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Large Reductions in Temperate Rainforest Biome Due to Unmitigated Climate Change

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Key Points:

- Temperate rainforests rely on a cool and moist climate biome that globally rare and vulnerable to climate change
- Unmitigated climate change would lead to a loss of 68% of the temperate rainforest biome, but climate mitigation limits loss to 9%
- We identify historical, intact and potential temperate rainforest extent and climate change vulnerability to inform conservation efforts

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Temperate rainforests are rare ecosystems globally; restricted to cool, moist conditions that are sensitive to a changing climate. Despite their crucial conservation importance, a global assessment of how temperate rainforests will be impacted by climate change is lacking. We calculated historical (1970–2000) climate conditions for the temperate rainforest biome using ERA5 reanalysis data for three key bioclimatic variables: warmest quarter temperature, annual precipitation and proportion of rainfall during warmest quarter. We used high-spatial resolution climate projections for these variables to identify regions likely to become unsuitable for temperate rainforests under four future shared socioeconomic pathway (SSP) scenarios. We predict unmitigated climate change (SSP 5–8.5) would lead to a 68.3 (95% confidence interval (95 CI): 53.4–81.3)% loss in the existing temperate rainforest biome by 2100 at a global scale with some national-level reductions exceeding 90%. Restricting global warming to <2°C (consistent with SSP 1–2.6), limits loss of global temperate rainforest biome to 9.7 (95 CI: 7.8–13.3)% by 2100 and is crucial to ensuring temperate rainforest persistence. Deforestation has resulted in loss of up to 43% of the current temperate rainforest biome with only 37% of primary forest remaining, and some regions like Europe with virtually none. Protection and restoration of the temperate rainforest biome, along with emissions reductions, are vital to its climate future.

Plain Language Summary

Temperate rainforests are rare ecosystems found only in wet and cool regions, making them vulnerable to a warming climate. They are important to conserve because they host unique species and can store high amounts of carbon. We use global maps of forest cover and condition to assess how much temperate rainforest remains, and how much it has been impacted by human activity. We find that only 37% of the temperate rainforest area is still covered by primary forest. We use a map of existing temperate rainforests along with records of past weather conditions to estimate what climate conditions are needed for its survival. We then use estimates of future climate under four different scenarios of greenhouse gas emissions to see which areas of temperate rainforest will maintain these conditions up to 2100. We find that under the most pessimistic scenario, 68% of temperate rainforest will be lost, while under the most optimistic scenario, only 9% will be lost. Our study can aid temperate rainforest conservation by identifying the areas of temperate rainforest that are least/most vulnerable to climate change, and where there is potential to restore forest.

1. Introduction

Temperate rainforests are a rare forest ecosystem globally, restricted to cool, moist climates biomes that cover less than 1% of the Earth's land surface and account for 2.5% of total forest cover (Alaback, 1991; DellaSala, 2011). They are recognized for their global ecological importance, high ecosystem productivity and carbon storage, with intact temperate rainforest having higher carbon density than intact forests in other latitudes, and regions of temperate rainforest in Australia having the highest known carbon density in the world (>1,000 tonnes of carbon ha^{-1}) (Brandt et al., 2014; Buma et al., 2019; Carpenter et al., 2014; Keith et al., 2009; Kranabetter et al., 2021; Smith-Ramírez, 2004). However, they have lower average gross ecosystem productivity rates compared with tropical rainforest (1318 vs. 1961 g CO_2 m^{-2} $year^{-1}$), demonstrating that their carbon storage is slower to accumulate (Keith et al., 2009). The moist climate within temperate rainforests supports a high diversity of bryophyte and lichen epiphytes (Ellis & Eaton, 2021; Galloway, 1992) including many endemic species. A large fraction of temperate rainforests have already been lost to deforestation and conversion to plantation forests; protection and restoration of temperate rainforests is therefore a global conservation priority (DellaSala, 2011).

Climate change is causing global shifts in species and ecosystem distribution, including poleward and upslope shifts of forest ecosystems (Parmesan et al., 2022). However, climate change assessments of potential future

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temperate rainforest distributions are mostly restricted to the Americas (e.g., Shanley et al. (2015); Buma et al. (2019)) and do not use the full suite of future climate model projections. Warmer temperatures and increased precipitation have been predicted for temperate rainforests of the North Pacific coast (Shanley et al., 2015), and in the coastal temperate rainforests of the Americas, a shift in precipitation from snow to rain and a projected increase in fire occurrence is likely to increase tree mortality rates (Buma et al., 2019) and contraction of temperate rainforests in their trailing edge (DellaSala et al., 2018). In Tasmania, climate change is projected to cause shifts in the distribution of key temperate rainforest species (Mackey et al., 2017). Whilst these studies hint at future impacts, a global analysis of how climate change will affect temperate rainforests is currently lacking.

We combined a map of the temperate rainforest biome from DellaSala (2011) with climate data from the late twentieth century to establish the historical climate biome for temperate rainforest regions using three bioclimatic variables that represent the unique cool and moist climate of temperate rainforests. These bioclimatic variables, originally identified in Alaback (1991) are the warmest quarter temperature (relatively low), annual precipitation (relatively high) and proportion of annual precipitation that occurs during the warmest quarter (relatively high), which are typical features of an oceanic climate. Together these variables serve to delineate areas which remain cool and wet throughout the summer, which creates the conditions to maintain their unique characteristics, including epiphytic growth of lichens and moss, giant trees and low fire disturbance (DellaSala, 2011).

