Tracing climate and land-use instability reveals new insights into the future of Earth's remaining wilderness

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Abstract

Accelerated loss of Earth's wilderness over the last five decades underscores the urgency for efforts to retain the conservation value of these areas. Assessing how wilderness areas are likely to be impacted by the future environmental change is fundamental to achieving global biodiversity conservation goals. Using scenarios of climate and land-use change during baseline (1970–2005) and future (2015–2050) epochs, we found that climate change within wilderness areas is predicted to increase by ~ 47%, compared to a 19% increase in land-use change. Half (52%) of all wilderness areas may undergo climate change by 2050, limiting their capacity to shelter biodiversity. More significant changes are especially predicted to occur in the unprotected wilderness that supports unique assemblages of species and are therefore more important for biodiversity persistence. Countries with smaller and disconnected wilderness areas are disproportionately at risk from the combined impacts of climate and land-use change. Mitigating greenhouse gas emissions and preserving remaining intact natural ecosystems can help fortify these frontiers of biodiversity.

Introduction

Human activities are causing unprecedented modifications to natural systems. With at least 58% of terrestrial areas now considered moderately to highly modified¹, human activities have caused an average decline of over 68% among monitored mammal, bird, amphibian, reptile, and fish populations since the 1970s². Simultaneously, global warming amplifies pressures from human-induced landscape modifications and has already altered over 82% of 94 ecological processes within terrestrial, freshwater, and marine ecosystems³. These alterations have broadly manifested as fundamental changes in populations phenology and abundance, distributions of species, ecosystem productivity, and interspecific relationships³. Without improved climate action, such as limiting warming to 1.5 °C above preindustrial levels by 2100, ~66% of insect and 50% of plant and vertebrate species are projected to lose more than 50% of their current climatic ranges⁴. Future projections suggest that climate change and land-use change will interact synergistically, contributing to large-scale biodiversity losses^{4–9}.

Wilderness, which we define as contiguous areas of intact natural ecosystems free from industrial-scale activities¹⁰, are now the only remaining places that contain species at near-natural levels of abundance¹¹. Wilderness areas serve as reservoirs of genetic information, act as references for efforts to rewild degraded land and seascapes, contain over 40% of aboveground tropical forest carbon, and buffer species against extinction risk^{11–14}. However, landscape modifications through road and railway development, industrial logging, agricultural expansion, fire, and resource extraction have reduced the extent of wilderness, as mapped by the human footprint¹, by 10% (3.3 million km²) since the 1990s¹⁰. Wilderness conservation has been explicitly referenced for the first time in the Post-2020 Zero-draft of the Global Biodiversity Framework, which aims to retain “most of the existing intact and wilderness areas”

left on Earth¹⁵. This goal underscores the need to secure wilderness values to achieve CBD's global vision of regulating local climate regimes, help human populations adapt to climate change and provide connectivity to global biodiversity under prevailing and future environmental conditions^{3,16}. Successfully achieving this vision requires understanding how future climate and land-use change will affect the world's remaining wilderness, so nations can best plan for their successful long-term conservation. Yet, the nature and extent of these two interacting pressures remain largely unknown.

Here we examine the predicted velocity of climate and land-use change throughout Earth's remaining wilderness areas. We use moderate-resolution Coordinated Regional Climate Downscaling Experiment (CORDEX) climate and Harmonized Global Land Use [LUH2 v2f] layers¹⁷ to generate climate velocity and land-use instability metrics. The velocity of change estimates the quotient of temporal and spatial gradients, allowing a comparison of risk within and outside wilderness areas. We measured velocity of change from 1970 (hereafter "baseline" epoch) up to 2050 (hereafter "future" epoch) under two alternative Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios. We selected a scenario representing low emissions with limited land-use change under a sustainable development narrative (SSP1–RCP2.6) and one representing high emissions with more intense land-use change under a fossil-fueled development narrative (SSP5–RCP8.5). We refer to these as the "*global sustainability*" scenario and the "*fossil-fueled development*" scenario, respectively, hereafter. We then assessed risk to the protected vs unprotected wilderness areas by examining absolute velocities of change and projected probability of retaining baseline climate or land-use conditions. Finally, we evaluated the capacity for wilderness to effectively shelter species within the CBD's 2030 and 2050 policy timeframes by determining the climatic turnover for each area (hereafter "climate residence time (yr) + 2015").

