Forests of silver fir (*Abies alba*), Norway spruce (*Picea abies*), and European beech (*Fagus sylvatica*), Valea Boia Mică, Munții Făgăraș, România
Photograph by Matthias Schickhofer

Climate Change and Forest Carbon in the Proposed Parcul Național Făgăraș, România

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Abstract

The Munții Făgăraș range in the southern Carpathian Mountains, Romania, harbors expanses of primary forest and high biodiversity, for which the European Union designated the area as a Natura 2000 site. Local initiatives seek to conserve Făgăraș ecosystems and services through its protection as the proposed Parcul Național Făgăraș, which would be one of the most extensive national parks in continental Europe. Uncontrolled logging poses an immediate threat. At the same time, climate change, caused by carbon dioxide emissions from power plants, motor vehicles, deforestation, and other human sources, threatens ecosystem integrity. Făgăraș forests naturally help prevent climate change by storing carbon. To assist long-term conservation of Făgăraș ecosystems, this climate change assessment presents locally specific scientific information on climate change, ecological impacts, risks, and the magnitude of forest carbon and its ecosystem service. Climate change increased annual average temperature of the proposed national park 1.5 ± 0.2ºC from 1901 to 2022, an increase that was statistically significant and higher than the global average. Precipitation showed no statistically significant long-term trend. Observed ecological changes detected in Europe and attributed by published scientific research to anthropogenic climate change include extirpations (local disappearances) of plant and animal species, upslope biome shifts, loss of bumble bee species, and warming of lake waters. Continued climate change under the highest greenhouse gas emissions scenario of the Intergovernmental Panel on Climate Change could increase annual average temperature of the proposed park area up to 6.4 ± 2.0ºC above the 1901-1910 average by 2100. Cutting emissions to meet the Paris Agreement goal globally could limit that projected local heating more than half. Under the highest emissions scenario, climate change could reduce total annual precipitation of the proposed park area 8 ± 4% below the 1901-1910 average by 2100. Meeting the Paris Agreement goal could result in precipitation at or slightly above the 1901-1910 average. Published research indicates that continued climate change could increase numerous risks to Făgăraș ecosystems, including biome shifts, tree mortality of European beech (*Fagus sylvatica*), silver fir (*Abies alba*), and Norway spruce (*Picea abies*), wildfire in an ecosystem where fire is unnatural, and range shifts of mammals. Forests in the proposed national park store 20 ± 9 million tons of carbon in aboveground biomass at densities up to 250 tons per hectare. The proposed Parcul Național Făgăraș could prevent this carbon from contributing to climate change, providing an ecosystem service equivalent to one year of emissions of 20 ± 9 million Romanians, the population of the entire country.

Table of Contents

Figures

page

Tables

page

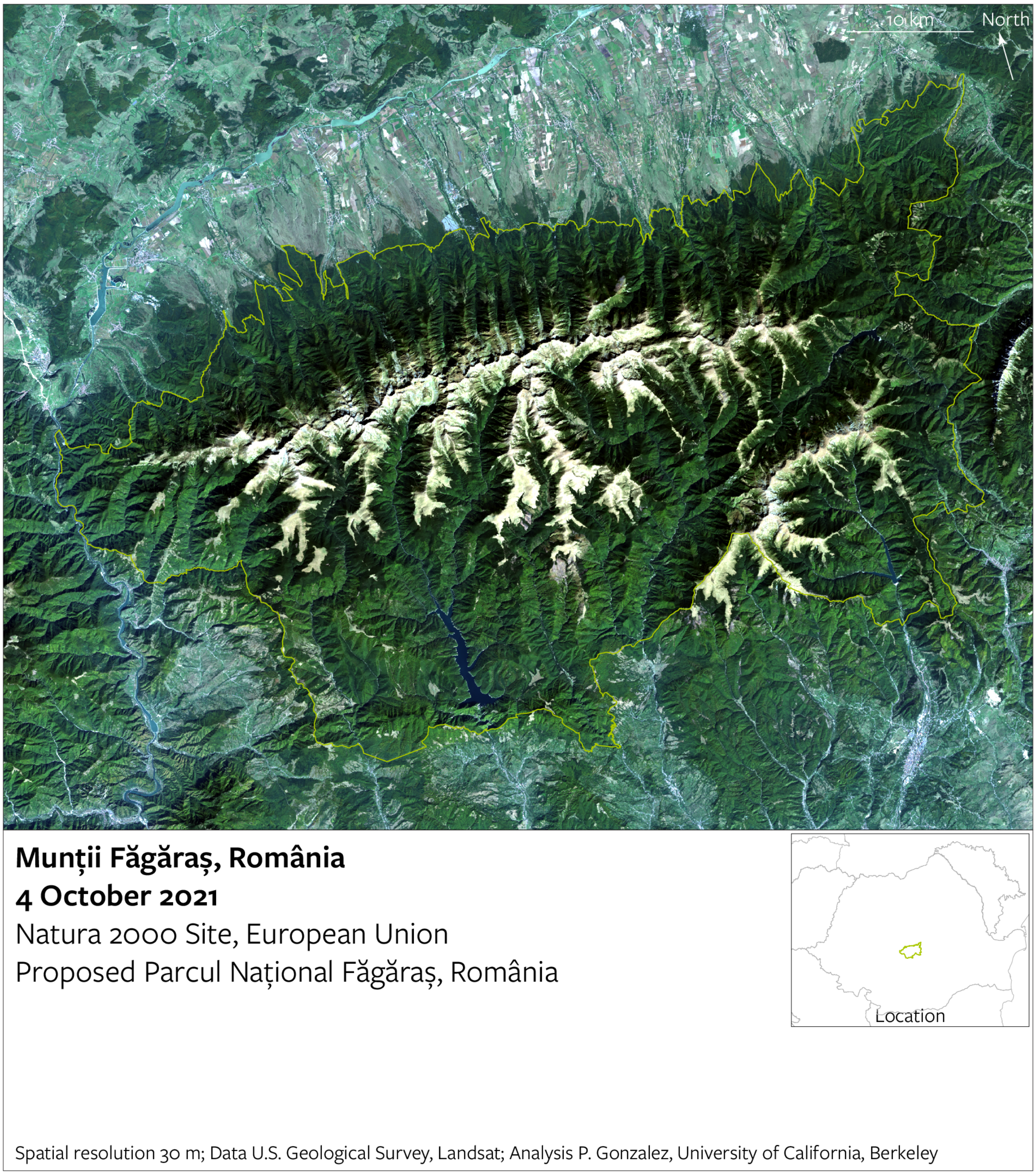

Figure 1. **Proposed Parcul Național Făgăraș, România**, 4 October 2021. Data from U.S. Geological Survey, Landsat remote sensing, <https://glovis.usgs.gov>, real-color analysis by P. Gonzalez.

Introduction

The Munții Făgăraș range in the southern Carpathian Mountains, Romania, (Figure 1) harbors one of the most extensive areas of primary forest in the temperate zone of Europe (Sabatini et al. 2021, Kameniar et al. 2023). The area conserves biodiversity that includes at least 1500 plant and animal species (Linnell et al. 2016). The European Union (EU) recognized Munții Făgăraș for its ecological importance through designation of 1986 km^2 as a Natura 2000 site, in 2007.

The land is not under permanent protection by the national government but is held in private property, municipal land, and local commons. Uncontrolled logging after 1989 accelerated deforestation and degradation of natural habitats (Griffiths et al. 2012). The Foundation Conservation Carpathia and local communities have been conserving and re-planting forests in the area since 2009 (Hartup et al. 2022) and seek permanent protection of Munții Făgăraș as the proposed Parcul Național Făgăraș. It would be one of the most extensive national parks in continental Europe (UNEP and IUCN 2024).

Climate change, caused by carbon dioxide and other greenhouse gases from power plants, motor vehicles, deforestation, and other human sources, also threatens ecosystem integrity, through increases in heat and other unnatural physical and ecological disruptions. Anthropogenic climate change has increased global average surface temperature 1.1°C above pre-industrial levels (increase between the periods 1850-1900 and 2011-2020; IPCC 2021).

Published field research shows that the increased heat of climate change has damaged ecological integrity and biodiversity at sites around the world, through animal species extinctions (Pounds et al. 2006, Waller et al. 2017, Australia Threatened Species Scientific Committee 2019), plant and animal species extirpations (Wiens 2016, Roman-Palacios and Wiens 2020), elevational and latitudinal plant and animal range shifts (Parmesan and Yohe 2023, Rosenzweig et al. 2008), tree mortality increases (van Mantgem et al. 2009, Gonzalez et al. 2012, Robbins et al. 2022), wildfire above natural levels (Abatzoglou and Williams 2016, Turco et al. 2023), biome shifts (geographic displacements of major vegetation formations; Gonzalez et al. 2010), and other impacts (IPCC 2022, Parmesan et al. 2022).

The world needs to limit heating to 1.5ºC to 2ºC above pre-industrial levels to avoid the most drastic impacts of climate change to people and nature (IPCC 2021, 2022), the goal of the Paris Agreement (UNFCCC 2015) of the U.N. Framework Convention on Climate Change (UNFCCC 1992), under which all 194 independent nations in the world have pledged to reduce carbon dioxide and other greenhouse gas emissions. If we do not cut emissions to net zero by 2050, climate change under a worst-case scenario could increase global temperature up to 4ºC above pre-industrial levels (IPCC 2021). Projected future climate change increases risks to ecosystems and the services they provide.

Forests reduce climate change by naturally storing carbon in vegetation, preventing carbon emissions that cause climate change, an important ecosystem service. Globally, terrestrial ecosystems contain stocks of 450 (range 380–540) billion tons of carbon in vegetation (IPCC 2022, Friedlingstein et al. 2023). Conservation and restoration of forests in the proposed Parcul Național Făgăraș would provide this ecosystem service, although the magnitude of the local carbon stock is not currently known. While the principal solution to climate change is eliminating the 90% of total carbon emissions from cars, power plants, and other human sources that burn fossil fuels (IPCC 2021), the natural carbon solution of forest conservation is also essential. Halting deforestation also helps to safeguard biodiversity.

Effective conservation under climate change will involve natural resource management practices to identify and protect potential refugia, restore degraded ecosystems with native species or populations more adapted to hotter conditions, and other measures to improve resilience. Scientific information specific to the Făgăraș region on climate change trends, impacts, and risks would support long-term effective conservation of the proposed national park under climate change. While scientists have published individual climate change research results for the Carpathian Mountains, a comprehensive scientific assessment of climate change has not previously been conducted for Făgăraș ecosystems.

Quantification of the carbon stock of Făgăraș forests would show the contribution of the future national park to the ecosystem service of preventing climate change through protection of carbon stocks. While scientists have published global spatial data and field data in Romania on forest carbon, a spatial analysis of the carbon stock of Făgăraș forests has not previously been conducted. Quantification of the forest carbon stock and its ecosystem service can highlight the importance of protecting the area permanently as a national park.

This report is a climate change science assessment that presents information specific to the proposed Parcul Național Făgăraș on climate change, ecosystems, and the forest carbon ecosystem service. Report objectives are:

1. Analyze the magnitude and spatial patterns of observed temperature and precipitation changes and future projections for the proposed Parcul Național Făgăraș.
2. Assess published scientific research on observed impacts and projected risks of anthropogenic climate change on ecosystems and plant and animal species of the region.
3. Analyze the magnitude and spatial patterns of the carbon stock in aboveground forest vegetation and quantify the magnitude of the carbon ecosystem service of the proposed Parcul Național Făgăraș.

Research Area

The Munții Făgăraș range in the southern Carpathian Mountains, Romania, is an area of intact forests, alpine grasslands, and lakes that the EU designated in 2007 as a Natura 2000 site and which Romanian organizations and local communities propose as the Parcul Național Făgăraș. The EU lists the surface area as 1986 km^2 (EU EEA 2021). Spatial analyses for this report found a surface area of 2120 km^2 (section Methods). Elevation in the proposed national park ranges from 359 m (National Aeronautics and Space Administration, Shuttle Radar Topography Mission, digital elevation model; Farr et al. 2007) to 2544 m, at Vârful Moldoveanu, the highest point in Romania.

In the southern Carpathian Mountains, as elevation increases, temperature decreases and precipitation increases (section Observed Climate), differentiating natural vegetation into five biomes: temperate woodland (dominated by oaks (*Quercus spp.*)) at low elevation; temperate broadleaf forest (dominated by European beech (*Fagus sylvatica*)); mixed broadleaf-conifer forest; temperate conifer forest (dominated by silver fir (*Abies alba*)); sub-alpine conifer forest (dominated by Norway spruce (*Picea abies*)); and alpine grassland at the highest elevations (San Miguel-Ayanz et al. 2016). Spatial analysis of EU Corine land cover data for 2018 (EU Copernicus 2020), indicates that forests cover 72% of the area (section Methods). The major land cover types and fractional coverage of the proposed Parcul Național Făgăraș are, from lower to higher elevation: woodland and shrubland 3%, broadleaf forest 14%, mixed forest 31%, conifer forest 27%, alpine grassland 23%, other land cover 2% (Figure 2).

