Underexplored microbial metabolisms in agricultural soils: can they contribute to ecological nutrient management?

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Ecological Nutrient Management

Central argument: Inherent properties of native plant-soil systems facilitate nutrient use efficiency by enabling diverse, adaptive microbial metabolisms (Table 1).

Table 1. Habitat conditions in native soils that can promote microbial metabolic diversity

"Target" native soil property	Microbial habitat conditions
Biophysical integrity	Greater retention of CO_2 and volatile compounds within the soil; *in situ* microbial adaptation?
High proportion of macroaggregate volume	More varied biochemical gradients and micro-site heterogeneity (Eh, pH, pO_2, pCO_2, volatile organics)
Macropore connectivity and tortuosity	Facilitated diffusion of gases and volatile compounds
High root density and turnover	Increased proportion of rhizosphere-affected soil and particulate carbon substrates
Long periods of root exudation	Increased supply of labile carbon substrates
Diversified root exudates	More varied supply of labile carbon substrates

How might integrated agricultural management practices achieve soil conditions that begin to simulate those in native soils to improve nutrient use efficiency?

- Reduced tillage or no-till helps restore biophysical integrity and micro-site heterogeneity
- Zone tillage maintains "propagule banks" for microbial recolonization
- Cover cropping increases root density and diversity (temporally and spatially)
- Legume rotations increase biological N_2 fixation, H_2 supply, and organic N inputs
- Organic amendments enhance and diversify carbon supply

Microbial processes known to occur in soils but which are relatively unexplored for their potential to improve nutrient use efficiency in agriculture are: 1) heterotrophic CO_2 consumption; 2) H_2 uptake; and 3) N cycle diversification.

1. Heterotrophic consumption of CO_2

It has long been known that CO_2 stimulates the growth of microorganisms because it is assimilated in "anaplerotic" reactions of the TCA cycle, e.g., carboxylation of pyruvate to oxaloacetate (Krebs, 1941).

Roslev et al. (2004) demonstrated assimilation of $^{13}CO_2$ into membrane lipids by diverse heterotrophic bacteria. Between 1.4-6.5% of the biomass of bacterial cultures grown in complex medium was derived from CO_2.

In a study by Miltner et al. (2005), $^{14}CO_2$ incorporation into organic matter was enhanced in the presence of labile carbon (manure) to soils.

CO_2 incorporation was linearly related to respiration and amounted to 3-5% of net respired C in 20 days. After 20 days, CO_2 uptake slowed and accounted for 1-2% of respiration (Figs. 1a-b).

It therefore follows that microbial growth and mineralization activity would be favored in the presence of higher CO_2 concentrations in low-disturbance-higher-carbon soils.