Results

Past climate velocity and land-use instability within Earth's remaining wilderness areas. To examine how anthropogenic impacts on the environment shape the ecological structure of Earth's remaining wilderness, we first measured climate velocity between 1970–2005. Over this 35 yr period, climate velocity averaged 2.76 km/yr across wilderness areas (geometric mean, standard deviations [sd] = 4.15 km/yr; Fig. 1a, Extended Data Table 1), with more than 80% of these areas experiencing velocity of change of at least 1 km/yr since the 1970s. Climate velocity was slowest in high elevation areas of the Indomalayan wilderness (mean = 0.72 km/yr, sd = 1.25 km/yr), and highest in flat landscapes of Australasia (mean = 4.77 km/yr, sd = 6.22 km/yr).

To examine how land-use change impacts the velocity at which species may be required to track suitable climate within wilderness areas, we calculated land-use instability. Land-use instability, defined as

changes in land-use composition across a landscape, was estimated as the maximum of five univariate land-use velocities (Methods). Land-use instability across wilderness areas averaged 0.19 km/yr (sd = 1.61 km/yr) between 1970–2005, with over 26% of these areas (~6.2 million km²) modified above the average pace of forest regrowth. Unlike climate velocity, land-use instability was fastest in the Indomalay (mean = 0.91 km/yr, sd = 1.6 km/yr) and slowest in Australasia (mean = 0.12 km/yr, sd = 0.52 km/yr).

Climate and land-use velocity differ across protected and unprotected wilderness areas in the baseline period, with unprotected wilderness experiencing higher rates of both metrics especially land-use velocity (climate: mean = 2.83, sd = 4.04 km/yr; land use: mean = 0.2, sd = 1.69 km/yr) than protected wilderness (climate: mean = 2.36, sd = 4.75 km/yr; land-use: mean = 0.15, sd = 1.03 km/yr) (Fig. 1a, Extended Data Table 1). However, merely contrasting these metrics between protection statuses may be an inadequate counterfactual analysis due to the non-random distribution of PAs within wilderness areas. Therefore, we implemented a sample matching method to account for this non-random distribution and the consequent confounding effects (Supplementary Table S1). Post-matching results confirmed the findings and further highlighted that protected wilderness areas have experienced, on average, 13% lower climate velocity compared to unprotected wilderness (95% Confidence Interval [CI] = –16%, –10%, Extended Data Table 2). Likewise, land-use change within protected wilderness areas have been 18% lower than in unprotected wilderness areas (95% CI = –21%, –15%). These results suggest that protected areas could serve as a refuge against land-use change (i.e., consistent with a global assessment of PAs resistance to anthropogenic pressures¹⁸) and provide potential adaptation opportunities for species under climate change.

Climate velocity has a weak negative correlation with land-use instability ($r_{spatial} = -0.4$, $P < 1 \times 10^{-6}$), suggesting land-use change might intensify climate change stress in some areas but have acted independently in most cases (Fig. 1b). Therefore, to better identify wilderness areas most affected by these two stressors, we mapped climate velocity against land-use instability (Fig. 1c). In general, climate velocity tended to increase across the edges of the Amazonian wilderness, Northern Russia, and Central Africa where land-use instability is highest.

Future climate velocity and land-use change. According to our results, past climate and land-use velocities may be reversed by 2050, continued, or accelerated depending on the global emission and socio-economic pathway chosen in the coming years (Fig. 2). Under a *fossil-fueled development* scenario, average climate velocity within wilderness areas could reach up to 4.41 km/yr (sd = 4.91 km/yr), a 47% increase compared to the baseline epoch. Instead, climate velocity will decline by 8% compared to the baseline, to 2.56 km/yr (sd = 3.8 km/yr), under a *global sustainability* scenario (Fig. 2a; Extended Data Table 1). Climate velocity under this latter scenario was significantly slower compared to former (%)

