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Abstract

Soils are a predominant source for the greenhouse gases nitrous oxide (N₂O) and methane (CH₄). Moreover, soils may also act as significant sinks for both gases, though the sink strength is still not well defined with regard to N₂O. The soil-atmosphere exchange of N₂O and CH₄ is driven by reductive as well as oxidative microbial C and N turnover processes, both of which largely depend on soil environmental conditions but also on the availability and dispersion of substrates at site and landscape scales. Climate, specifically soil temperature and moisture, is a key primary driver of microbial activity in soils. Therefore, any change in climate is expected to have an impact on soil microbial processes. However, due to the complexity of processes involved in the microbial production and consumption of CH₄ and N₂O in soils and the close networking of these processes with ecosystem (e.g., plant N uptake and C assimilation and respiration) and landscape processes (nutrient dispersion, regional hydrology), we are far from predicting how climate change will affect biosphere-atmosphere CH₄ and N₂O exchange. To be able to predict these climate change effects, it will be necessary

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to improve our process understanding and to carry out regional studies across various ecosystems and climate zones which closely link experimental as well as modeling activities. This will result in a better understanding of regional nutrient cycling and drivers of biosphere-atmosphere exchange at regional scale. This information is needed to define efficient mitigation and adaptation strategies to minimize the detrimental effect of soil greenhouse gas emissions on our global climate system.

Keywords

Methanogenesis • Methane oxidation • Nitrification • Denitrification • Soil greenhouse gas emission

Introduction

The United Nations Framework Convention on Climate Change defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” Human alteration of atmospheric composition is expected to lead to an increase of global surface temperatures for the period 2090–2099 as compared to the period 1980–1999 by 1.8 °C to 4.0 °C (uncertainty range 1.1–6.4 °C) depending on the underlying scenario. The temperature increase is expected to be most pronounced over many land areas and be accompanied by an increase in global mean precipitation, indicating an intensification of the hydrological cycle. The spatial variability of precipitation will generally increase, with decreased rainfall in the subtropics and an increase of rainfall at higher latitudes and in parts of the tropics. These predicted changes in climate are likely to affect plant and microbial processes driving carbon (C) and nitrogen (N) turnover and cross-compartment exchange (hydrosphere-atmosphere-biosphere) of nutrients and trace gases at terrestrial ecosystem and landscape levels. In addition, the functioning of C and N cycling at ecosystem, landscape, and global scales is directly and indirectly affected by changes in concentrations of atmospheric substances such as CO₂ and O₃ and the human perturbation of the regional and global N cycling, which is resulting in increased inputs of reactive N to natural and semi-natural ecosystems (Erismann et al. 2008).

This chapter evaluates how climate change may influence microbial production and consumption of the atmospheric trace gases nitrous oxide (N₂O) and methane (CH₄) in soils. Methane contributes 18.1 %, and N₂O contributes 6.24 % to the overall global radiative forcing (Forster et al. 2007). About 2/3 of all sources for both greenhouse gases (GHGs) are associated with microbial production processes in soils (Conrad 2009), with fluxes at the soil surface being the net product of simultaneous occurring production and consumption processes. Therefore, soils and microbial processes in soils are of outstanding importance for regulating atmospheric concentration of CH₄ and N₂O. As all biological processes are affected by climate conditions, climate change is likely to affect soil microbial processes and associated

GHG production and consumption processes in soils too. Hence, the explicit understanding of the feedbacks between temperature and precipitation and soil microbial processes involved in N_2O and CH_4 exchange is an indispensable prerequisite to better predict how climate change will alter the source (and sink) strength of soils for atmospheric N_2O and CH_4 . Consequently, such mechanistic understanding between environmental drivers and soil microbial processes is required to develop mitigation and adaptation strategies targeted at a minimization of the source strength or a maximization of the sink strength of soils for CH_4 and N_2O .

