# Combined speeds of climate and land-use change of the conterminous US until 2050

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**High rates of climate and land-use changes threaten biodiversity and ecosystem function[1,2], creating a need for integrated assessments and planning at regional to global scales. We develop a new approach to measure multivariate estimates of climate and land-use change that builds on recently developed measures of climate velocity[3-6], and apply it to assess the combined speeds of climate and land use for the conterminous US from 2001 to 2051. The combined speeds of climate and land-use change are highest in a broad north-to-south swath in the central US and in parts of the intermountain west. Climate speeds are roughly an order of magnitude higher than land-use speeds in most regions, but land-use speed is particularly high in the Appalachians and north-central forests. Joint speeds are low across much of the intermountain west. Our results highlight areas expected to be most vulnerable to changes in biodiversity and ecosystem function due to the individual or combined effects of climate and land-use change. The integration of climate and land-use scenarios suggests different conservation prioritization strategies from climate velocities and species alone[7].**

Most quantitative global-change assessments of rates of change have focused on future climate alone[3,5,6,8,9], without considering other factors. Conversely, most future land-use scenarios do not consider climate change[10–12] and emphasize total habitat losses rather than rates of change. As the distributions of species and diversity are affected by multiple environmental factors, multivariate approaches to assess the rates of climate or land-use change are needed. Using a new joint measure of exposure to climate and land-use changes that combines elements of velocity-based[3,5,6] and analogue-based methods[6,8,9] (Methods), here we measure the combined speeds of climate and land-use change for the conterminous US based on multiple land-use and climate scenarios.

Our approach is based on the univariate velocity of change, measured as the ratio of temporal anomalies to spatial gradient[3] (Methods); for example,

$$\frac{\text{Temporal anomalies}}{\text{Spatial gradient}} = \frac{\text{km}}{\text{decade}} = \frac{°C \times \text{decade}^{-1}}{°C \times \text{km}^{-1}} \text{ or } \frac{\text{Ha} \times \text{decade}^{-1}}{\text{Ha} \times \text{km}^{-1}}$$

to translate estimates of temporal rates of changes into estimates of spatial velocities. This metric provides a standardized measure of exposure[2] of species to spatially rapid rates of change. Climatic velocities determine the rates at which a given species needs to move to stay within a given range of climate. Land-use velocities index the rapidity of land-cover conversion, which can lead to habitat loss, spatial isolation and the emergence of dispersal barriers.

We build on this to develop a new estimate of the exposure of ecosystems to rapid change across multiple dimensions of climate and land use (Methods), providing an overarching index that is independent of the natural history attributes of individual species. This measure combines the principle of individual velocity-based metrics[3,5,6] with the multivariate assessments enabled by analogue-based methods[6,8,9]. As with univariate velocity measurements, multivariate speed is the ratio of rates of changes in space and time, but the underlying variable is a multivariate dissimilarity index: standardized Euclidean distance (SED) calculated as

$$\sqrt{\sum_{k=1}^{n}\left[\frac{(b_{k,j}-a_{k,i})^2}{s_{k,i}^2}\right]}$$

where $a_{k,i}$ and $b_{k,j}$ are means for the climatic or land-use variable $k$ at the contrasted ($j$) and target ($i$) grid points, and $s_{k,i}^2$ is the historical interannual variability. SED is unitless, so that

$$\text{SED}_{\text{Velocity}} = \frac{\text{SED}_{\text{time}}}{\text{SED}_{\text{Space}}} = \frac{[\text{unitless}] \times \text{decade}^{-1}}{[\text{unitless}] \times \text{km}^{-1}} = \frac{\text{km}}{\text{decade}}$$

Note that we define our multivariate rates as 'speeds' rather than 'velocities' because multivariate spatial estimates do not include direction[5] but retain velocities when referring to univariate rates of change. Furthermore, in contrast to previous analogue-based estimates of spatiotemporal change[6,9], the normalization by local spatial dissimilarity gradients means that our metric is an index of local climatic or land-use composition change across a spatially varying gradient, rather than regional displacement vectors typical of analogue-based approaches[6,9].

We map estimates of univariate velocity and multivariate speeds for climate and land use from AD 2001–2011 to 2041–2051 for the conterminous US, using the Intergovernmental Panel on Climate Change scenarios of the 5th Assessment Report[13], and future land-use changes under alternative socioeconomic scenarios, based on an econometric model extrapolations of the US Natural Resources Inventory for the period 2001–2051[11,12]. The primary results presented here are for intermediate climate and land-use scenarios (Representative Concentration Pathway (RCP) 6.0 for climate and land-use projections following 1990s trends), and thus are conservative with respect to future outcomes. Results for other scenarios are presented as figures and in the Supplementary Information.