change [natural-log-difference] = 54%, Wilcoxon rank-sum test with discontinuity corrections, $W = 5.8 \times 10^8$, $P < 1 \times 10^{-6}$). We observed marked differences in projected velocity between the two scenarios in five biogeographic realms: Nearctic, -72%; Palearctic, -56%; Neotropical, -47%; Afrotropical, -46%; Indomalaya, -44%. There was an exception for Australasia, where climate velocity was 2% higher under the sustainability scenario. This finding is likely a result of faster precipitation velocities projected to occur within Australasia under the sustainability scenario (Table S2). Nonetheless, absolute velocity remained highest in Australasia and lowest in Indomalaya under both scenarios (Extended Data Table 1).

Average land-use instability is projected at 0.23 km/yr (sd = 1.89 km/yr) across the future epoch under the *fossil-fueled development* scenario, a 19% increase over the baseline epoch (Fig. 2a). By 2050, the land-use change could affect up to 44% of Earth's wilderness (Supplementary Fig. S3). In contrast, four of the six biogeographic realms could benefit from a *global sustainability* scenario, with percentage differences ranging between -69% (Afrotropical) and -5% (Palearctic). Like climate velocity, we found an important exception in Australasia, where land-use velocity under the sustainability scenario is projected to increase 8% more than under the other scenario. A less prominent exception is in the Nearctic, with a 4% increase.

By 2050, 88% of nations (57 out of 65) presently hosting >2,500 km² of wilderness may be exposed to higher climate velocity compared to the average during the baseline epoch (Fig. 3). Nearly half of these nations may experience climate velocity more than 50% higher than the baseline, with nations containing small and disconnected wilderness patches being especially exposed (Mauritania, Yemen, Mali, Oman, Ecuador, among others). Interestingly, nations most at risk of projected climate change under the *fossil-fueled development* scenario are also the ones most likely to benefit from the sustainable development scenario. These included nations hosting large extents of wilderness (i.e., Canada, Russia, Brazil, and Australia, representing over 60% of the Earth's remaining wilderness¹⁹).

Most of Earth's remaining wilderness areas are found in regions with high importance for global biodiversity (Fig. S1). Under a *fossil-fueled development* scenario, wilderness areas projected to experience moderate to highest velocities of climate and land-use change also overlapped with areas of high biodiversity importance (conservation value > 0.8 on a 0-1 scale, see Methods). Exposure to both climate and land-use change (yellow and yellowish-green) is projected to be high within the high-value wilderness of Brazil and Russia and among several patches across the African Sahara and Australia (28%, >6.7 million km², Fig. 4a). Managing land-use threats in these areas may be essential to retain their conservation value, yet only 15% of these are currently protected. Still, the risk from climate change will persist without a strong international commitment to reduce emissions. Meanwhile, ~6% of the least exposed but high-value wilderness is spread across the Himalayas, Australia's arid regions, Africa, and

Latin America (Fig. 4a). Regions of high biodiversity value expected to experience low climate velocity and land-use instability may be putative refugia for species. Still, it is important to ensure proper monitoring of these areas as 80% of them are currently unprotected.

The climate residence time within wilderness areas. The current draft of the post-2020 global biodiversity framework envisages no net loss by 2030 in the area and integrity of ecosystems and an increase of at least 20% by 2050. Retaining the existing intact and wilderness areas is fundamental to achieving this goal under climate change. To evaluate the capacity for wilderness areas to effectively shelter species within the CBD's 2030 and 2050 policy timeframes, we used climatic velocity to estimate climatic turnover (hereafter "climate residence time (yr)") [Fig. 5]. Climate residence time describes the number of years wilderness areas will potentially be suitable for species (e.g., ref²⁰). Under a *fossil-fuelled development* scenario, approximately 80% of wilderness areas have climatic residence time exceeding the time to 2030 (~15 years), suggesting relatively lower climate impacts on their potential to shelter species by 2030. However, high velocities under the same scenario indicate that 52% of global wilderness areas could experience climate shifts with a climate residence time not compatible with the 2050 timeframe (i.e., residence time <35 years, considering a 2015 starting time). Despite the ambitious biodiversity conservation targets set in the post-2020 policy, climate change across wilderness areas may increase the extinction risk of species residing in these areas.