Climate Change and CH_4 Exchange

Methane is predominantly produced in anaerobic sites of soils and sediments by methanogenic bacteria as a final step of the anaerobic decomposition of organic matter. CH_4 produced in soils may be emitted to the atmosphere by several pathways (diffusion, bubble, or plant-mediated transport) with CH_4 getting potentially oxidized while passing by sites dominated by CH_4 -oxidizing microbial communities. These communities are mostly using O_2 – but under certain circumstances also sulfate or nitrate – as electron acceptors (Conrad 2009). Oxidation of CH_4 in soil, sediments, and even in the aerenchyma cavities of vascular plants is a significant process. In rice paddies, 10–30 % of the produced CH_4 may get oxidized before emission (Conrad 2009). High-affinity methanotrophic bacteria are capable to gain energy from CH_4 concentrations <1.7 ppmv in air. Methanotrophic bacteria inhabits predominantly oxic upland soils. Though net CH_4 uptake rates are rather low (approx. 0.1 – 5 kg CH_4 -C ha^{-1} year $^{-1}$) (Dutour and Verchot 2008), at a global scale upland soils are representing a significant sink (approx. 10 %) within the global budget of atmospheric CH_4 .

Climate change interacts in several ways with CH_4 production and consumption processes in soils (Figs. 38.1 and 38.2). On the one hand, climate changes will directly affect soil environmental conditions, namely, moisture and temperature, and by this the balance of oxidative to reductive processes. For example, temperature increases will – as far as water availability is not limiting – likely result in an increase in respiration, thus decreasing O_2 availability and the CH_4 oxidizing capacity of upland soils. On the other hand, global change and thus also changes in atmospheric $[CO_2]$ will affect plant biomass production, the ratio of aboveground to belowground biomass production, root exudation, and litter quality. All these changes will finally affect ecosystem CH_4 exchange, with results being different across different ecosystem types and climate zones. Finally, climate change will also affect regional water balances and thus landscape groundwater levels. This will ultimately control the expansion of wetlands and emission magnitudes of CH_4 at landscape scales (Figs. 38.1 and 38.2). For example, Liu et al. (2009) demonstrated for landscapes in Inner Mongolia that CH_4 emissions from riparian areas outweigh CH_4 uptake by adjacent upland steppe soils though the riparian areas contributed only 1.5 % to the total area. Comparable landscape effects of climate change are also expected with regard to the thawing of permafrost areas in northern latitudes,

