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PERSPECTIVE CLIMATE CHANGE

Greenhouse gas mitigation requires caution

Strategies to mitigate emissions must consider methane and nitrous oxide together

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Methane (CH_4) and nitrous oxide (N_2O) are greenhouse gases that rank second and third behind carbon dioxide (CO_2) as primary contributors to global warming and climate change. Outside of fossil sources, these gases are emitted by microorganisms as they interact with their environment. Many strategies have targeted reduction of methane emissions. Although such efforts are well meaning, the microbial communities that live in these settings can respond to mitigation efforts by producing more N_2O, which reduces or even negates the positive climate impact (*1*, *2*). Mitigation approaches too often have not accounted for these trade-offs, and doing so requires additional monitoring to make sure any specific strategy achieves a net climate benefit.

Compared to CO_2, N_2O is 300 times more potent in holding heat on a 100-year timescale. Methane is over 80 times more potent on a 20-year timescale. Outside of fossil sources, CH_4 and N_2O emissions from soils, wetlands, agriculture, thawing permafrost and Arctic lakes, wastewater, and land-use change are largely controlled by microorganisms and their activities in concert with chemical and physical properties of the environment. A portion of these emissions is exacerbated by human activities (*1*).

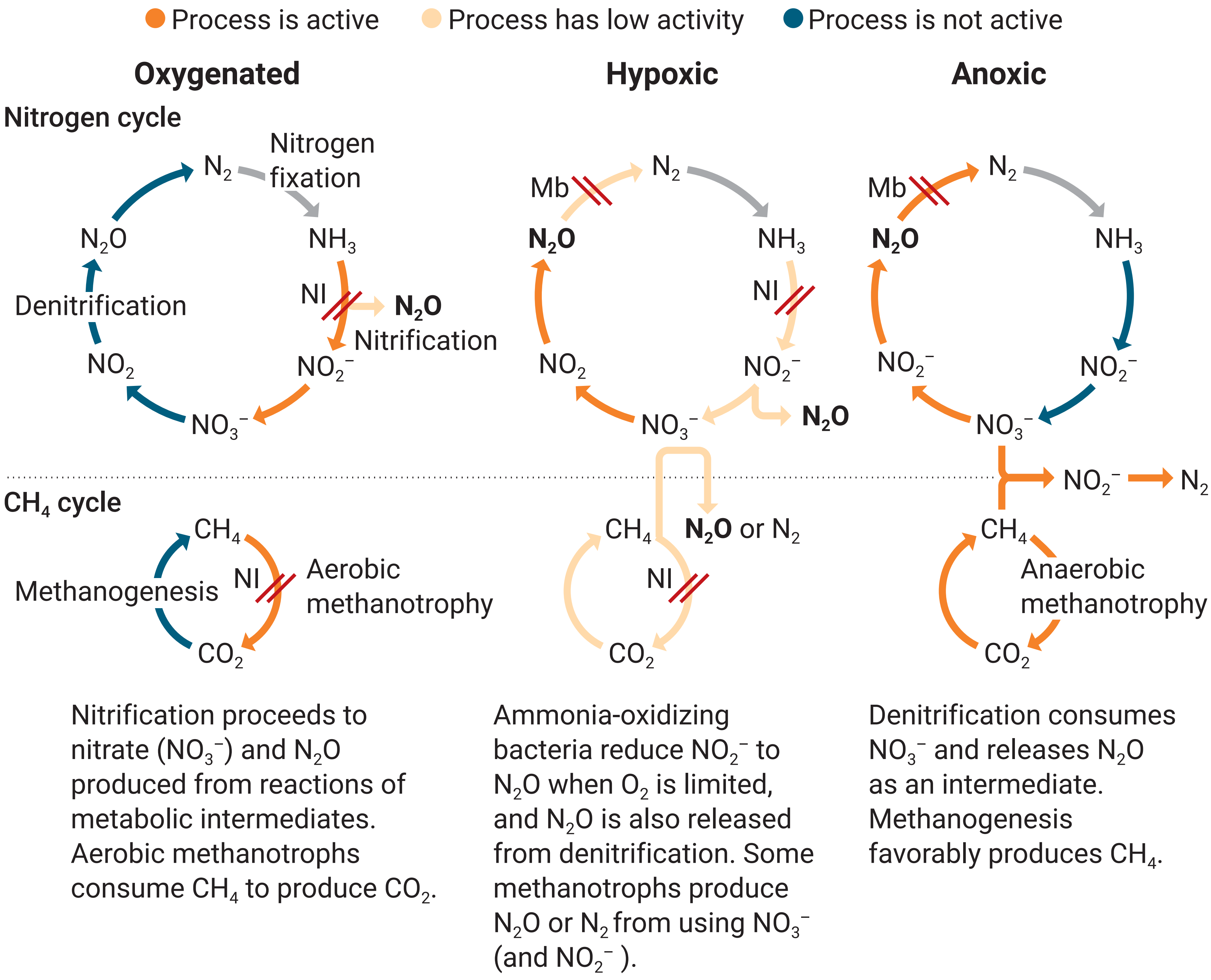
The interactions between the CH_4 and N cycles that underlie the relationship between CH_4 and N_2O emissions are complex (see the figure). Aerobic bacteria that live on CH_4 (methanotrophs) rely on nitrogen as an essential macronutrient. Some organisms can use NO_3^- and/or NO_2^- as terminal electron acceptors to form N_2O when O_2 availability becomes limited (*2*). In addition, some methanotrophs produce a copper-chelating chalkaphore (methanobactin) that effectively outcompetes copper from denitrifying microorganisms, preventing them from synthesizing the enzyme that consumes N_2O (*3*). In these circumstances, the copper competition can result in increased N_2O emission by preventing its conversion and return to atmospheric N_2 (*3*). Synthetic or biological amendments aimed at inhibiting microbial communities that convert ammonia to nitrate (nitrifying communities) can reduce N_2O emissions (*4*). However, many classes of nitrification inhibitors (NIs) will also inhibit methanotrophs, potentially increasing CH_4 emissions. Conversely, in the anoxic zone, methanogens produce CH_4, but some anaerobic methanotrophs consume CH_4 and reduce NO_3^- or NO_2^- without N_2O release.