Discussion

Our analyses suggest that climate change and land-use change within the world's wilderness areas could increase significantly between 2015–2050, compared to the 1970–2005 baseline epoch, but with significant differences between socioeconomic scenarios. These stressors could synergistically intensify pressure placed on regions of biodiversity importance within wilderness areas across biogeographic realms. Over the next 35 yrs, without efforts to lower the impact of climate change, the biodiversity contained in almost all of the Earth's remaining wilderness will face climate velocities that could be of increasing magnitude compared to the baseline epoch. But promisingly, the *global sustainability* scenario, a pathway with more aggressive GHG emissions reduction and limited land-use change, could reduce these impacts by 54% by 2050. This finding supports a wealth of previous evidence that a bold decrease in global emissions will reduce climate change impacts on biodiversity within discrete areas worldwide (e.g., refs^{4–6}). Here, we also show that changes to the use of landscapes will occur in addition to high rates of climate change, thereby decreasing the permeability of these areas for species needing to track their suitable climate rapidly. In previous assessments, the potential for land-use to constrain species movement to suitable climate has only been considered a static variable^{21,22}, limiting inferences about the dynamic processes of land-use change. Our spatially explicit estimates of past and future states of Earth's remaining wilderness and how they might be impacted by climate and land-use change have profound implications for the taxa that require wilderness areas for their survival. These findings can inform conservation decisions about area-based intervention and sustainable land-use policy needed

to avoid land conversion in areas of high conservation value. These findings also reinforce the critical need for achieving international climate commitments.

Net-zero anthropogenic emissions goals of the Paris Agreement and the development of post-2020 strategic plans for the CBD create an imperative to develop improved metrics and prioritise targets to facilitate global goals²³. Maps of climate velocity and land-use instability metrics enable identifying areas where species may be under the most significant pressure to undergo rapid shifts in their bioclimatic envelop while simultaneously having their potential movement constrained by land-use instability. The vast majority of these high-risk areas retain very high biodiversity value, hosting species assemblages unique to or live in more degraded environments elsewhere. Notably, more than 85% of these areas are unprotected. Our identification of the pace of climate and land-use change in wilderness areas is essential for current discussions around the post-2020 CBD target of limiting further extinctions and species declines¹⁵. Our results show that there is a need to expand area-based conservation strategies for Earth's wilderness significantly. Given that strictly protected areas are generally limited in size in relation to the ecosystems that they aim to conserve and are therefore vulnerable to climate and land-use change, biodiversity conservation will need to focus on increased investment in managing the broader landscape taking advantage of 'other-effective conservation measures' being proposed^{24,25} and adopt more localised actions towards land-use change.

Climate velocity is a useful surrogate of the potential requirement for species movement to track climate conditions. We note that our models did not consider species-specific information, such as species' life-history, natural dispersal and phenotypic plasticity that may assist them in adapting to new climate conditions^{26–28}. However, a rapidly warming climate may outpace organisms' dispersal abilities and adaptive capacities²⁶, likely resulting in species assemblage disaggregation³¹. As an example, more than 74% of non-volant mammals have dispersal velocity slower than our estimated climate velocity under a *fossil-fueled development* scenario (Figure S2, Table S3²¹).

Moreover, we also demonstrate that climate tracking via dispersal may become challenging for species in many areas due to increasing land use within wilderness areas. For example, canopy discontinuity caused by the land-use change may limit the dispersal abilities of arboreal species in keeping pace with changing climate²⁶. Indeed, the interaction between the increase in temperature and the intensification of human activities has already had a magnifying effect on range contraction—i.e., the disappearance of a species from part of its past range³².

Wilderness areas are projected to experience climate velocity that is ~42% faster than non-wilderness areas, suggesting that if change continues unabated, species living in wilderness areas might need to migrate long distances to remain in their original bioclimatic envelope (that is, long-distance dispersal³³). This is primarily a concern for species expected to move to higher latitudes (or altitudes) under global warming³⁴, as their current thermal niches might disappear altogether as polar and mountain areas rapidly warm³⁵. Moreover, faster climate velocity inside wilderness areas, compared to outside it, indicates species may need to disperse beyond wilderness areas to track their climate envelope, but this comes at the cost of lower habitat quality. The higher magnitude of land-use instability outside wilderness areas than within is likely detrimental to species undergoing range shifts. Therefore, there is a need to employ a mix of proactive and reactive strategies, including conservation efforts across landscapes surrounding key biodiversity areas³⁶.

