How does drought impact Amazon nutrient cycling?

By tracking the chemistry of dissolved organic matter at ATTO, we integrate plant and microbial activity to diagnose nutrient limits and how they are affected by drought stress. Our results provide insights into how Amazon forests sustain productivity on poor soils and why drought responses vary among forest types.

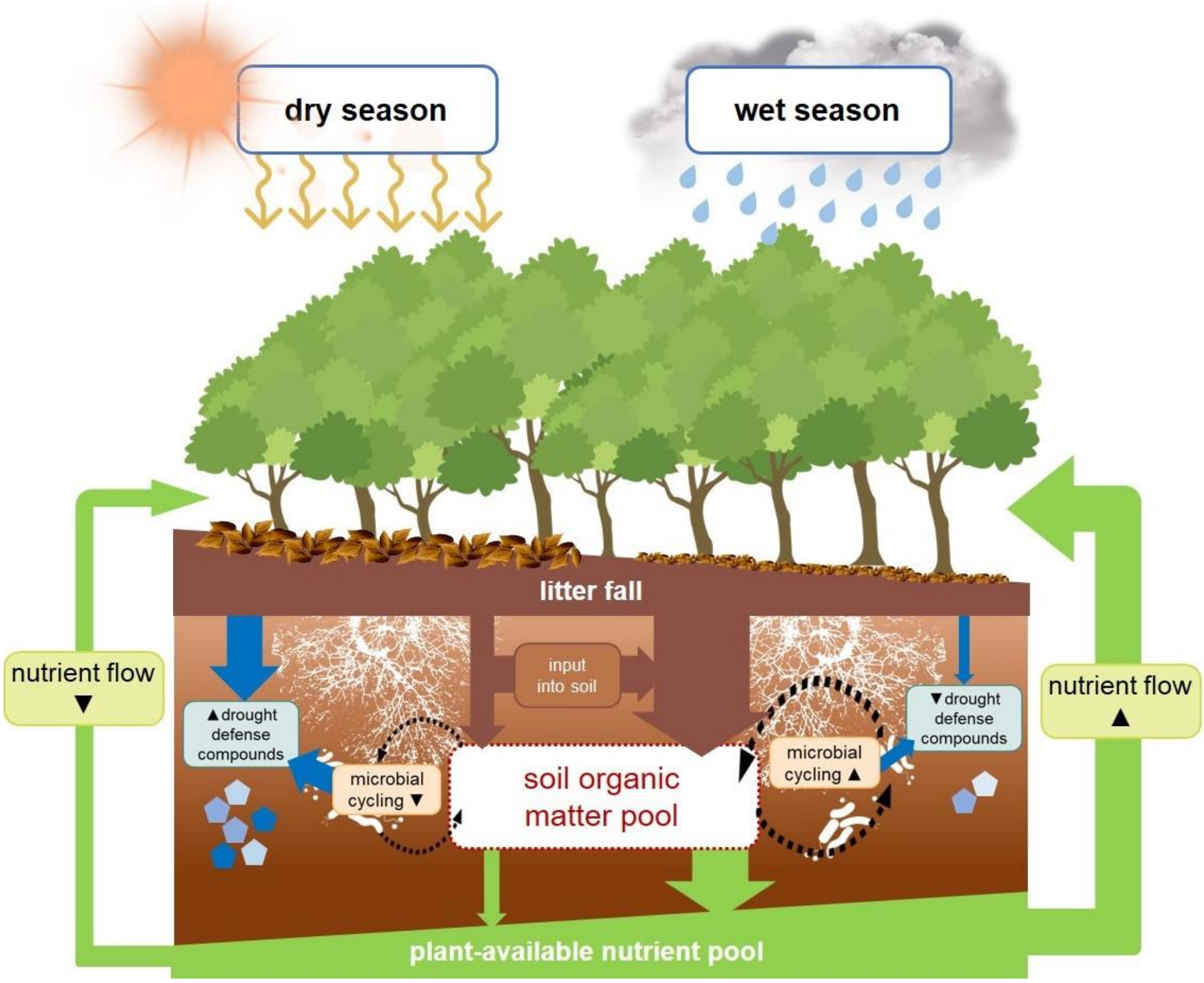

Figure 1. Seasonal drought brings more sunlight and less rainfall, and is a time of increased leaf litterfall. Dry soils reduce microbial activity, so less of this plant-derived litter is decomposed and incorporated into soils. When rain returns, the remaining dry-season litter is rapidly decomposed, and more dissolved organic matter (DOM) is leached from the litter into the soil below. Drought thus lowers plant-available nutrients and slows nutrient cycling; among the soluble compounds in DOM we find an accumulation of drought-defense compounds. Responses vary by forest type: in seasonally dry white-sand forests, litter decomposition declines, but soil organic matter decomposition and root exudation persist.

Preface

The Amazon rainforest is an important terrestrial carbon sink, offsetting anthropogenic CO_2 emissions[1]. The size of this sink depends on the balance between plant growth (its productivity) and decomposition of dead organic material. Rainforest soils, particularly near ATTO, are very nutrient-poor, and limited phosphorus availability constrains growth[2].

The interplay between plant productivity and the activity of microbial decomposers in soils is thus crucial for sustaining rainforest productivity and carbon storage. Recycling of organic matter and its nutrients supports soil microbial communities while releasing nutrients for plant growth[3].

Dissolved organic matter (DOM) - the most mobile and bioavailable fraction of organic molecules - plays a key role in nutrient cycling in tropical ecosystems and integrates and helps reveal the highly complex interactions between plants and the soil microbiome[4]. DOM in soils has multiple sources, each with distinct molecular signatures. For example, decomposing plant litter releases small, aromatic compounds. Plant roots exude diverse low-molecular-weight compounds to stimulate microbial activity, enhance nutrient uptake, and regulate interactions with soil organisms. In contrast, soil organic matter and microorganisms contribute larger, more aliphatic molecules. Microorganisms also produce stress-response compounds such as osmolytes during drought. Across these processes, microorganisms continuously decompose and transform DOM from all sources, generating a dynamic and complex soil chemistry.

