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Isoscapes to Address Large-Scale Earth Science Challenges

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Sugar cane cropping for biofuel production reduces water discharge from a northern Indian basin and threatens downstream communities. Regulators want to partition blame between climate change–induced declines in mountain snowpack and excessive evaporation from poorly managed fields. In the same basin, a tiger is found shot. Is it the nuisance animal that has been tormenting local communities, or is it a different animal poached from the upland forests?

Insight into these issues may lie in a new approach to analyzing and interpreting isotopic data.

Stable isotopes of hydrogen (H), carbon (C), nitrogen (N), oxygen (O), and heavy elements like strontium (Sr) vary in concentration within environmental substrates depending on spatially and temporally distributed Earth systems processes. The resulting geographically patterned variation in isotopic compositions of a substrate is known as an "isoscape."

The underlying premise behind isoscapes is that isotopic composition can be predicted as a function of time, location, and spatially explicit variables describing isotope-discriminating processes. Models of isoscapes therefore provide a means of interpreting observed isotopic data in terms of spatial patterns within Earth systems. Well-calibrated models also help predict patterns of environmental isotope variation that can be used to "fingerprint" the origin of geological and biological materials.

For example, in the global water cycle, heavy isotopes of hydrogen and oxygen tend to preferentially precipitate early on as clouds move across land, leading to strong, predictable spatial partitioning of water isotopes across landscapes. Analysis of isotopic data relative to precipitation isoscape models provides information that cannot routinely be recovered from concentration measurements or elemental chemistry alone, such as on sources of water to the atmosphere or the location of origin of plant tissues synthesized using local water.

Recent and future increases in data availability and the development of user-friendly, geographic information system (GIS)–based spatial modeling tools are opening doors to new uses of isotopes. These developments promise to expand the use of isoscapes in carbon cycle science and migration ecology and advance new approaches in areas such as water cycle science, biogeochemistry, anthropology, and forensic science.

Identifying Carbon Sources and Sinks

In studies of anthropogenic perturbations of the global carbon cycle, networked measurements of carbon dioxide (CO_2) concentrations can be used to identify regional sources or sinks of carbon, but cannot directly attribute these fluxes to specific processes.

To learn more, scientists can study carbon isotopes through high-precision monitoring that documents the spatial and temporal trends in the ratio of carbon-13 to carbon-12 within atmospheric CO_2 ($\delta^{13}CO_2$). Variations of $\delta^{13}CO_2$ values along seasonal cycles and latitudinal gradients reflect the integration of biosphere-atmosphere processes and anthropogenic emissions. For example, during photosynthesis, plants preferentially assimilate isotopically light carbon—thus, decomposing and burning plant material or fossil fuels will release ^{13}C-depleted CO_2 into the atmosphere. This creates seasonal oscillations in ^{13}C-depleted CO_2 driven by net summertime uptake to and wintertime release from terrestrial ecosystems, along with a long-term decrease in $\delta^{13}CO_2$ associated with the anthropogenic emission of ^{13}C-depleted CO_2 from fossil fuel burning and deforestation (Figure 1a).