We analyzed climate reanalysis data to explore the current distribution of these climate variables across the temperate rainforest biome. We then used future predictions of climate from the CMIP6 models downscaled to high spatial resolution to quantify the degree to which these climate variables may change under future scenarios. Where one or more of the bioclimatic variables shifts by >3 standard deviations from its historical distribution, we consider that the climate biome has shifted and that location is no longer be suitable for temperate rainforest. We explored the sensitivity of our results to this assumption (see Methods) and find consistent trends for a range of thresholds. We calculated the change in the existing temperate rainforest biome from 1965 to 2100 through combining reanalysis (ERA5; 1965–2022) and climate model (WorldClim; 1970–2100) data under different scenarios. Finally, to assess the potential for forest protection and restoration to mitigate some of these impacts, we analyzed contemporary forest cover data to assess the extent, condition and current threats to temperate rainforests at the global scale. Our analysis provides new evidence on the threats posed by climate change to temperate rainforests, the urgent need for stringent efforts to reduce climate change and increasing protection and restoration of this rare ecosystem.

2. Materials and Methods

2.1. Forest Coverage Data

To calculate the area of forest within the temperate rainforest climate biome, we used the Global Forest Coverage (GFC, version 1.9) data set (Hansen et al., 2013), which estimates forest coverage during 2000–2020, and used this to estimate annual forest loss within those regions. The GFC data estimates the percentage of canopy cover at a resolution of 30 m. We use a canopy cover threshold of 50% tree cover to represent forest (Tang et al., 2019), and then regrid the 30 m resolution data to the Worldclim data resolution.

We used multiple data sets for global estimates of forest coverage, management and loss. We used the Intact Forest Landscapes (IFLs) (Potapov et al., 2017) data set to estimate the distribution of extant primary or unmanaged temperate rainforest. IFLs are defined as "an unbroken expanse of natural ecosystems within the zone of current forest extent, showing no signs of significant human activity and large enough that all native biodiversity, including viable populations of wide-ranging species, could be maintained." IFL have a minimum size of 500 km^2 so exclude smaller patches of primary forest. For this reason we also used a data set of forest management levels (FML) at 100 × 100 m resolution (Lesiv et al., 2022), that classified whether forests are "naturally regenerating forest without any signs of management" which we refer to as primary, "Naturally regenerating forest with signs of management" which we refer to as regenerating, or managed as forestry, a plantation, oil palm or agroforestry.

2.2. Climate Data

To map the spatial extent of the temperate rainforest climate biome under historical and future climates, we used gridded data sets of downscaled 2.5 degree-minute (∼0.0416°) resolution climate data from worldclim.org (Fick & Hijmans, 2017). The "historical" Worldclim data refers to a high-resolution climate average for the 1970–2000 period created by an interpolated fusion of weather station and satellite data sets. We created Worldclim future climate scenarios by scaling the 1970–2000 historical scenario by simulations from the Coupled Model Intercomparison Project-6 (CMIP6) (Eyring et al., 2016). Additionally, we created future scenarios for four 20-year time periods (2021–2040, 2041–2060, 2061–2080, 2081–2100). Projections are available for four future shared socioeconomic pathway (SSP) climate scenarios. At the time of downloading, 25 different models were available, but three had missing data in one or more time periods, and one was found to have anomalously high temperature and precipitation. We use data from the remaining 21 CMIP6 models.

We use $0.1° \times 0.1°$ ERA5 monthly averaged reanalysis data (Hersbach et al., 2020) for the period 1965–2022. ERA5 data is available from 1950, however the lack of satellite data before around 1965 results in larger errors in temperature and precipitation prior to this date (Bell et al., 2021). Our historical climate period is relatively short, but long enough to capture interannual climate variability (Holmgren et al., 2013). We calculated a 20-year rolling mean climatology to match the averaging period of future climate data from Worldclim.

2.3. Comparison With Baseline Climate Windows

To establish baseline climates for each of the regions, we first obtained a map of the temperate rainforest biome that was estimated in DellaSala (2011; available at https://databasin.org/datasets/e60e7ca203b74f06b1-ba027a4a326406/). For simplicity, we combine geographically and climatologically similar regions to create six temperate rainforest regions: (a) North Pacific Coast in North America, (b) Northwest Atlantic in North America, (c) Chile and Argentina in South America, (d) Europe, (e) Japan and Korea and (f) Australasia. We calculate baseline climate windows for the three key bioclimatic variables (warmest quarter temperature, annual precipitation and the proportion of annual precipitation that occurs during the warmest quarter) that are known to be key delimiters of global temperate rainforest extent (Alaback, 1991; DellaSala, 2011). For each year, at each temperate rainforest gridcell, we calculate the value for these three bioclimatic variables using the equations from Xu and Hutchinson (2011).