Figure 2. Field sampling of soil pore water for the extraction of dissolved organic matter. Samples were collected using sintered glass suction plates installed at four sites at soil depths of 5, 10, 20, and 30.

Modern analytical techniques, such as ultra-high-resolution mass spectrometry, can resolve these interactions and create a detailed picture of environmental chemodiversity and molecular processes that are mediated by plants and microorganisms[5]. In parallel, molecular techniques like amplicon sequencing reveal the functional capacities of the soil microbiome, linking the genetic composition of microorganisms to the molecular composition of the surrounding water.

Nutrient limitations across the Amazon remain poorly understood and likely vary among rainforest types[6]. Understanding these differences across ecosystems is essential for predicting large-scale responses of the Amazon Basin to environmental change. Moreover, the impacts of regular and extreme drought on DOM cycling and soil microbial community dynamics remain largely unexplored in the Amazon rainforest, despite their importance for maintaining ecosystem functioning and productivity under a changing climate.

Relevance of ATTO observations

At the ATTO site, sintered glass collectors capture water freely percolating through surface litter and soil across four different forest types in the region. Every two weeks, the samples are analyzed for nutrients and the detailed molecular composition of dissolved organic matter. Soil samples from the same sites are collected to analyze the composition of the microbial community. This co-located, long-term sampling enables an integrated assessment of the complex biochemical and biological processes linking plants and soils. The resulting baseline clarifies ecosystem functioning under typical conditions and reveals responses to regular and extreme drought.

Nutrient limitation differs between *terra firme* and white-sand forests

Rising atmospheric CO_2 can stimulate photosynthesis, but forest growth responses in the Amazon depend on nutrient availability. Using DOM variability and derived soil process indicators, we assessed nutrient constraints across representative forest types.