Climate velocities varied widely among variables (Fig. 1a–i) and ecoregions (Table 1), ranging from 1.8 to 37.1 km decade⁻¹. Among climate variables, evapotranspiration and water deficit had

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faster velocities than annual mean temperature and precipitation (Fig. 1). Velocities were highest in regions with little topographic relief, such as the Great Plains and the northeast, and lowest in the western US, and varied greatly among ecoregions owing to variations in both temporal trends of climate change and contemporary spatial patterns. The spatial patterns of our projected future climate velocities closely resemble those for historic climate velocities in the US[5], highlighting the importance of topographic controls on climate velocity. The projected velocities and speeds that we report are higher than previous estimates of historical velocities[5] (0.80–1 km decade$^{-1}$ for 1916–2005, and 2–5 km decade$^{-1}$ for 1976–2005). However, these historical velocities were calculated from 1-km-resolution data sets, and these velocities increase by a factor of 10 when analysed at the 10-km resolution of our study[5], bringing the previously estimated historic and our projected rates of change into closer alignment. Spatial patterns of multivariate climate speeds (Fig. 1a) are consistent with univariate patterns, with slower multivariate speeds in the topographically heterogeneous west and northeast.

Estimates of land-use velocity (Table 1) ranged from 0.11 to 47.0 km decade$^{-1}$ among variables, with pasture velocity the fastest and rangeland velocity the slowest. Combined land-use speeds were highest in the eastern Great Plains (Fig. 1g) and were associated with increases in forest, pasture and urban land-cover types (Fig. 2h,j). The projected increases in forest underscore that some land-use changes may favour species conservation and potential restoration of natural communities (Fig. 2b,c). Therefore, when using the multivariate land-speed estimates, it is necessary to carefully consider which land-use categories are considered and in which direction these are changing. In contrast, low land-cover speeds prevailed in the interior West, where land cover is projected to be relatively stable[11]. Land-use speeds were generally insensitive to topographic heterogeneity.

Many areas were projected to experience high speeds of both climate and land-use change, with a significant positive correlation between local multivariate speeds ($n = 133,690$, $p < 0.001$; Spearman's $\rho = 0.45$; density plot Fig. 2a), a pattern consistent across all combinations of climatic and land-use scenarios (Supplementary Information). Combined climate and land-use speeds were projected to be highest in a broad north-to-south swath in the central USA, the midwest and low-lying areas in the intermountain west (Fig. 2). Climate speeds across the conterminous US generally were an order of magnitude higher than land-use speeds. However, this pattern varied by region (Table 1). Climate speeds were particularly high relative to land-use speeds in the central plains and southern Florida. In contrast, forested regions of the north-central US, New England and the Appalachians, and arid areas in the south had relatively high land-use speeds. Combined speeds were low across much of the interior west, because of low temporal rates of land-cover change and low climate speeds in this topographically complex region. The strong interregional differences show the importance of developing regional-scale adaptation plans that integrate quantitative assessments of exposure to multiple global change factors.

By rescaling climate and land-use changes to a standardized measure of change (km decade$^{-1}$), it is possible to assess the prospect of lagged responses or climatic debts due to spatial shifts in environmental conditions and species[14] or community[15,16] responses to these factors. For example, in areas of slow climate and land-use speed, species may be able to persist in place, or move unassisted into newly emerging favourable microclimates, especially in topographically complex regions. In contrast, areas with both high climate and high land-use speeds will experience the fastest changes in community composition and ecosystem function, and these changes will probably lag behind the changes in environmental forcing[15].
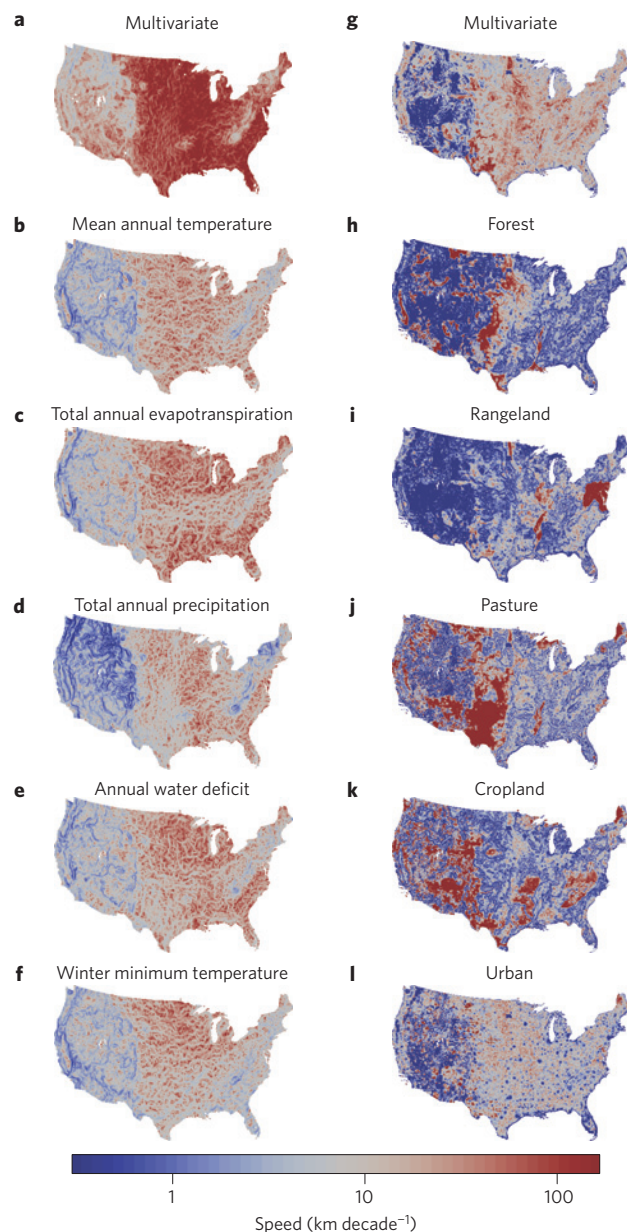