We generated the historical climate variability for each of the six key regions using both the ERA-5 and Worldclim historical scenario, by calculating the mean and standard deviation of the distribution of 30-year means within the temperate rainforest biome climate zone for each variable. We calculate a separate historical climate window for each of the regions, so we can reflect the diversity of climate occupied by biota recognized as "temperate rainforest" throughout the world, and including regions that do not meet the rigid climate envelope defined in Alaback (1991), and reflecting the variability that was recognized in DellaSala (2011). We calculated the historical baseline separately for ERA5 and Worldclim because they each use different methodologies and data sources, and are at a different resolution, so their values are not an exact match for the overlapping 1970–2000 period.

In order to estimate the impact of future climate shifts, we then compared the 20-year ERA-5 and Worldclim means with the regional historical baselines, and calculate the z-score (i.e., the number of standard deviations from the mean), to quantify the shift in climate. For ERA-5, we use a rolling 20-year mean across the 1965 to 2022 period. For Worldclim, we calculate separately for each SSP and time period. We averaged across the 21 models to obtain the most robust future climate prediction, and report the lower and upper 95% confidence limits of the multi-model mean.

To estimate future change in temperate rainforest extend, we calculated the suitability of each pixel as temperate rainforest based on whether any of the three bioclimatic variables transitioned substantially outside their historical climate variability. We classified a pixel of the historical temperate rainforest biome as "lost" when the z-score for one or more climate variables exceeds ± 3, meaning that over a 20-year period the majority of individual years will not lie within the historical range of the variable. We tested the sensitivity to this assumption through also testing thresholds of ± 2 and $\pm$ 4. Under a threshold of ± 2 assumption loss of temperate rainforest is even more severe (Figure S1 in Supporting Information S1) with a global loss of 90.3 (95 CI: 83.3–94.1)% under SSP 5–8.5 and 35.6 (95 CI: 27.8–45.1)% under SSP 1–2.6 by 2081–2100. Under a threshold of ± 4, much less loss of temperate rainforest biome is estimated, with a global loss of 37.0 (95 CI: 24.6–53.3)% under SSP 5–8.5 and 2.9 (95 CI: 2.7–4.6)% under SSP 1–2.6 (Figure S2 in Supporting Information S1). When the change in the mean exceeds a z-score of ± 3, there is little overlap of past and future distributions, suggesting this is the most appropriate threshold.

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3. Results

3.1. Temperate Rainforest Global Extent

The global temperate rainforest biome totals 792,000 km^2, equivalent to about 2% of global forest area (Figure 1a) (as in DellaSala (2011)). The countries with the largest temperate rainforest climate biome are Canada (27.0% of the global potential area), United States (18.7%), Chile (13.8%), Japan (11.0%), United Kingdom (7.5%), New Zealand (7.4%), Norway (6.1%), Australia (4.6%), Ireland (1.8%), Austria (1.2%) and South Korea (0.9%).

Globally 56.8% of the potential temperate rainforest climate zone is forested with Japan having the highest forest coverage of 80.6%, followed by Australia (77.0%), South Korea (62.4%), Canada (61.5%), United States (61.2%), New Zealand (59.2%), Chile (53.1%) and Austria (52.7%) (Figure 1b), with the remaining countries having <50% forest cover. The UK and Ireland have notably low forest coverage, with 13.9% and 12.1% of the temperate rainforest biome covered by forest respectively, due to the extensive deforestation.

3.1.1. Forest Management Within the Temperate Rainforest Biome

We used a new data set of forest management (Lesiv et al., 2022) to explore the different types of forest management within the temperate rainforest biome. Globally, 36.8% of the world's temperate rainforest climate biome is classified as primary rainforest (with no signs of management such as logging) with 25.7% classified as regenerating forest with signs of management, 8.7% planted forest, 2.6% plantation forest and 25.7% unforested. In most countries more than half of the temperate rainforest climate biome is classified as primary or naturally regenerating forest (Figure 1b, Figure S3 in Supporting Information S1). In contrast, the European countries (United Kingdom, Ireland and Norway), most of the forest within the temperate rainforest biome is planted forest. In the United Kingdom and Ireland <1% of the temperate rainforest biome is covered by primary or naturally regenerated forests, highlighting a heavily degraded ecosystem with high potential for restoration. Regional studies using national data sets are needed to confirm these numbers. These three European countries (United Kingdom, Ireland and Norway) together account for 40.1% of the unforested land within the temperate rainforest climate biome globally.

We used a map of “Intact Forest Landscapes (IFL)” (Potapov et al., 2017) to estimate how much of the temperate rainforest climate biome is occupied by “old growth” or primary forest based on the IFL definition. We found 31.6% of the temperate rainforest biome is currently (2020) covered by IFL. The IFL coverage is around 5.2% less than the primary forest coverage estimated using the FML data, likely because IFLs are defined as areas with an area >500 km^2, which excludes smaller fragments of surviving primary forest. Countries with the highest proportions of IFL temperate rainforest are Canada (48.9% of suitable climate is an IFL), Chile (41.3%), United States (33.8%), New Zealand (62.6%) and Australia (31.1%). Together, these five countries account for >99% of the world’s IFL in the temperate rainforest climate biome.