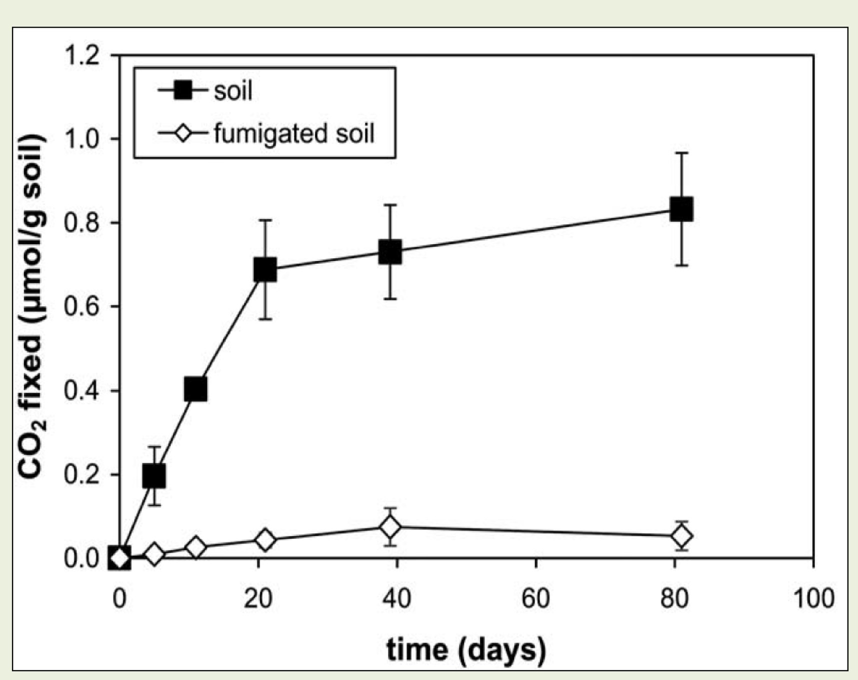


Fig. 1a. Amounts of CO_2 fixed

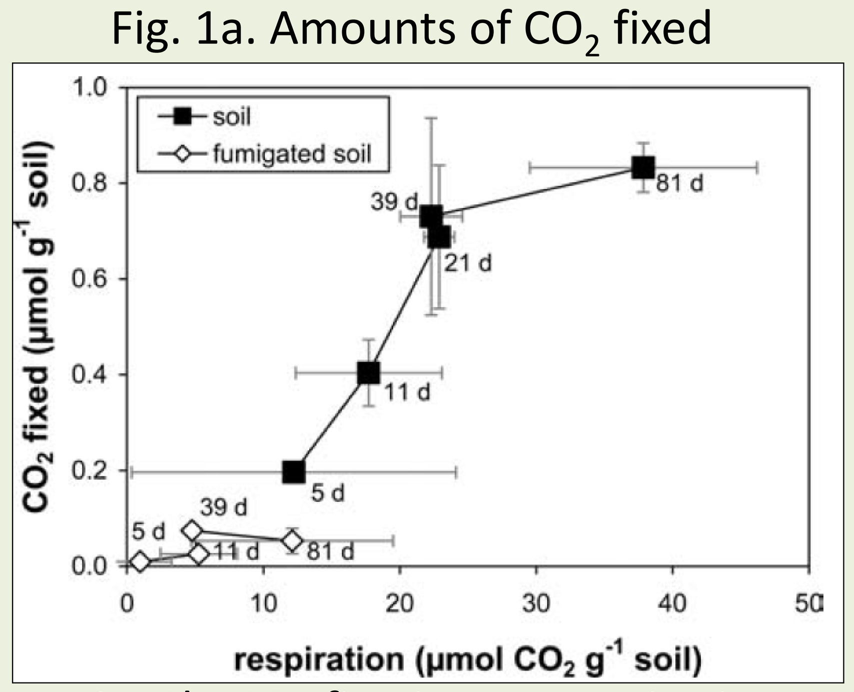


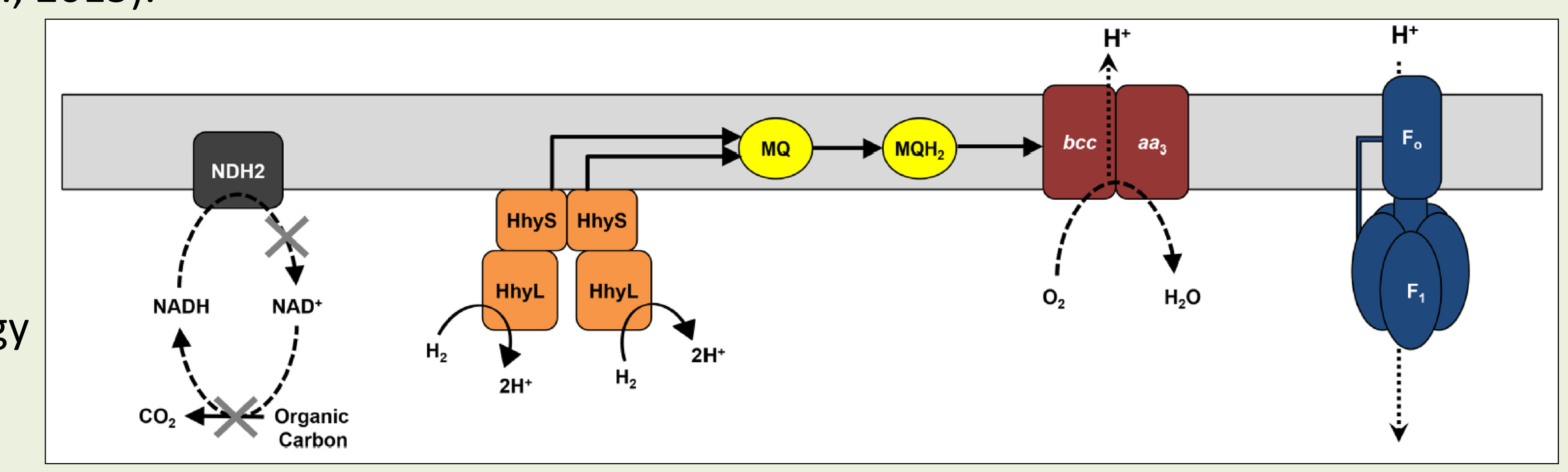
Fig. 1b. CO_2 fixation vs. respiration

2. H_2 uptake for energy supplementation

Trace concentrations of H_2 are present in the lower atmosphere (530 ppbv), where H_2 molecules have average lifetimes of 1.4 years. Biological consumption by soils is the main sink, with estimates of annual H_2 uptake up to 88 Tg (Rhee et al., 2006).

Atmospheric scavenging by "high-affinity" H_2 oxidizers (i.e., *Actinobacteria* spp.) is proposed to play a "major role in sustaining aerated soil communities…during periods of nutrient deprivation" (Figure 12 from Greening et al., 2015).

Figure 2. Proposed pathway of H_2 oxidation by "high-affinity" hydrogenase enzymes during energy starvation



In soils, H_2 is produced by fermentation and N_2 fixation, and H_2 concentrations can vary across micro-sites by several orders of magnitude. H_2 passes readily through lipid membranes, with assumed to be taken up rapidly by diverse, "low-affinity" H2 oxidizers (Alpha-, Beta-, Gammaproteobacteria) without ever entering the atmosphere.