**Figure 1 | The speed and velocity (km decade$^{-1}$) of climate and land-use change across the conterminous US, from 2001–2010 to 2041–2050 under RCP 6.0 and 1990s land-use scenarios. a,b**, Multivariate speeds represent the ratio between SEDs in time (temporal change) and space (spatial heterogeneity), integrated across climate (**a**) and land-use (**b**) variables. **b–l**, Univariate velocities represent the ratio between temporal and spatial gradients across climate (**b–f**) and land-use (**h–l**) variables. Multivariate speeds (**a–g**) are generally faster than for individual climatic (**b–f**) or land-use (**h–l**) variables.

Combinations of alternative climate and land-use scenarios did affect some of the regional estimates of land-use and climate speeds (Fig. 3 and Supplementary Information), but did not reverse underlying patterns in climate and land-use speed. Speeds in the western US were consistent among scenarios (Supplementary Information). The central and eastern US were more sensitive to choice of climate and land-use scenario (Fig. 2). The upper midwest, with its lower topographic complexity, had a particularly high sensitivity to choice of climate scenario (Fig. 2), whereas the northeastern US was more sensitive to land-use scenario, particularly the high-cropland-demand scenario
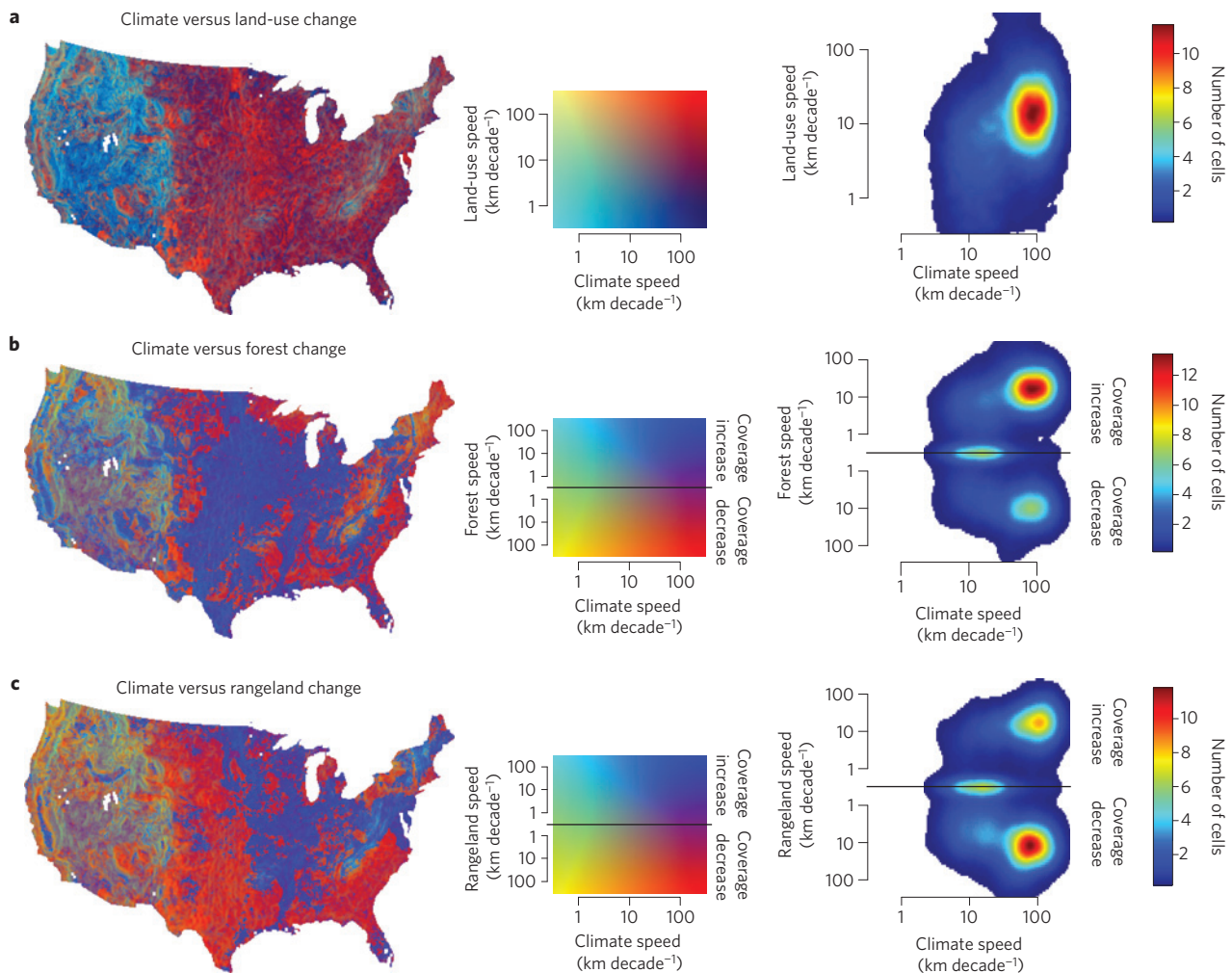
**Figure 2 | Combined exposure of US ecosystems to high speeds of climate speeds and local land use. a–c,** Land-use contras represent changes across all land-use types (**a**), forests (**b**) and rangelands (**c**). Colour ramp for land-use change shows the colour of all possible multivariate climate and land-use speed combinations. Kernel-density plots show the proportion of cells within the continental US with a particular combination of speeds of climatic and land-use, forest and rangeland change.