3.1.2. Rates of Temperate Rainforest Loss

Temperate rainforests have experienced high rates of forest loss over the last two decades (2000–2020; Figure S4 in Supporting Information S1). The relative rate of primary forest loss within temperate rainforest regions was greatest in the Northwest Atlantic region with over 4% of primary forest lost during the past 20 years. Primary forest is also being lost in Europe, North Pacific Coast and Australasia, with 2%–4% lost during 2000–2020. Less than 1% has been lost in Japan and Korea as well as Chile and Argentina. Secondary forests are being lost ~3 times faster than primary, with Australasia losing 15% during 2001–2020. The largest loss rates occurred in planted forest with >10% loss over 2000–2020 in all regions except Japan and Korea. The fast rate of loss in plantations is likely due to logging activities and short timber rotations associated with this forest management. It is not clear how much of the forest loss recorded in this data is from anthropogenic versus natural causes.

3.2. Temperate Rainforest in an Changing Climate

3.2.1. Observed Climate Shifts During 1965–2022

We used ERA5 data to explore the spatial variability of three bioclimatic variables within the temperate rainforest biome regions (Figures 2a–2c). The majority of temperate rainforest biome had a warmest quarter temperature

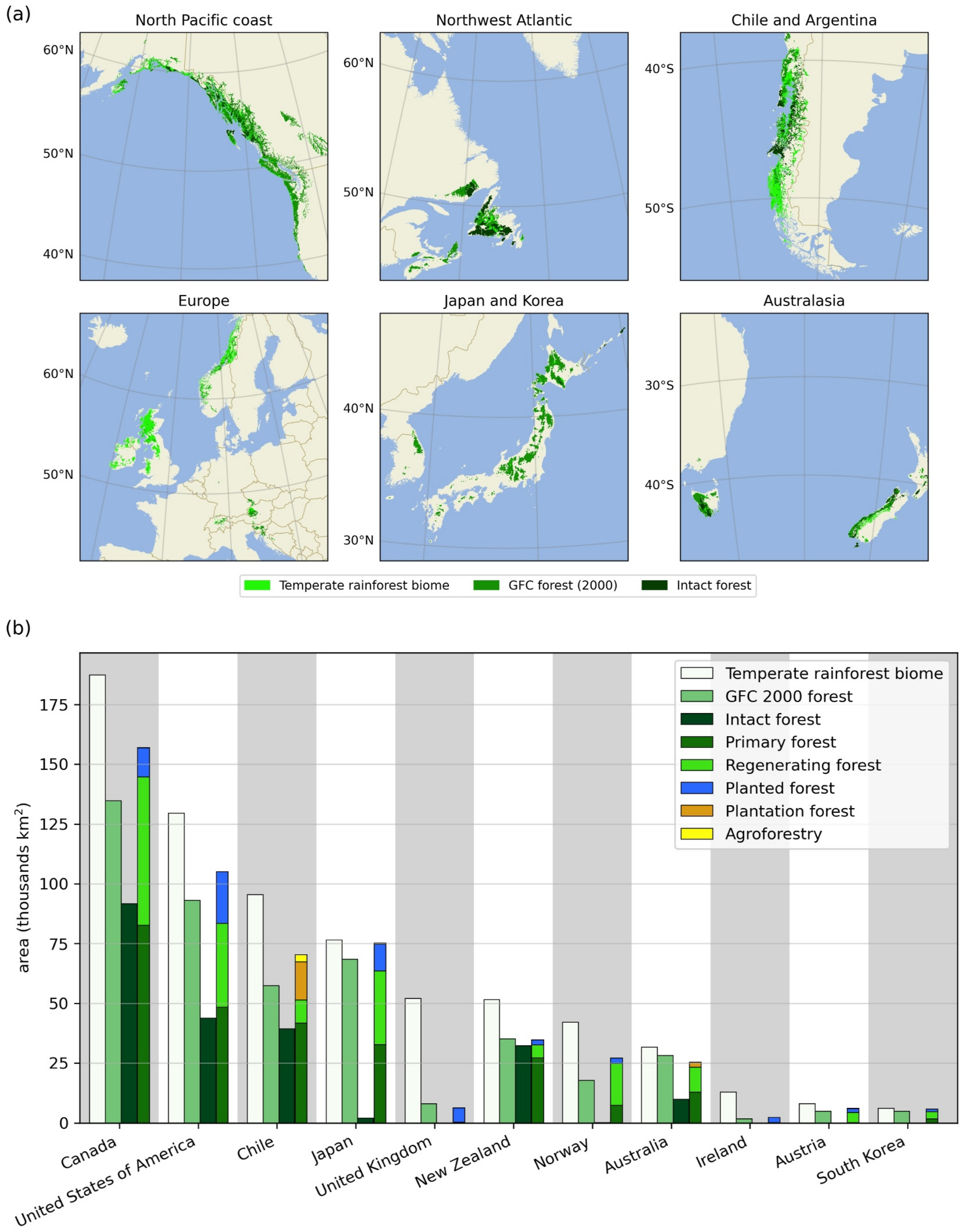

Figure 1. Historical (1970–2000) extent of the temperate rainforest biome based on DellaSala (2011) combined with data sets of forest coverage and type. (a) Distribution of temperate rainforest biome (bright green) across six key regions. Areas currently covered in forest in the year 2000 based on "Global Forest Change" data (Hansen et al., 2013) (middle green) and intact temperate rainforest using data from the "Intact Forest Landscapes" map (Potapov et al., 2017) (dark green) are shown. (b) Area of temperate rainforest biome for the countries with temperate rainforest biomes >5,000 km^2. Estimates of the suitable temperate rainforest climate biome that is occupied by forest are given using MODIS, GFC and Intact Forest Landscapes data. Additionally, the Forest Management Level data set, which includes a "primary forest" category, is shown as a stacked bar.

