Mitigating N_2O emissions from soil: From patching leaks to transformative action

C. Decock[1], J. Lee[1], M. Necpalova[1], E.I.P Pereira[1], D.M. Tendall[1], J. Six[1]
[1] {Department of Environmental Systems Science, ETH Zurich, Universitätsstrasse 2, 8092 Zürich, Switzerland}
Correspondence to: C. Decock (charlotte.decock@usys.ethz.ch)

Abstract

Further progress in understanding and mitigating N_2O emissions from soil lies within transdisciplinary research that reaches across spatial scales and takes an ambitious look into the future.

1 Introduction

Atmospheric concentrations of nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance, have increased steadily from 270 ppb in the pre-industrial era (1000-1750) to 328 ppb in 2015 (IPCC, 2013;NOAA, 2015). The vast majority of N_2O emissions comes from agriculture, where it is emitted from soil, especially following management or weather events, such as N fertilization, manure application, tillage, and precipitation (Denman et al., 2007;Dobbie et al., 1999). Recent projections indicate that to stabilize atmospheric N_2O concentrations between 340 and 350 ppb by 2050, reducing emissions by 22% relative to 2005 (i.e., 5.3 Tg N_2O-N yr^{-1}) will be necessary (UNEP, 2013). Meanwhile, N_2O emissions have further increased since 2005 (FAO, 2014), indicating that the currently required emission reductions are even greater. Only concerted efforts combining the most pertinent mitigation strategies, such as increasing N use efficiency in agricultural production systems, in combination with diminishing food waste and reducing meat and dairy consumption can realize such emission reductions (UNEP, 2013). Under business-as-usual conditions, anthropogenic N_2O emissions are expected to almost double by 2050, leading to a high risk of unprecedented increases in the global temperature and in UVB radiation, with severe consequences for human health and the environment (UNEP, 2013). Despite the clear urgency of reducing N_2O emissions, adoption of the proposed mitigation options remains slow. Political and societal inertia may partly be to blame, but the large uncertainty around management-, crop- and region-specific predictions of N_2O emissions also presents an important challenge to designing and implementing mitigation options. In this forum article, we use examples of on-going research on N_2O emissions to illustrate and discuss how soil scientists can collaborate with experts from other disciplines, to reduce the uncertainty around N_2O emissions estimates, hence improving the development and implementation of successful mitigation strategies. We use a framework of 5 interacting research themes across different spatial scales; Namely, (1) identification of soil processes underlying N_2O emissions, (2) assessing effects of crop and region-specific management on N_2O emissions, (3) assessing effects of systemic or land-use change on N_2O emissions, and (4) assessing synergies and trade-offs between N_2O mitigation and other sustainability indicators, culminating into (5) sustainable provisioning of food and nutrition security, energy and goods (Fig. 1). Each research theme is associated with a set of commonly used research tools. We then specifically highlight how researchers working on N_2O emission understanding and reductions need to proactively seek out relevant collaborations across disciplinary boundaries (Fig. 2), in order to play a significant role in the global challenge of achieving sustainable agricultural and food systems.

