



## BIOGEOSCIENCES CONNECTING EARTH'S SPHERES FROM MICROSCOPIC TO GLOBAL SCALES

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**Biogeosciences is focused** on the interactions of marine and terrestrial life in and across the Earth's main spheres: the biosphere, atmosphere, hydrosphere and geosphere. These spheres are intricately connected and interact by exchanging energy and matter through biological, physical and chemical processes across a range of scales. Biochemically mediated reactions and transports across intracellular membranes occur at microscopic scales, yet they profoundly influence the composition of Earth's atmosphere and climate. Macroscopic properties, in turn, determine which biota and biochemical pathways are prevalent in various environments on Earth.

The wealth of interactions across spheres and scales leads to feedback mechanisms that can dampen or amplify natural and human influences. A striking example of a human perturbation to natural mass and energy flows on Earth is the steep rise in atmospheric carbon dioxide (CO<sub>2</sub>) due to fossil fuel combustion, cement production and deforestation, which leads to global warming and acidification of the ocean. Because of human influences, we now refer to the period since the beginning of industrialization as the Anthropocene. The Anthroposphere, i.e. the sphere that is directly influenced by humans, permeates practically all other spheres on Earth.

Perhaps the prime example of microscopic processes fundamentally altering the global environment and the course of evolution is the oxygenation of Earth's atmosphere and ocean about two billion years ago. On the early Earth free oxygen was rare. The rise of photosynthesis in single-celled marine algae led to the accumulation of oxygen in atmosphere and ocean, and thus made the evolution of diverse multicellular life forms possible. In today's ocean the explosive growth of single celled algae, which occurs when light and nutrient conditions are favourable, can create accumulations of biomass that are visible from space. During senescence of these blooms, organic matter sinks to the deep ocean effectively sequestering carbon at ocean depths and mitigating global warming. As the surface ocean warms, the efficiency of carbon export to the deep ocean may slow, potentially creating a positive feedback that would amplify warming.

The ocean has taken up a large fraction of anthropogenic CO<sub>2</sub> from the atmosphere (estimated at a third to half of anthropogenic emissions) by a combination of sinking organic matter and physical equilibration processes, and continues to do so. The ocean has thus slowed man-made global warming, but at a price to ocean ecosystems. The increase in ocean inorganic carbon concentrations acidifies ocean water, making it more corrosive to calcium carbonate, which forms the solid structures of many marine organisms from select phyto- and zooplankton species (phytoplankton are small drifting algae and zooplankton their equally small predators) to bivalves (clams, mussels, oysters) and crustaceans (lobsters, crabs, shrimp). Perhaps the best-known early victims of ocean acidification and warming will be coral reefs – elaborate calcium carbonate structures built by symbiotic coral-algae associations that provide shelter to diverse tropical ecosystems.

On land, photosynthetic activity by vegetation results in the largest flux of carbon between the biosphere and the atmosphere, a large portion of which returns to the atmosphere as respired CO<sub>2</sub> within timescales of days to weeks. A smaller part of the assimilated carbon transiently remains in living biomass and ultimately feeds into the large carbon reservoir of soils, where the unseen majority of microorganisms transform soil organic matter, in turn sustaining the supply of nutrients for the vegetation.

Substantial alterations of biogeochemical cycles also include land cover changes and the introduction of non-native species impacting the structure and functioning of ecosystems. Industrial fertilizer production, a major advance that enables feeding the growing human population, has also massively perturbed the nitrogen cycle. Increased nitrogen deposition, which may take place over distances as large as several hundred or even thousand kilometres from the sources of production/emission, has consequences for the balance of macro- and micronutrients of organisms from the smallest microbe to the largest organisms on Earth. The laws of stoichiometry determine to which degree and how efficiently organisms compete for and process the elements, take up and store carbon and release greenhouse gases to the atmosphere. While increased nitrogen inputs to ecosystems can enhance the capacity of the vegetation to take up CO<sub>2</sub> from the atmosphere, they also speed up the microbially driven nitrogen turnover in the soil and stimulate the emissions of nitrous oxide, a potent greenhouse gas whose global warming potential is almost 300 times as high

An algal bloom on Lake Erie was observed from space in 2011 and is thought to result from runoff of agricultural fertilizers.

Greenhouse gas measurements of grazed pasture requires a combination of complex measurement technology and the management of the cow herd. Each cow is equipped with a GPS sensor and a mastification sensor.

as for CO<sub>2</sub>. On the continental scale, agricultural practices have recently been suggested to contribute to turning a small continental carbon sink into a net source of radiative forcing for both Europe and Africa. Along the nitrogen cascade, deposited nitrogen may also leach from terrestrial ecosystems and have downstream consequences for rivers, streams, lakes and coastal oceans.

Dairy products play a growing role in the nutrition of the expanding world population. Key to the growing importance of dairy products is the husbandry of ruminants. Ruminants are mammals that can acquire nutrients from grasses by bacterial fermentation processes in their first stomach – a complex bioreactor. The fermentation creates a range of gaseous byproducts including the potent greenhouse gas methane, which escape in large enough quantities to alter atmospheric greenhouse gas concentrations and thus climate.