(WQT) of less than the 16°C threshold identified in Alaback (1991). The "Japan and Korea" region was a notable outlier, with higher WQTs, but also a higher proportion of rainfall during the summer, reflecting a monsoonal climate.

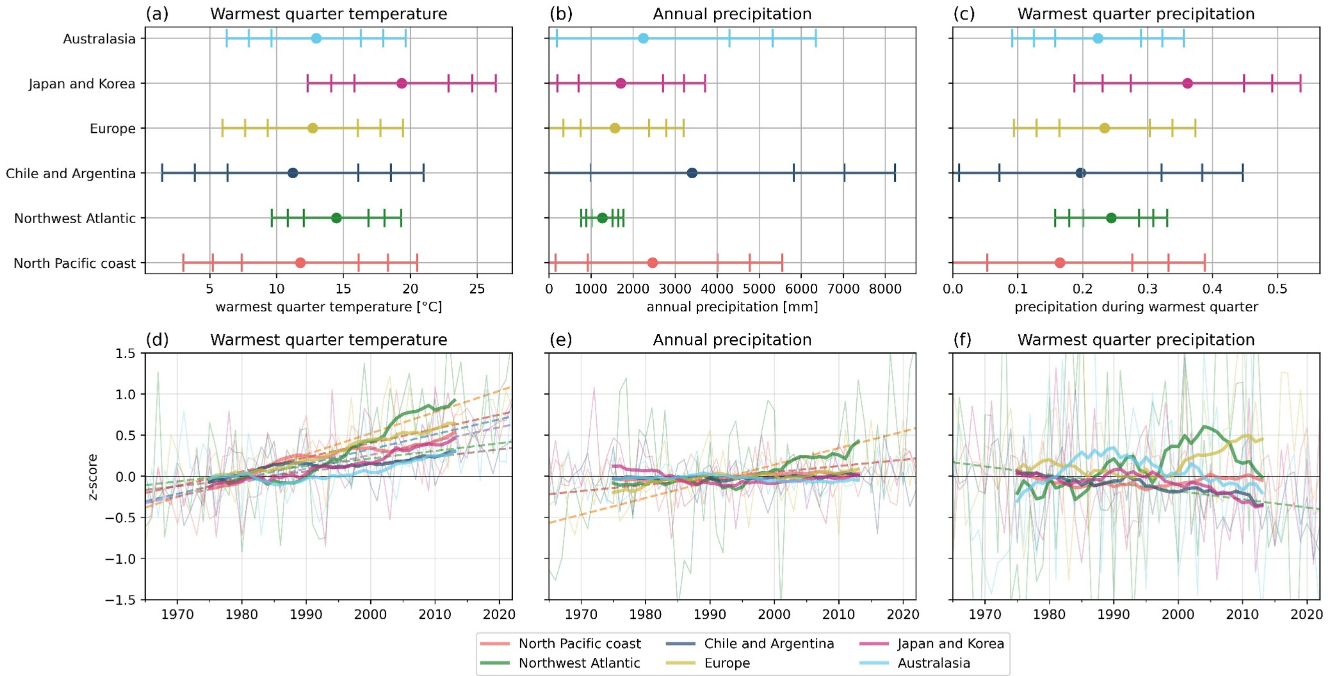

Figure 2. Upper panels (a–c): historical (1970–2020) climate variability across temperate rainforest biomes for the three bioclimatic variables (a) warmest quarter temperature, (b) annual precipitation and (c) precipitation during the warmest quarter. The circle shows the mean value in each region, with the outer lines showing ±2, ±3 and ± 4 standard deviations from the mean respectively. Lower panels (d–f): regional shifts in climate within the temperate rainforest biome with respect to 1970–1999 baseline period calculated from ERA5 data, during 1965–2022, averaged by 20-year rolling periods. The *z*-score refers to the number of standard deviations from the baseline climate mean. For regions with a significant trend (according to the Mann-Kendall test, $p < 0.05$), the linear trend (calculated using the TheilSen estimator) is shown as a dotted line.

First, we explored changes in climate in the temperate rainforest biome over the past 5 decades using the ERA5 reanalysis data. The 20-year mean WQT has already begun to increase to regional average levels that are 0.5–1 standard deviation (σ) higher than their historical mean (*z*-score), and all regions had a significant positive trend (Figure 2d), with absolute trends ranging from 0.15 (Australasia) to 0.40 (North Pacific coast) °C decade^{-1}. Annual precipitation and the proportion of rainfall occurring during the warmest quarter changed less in temperate rainforest regions (regional *z*-scores < ±0.5, Figure 2d). However, there are significant trends in some regions, with annual precipitation significantly increasing in the Northwest Atlantic (25 mm decade^{-1}) and Europe (31 mm decade^{-1}). Increases in annual precipitation are likely to have a positive impact on temperate rainforest climate, especially lichens and bryophytes that depend on high moisture levels. In Chile and Argentina, currently the wettest region of temperate rainforest in terms of annual mean precipitation (>3,000 mm year^{-1} on average, Figure 2b), warmest quarter precipitation proportion is significantly decreasing at rates of −0.6% decade^{-1} (Figure 2f).

