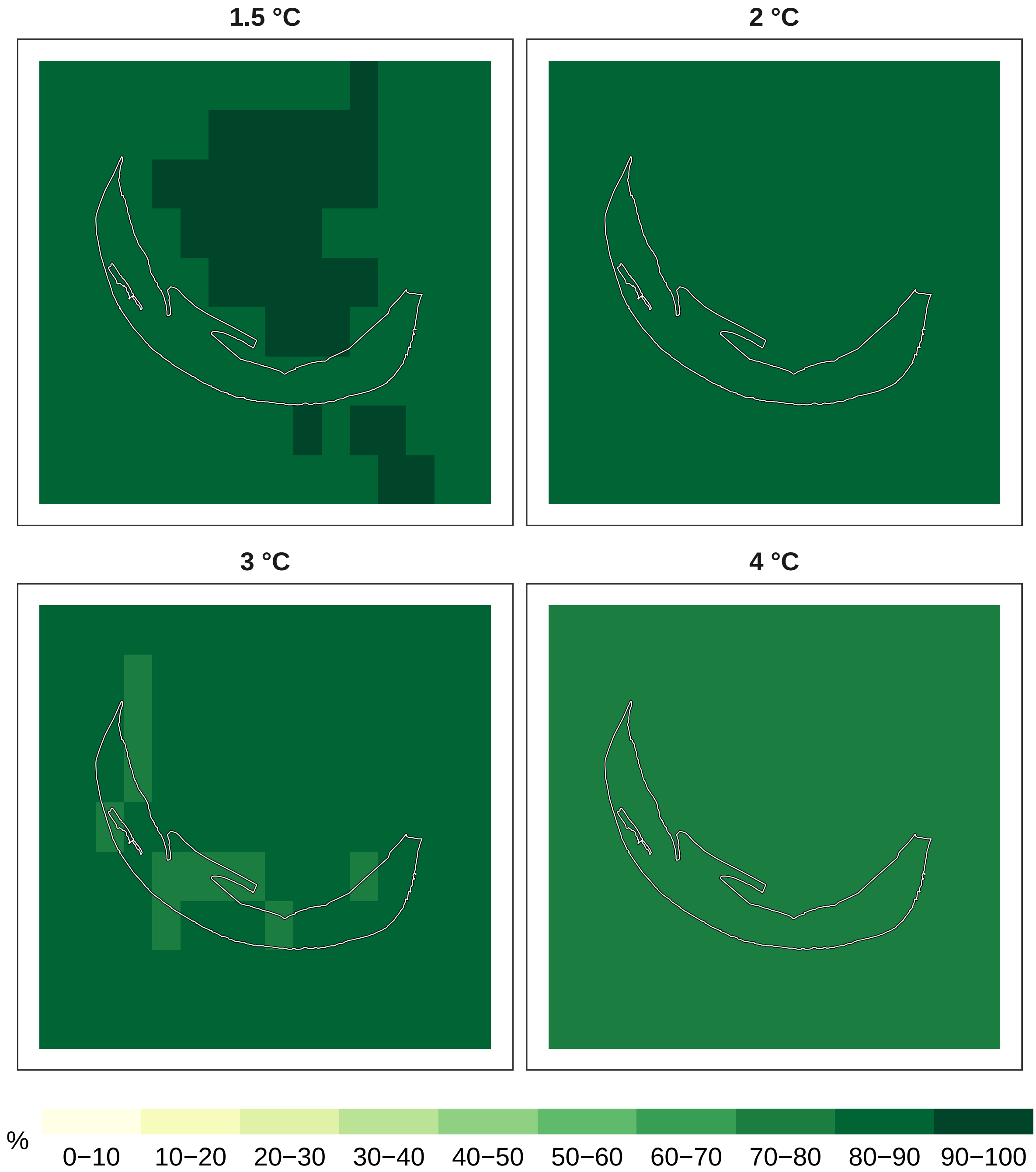

Figure 4: Percent birds remaining at 1 km resolution.

Mammals

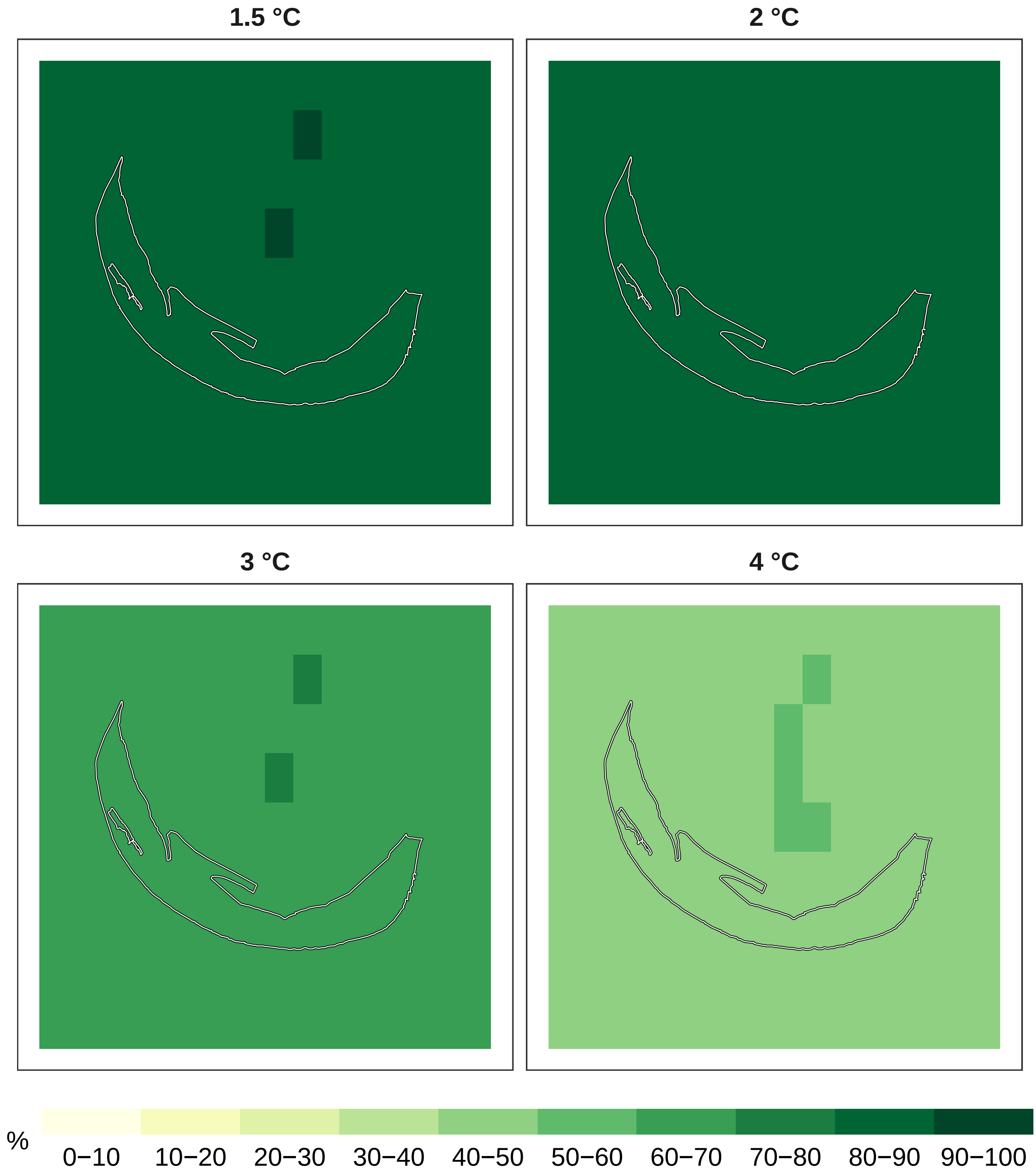

Figure 5: Percent mammals remaining at 1 km resolution.

Reptiles

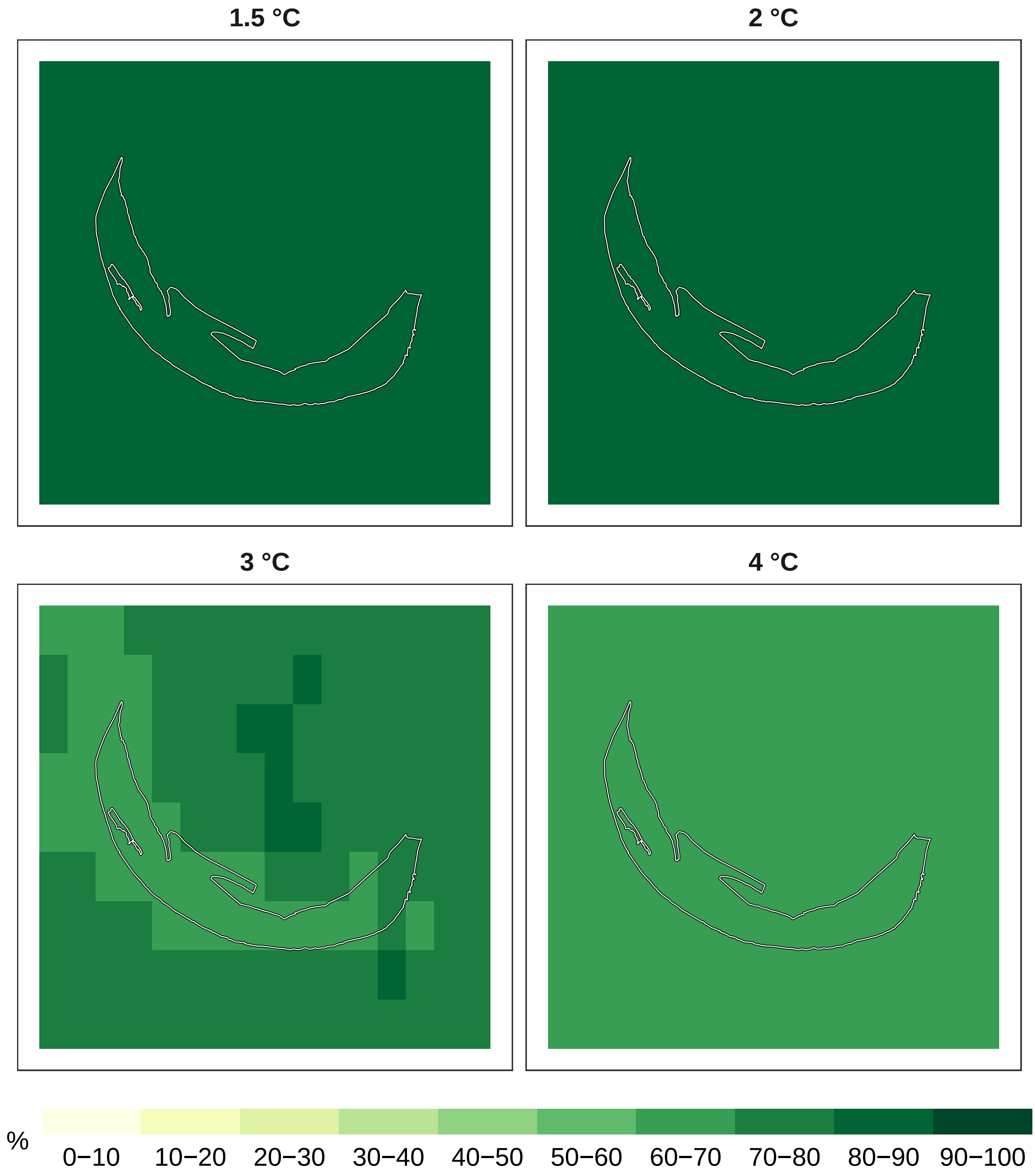

Figure 6: Percent reptiles remaining at 1 km resolution.