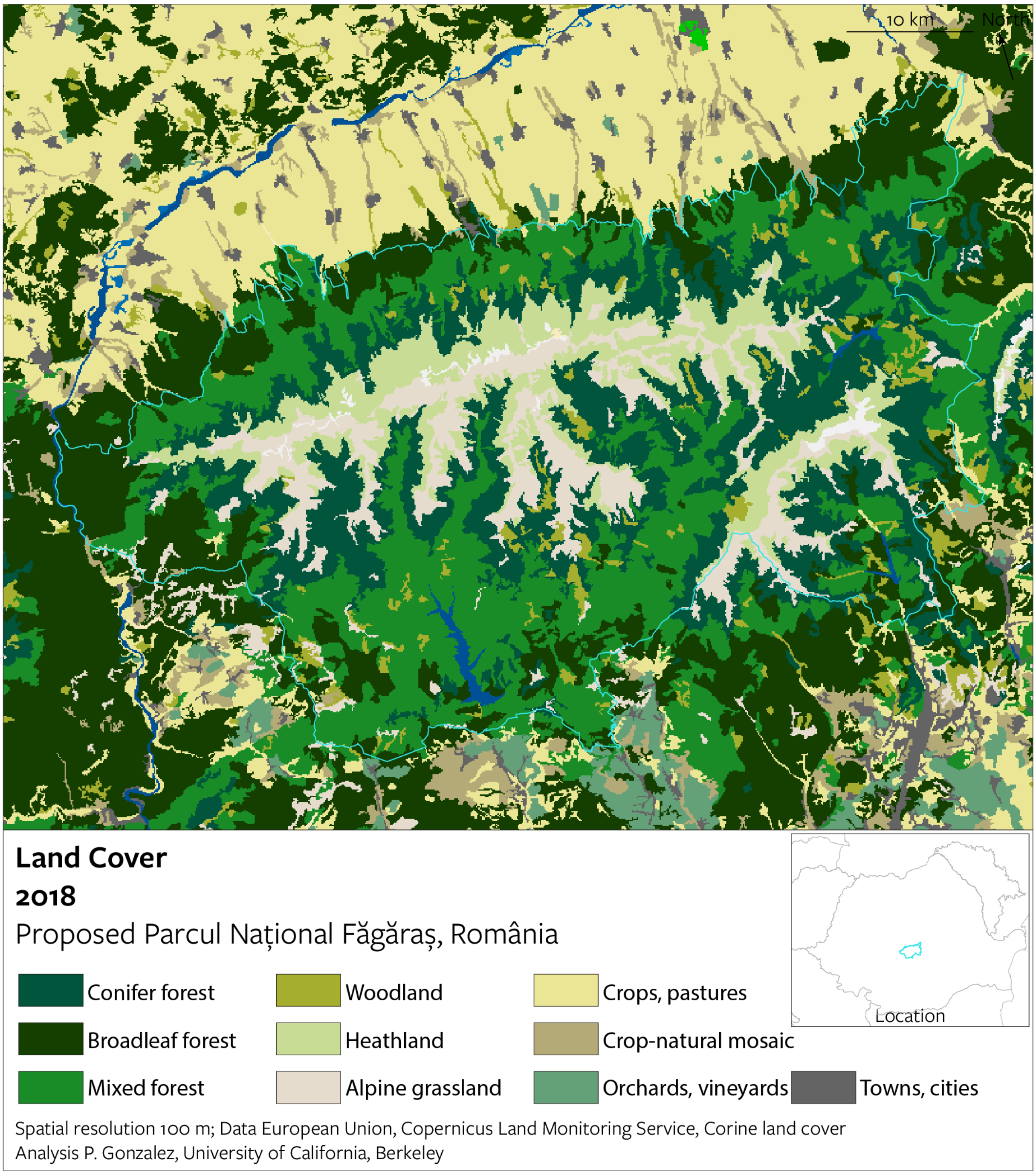

Figure 2. Land cover, 2018, proposed Parcul Național Făgăraș, România. From European Union Copernicus Land Monitoring Service Corine land cover at 100 m spatial resolution (EU Copernicus 2020).

The proposed national park would protect one of the most extensive areas of primary forest in the temperate zone of Europe (Sabatini et al. 2021, Kameniar et al. 2023). Făgăraș habitats conserve a level of biodiversity that is relatively high for Europe, including at least 875 plant species, 216 mammal and other vertebrate species, and 580 butterfly and other insect species (Linnell et al. 2016).

The recent environmental history of Romania has left Făgăraș ecosystems only partially protected. When a communist government took power in 1947, it collectivized agricultural farms and nationalized forest lands, which remained state-owned until the fall of communism in 1989. Three national laws, in 1991, 2000, and 2005, enacted restitution of agricultural land and 70% of forest land from the national government to individuals, municipalities, and groups of people who manage parcels as commons (Griffiths et al. 2012, Aastrup 2020).

After 1989, abandonment of cropland led to natural regeneration of some grasslands and woodlands (Kuemmerle et al. 2009), while land sales and uncontrolled logging of forests led to a rapid doubling of deforestation in the southern Carpathian Mountains (Griffiths et al. 2012). From 1985 to 2010, natural regeneration of forests in the southern Carpathian Mountains restored a fraction of deforested land (Griffiths et al. 2014). Since 2009, the Foundation Conservation Carpathia <https://www.carpathia.org> has purchased land, worked with local communities to protect forests, re-plant logged areas, develop sustainable economic activities, and advocate for more effective natural resource management policies. The Foundation has purchased more than 6% of the area (Hartup et al. 2022), which it plans to return to the public for protection of the area as the Parcul Național Făgăraș.

Observed Climate

Temperature Annual average temperature of the proposed national park area increased a statistically significant 1.5 ± 0.2ºC (mean ± standard error) from 1901 to 2022 (Table 1, Figure 3). This is higher than the global average temperature increase of 1.1 ± 0.1°C (mean ± 90% confidence interval) during nearly the same time, from the pre-industrial period (1850-1900) to the recent decade (2011-2020).

Intergovernmental Panel on Climate Change (IPCC) assessments and other scientific research use detection and attribution analyses to estimate the relative weights of human

Table 1. Observed temperature and precipitation, proposed Parcul Național Făgăraș, România. Results show averages for the area of the proposed national park. Results for 1901-2022 derive from spatial analyses (Gonzalez, this report) and linear regression, corrected for temporal autocorrelation, of weather station data interpolated to 50 km spatial resolution (Harris et al. 2020). Results for 1981-2010 derive from spatial analyses (Gonzalez, this report) of climate data interpolated to 1 km spatial resolution from a combination of satellite and weather station measurements and modeling (Karger et al. 2017). Temporal variation for 1901-2022 calculated as standard deviation (SD) or standard error (SE). Temporal variation for 1981-2010 not present in the source data.

	Temperature	**Precipitation**
1901-2022		
Total change ± SE	1.5 ± 0.2°C	0 ± 4%
Rate of change ± SE	1.2 ± 0.2°C per century	0 ± 4% per century
Probability (p) that change is random	<0.0001	>0.99
Statistically significant	yes	no
Annual average, mean ± SD	7.6 ± 0.8°C	780 ± 110 mm per year
1981-2010		
Annual average, mean	4.1°C	1100 mm per year
Maximum in proposed national park	10.2°C	1500 mm per year
Minimum in proposed national park	-2.5°C	680 mm per year

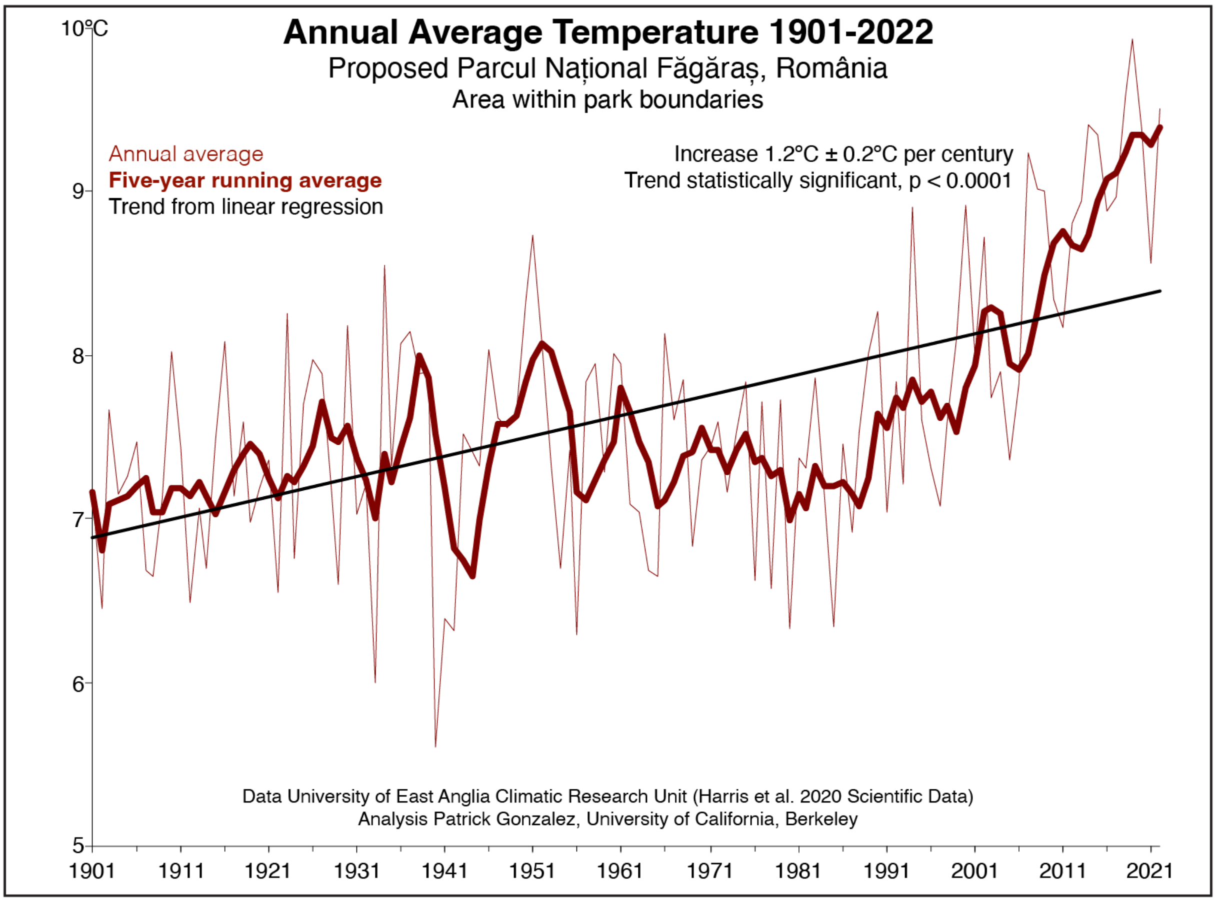

Figure 3. Annual average temperature time series, 1901-2022, proposed Parcul Național Făgăraș, România. Trend calculated by linear regression, corrected for temporal autocorrelation, from spatial analysis (Gonzalez, this report) of weather station data interpolated to 50 km spatial resolution (Harris et al. 2020).

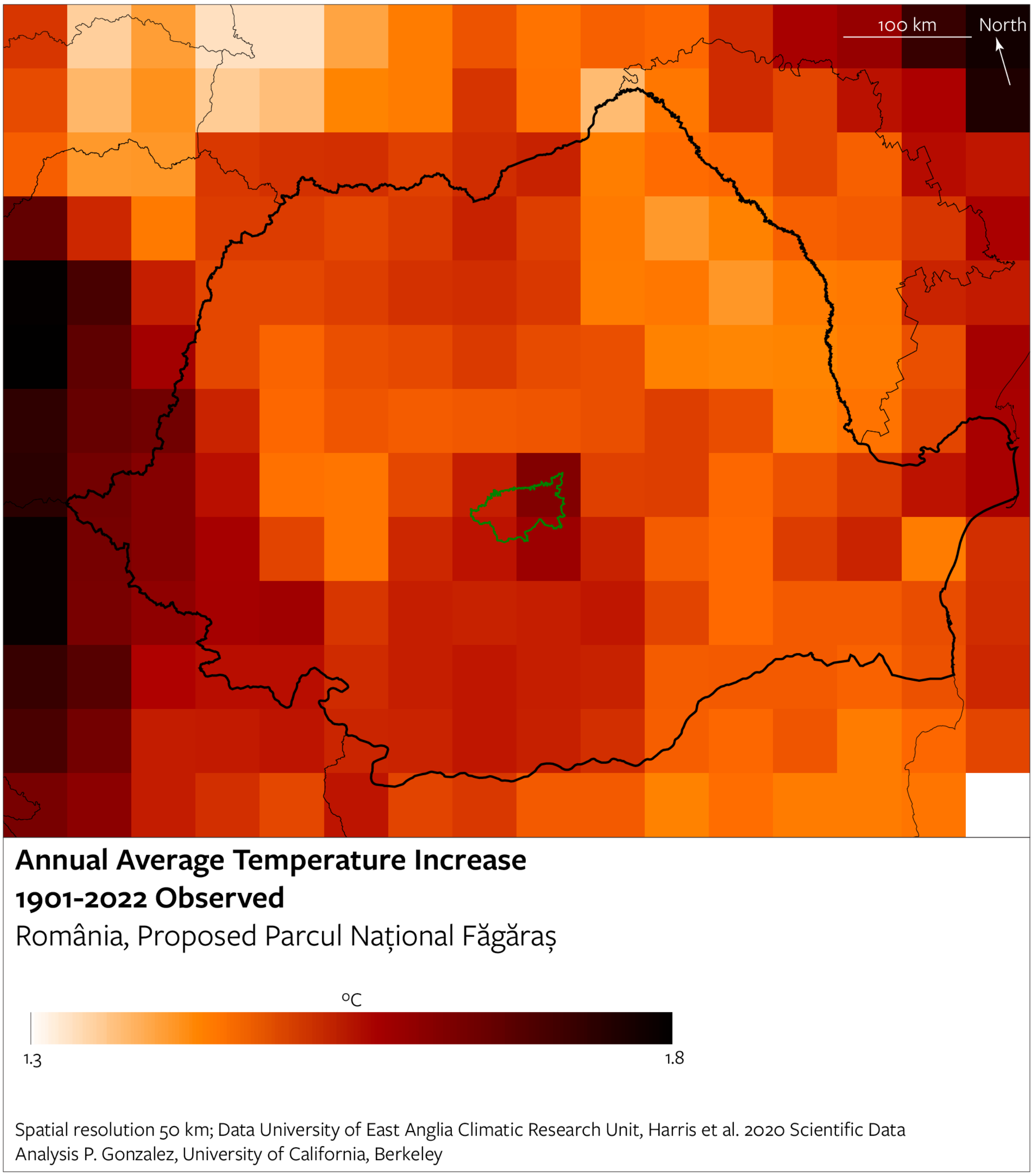

Figure 4. Observed temperature change, 1901-2022, România. Trend in annual average temperature from linear regression, corrected for temporal autocorrelation, from spatial analysis (Gonzalez, this report) of weather station data interpolated to 50 km spatial resolution (Harris et al. 2020).

factors and natural factors in causing measured changes. Detection and attribution analyses have found that greenhouse gases from human burning of coal, oil, methane have caused over 99% of the global measured temperature increase. Anthropogenic climate change has already pushed the Făgăraș region above the lower level of the Paris Agreement goal.