Promising biology-based CH_4 mitigation technologies under development include CH_4 biofilters both as open treatment systems and closed bioreactors, bioconversion of CH_4 into protein and bioplastics, and development of biocontrol treatments to reduce CH_4 production in rice paddy and landfill soils and in ruminants (*5*). Each strategy has an impact on the N cycle, including the possibility of increasing N_2O emissions. Using porous biocovers such as compost, for example, to decrease CH_4 emissions by enhancing aerobic methanotroph-mediated CH_4 consumption unfortunately resulted in increased N_2O emissions (6). Instead, biocovers enriched in iron and copper might simultaneously reduce N_2O and CH_4 emissions by relieving essential nutrient limitations. A similar situation can be expected if aerobic or anaerobic CH_4 consumption is enhanced in rice paddies by nutrient addition to stimulate the natural methanotrophic populations owing to nitrogen excess. In these cases, amendments that include an N source to increase methanotroph biomass may lead to N_2O production when the C:N balance of the system is lowered. Because the combination of landfills and rice paddies generates about 100 to 150 million tonnes per year of CH_4 (7), the potential impact for mitigating gas release from these two sources is substantial.

Beyond these specific examples, monitoring both CH_4 and N_2O across other emissions reduction scenarios is important to make sure excess NO_3^- is not present. Further, the amount of CO_2 fixation needs to also be determined to ensure a net climate benefit. Capped or inactive gas wells, coal mines, and hydroelectric reservoirs are all places where this balance is important to quantify.

Microbial processes controlling methane and nitrous oxide production

Nitrification inhibitors (NI) can block both nitrification and aerobic methanotrophy, preventing methane (CH_4) consumption and nitrous oxide (N_2O) production. Methanobactin (Mb) blocks N_2O consumption, potentially increasing N_2O emissions.



