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Functional regimes of soil-microbiomes

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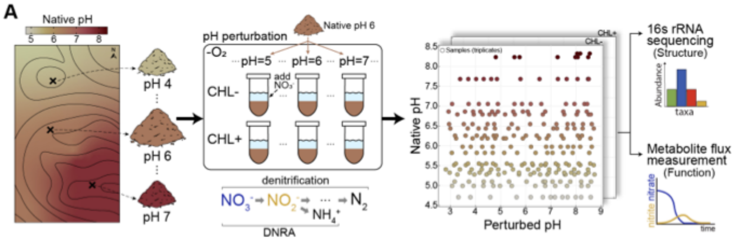

Figure 1 Soil microbiome metabolite and abundance dynamics under short and long-term pH variation. (A) Schematic of field sampling across a long-term pH gradient (20 soils, pH 4.7 to 8.3, Cook Agronomy Farm, Pullman, WA, USA). With each of the 20 soils, we created slurries. ~1,500 soil microcosms are depicted in a grid of different pH conditions (perturbed pH vs. native pH). Microcosms were incubated anaerobically for 4 days while nitrate and nitrite were quantified colorimetrically. Communities were quantified by 16S rRNA amplicon sequencing before and after incubation.

Our study aims to identify the "right variables" that describe the emergent dynamics of living systems—nonlinear and complex functions of naive ones. How can such variables be identified in the face of immense biological and abiotic complexity? We approach this challenge in the context of microbial ecosystems, specifically, nitrogen cycling in soil microbiomes, guided by three principles. First, we focus on collective metabolism rather than species abundances, shifting from traditional ecological models to a phenomenological mathematical framework based on quantitative metabolic measurements in natural soil settings. Second, rather than reducing complexity, we preserve the full biotic and abiotic landscape by integrating quantitative metabolic measurements with modeling in intact farmland soil microcosms. Third, we emphasize that microbial dynamics must be understood in relation to environmental context, as organisms adapt across multiple timescales. Using large-scale surveys of natural topsoil microbiomes, we experimentally characterize and mathematically model how collective metabolic dynamics vary with pH, a key factor in denitrification.

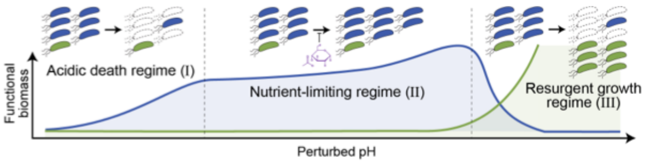

Figure 2: Schematic depicting three different functional regimes that capture how the soil community responds to pH perturbations. With moderate pH perturbations, the functional response can be characterized as the Nutrient-limiting regime (Regime II), where nitrate utilization is performed by dominant taxa (blue) that utilize nutrients released from the soil matrix. Growth is limited by available nutrients (purple). During strong basic perturbations, growth-limiting nutrients are in excess due to being released from the soil matrix, and rare taxa (green) rapidly outgrow dominant populations that cannot perform nitrate reduction in basic conditions (Resurgent growth regime, Regime III). Strong acidic perturbations exhibit little metabolic activity(Acidic death regime, Regime I). Functional biomass (y-axis) of the dominant (blue) and rare (green) taxa are shown by the lines.

Our results reveal three functional phases of microbial ecosystems—growth, stationary, and death— with transitions dictated by environmental pH. Near native soil pH, the system exists in a carbon-limited stationary phase. Strikingly, our findings suggest that pH adaptation occurs through pH-dependent carbon release from the soil, eliciting a near-linear, low-dimensional metabolic response. Under highly basic conditions, a resurgent growth phase emerges, driven by the proliferation of previously low-abundance strains, whereas extreme acidity leads to microbiome collapse and metabolic decline.

Reference: https://pubmed.ncbi.nlm.nih.gov/38559185/. This research was supported in part by grants from the NSF (DMS-2235451) and Simons Foundation (MP-TMPS-00005320).