The Făgăraș region has experienced nearly the highest temperature increase in Romania (Figure 4). Temperature in the Făgăraș region did not substantially increase until the late 1980s, when it greatly accelerated (Figure 3). The rate of temperature increase for the entire 1901-2022 period was 1.2ºC ± 0.2ºC per century; for the period 1987-2022 the rate was 6.0 ± 0.9ºC per century. Spatial interpolation of weather station data from 1961 to 2010 by the Administrației Naționale de Meteorologie România shows that maximum temperatures in the southern Carpathian Mountains have increased at a greater rate than average temperatures (Micu et al. 2021). Seasonally, summer (June-August) has experienced the highest rate of temperature increase, followed by winter (December-February) (Micu et al. 2021). In addition, climate change has increased extreme heat in central Romania, with the maximum temperature for the year increasing from 1950 to 2018 (IPCC 2021).

In the Făgăraș Mountains, as elevation increases, average temperature decreases (Figure 8, out of sequence to facilitate comparison to Figure 9). Annual average temperature for the period 1981-2010 range from 10.2ºC at low elevations to -2.5ºC at mountain summits (Table 1). In the southern Carpathian Mountains, the elevation of 10ºC July average temperature shifted 350 m upslope from 1961 to 2010 (Micu et al. 2021).

Precipitation Total annual precipitation of the proposed national park area showed high year-to-year variation but no statistically significant trend for the period 1901-2022 (Table 1, Figure 5). This situation is common globally, with over half of global land area not experiencing a statistically significant change in total precipitation (IPCC 2021). The proposed national park is located is a zone of transition between areas of precipitation decreases to the northwest and increases to the southeast (Figure 6).

For the period 1850-2012, reconstruction of the Palmer Drought Severity Index using tree ring data from across Europe, including Romania, indicates that central Romania experienced statistically significant drought for the period as a whole (Cook et al. 2015), possible if precipitation in the 19th century were higher than in the 1901-2022 time series.

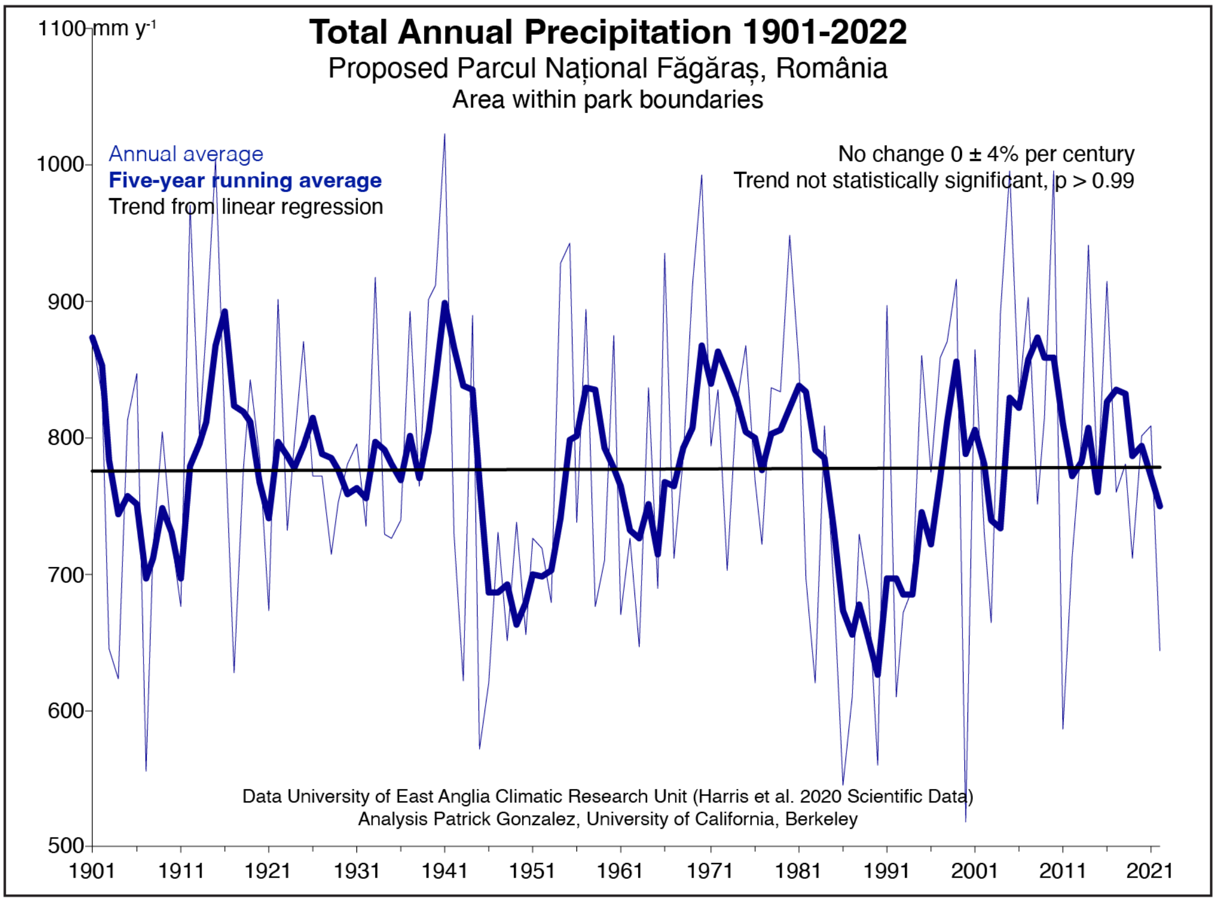

Figure 5. Total annual precipitation time series, 1901-2022, proposed Parcul Național Făgăraș, România. Trend calculated by linear regression, corrected for temporal autocorrelation, from spatial analysis (Gonzalez, this report) of weather station data interpolated to 50 km spatial resolution (Harris et al. 2020).

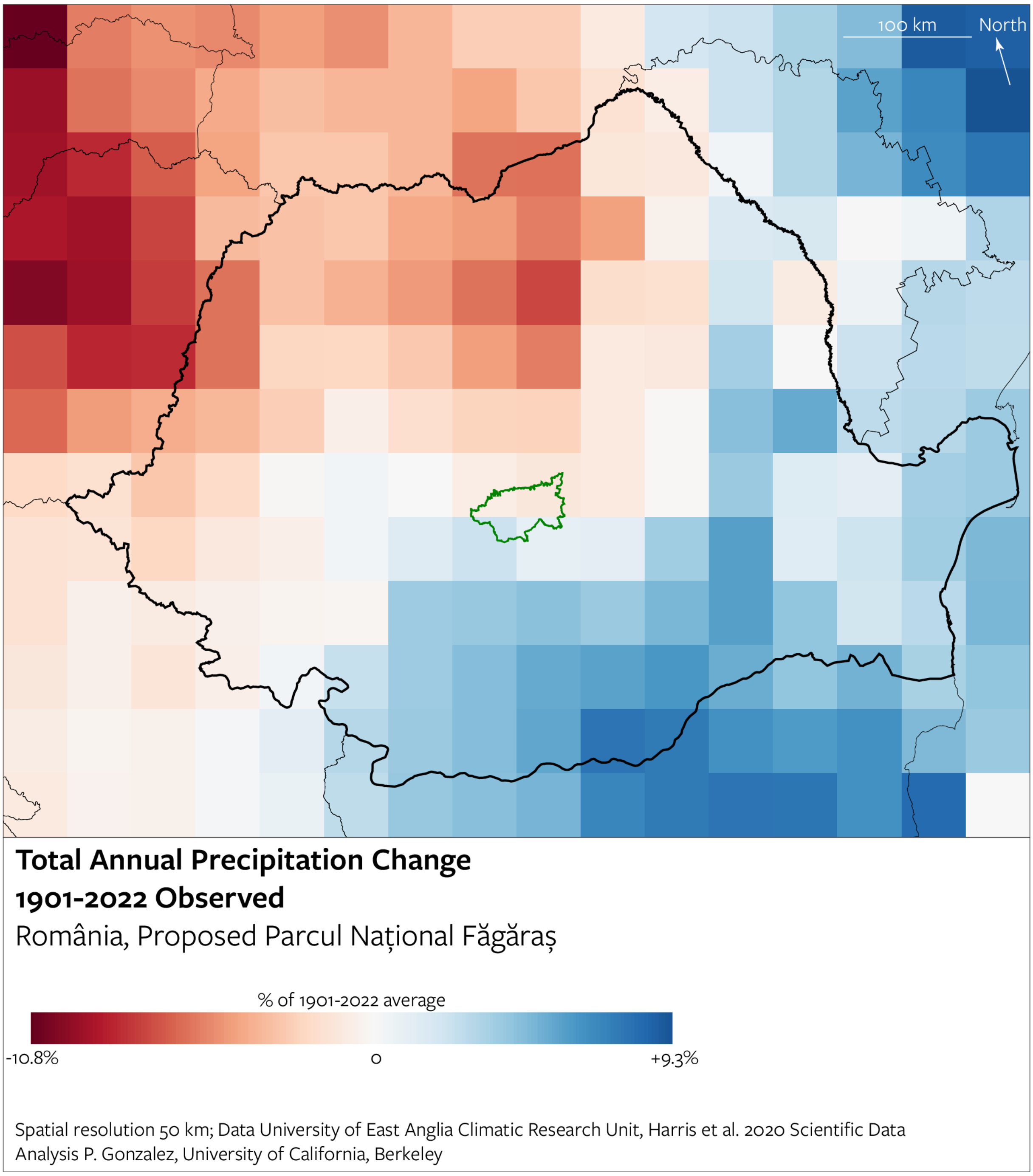

Figure 6. Observed precipitation change, 1901-2022, România. Trend in total annual precipitation from linear regression, corrected for temporal autocorrelation, from spatial analysis (Gonzalez, this report) of weather station data interpolated to 50 km spatial resolution (Harris et al. 2020).

In the Făgăraș Mountains, as elevation increases, average precipitation increases (Figure 10, out of sequence to facilitate comparison to Figure 11). In the proposed national park, annual average precipitation for the period 1981-2010 ranged from 680 mm per year at low elevations to 1500 mm per year at mountain summits (Table 1).

Temperature increases have reduced the fraction of precipitation that falls as snow globally, (Raisanen 2023), reduced Northern Hemisphere snow cover extent 9% from 1922 to 2012 (Rupp et al. 2013, Najafi et al. 2016), and decreased relative humidity in Europe, including the Făgăraș region, in the period 1979-2013 (IPCC 2021). While climate change has increased the frequency of extreme storm events in some regions of the world, annual maximum daily precipitation has not shown a statistically significant change in Romania (IPCC 2021).

Observed Ecological Impacts

Detection and attribution Because many factors, including deforestation, urbanization, agricultural expansion, and air and water pollution, cause changes in ecosystems, Intergovernmental Panel on Climate Change (IPCC) assessments and other scientific research use detection and attribution analyses to determine the role of anthropogenic climate change. Detection is finding a statistically significant change from natural variability. Attribution is determination of the relative importance of potential causal factors to estimate the relative influence of anthropogenic climate change and other factors. This section describes ecological changes detected and attributed to anthropogenic climate change more than other factors.

A systematic literature search did not find cases of attribution that used data from the Făgăraș region. Key cases of global attribution have used data from temperate montane and alpine ecosystems elsewhere in Europe.

Plant and animal species extirpations Globally, climate change has caused extirpations (local disappearances) of more than 400 plant and animal species, from 1849 to 2012 (Wiens 2016, Roman-Palacios and Wiens 2020). The global analysis included cases of extirpation along mountain slopes in Europe for nine plant species (Felde et al. 2012), 36 insect species (Franco et al. 2006, Dieker et al. 2011, Ploquin et al. 2013, Menendez et al. 2014), and 23 fish species (Comte and Grenouillet 2013). These occurred between 1900 and 2009.

Plant and animal range shifts For 42 of 60 mountain summits across Europe, mainly isolated from local human land-use change, including two of four in the eastern Carpathian Mountains, Romania, plant species adapted to warmer conditions increased in abundance from 2001 to 2008 (Gottfried et al. 2012), effectively shifting ranges upslope. In the Northern Hemisphere, climate change shifted the ranges of more than 300 plant and animal species at rates of 6 km per decade northward or 6 m per decade upslope in periods during the 20th century (Parmesan and Yohe 2003, Root et al. 2003, Rosenzweig et al. 2008). Analyses included cases of plants, birds, and insects in Europe.

