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Preface

Mitigating greenhouse gas emissions from croplands and pasturelands — climate-smart agriculture

One of the main challenges facing humankind is ensuring food security for a rapidly growing population with lower environmental footprints under changing climate. Environmental unsustainability of agro-food systems is multi-faced, but alteration of biogeochemical cycles (*e.g*., nitrogen (N) and phosphorus (P) cycles) and emissions of greenhouse gases (GHGs) to the atmosphere have been reported as one of the main disruptive forces over safe-operating space of planetary boundaries (Springmann *et al*., 2018). In a recent special report on climate change and land, the UN Expert Panel on Climate Change (Intergovernmental Panel on Climate Change, IPCC) highlighted the need to decrease GHG emissions from the agriculture, forestry, and other land use change (AFOLU) sector, as this is estimated to be responsible for approximately 35% of global GHG emissions (IPCC, 2019). To enhance the efficacy of such measures, any mitigation strategy must be designed and implemented within a regional basis (*e.g*., Sanz-Cobena *et al*., 2017b). With this premise, Soil and Water Management & Crop Nutrition Section, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency (IAEA) (Vienna, Austria) supported the creation and consolidation of an international network, the Coordinated Research Project (CRP). The primary objective was to assess, within a regional basis, GHG mitigation strategies to abate direct nitrous oxide (N_2O) emission and minimize reactive N losses from agricultural systems (*e.g*., volatilized ammonia (NH_3)), while enhancing agricultural productivity and sequestering carbon (C) in agricultural soils in different regions of the world. The knowledge generated ranges from the understanding of microbial processes leading to the production and consumption/fixation of N and C in agricultural soils to the on-site measurement of GHG losses and N/C pools, including the development of new techniques for on-site assessment of GHGs and their mitigation strategies. To derive effective N_2O mitigation options, it is important to know which microbial processes are involved in the production of this GHG and how much N_2O and N_2 gases are emitted from soil following N application (synthetic N fertilization or animal manure application). The ^{15}N stable isotope technique is currently the only method to precisely identify these microbial processes in N_2O production, as well as to trace the origin and extent of N_2O and N_2 gases. Similarly, carbon dioxide (CO_2) levels in the atmosphere started to increase from the beginning of the industrial revolution in the late eighteenth century, while methane (CH_4) levels in the atmosphere have increased by more than 150% since 1750. As both these gases contain a C atom, their movement and sources in the soil-atmosphere system can be precisely measured by the ^{13}C stable isotope technique and thereby provide information for mitigation of these GHGs. Ten countries have participated in the CRP: seven research contract holders, one each from Brazil, Chile, China, Costa Rica, Ethiopia, Pakistan, and Iran, two agreement holders from Estonia and Spain, and one technical contract holder from Germany. After five years of scientific activity, important and novel information has been generated, particularly in regions with scarce information on GHG emissions and potential mitigation within the agro-food sector. Some of the most relevant scientific results of the CRP are presented within this special issue (SI). Despite an increasing body of research being published in the last few decades addressing GHG emission quantification and mitigation, the available information is often biased towards high-income regions with a strong scientific tradition. Therefore, the first aim of this SI, as well as the CRP, is to show novel results on both the soil processes responsible for GHG emissions and the potential of certain agronomic practices to mitigate GHG emissions. The SI begins with a first set of papers focusing on means to effectively quantify GHG and reactive N fluxes in agroecosystems and trace main processes responsible for the production of such compounds in soil. This is followed by a set of research papers mostly focusing on technical ways to mitigate direct GHG emissions in regions with little or no published information on the matter up to now. The SI is also completed with five publications strongly related to the FAO/IAEA CRP scope, but out of the CRP itself. These studies focus on GHG dynamics in forests and croplands.

Robust methods for effective GHG quantification. In the two studies opening this SI, Martins *et al*. (this issue) showed how NH_3-N losses can be accurately estimated with a simple open chamber covering 0.025% of the plot (31.4 m^2) (within an expected margin of error of 15% when using 5 chambers per plot). The method was tested in Brazil, where the NH_3 volatilization is expected to be high under certain crop management practices (*e.g.*, presence of crop residues when urea fertilizer is surface applied), and it was validated by ^{15}N balance. Although an on-site effective method to quantify volatilized NH_3 should be sensitive to changes in weather conditions (*e.g.*, micrometeorological method, Viguria *et al.*, 2015), these approaches are sometimes expensive in terms of material and human resources. Therefore, results by Martins *et al.* (this issue) confirm the possibility of achieving good measurement performance with a cost-effective method, which is particularly important in low-income regions worldwide where these data are not readily available. In the case of GHG (CO_2, CH_4, and N_2O) fluxes, cavity ring-down spectroscopy (CRDS) provides an easy-to-use quantification method in the field with appropriate accuracy and sensitivity. As shown in one of the studies composing this SI, the method was satisfactorily used in research carried out in Costa Rica (Pérez-Castillo *et al.*, this issue), where there was no information on this topic until the release of this SI. This technique was suitable for the determination of the ^{15}N signature of N_2O, to quantify the effectiveness and suitability of mitigation options (*e.g.*, nitrification inhibitor (NI) and biochar) on individual N transformation processes (*e.g.*, processes responsible for nitrate (NO_3^-) production).