Biosphere-atmosphere exchange measurements by the eddy covariance technique are a typical example of how to bridge the scale from individual point sources, the cows, to the whole grazing field, typical on the hectare scale. The application of eddy covariance over pastures is challenging due to the spatially and temporally uneven distribution of the grazing animals. Individual cow positions can be recorded by GPS trackers to attribute fluxes to animal emissions using a dispersion model that makes assumptions about the upwind sources of the fluxes. Meaningful interpretation of measured fluxes can only be gained if several disciplines work together, ranging from the development of instrumentation, to numerical modelling and animal physiology.

Another potential influence of animal husbandry is the release of amines into the atmosphere, which act as condensation nuclei that stimulate cloud formation thereby increasing Earth's albedo and slowing down global warming. The process interactions span scales from microscopic (bacterial fermentation and cloud condensation nuclei) to scales of metres (cows and their human handlers) to global (climate on Earth).

Critical questions for civilization are to what degree the biosphere can absorb greenhouse gases, tolerate warming and other environmental perturbations, and maintain livable conditions on Earth. During a period of rapid losses of biodiversity across the globe we need to understand how organisms and their interactions influence the fluxes of matter and energy across scales, and how these patterns and processes are altered by changing environmental conditions.

Biogeosciences research includes a wide range of perspectives from laboratory studies that quantify processes under controlled conditions, and field investigations that observe complex natural systems with feedbacks, to theoretical and numerical modelling studies that synthesize observations and allow a scaling up of local observations in space and time. The buildup of information resembles a puzzle with infinite pieces, but each new piece sharpens the contour of a steadily evolving picture of intricate patterns and interacting processes from microscopic to global scales.