Insects

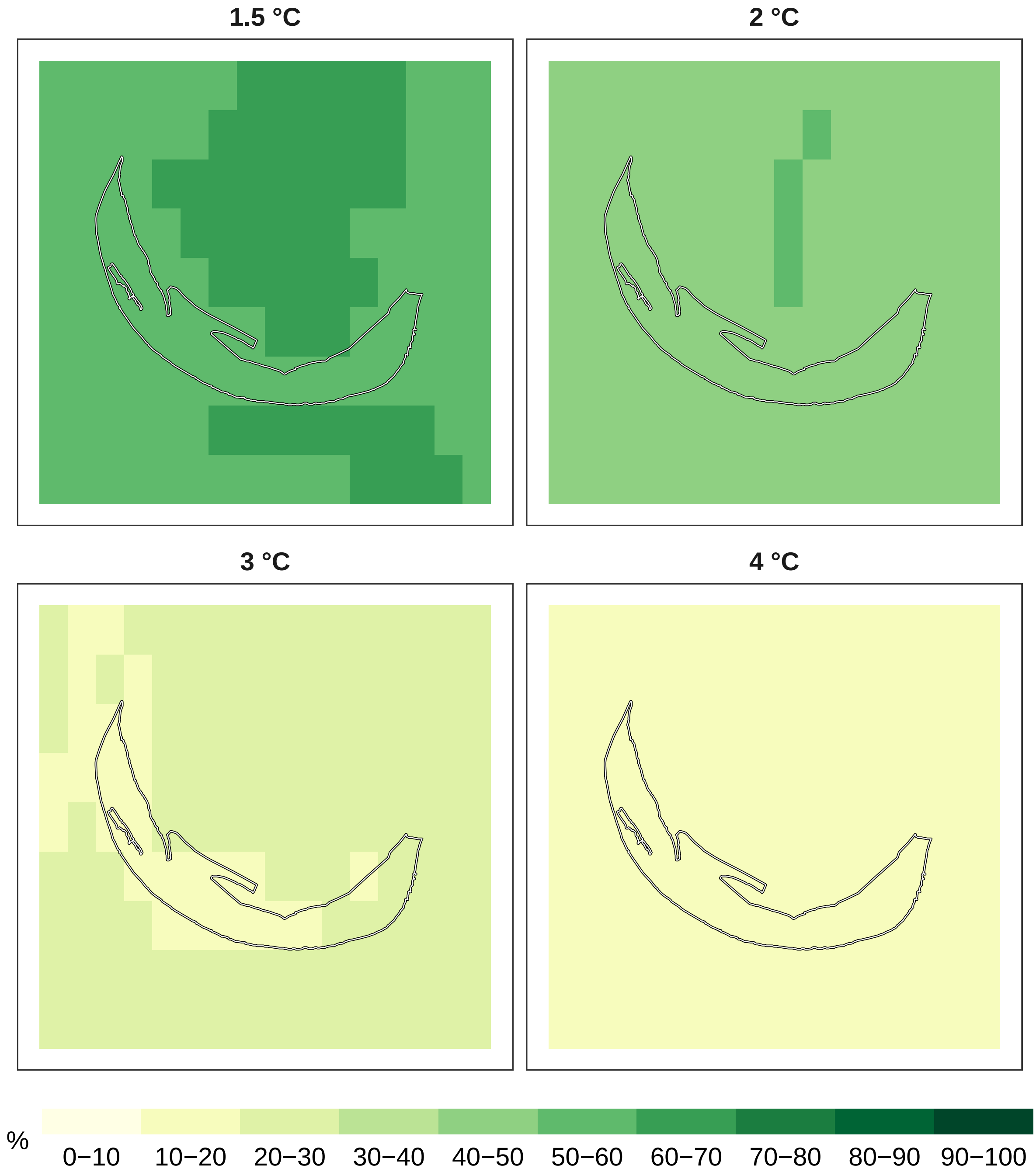

Figure 7: Percent insects remaining at 1 km resolution.

Pollinators

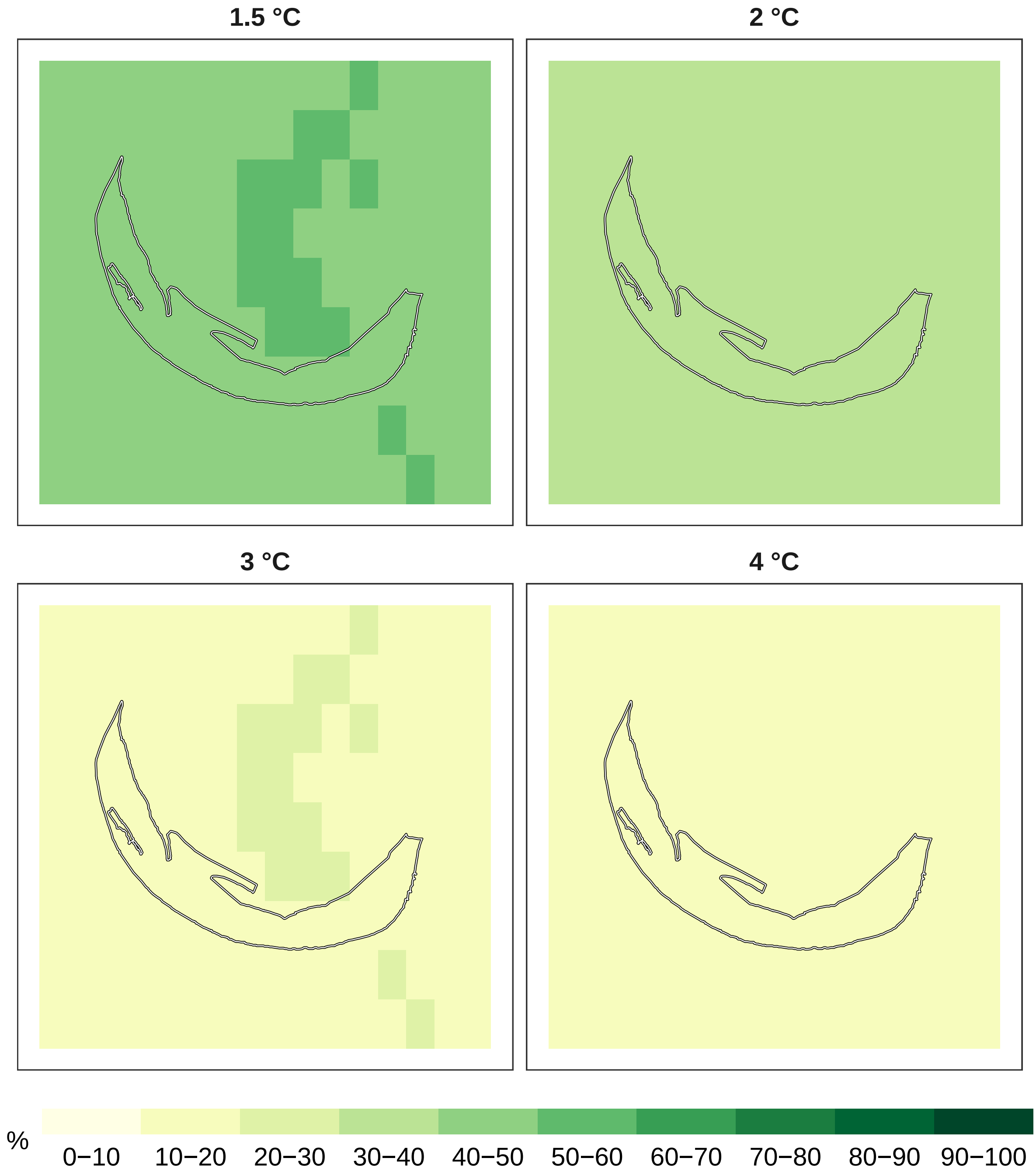

Figure 8: Percent pollinators remaining at 1 km resolution.

Timber species

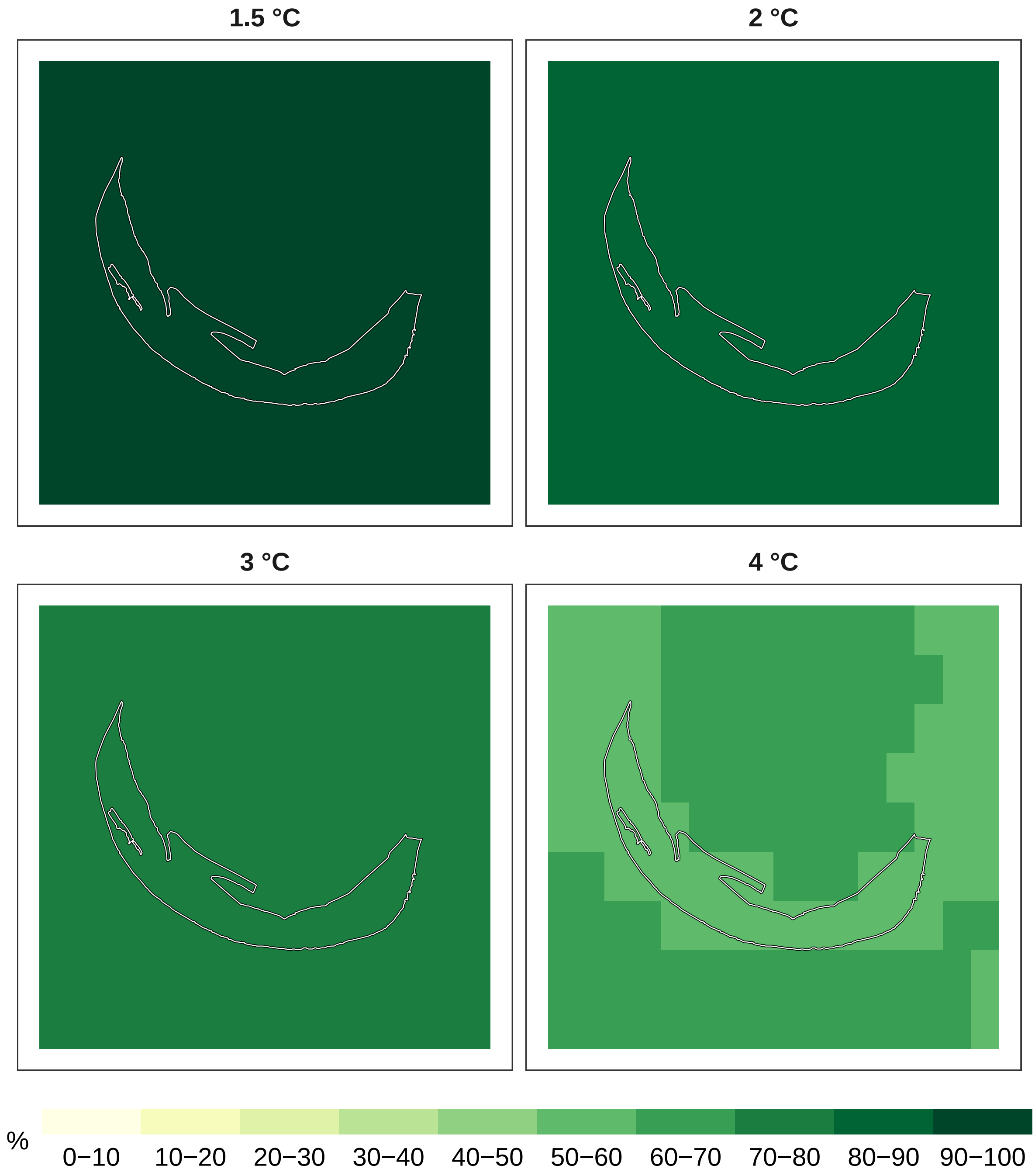

Figure 9: Percent timber species remaining at 1 km resolution.

Refugia

Table 16 shows the percent of the area remaining a climatic refugium for different groups of species. Climatic refugia are defined as areas remaining climatically suitable for >75% of the species in each group. The two columns, for each warming level, are >0 (meaning at least one climate change model projects that the area is a refugium) and >10 (meaning that at least half of the models project an area is a refugium). The shading is – darker green, >75% of the area is a refugium; medium green, 50%-75% of the area is a refugium; light green, 25%-50% of the area is a refugium; and white, less than 25% of the area is a refugium.

Figures 10 to 17 show the number of climate models agreeing that a particular pixel (cell) is a refugium for the taxa indicated. These maps provide a spatial representation of the agreement in the models (or areas with potentially lower uncertainty) to be refugia for the different groups as well as how this potentially varies within the area under study.

Table 16: Percentage of area remaining a climatic refugia (i.e., remaining climatically suitable for > 75% of the species across > 11 climate models) for different taxonomic groups at 1km resolution.

	1.5 °C		2.0 °C		3.0 °C		4.0 °C	
Taxa	> 0	> 10	> 0	> 10	> 0	> 10	> 0	> 10
Biodiversity	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0
Plants	100.0	100.0	100.0	1.5	0.3	0.0	0.0	0
Ferns	100.0	100.0	100.0	100.0	100.0	0.0	100.0	0
Mosses	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Pines	100.0	100.0	100.0	100.0	100.0	0.0	100.0	0
Flowering plants	100.0	100.0	100.0	9.1	100.0	0.0	13.7	0
Magnoliopsida	100.0	100.0	100.0	9.1	100.0	0.0	13.7	0
Liliopsida	100.0	100.0	100.0	1.5	100.0	0.0	0.0	0
Grasses	100.0	100.0	100.0	1.5	100.0	0.0	0.0	0
Lilies	100.0	0.0	100.0	0.0	100.0	0.0	0.0	0
Orchids	100.0	100.0	100.0	100.0	100.0	0.0	100.0	0
Palms	NA	NA	NA	NA	NA	NA	NA	NA
Vines	NA	NA	NA	NA	NA	NA	NA	NA
Timber species	100.0	100.0	100.0	100.0	100.0	0.3	100.0	0
Animals	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0
Arthropoda	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
Arachnida	100.0	0.0	100.0	0.0	0.0	0.0	0.0	0
Spiders	100.0	0.0	100.0	0.0	0.0	0.0	0.0	0
Insecta	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
Bees	100.0	100.0	100.0	0.0	0.3	0.0	0.0	0
Beetles	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
True Bugs	100.0	0.0	0.3	0.0	0.0	0.0	0.0	0
Flies	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
Lepidoptera	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
Butterflies	100.0	100.0	100.0	100.0	100.0	0.0	0.0	0
Moths	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
Dragonflies	100.0	1.5	100.0	0.0	0.0	0.0	0.0	0
Pollinators	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0
Chordata	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0
Amphibia	100.0	0.0	100.0	0.0	0.0	0.0	0.0	0
Aves	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
Mammals	100.0	100.0	100.0	100.0	100.0	0.0	13.7	0
Reptiles	100.0	100.0	100.0	100.0	100.0	13.7	100.0	0