The finding that most nations with small, structurally disconnected, and exposed wilderness areas are developing economies reiterates the need for support mechanisms in managing risks from climate change. Most of these countries are currently underfunded¹⁰. Furthermore, climate velocity within Australia (i.e., one of the top four countries hosting with over 60% of the Earth's remaining wilderness areas¹⁹) was higher under the *global sustainability* scenario than the *fossil-fueled development*, suggesting that strong locally and regionally coordinated actions are required to enhance species adaptation responses even under global sustainability scenario. Wilderness areas overlap with large stretches of Indigenous lands, and climate change poses a risk to the spiritual-cultural connections these places represent between indigenous people and nature³⁷. Preserving these places requires a multi-scale approach that includes the achievement of international climate commitments, regional land-use policy and area-based interventions (including but not limited to protected areas), and explicit integration of Indigenous knowledge and perspectives into local-scale management.

Methods

Our main aim was to assess the potential threat that climate and land-use change present to the biodiversity in wilderness areas by combining climate velocity and land-use instability metrics estimated for the near future epoch of 2015–2050 compared to a baseline epoch (1970–2005). We focused on wilderness areas, using openly available, temporally inter-comparable shapefiles of terrestrial wilderness and the Last of the Wilderness datasets³⁸. These are areas across Earth's terrestrial surfaces that are less exposed to industrial-scale activities and other human pressures, which result in significant biophysical disturbance³⁸. Datasets were available as vectors identifying all areas with cumulative human impact scores of approx. zero and have a contiguous area >10,000 km². By 2013, Earth's remaining wilderness spanned ~30 million km², covering ~20% of Earth's terrestrial areas. These wilderness areas are distributed within 275 ecoregions, 14 biomes, and six biogeographic realms.

Climate and land-use datasets: To quantify climate velocity, we used mean annual temperature and annual precipitation layers of regionally downscaled models of the Coupled Model Intercomparison Projects (CMIP5) generated by CORDEX³⁹. We obtained data from three global circulation models (GCMs); MOHC-HadGEM2-ES⁴⁰, MPI-M-MPI-ESM-LR⁴¹, and NCC-NorESM1-M⁴². These GCMs, downscaled by the REMO2015 regional climate model at $\sim 0.22^\circ$ spatial resolution (~ 24 km in Mollweide projection at the Equator), were the only available across all ten CORDEX domains. To generate estimates of globally consistent climate velocity at 0.22° square grids, we combined ten CORDEX regional rasters into a seamless global surface.

To quantify land-use change, we harnessed a new generation of land-use harmonisation data (LUH2 v2f) that builds upon past work from CMIP5 but at higher spatial resolution ($0.25^\circ \times 0.25^\circ$)¹⁷. We considered socioeconomic pathways, which transitioned continuously from IMAGE and ReMIND-MAGPIE using new CMIP6 future *global sustainability* and *fossil-fueled development* scenarios, respectively. We consider nine of twelve of the original land-use classes provided in LUH2, including primary forest, managed pasture, rangeland, cropland (i.e., five crop functional types) and urban class. We selected these classes to represent human-dominated ecosystem modifications. Nonetheless, the geographic extent of land-use change within these areas was compared to areas unchanged or without significant regrowth of secondary forest (see below).

Estimating velocity of change: The velocity of change measures the rate at which climate displaces spatially every year (km yr^{-1})²⁰. To quantify the velocity of change, we applied the gradient-based approach of the velocity of change (gVoCC) implemented in R (v4.0.2)^{33,43}. We quantified gVoCC of both climate and land-use changes as the quotient of temporal trends ($^\circ\text{C yr}^{-1}$ or $\% \text{ yr}^{-1}$) across each epoch by their spatial gradients ($^\circ\text{C km}^{-1}$ or $\% \text{ km}^{-1}$). The temporal rate of change (slope) was estimated using a simple ordinary least squares (OLS) regression model over 35 years. The spatial gradient is a vector sum of longitudinal and latitudinal pairwise differences at each focal cell using a 3×3 -cell neighbourhood. We calculated velocity for each regionally downscaled climate model ($N = 3$) for the two RCPs. We averaged velocity estimates between GCMs for the same variable within an RCP scenario to produce an ensemble estimate. Multi-model averaging potentially mitigated, to some extent, the significant uncertainties that can be found between different GCMs in climate-change projections.