The change in global area of the temperate rainforest biome from 1965 to 2100 is shown in Figure 3a (black line). During the 1965–2022 period covered by the ERA5 data, ∼1% of the temperate rainforest biome has shifted by a *z*-score of more than ±3σ, where we define climate conditions suitable for temperate rainforest to have been lost. This means that little of the climate has currently shifted to a completely unprecedented state where temperate rainforest is unlikely to persist. However, it is clear from the widespread positive trends of WQT in temperate rainforest regions, that temperate rainforest climate may be increasingly lost in the decades to come.

3.2.2. Projected Climate Shifts During the 21st Century

We then used high-spatial resolution data from WorldClim to estimate changes in climate during the 21st century, relative to historical climate variability, under the four SSP scenarios. Over the 21st century, we predict that the temperate rainforest biome will decline under all scenarios (Figure 3a). We estimate that over the period 1965–2100, the global temperate rainforest biome will be reduced by 68.3 (95 CI: 53.4–81.3)% under SSP 5–8.5 and by 48.1 (95 CI: 34.2–63.2)% under SSP 3–7.0. More moderate climate change scenarios, experience smaller loss

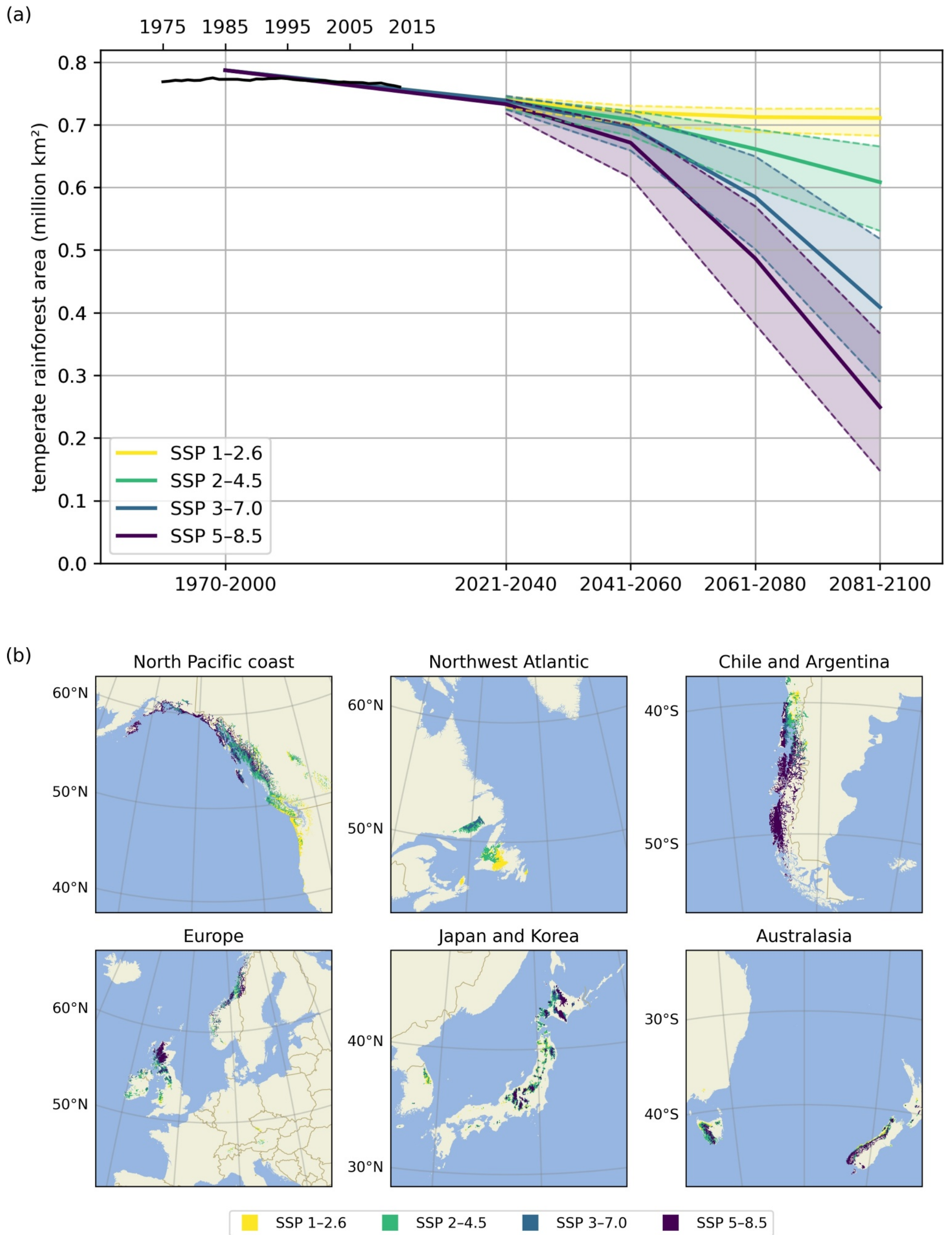

Figure 3. Impacts of climate change on the temperate rainforest biome. (a) Changes in the projected area of temperate rainforest biome from 1970 to 2100. The black line shows current conditions from ERA5 for 1965 to 2020. Future temperate rainforest biome extent is shown for four SSP scenarios (colored lines) with the shaded regions showing the spread amongst the central third of CMIP models. (b) Estimated distribution of extant temperate rainforest during 2081–2100 under the four SSP scenarios. The color shows the maximum (in terms of carbon emissions) SSP scenario in which the temperate rainforest biome survives.