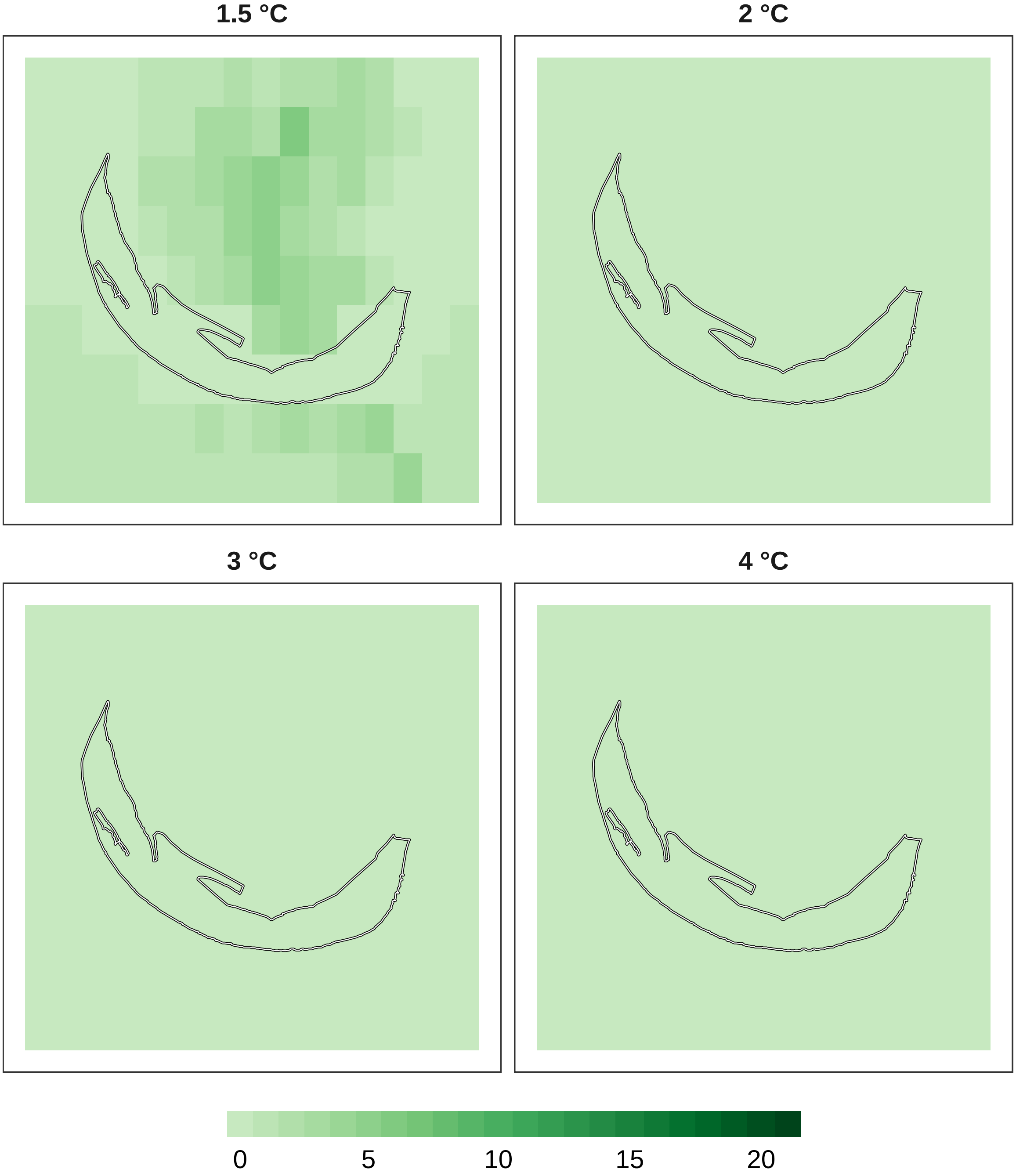

Figure 10: Number of models in agreement for overall biodiversity refugia at 1 km resolution.

Plants

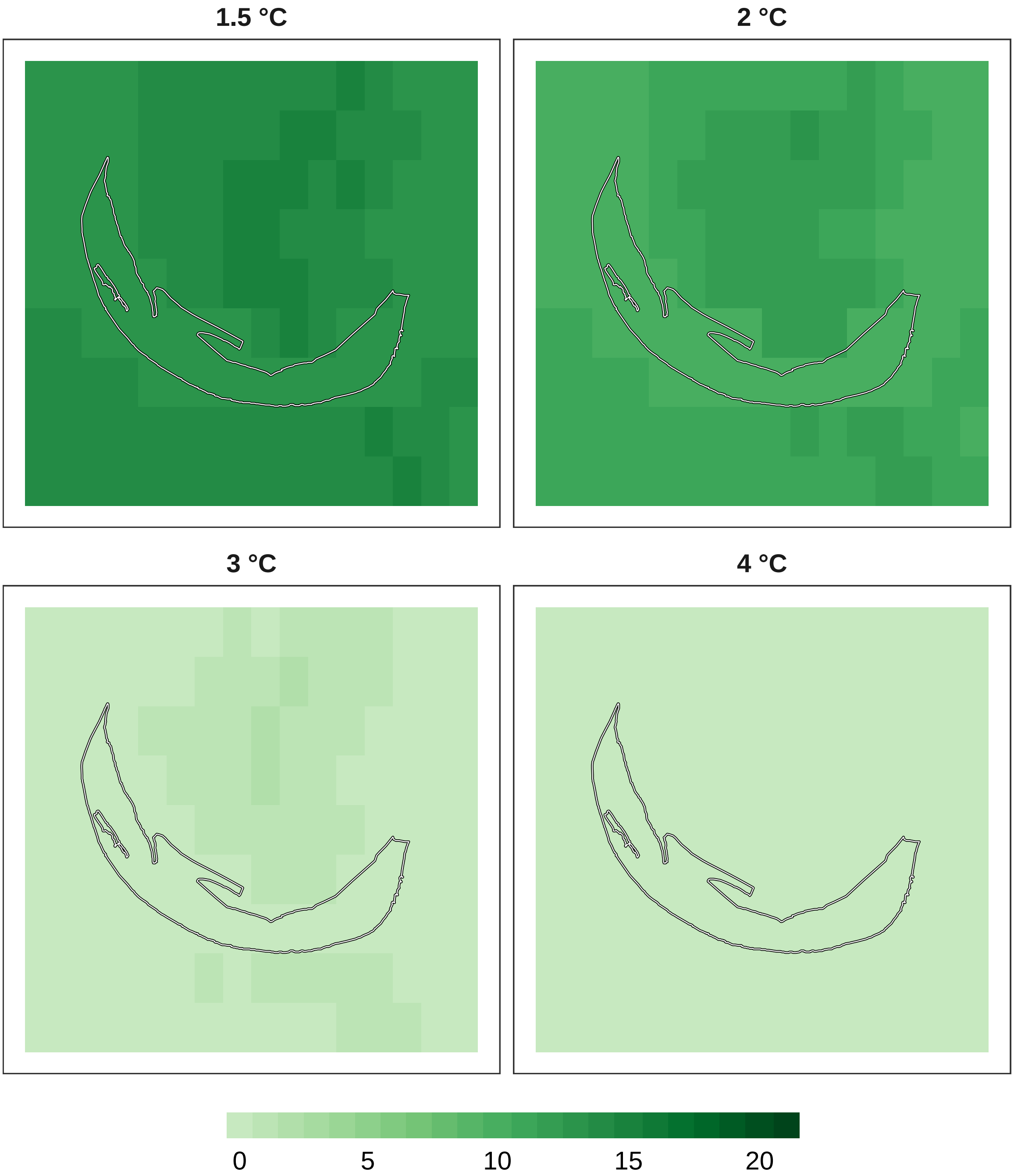

Figure 11: Number of models in agreement for plant refugia at 1 km resolution.

Amphibians

Figure 12: Number of models in agreement for amphibian refugia at 1 km resolution.

Birds

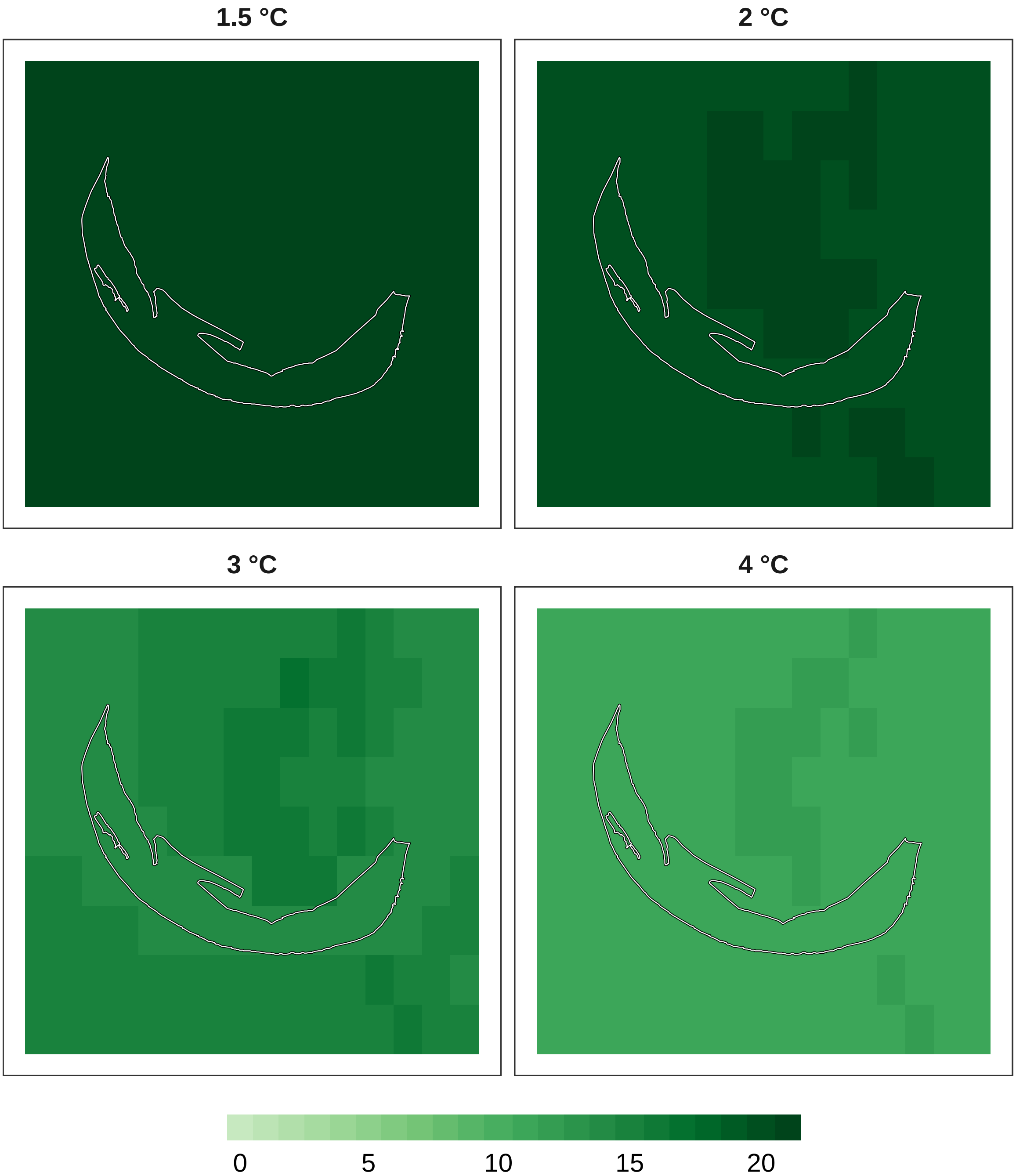

Figure 13: Number of models in agreement for bird refugia.

Mammals

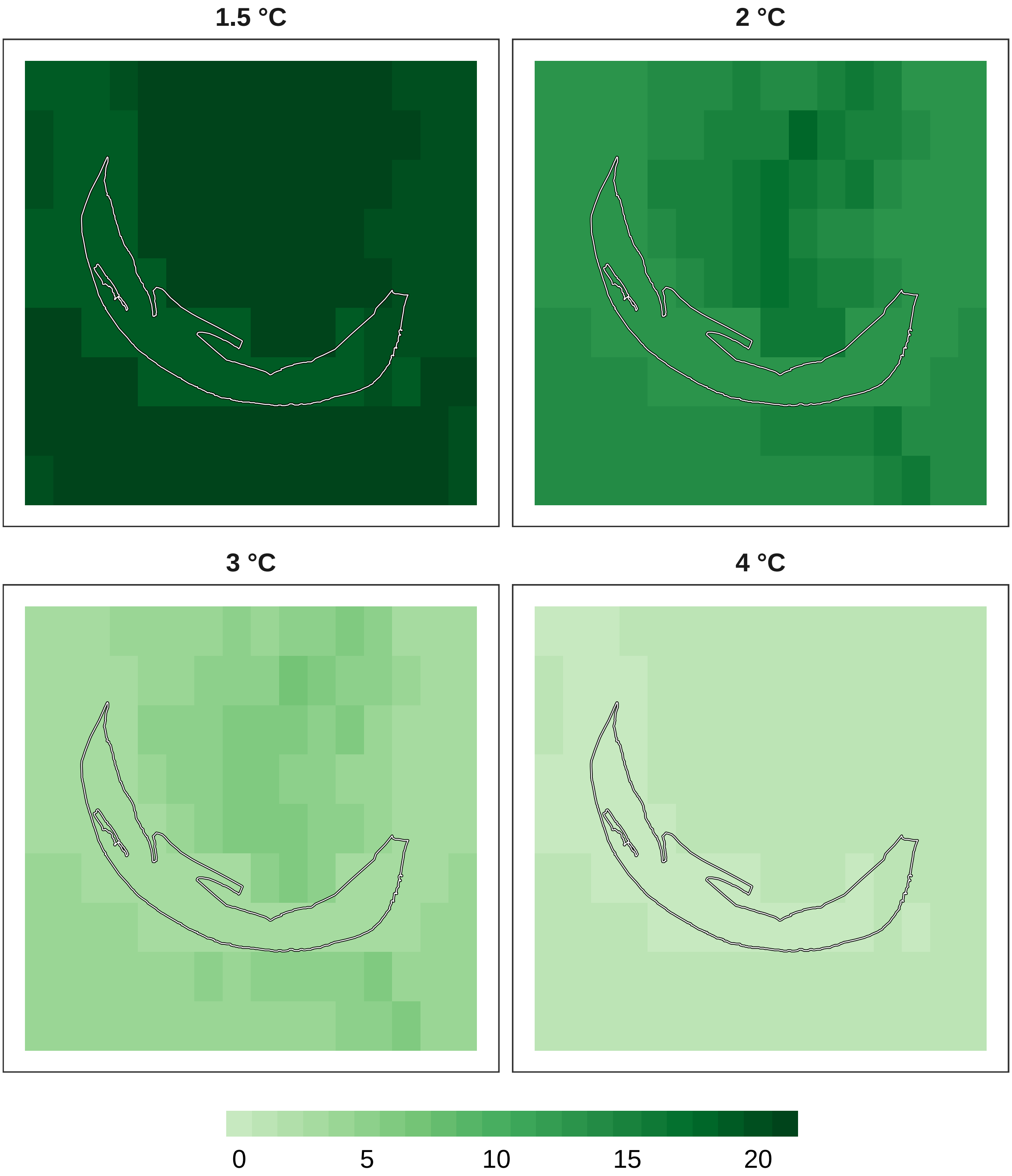

Figure 14: Number of models in agreement for mammal refugia at 1 km resolution.