(Fig. 2). Interestingly, the directional effects of high cropland demand on land-use speed varied by region, with land-use speeds increasing in New England (with more forest to cropland conversion) and decreasing in the upper midwest (slower rates of urbanization). At a continental scale, speeds were lower for the RCP 2.6 scenario ($-4$ km decade$^{-1}$ relative to RCP 6.0 and 1990s land-use trends) and the land-use scenario of restricted future urban growth ($-1.2$ km decade$^{-1}$), but higher for the RCP 8.5 scenario ($+12$ km decade$^{-1}$) and the land-use scenario of growth in future demand for agricultural commodities ($+1.2$ km decade$^{-1}$). Among the evaluated scenarios, the combined effect of high $CO_2$ concentrations and the expansion of agricultural demands resulted in the biggest differences relative to the RCP 6.0 and 1990s land-use scenarios. Overall, changes in market and societal preferences influenced future land use in some regions[13], but speed was more sensitive to alternate climate scenarios.

Species with limited dispersal ability or endemic distributions may be particularly sensitive to high climate[17] and land-use speeds, as well as other anthropogenic pressures on biodiversity[18]. Climate speeds are high relative to observed rates of range shifts for plants and animals[3,13], during the late twentieth century (6 km decade$^{-1}$; ref. 19), the early twenty-first century (16.9 km decade$^{-1}$; ref. 20), and the last deglaciation (17.0–27.0 km decade$^{-1}$; ref. 14). Land-use speeds are more

comparable to these dispersal estimates, but place additional pressures through the effects of habitat transformation[21,22] (for example, from forest or rangelands to urban or agriculture), habitat fragmentation, by creating barriers to dispersal, and due to socioeconomic pressures on species distributions[23] that can result in an endangered status[18,22]. Species-specific rates of response are likely to promote the reshuffling of species into new ecosystems[24] and may increase the likelihood of extirpation or extinction.

The combined patterns of climate and land-use speeds imply different adaptation actions and priorities from either climate or land-use speeds by themselves[2,7]. At a national scale, regions exposed to both high climate speeds and reductions in forest or rangelands (for example, areas in red; Fig. 2b,c) may be priorities for land acquisition and protection efforts. Nonetheless, these areas should be carefully triaged given the cost of the required land-acquisition effort due to the strong urbanization trend. Furthermore, the high uncertainty regarding the composition of the habitat matrix in protected areas would decrease the certainty in how natural resource managers should manage these areas.