with the extent of temperate rainforest reduced by 22.7 (95 CI: 15.5–32.6)% under SSP 2–4.5 and only 9.7 (95 CI: 7.8–13.3)% under SSP 1–2.6.

Figure 3b shows the distribution of the surviving temperate rainforest biome under the different SSP scenarios during the 2081–2100 period. Temperate rainforest biome is more likely to survive in cooler areas, either at high altitudes or poleward regions. With the exception of the "Northwest Atlantic" region all of the regions have large contiguous areas that are predicted to be maintained even under SSP5-8.5, with notable examples including

Patagonia, the Alaskan coastal temperate rainforests, the South Island of New Zealand, and the highlands of Scotland.

In all of the scenarios, the loss of temperate rainforest biome is driven by the warmest quarter temperature exceeding the +3σ threshold (Figure S5 and S6 in Supporting Information S1). A warmer summer temperature is likely to be damaging to many of temperature rainforest lichens (Mallen-Cooper et al., 2023). As for the other bioclimatic variables, in the majority of regions the annual precipitation is predicted to increase, while the proportion of the precipitation occurring during the summer decreases slightly, with the notable exception of Chile and Argentina that are predicted to experience drying, but by far less than 3σ on average. This result partially continues the observed trends from ERA5, with some increases in total precipitation but a significant decrease of ∼3% in summer precipitation proportion in Chile and Argentina (Figure S7 in Supporting Information S1).

Across the six key temperate rainforest regions, the Northwest Atlantic region experiences the most warming relative to its baseline climate under all SSP scenarios (Figure S6 in Supporting Information S1), with WQT increasing by on average >2σ under SSP 1–2.6 and almost 6σ under SSP 5–8.5. The regions with the least warming relative to their baseline climates are Chile and Argentina, and Australasia, which both warm by less than 1σ on average under the SSP 1–2.6 and around 3σ on average under the SSP 5–8.5 scenario.

Unmitigated climate change (SSP 5–8.5 or SSP 3–7.0) will cause a significant reduction in the temperate rainforest biome across all regions, with all countries losing at least 20% of their temperate rainforest extent by 2100 (Figure 4). However, under SSP 2–4.5, many countries including Chile, New Zealand and Australia, retain at least 90% of their temperate rainforest biome.

4. Discussion

Our analysis shows that unmitigated climate change (SSP 5–8.5) will lead to loss of 68% of the temperate rainforest biome's historical climate envelope over the next century. Rapid reduction in greenhouse gas emissions are needed to ensure widespread survival of temperate rainforests, with global-scale loss reduced to 9% under SSP 1–2.6. Strong action to mitigate climate change will lead to survival of the temperate rainforest biome in most countries (Figure 4). Communicating this positive environmental outcome for such an iconic forest ecosystem may help inspire conservation engagement and climate action (McAfee et al., 2019). However, our analysis may underestimate the impacts of climate change. Our climate scenarios cannot capture the effects of extreme events such as heatwaves (Hirsch et al., 2021), which may push endemic temperate rainforest species more quickly toward extinction (He et al., 2016). At a regional scale trends in the abundance of temperate rainforest indicator species such as lichens and bryophytes may be an alternative indicator of the impact of climate change (Ellis, 2016).

Our analysis was restricted to analyzing the loss of the existing temperate rainforest biome, which was delineated by historical climate conditions. We were not able to assess the potential for a warming climate to create new potential temperate rainforest biomes, as the full suite of climate variables required to delineate the temperate rainforest biome is not available in future projections. We acknowledge that there is the potential for climate change to lead to expansion of the biome to new areas. Future work is required to assess potential gains in biome and understand whether temperate rainforest species can keep up with the rate of change. We were also unable to assess how sensitive temperate rainforests are to the rate of climate change. For example, little is known about the tolerance of mature trees in temperate rainforests to rapidly changing climatic envelopes. It is possible that the climatic envelope that defines the temperate rainforest biome differs from the climate conditions that mature trees can tolerate. Future work is needed to further understand the sensitivity of temperate rainforest trees and associated biodiversity to the rate and extent of climate change.

4.1. A Global Call for Stepped-Up Temperate Rainforest Protection and Restoration

We provide evidence to support temperate rainforest protection and restoration as immediate climate adaptation options. Primary and old growth temperate rainforests are generally less fire prone and have global importance for climate and biodiversity as refugia (Kun et al., 2020; Luyssaert et al., 2008; Watson et al., 2018). Other natural disturbances, such as landslides and windstorms, may become more frequent under climate change (Shanley et al., 2015). Despite this importance, logging of primary temperate rainforests continues in the USA (Albert &

Figure 4. Extent of the temperate rainforest biome under future climate scenarios. Potential area shown as percentage of current extent for the countries with a current area of potential temperate rainforest of >5,000 km^2. The *y*-axis represents severity of climate change, while the *x*-axis represents time period. The percentages are an average of the predictions between the CMIP models. Numbers less than 100 represent loss (shaded red). The green bar represents the current extent of potential temperate rainforest in each country relative to the largest (Canada).