Biome shifts Biomes are major vegetation zones characterized by a distinctive plant form. At sites in tropical, temperate, and boreal ecosystems around the world, climate change has caused biome shifts up to 20 km latitudinally and 300 m upslope (Gonzalez et al. 2010). The global analysis included a case of temperate broadleaf forest dominated by European beech in Spain shifting upslope into alpine heathland (Peñuelas and Boada 2003) and cases of sub-alpine or boreal forest shifting into, respectively, alpine or tundra.

For the Făgăraș Mountains, analysis of topographic maps from 1945 and satellite images from 2018 indicated that the average upper forest limit may have shifted upslope ~10 m, the maximum upper forest limit shifted downslope ~150 m, and upper forest area increased (Kucsicsa and Balteanu 2020). Logging, pasture expansion or abandonment, and other human factors exert a substantial influence on treeline in this area, so the shifts have not been attributed to anthropogenic climate change. In Retezat National Park in Romania, west of Făgăraș, a 35 m upslope shift of sub-alpine forest into alpine grassland from 1981 to 2014, observed in Landsat images, in an area protected since 1935, suggests influence of climate change, though does not provide attribution (Dinca et al. 2017).

Biome shifts alter the fundamental characteristics of an ecosystem, including biodiversity, canopy structure, and biomass. In turn, these changes alter primary functions and services of ecosystems, including habitat for plants and animals, carbon storage to reduce climate change, soil protection against desertification, and water provision for people (IPCC 2022).

Tree mortality Analysis of the Romania National Forest Inventory found no substantial tree mortality in the southern Carpathia Mountains from 1992 to 2010 (Badea et al. 2013). Anthropogenic climate change has driven drought-induced tree mortality in the 20th and 21st centuries in Africa and North America but not in Europe (IPCC 2022).

Wildfire Fire is not currently natural in Făgăraș forests (Feurdean et al. 2017). In the period 1996-2016, the maximum burning that occurred in any part of the proposed Parcul Național Făgăraș was less than 5% in a year and was near zero for much of the area (Senande-Rivera et al. 2022). In 2015, less than 1% of the national forest area of Romania burned (Zaimes et al. 2020). Anthropogenic climate change has lengthened the fire weather season from 1979 to 2013 on one-quarter of global vegetation area but not in central Romania (Jolly et al. 2015). Anthropogenic climate change has also increased the area burned by wildfire in the 20th and 21st centuries in North America but not in Europe (IPCC 2022).

Phenology changes Phenology is the timing of life events, including plant flowering, tree leaf fall, and animal migration. In Romania, anthropogenic climate change lengthened the growing season four to six days from 1950 to 1999 (Christidis et al. 2007). In Austria, Germany, and Switzerland, anthropogenic climate change advanced spring leafing and flowering of fruit and wild trees more than two weeks earlier from 1951 to 2018 (Menzel et al. 2020). In the Northern Hemisphere, climate change advanced phenology two days per decade earlier in time periods of varying length during the 20th century (Parmesan and Yohe 2003, Root et al. 2003, Rosenzweig et al. 2008). Analyses included cases of plants, birds, and insects in Europe.

Migratory birds Analyses of observations of 51 bird species across Europe starting in the 1970s found that climate change increased growth rates of migratory birds more than non-climate factors (Jorgensen et al. 2016). Annual growth rates increased for short-distance migrating birds after spring seasons with higher vegetation production, for long-distance migrating birds after warm summers, and for all migrating birds in spring in the colder part of their range (Jorgensen et al. 2016).

Bumble bees Climate change reduced bumble bee (*Bombus spp.*) species richness and abundance up to one-third in North America and Europe and up to 15% in the Făgăraș region, between the periods 1901-1974 and 2000-2014 (Soroye et al. 2020).

Lake temperatures and ice Climate change increased lake water temperatures 0.4ºC for the annual average globally and 1.5ºC for summer (June-August) in central Romania, between the periods 1981-1990 and 2010-2019 (O'Reilly et al. 2015, Grant et al. 2021). The temperature increases reduced lake ice cover duration nine days on average globally and five to ten days in central Romania (Grant et al. 2021).

Projected Climate

Temperature Under a very high greenhouse gas emissions scenario (SSP5-8.5), annual average temperature of the proposed park area could increase to 6.4 ± 2.0ºC above the 1901-1910 near-pre-industrial level by 2100 (Figure 7, Table 2) or 5.7 ± 2.0ºC above the 1981-2010 level (Table 2). Cutting emissions from human activities (SSP1-2.6) to meet the Paris Agreement goal globally could reduce projected heating of the proposed park area by more than half (Figure 7, Table 2).

Maximum annual average temperature in the proposed park area could increase from 10.2ºC in the period 1981-2010 (Figure 8, Table 1) to 16ºC in the period 2071-2100 under the very high greenhouse gas emissions scenario (SSP5-8.5; Figure 9, Table 2). Under the very high greenhouse gas emissions scenario, climate change could reduce areas that experience an annual average temperature less than freezing (0ºC) from 8% of the proposed park area (Figure 8) to none of the proposed park area (Figure 9). Cutting emissions from human activities (SSP1-2.6) could conserve a small area (<1% of proposed national park area) that would still experience an annual average temperature less than freezing.

Continued climate change could increase extreme heat. Under the very high greenhouse gas emissions scenario (SSP5-8.5), the region could experience 40 more days per year with a maximum temperature >35ºC (Table 3). Cutting emissions from human activities (SSP1-2.6) could limit the increase to 10 more days per year (Table 3).

Precipitation Under the very high greenhouse gas emissions scenario (SSP5-8.5), total annual average precipitation of the proposed park area could decrease to 8 ± 4% below the 1901-1910 near-pre-industrial level and the recent 1981-2010 level by 2100 (Figure 7, Table 2). Cutting emissions from human activities (SSP1-2.6) could result in no change or a slight increase in total annual precipitation (Figure 7, Table 2). Even if precipitation increases,

Table 2. Projected temperature and precipitation, proposed Parcul Național Făgăraș, România. Results are spatial averages of the area of the proposed national park, from spatial analyses (Gonzalez, this report) of Intergovernmental Panel on Climate Change (IPCC 2021) general circulation model (GCM) output downscaled to 1 km spatial resolution (Karger et al. 2020). Results are annual averages and standard deviations of projections from five GCMs representing the range of independent GCMs, for the three main emissions scenarios (Shared Socio-economic Pathways (SSP; IPCC 2021)).

	Temperature	**Precipitation**
Change 1901-1910 to 2071-2100		
SSP1-26 very low emissions	+2.8 ± 1.1°C	+2.5 ± 5.3%
SSP3-70 high emissions	+5.4 ± 1.7	-4.5 ± 4.5
SSP5-85 very high emissions	+6.4 ± 2.0	-8.2 ± 3.7
Change 1981-2010 to 2071-2100		
SSP1-26 very low emissions	+2.2 ± 1.1°C	+2.5 ± 5.3%
SSP3-70 high emissions	+4.8 ± 1.7	-4.5 ± 4.5
SSP5-85 very high emissions	+5.7 ± 2.0	-8.2 ± 3.7
Projected climate 2071-2100		
SSP1-26 low emissions		
Annual mean	6.3 ± 1.1°C	1200 ± 60 mm per year
Maximum in proposed national park	12.4	1500
Minimum in proposed national park	-0.4	700
SSP3-70 high emissions		
Annual mean	8.9 ± 1.7°C	1100 ± 50 mm per year
Maximum in proposed national park	15	1400
Minimum in proposed national park	2.2	650
SSP5-85 highest emissions		
Annual mean	9.8 ± 2.0°C	1000 ± 40 mm per year
Maximum in proposed national park	16	1400
Minimum in proposed national park	3.2	620

Table 3. Projected temperature and precipitation extremes, proposed Parcul Național Făgăraș, România. Results at approximately the center of the park, ~46° North latitude, ~24.5° East longitude, from Intergovernmental Panel on Climate Change (IPCC 2021) general circulation model (GCM) output at 50 km spatial resolution, for the three main emissions scenarios (Shared Socio-economic Pathways (SSP; IPCC 2021)). Results are averages of projections from all available GCMs.

	Change from 1850-1900 to 2081-2100	**Change from 1981-2010 to 2081-2100**	**Projected climate 2081-2100**
Maximum temperature >35°C			
SSP1-26 very low emissions	+140%	+120%	17 days per year
SSP3-70 high emissions	+390	+340	37
SSP5-85 very high emissions	+580	+510	47
Snowfall			
SSP1-26 very low emissions	-25%	-25%	11 cm per year
SSP3-70 high emissions	-50	-50	7.3
SSP5-85 very high emissions	-75	-67	3.6
Consecutive dry days			
SSP1-26 very low emissions	+21%	+19%	30 days per year
SSP3-70 high emissions	+40	+37	33
SSP5-85 very high emissions	+53	+49	37
Maximum five-day precipitation			
SSP1-26 very low emissions	+8%	+7%	66 mm
SSP3-70 high emissions	+12	+10	68
SSP5-85 very high emissions	+11	+10	68

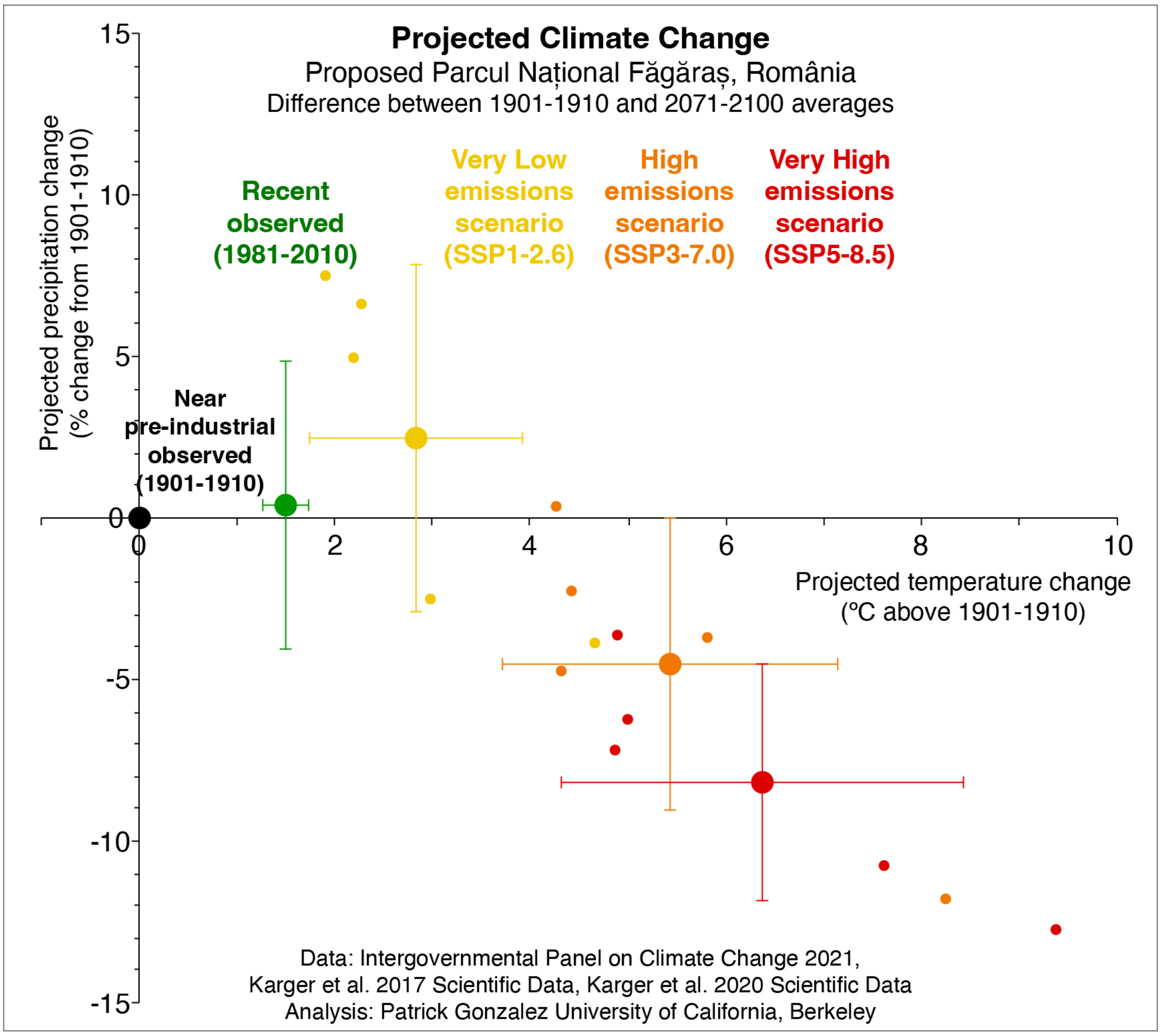

Figure 7. Projected temperature and precipitation changes, proposed Parcul Național Făgăraș, România, difference between 1901-1910 and 2071-2100 averages. Averages for the area of the proposed national park, from spatial analyses (Gonzalez, this report). Large black dot represents the 1901-1910 base value, in the absence of local data for the standard 1850-1900 pre-industrial period. Large green dot shows the 1981-2010 change, from spatial analyses of climate data interpolated to 1 km spatial resolution from satellite and weather station measurements and modeling (Karger et al. 2017) and weather station data interpolated to 50 km spatial resolution (Harris et al. 2020). Each small color dot is the output of an Intergovernmental Panel on Climate Change (IPCC 2021) general circulation model (GCM), downscaled to 1 km spatial resolution (Karger et al. 2020). The large yellow, orange, and red dots and the crosses are the averages and standard deviations, respectively, of five GCMs representing the range of independent GCMs, for each of the three main emissions scenarios (Shared Socio-economic Pathways (SSP; IPCC 2021)).