The variability in exposure across and within regions highlights the need for regionalized management and adaptation planning, rather than attempts to institute uniform national policies, or the same management actions everywhere. A good point-in-case example was the differences between the upper midwest (Fig. 3a–h),
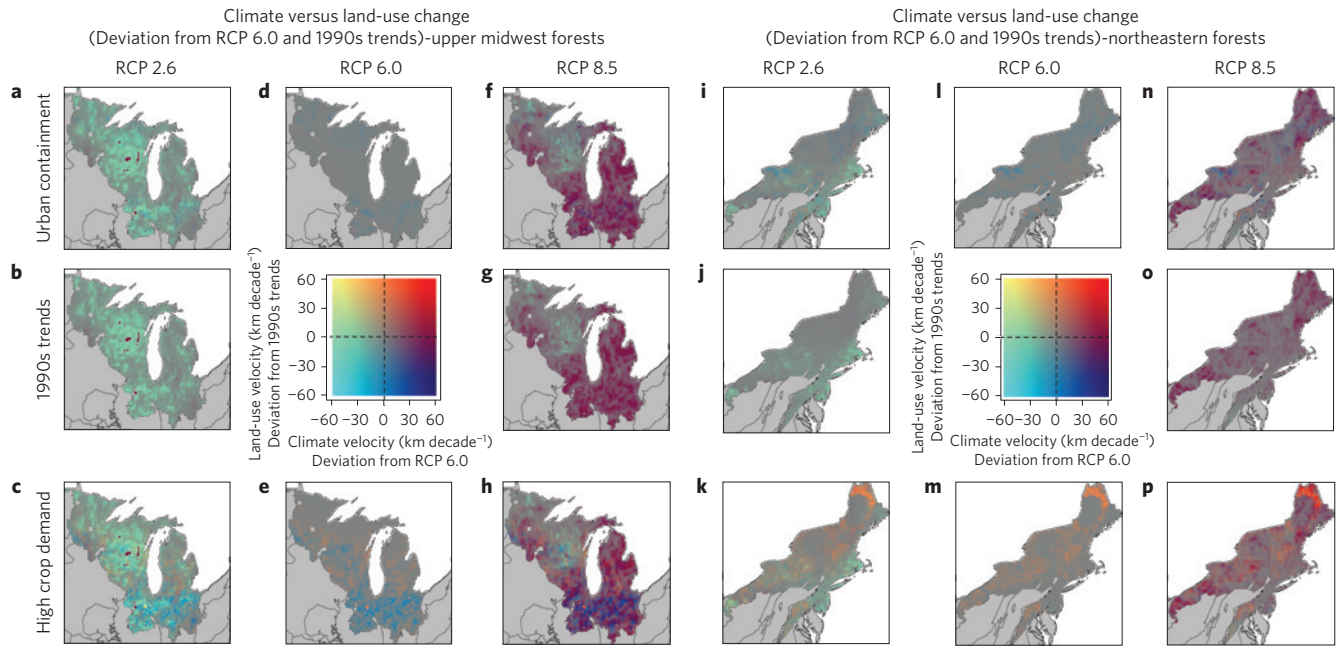
**Figure 3 | Sensitivity of projected climate and land-use speeds to alternative scenarios. a–p**, Speeds for upper midwest forest (**a–h**) and northeastern forest (**i–p**). Regions were picked for their contrasts in the relative magnitudes of climate and land-use speeds. Speeds are shown as the difference relative to projections under RCP 6.0 and 1990s land-use scenarios (**a**).

**Table 1 | Geometric means of speeds (km decade⁻¹) from Environmental Protection Agency level II ecoregions.**

| Ecoregion | Climate speed (RCP 6.0) | | | | | | Land use speed (1990s trends) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAT | PET | AnnP | Deficit | $T_{min}$ | $Clim_{multi}$ | Forest | Rangeland | Pasture | Crop | Urban | $Land_{multi}$ |
| Atlantic highlands | 7.7 | 19.4 | 3.7 | 11.8 | 8.0 | 28.9 | 1.4 | 1.9 | 4.6 | 8.2 | 6.5 | 9.6 |
| Central USA plains | 19.5 | 27.6 | 14.5 | 26.8 | 20.9 | 107.4 | 2.3 | 4.4 | 3.4 | 2.2 | 3.9 | 16.3 |
| Cold deserts | 4.9 | 7.3 | 2.2 | 5.7 | 5.9 | 18.5 | 0.8 | 0.3 | 2.4 | 8.4 | 1.9 | 1.5 |
| Everglades | 12.9 | 16.0 | 9.9 | 10.3 | 3.6 | 66.2 | 0.7 | 1.2 | 1.7 | 0.4 | 0.2 | 0.9 |
| Marine west coast forest | 4.3 | 6.3 | 1.2 | 3.4 | 3.4 | 8.9 | 0.7 | 1.5 | 3.4 | 7.9 | 3.5 | 8.0 |
| Mediterranean California | 3.5 | 3.3 | 2.3 | 4.2 | 2.8 | 15.9 | 3.0 | 1.0 | 2.6 | 2.0 | 2.7 | 7.2 |
| Mississippi alluvial and southeast coastal plains | 20.4 | 27.7 | 19.7 | 21.9 | 8.0 | 124.4 | 1.7 | 4.9 | 3.1 | 1.8 | 2.4 | 8.3 |
| Mixed wood plains | 15.5 | 24.3 | 10.0 | 19.5 | 15.2 | 75.4 | 1.4 | 1.9 | 3.0 | 1.6 | 5.0 | 12.2 |
| Mixed wood shield | 20.2 | 30.2 | 12.5 | 28.2 | 21.6 | 99.7 | 0.7 | 0.7 | 4.7 | 2.8 | 4.4 | 5.1 |
| Ozark, Ouachita-Appalachian forests | 10.4 | 14.3 | 7.6 | 11.0 | 8.0 | 51.9 | 1.1 | 5.5 | 2.3 | 10.2 | 5.7 | 12.9 |
| South-central semi-arid prairies | 15.1 | 16.3 | 8.9 | 12.7 | 12.4 | 68.8 | 5.0 | 1.7 | 47.3 | 3.1 | 7.1 | 15.4 |
| Southeastern USA plains | 16.4 | 24.0 | 14.3 | 19.4 | 9.2 | 96.7 | 1.4 | 3.5 | 2.7 | 4.8 | 5.7 | 14.1 |
| Tamaulipas-Texas semi-arid plain | 15.3 | 18.2 | 7.7 | 18.8 | 10.1 | 66.3 | 43.8 | 2.8 | 4.2 | 13.6 | 5.7 | 22.1 |
| Temperate prairies | 20.2 | 27.5 | 16.5 | 26.0 | 23.2 | 117.1 | 9.2 | 1.9 | 4.7 | 2.6 | 10.0 | 21.7 |
| Texas-Louisiana coastal plain | 22.8 | 33.2 | 11.7 | 14.9 | 8.7 | 87.8 | 4.5 | 1.5 | 1.9 | 2.0 | 2.5 | 10.5 |
| Upper Gila mountains | 2.8 | 4.4 | 3.0 | 4.1 | 2.8 | 19.8 | 0.1 | 0.1 | 26.8 | 40.0 | 1.4 | 0.5 |
| Warm deserts | 4.5 | 6.1 | 4.3 | 7.3 | 3.8 | 28.0 | 2.1 | 0.4 | 13.0 | 6.3 | 1.2 | 1.6 |
| West-central semi-arid prairies | 14.2 | 20.1 | 10.8 | 16.6 | 16.6 | 76.8 | 1.6 | 1.1 | 10.0 | 1.9 | 9.5 | 9.3 |
| Western cordillera | 2.8 | 5.4 | 1.3 | 3.9 | 3.4 | 9.2 | 0.2 | 0.2 | 1.9 | 5.8 | 1.9 | 0.9 |
| Western Sierra Madre Piedmont | 3.8 | 5.4 | 3.5 | 7.4 | 2.8 | 22.3 | 0.4 | 0.3 | 7.2 | 3.1 | 1.4 | 1.8 |
| Continental geometric mean | 11.5 | 15.6 | 7.7 | 12.5 | 8.9 | 56.7 | 1.4 | 1.1 | 4.7 | 4.0 | 3.7 | 5.7 |
| Arithmetic mean across ecoregions | 11.8 | 16.8 | 8.3 | 13.7 | 9.5 | 59.5 | 4.1 | 1.8 | 7.5 | 6.4 | 4.1 | 9.0 |