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Closed bioreactor-based systems have the advantage of purposely controlling microbial populations, thereby tightly controlling CH_4 and N_2O emissions. Ensuring proper oxygenation and avoiding NO_3^- addition, or utilizing methanotrophs without the capability to generate N_2O from NO_3^-, avoids increased N_2O emissions. These systems have the added advantage of producing biomass in addition to CO_2, which is a sustainable protein source for fish feed or the production of bioproducts, fuels, and chemicals (8, 9). Methane bioreactor systems potentially capture methane from airstreams at concentrations below 100 parts per million (ppm). However, air with 500 ppm methane or higher is a more realistic target to scale the technology and make it economically feasible. Several types of emissions meet this criterion, including leaking oil and gas wells, landfills, manure lagoons, effluent from rice paddies, and effluent from anaerobic digestors (9). These systems should be continuously monitored for O_2, CH_4, and N_2O

levels along with CO_2 production to ensure their expected net greenhouse gas remediation function (10). Another option is to ensure the complete removal of O_2 to encourage anaerobic consumption of CH_4 without N_2O production (11). However, the latter approach is suboptimal for dilute CH_4 gas streams where O_2 is a requirement for effective CH_4 consumption. Finally, the development of synthetic and natural catalysts should also be encouraged, as these may provide mitigation strategies for both CH_4 and N_2O.

Control over CH_4 by enteric fermentation in ruminant animals, such as cows, is complicated as the rumen contains a vast microbial community with tight interrelationships that is sensitive to nutrient perturbation. Enteric fermentation is responsible for ~1.5 billion tonnes (Gt) of CO_2 equivalents per year from CH_4 production. Another 0.7 Gt CO_2 equiv. per year from N_2O production is derived from microbial transformation of nitrogen in urine and feces. Methane biocontrol has been achieved by supplementing livestock diets with inhibitors of rumen-based methanogenic microbes and their enzymes such as algae, plant metabolites, lipids, and 3-nitrooxypropanol (12). Supplementing diets with vitamin B12 may also restructure the methanogenic microbial population to reduce CH production. However, N_2O inactivates vitamin B12, such that N_2O production in the rumen could antagonize this vitamin supplementation. Nitrous oxide production in the rumen and from manure is connected to the forage type and undigested proteins in the feed (13). Examining the coemission of CH_4 and N_2O from rumen and livestock waste has led to the development of better gas sensor technologies that could be used for soil and land management.

Biology-based strategies under development to mitigate N_2O emissions include crop amendments such as biofertilizers, biological nitrification inhibitors, biopesticides, and biochar (14). Changes to management practices such as timed irrigation and fertilization and reduced tillage are effective means to reduce N_2O emissions by reducing N loading and excessive disturbance of the soil. However, analysis of these strategies does not always take CH_4 emissions into account. Determining if crop amendments can stimulate microbial N_2O removal is currently being investigated (15). An interesting angle for mitigating greenhouse gas emissions from soils is the manipulation of O_2 availability, as microbial CH_4 production occurs mainly under strict anoxia (absence of O_2) and microbial N_2O production is not as O_2 sensitive (15). Thus, in soils where O_2 is limited (e.g., flooded soil), processes that increase O_2 availability could be effective in accelerating methanotrophy, decreasing methanogenesis, and reducing N_2O production. However, aeration can also stimulate the nitrification process, which is a major source of NO_3^- and N_2O. Monitoring microbial communities at scale is vital for greenhouse gas mitigations because the complex feedback between microbial populations and soil management will always be an issue.

Any approach to mitigate or remove CH_4 or N_2O has the potential to alter emission of the other greenhouse gases. This creates substantial challenges in slowing global warming. However, investment in the fundamental understanding of microbial community functions and related technologies may help circumvent these issues. Progress in these areas, both in closed and open systems, provides different ways to mitigate multiple greenhouse gas emissions in the same system, which may end up being far more powerful than the more simplistic attempts at reducing a single emission source.

References and Notes

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