2 Patching the leaks: From 'Understanding soil processes' to 'Crop- and region-specific management'

The most discussed and investigated strategies for reducing N_2O emissions from agricultural soils is "to patch the leaks", i.e., improve the N use efficiency of croplands and grasslands, mostly by optimizing fertilizer N management (e.g., rate, timing, source, and placement of N fertilizers). Patching the leaks is probably one of the more achievable mitigation options in the shorter term. In fact, a N fertilizer tax for reducing external N inputs and associated N_2O emissions has been evaluated (Franks and Hadingham, 2012;Mérel et al., 2014), and several C-offset programs already hold a protocol to estimate net N_2O emission reductions from cropping systems, for trading on the C-market (Davidson et al., 2014). From a technical point of view, the potential to reduce N_2O emissions through optimized N management has been demonstrated (Snyder et al., 2014;Hoben et al., 2011). However, taking up such management options in regulation and policy formulations requires a clear and quantitative description of the conditions under which the management strategy is effective, and the associated uncertainty range. For example, it is well known that N_2O emissions generally increase with increasing N-input (Bouwman, 1996;Hoben et al., 2011), but the shape of this response curve varies between agricultural production systems and regions (Decock, 2014;Kim et al., 2012). If the aim of a policy is to achieve a certain N_2O emission reduction target through reduced N input rates, not only the response curve at the research station, but the response curve for all fields targeted by this policy needs to be estimated. Hence, one needs to extrapolate for which soil types, climate conditions, or management practices a certain response is valid. Moreover, because of the high variability typically associated with N_2O emissions, policies need to take into account a certain amount of risk. To do so, a good estimate of the confidence interval around an achievable emission reduction is just as important as the mean value (Springborn et al., 2013). Long-term N_2O measurements across a wide range of biophysical conditions (i.e., ecoregions) and mitigation options are important to understand and quantify this uncertainty and variability, but the cost and time required for direct N_2O measurements limits the number of datasets that can be collected. Here, biogeochemical process models are practical tools to bridge data gaps, and improve the precision and accuracy of the efficiency and applicability conditions of mitigation options.

Modellers use field- and laboratory-derived N_2O data collected for continuous biogeochemical model development, evaluation, and subsequent application of the model to simulate field-level N_2O emissions toward regional scale simulations across a wide range of environmental conditions upon adoption of different management practices (Rochette et al., 2008;Fitton et al., 2011). Models are in essence a mathematical representation of our understanding of functional relationships between the key drivers, their interactions and the ecosystem responses under different agricultural managements (Chen et al. 2008). Hence, model predictions can only be as accurate as our current understanding of the underlying mechanisms is. The simplified process algorithms for estimating N_2O emissions from nitrification and denitrification differ between the developed biogeochemical process models in terms of the effects of environmental drivers taken into account (Fang et al., 2015) and consequently result in different responses to the environmental factors and a diverse models' performance in simulating N_2O emissions under different climate, soil and management conditions (Frolking et al., 1998;Vogeler et al., 2013). Current experimental research is constantly making progress in improving our understanding of mechanisms underlying N_2O emissions by using state-of-the art molecular and isotope methods (Baggs, 2008;Baggs, 2011;Butterbach-Bahl et al., 2013;Decock and Six, 2013). It is important that these insights will inevitably lead to further refining and re-evaluation of N_2O emission process algorithms. To further improve model simulations, modellers and experimentalists could jointly design experiments that provide mechanistic information suitable for improvements in model structure, especially regarding management practices that are difficult to simulate at present (Venterea and Stanenas, 2008) (Fig. 2).

Modellers can not only benefit from communication with biophysical scientists regarding the model input requirements and availability of the measured data at the studied domain for the model application, constraining parameter values and model evaluation, but could also provide feedback on which data should be measured more accurately, where the major data gaps and uncertainties lie for upscaling, and providing relevant and reliable predictions to support policies. Adoption of different management practices should be evaluated across a wide range of environmental conditions, at larger spatial scales and for longer time periods. This would enable identification of areas with higher mitigation potential and boundary conditions for delivering emission reductions. Furthermore, model simulations could highlight where uncertainty around N_2O predictions and potential emission reductions is the highest, and inform where to invest in new field trials (Hillier et al., 2012;De Gryze et al., 2011). The sensitivity analyses of N_2O model predictions could indicate where threshold values (e.g., percent clay content, mean daily precipitation) might lie regarding the effectiveness of mitigation options. Cooperative efforts between modellers and biophysical scientists could accelerate the identification of applicability conditions and quantification of uncertainty around emission reductions, providing a more solid and refined basis to apply theory in practice (Fig. 2).