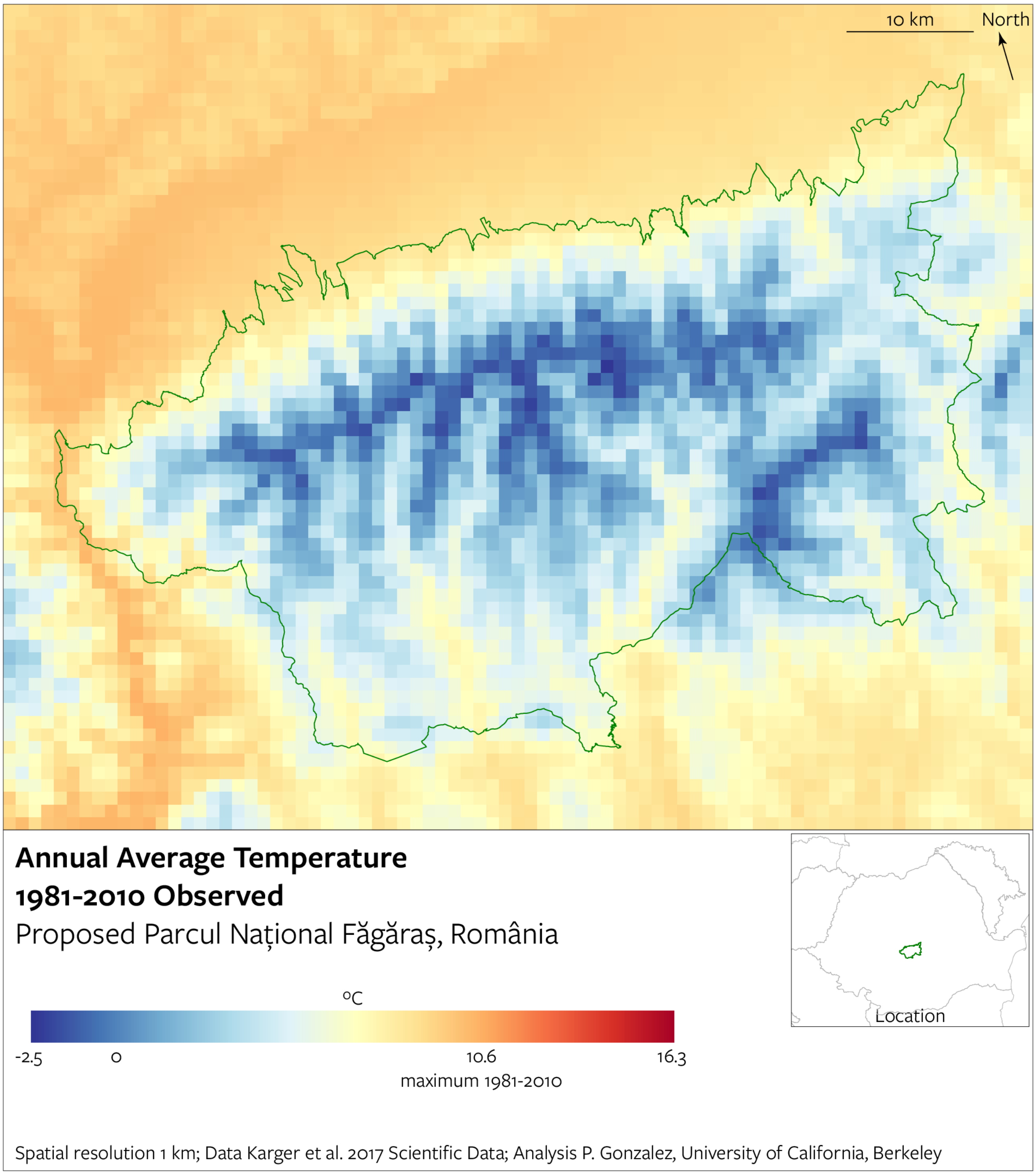

Figure 8. Observed annual average temperature spatial patterns, 1981-2010, proposed Parcul Național Făgăraș, România. From spatial analyses (Gonzalez, this report) of climate data interpolated to 1 km spatial resolution from a combination of satellite and weather station measurements and modeling (Karger et al. 2017).

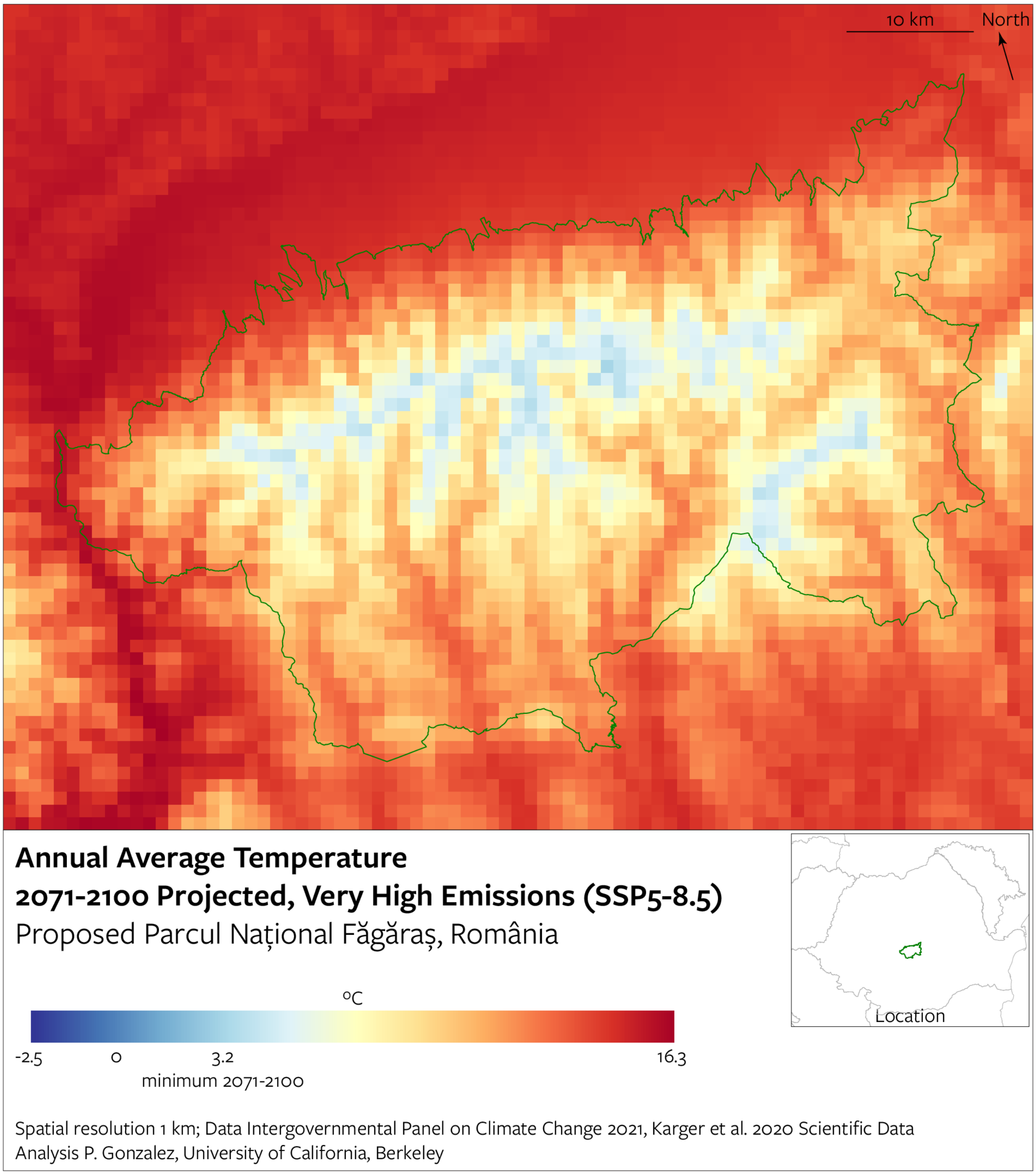

Figure 9. Projected annual average temperature spatial patterns, 2071-2100, proposed Parcul Național Făgăraș, România. Average of five Intergovernmental Panel on Climate Change (IPCC 2021) general circulation models, representing the range of independent models, under the highest emissions scenario (SSP5-8.5), downscaled to 1 km spatial resolution (Karger et al. 2020).

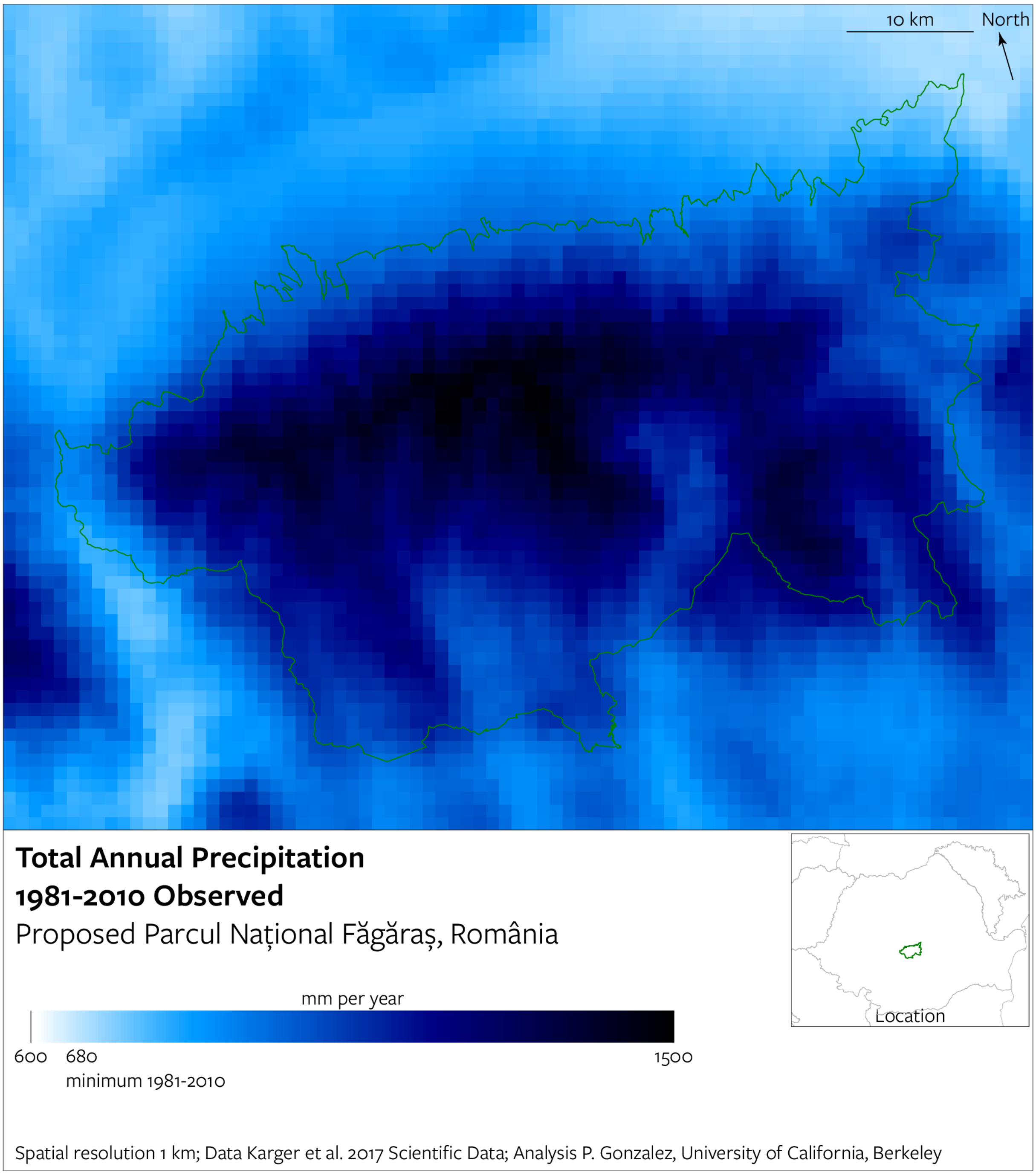

Figure 10. Observed total annual precipitation spatial patterns, 1981-2010, proposed Parcul Național Făgăraș, România. From spatial analyses (Gonzalez, this report) of climate data interpolated to 1 km spatial resolution from a combination of satellite and weather station measurements and modeling (Karger et al. 2017).