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Schoen, 2013) and Canada (DellaSala et al., 2021; DellaSala, Keith, et al., 2022). To prevent further loss of primary (old growth) temperate rainforests they require the strongest protection. This is particularly important where large extents of primary forest remain in regions with resilience to future climate change such as the Tongass National Forest in Alaska (DellaSala, Gorelik, et al., 2022). Where temperate rainforests have been degraded by logging there is substantial potential for restoration (DellaSala, 2011).

In countries with extensive historical deforestation, such as UK and Ireland, reforestation of native woodlands within the temperate rainforest biome is needed. For example, the UK hosts more than 7.5% of the global temperate rainforest biome but only 14% of this is forested, with large areas of non-native plantations. This highlights an opportunity for the UK and Ireland to become global leaders in restoration and reforestation of temperate rainforests.

We also provide an assessment of the impacts of future climate change and ongoing forest degradation of temperate rainforests globally. Little is known about how forest microclimate will respond to global climate warming (De Frenne et al., 2021), particularly in combination with accumulating land-use stressors. It is well known that the microclimate of intact forests is typically cooler than ambient temperatures and this buffering may reduce the severity of warming impacts on forest functioning and biodiversity (De Frenne et al., 2019; Frey et al., 2016). For example, increases in forest canopy density in recent decades has been shown to attenuate microclimate warming in some temperate forests (De Frenne et al., 2013; Frey et al., 2016). Our analysis of changes in macroclimate does not include this important role of microclimatic variability and buffering of temperate rainforest refugia under climate change.

Fragmented and isolated forests and forest edges are likely to experience greater climate warming compared to more intact forests (Zhu et al., 2023). Reforestation around existing areas of temperate rainforest may help reduce these impacts and increase climate resilience. Future work is needed to understand the potential of targeted reforestation to contribute to climate adaptation (Ellis & Eaton, 2021). In contrast, forest management with short rotation timber cycles often leads to even-aged forest stands with reduced structural complexity and few older trees (Esseen et al., 2022) that are likely to be less resilient to a changing climate (Forzieri et al., 2022). Restoration of logged and degraded forests may help reverse these negative impacts. Our work highlights the large-scale areas in which temperate rainforests are more likely to survive under different scenarios of climate change (see Figures 3b and 4). Local and regional-scale work is urgently needed to identify and prioritize conservation and restoration of temperate rainforest microclimate refugia that are more likely to survive under a warming climate.

Restoration of temperate rainforest faces a range of regionally specific opportunities and challenges. In England, the Government's plan to restore the nation's temperate rainforest identifies the need for stronger protection, to control invasive species (specifically Rhododendron ponticum) and manage herbivores (DEFRA, 2023). In Scotland, a voluntary partnership of more than 20 organizations, aims to restore all existing temperate rainforest and double the area of temperate rainforest in Scotland by 2045; key challenges include invasive species and overgrazing (Alliance for Scotland's Rainforest, 2024). In North and South America, large areas of temperate rainforest have been protected and restored through partnerships led by and closely involving First Nations and Native Americans. Where active restoration is proposed, for example, removal of non-native trees, new research is needed to refine restoration approaches to maximize positive impacts on rainforest diversity (Broome et al., 2021).

Our findings generally support the inclusion of the temperate rainforest biome in global efforts to protect at least 30% (Dinerstein et al., 2019) to 50% of nature (Dinerstein et al., 2017; Pimm et al., 2018). Protection of this biome needs to be adopted by nations seeking to comply with the United Nations Sustainable Development Goals (Mackey et al., 2015). Importantly, intact ecosystems (Martin & Watson, 2016; Watson et al., 2018) and primary forests (Mackey et al., 2015) provide the best defense against climate change and therefore should be prioritized for full protection at the regional scale. In countries with little remaining temperate rainforest (e.g., Europe), restoration and reforestation should be the primary objectives. Restoration of degraded forests and reforestation to create larger forest landscapes via re-wilding may enhance microclimate buffering, ecosystem integrity and make forests more resilient to a changing climate (Mackey et al., 2017).

Data Availability Statement

Code used to perform the analysis and visualize the results is available from figshare (Silver et al., 2024). Historical and future climate WorldClim is available in Fick and Hijmans (2017). The Intact Forest Landscapes shapefiles are available in Potapov et al. (2017). The FML data is available in Lesiv et al. (2022). GFC data set is available in Hansen et al. (2013). The ERA5 Land monthly averaged data can be downloaded from the Copernicus Climate Data Store (Muñoz, 2021). Natural Earth data is used for country borders, available from https://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-admin-0-details/.

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Erratum

The originally published version of this article contained a typographical error. In Figure 4, the orientation of the key in the bottom right-hand corner did not match the orientation of the data. The error has been corrected, and this may be considered the authoritative version of record.