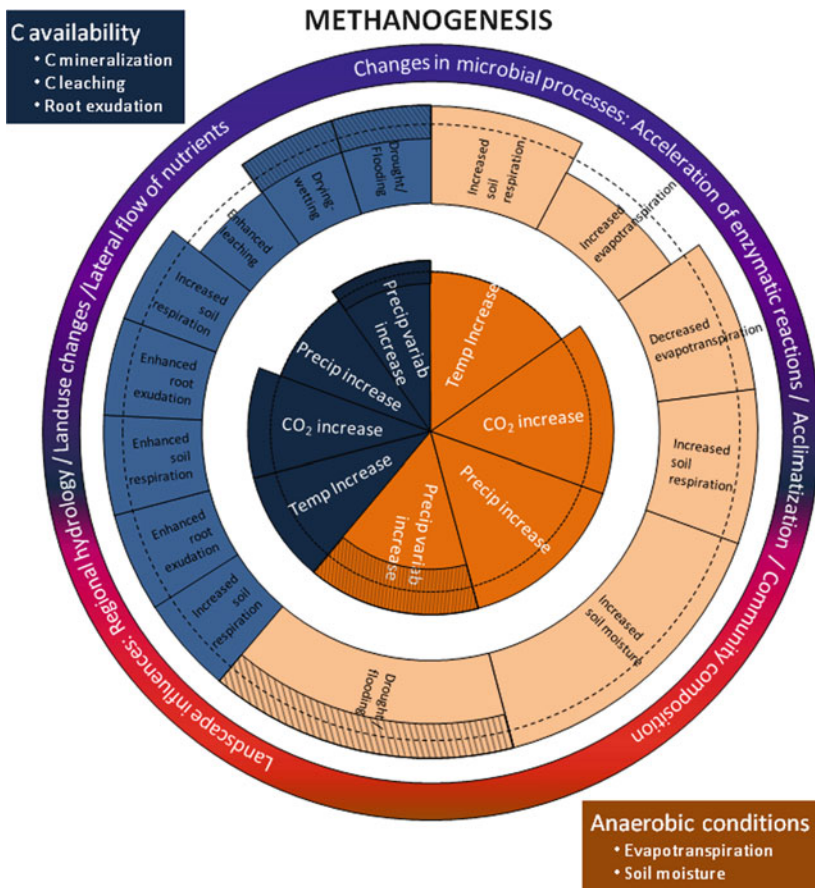


Fig. 38.1 Conceptual scheme of global change-induced effects on CH₄ production by methanogens in soils and sediments. The figure is composed by (a) an inner ring divided into two sectors representing two major parameters controlling methanogenesis (anaerobic conditions and C availability) which may be affected by climate change factors (temperature increase, atmospheric [CO₂] increase, precipitation increase, and increase in precipitation variability (droughts/flooding)). Here, the sector size represents an approximate of the importance of the relevant climate change factor for overall methanogenesis. (b) The second ring shows the effects of changes in environmental conditions on ecosystem processes (e.g., root exudation, evapotranspiration) while (c) the outer ring represents alterations driven by landscape level and microbial community changes, which will likely affect the drivers for methanogenesis, too. Dotted circumferences are representing a response function of 1. Therefore, a sector of the circle above the dash-lined inner circumference indicates a positive effect of each expected change on the respective controlling process; a sector below the circumference indicates a negative effect on the respective controlling process. The overall size of each circle sector is calculated by summing up the contribution of the single effects driven by each global change-expected variation. For example, temperature increase will on the one hand enhance soil anaerobiosis due to the stimulation of respiratory processes but on the other hand also increase evapotranspiration and, thus, decrease soil moisture and anaerobiosis. This is indicated by expanding the sector for the soil respiration effect beyond the dotted ring, while it is opposite for the evapotranspiration effect. Shaded areas are indicating uncertainties

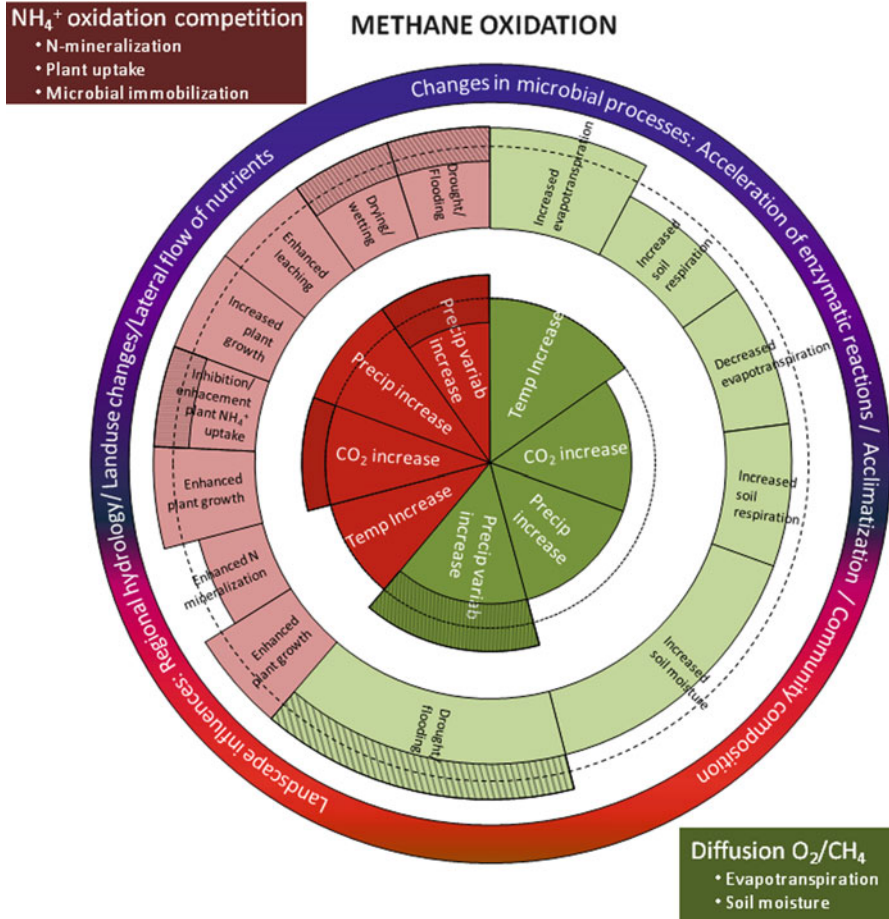


Fig. 38.2 Conceptual scheme of global change-induced effects on CH₄ consumptions by methanotrophic bacteria in soils. For a further explanation of interactions between climate change factors (inner circle) and controllers of methanotrophy in soils (diffusion of O₂/CH₄, NH₄ competition effects) which can be depicted from the graph, see explanations for Fig. 38.1

which may not only go along with the release of CH₄ captured in so far permanently frozen soils but also with the generation of new wetlands and resulting net emissions of CH₄ from these areas following the anaerobic decomposition of inundated organic matter.