Reptiles

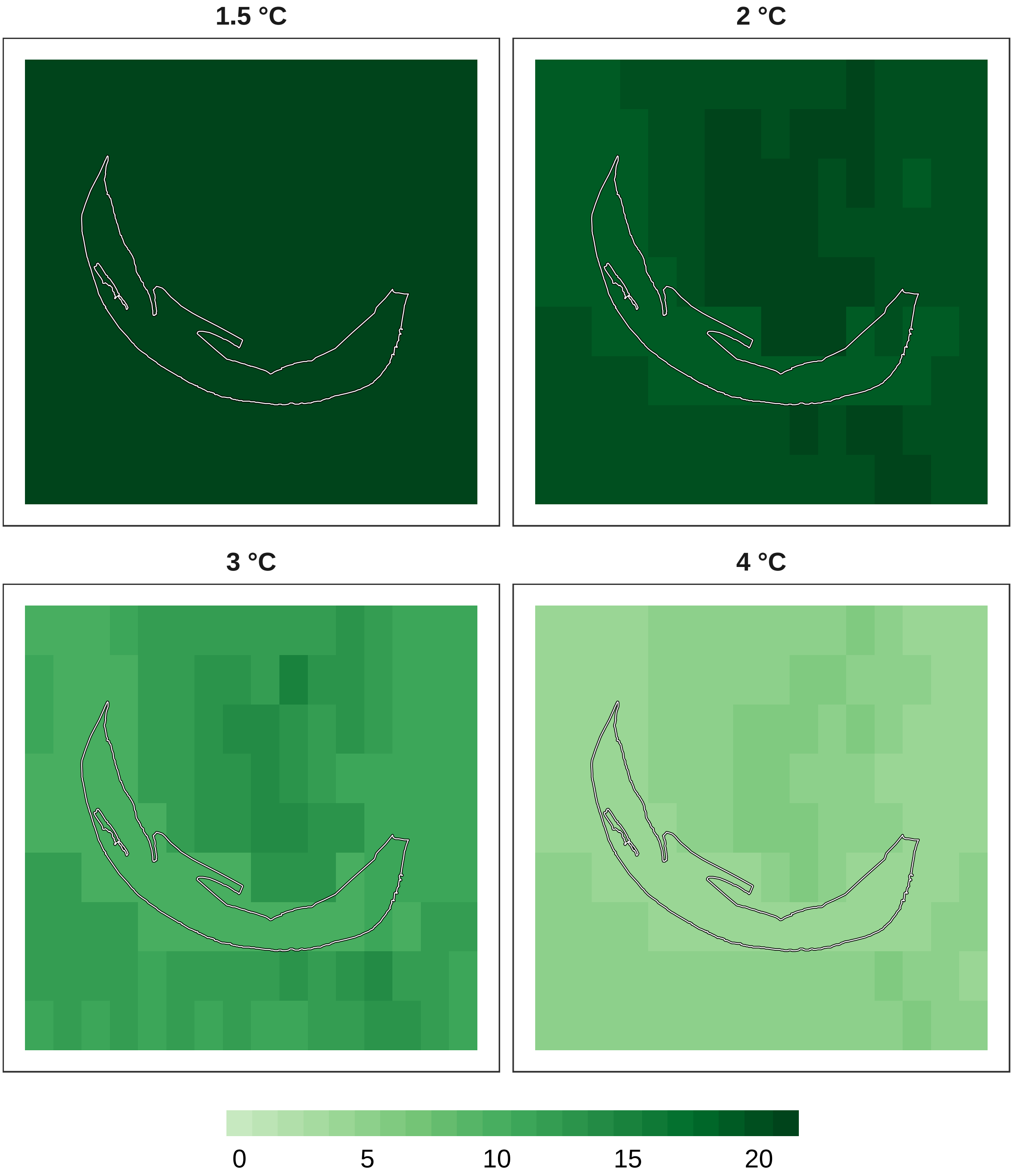

Figure 15: Number of models in agreement for reptile refugia at 1 km resolution.

Insects

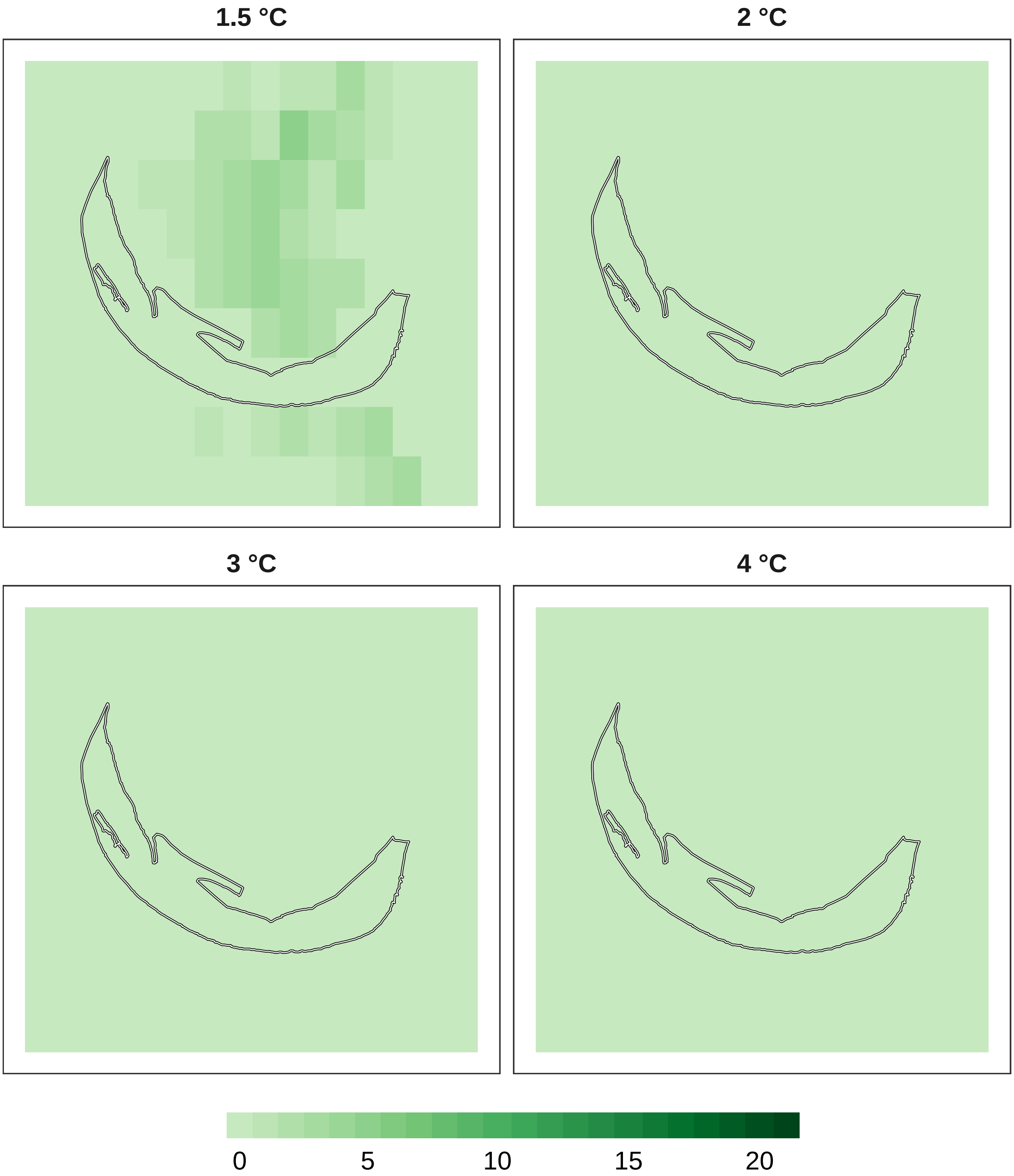

Figure 16: Number of models in agreement for insect refugia at 1 km resolution.

Pollinators

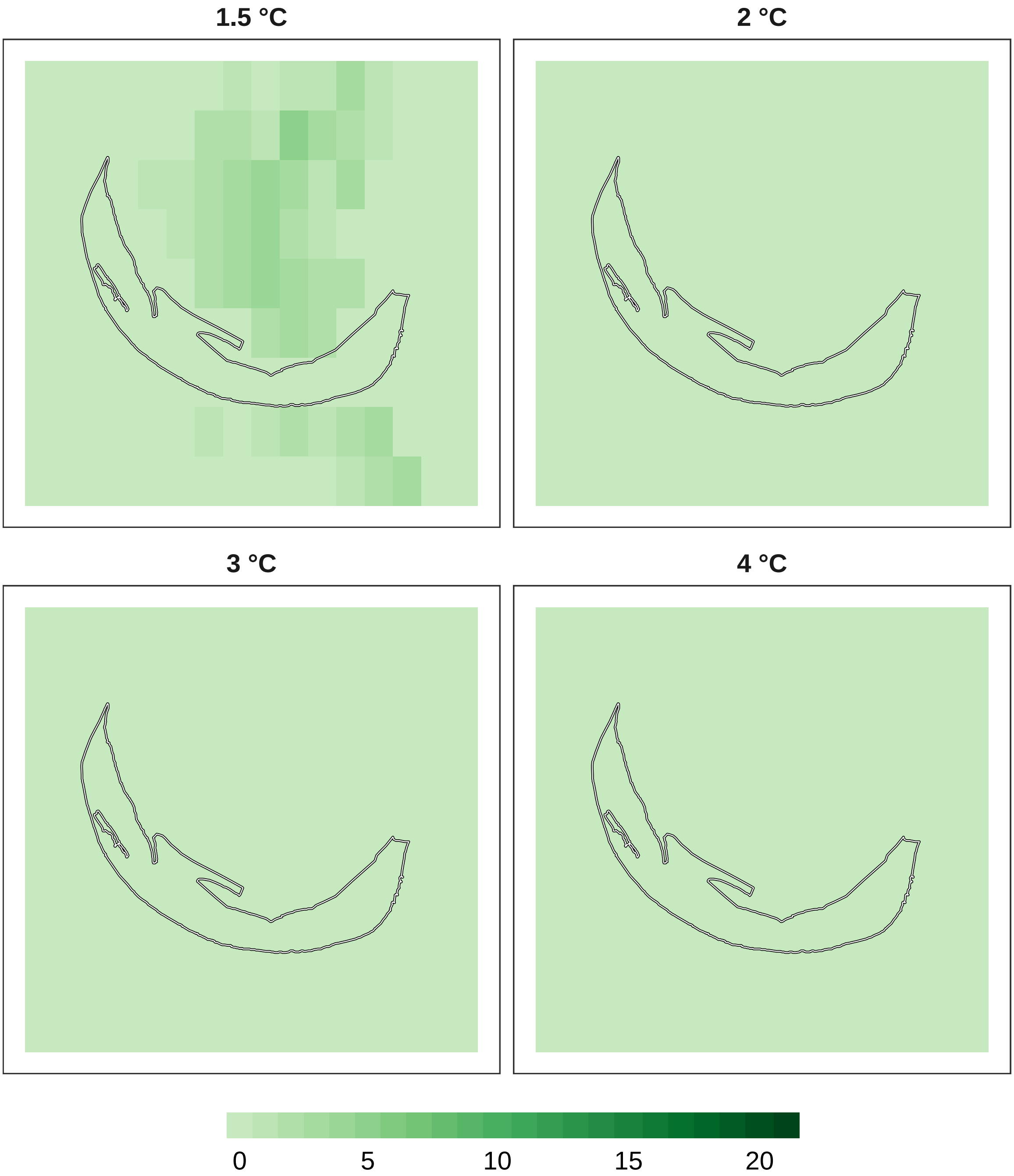

Figure 17: Number of models in agreement for pollinator refugia at 1 km resolution.