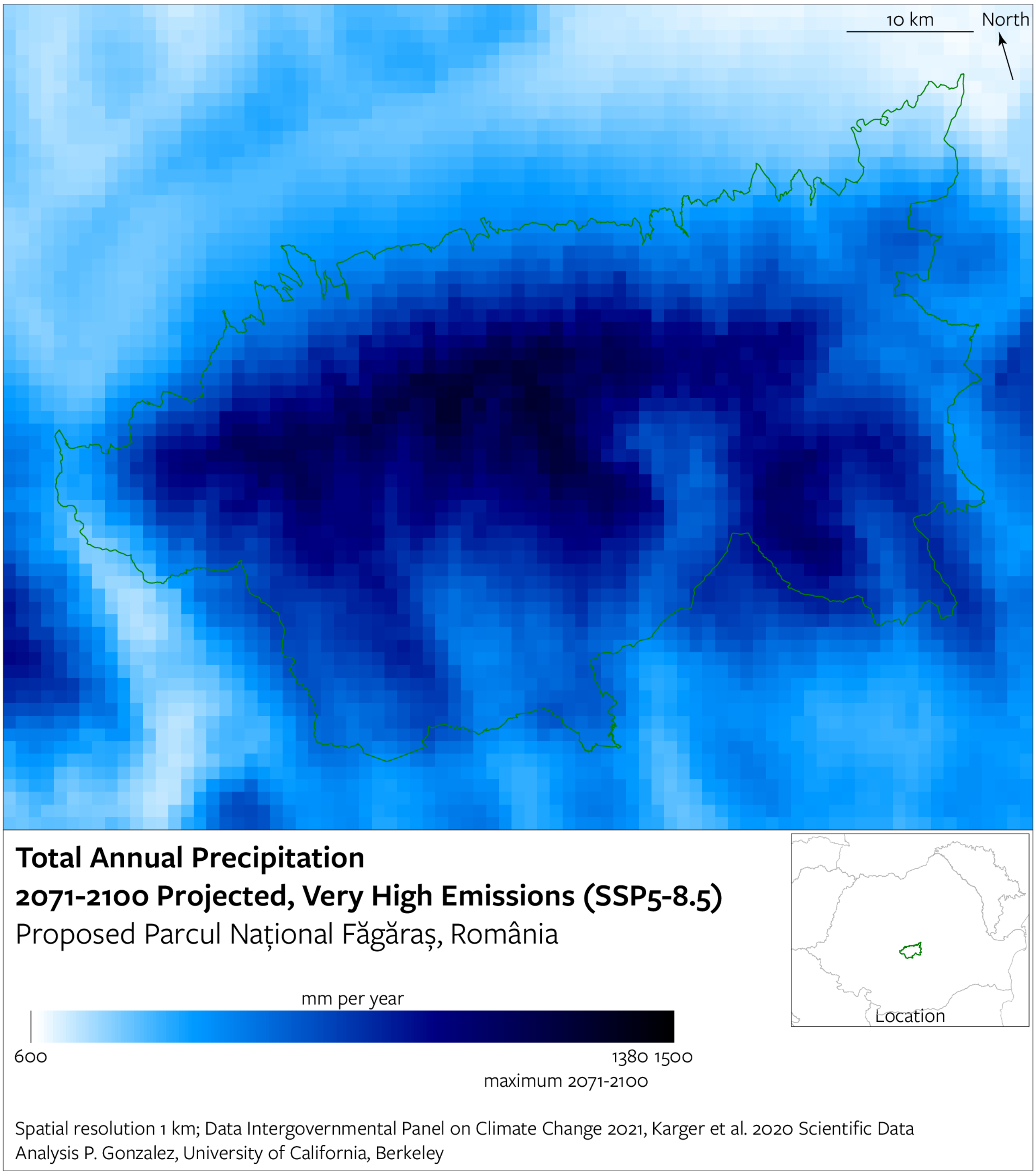

Figure 11. Projected total annual precipitation spatial patterns, 2071-2100, proposed Parcul Național Făgăraș, România. Average of five Intergovernmental Panel on Climate Change (IPCC 2021) general circulation models, representing the range of independent models, under the highest emissions scenario (SSP5-8.5), downscaled to 1 km spatial resolution (Karger et al. 2020)

higher temperatures could increase aridity by raising evapotranspiration (Byrne and O'Gorman 2015). Maximum annual precipitation in the proposed park area could decrease from 1500 mm per year in the period 1981-2010 (Figure 10, Table 1) to ~1400 mm per year in the period 2071-2100 under very high greenhouse gas emissions (Figure 11, Table 2).

Continued climate change could decrease snowfall and increase precipitation extremes (Table 3). Under very high greenhouse gas emissions (SSP5-8.5), annual snowfall in the region could decline three-fourths from pre-industrial levels and two-thirds from the recent level. Cutting emissions from human activities (SSP1-2.6) could limit the decrease in snowfall to one-fourth. The number of consecutive days without precipitation could increase from 25 days recently to 37 days under very high greenhouse gas emissions (SSP5-8.5). On the other hand, continued climate change could increase the maximum five-day precipitation 10% above the recent level.

Projected Ecological Risks

Without reductions of greenhouse gases from human sources, continued climate change increases risks to species and ecosystems (IPCC 2022). Published analyses of projected climate change in the Făgăraș Mountains or on species found in the region have identified numerous future risks.

IPCC (2023) has confirmed that concerted global action can reduce emissions from human activities enough to meet the Paris Agreement goal of limiting the global temperature increase to 1.5 to 2ºC above pre-industrial levels. The difference between the emissions reductions scenario (SSP1-2.6) and the highest emissions scenario (SSP5-8.5), as shown in this report, shows that cutting carbon emissions from human activities can reduce future heating and risks to the unique ecosystems of the proposed Parcul Național Făgăraș.

Biome shifts Under continued climate change, upslope shifts of warmer temperatures increase the risk of biome shifts. For the southern Carpathian Mountains, one analysis of equilibrium climate requirements projects a risk of biome shifts greater than 80% under a global temperature increase of 2ºC (Dobrowski et al. 2021). A separate analysis, combining statistical analyses of observed temperature and precipitation change and future projections of a dynamic global vegetation model, projects a risk of 20% to 80% of biome shifts in the region, under global temperature increases of 2°C to 4°C (Gonzalez et al. 2010).

With an environmental lapse rate of 1°C temperature for a 167 m elevation change (Jump et al. 2009), the observed annual average temperature change for the proposed Parcul Național Făgăraș from 1901 to 2022 was equivalent to an elevation shift of 250 ± 30 m. Under the very high emissions scenario (Table 2), the projected temperature change could be equivalent to an upslope shift of more than 1000 m elevation.

The elevation sequence of biomes in the Făgăraș Mountains of temperate woodland (oaks) at the lowest elevation–temperate broadleaf forest (European beech and other species)–temperate conifer forest (silver fir and other species)–subalpine forest (Norway spruce and other species)–alpine grassland at the highest elevation, would tend to shift upward (Gonzalez et al. 2010). Field research in the western Carpathian Mountains, Romania, indicates possible future upslope retraction of European beech at the lower, dry end of its range, in favor of oaks (Hohnwald et al. 2020). Climate change under very high emissions places alpine grasslands at risk of completely losing suitable climate from mountain tops.

Logging, livestock pastures, roads, and other forms of habitat fragmentation create barriers to dispersal of native plant species (Dullinger et al. 2015). In the Făgăraș region, habitat fragmentation places ecosystems at 20% to 95% risk of biome shifts by 2100, based on spatial analysis of observed land cover change and future projections of a dynamic global vegetation model (Eigenbrod et al. 2015).

Tree mortality Under continued climate change, a combination of hotter temperatures and decreased precipitation could increase water stress, the main mechanism of drought-induced tree mortality (Anderegg et al. 2016). Research indicates that all three principal tree species in Făgăraș forests are sensitive to drought.

European beech shows sensitivity to drought, based on field research in the Carpathian Mountains west of Făgăraș (Hohnwald et al. 2020) and east of Făgăraș (Budeanu et al. 2016) and on analyses of tree rings from the Carpathian Mountains west of Făgăraș (Kasper et al. 2023) and across Europe, including northern Romania (Hacket-Pain et al. 2016) and the Făgăraș Mountains (Martinez del Castillo et al. 2022). Modeling under a range of climate change scenarios indicates risks of drought-induced mortality of European beech in Făgăraș forests (García-Duro et al. 2021) or a potential growth decline of 20% under SSP1-2.6 or 50% under SSP5-8.5 at lower elevations of the Făgăraș Mountains (Martinez del Castillo et al. 2022).

Silver fir showed sensitivity to drought in one analysis of tree rings from forests in Spain, Italy, and Romania, including the Făgăraș Mountains (Gazol et al. 2015).

Norway spruce has shown reduced growth due to drought, in analyses of tree rings from forests in the eastern Carpathian Mountains (Svobodova et al. 2019), particularly at lower elevations (Primicia et al. 2015, Popa et al. 2024), from Făgăraș and across the Carpathian Mountains (Bosela et al. 2021), and from Făgăraș and across Europe (Marchand et al. 2023). Norway spruce was less drought-tolerant than European beech (Marchand et al. 2023).

Field measurements in nine Norway spruce stands in Făgăraș forests, repeated in a five-year interval between 2011 and 2018, found a natural mortality rate of 1% per year, with European spruce bark beetle (*Ips typographus*) the most frequent cause of tree mortality, causing over half of the tree deaths (Synek et al. 2020). The northern bark beetle (*Ips duplicatus*) and the black stem borer (*Xylosandrus germanus*) were both captured at a monitoring site in the Făgăraș Mountains in 2016 (Olenici et al. 2022). Modeling of climate change in Switzerland indicated that warmer and drier conditions increase the susceptibility of Norway spruce to bark beetle attacks (Jakoby et al. 2019).

Tree growth Climate change can drive an increase in growth due to the enhancement of photosynthesis by increased atmospheric carbon dioxide (CO_2 fertilization; Idso 1991, Chen et al. 2022) and by a combination of warmer temperatures and increased moisture. Modeling of Făgăraș forests under climate change under those conditions projected an increase of biomass in all biomes (García-Duro et al. 2021).

Silver fir has shown recent growth increases correlated to temperature increases, in analyses of tree rings from a plot at Sinca, in Făgăraș (Bosela et al. 2018), plots across the Carpathian Mountains, including one plot in Făgăraș (Adamic et al. 2023), and plots in Spain, Italy, and Romania, including Făgăraș (Gazol et al. 2015). Provenance trials of seeds from across Europe, including Romania, indicate that silver fir exhibits wide genetic variation of temperature adaption potential (Mihai et al. 2018, 2021).

Growth of European beech at higher elevations could potentially increase 10% under SSP1-2.6 and 50% under SSP5-8.5, based on modeling of sites across Europe, including Făgăraș (Martinez del Castillo et al. 2022). European beech and Norway spruce show increasing growth correlated to increasing temperatures in an analysis of tree rings from across Europe, including Făgăraș (Marchand et al. 2023). Norway spruce has shown higher growth rates at higher elevations, from analyses of tree rings from the Făgăraș Mountains (Schurman et al. 2019) and the eastern Carpathian Mountains (Primicia et al. 2015).

Wildfire The three main tree species in the proposed national park, European beech, silver fir, and Norway spruce, are not fire-adapted (San-Miguel-Ayanz et al. 2016), so any wildfire risk generates a risk of unnatural tree mortality. Modeling of fire factors indicates no wildfire spread capacity or risk currently in the Făgăraș region (Hysa et al. 2021). (One modeling effort (Mallinis et al. 2019) seemed to erroneously find the highest fire risk in Romania in the Carpathian Mountains.)

Climate change intensifies the heat that drives wildfires. Under very high emissions, climate change increases potential fire frequency in the Făgăraș region from ~10% (Moritz et al. 2012) to ~80% (Gonzalez et al. 2010) by 2100. For areas in or near the proposed national park, it would be prudent to avoid intentional burning to expand pastures or clear crop stubble (Fernandez-Anez et al. 2021).

Invasive Species Climate change can favor invasive alien plants in temperate zones through (1) carbon dioxide (CO_2) enrichment, favoring alien plants that can exploit atmospheric CO_2 more efficiently than native species (Davidson et al. 2011, Liu et al. 2017), (2) increasing warmth and moisture that can increase the suitability of temperate zone ecosystems to plants from tropical zones (Theoharides and Dukes 2007, Hellmann et al. 2008), and (3) disturbance by vegetation changes, such as biome shifts (Theoharides and Dukes 2007, Hellmann et al. 2008). A global analysis of alien species introduction by human action and establishment under climate change indicated that the Făgăraș region is in an area of high to very high risk of invasive alien species (Early et al. 2016). Extensive areas of Europe, including the southern Carpathian Mountains could become suitable habitat for North American tree species under climate change (Puchałka et al. 2023).

Mammals For animal species, climate change can increase risks of lower growth or reproduction, extirpation, or extinction by exceeding physiological tolerances, altering or eliminating habitat, and reducing the abundance of food and water. Climate change of 4.4°C above pre-industrial levels could expose one-third to two-thirds of 33 000 land vertebrate species to heat extremes beyond the historical levels of half their range (Murali et al. 2023). The literature search found scientific information for five mammal species found in the proposed national park.

Roe deer (*Capreolus capreolus*) are vulnerable to the effects of climate change on food plants. Vegetation productivity comprises the most important factor for roe deer survival, based on field research in Sweden (Davis et al. 2016) and across Europe, including Romania (Melis et al. 2009). Phenology affects this relationship. Roe deer behavior in Spring advanced one month earlier from 1982 to 2018, a period in which temperatures increased 2°C, in the Czech Republic (Bil et al. 2023). Flowering of forage plants advanced five times more rapidly than birth timing of roe deer, from 1971 to 2015, in Switzerland (Rehnus et al. 2020). This type of phenology mismatch led to a 40% decrease in roe deer juvenile survival per month of mismatch, from 1985 to 2011, in France (Plard et al. 2014).

For wild boar (*Sus scrofa*), warmer winters and higher production of European beech nuts could increase survival, suggested by one Europe-wide analysis (Vetter et al. 2015).

For chamois (*Rupicapra rupicapra*), climate change could reduce suitable habitat by reducing snow cover (Rosca and Ceuca 2023) and driving replacement of forbs with grasses at high elevations (Varricchione et al. 2021).

For Eurasian lynx (*Lynx lynx*), climate change under very high emissions (SSP5-8.5) could slightly reduce suitable habitat in the southern Carpathian Mountains (Serva et al. 2023), probably due to reductions of snow cover and sub-alpine forest cover, key habitat requirements. Lynx exhibit an ability to adjust birth timing in Spring, reducing risks of phenology mismatches (Mattisson et al. 2022).

