CLIMATE CHANGE

Past and future global transformation of terrestrial ecosystems under climate change

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Impacts of global climate change on terrestrial ecosystems are imperfectly constrained by ecosystem models and direct observations. Pervasive ecosystem transformations occurred in response to warming and associated climatic changes during the last glacial-to-interglacial transition, which was comparable in magnitude to warming projected for the next century under high-emission scenarios. We reviewed 594 published paleoecological records to examine compositional and structural changes in terrestrial vegetation since the last glacial period and to project the magnitudes of ecosystem transformations under alternative future emission scenarios. Our results indicate that terrestrial ecosystems are highly sensitive to temperature change and suggest that, without major reductions in greenhouse gas emissions to the atmosphere, terrestrial ecosystems worldwide are at risk of major transformation, with accompanying disruption of ecosystem services and impacts on biodiversity.

Terrestrial ecosystem function is governed largely by the composition and physical structure of vegetation (*1*–*3*), and climate change impacts on vegetation can potentially cause disruption of ecosystem services and loss of biodiversity (*4*, *5*). It is critical to assess the likely extent of ecosystem transformation as global greenhouse gas (GHG) emissions increase (*6*) and to understand the full potential magnitude of impacts should current GHG emission rates continue unabated.

Ecosystem transformation generally involves the replacement of dominant plant species or functional types by others, whether recruited locally or migrating from afar. Observations from around the globe indicate that current climate change may already be driving substantial changes in vegetation composition and structure (*3*). Ecosystem change is accelerated by mass mortality of incumbent dominants (*7*, *8*), and widespread dieback events and other large disturbances are already under way in many forests and woodlands (*9*–*11*), with further mortality events predicted under increasing temperatures and drought (*3*, *9*, *10*, *12*). Replacement of predisturbance dominants by other species and growth forms has been widely documented (*8*, *13*, *14*). In addition, evidence is accumulating for geographic range shifts in individual species, and climate change is interacting with invasive species, fire regimes, land use, and CO_2 increase to drive vegetation changes in many regions (*15*, *16*).

Beyond observations of recent and ongoing change, models indicate ecosystem transformation under climate projections for the 21st century. These include dynamic global vegetation models (*3*, *17*), species distribution models (*18*), and comparison of the multivariate climate distance between biomes with that between modern and future climates (*19*). However, the capacity for assessing the magnitudes of ecosystem transformation under future climate scenarios is limited by the difficulty of evaluating model performance against empirical records, particularly when projected climate states are novel (*19*, *20*).

Paleoecological records of past ecological responses to climate change provide an independent means for gauging the sensitivity of ecosystems to climate change. High-precision time-series studies indicate that local and regional ecosystems can shift rapidly, within years to decades, under abrupt climate change (*21*–*23*), but sites with such detailed chronologies are scarce. In this study, we used published reports to compile a global network of radiocarbon-dated paleoecological records of terrestrial vegetation composition and structure since the Last Glacial Maximum (LGM), ~21,000 years before the present (yr B.P.) (*24*). Most postglacial warming happened 16,000 to 10,000 yr B.P., although it commenced earlier in parts of the Southern Hemisphere (*25*, *26*). Global warming between the LGM and the early Holocene (10,000 yr B.P.) was on the order of 4 to 7°C, with more warming over land than oceans (*26*, *27*). These estimates are roughly comparable to the magnitude of warming that Earth is projected to undergo in the next 100 to 150 years if GHG emissions are not reduced substantially (*28*). The magnitudes of changes in vegetation composition and structure since the last glacial period (LGP) provide an index of the magnitude of ecosystem change that may be expected under warming of similar magnitude in the coming century (*29*). Although the rate of projected future global warming is at least an order of magnitude greater than that of the last glacial-to-interglacial transition (*26*), a glacial-to-modern comparison provides a conservative estimate of the extent of ecological transformation to which the planet will be committed under future climate scenarios.

We reviewed and evaluated paleoecological (pollen and macrofossil) records from 594 sites

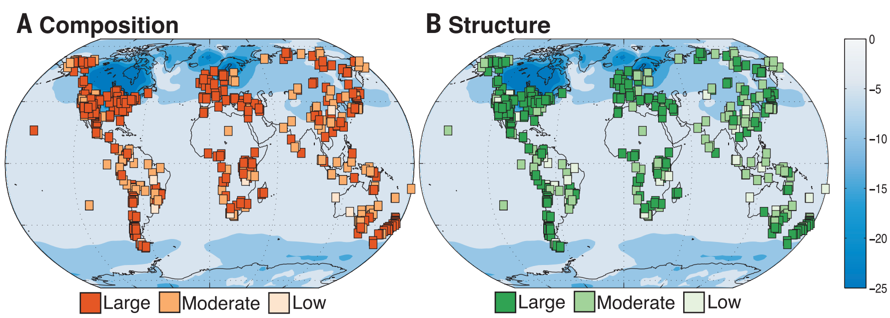

Fig. 1. Vegetation differences between the LGP and the present. Each square represents an individual paleoecological site. The color density indicates the magnitude of estimated vegetation change since the LGP (21,000 to 14,000 yr B.P.). Background shading denotes the estimated temperature anomaly between the LGM 21,000 years ago and today on the basis of assimilated proxy-data and model estimates (*27*). (**A**) Composition. (**B**) Structure.