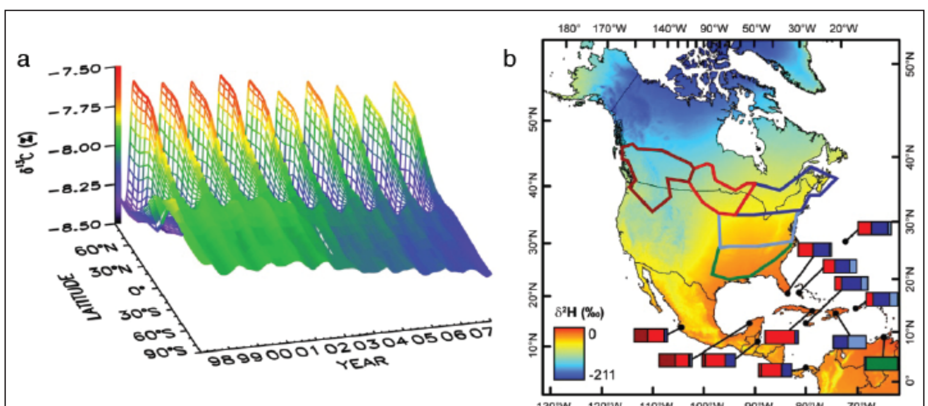

*Fig. 1. Isoscapes and spatial isotope applications. (a) Isotope map showing variation in the carbon isotope ratio of atmospheric CO_2 with latitude and time from the U.S. National Oceanic and Atmospheric Administration's (NOAA) Global Flask Network of more than 55 sites. The patterns shown reflect fluxes of ^{13}C-depleted carbon between the atmosphere and the terrestrial biosphere (e.g., seasonal cycles reflecting summer uptake and winter release of C from the biosphere) and fossil fuels (e.g., long-term decrease in $\delta^{13}C$ due to burning of ^{13}C-depleted fossil fuel). This isoscape can be used to quantify these fluxes through inverse modeling. Image courtesy of the Institute of Arctic and Alpine Research, University of Colorado, and NOAA Global Monitoring Division. (b) Connectivity between American Redstart winter range (dots) and summer range (polygons) from 2001 to 2004 based on comparison of H isotope ratios in feathers to an isotope map for H in water. The background color map is based on data from the Global Network for Isotopes in Precipitation (see http://www-naweb.iaea.org/napc/ih/index.html). Bars show the fraction of birds sampled at each wintering site that were assigned to each summer range based on a maximum likelihood criterion [*Norris et al., *2006].*

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Through atmospheric models that include isoscapes, this $\delta^{13}CO_2$ variability can be translated into quantitative estimates of the magnitude and spatial distribution of CO_2 fluxes to or from the atmosphere. For example, the long-term decline in $\delta^{13}C$ values of CO_2 illustrated in Figure 1a allows scientists to partition uptake of anthropogenic CO_2 by the oceans (with minimal carbon isotopic fractionation) and terrestrial biota (with preference for ^{12}C). Results from this approach were among the first to suggest a large Northern Hemisphere land sink for anthropogenic CO_2 [e.g., *Ciais et al.*, 1995].

Building from this isoscape inversion method—where scientists take the isotopic signatures recorded through time and work backward to infer locations and pathways of carbon emission and uptake—scientists are now working to understand and model terrestrial and oceanic carbon isotope fractionation in more detail and at higher spatiotemporal resolution. Combining these efforts with more abundant monitoring data for atmospheric $^{13}CO_2$ may provide new opportunities to understand biosphere "breathing" [e.g., *Rayner et al.*, 2008].

Tracking Migratory Animals

In animal migration research, extremely low recovery rates by traditional methods such as mark-recapture and practical constraints associated with new technologies (e.g., prohibitive cost and size of satellite tags) have severely limited understanding of the behavior of many migratory animals that are of interest to those in conservation, evolution, and public health. Around the end of the twentieth century, researchers capitalized on a long-term project that monitored precipitation water isotope ratios (Global Network for Isotopes in Precipitation (GNIP); http://www.naweb.iaea.org/napc/ih/index.html) and developed a new approach that used the stable H isotope ratios of body tissues such as claws and bird feathers.

Feathers of most migratory bird species are grown during a fixed window of time prior to migration, and are chemically inert following formation. Feather samples from birds captured at the end of their migration can therefore be analyzed for H isotopes, and a region of origin for the birds can be determined based on GNIP-derived water isoscapes and models of isotopic fractionation between water and feather keratin. For example, using feathers from birds wintering in the Caribbean, *Norris et al.* [2006] found systematic, geographic patterns of migration for the American Redstart (Figure 1b). Such information can be combined with data from other isotopic or elemental systems (e.g., C or Sr isotope ratios) and measurements of tissues that record more recent dietary intake (e.g., blood, muscle) to document an animal's migratory movements and behavior with increased specificity (e.g., revealing shifts in diet during the course of migration).

The resultant method of migratory tracing using inherent, isotopic tracers has provided unprecedented documentation of animal migration behavior, supporting conservation efforts and an improved modeling of the evolution of migratory behavior [e.g., *Clegg et al.*, 2003]. A particular strength of the method is its broad generality, and recent work has extended hydrogen isotope tracing to a range of nonavian ecological systems [*Hobson and Wassenaar*, 2008]. Similar methods using other isotopic systems promise to advance our understanding of animal movement within the marine realm, although the relative lack of observational data for marine systems must be overcome.

Future Applications

As scientific infrastructure and technology advance, opportunities to generalize and apply the isoscapes concept in different fields will continue to grow.

In water cycle research, mature isotopic theory exists to support estimates of evaporation and transpiration partitioning over large scales, providing unique information on regional water balance, ecosystem gas-exchange physiology, and latent heat flux [*Ferguson et al.*, 2007]. Building on this, scientists can also identify changes in water sources within large hydrological systems. For example, a community in India curious about whether water reduction resulted from reduced mountain runoff or from agricultural changes could gain insight from water isoscapes, which could be used to quantify the amount of water derived from mountain sources; these sources are generally depleted in ^{2}H and ^{18}O.