Emission of N₂O from Soils and Effects of Climate Change

Nitrous oxide production and consumption in soils is mainly performed by a series of microbial N turnover processes, which can either be oxidative or reductive.

Oxidative processes involved in N_2O production, i.e., autotrophic and heterotrophic nitrification, use reduced N-forms such as ammonia (NH_3) or organic N-forms. Both autotrophic and heterotrophic nitrification are carried out by various groups of bacteria and archaea (Hayatsu et al. 2008). Nitrifiers oxidize NH_3 or organic N compounds to nitrite and nitrate, thereby obligatorily involving molecular O_2 and releasing N_2O as a trace by-product. Oxidized inorganic N substances such as nitrate, nitrite but also nitric oxide, and even N_2O can be used, e.g., by denitrifying microorganisms (bacteria, archaea, fungi) as electron acceptors if anaerobiosis occurs. Furthermore, nitrate and/or nitrite may be used by fermentative bacteria in the process of dissimilatory nitrate reduction to ammonium (DNRA) to regain ammonium (NH_4^+) in strictly anaerobic environments. DNRA has been shown to occur predominantly in anaerobic sludge and sediments and is considered as a potential important process for securing ecosystem N retention (Silver et al. 2001). Since both DNRA and denitrification appear to be favored by similar soil conditions (low redox potential, high nitrate (NO_3^-), and labile C availability) (Butterbach-Bahl et al. 2011), global change may affect both processes in the same way. As for CH_4 , N_2O produced in the soil is not necessarily emitted but can undergo microbial consumption before reaching the soil-atmosphere interface.

There is an increasing number of studies showing net uptake of atmospheric N_2O by soils or consumption of N_2O in soil layers during its diffusion from production sites to the soil surface. Nitrous oxide consumption is likely associated to the activity of the N_2O reductase, the final enzyme in the denitrification chain. N_2O removal can be rather effective: up to 2/3 or even 90 % (Vieten et al. 2009) of the produced N_2O may get further reduced to N_2 . N_2O reduction does not only occur in anaerobic but also in predominantly aerobic soils. Goldberg and Gebauer (2009) determined isotopic ($^{15}N/^{14}N$) signatures of N_2O along a soil profile of a temperate forest and simultaneous N_2O flux measurements at the soil-atmosphere interface. Their data indicate that soil N_2O consumption may be less affected by prolonged drought as compared to subsoil N_2O production. This may be explained by reduced nitrate but improved N_2O diffusion to anaerobic microsites, thus, providing a concept why in drought affected soils atmospheric N_2O consumption may prevail.

The mentioned oxidative and reductive processes involved in N_2O production and consumption in soils are complex and closely interwoven with ecosystem and landscape-scale N cycling (Figs. 38.3 and 38.4). For example, plant-microbe competition for mineral and organic N in soils, volatilization, and redeposition of NH_3 at landscape scales or lateral transport of nutrients by leaching or erosion/deposition processes need to be considered for predicting how changes in climate will finally feedback on regional soil N_2O emissions (Butterbach-Bahl and Dannenmann 2011) (Figs. 38.3 and 38.4). These indirect effects may override direct climate change effects such as the immediate response of nitrification and denitrification to changes in soil temperature and moisture. However, even the understanding of direct temperature effects on microbial production and consumption processes in soils is limited due to our still hampered ability to unravel which specific processes or microbial communities are driving N_2O