Mean annual temperature (MAT), potential evapotranspiration (PET), total annual precipitation (AnnP), annual water deficit (Deficit), minimum temperature ($T_{min}$), forest, rangeland, pasture, crop and urban land use, and multivariate changes in climate composition ($Clim_{multi}$) and land-use structure ($Land_{multi}$). Continental and ecoregional means are calculated across all grid cells within a category using geometric means, and across all ecoregional means using arithmetic means.

and northeastern US (Fig. 3i–p), which differ considerably in their sensitivity to climatic and land-use scenarios, and different coverage trajectories for forest and rangelands.

In the upper midwest, where climate velocities were high, adaption strategies will almost certainly be required (Fig. 3). Applicable actions in this region could range from the management of species and ecosystem *in situ* to increase resilience[25] to more extreme approaches such as habitat engineering[26], *ex situ* conservation, managed relocations[27], and even abandonment of conservation efforts for some populations in favour of populations elsewhere[28].

In contrast, in the northeastern Atlantic highlands, where climate velocities were relatively low and sensitivity to land-use scenario was high, management strategies may place a premium on land acquisition to stem high rates of habitat loss, as well as on developing private conservation partnerships, to protect remaining habitat, maintain ecosystem functions and facilitate species adaptation. In urbanizing areas, it will be difficult to reverse habitat losses, because land rents for urban use are high (Fig. 2b). Moreover, areas where natural vegetation is expected to expand over the next 50 years (for example, east-central US forests and pastureland in the Great Plains; Fig. 2b,c) may provide opportunities for ecosystem restoration.

By extending the assessment of change speeds beyond individual climatic variables, assessing land-use speed, and doing these comparisons at both national and regional scales, we captured the combined effect of multiple factors that together determine the magnitude of changes that species and ecosystems may face until 2051, providing a better understanding of future environmental impacts and potential regional conservation actions. Our work builds on previous assessments of the exposure of natural systems to climatic[3–6,8] or land-use changes[10,11], and advances these by providing a quantitative assessment of the effect of multiple climatic and land-use conditions, and of the potentially negative combined effect of climate change and habitat loss. By identifying future exposure based on climatic and land-use stability, we highlight the limitation of assessments that focus on climate change alone at either global[3,4,8] or regional scales[5,6], because land-use change is another key component of global change, and can be altered by broad-scale management strategies, interventions and policies[10,11].

Our approach is general and could be used to assess the combined effects of climate and land-use change in other regions, or extended to indices of ecosystem intactness and adaptive capacity[29] and to characterize the spatial rates of expansion of stressors to biodiversity (for example, how rapidly a pollutant isocline moves in space?). However, all such work is dependent on the availability of spatiotemporal data sets of the current and projected states. Ultimately, this would allow quantification of the rate, magnitude and direction of changes in multiple biologically relevant dimensions, to inform conservation planning at landscape to global scales.