Adaptation Effort

Figures 18 to 25 present a spatial representation of the potential ‘adaptation effort’ that might be needed to maintain at least 75% of the species modelled. Adaptation effort is a combination of the number of climate models (+ 1 to 21) projecting an area is a refugia well as the number of climate models (- 1 to -21) projecting the area to be an Area of Concern (becomes climatically unsuitable for >75% of the species) in each pixel. One way of looking at this is to consider areas with high values (+18 to +21) as being less exposed to climate change and thus potentially more resilient. Business-as-usual conservation, especially if coupled with building resilience around extreme climates (e.g., drought, heat waves) might be a reasonable adaptation approach to take. As the score drops, increasingly greater amounts of adaptation might be needed to maintain the existing species composition. Once the adaptation effort drops into the negative zone, adaptation to maintain existing species is likely to become increasingly difficult. At a score of -15 to -21 the best approach might be to consider facilitating change as opposed to putting large efforts into trying to maintain existing species. Scores this low indicate that the area becomes climatically unsuitable for a large percentage of species.

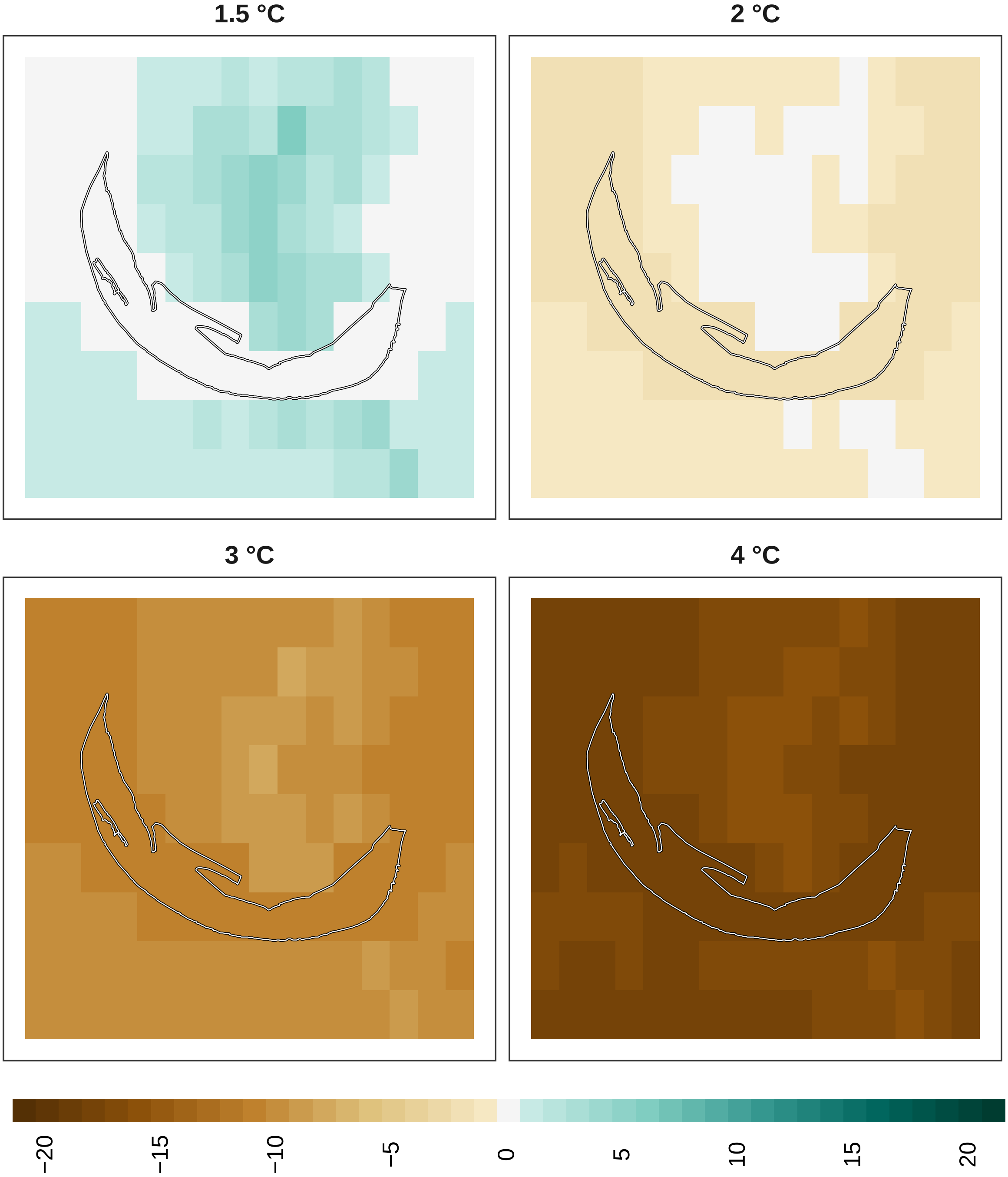

Figure 18: Adaptation effort for overall biodiversity at 1 km resolution.

Plants

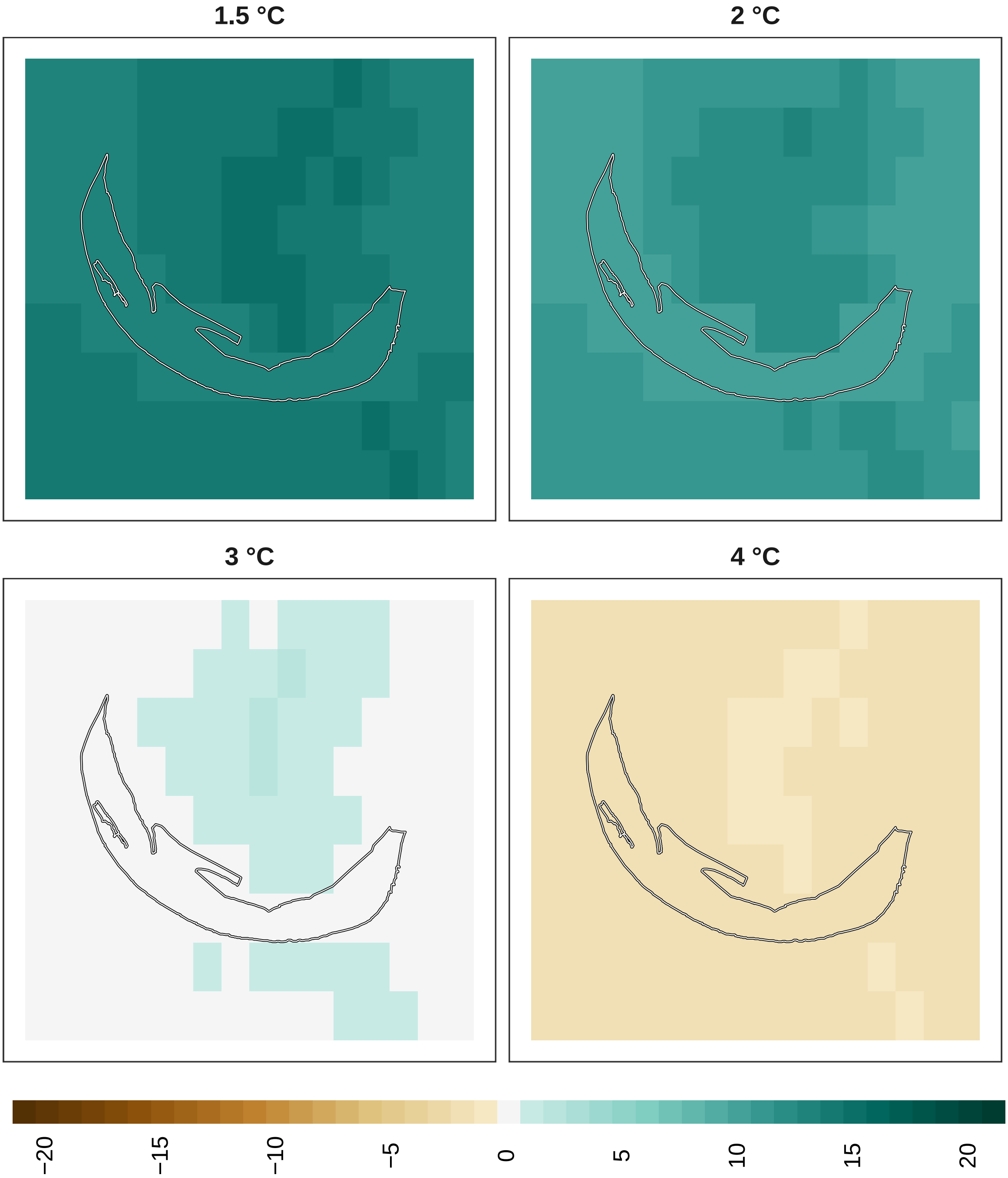

Figure 19: Adaptation effort for plants at 1 km resolution.

Amphibians

Figure 20: Adaptation effort for amphibians at 1 km resolution.

Birds

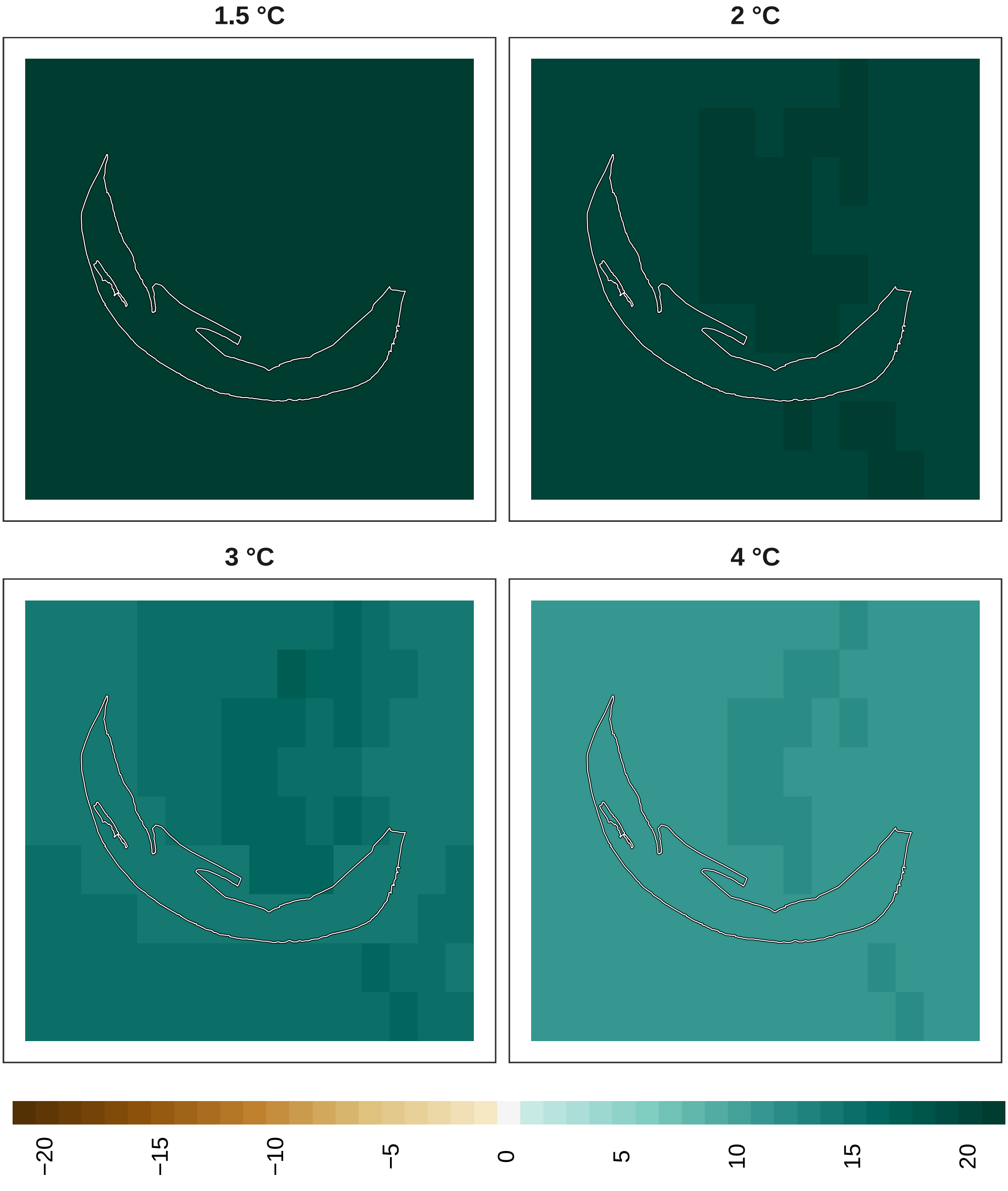

Figure 21: Adaptation effort for birds at 1 km resolution.