Analysis. To extract summaries for further analysis, first, we converted univariate velocities into multivariate metrics of exposure using per-grid maximum among rasters. This approach is adapted to account for the maximum potential land-use transition possible within a defined grid among the five land-

use classes. For both metrics, we report geometric means for both metrics, given the skewness of the data (ref⁴⁴). We added 0.1 km yr⁻¹ to land-use instability data. In addition to averages, we report the extent of change for land-use instability across wilderness areas. To do this, we computed the areas of non-zero instability values as a percentage of the entire wilderness for each epoch. We set this threshold to the value more significant than half of the global average of the secondary forest instability, beyond which the pace of forest regrowth may not compensate for human-induced wilderness modifications.

Examining the risk of climate and land-use change at PA locations. To estimate climate and land-use risks to wilderness areas, we contrasted protected and unprotected wilderness. However, simply contrasting these metrics between protection statuses may be an inadequate counterfactual analysis due to the non-random distribution of protected areas (PAs) within wilderness areas. As such, we apply statistical matching in selecting samples of the unprotected wilderness that have similar characteristics to the protected wilderness. Statistical matching has been applied in several ecological impact evaluation studies^{12,18}. During matching, we controlled for four covariates, including tetrapod richness, elevation (km), distance to the coast (km), and biogeographic realms (see below). We use the nearest neighbour matching within 0.25 standard deviations calliper, using the “*MatchIt*” package⁴⁵ implemented in the R statistical platform. We performed these without replacement but discarded both control and treatment observations outside the regions of common support. After matching, characteristics of legally protected wilderness were statistically similar to matched controls ($\chi^2 = 8.91$; $df = 8$, $P = 0.35$) using *xBalance* function of the Rtools library. Characteristics before matching were ($\chi^2 = 3,797$; $df = 8$, $P < 1 \times 10^{-6}$). Therefore, we did not vary the model specifications. We estimate the probable margins (%) in a nested regression framework using the *lme4*⁴⁶ (Extended Data Table 2).

We use the 2018 World Database on Protected Areas [WDPA] polygons⁴⁷. During processing, we used only levels I–VI management categories (i.e., *attr*“IUCN_CAT” == “Not Reported” or “Not Applicable” were removed from our analysis), strictly terrestrial (*attr*MARINE == “0”), and only those that intersect wilderness boundaries. To estimate tetrapod richness, we re-gridded the data on expert verified range maps on birds, amphibians, mammals, and reptiles from the International Union for Conservation of Nature (<https://www.iucnredlist.org/resources/spatial-data-download>) and BirdLife International (<http://datazone.birdlife.org/species/requestdis>). Distance from the coast was defined as a Euclidean distance (km) using a boundary shapefile retrieved from the Global Administrative Area Database [GADM v3.4] (www.gadm.org) and implemented in ArcGIS (v10.6.1). To represent elevation, we use the shuttle radar topography mission’s digital elevation model (STRM-DEM)⁴⁸. A Shapefile of biogeographic realms was obtained from Worldwide Fund for Nature database [WWF]⁴⁹.

Assessing risk to wilderness areas and the persistence of their biodiversity services. Next, we evaluated the implications of the intensifying climate and land-use instability on biodiversity conservation. To achieve this, we measured the overlap between these pressures and the contextual intactness datasets. Contextual intactness represents the proportion of habitat expected to host a similar assemblage of species but is worse (that is, has a higher human footprint)⁵⁰. Contextual intactness values range between 0 and 1, with 1 presenting terrestrial location where all other biologically similar places are in a worse condition, otherwise 0 (Supplementary Fig. S1). For simplicity, we refer to the contextual intactness hereafter as the conservation value of wilderness. The conservation value of Earth's last remaining wilderness averaged 0.71 (sd = 0.13), which is ~38% higher than non-wilderness areas. We assumed that both metrics would have magnified effects on global biodiversity (ref.³²). Therefore, vulnerable wilderness areas are those where joint climate velocity and land-use instability are highest. Both metrics were grouped into terciles bins.