For brown bears (*Ursus arctos*), research in Spain indicates that den exit times are advancing in Spring (Gonzalez-Bernardo et al. 2020), perhaps due to increased temperatures. Projections indicate that contraction of the ranges of food plants, particularly bilberry (*Vaccinium myrtillus*), European beech (*Fagus sylvatica*), chestnut (*Castanea sativa*), and oaks (*Quercus spp.*) could reduce potential habitat one-third under a low emissions scenario and 90% under a very high emissions scenario (Penteriani et al. 2019).

Lake Ecology Continued climate change could increase lake water temperatures more than air temperatures in temperate ecosystems globally, 1.5 to 4°C by 2100 (Grant et al. 2021). Analyses of sediments of Lacul Bâlea, an alpine lake in the proposed national park, found increases in diatoms that indicated possible effects of long-range nitrogen deposition from industrial fertilizers at lower elevations and water temperature increases, suggesting possible risks to lake chemistry and food webs under continued climate change (Szabó et al. 2020).

Forest Carbon Ecosystem Service

The forests of the proposed Parcul Național Făgăraș contained 20 ± 9 million tons of carbon (mean ± standard deviation) in aboveground biomass in 2020 (Table 4, Figure 12), based on spatial analysis of European Space Agency biomass estimates derived from remote sensing, field measurements, and modeling of biomass (section Methods). The forest carbon results here include statistical quantification of uncertainty (Table 4, Figure 13), calculated as standard deviation, accounting for variation and errors in remote sensing, field measurements, computer modeling, and estimates of the carbon fraction of biomass.

The proposed Parcul Național Făgăraș could help prevent climate change by protecting the carbon stock of the area, providing an ecosystem service equivalent to one year of greenhouse gas emissions of 20 ± 9 million Romanians. This is more than the current population of the entire country.

Aboveground forest carbon occurs at an average density of 120 ± 50 tons per hectare, with a maximum density of 250 tons per hectare, for the central estimate (Table 4). High forest carbon stocks distinguish the proposed national park from the surrounding lower-carbon areas, with high-carbon areas covering the north, east, and south mountain slopes at mid-elevations (Figure 12). Forest carbon density exceeds 200 tons per hectare for 8% of the proposed park area or 10% of the proposed national park forest area. Conifer forests contain carbon at the highest density, 140 ± 50 tons per hectare (Table 4). Broadleaf forests contain carbon at a density of 110 ± 50 tons per hectare.

Table 4. Forest carbon and its ecosystem service, proposed Parcul Național Făgăraș, România. Aboveground forest vegetation, 2020, total in the area of the proposed national park, from spatial analyses (Gonzalez, this report) of European Space Agency data at 100 m spatial resolution (Santoro et al. 2021, Santoro and Cartus 2023). Ecosystem service estimated as the number of people in Romania whose annual greenhouse gas emissions is equivalent to the forest carbon stock of the proposed national park, based on 2020 emissions (WRI 2024). Upper and lower estimates calculated as standard deviation (SD), accounting for variation and errors in remote sensing, field measurements, statistical modeling of biomass, and estimates of the carbon fraction of biomass.

	Central estimate	**Upper estimate** (+1 SD)	**Lower estimate** (-1 SD)
Forest carbon stock (tons carbon)	20.5 million	29.6	11.6
Ecosystem service (people)	19.9 million	28.7	11.3
Carbon density (tons per hectare)			
Average	120	180	70
Maximum	250	410	250
Conifer forest	140	190	80
Mixed forest	130	190	70
Broadleaf forest	110	160	60

Table 5. **Ecosystem carbon data comparison**. Results of spatial analyses (Gonzalez, this report) of three global data sets of aboveground ecosystem biomass or carbon for the proposed Parcul Național Făgăraș, România, and a comparison of data set accuracy, for Yosemite National Park, USA. Estimates in tons of carbon. Upper and lower estimates calculated as standard deviation (SD), standard error (SE), or 95% confidence interval (95% CI), for variation and errors. Maximum carbon density across the area is given for the central estimate.

	European Space Agency	**University of Wisconsin, USA**	**World Resources Institute**	**University of California, Berkeley, USA**
Type of original data	Biomass	Carbon	Biomass	Carbon
Vegetation included	Forests	All	Woody	All
Spatial resolution	100 m	300 m	30 m	30 m
Year of estimate	2020	2010	2000	2010
Range of estimate	SD	SE	SD	95% CI
proposed Parcul Național Făgăraș, România				
Carbon stock	20.5 million t	10.7 million t	12.9 million t	
Higher estimate	29.6	15.7	21.9	
Lower estimate	11.6	5.7	4.0	
Carbon density	120 t per ha	50 t per ha	70 t per ha	
Higher estimate	180	70	120	
Lower estimate	70	30	20	
Maximum, central	250	130	140	
Area analyzed	1680 km^2	2110 km^2	1800 km^2	
Reference	Santoro and Cartus 2023	Spawn et al. 2020	Harris et al. 2021	
Yosemite National Park, USA				
Carbon total	10.9 million t	8.9 million t	31.5 million t	14.8 million t
Higher estimate	17.2	13.8	54.3	22.7
Lower estimate	4.6	4.1	8.7	6.9
Carbon density	60 t per ha	40 t per ha	170 t per ha	50 t per ha
Higher estimate	100	65	300	80
Lower estimate	30	20	50	20
Maximum, central	210	220	560	560
Area analyzed	1770 km^2	2740 km^2	2370 km^2	2970 km^2
Reference				Gonzalez et al. 2015

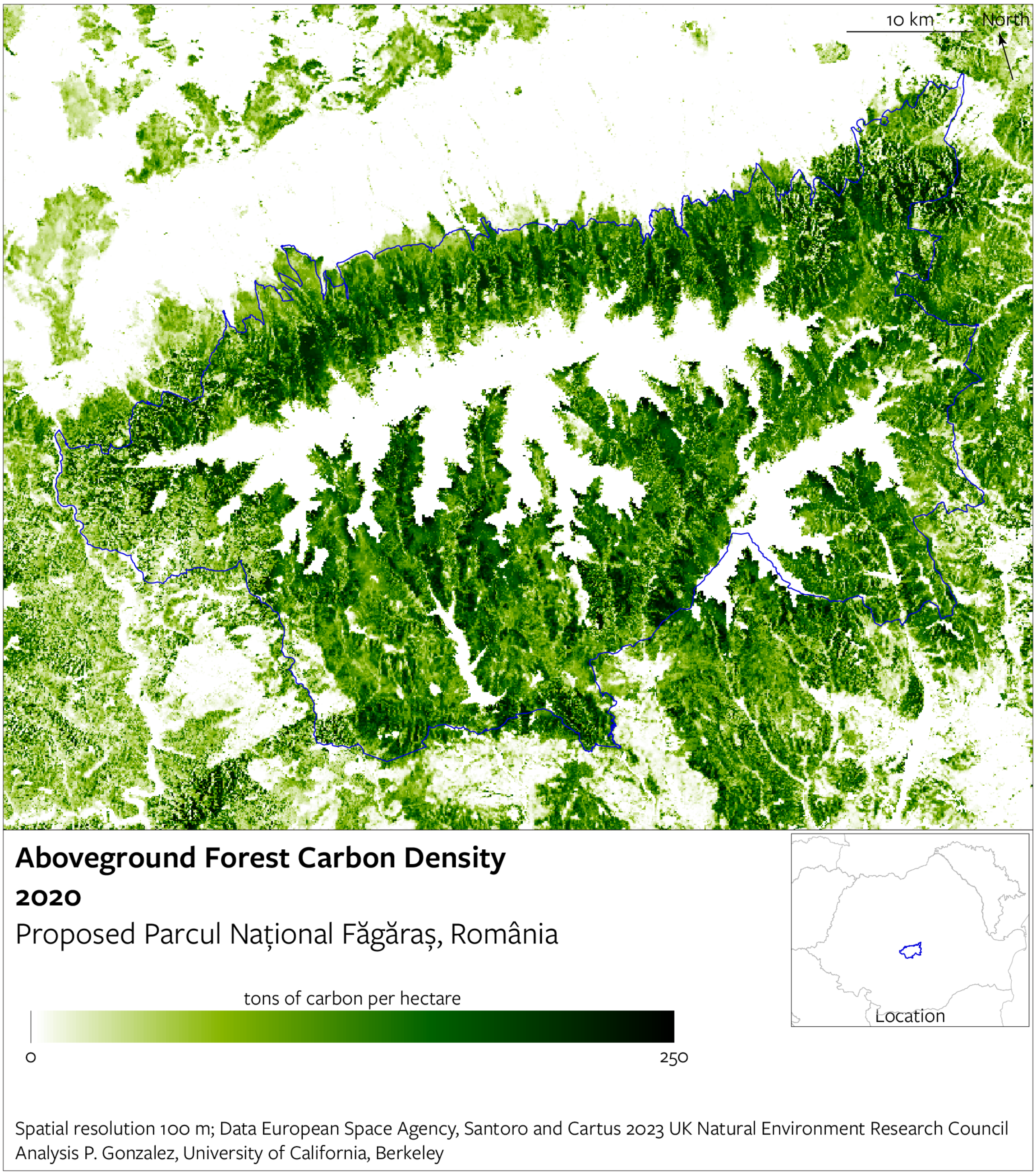

Figure 12. **Forest carbon, 2020**, proposed Parcul Național Făgăraș, România. Carbon density of aboveground forest vegetation, from spatial analyses (Gonzalez, this report) of European Space Agency (ESA) biomass data at 100 m spatial resolution (Santoro et al. 2021, Santoro and Cartus 2023). Vegetation outside of forests contains carbon, at lower densities, but was not analyzed by ESA.

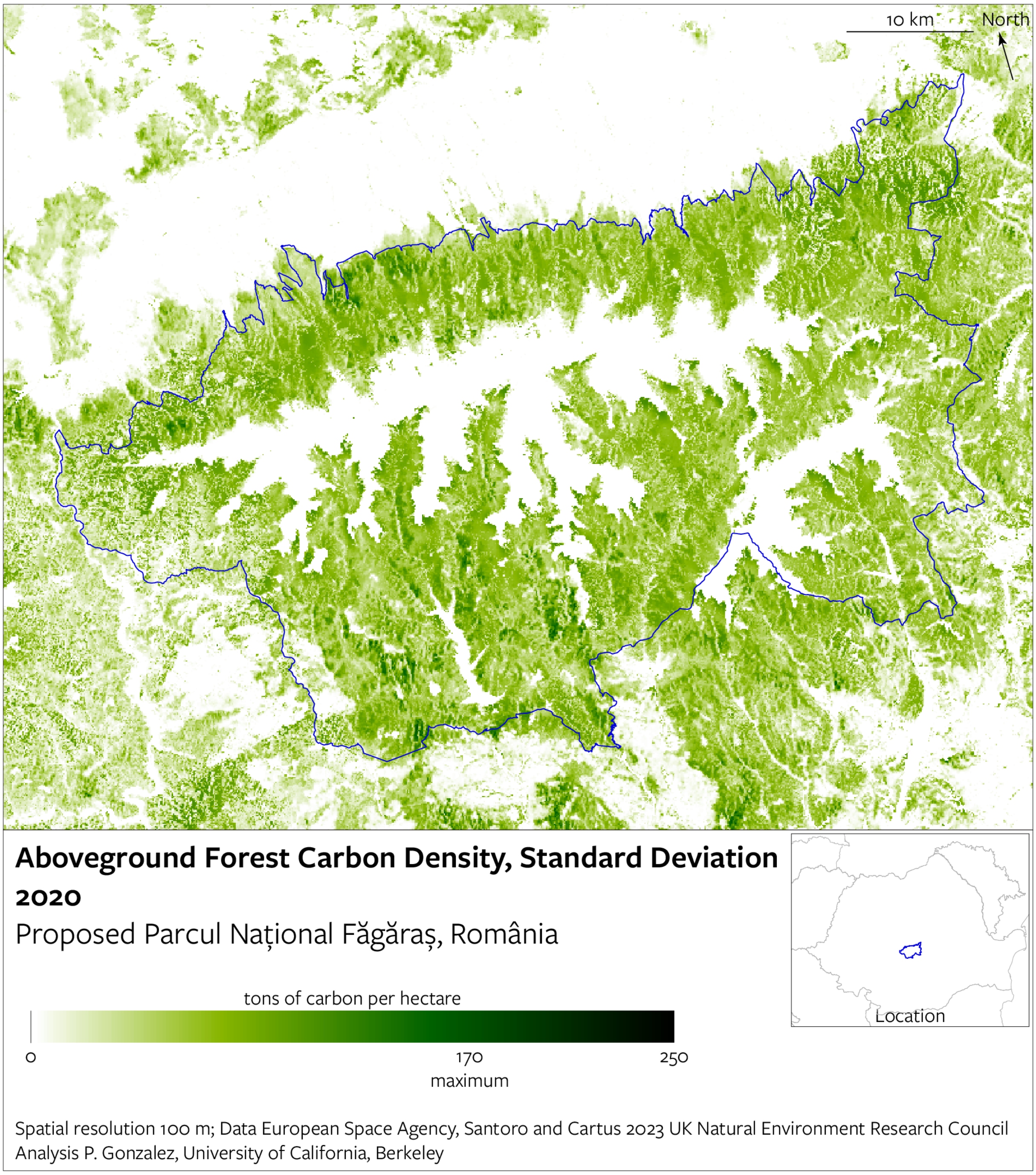

Figure 13. **Forest carbon standard deviation, 2020**, proposed Parcul Național Făgăraș, România. Standard deviation (variation around the average) of estimates of carbon density in aboveground forest vegetation, from spatial analyses (Gonzalez, this report) of European Space Agency (ESA) biomass data at 100 m spatial resolution (Santoro et al. 2021, Santoro and Cartus 2023). Vegetation outside of forests contains carbon, at lower densities, but was not analyzed by ESA.