Mammals

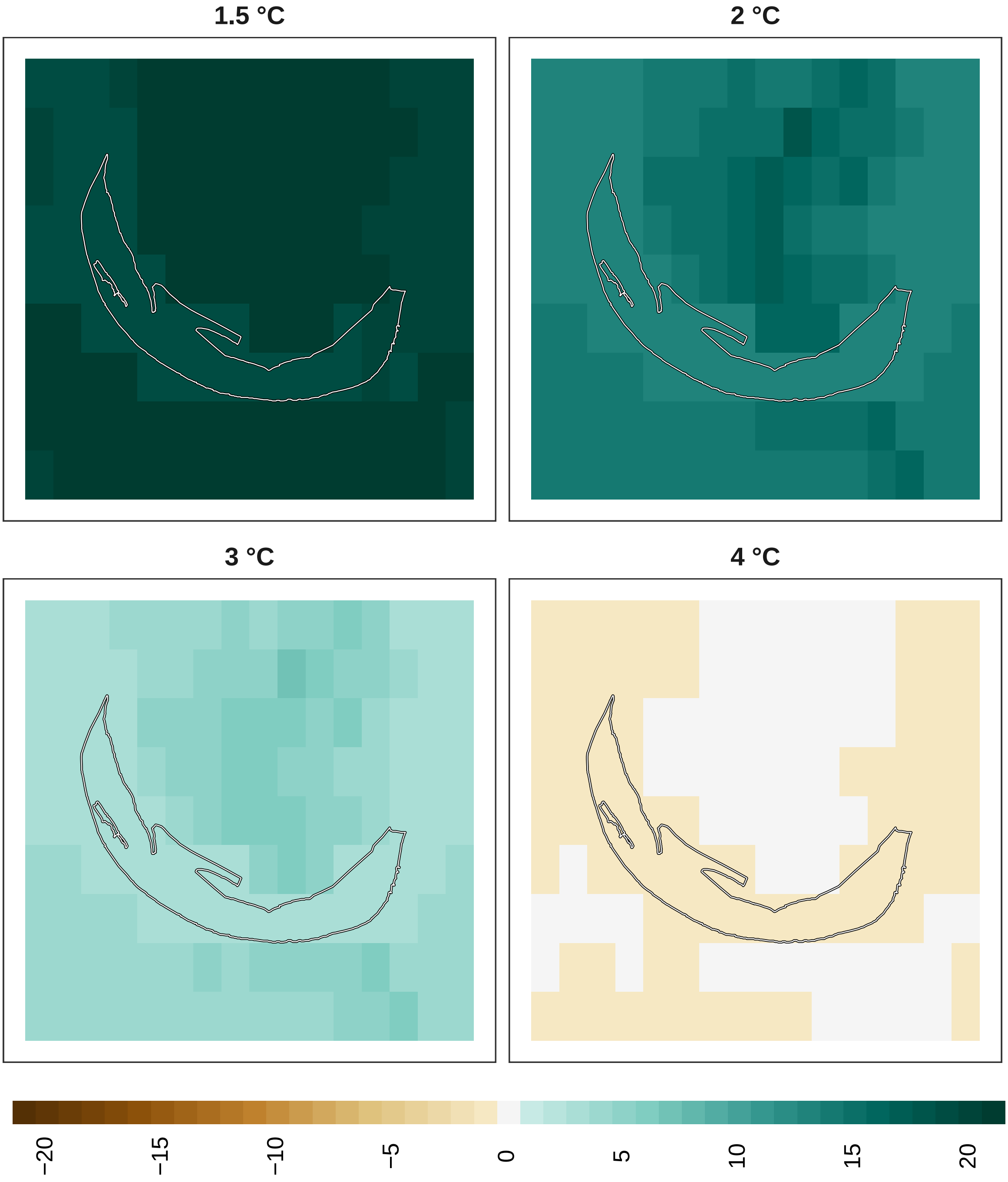

Figure 22: Adaptation effort for mammals at 1 km resolution.

Reptiles

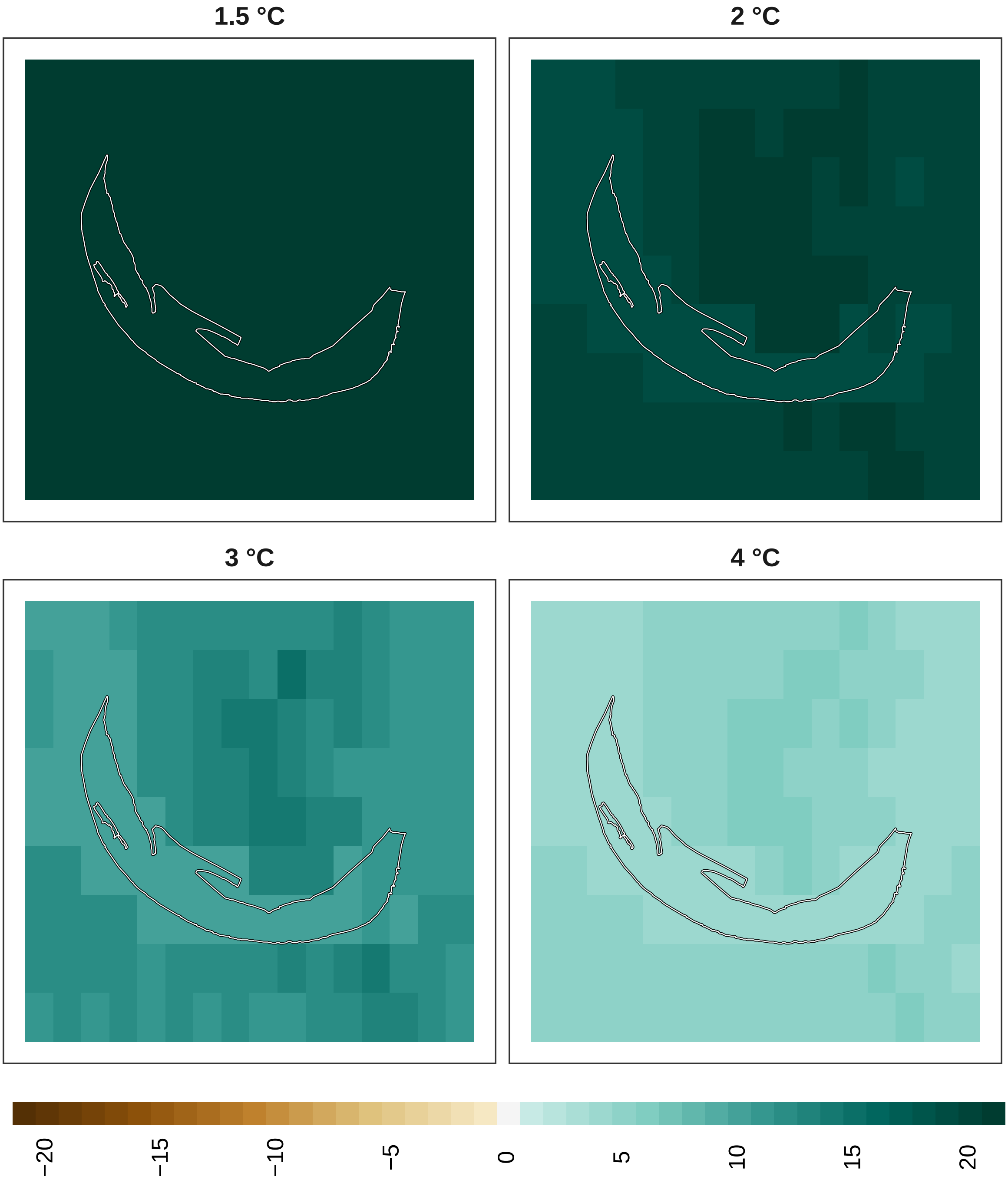

Figure 23: Adaptation effort for reptiles at 1 km resolution.

Insects

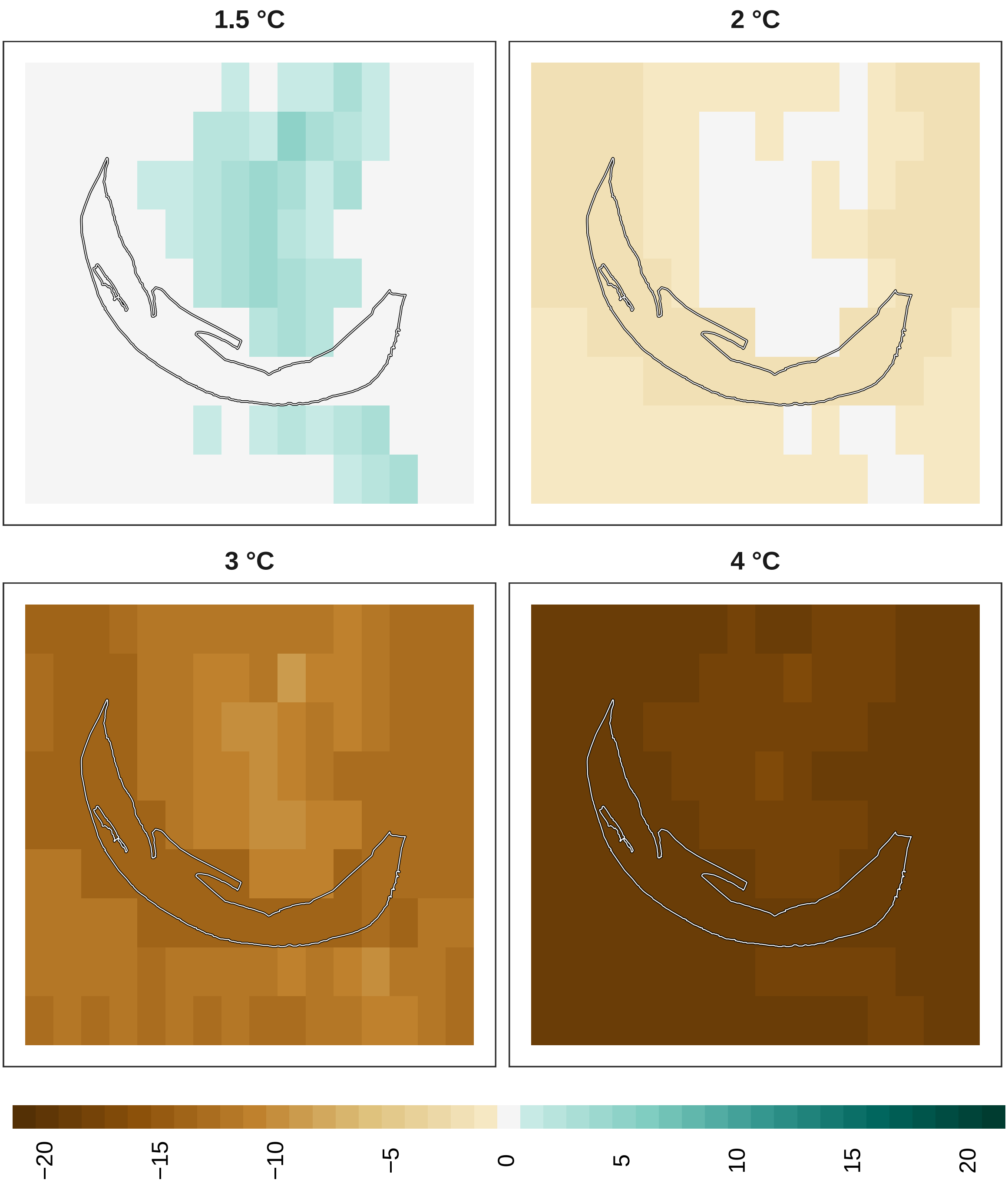

Figure 24: Adaptation effort for insects at 1 km resolution.

Pollinators

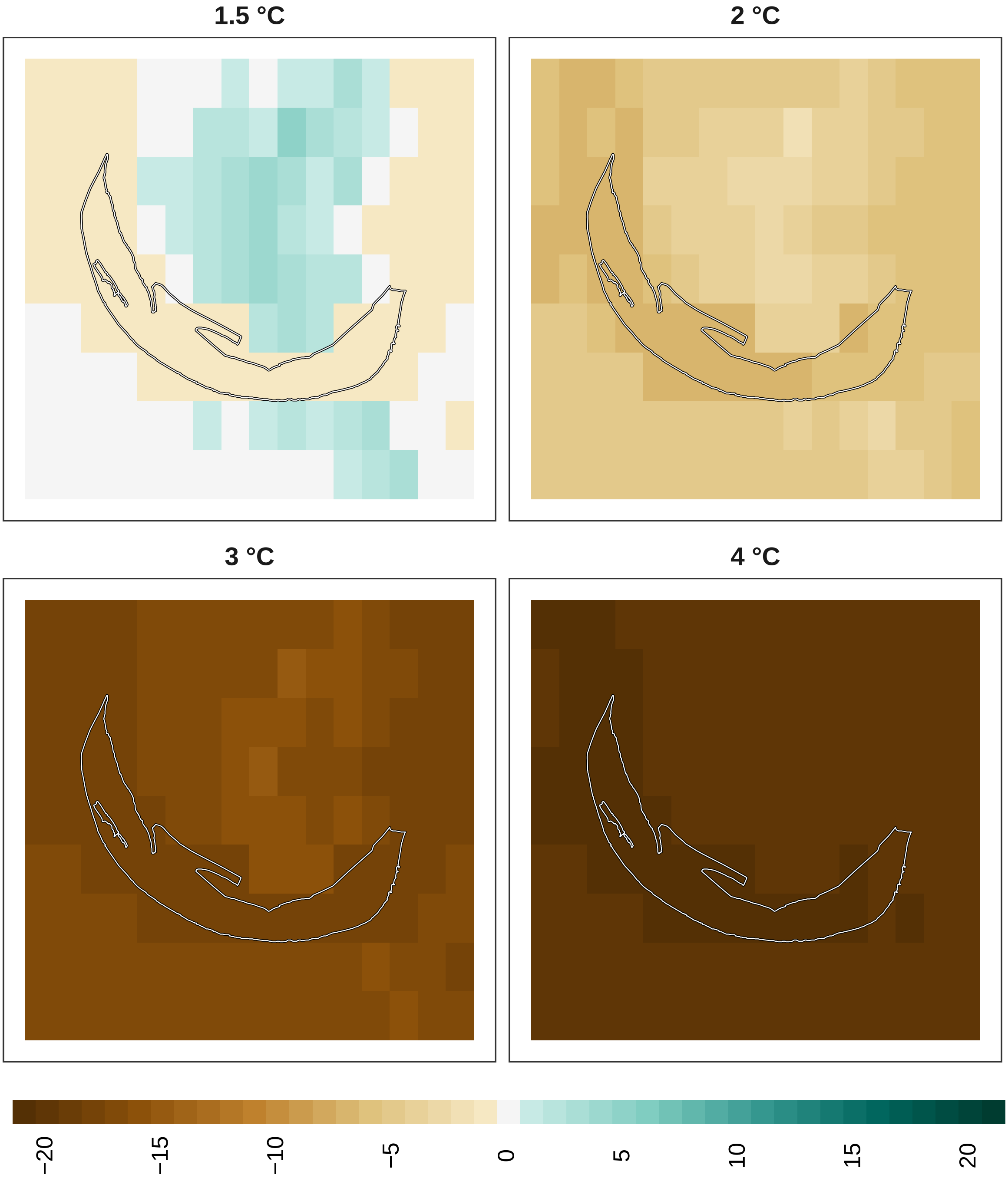

Figure 25: Adaptation effort for pollinators at 1 km resolution.