Declarations

Code availability: R (v4.0.2)⁵¹, *VoCC*⁵², *lme4*⁴⁶, *MatchIt*⁴⁵, and *Rltools*⁵³. Model outputs and codes for visualisations are available from the corresponding authors upon request.

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Figures

Figure 1

Climate velocity and land-use instability across Earth’s remaining wilderness since the 1970s. (a) The bar plot shows the mean of climate velocity and land-use instability across all wilderness (AW), protected wilderness (PW), and unprotected wilderness (UW) areas. Uncertainty illustrated by 95% Confidence Interval is shown as error bars. (b) The bivariate kernel density plot shows the relationship between climate and land-use velocities. Both axes are stretched on a natural-log scale. (c) The map illustrates the overlap of climate and land-use instability for the baseline period (1970–2005). Both climate velocity and land-use instability were natural-log-transformed and grouped into tercile bins. Pressure space defined by a bivariate combination of the two metrics included (extremes quadrants): slow-moving climate and stable land use (blue shades); fast-moving climate and stable land-use change (green shades); fast-moving climate and rapidly–changing land use (yellow shades); and slow-moving climate and rapidly changing land use pressure bins (red shades). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Projected changes in climate velocity and land-use instability between 2015–2050. (a) The bar graph shows changes (%) between the projected estimates and global average of baseline estimated across all wilderness (AW), protected wilderness (PW), and unprotected wilderness (UW) areas and grouped by scenarios. Maps report the overlap of projected changes in climate velocity and land-use instability relative to the global average for (b) global sustainability and (c) fossil-fueled development scenarios. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Percentage change in climate and land-use velocity within wilderness areas for countries with >2,500 km² remaining wilderness. The circular plot shows climate velocity predicted under global sustainability (blue bars) and fossil-fueled development (mauve bars) scenarios in 2050 (relative to the mean of the baseline [1970–2005]). Countries' whose wilderness areas overlap many biogeographic realms appears at least once. The figure is grouped by biogeographic realm: Afrotropical, AT; Australasia, AA; Indomalaya, IM; Nearctic, NA; Neotropical, NT; Palearctic, PA.

Figure 4

Global assessment of climate and land-use change risks compared to relative biodiversity importance of wilderness areas. Map (a) shows global wilderness areas, where projected joint climate velocity and land-use instability may magnify effects on biodiversity (conservation value), as measured under scenario SSP5–RCP8.5. Both axes of the bivariate colour-scale legend are binned into terciles. Colour-scale legend also shows proportions of wilderness under each bivariate space, including low-value habitat and low-

pressure (blue shades), high-value habitat and low-pressure (green shades), low-value habitat and low-pressure (red shades), and high-value habitat and high-pressure bins (yellow shades). Circular plot (b) shows the risk of each country's biodiversity to climate and land-use change by 2050 (for countries with >2,500 km² wilderness areas). Countries' whose wilderness areas overlap many biogeographic realms appear at least once. Colour scale legend corresponds to maps grouped by biogeographic realms: Afrotropical, AT; Australasia, AA; Indomalaya, IM; Nearctic, NA; Neotropical, NT; Palearctic, PA. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Estimated year of potential climate shift (residence time + 2015) within Earth's remaining wilderness and the proportion of wilderness areas expected to undergo a shift. The filled area corresponds to the number of years until CBD 2050 targets. The year of climate shift is estimated by adding residence time to 2015, the base year for projected velocity calculations. The median residence time estimated under the global sustainability and fossil-fueled development scenarios is 51 and 33 years (Extended Data Figure 3). The X-axis is truncated at the end of the twenty-first century (2100) for presentation purposes. More than 74% and 84% of the wilderness had residence time less than 100 years under the above scenarios.

Supplementary Files

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