These forest carbon densities are consistent with published estimates from field measurements in the Făgăraș Mountains and across Romania. One plot of 120-year old natural European beech at Mușetești in the proposed national park contained carbon at 190 tons per hectare while two plots of thinned or cut European beech south of the proposed national park contained carbon at 130 to 140 tons per hectare (Dobre et al. 2021). A plot of 150-year old natural Norway spruce at Mușetești in the proposed national park contained carbon at 120 tons per hectare (Dobre et al. 2021).

Analysis of Romania National Forest Inventory plots across the country found that European beech in protected areas contained carbon at a density of 200 ± 80 tons per hectare for trees greater than 100 years old and 110 ± 50 tons per hectare for trees less than 100 years old (Bouriaud et al. 2019). In the Romania National Forest Inventory, one European beech tree with a diameter of 60 cm at a height of 1.3 m contains 1.5 tons of carbon while one Norway spruce tree of that diameter contains 0.9 tons (Neumann et al. 2016). Plots in old-growth primary Norway spruce-silver fir forest in the eastern Carpathian mountains in Gorgany Nature Protection and Scientific Reserve, Ukraine, contained carbon at a density of 155 to 165 tons per hectare (Keeton et al. 2010).

Because aboveground biomass includes only the live parts of trees, dead matter is generally reported separately. At plots in primary European beech-silver fir forest at Sinca in the proposed national park, measurements found a dead wood carbon density of 16 ± 2 tons per hectare (Petritan et al. 2023).

To place Făgăraș forest carbon densities into a global context, they are in the range of Amazon forest carbon densities, which average 90 to 230 tons per hectare (Baker et al. 2004, Gonzalez et al. 2014, Mitchard et al. 2014), but are lower than montane conifer forest densities in California, USA, of 260 ± 14 tons per hectare (Gonzalez et al. 2010). Făgăraș forest carbon densities are much lower than the highest ecosystem carbon density in the world, in coast redwood forest (*Sequoia sempervirens*), which attains a maximum of 2600 tons per hectare, in California, USA (Busing and Fujimori 2005, Van Pelt et al. 2016).

The forest carbon results in this report derive from spatial analysis of European Space Agency forest biomass data, which combines synthetic aperture radar remote sensing, results from field plots, and statistical models of biomass (Santoro et al. 2021, Santoro and Cartus

2023). Because the Făgăraș area does not yet have a comprehensive local analysis of forest carbon, I analyzed the three principal published global spatial data sets of vegetation carbon or biomass to examine the range of estimates (Table 5). These data sets differed in fundamental aspects, including quantification of biomass or the carbon part of biomass, type of vegetation included, spatial resolution, year, and the statistical measure of uncertainty used to quantify the range of estimates. I analyzed each data set for the same area and found wide differences in carbon stock estimates. The results counter-intuitively indicated that the data set that covered all vegetation (University of Wisconsin, USA) yielded a carbon stock that was half the amount of the data set that only covered forests (European Space Agency). The third data set (World Resources Institute) yielded an intermediate amount.

To conduct an independent evaluation of the accuracy of the three global data sets, I analyzed and compared their results for Yosemite National Park, California, USA, for which I have published an ecosystem carbon analysis based on Landsat remote sensing and field measurements of trees (Gonzalez et al. 2015). For Yosemite, the estimate from European Space Agency data was closest to the published estimate, with the University of Wisconsin estimate lower and the World Resources Institute estimate double the published estimate (Table 5). The low estimates from the University of Wisconsin data for Făgăraș and Yosemite suggested a systematic underestimation while the doubled estimate from the World Resources Institute data for Yosemite suggested a lack of accuracy. Therefore, I assessed that the European Space Agency data were the most robust for Făgăraș forests.

National parks and other protected areas conserve ecosystem carbon, preventing emissions to the atmosphere that cause climate change. Protected areas, currently covering 17% of global land area (UNEP and IUCN 2024), contain ~20% of global ecosystem carbon and account for ~16% of annual ecosystem carbon removal from the atmosphere (Melillo et al. 2016).

High biodiversity and high ecosystem carbon generally occur together, with the tropical rainforests of the Amazon, the Congo, and Indonesia containing the largest aboveground ecosystem carbon stocks and highest plant species richness in the world (Soto-Navarro et al. 2020, Santoro et al. 2021, Sabatini et al. 2022). Aboveground carbon is correlated to genus richness globally (Cavanaugh et al. 2014) and to species richness locally (Poorter et al. 2015, Sullivan et al. 2017). So, conserving ecosystem carbon conserves biodiversity.

Published research and field experience show that protection of forests in a national park or other protected area offers one of the most effective ways to halt deforestation (Ernst et al. 2013, Gonzalez et al. 2014, Goncalves-Souza et al. 2021, Shah et al. 2021). Halting deforestation also helps to safeguard biodiversity. National parks and other protected areas also conserve higher biodiversity, with an average 10% more plant and animal species than non-protected areas (Gray et al. 2016, Cazalis et al. 2020, Brodie et al. 2023).

Therefore, national protection of a Parcul Național Făgăraș could end deforestation in the area, protect forest carbon, and help to halt climate change, benefitting nature and people.

Methods

Analysis Area The analyses covered the area of the Munții Făgăraș Natura 2000 site <https://natura2000.eea.europa.eu/?sitecode=ROSCI0122>, Romania, as given by an ArcGIS shapefile provided by the Foundation Conservation Carpathia. Analyses at 1 km and 50 km spatial resolutions included all pixels entirely enclosing the site. Analyses at 30 m, 100 m, and 300 m spatial resolutions included pixels approximating the edge of the site and pixels within that edge. The Natura 2000 standard data form (EU EEA 2021) lists the surface area of the site as 1986 km^2. For this report, spatial analyses at 30 m, 100 m, 300 m, and 1 km spatial resolutions found a surface area of 2120 km^2.

Equal Area Projection of Spatial Data Original data files on climate, biomass, and carbon were unprojected rasters in the geographic reference system, where the surface area of pixels varied with latitude. I projected all files to the Lambert Azimuthal Equal Area projection, European Terrestrial Reference System 1989 geodetic datum – the European Environment Agency standard coordinate reference system. This produced pixels of the same surface area for accurate calculation of spatial statistics. The equal area projection converted the original spatial resolutions of 0.00025, 0.00088888, 0.002777778, 0.008333, and 0.5 geographic degrees to 30, 100, 300, 1000, and 50 000 meters, respectively.

Observed climate Spatial analyses of observed climate trends used the University of East Anglia Climate Research Unit global data set of temperature and precipitation, CRU TS v. 4.07, 1901-2022, 0.5° spatial resolution (Harris et al. 2020) <https://doi.org/10.1038/s41597-020-0453-3>. These data derive from observations from weather stations, including stations of the

Administrației Naționale de Meteorologie România, interpolated to a grid. Linear least squares regression, following the method of Gonzalez et al. (2010), of 1901-2022 average annual temperature and total annual precipitation calculated rates of change over the time period. Restricted maximum likelihood analysis (Patterson and Thompson 1971, Cooper and Thompson 1977) calculated statistical significance of the trend over the time period, corrected for temporal autocorrelation. Temporal variation for the period 1901-2022 was calculated as standard error (SE) or standard deviation (SD). The results on observed climate trends (Table 1) were calculated as the average of all pixels that entirely enclose the proposed national park.

Calculation of average climate for the period 1981-2010 used the observed temperature and precipitation part of the "Climatologies at high resolution for the Earth's land surface areas" (Chelsa) data set, version 2.1, 0.008333° spatial resolution, (Karger et al. 2017) <http://www.chelsa-climate.org>. These data derive from a combination of satellite and weather station measurements and modeling. Chelsa does not include a measure of temporal variation for the period 1981-2010.

Projected climate Spatial analyses of future projections used the projected temperature and precipitation part of the Chelsa data set, version 2.1, 0.008333° spatial resolution, (Karger et al. 2020) <http://www.chelsa-climate.org>. Chelsa uses general circulation model (GCM) output of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al. 2016) data set developed for the most recent IPCC assessment report (IPCC 2021). Chelsa downscales the coarse-scale GCM output, from spatial resolutions of up to 200 km, using bias correction and adjustments for topography. Each GCM uses different methods to represent atmospheric processes. Among the 33 GCMs in CMIP6, Chelsa selected five GCMs that show a low level of interdependence and represent the range of variation of the GCMs (Sanderson et al. 2015).

IPCC has coordinated research groups to project possible future climate under five defined greenhouse gas emissions scenarios, each called a shared socio-economic pathway (SSP; O'Neill et al. 2016). These are storylines of the future (O'Neill et al. 2017) in which population, energy use, economic activity, and policies – all controlled by human behavior – determine greenhouse gas emissions. The five emissions scenarios are: SSP1-1.9 (reduced emissions from energy efficiency and renewable energy, achieving 1.5°C Paris Agreement goal), SSP1- 2.6 (very low emissions, achieving 2°C Paris Agreement goal), SSP2-4.5 (low emissions, 3°C temperature increase), SSP3-7.0 (high emissions), and SSP5-8.5 (very high emissions, high burning of fossil fuels). Note that SSP4 is intentionally omitted from the number sequence. Climate under each of the scenarios was projected by up to 33 GCMs. Chelsa includes data for three scenarios: SSP1-2.6, SSP3-7.0, and SSP5-8.5.

Uncertainties of future climate vary in two dimensions: (1) Human behavior as manifested across the emissions scenarios, (2) Computer modeling skill among the GCMs, quantified here as the standard deviation of the GCM ensemble for each scenario (Figure 7).

Results of the Chelsa projections (Table 2) are spatial averages of the area of the proposed national park. Results are annual averages and standard deviations of the GCM ensemble.

Projections of four temperature and precipitation extremes – days each year with maximum temperature >35°C, total annual snowfall, consecutive days each year with no precipitation, and maximum precipitation in a 5-day period in a year – derive from IPCC (2021) GCM output at 50 km spatial resolution. These are point estimates at approximately the center of the park, ~46° North latitude, ~24.5° East longitude, from the IPCC Atlas <https://interactive-atlas.ipcc.ch>, for the three main emissions scenarios. Results are averages of projections from all available models, up to 33 GCMs.

Observed impacts and future risks Information on observed ecological impacts and future ecological risks of climate change derive from a systematic search and synthesis of published scientific research that used field data from the Făgăraș area or surrounding regions or that examined the climate sensitivity of species or ecosystems found in the proposed national park. I conducted a systematic search on the Clarivate Analytics Web of Science <http://webofscience.com>, the authoritative database of scientific literature, and examined the latest IPCC assessment report (IPCC 2022), especially the chapter on ecosystems (Parmesan et al. 2022). To determine observed impacts, I assessed if research detected an ecological change and examined potential causal factors to attribute the change to anthropogenic climate change more than other factors.

Carbon The spatial analyses used three global data sets on biomass or vegetation carbon: (1) European Space Agency, Biomass Climate Change Initiative, above-ground forest biomass, version 4, 2020, 0.00088888° spatial resolution (Santoro et al. 2021, Santoro and Cartus 2023) <http://data.ceda.ac.uk/neodc/esacci/biomass/data/agb/maps/v4.0>,

(2) University of Wisconsin, USA, aboveground vegetation carbon, 2010, 0.002777778° spatial resolution (Spawn et al. 2020) <https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763>, (3) World Resources Institute, aboveground woody biomass, 2000, 0.00025° spatial resolution (Harris et al. 2021) <https://data.globalforestwatch.org/datasets/aboveground-live-woody-biomass-density>. Each of these data sets combine remote sensing, field measurements, and modeling of biomass. I projected all data to Lambert Azimuthal Equal Area projection and subset each data set to the rectangular extent shown in the maps.

For biomass data, I calculated carbon using the carbon fraction of biomass: conifer 0.501 ± 0.004 grams carbon per gram biomass, broadleaf 0.465 ± 0.003 grams carbon per gram biomass (Martin et al. 2018). For mixed forests, I used an estimate of half conifer, half broadleaf: 0.483 ± 0.0035 grams carbon per gram biomass.

To select the forest type-specific carbon fraction value for each pixel, I analyzed land cover, using the European Union Copernicus Land Monitoring Service Corine land cover, version V2020_20u1, 2018, 100 m spatial resolution (EU Copernicus 2020) <https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac>.

The forest carbon analyses quantified uncertainty as standard deviation (SD) to account for variation and errors in remote sensing, field measurements, modeling of biomass, and estimates of the carbon fraction of biomass. The University of Wisconsin data quantified uncertainty as the standard error (SE). The World Resources Institute data did not quantify uncertainty, so I used the author calculation of temperate zone ecosystem carbon emissions uncertainty, 69% (Harris et al. 2021).

The comparison for Yosemite National Park, California, USA used results from Gonzalez et al. (2015), aboveground vegetation carbon, 30 m spatial resolution. This used a carbon fraction of 0.47 ± 0.0235 grams carbon per gram biomass (McGroddy et al. 2004, Gonzalez et al. 2015).

Făgăraș carbon stock (Tables 4, 5) is calculated as the sum, for all pixels within the proposed national park, of the product of the carbon density and area of each pixel.

Ecosystem Service

The ecosystem service calculation sought to use an easily understood indicator, the number of people in Romania whose annual greenhouse gas emissions is equivalent to the forest carbon stock of the proposed national park. This uses total greenhouse gas emissions per person from all sectors for the most recent year available, 2020, from the World Resources Institute Climate Watch (WRI 2024). The average greenhouse gas emissions of Romania in 2020 was 3.78 t CO_2 equivalent per person, equal to 1.03 t carbon per person. The United Nations (UN 2024) lists the population of Romania for the most recent year available, 2022, as 19.2 million people.

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