Whole soils exhibit biphasic consumption of H_2, demonstrating presence of both low- and high-affinity populations (Greening et al., 2015).

Low-disturbance-higher-carbon soils should support higher H_2 concentrations over longer time periods, thus expanding the overall energy supply for microbial nutrient processing.

3. More circuitous and diversified N cycle pathways

Globally, only 40-50% of fertilizer N is taken up by crops, with the remainder lost as leached nitrate or denitrified N gases.

Conditions in low-disturbance-higher-carbon soils could put microbial "brakes" on N loss rates through:

- Increased carbon supply for heterotrophic recycling of N [$NH_4^+ \leftrightarrow$ cellular N $\leftrightarrow$ mineralized organic N], making NH_4^+ less available to autotrophic nitrifiers (Fig. 3)
- Higher H_2 concentrations in soil atmosphere fuels heterotrophic activity and lowers oxidative capacity to favor N speciation in reduced rather than oxidized states
- Lower Eh and small molecular weight carbon compounds favor dissimilatory nitrate reduction to ammonium (DNRA). Up to 5% of $NH_4{}^{15}NO_3$ was converted to 15NH4+ om 2 days in soils with added carbon (Schmidt et al., 2011)
- Increased utilization of biological N_2 introduces N into soil in carbon-associated forms. Cell-bound and organic N forms undergo nitrification less readily, because cells must die and be mineralized before NH_4^+ is released

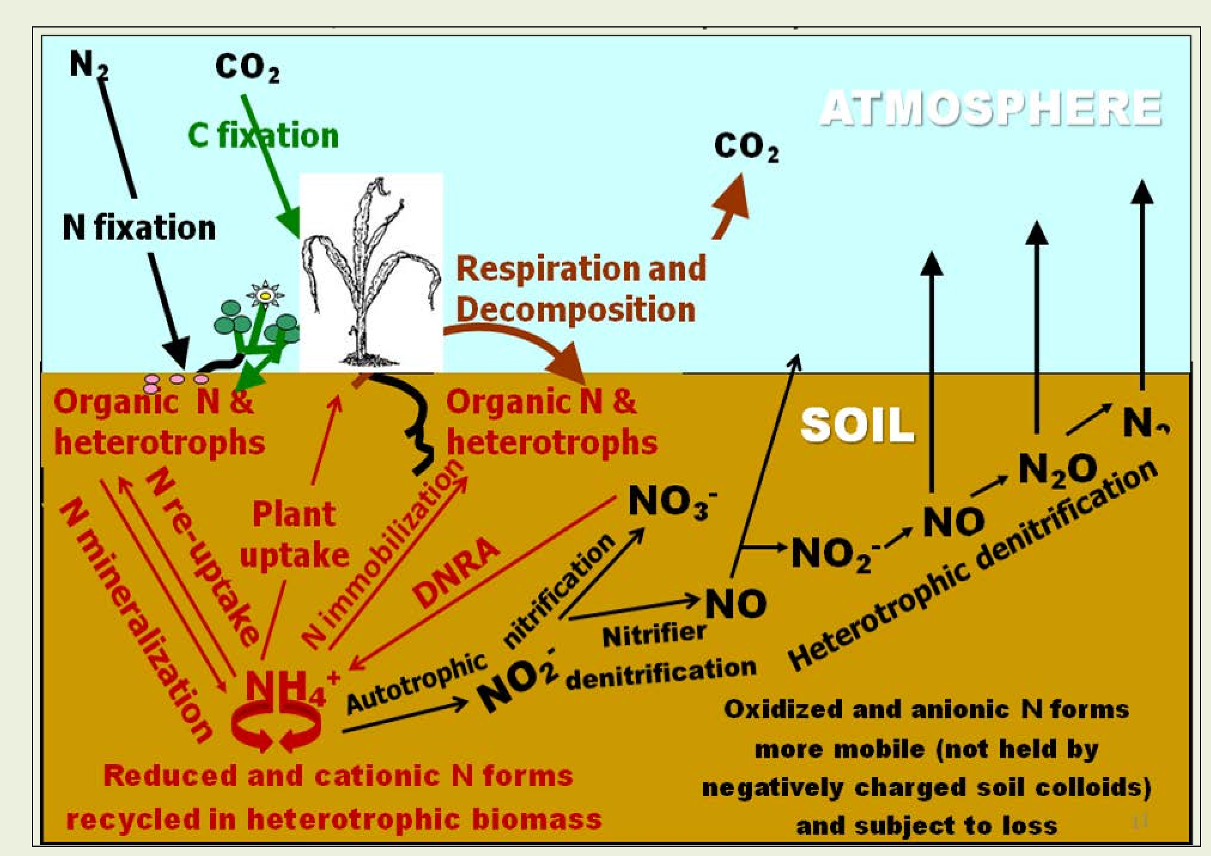


Fig. 3. Nitrogen oxidation processes (shown in black) result in faster N losses from system. Maintenance of N in reduced forms increases N recycling and retetntion.

References

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