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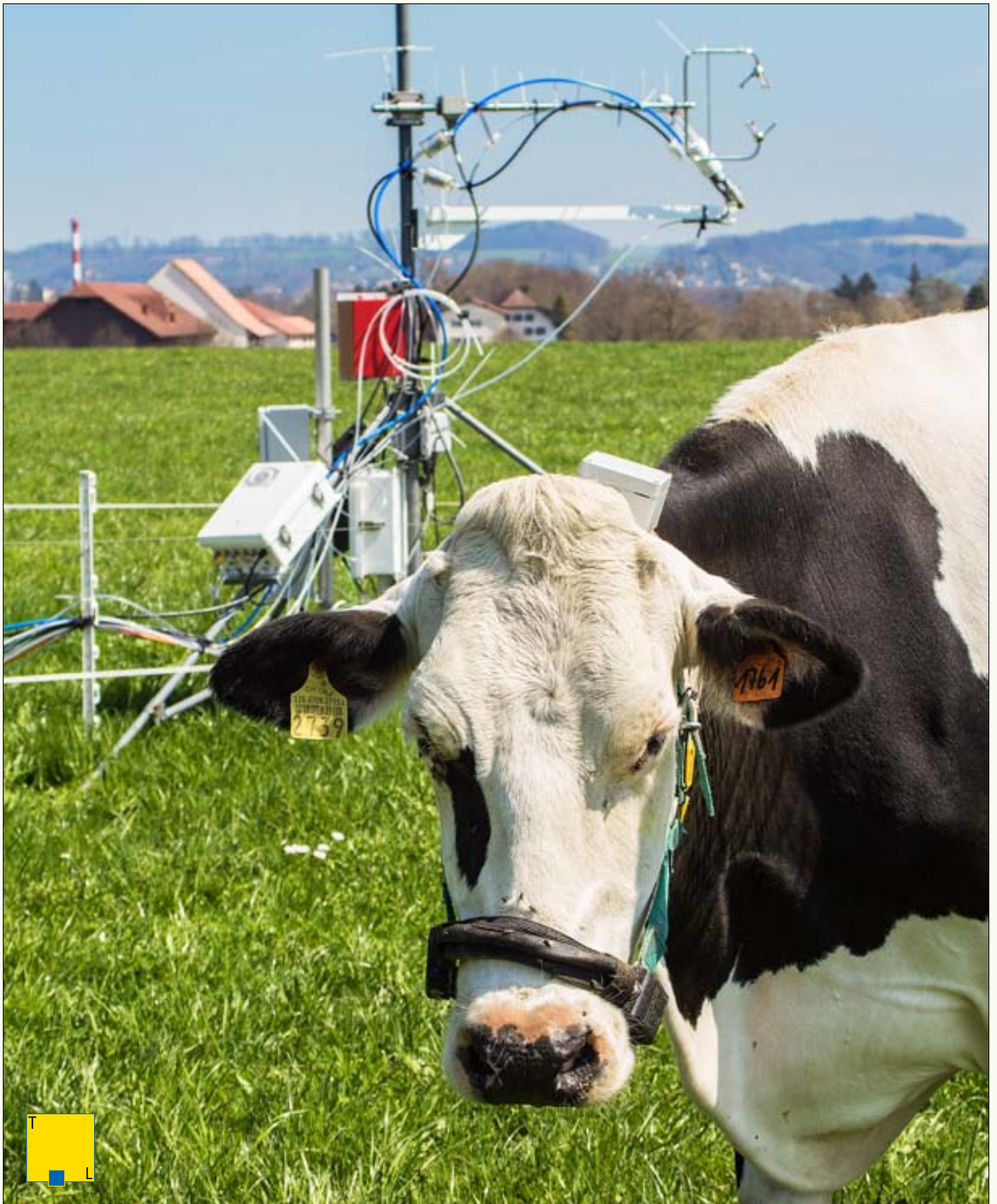
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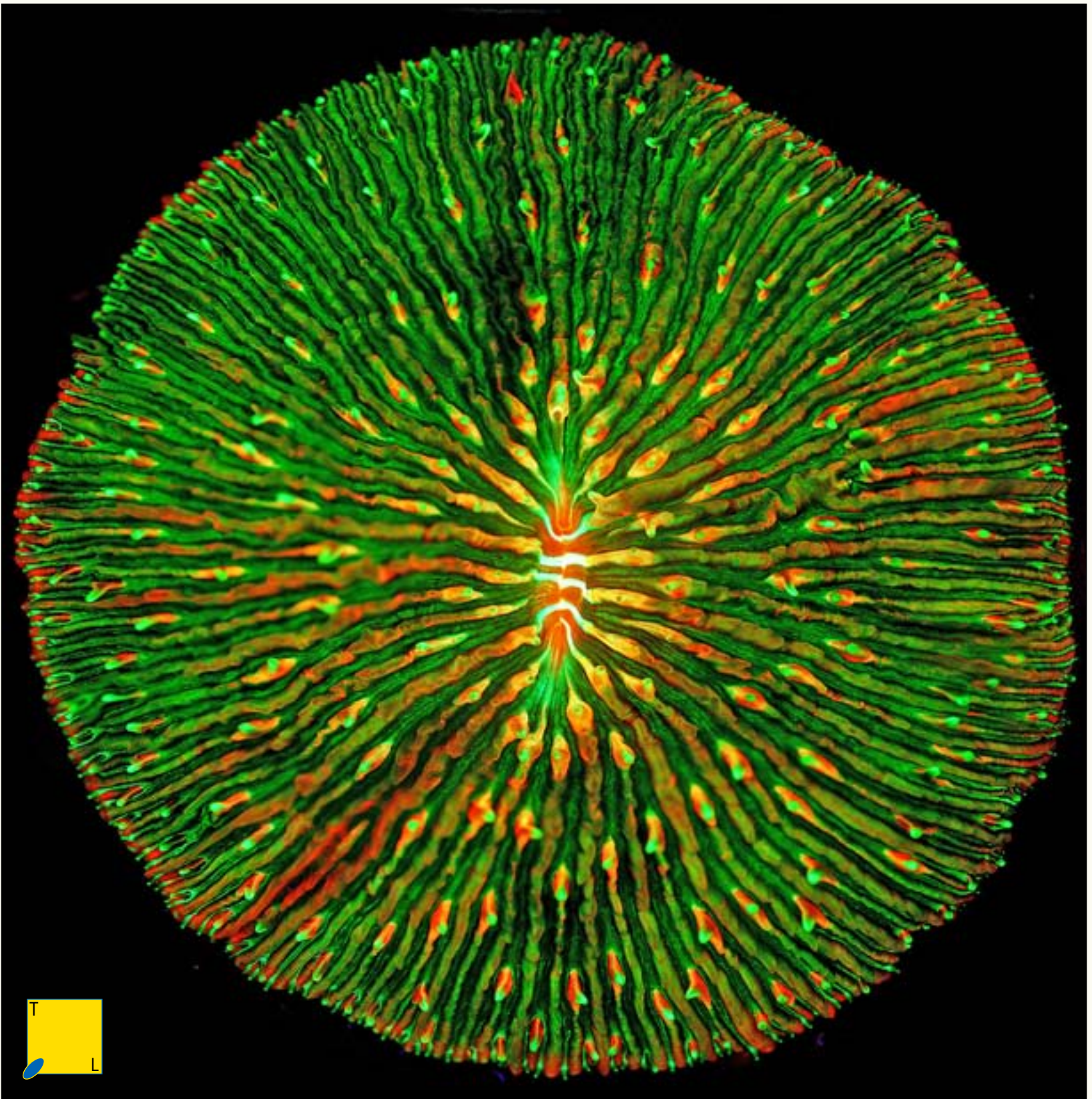
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A large single coral polyp under filtered light. This form of chromatography is used to diagnose disease in corals. The mouth is the vertical slit in its center.





The Global Challenge of Ocean Acidification  
<http://youtu.be/5cqCvcX7buo>



A garden of delicate coral in Kimbee Bay, Papua New Guinea, helps sustain local fishermen. Kimbee reef is a hotspot of biodiversity.