Technical GHG mitigation. Different technical (*i.e.*, agronomic) techniques aiming to mitigate the emission of N_2O or enhance the accumulation of C in plant or soil stocks have been assessed within the research papers composing this SI. Organic materials such as green manure from legume residues have been reported to contribute more than 300 kg N ha^{-1} (*e.g.*, Jack bean) to the pool of soil mineral N. Thus, they offer environmental advantages over synthetic N fertilizers with avoidance of the GHG emissions (360–944 CO_2-equivalent ha^{-1} year $^{-1}$) related to the Haber-Bosch production process, transportation, and field application (Pérez-Castillo *et al.*, this issue). Also in this issue, Geng *et al.* reported the effect of *Trichoderma guizhouense* (a plant growth-promoting fungus)-enriched organic fertilizer on soil N_2O emission from a greenhouse vegetable field fertilized with NPK and animal manure. They observed that the presence of *T. guizhouense* decreased N_2O emission because of its incidence on N cycling-related functional genes, also determined by quantitative polymerase chain reaction (qPCR), and that the use of bio-organic fertilizer containing plant growth-promoting microbes could benefit both crop yield enhancement and N_2O mitigation in vegetable fields. Closing the group of studies concerning impacts of organic amendments on GHG emissions from agricultural soils, Romero *et al.* (this issue) showed how the use of pine wood biochar, as part of the animal feed (*i.e.*, as dry matter in diets) or mixed with the manure, increased CH_4 and CO_2 emissions from cattle manure applied to two Mollisols with contrasting texture under controlled conditions. Nitrification inhibitors deactivate the enzyme responsible for the first step of nitrification, the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-). By reducing nitrification rates and subsequently the substrate for denitrification, the use of NI may lead to reduction in N_2O emission ranging from 30% to 50% (Guardia *et al.*, 2017). Assessing the effectiveness of NI to reduce the GHG budget of cropping systems has been a central part of the SI. In the particular case of nitrapyrin, the effect on N_2O emission ranged from no effect, measured in a tropical Andosol of Costa Rica by Pérez-Castillo *et al.* (this issue) and Monge-Muñoz *et al.* (this issue), to a 79% mitigation, compared to urea fertilization without the NI, under alkaline conditions in an Iranian maize cropping system (Borzouei *et al.*, this issue). This indicates that response rates of this fertilizer technology are governed by soil conditions and cropping systems. The use of ^{15}N isotopic technique enabled tracing of the N fate in soil and thus allowed for a detailed investigation regarding why NIs would or would not work as a suitable mitigation tool. If ecosystems exhibit high NO_3^- production *via* heterotrophic nitrification, NIs, which inhibit only autotrophic nitrification, are not a suitable mitigation option to reduce N_2O emission as shown by Pérez-Castillo *et al.* (this issue) and Monge-Muñoz *et al.* (this issue) in an Andosol of Costa Rica. The main limitation for implementation of NIs is the increase of fertilization costs (Timilsena *et al.*, 2015). This could be counterbalanced by an increment in crop productivity (Abalos *et al.*, 2014). However, in the study carried out by Monge-Muñoz *et al.* (this issue) on maize cropping, there was no significant effect of NI in terms of crop yield. This may be related to the additional NO_3^- produced by heterotrophic nitrification, which is not effectively inhibited by the NI nitrapyrin, and an over fertilization preventing an effect of inhibitors on N use efficiency (NUE) as shown on crop yields in the North China Plain (Ding *et al.*, 2015). In contrast, Pérez-Castillo *et al.* (this issue) observed an increasing effect of NI on maize yield (by approximately 23%) in association with increases in N uptake and grain yield by up to 15% and 17%, respectively. A potential enhancement in crop NUE when using NI may reduce N loss and, thus, decrease the rate of synthetic N applied, reducing fertilization costs (Abalos *et al.*, 2017). Expressing the GHG mitigation potential of any management strategy scaled to crop response in terms of crop yield (*i.e.*, emission intensities, van Groenigen *et al.*, 2010) has been considered to be a suitable proxy for the agro-environmental performance of such strategy. Dawar *et al.* (this issue) reported a 55% decrease in yield-scaled N_2O emission due to application of the NI nitrapyrin in a maize cropping system in Pakistan. Urease inhibitors (UIs) are commonly used to reduce the activity of the enzyme urease (urea hydrolase). Therefore, they can only be used when urea or urea-containing fertilizers (including organic sources) are used (Sanz-Cobena *et al.*, 2017a). Originally developed to reduce NH_3 volatilization, these products have recently been shown to also reduce N_2O emission, particularly under semiarid conditions and soils (Sanz-Cobena *et al.*, 2016, 2017a). Among the existing UIs, the most used form is N-(n-butyl) thiophosphoric triamide (NBPT) (Sanz-Cobena *et al.*, 2017a). In two of the studies included in this issue (Dawar *et al.*, Martins *et al.*), an NH_3 abating effect of 30%–50% was measured in two maize cropping systems in Pakistan and Brazil, respectively. In terms of crop responses, combining NI and UI increased plant N recovery by 20%–40% and grain yield by up to 27% in Brazil and Pakistan, respectively, while NUE was enhanced from 49% to 58%, compared with urea alone (Dawar *et al.*, this issue). The SI also includes a meta-analysis aiming to assess the effectiveness of contrasting yield-scaled N_2O mitigation scenarios implemented in N-fertilized Chinese croplands (Aliyu *et al.*, this issue). The NI 3,4-dimethylpyrazole phosphate (DMPP) and 20% reduction in N application rate plus the NI dicyandiamide (DCD) in maize, rice, and wheat cropping systems could lead, on average, to a 56% reduction in N_2O emission at the national level, while DCD led to a 14% and 8% greater yield than the current agricultural practice for maize and rice, respectively. The set of studies focusing on cropping systems ends with a modelling work by Hwang *et al.* (this issue), who estimated fluxes of CO_2 and CH_4 from rice paddy fields in South Korea using the DNDC process-based model. The model was used under the Climate Change Scenario RCP-8.5 showing that CO_2 emission gradually decreased with rising temperature because of reduced root respiration. Deep tillage increased emissions of both GHGs, with a more pronounced effect for CH_4 than CO_2, and intermittent drainage in the middle of the cropping season can attenuate CH_4 emission from paddy fields.