Our findings confirmed phosphorus (P)-limitation in the widespread *terra firme* forests, including ancient river terraces with intermediate soil fertility, which was previously debated[7]. In contrast, white-sand forests showed no evidence of the expected nitrogen (N) limitation. Instead, our results point to potential sulfur (S) limitation. The high variability in S-containing DOM molecules and strongly elevated organic S gases production in white-sand soils, with potential implications for aerosol and cloud formation, and regional atmospheric chemistry. Early microbiome results align with these patterns: *terra firme* soils show greater functional potential for nutrient cycling than white-sand soils, while drought reduces P-, N-, and S-cycling capacities—especially in *terra firme*—consistent with DOM indicators.

Ecosystem activity during drought

Regular annual and extreme drought events are expected to intensify due to climate change[8], threatening ecosystem productivity and nutrient

cycling. During drought, white-sand forests reduce plant litter decomposition while maintaining soil organic matter decomposition and root exudation. This results in lower but sustained resource availability for plant communities[9].

Across both *terra firme* and white-sand forests, drought decreased decomposer taxa, overall microbial diversity and functional potential for C, N, and S-cycling processes, with effects amplified under prolonged and severe droughts, like El Niño events. DOM also showed elevated drought defense compounds, indicating significant ecosystem stress under dry conditions, with stress responses markedly amplified during extreme drought events. Initial year-to-year results point to limited microbial resilience after extreme droughts, implying slower recovery of nutrient cycling in already nutrient-poor soils.

Overall, we observed that nutrient constraints differ by ecosystem, and drought further suppresses nutrient cycling and availability. This undermines microbial metabolism, slows down DOM processing, and could depress long-term productivity if microbial communities do not recover fully after extreme drought events.

Continued multi-ecosystem monitoring is needed to evaluate post-drought recovery and reduce uncertainties in carbon and nutrient budgets.

Figure 3. Soil sampling for the determination of soil texture, pH, and nutrient content. Sample processing in the lab for the analysis of the soil parameters and the microbiome.

Recommendations

Understanding the Amazon rainforest's response to climate change is crucial due to its significant impact on the global climate. Based on our findings, we recommend:

- **Implement DOM-centered soil function monitoring on different forest types**. The use of high-resolution mass spectrometry to identify the many different compounds found in DOM is relatively new, and much remains to be understood about how best to use these data to link plant-soil-microbial processes that determine characteristics like nutrient availability. We recommend establishing more sites such as the ones at ATTO, where routine dissolved organic matter analysis is performed together with inorganic nutrients and core in situ variables (soil moisture, temperature, oxygen, etc.).

- **Translate DOM and microbiome shifts into understanding by extending local monitoring efforts.** DOM signatures provide sensitive, early indicators of nutrient limitation and drought stress, improving diagnosis of risks to productivity and carbon storage. In the ATTO region, a pilot project can use the four ATTO forest types in the region - especially *terra firme* and white-sand - using existing collectors and biweekly sampling to build a consistent baseline. Apply standardized protocols and QA/QC so results are comparable over time and across sites. The ATTO consortium, in partnership with INPA and regional environmental agencies, should coordinate operations and data stewardship.

- **Define clear thresholds in DOM chemistry (e.g., stress-response compounds; shifts in P- and S-bearing molecules) and in microbial community function that indicate mounting drought stress**. Use these to indicate and differentiate potential long-term impacts of severe drought events, including how quickly nutrient cycling functions decline and rebound, and the implications for resilience of forest functions like productivity.

- **Expand co-located microbiome–DOM research to assess resilience and recovery across more Amazon biomes.** Increase the number of sites with co-located soil microbiome and DOM samples. Use harmonized methods (amplicon/shotgun sequencing, functional inference aligned with DOM profiles) and maintain open, quality-controlled datasets.

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