More Detailed Information

Climate

The following text reviews the observed climate, climate variability and potential climate changes in the region listed at the top of the tables.Text on the projected changes to biodiversity then follows. The climate output contains an analysis of the output of the Community Integrated Assessment System (CIAS; Warren et al., 2008) with downscaled climate change projections from the IPCC CMIP5 climate model patterns from the ClimGEN pattern scaling system (Osborn et al., 2016). Also provided are analyses of observed climate data from the Climatic Research Unit (CRU) TS 4.07 database (Harris et al., 2020).

This report looks at high, low, and average temperatures, precipitation,and meteorological drought/waterlogging (Price et al., 2022) for the area listed. These projected changes are explored in the context of the current climate variability to which the area is already exposed (1-2 standard deviations, shaded as yellow or red respectively). This assumes that many human and ecological systems may be largely resilient to changes laying within the bound of recently experienced natural variability, depending on the return rate of the event. The first set of tables (1 to 12) summarise observed climate variability and projected climate change. For most variables, comparisons are also provided between two recent time periods to show the current trends in climate in the area. The tables also provide a comparison between the magnitudes of projected climate changes with observed climate variability in terms of standard deviations (yellow - >1 standard deviation, occurring ~1 in 3 years; red is >2 standard deviations, occurring ~1 in 20 years). Thus, if a month is shaded as red it means that the future average climate is projected to exceed that currently occurring only once in every twenty years.

Both observational and projected climate change data presented here have a spatial resolution of 0.5° of latitude by 0.5° of longitude, all calculated monthly. The observed climate data comes from the University of East Anglia Climatic Research Unit CRU TS 4.07 dataset (Harris et al., 2020), which provides monthly gridded climate data through 2022. Versions of these data have previously been used extensively in IPCC reports, and in many different works on climate change impacts. The data presented here cover two time periods: 1961–1990 and 1991–2020 (except drought which uses 1986–2015). Summary statistics are provided giving the difference between the climates in 1961–1990 and 1991–2020 to provide information on what changes (if any) in temperature and precipitation have been observed between these two time periods. The first period, 1961–1990, is one of the standards used for climate modelling results and is a commonly used baseline for impact models (including the biodiversity results presented here); by this time, the world had warmed by 0.35°C since 1861–1890 (see HadCRUT4 dataset of Morice et al., 2012). By the second period (1990–2020) warming had increased to ~0 9–1.0 °C since 1861–1890. Similarly, the IPCC (2023) states that global land temperatures were 1.59 °C (1 34–1.83 °C) warmer between 1850–1900 and 2011–2020.

Future Climates

Projected climate data comes from the Community Integrated Assessment System (CIAS; Warren et al., 2008) and its component module ClimGen (Osborn et al., 2016). In this approach, a simple climate model is first used to project global temperature rises (using a probabilistic approach to encompass the key uncertainties in state-of-the-art global climate change projections) over the 21st century, as a time series. The Climatic Research Unit has a database of stored outputs from 21 general circulation models (GCM) from a model inter-comparison project known as CMIP5. These outputs provide the pattern of how climate variables are projected to change regionally for specific levels of global temperature rise. ClimGEN scales these patterns to the amount of warming provided by the time series, to create 21 new patterns of projected changes corresponding to the desired future time periods/warming levels for each area. These are the changes provided here.

The projected climate change data are expressed as quantified changes, typically called anomalies (e.g., degrees of temperature rise, millimetres of precipitation), relative to the baseline climate of 1961–1990. For example, an anomaly of 2.3 °C means that the temperature is projected to be 2.3 °C warmer than the 1961–1990 average. In preparing these reports, these projected changes are generally averaged across the 21 patterns, and then compared against the observed baseline, as well as to the standard deviation in the observed (1961–1990) baseline.

Warming Levels

The tables of projected results give the projected monthly average changes in the different climate variables, tied to the corresponding projected global temperature rise (also referred to as specific warming level). The warming levels used in this report are: 1.5 °C (Paris Accord's aspirational goal); 2 °C (upper limit of Paris Accord goals); 2.5 °C; 3 °C; 3.5 °C (approximately the range of warming projected if countries meet their Intended Nationally Determined Contributions and make no additional improvements); and 4 °C as a Business as Usual (BAU) pathway if temperature trajectories follow their current trajectory. In general, many impacts are tied to an amount of warming and its accompanying climate change and are not strongly dependent on time (as different scenarios reach the same temperature 2 °C at different times). This approach is used to aid the reader in determining potential projected changes depending upon agreed (and followed) global policies from international negotiations. The projected climate change model data presented here is provided for different warming levels as averages of 30-year periods.

The tables of projected climate change (Tables 2, 4, 6, 8, 11 and 12) provide monthly values averaged across the 21 climate change model patterns AND across the entire area of interest (e.g., Country, Protected Area, Key Biodiversity Area, Ecoregion, etc.). The values are the average relative change (also called the delta or anomaly) compared to the observed data for 1961–1990. Yellow and red shading in the tables show the warming level when the average projected climate exceeds individual years that are one (yellow) or two (red) standard deviations (SD) from the 1961–1990 average. Some adaptation practitioners use 2 SD as the limit to which systems may have autonomously adapted; greater deviations potentially leading to greater impacts. For example, a change of greater than 2 standard deviations in rainfall is classified as either being extremely dry or extremely wet. For climate change this is considered RELATIVE climate change — the amount of climate change (expressed as an anomaly) RELATIVE to the observed climate variability. For example, the absolute climate change in temperature is projected to be greatest nearer the poles. However, the relative climate change in temperature is projected to be greater in the tropics. This is because the year-to-year variability in temperature, for a given season, is greater near the poles than it is in the tropics.

Climate Variables

Temperature

This report provides information on observed (Tables 1, 3, and 5) and projected values (Tables 2, 4, and 6) of three terrestrial seasonal temperature variables — high, average, and low. The data does not give the maximum temperature of each day but the average value of these ~30 daily high temperatures, to give the monthly average high (usually mid- to late-afternoon). This is similar for the monthly average low (usually right before dawn) temperature.

Observed

For observed data, differences between the two observed time periods, 1961–1990 and 1991–2020, are provided. Two additional metrics are also provided — the average of each of the variables in the warmest year and the coolest year. In other words, for a given 30-year period the warmest/coolest/average monthly temperature (for low, high and average) were calculated. As previously mentioned, this is not derived from the extremes of daily data but is rather an indication of how warm the 'warmest' overall month was and how cool the 'coolest' overall month was. This can be viewed as the warmest month and coolest month observed (and thus experienced by the people and biodiversity in the area) in the 30-year period of 1961–1990 and for 1991–2020. Given the size of spatial area analysed, the warmest year may not have been the same year in every part of the area.

Precipitation

Also provided are observed and projected values for terrestrial precipitation (Tables 7 and 8). As for temperature, for a given 30-year observational period, the wettest monthly average and the driest monthly average are also provided. This is often driven by exceptionally wet or dry years, so the variability is much greater than with temperature and the number of 'extreme' years (i.e., $>$ 2 SD) are fewer. For future projections of precipitation, when averaging across the 21 GCM patterns used, the median is used rather than the mean as the median is a better measure of central tendency. Finally, summary statistics are provided giving the difference between 1961–1990 and 1991–2020 for average precipitation to show what changes (if any) may have already been observed. Unlike temperature, the average precipitation projections in the future rarely exceed the wettest or driest years of the past ($>$1 or $>$2 SD). The extremes in one direction or another may become more common (and true extreme events will also usually become greater and more common) but the median does not shift by that much.

Note on interpreting projected precipitation changes — While looking at climate change projections for temperature is relatively straightforward, it is less so for precipitation. For a given area, patterns of change from some GCM models will project a wetter future whilst others will project a drier one, as illustrated in Figure 12.22 of IPCC's Working Group I report (IPCC, 2013), which presents the degree of concurrence of the sign of projected precipitation change across models. In general, GCMs tend to project that wet areas in mid- and high-latitudes become wetter, and dry, low latitude areas become drier as climate changes, and there is high confidence that "the contrast of seasonal mean precipitation between dry and wet regions will increase in a warmer climate over much of the globe' ' (IPCC, 2013). However, there is a great deal of variation in the details and there are some parts of the world where model agreement on the sign of precipitation change is poor. This means that use of an overall mean, or even median, change across models could potentially lead to maladaptive responses and planning. Care must be taken in deciding how these climate changes might turn into impacts. One overview on how climate impact drivers can turn into impacts can be found in the IPCC Working Group 1 Fact Sheet on Biodiversity and Ecosystems (https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Sectoral_Fact_Sheet_Terrestrial_Freshwater_Ecosystems.pdf).

The following provisions should also be kept in mind:

1. Depending on the size of the area/park analysed the changes may not be the same, or even in the same direction in all parts of the park (mostly true for larger areas). Thus, some parts might currently be being observed to be becoming drier, while others are becoming wetter. However, some parts of this study only look at the area as an overall average so some levels of important detail may be lost.

2. The monthly differences may be in different directions. So, some months might become wetter while others become drier in the same area of study. IPCC gives "high confidence that the contrast between wet and dry seasons will increase over most of the globe as temperatures increase" (IPCC, 2013, p. 1079).

3. One approach to consider in adaptation planning is to look for the trend in precipitation (or the differences between 1961–1990 and 1991-2020) and use that to think about how precipitation (at least in the near term) might change. So, if it is getting drier now, this drying trend may continue (and vice versa).

Role of elevation and topography

The climate data used in these reports is at a spatial resolution of ~50 km x 50 km (0.5° of latitude and longitude) and the original biodiversity models at ~20 km x 20 km (subsequently elevationally downscaled to ~1 km x 1 km). This means that it is an average across a pixel (cell) of this size. As an average there may be areas that are hotter and others that are cooler (or wetter and drier) than the average. Thus, areas with varying topography (differences in elevation) will have more hotter/drier or cooler/wetter areas. Thus, elevation differences might 'buffer' the overall climate in a given cell. For example, the same elevation on two sides of a mountain may not have the same temperature as one side of the mountain may be moister and the other drier (depending on prevailing wind/moisture patterns).

Drought

The drought metric used here (Tables 9 to 12) is the Standardized Precipitation Evapotranspiration Index (SPEI) as it uses changes in both precipitation and temperature. Specifically, the metric used here is SPEI12, which accumulates the effective rainfall (precipitation minus potential evaporative losses) over the preceding 12 months and expresses any excess (positive values) or deficit (negative values) relative to the variations typically observed in the region. This metric is often used when looking at potential drought issues for agricultural and natural lands. For this report, the specific metric was SPEI12 -1.5, severe drought. SPEI12 means that the drought has been developing over the preceding 12 months before the 'counting' begins. Thus, an area identified as having a drought duration of 12 months has really had a deficit in effective rainfall for up to 24 months. The values in the table are calculated for the 30-year period that includes the specific warming level given. More data on the drought metric and interpretation can be found in Price et al. (2022).

Waterlogging

Waterlogging (Tables 9 to 12) is the reverse of the drought metric and uses an SPEI12 of +1.5 (precipitation > 1.5 SD of the mean precipitation). This is an indication of areas having excess moisture for extended periods of time, potentially leading to waterlogged soils. Two different metrics are provided for observed and for projected. The first is number of months and the second is the maximum number of consecutive months, both in a 30-year period. The first could have other months in between not meeting the threshold of -1.5 or +1.5. Consecutive months means there is no break in the run of months meeting the threshold (there could also be other, shorter, consecutive months with severe drought/waterlogging in the given 30-year period).

Population Data

Table 13 presents the projected population for the years 2000 through 2100 at a 1 km spatial resolution. These data are provided both in terms of the total (summed across all 1 km cells) population within the boundary, and those within an area that includes a 15 km wide buffer zone around the boundary. The data from 2000 and 2010 are interpolations of observed population sizes, the other time periods are projections of future change. There are several caveats around these data: First, in many cases, a protected area may be managed in a way that precludes any population or population growth within the protected area. These may not have been captured in the modelling underpinning these population data but would still be captured in the second row (area +15 km buffer). Second, the population change projections are from what is known as the

Shared Socioeconomic Pattern (SSP) 2 scenario. This is one of five scenarios used in the IPCC to look at alternative pathways for climate change. In the SSP2 scenario, the trends into the future basically follow those existing today; sometimes referred to as a 'middle of the road scenario'. A good general source on the different SSPs can be found at https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/ with the underpinning science data discussed in Riahi et al. (2017). Different SSPs would therefore provide different projections of future populations. The projections themselves use a weighting where areas currently increasing in population continue to increase, and those that are decreasing continue to decrease. This is a major assumption that may or may not hold up over time. More information on the process used to derive the population projections and subsequent downscaling can be found in Jones and O'Neill (2016), and Gao (2017).