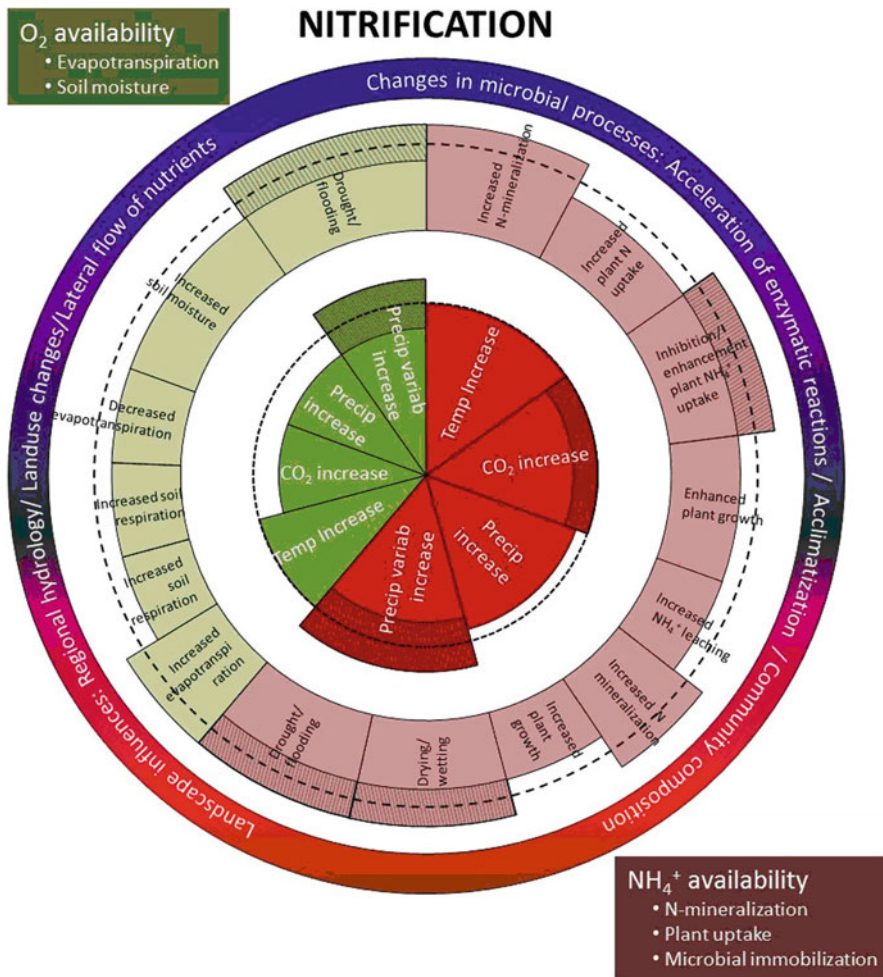


Fig. 38.3 Conceptual scheme of global change-induced effects on N₂O production via nitrification. See Figs. 38.1 and 38.2 for explanations on how to interpret the graph

exchange at the soil-atmosphere interface. For example, reported Q_{10} values for denitrification – a measure of the rate change upon temperature increases – widely vary from 2 to 10 (Abdalla et al. 2009). Such Q_{10} values of high variability and magnitude indicate that the temperature response of denitrification is not solely enzymatic but that temperature affects the delicate balance of oxidative and reductive processes in soils and, thus, also the relative importance of nitrification versus denitrification. Therefore, the temperature response of soil N₂O emissions has been attributed to increases in the anaerobic volume fraction, brought about by an increased respiratory sink for O₂. Also spring-thaw N₂O pulse emissions, which in some ecosystems (e.g., steppe, temperate forest, and temperate agricultural land) may dominate annual N₂O fluxes, are largely decoupled from