Forest GHG dynamics. Beside the presented research run in arable systems worldwide, the SI is completed with three studies focusing on GHG dynamics in forests of Peruvian western Amazonia, Northeast China, and South Korea. In the former case, Docherty and Thomas (this issue) quantified the impact of seasonal flooding on soil organic matter decomposition and CO_2 fluxes of a Várzea forest. They found that the decomposition rates were not affected by changes in flooding conditions and soil moisture and, in contrast, the latter was the dominant controlling factor of CO_2 flux, which significantly decreased at the maximum flood height even after floods had subsided. These results highlight the importance of future climatic patterns to C budgets of these forests. In the Chinese case, Han *et al.* (this issue) evaluated the effect of thinning over soil respiration in a managed pine forest and concluded that forest thinning may increase soil CO_2 emission even several decades after treatment application and reduce the temperature sensitivity of soil respiration during the mid-growing season. Finally, Moonis *et al.* (this issue) assessed the impact of climatic (*i.e.*, temperature and water input) and environmental (*i.e.*, N deposition) variables on soil respiration and temperature sensitivity of a temperate forest soil. Following an incubation experiment, main findings showed that soil moisture was the main controlling factor of substrate-induced respiration (SIR) and temperature sensitivity and the effect of warming on SIR and temperature sensitivity can be modified significantly by rainfall variability under conditions of high N availability. Therefore, this study emphasizes that concurrent climatic and environmental changes, such as increasing rainfall variability and N deposition, should be taken into consideration in predicting warming-induced changes in soil respiration and its temperature sensitivity.

Concluding remarks. Average N_2O emission factor (*i.e.*, average emission rate of a given source) values reported by the work carried out in the framework of the FAO/IAEA CRP and presented in this SI were generally lower than 1% (IPCC Tier 1 default value) of applied N and further reduced with the implementation of technological strategies at the production phase such as application of NI (this issue) and biochar (by 31%–40%, Niu *et al.*, 2017). The low GHG potentials of the studied systems in field experiments in Brazil, China, Iran, Pakistan, and Costa Rica provide an incentive for member states to maintain and further implement climate-smart agricultural practices. More quantitative information on the effect of soil processes (*e.g.*, C and N dynamics and GHG emissions) in relation to land use change (especially of high-organic matter soils) and with respect to various soil conditions (*e.g.*, soil temperature, moisture, and pH) and ecofriendly management options (*e.g.*, cropping options with plants having biological nitrification inhibition (BNI) or biological N fixing (BNF) potential and agroforestry) is urgently needed.

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