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Modeling global vegetation in the late Quaternary: What progress have we made and what are the priorities for the future?

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More than two decades ago, the development of the first global biogeography models led to an interest in simulating global land cover in the past. These models promised the possibility of creating a coherent picture of the Earth's vegetation that went beyond qualitative extrapolation of site-based observations, e.g., from paleoecological archives, and was not limited to areas with a high density of sites. Then as now, the goal of much work simulating past vegetation was to explore and understand the role of biogeophysical and biogeochemical feedbacks between the Earth's land surface and the climate system. Paleovegetation modeling for the late Quaternary has also influenced debates on the character of natural vegetation, conservation and ecological restoration goals, and the co-evolution of humans, civilizations, and the landscapes in which they live.

The first simulations of global land cover in the past used equilibrium vegetation models, e.g., BIOME1, BIOME3, and BIOME4, and focused on well-known timeslices of interest in paleoclimate research, including the Last Glacial Maximum (21,000 BP) and the mid-Holocene (6,000 BP). Questions addressed included: quantification of the importance of terrestrial vegetation in the glacial carbon cycle, the role of changing vegetation cover on glacial inception, and the influence of biogeophysical feedbacks on the amplitude and spatial pattern of the mid-Holocene African Monsoon. In the intervening years, as both vegetation and climate models evolved and improved, the spatial resolution, number of periods studied, and the type of research questions addressed expanded greatly. Studies covered the dynamics of Arctic vegetation, wetland area, wetland methane emissions, and paleo-atmospheric chemistry, dust emissions and effects on paleoclimate, among others.

A major recent advance in paleovegetation modeling for the late Quaternary has come with the development of Dynamic Global Vegetation Models (DGVMs) that are capable of simulating changing vegetation cover over time, continuously. Several DGVMs have been directly incorporated into the land surface scheme of modern Earth System Models (ESMs), further allowing the exploration of land-atmosphere feedbacks, e.g., during abrupt climate change events, such as those that occurred during the last deglaciation. Recent increases in computer power have also allowed offline simulations, i.e. not directly coupled to an ESM, with DGVMs to simulate vegetation change over long time periods, e.g., continuously for the entire Holocene. Realizing that climate change alone was not the only driver of land cover change over the late Quaternary, the most recent developments in paleovegetation modeling for this period have incorporated human agency as an influence on vegetation. Incorporation of scenarios of Anthropogenic Land Cover Change into DGVMs has allowed a quantitative contribution to the ongoing, lively debate regarding the role of humans in influencing Holocene atmospheric greenhouse gas concentrations.

With the further advances in ESMs and the availability of very long climate model simulations, e.g., TraCE-21ka, improvements to DGVMs such as the explicit representation of age structure and plant traits, and the increasing awareness of the importance of human-environment interactions, the future of paleovegetation modeling for the late Quaternary presents a variety of opportunities. One important focus for future modeling should be on simulating the dynamics of ecotones, e.g., forest-grassland boundaries, over time, particularly during abrupt transient climate change events. Accurate simulation of ecotone boundaries is traditionally a weakness in DGVMs, yet these environments are highly valued by humans for their ecosystem services both at present and in the past, paleoecological evidence suggests that ecotone boundaries were very sensitive to past climate change, and they are critical locations where land-atmosphere feedbacks could have amplified or attenuated ongoing, externally-forced climate change. Lessons drawn from paleovegetation simulations may shed new light on the behavior of the earth system that will be valuable for understanding the future.