Earth's air war: Explaining the delayed rise of plants and animals on land

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If you like the smell of spring roses, the sounds of summer bird song, and the colors of fall foliage, you have the stabilization of the ozone layer to thank for it. Located in the stratosphere, where it shields Earth from harmful ultraviolet radiation, the ozone layer plays a key role in preserving the planet's biodiversity.

Now we may have a better idea of why that took so long—more than 2 billion years—to happen.

According to a new, Yale-led study, Earth's early atmosphere hosted a battle royale between iodine and oxygen—effectively delaying the creation of a stable ozone layer that would shield complex life from much of the sun's ultraviolet radiation (UVR).

The new theory, described in a study in the journal *Proceedings of the National Academy of Sciences*, may solve a mystery that has puzzled scientists for hundreds of years.

"The origin and diversification of complex life on Earth remains one of the most profound and enduring questions in natural science," said Jingjun Liu, a doctoral student in Earth and planetary sciences at Yale and first and corresponding author of the new study.

Indeed, scientists have long wondered why land plants did not emerge on Earth until 450 million years ago, even though their progenitors, cyanobacteria, had been in existence for 2.7 billion years. Likewise, there are no fossils of complex land animals or plants before the Cambrian era (541 to 485 million years ago) despite the evidence of much older microfossils.

"The only existing explanation states that this delay is an intrinsic characteristic of evolution—that an enormous amount of time is required," said Noah Planavsky, a professor of Earth and planetary sciences, faculty member of the Yale Center for Natural Carbon Capture, and senior author of the new study. "Yet that notion fails to explain how and why complex life originated and diversified."

The new study suggests that something beyond the need for time was responsible: the delayed stabilization of Earth's ozone layer, caused by elevated marine iodine concentrations that prevented a protective UVR shield from forming in the atmosphere.

Ozone production depends on atmospheric oxygen and background UVR. It has been widely accepted by scientists that once Earth established a substantial concentration of atmospheric oxygen, the planet formed an ozone layer that allowed for biological evolution to proceed unimpeded.

"We challenge this paradigm by considering how Earth's evolving iodine cycle may have influenced ozone abundance and stability," Liu said.

For the study, a Yale-led research team analyzed multiple lines of independent geological evidence and developed an ocean-atmosphere model to reconstruct the iodine-ozone dynamics of early Earth. The researchers found that elevated marine iodide content (formed when iodine combines with another element to form a salt) prevailed throughout most of Earth's history, which would have led to significant inorganic iodine emissions into the atmosphere after the rise of oxygen—with the potential for disrupting ozone.

The mechanism of ozone destruction by iodine is similar to the process by which chlorofluorocarbons (CFCs) created the ozone hole over Antarctica. When CFCs undergo photolysis, they release reactive chlorine, which catalytically destroys ozone in the stratosphere, leading to as much as a 50% depletion over continental Antarctica at the peak of the problem.

"Iodine-driven catalytic cycles for ozone destruction follow a similar process and are kinetically much faster than those involving reactive chlorine," Planavsky said. "Our photochemical calculations indicate that even a moderate increase in marine inorganic iodine emission could result in a whole atmosphere ozone depletion by tens or even hundreds of times relative to modern levels."

Liu noted that at a global scale, unstable and low ozone levels likely persisted from 2.4 billion years ago until roughly half a billion years ago.

"During this interval, even under high levels of oxygen production, atmospheric ozone could have been very low and was likely unstable, leading to periodic or persistent high fluxes of solar UVR at Earth's surface," Liu said.

Dalton Hardisty of Michigan State University, James Kasting of Pennsylvania State University, and Mojtaba Fakhraee of Yale are co-authors of the study.

More information: Jingjun Liu et al, Evolution of the iodine cycle and the late stabilization of the Earth's ozone layer, *Proceedings of the National Academy of Sciences* (2025). DOI: 10.1073/pnas.2412898121

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