The isoscapes approach has shown great potential in applied fields such as forensic science and trade regulation. The region of origin of illicit drugs and products can be constrained using isotopes of elements such as C, N, H, and O, allowing law enforcement agencies to target their efforts to eliminate sources and reduce trafficking of such substances [*Ehleringer et al.*, 2000]. The same principle can be applied to foods and commercial products, allowing regulatory agencies and trade organizations to test the authenticity of products and identify cases of fraud. Isotopic signatures taken up by animal body tissues can similarly be related to location of origin. In the case of the dead tiger found in India, for example, isoscapes could reveal the elevation at which a poached animal lived or whether it fed in natural or human-influenced food webs.

Isoscapes of human hair and fingernails can also help identify the travel history of individuals. As with reconstruction of bird migration, continuously growing tissues such as hair or nails can serve as a "tape recorder" of recent travel. Even in modern human society, where travel and long-distance distribution of food and beverages are the norm, the locally varying contribution of environmental water isotopes to the human body leads to strong geographic variation in hair and nail isotope ratios [*Ehleringer et al.*, 2008]. As a result, isoscapes can be used to estimate the origin of unidentified corpses, verify travel histories reported by suspected criminals, or reconstruct the last wanderings of mummified prehistoric humans.

The fusion of spatially distributed isotope data with isoscape models could even be used to help characterize the spatially distributed environmental impacts of human activities. For example, isoscapes for nitrogen deposition in the northeastern United States show strong, spatially coherent patterns of $\delta^{15}N$ variation, suggesting regional variation in sources of nitrogen oxides (NO_x), which are strong pollutants generated by combustion [*Elliott et al.*, 2007]. With improvements in isotopic modeling of such systems, accurate attribution of pollutants to specific sources may become a reality.

The Path Forward

Given that the isoscapes approach involves the analysis of spatial isotopic variability, commonly over large geographic regions, it often requires data collection beyond the scope of short-term, single-investigator projects. Fortunately, several emerging scientific monitoring programs within the U.S. research community, such as the National Ecological Observatory Network (NEON; http://www.neoninc.org) and the Water and Environmental Research Systems (WATERS; http://www.watersnet.org) network, are well poised to facilitate advances in isoscapes-based research.

Nonetheless, networks that are not defined by political boundaries are preferable and may be attainable through coordination with programs administered by organizations such as the European Union and the International Atomic Energy Agency. To maximize the usefulness of isotope data gathered from such programs, emphasis should be placed on standardized measurements of substrates that provide signals of local or regional processes (e.g., atmospheric aerosols and trace gases, water and aqueous solutes). The development of such international programs will rapidly grow data availability and foster new isoscape-based approaches to regional, national, and global challenges.

Isoscapes have great power as a cross-disciplinary research tool, as exemplified by the translation of hydrology-focused GNIP data into tools for animal migration research. To promote this, the U.S. National Science Foundation (NSF) is supporting an effort to develop new cyberinfrastructure for analysis and visualization of spatiotemporal isotope distributions (Isoscape Modeling, Analysis, and Prediction (IsoMAP); http://isomap.org). This resource will help researchers conduct isotope data exploration, modeling, and spatial analysis in a Web-GIS environment and will provide a platform for sharing models and derived data products within and beyond the community of specialists. Near–real time environmental data sets will be integrated to support modeling in IsoMAP, enabling the development of new isotope maps with finer temporal resolution. Integration of isotope models within other Web-based spatial data analysis tools such as Carbon Tracker (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/) will further advance the proliferation of isoscape data products.

Finally, a steady stream of advances in technology and theory promise to open new frontiers for isoscape-based research. Improvements in laser-based optical technology are enabling a new generation of rapid, inexpensive spectroscopic instruments for isotope measurements, and these systems soon may be routinely deployed in the field to support networked monitoring efforts. For some systems there is potential to directly measure spatial isotope distributions using remotely sensed data [*Worden et al.*, 2007], allowing comparison with isotope maps from empirical or process-based models. Additionally, the development and integration of new isotopic and GIS theory will lead to improved prediction and analysis of spatial isotope distributions and new applications to systems with complex spatial connectivity and geometry (e.g., river networks and urban ecosystems).

Research capitalizing on the isoscapes paradigm is uniquely poised to shed light on scientific challenges involving large-scale movement and spatially distributed biogeochemical processes, and the stage is set for widespread application to broad research problems and societal concerns. This work requires the melding of spatially distributed data with spatial models of isotope distributions and isotope-fractionating processes. Ongoing developments in technology, data accessibility, and theory make this an exciting and promising time for the development of new isoscape-based approaches to complex questions.

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