## Methods

We analysed present and future climatic decadal projections (to reduce the effect of interannual variability and extreme events), at 10-km resolution based on the ensemble forecast of 39 downscaled climatic simulations[30] for the periods 2001–2011 and 2041–2051 under a range of RCPs developed for the Intergovernmental Panel on Climate Change 5th Assessment Report[13]. Historical climate velocities have already been studied for this region[5], and we focus here on the combination of future climate and land-use change.

Future climate change was initially mapped using the climate change velocity metric[3]. Univariate climate velocities were estimated as the ratio between univariate temporal trends (that is, anomalies between 2001–2010 and 2041–2050) and vector-based spatial gradients[4] (that is, spatial dissimilarity in a $3 \times 3$ grid-cell neighbourhood, a neighbourhood size that maximizes the effective spatial resolution of the analysis)[3,5]. Our analyses were based on five variables, which all determine species' distributions and diversity patterns: mean annual temperature, potential evapotranspiration, total annual precipitation, annual water deficit and winter minimum temperature. These variables are among the most commonly used in species distributions modelling to describe the environmental tolerances of Nearctic[14] and Palaearctic[23] biota. We then calculated and mapped multivariate climate speeds based on all 5 variables as we describe below.

In adapting the climate velocity index to land-cover change, we first measured the rate of change of single land-cover types. Land-use velocities were determined as the ratio between the expected amount of change over time (that is, for the 10-km grid we calculated the area of each land use in the future minus the area of the same land use at the present time) and the spatial heterogeneity of land use (that is, for a 10-km grid we calculated the difference in coverage of each land use under present conditions in the $3 \times 3$ surrounding cells). This metric evaluates the degree of land-use-coverage stability (that is, prevalence of a given land-use coverage in the future weighted by the coverage in the surrounding areas), summarizing the exposure to future land-use changes relative to current heterogeneity in land composition. High land-use velocity occurs when the rate of land-cover change is high or when land use is locally uniform, implying few refuges for species displaced by land-use change.

We focused on five land-cover classes: forests, rangelands, pasture, croplands and urban. Present and future land-use coverage for each of the five land-cover classes were determined based on an econometric model[11,12] that predicts spatially explicit land-use changes across the conterminous US for the period 2001–2051. These projections of future land-use change are driven only by alternative economic incentives, which at the timescale of this study (~50 yr) are more important drivers of land-use change than climate. We focus on future conditions over historical changes to illustrate how alternative land-use policy and economic scenarios (increased crop commodity prices, restricted urban growth) could intersect with scenarios of future climates, together altering the local exposure to future changes.

Our multivariate spatiotemporal rates of change, which we define as 'speeds' owing to their no-directional nature, combine dissimilarity metrics such as those used in analogue-based analyses[6,8,9] with the buffering effect of spatial heterogeneity used in climate-velocity analyses[3,5,14]. This index measures the ratio between multivariate dissimilarities in space and time, and thus represents the expected reshuffling over time based on the changes in both climatic or land-use composition, weighted by the environmental similarity in the surrounding cells. By normalizing the changes by local spatial dissimilarity, we advance from regional displacement vectors[6,9] to an index of local speed of a climatic or land-use composition.

For both climate and land use, we quantified dissimilarities in time (between 2001–2010 and 2041–2051) and space (mean SED from all pairwise SEDs in the $3 \times 3$-cell neighbourhood) by using the SED as it equally weights all variables and emphasizes trends that are large relative to the 1950–2001 interannual variability:

$$\mathrm{SED}_{i,j} = \sqrt{\sum_{k=1}^{n}\left[\frac{(b_{k,j}-a_{k,i})^2}{s_{k,i}^2}\right]}$$

where $a_{k,j}$ and $b_{k,i}$ are the means for climate or land-use variable $k$ at grid points $j$ (future or neighbouring cell conditions) and $i$ (target cell), and $s_{k,i}^2$ is the historical standard deviation of the interannual variability for grid point $i$ from 1950 to 2001.

Finally, we merge the climate and land-use multivariate metrics into a single combined speed map (Figs 2 and 3), representing the combined exposure to climate and land-use change. For this, we created a colour-coded composite of climatic and land-use speeds (multivariate, forest and rangeland).