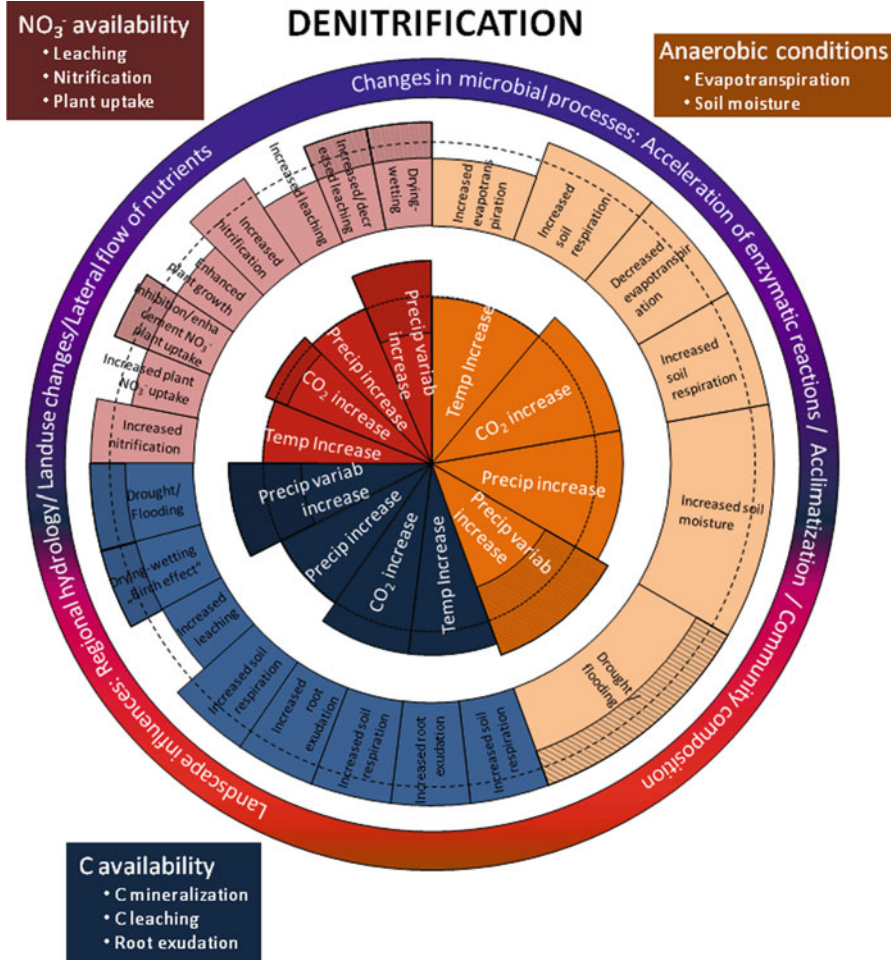


Fig. 38.4 Conceptual scheme of global change-induced effects on N₂O production via denitrification. See Figs. 38.1 and 38.2 for explanations on how to interpret the graph

long-term temperature changes but strongly depending on the severeness and frequency of frost period and the availability of soil water in the winter and spring period (Wolf et al. 2010). The situation is even further complicated by likely shifts in the product ratios of denitrification (N₂O:N₂) due to changes in soil environmental conditions. Predicting the response of European forest soil N₂O and N₂ emissions to future climate conditions (2031–2039) compared to present-day climate (1991–2000) by use of the biogeochemical model PnET-N-DNDC revealed a decrease in N₂O emissions by 6 % (Kesik et al. 2006). This decrease in N₂O emissions was mainly due to a shift in the N₂O:N₂ ratio driven by enhanced denitrification. The favoring of N₂ as end product of denitrification at elevated temperatures can be explained by the decreasing availability of electron acceptors with increasing anaerobiosis forcing

denitrifiers to be more resource efficient and, thus, to express the full chain of denitrification enzymes (Butterbach-Bahl and Dannenmann 2011). It is worthwhile to notice that also further increases in atmospheric $[\text{CO}_2]$ will feedback on soil N_2O emissions (Figs. 38.3 and 38.4) due to both increased soil moisture following improved water use efficiency of plants at higher $[\text{CO}_2]$ and increased root exudation alleviating potential C substrate limitation of denitrification (Butterbach-Bahl and Dannenmann 2011).

These few examples, and the complexity of interacting processes as shown in Figs. 38.3 and 38.4, demonstrate that a better prediction of how climate change will affect soil N_2O emissions will require both a detailed process understanding and a specific assessment at regional scale. The latter is of outstanding importance, since at the landscape level not only N use is affecting N availability in soils but also changes in hydrological fluxes, land management, and land use will finally drive the response of the soil microbial community to climate changes and offer possibility for intervention to mitigate soil N_2O emissions in a changing climate.

Conclusions

It is obvious that we are still not capable to predict how climate change will finally affect the emission and the deposition of the greenhouse gases CH_4 and N_2O from/to soils. The reason is not only a partially missing process understanding but even more our still restricted ability to relate surface fluxes at the soil-atmosphere interface to underlying microbial, physicochemical, and plant processes in the soil. To unravel complexity, controlled studies under laboratory conditions have helped to improve our understanding. Nevertheless, the complex C, N, and water interactions at ecosystem and landscape levels are still not sufficiently understood to allow for generalization and to predict climate change effects on CH_4 and N_2O exchange. Furthermore, regional drivers of greenhouse gas exchange such as regional hydrology or the dispersion of nutrients due to volatilization and redeposition, lateral transport of nutrients by soil water, and surface erosion have been neglected in most studies, though the mentioned processes will as well be affected by climate change. Therefore, targeted regional climate change studies are needed to overcome uncertainties, to improve process understanding, and to better predict climate change feedbacks of ecosystem processes at site, regional, and global levels.