Landcover Changes

Table 14 shows the percentage of different landcover types in 1992 and 2020 as well as the change between these two time periods within the boundaries of the area in this report. These data come from the European Space Agency Climate Change Initiative (Copernicus Climate Change Service, Climate Data Store, 2019; ESA, 2017) and have a resolution of 300 metres. The main limitation of the ESA data is that it is classified without supervision, and not 'ground-truthed'. This means that areas designated as 'forest' may be plantations of non-native species. These figures are provided to assist in understanding how these land cover classes have changed over time as this may have immediate biodiversity implications in the area studied for this report.

Biodiversity

The biodiversity information presented here is from the Wallace Initiative. The Wallace Initiative modelled ~135 000 terrestrial fungi, plants, invertebrates, and vertebrates, at warming levels ranging from 1.5 °C to 6 °C, across 21 CMIP5 climate model patterns at a spatial resolution of ~20 km x 20 km based on occurrence data obtained from the Global Biodiversity Information Facility (GBIF.org, 2015). More information on the overall project, results, modelling methodology, caveats, and uses can be found in a series of papers (Jenkins et al., 2021; Price et al., 2024a; Saunders et al., 2023; Smith et al., 2018; Warren et al., 2018a,b, 2013). The data were also used for a number of figures and tables in Working Group II of the IPCC Sixth Assessment Report (AR6). The data used in these reports were then subsequently elevationally downscaled to ~1 km x 1 km (Saunders et al., 2023) to better understand which areas of each modelled 20 km cell or pixel might be lost sooner or persist longer. In short, a given 50 km or 20 km cell is an average of the temperatures for all elevations within that cell (i.e., the average elevation). In areas with a varied terrain, some areas will be warmer than the average and some will be cooler. Species in areas that are warmer than the average would be expected to potentially be more susceptible (exposed) to warming, while those in cooler areas would be expected to potentially be less susceptible (or be able to shift into these areas if they are currently too cool). Therefore, species within cooler areas within a climate 'cell' or 'pixel' would be expected to potentially be able to persist in that area longer.

Local Extinctions (extirpations)

Table 15 shows the percentage of species in different taxa projected to be at risk of local extinction (extirpation, losses within the area of the report) owing to changes in climate alone. Yellow shaded areas are projected to become climatically unsuitable for >25% of the species studied (by taxa listed); orange areas are projected to become climatically unsuitable for >50% of the species studied; and red areas are projected to become climatically unsuitable for >75% of the species studied. NA means there is insufficient data in the cell to assess overall likelihoods. The climate suitability is the average change (ensemble of biodiversity models) across the 21 climate models examined.

Species Richness Remaining

Figures 1 to 9 show the species richness remaining in each 1 km cell within the boundaries of the area under study (also depicted on the map as a solid black line) for selected taxa. This shows the spatial variability in the potential patterns of loss.

Refugia

Table 16 shows the percent of the area remaining a climate refugia for the taxa. We define a climate refugium as an area remaining climatically suitable for >75% of the species in those taxa. The two columns, for each level of warming, are >0 (meaning at least one climate change model projects that the area is a refugium) and >10 (meaning that more than 10 models, out of 21, project the area remains a refugium). The shading is – darker green, >75% of the area is a refugium; medium green, 50–75% of the area is a refugium; light green, 25–50% of the area is a refugium; and white, less than 25% of the area is a refugium.

Figures 10 to 17 show the number of models in agreement that a particular pixel (cell) is a refugium for the taxa indicated. These maps provide a spatial representation of the agreement in the models (or areas with potentially lower uncertainty) to be refugia for the different taxa as well as how this potentially varies within the area under study.

The biodiversity refugia map is the minimum models in agreement between the plant and animal refugia.

Adaptation Effort

Figures 18 to 25 present a spatial representation of the potential 'adaptation effort' that might be needed to maintain at least 75% of the species modelled (i.e., area remains climatically suitable) in each ~1km pixel. Adaptation effort is a combination of the number of climate models (+ 1 to 21) projecting an area is a refugium (remaining climatically suitable for >75% of the species) as well as the number of climate models (- 1 to -21) projecting the area to be an Area of Concern (becomes climatically unsuitable for >75% of the species) in each pixel. One way of looking at this is to consider areas with high values (+18 to +21) as being less exposed to climate change and thus potentially more resilient. Business-as-usual conservation, especially if coupled with building resilience around extreme climates (e.g., drought, heat waves) might be a reasonable adaptation approach to take. As the score drops, increasingly greater amounts of adaptation might be needed to maintain the existing species in that pixel. While micro-refugia (areas <1km) might be available, the amount of habitat available as micro-refugia would be less than the pixel. Once the adaptation effort drops into the negative zone, adaptation to maintain the existing species is likely to become increasingly difficult. At score of -15 to -21 the best approach might be to consider facilitating change as opposed to putting large efforts into trying to maintain existing species. Scores this low indicate that the area becomes climatically unsuitable for a large percentage of species. While this does not preclude micro-refugia, large areas (and potentially the area of conservation interest) would appear to be transforming. In the case of an area where restoration or reforestation is planned, then consideration might be given to planting the species that might be expected to move into the area, given enough time (considering species with similar structure and native, if possible). This type of adaptation begins to make the new 'habitat' that species from surrounding areas will need to autonomously adapt to climate change.

There are many complexities in these analyses. Not least of which is that an area may remain a refugium for vertebrates and yet potentially become unsuitable for many of the species making up the habitat or food resources for these species. If the habitat becomes unsuitable, or food becomes more unavailable then this is likely to have major implications for those taxa that a cell remains a refugium for. With increasing warming, fewer areas remain refugia, more areas become areas of concern, and adaptation effort increases (i.e., becomes more negative).

Developing robust adaptation plans in the light of climate projection uncertainties

Climate change adaptation experts recommend an iterative risk management approach, particularly where climate change projections or future vulnerability is uncertain. Conceptual approaches for prioritising potential adaptation options might include: (i) implementing low cost 'no regret' adaptation plans, such as removal of concomitant stresses; (ii) in areas where it is unclear whether drying or wetting is projected, creating adaptation plans relating to changes in management to incorporate future projected climate change that remain flexible (e.g., either to adaptively manage or plan for both wetting and drying, or to be able to switch rapidly from managing/planning for wetting to what is needed for drying). Since climate change generally includes increases in climate variability, even in a future wetter climate, there may still be more droughts. This implies that adaptation to changes in precipitation needs to incorporate flexibility on both long and short timescales to cater for both wetting and drying in areas where the sign of precipitation projection differs across models. Even in areas where the sign of precipitation change is consistent between models (e.g.~positive), increases in climate variability on shorter timescales may still imply a need to cater for increased short-term drying. (iii) avoiding implementing plans that lock in the system to being able to cater for only the present day climate, (thus ignoring warming) or catering only for wetting (when actually drying may occur).

Literature Cited

Copernicus Climate Change Service, Climate Data Store (2019). *Land Cover Classification Gridded Maps from 1992 to Present Derived from Satellite Observation*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.006f2c9a.

ESA (2017). *Land Cover CCI Product User Guide Version 2*. Technical Report. URL: http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf.

Gao, J. (2017). *Downscaling Global Spatial Population Projections from 1/8-Degree to 1-Km Grid Cells*. NCAR Technical Note NCAR/TN-537+STR. DOI: 10.5065/D60Z721H.

GBIF.org (2015). *GBIF Occurrence Download*. Version March 2015. The Global Biodiversity Information Facility. DOI: 10.15468/DL.KECDHX. URL: https://www.gbif.org/occurrence/download/0000129-150523225239109.

Harris, I., Osborn, T. J., Jones, P., and Lister, D. (2020). Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. *Scientific Data* 7 (1) (1), pp. 1–18. DOI: 10/ggq4fw.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 1535 pp.

IPCC (2023). Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by Core Writing Team, H. Lee, and J. Romero. Geneva, Switzerland: IPCC, pp. 1–34. DOI: 10.59327/IPCC/AR6-9789291691647.001.

Jenkins, R. L. M., Warren, R. F., and Price, J. T. (2021). Addressing Risks to Biodiversity Arising from a Changing Climate: The Need for Ecosystem Restoration in the Tana River Basin, Kenya. *PLOS ONE* 16 (7), e0254879. DOI: 10.1371/journal.pone.0254879.

Jones, B. and O'Neill, B. C. (2016). Spatially Explicit Global Population Scenarios Consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters* 11 (8), p. 084003. DOI: 10.1088/1748-9326/11/8/084003.

Morice, C. P., Kennedy, J. J., Rayner, N. A., and Jones, P. D. (2012). Quantifying Uncertainties in Global and Regional Temperature Change Using an Ensemble of Observational Estimates: The HadCRUT4 Data Set. *Journal of Geophysical Research: Atmospheres* 117 (D8). DOI: 10.1029/2011JD017187.

Osborn, T. J., Wallace, C. J., Harris, I. C., and Melvin, T. M. (2016). Pattern Scaling Using ClimGen: Monthly-Resolution Future Climate Scenarios Including Changes in the Variability of Precipitation. *Climatic Change* 134 (3), pp. 353–369. DOI: 10.1007/s10584-015-1509-9.

Price, J., Warren, R., and Forstenhäusler, N. (2024a). Biodiversity Losses Associated with Global Warming of 1.5 to 4 °C above Pre-Industrial Levels in Six Countries. *Climatic Change* 177 (3), p. 47. DOI: 10.1007/s10584-023-03666-2.

Price, J., Warren, R., Forstenhäusler, N., Jenkins, R., and Graham, E. (2024b). Assessing the Potential Risks of Climate Change on the Natural Capital of Six Countries Resulting from Global Warming of 1.5 to 4 °C above Pre-Industrial Levels. *Climatic Change* 177 (3), p. 46. DOI: 10.1007/s10584-023-03650-w.

Price, J., Warren, R., Forstenhäusler, N., Wallace, C., Jenkins, R., Osborn, T. J., and Van Vuuren, D. P. (2022). Quantification of Meteorological Drought Risks between 1.5 °C and 4 °C of Global Warming in Six Countries. *Climatic Change* 174 (1), p. 12. DOI: 10.1007/s10584-022-03359-2.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., and Tavoni, M. (2017). The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview. *Global Environmental Change* 42, pp. 153–168. DOI: 10.1016/j.gloenvcha.2016.05.009.

Saunders, S., Grand, J., Bateman, B., Meek, M., Wilsey, C., Forstenhaeusler, N., Graham, E., Warren, R., and Price, J. (2023). Integrating Climate-Change Refugia into 30 by 30 Conservation Planning in North America. *Frontiers in Ecology & the Environment* 21 (2). DOI: 10.1002/fee.2592.

Smith, P., Price, J., Molotoks, A., Warren, R., and Malhi, Y. (2018). Impacts on Terrestrial Biodiversity of Moving from a 2°C to a 1.5°C Target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376 (2119). DOI: 10.1098/rsta.2016.0456.

UNEP-WCMC and IUCN (2024). *The World Database on Protected Ar- Eas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM)*. Version March 2024. Cambridge, UK: UNEP-WCMC and IUCN. URL: www.protectedplanet.net.

Warren, R., Price, J., Graham, E., Forstenhaeusler, N., and VanDerWal, J. (2018a). The Projected Effect on Insects, Vertebrates, and Plants of Limiting Global Warming to 1.5°C Rather than 2°C. *Science* 360 (6390), pp. 791–795. DOI: 10.1126/science.aar3646.

Warren, R., de la Nava Santos, S., Arnell, N. W., Bane, M., Barker, T., Barton, C., Ford, R., Füssel, H. .-M., Hankin, R. K. S., Klein, R., Linstead, C., Kohler, J., Mitchell, T. D., Osborn, T. J., Pan, H., Raper, S. C. B., Riley, G., Schellnhüber, H. J., Winne, S., and Anderson, D. (2008). Development and Illustrative Outputs of the Community Integrated Assessment System (CIAS), a Multi-Institutional Modular Integrated Assessment Approach for Modelling Climate Change. *Environmental Modelling & Software* 23 (5), pp. 592–610. DOI: 10.1016/j.envsoft.2007.09.002.

Warren, R., Price, J., VanDerWal, J., Cornelius, S., and Sohl, H. (2018b). The Implications of the United Nations Paris Agreement on Climate Change for Globally Significant Biodiversity Areas. *Climatic Change* 147 (3), pp. 395–409. DOI: 10.1007/s10584-018-2158-6.

Warren, R., VanDerWal, J., Price, J., Welbergen, J. A., Atkinson, I., Ramirez-Villegas, J., Osborn, T. J., Jarvis, A., Shoo, L. P., Williams, S. E., and Lowe, J. (2013). Quantifying the Benefit of Early Climate Change Mitigation in Avoiding Biodiversity Loss. *Nature Climate Change* 3 (7), pp. 678–682. DOI: 10.1038/nclimate1887.

WWF (2018). *Wildlife in a Warming World: The Effects of Climate Change on Biodiversity in WWF's Priority Places*. URL: https://www.wwf.org.uk/sites/default/files/2018-03/WWF_Wildlife_in_a_Warming_World.pdf.