## References

1. Chapin, F. S. III *et al.* Consequences of changing biodiversity. *Nature* **405**, 234–242 (2000).
2. Dawson, T. P., Jackson, S. T., House, J. I., Prentice, I. C. & Mace, G. M. Beyond predictions: Biodiversity conservation in a changing climate. *Science* **332**, 53–58 (2011).
3. Loarie, S. R. *et al.* The velocity of climate change. *Nature* **462**, 1052–1055 (2009).
4. Burrows, M. T. *et al.* The pace of shifting climate in marine and terrestrial ecosystems. *Science* **334**, 652–655 (2011).
5. Dobrowski, S. Z. *et al.* The climate velocity of the contiguous United States during the 20th century. *Glob. Change Biol.* **19**, 241–251 (2013).
6. Ordonez, A. & Williams, J. Projected climate reshuffling based on multivariate climate-availability, climate-analog, and climate-velocity analyses: Implications for community disaggregation. *Climatic Change* **119**, 659–675 (2013).
7. Tingley, M. W., Estes, L. D. & Wilcove, D. S. Ecosystems: Climate change must not blow conservation off course. *Nature* **500**, 271–272 (2013).
8. Williams, J. W., Jackson, S. T. & Kutzbach, J. E. Projected distributions of novel and disappearing climates by 2100 AD. *Proc. Natl Acad. Sci. USA* **104**, 5738–5742 (2007).

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9.  Ohlemüller, R., Gritti, E. S., Sykes, M. T. & Thomas, C. D. Towards European climate risk surfaces: The extent and distribution of analogous and non-analogous climates 1931–2100. *Glob. Ecol. Biogeography* **15,** 395–405 (2006).
10. Martinuzzi, S. *et al.* Key areas for conserving United States' biodiversity likely threatened by future land use change. *Ecosphere* **4,** art58 (2013).
11. Radeloff, V. *et al.* Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. *Ecol. Appl.* **22,** 1036–1049 (2012).
12. Lawler, J. J. *et al.* Projected land-use change impacts on ecosystem services in the United States. *Proc. Natl Acad. Sci. USA* **111,** 7492–7497 (2014).
13. IPCC *Climate Change 2013: The Physical Science Basis* (Cambridge Univ. Press, 2013).
14. Ordonez, A. & Williams, J. W. Climatic and biotic velocities for woody taxa distributions over the last 16 000 years in eastern North America. *Ecol. Lett.* **16,** 773–781 (2013).
15. Svenning, J-C. & Sandel, B. Disequilibrium vegetation dynamics under future climate change. *Am. J. Bot.* **100,** 1266–1286 (2013).
16. Devictor, V. *et al.* Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Clim. Change* **2,** 121–124 (2012).
17. Sandel, B. *et al.* The influence of late quaternary climate-change velocity on species endemism. *Science* **334,** 660–664 (2011).
18. Dullinger, S. *et al.* Europe's other debt crisis caused by the long legacy of future extinctions. *Proc. Natl Acad. Sci. USA* **110,** 7342–7347 (2013).
19. Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421,** 37–42 (2003).
20. Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B. & Thomas, C. D. Rapid range shifts of species associated with high levels of climate warming. *Science* **333,** 1024–1026 (2011).
21. Jetz, W., Wilcove, D. S. & Dobson, A. P. Projected impacts of climate and land-use change on the global diversity of birds. *PLoS Biol.* **5,** 1211–1219 (2007).
22. Bomhard, B. *et al.* Potential impacts of future land use and climate change on the red list status of the proteaceae in the cape floristic region, South Africa. *Glob. Change Biol.* **11,** 1452–1468 (2005).
23. Thuiller, W., Lavorel, S., Sykes, M. T. & Araujo, M. B. Using niche-based modelling to assess the impact of climate change on tree functional diversity in Europe. *Divers. Distrib.* **12,** 49–60 (2006).
24. Williams, J. W., Shuman, B. N., Webb, T., Bartlein, P. J. & Leduc, P. L. Late-quaternary vegetation dynamics in North America: Scaling from taxa to biomes. *Ecol. Monograph* **74,** 309–334 (2004).
25. Millar, C. I., Stephenson, N. L. & Stephens, S. L. Climate change and forests of the future: Managing in the face of uncertainty. *Ecol. Appl.* **17,** 2145–2151 (2007).
26. Brook, B. W., Sodhi, N. S. & Bradshaw, C. J. A. Synergies among extinction drivers under global change. *Trends Ecol. Evol.* **23,** 453–460 (2008).
27. Hoegh-Guldberg, O. *et al.* Assisted colonization and rapid climate change. *Science* **321,** 345–346 (2008).
28. Bottrill, M. C. *et al.* Is conservation triage just smart decision making? *Trends Ecol. Evol.* **23,** 649–654 (2008).
29. Watson, J. E. M., Iwamura, T. & Butt, N. Mapping vulnerability and conservation adaptation strategies under climate change. *Nature Clim. Change* **3,** 989–994 (2013).
30. Brekke, L., Thrasher, B., Maurer, E. P. & Pruitt, T. *Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs* (US Dept of Interior, Bureau of Reclamation, 2013).

## Author contributions
A.O. and J.W.W. developed the multivariate metric, A.O. downscaled the climatic data, ran analyses, and produced figures and tables. S.M. and V.C.R. produced the land-use-change model scenarios. A.O. led the writing, with the assistance of J.W.W., S.M. and V.C.R. All authors contributed equally to development and discussion of ideas.

## Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.O.

## Competing financial interests
The authors declare no competing financial interests.