References

- Abdalla M, Jones M, Smith P, Williams M (2009) Nitrous oxide and denitrification sensitivity to temperature in Irish pasture soils. *Soil Use Manage* 25:376–388
- Butterbach-Bahl K, Dannenmann M (2011) Denitrification and associated soil N_2O emissions due to agricultural activities in a changing climate. *Curr Opin Environ Sustain* 3:389–395
- Butterbach-Bahl K, Gundersen P, Ambus P, Augustin J, Beier C, Boeckx P, Dannenmann M, Gimeno BS, Rees RM, Smith KA, Stevens C, Vesala T, Zechmeister-Boltenstern S (2011) Nitrogen processes in terrestrial ecosystems. In: Sutton MA, Howard CM, Erisman JW, Billen G,

- Bleeker A, Grennfeldt P, Van Grinsen H, Grozetti B (eds) The European nitrogen assessment: sources effects, and policy perspectives. Cambridge University Press, New York, pp 99–125
- Conrad R (2009) The global methane cycle: recent advances in understanding the microbial processes involved. *Environ Microb Rep* 1:285–292
- Dutaur L, Verchot LV (2008) A global inventory of the soil CH₄ sink. *Global Biogeochem Cycles* 21, GB4013
- Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W (2008) How a century of ammonia synthesis changed the world. *Nat Geosci* 1:636–639
- Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M and Van Dorland R (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Goldberg SD, Gebauer G (2009) Drought turns a Central European Norway spruce forest soil from an N₂O source to a transient N₂O sink. *Glob Chang Biol* 15:850–860
- Hayatsu M, Tago K, Saito M (2008) Various players in the nitrogen cycle: diversity and functions of the microorganisms involved in nitrification and denitrification. *Soil Sci Plant Nutr* 54:33–45
- Kesik M, Brüggemann N, Forkel R, Knoche R, Li C, Seufert G, Simpson D, Butterbach-Bahl K (2006) Future scenarios of N₂O and NO emissions from European forest soils. *J Geophys Res* 111, G02018
- Liu C, Holst J, Yao Z, Brüggemann N, Butterbach-Bahl K, Han S, Han X, Tas B, Susenbeth A, Zheng X (2009) Growing season methane budget of an Inner Mongolian steppe. *Atmos Environ* 43:3086–3095
- Silver WL, Herman DJ, Firestone MK (2001) Dissimilatory nitrate reduction to ammonium in upland tropical forest soils. *Ecology* 82:2410–2416
- Vieten B, Conen F, Neftel A, Alewell C (2009) Respiration of nitrous oxide in suboxic soil. *Eur J Soil Sci* 60:332–337
- Wolf B, Zheng X, Brüggemann N, Chen W, Dannenmann M, Han X, Sutton MA, Wu H, Yao Z, Butterbach-Bahl K (2010) Grazing-induced reduction of natural nitrous oxide release from continental steppe. *Nature* 464:881–884

Additional Recommended Reading

- Chapuis-Lardy L, Wrage N, Metay A, Chotte J-L, Bernoux M (2007) Soils, a sink for N₂O? A review. *Glob Chang Biol* 13:1–17
- Conrad R (1996) Soil microorganisms as controllers of atmospheric trace gases (H₂, CO, CH₄, OCS, N₂O, and NO). *Microbiol Rev* 60:609–640
- Fowler D, Pilegaard K, Sutton MA, Ambus P, Raivonen M, Duyzer J, Simpson D, Fagerli H, Fuzzi S, Schjoerring JK, Granier C, Neftel A, Isaksen ISA, Laj P, Maione M, Monks PS, Burkhardt J, Daemmgen U, Neiryck J, Personne E, Wichink-Kruit R, Butterbach-Bahl K, Flechard C, Tuovinen JP, Coyle M, Gerosa G, Loubet B, Altimir N, Gruenhage L, Ammann C, Cieslik S, Paoletti E, Mikkelsen TN, Ro-Poulsen H, Cellier P, Cape JN, Horvath L, Loreto F, Niinemets U, Palmer PI, Rinne J, Misztal P, Nemitz E, Nilsson D, Pryor S, Gallagher MW, Vesala T, Skiba U, Brüggemann N, Zechmeister-Boltenstern S, Williams J, O'Dowd C, Facchini MC, de Leeuw G, Flossman A, Chaumerliac N, Erisman JW (2009) Atmospheric composition change: ecosystems – atmosphere interactions. *Atmos Environ* 43:5193–5267
- Gruber N, Galloway JN (2008) An earth-system perspective of the global nitrogen cycle. *Nature* 451:293–296