3 Systemic change: balancing environmental protection, food and nutrition security, and provisioning of energy and goods

Recent N_2O emission projections clearly indicate that patching the leaks is essential, but not sufficient, to stabilize atmospheric N_2O concentrations at an acceptable level by 2050 (UNEP, 2013). Systemic change driven by, for example, reduced meat and dairy consumption in the developed world is needed to reach the N_2O emission target. Various simulation studies have shown that reduced meat and dairy consumption decreases N_2O emissions through reduced manure application and cultivation of feed crops (Popp et al., 2010;Stehfest et al., 2009;Westhoek et al., 2014). However, emission reduction estimates are relatively coarse, mostly due to the lack of information on land-use changes and associated emissions induced by reduced meat and dairy consumption. Would there be a shift toward grass-fed animal production? Would there be increased consumption of fruit and vegetables, driving up the acreage dedicated to horticulture? Would there be increased demand for legumes in human diets? Would consumers cut down on their total calorie and protein intake, making part of the land available for bio-energy crops, or nature conservation and recreation areas? Or would production be sustained by increased exports? Clearly, there is a multitude of alternative land-use options, but the greenhouse gas emissions associated with these land-use conversions are not well quantified. Currently available foresight studies on the effects of dietary change on N_2O emissions attempt to take into account alternative land-use to a certain extent. Estimated emissions from alternative systems are, however, typically based on Intergovernmental Panel on Climate Change (IPCC) emission factors, where N_2O emissions are a fixed fraction of N-inputs (Popp et al., 2010;Stehfest et al., 2009;Westhoek et al., 2014). The IPCC emission factors are based on N_2O emission data available when the IPCC guidelines were developed, which mainly consists of experiments in cereal cropping systems in temperate regions (Bouwman, 1996;IPCC, 2006). Empirical data shows, however, that crop type and geographic location have a significant effect on N_2O emissions, irrespective of N-input rate (Stehfest and Bouwman, 2006;Linquist et al., 2012;Verhoeven et al., 2013;Decock, 2014). Therefore, awareness campaigns or policies aimed at reduced meat and dairy consumption should go hand in hand with considerations on how to steer and account for direct and indirect land-use change (Franks and Hadingham, 2012). This requires a whole system approach involving soil scientists, agricultural economists, social and political scientists, geographers and policy makers (Fig. 2) to identify the most likely or most desirable alternative cropping systems and/or land-use scenarios and the associated greenhouse gas emissions in various regions of the world.

Overconsumption of meat and dairy in developed countries is only a part of the global challenge of "the starving, the stunted and the stuffed". Millions of people are hungry or malnourished, both in the global South and North (FAO et al., 2014). The prevalence of hunger might even be exacerbated as the global population increases in the coming decennia (Alexandratos and Bruinsma, 2012). The problem could be partly alleviated by reducing food waste, improving food distribution and access to markets, and addressing socio-economic inequalities. In many developing countries, however, the low productivity of agricultural systems is a major concern. For example, annual maize yields in Africa and South America ranged from 2 to 5 Mg ha^{-1} between 2009 and 2013, compared to 8 to 10 Mg ha^{-1} in Western Europe and North-America in the same period (FAOSTAT, 2015). The low productivity often observed in developing countries is typically associated with soil degradation and resource limitations. More specifically, farmers in many developing countries lack access to sufficient synthetic and/or organic fertilizers to meet crop requirements, other improved inputs (e.g. high quality seed, crop protection measures, and reliable irrigation facilities), availability of labour and machinery, and access to financial support structures (e.g. insurance or loans). Meanwhile, developing countries are the areas where the largest population increases are predicted (UN, 2013). As more food will be needed to nourish the increasing global population, it is important to contemplate which food should be produced, where it should be produced, how the production system should be managed, and at what environmental cost. While increases in N_2O emissions due to increased N fertilizer use in many developing countries have been predicted (IPCC, 2007), little is known about the actual effect of intensification on N_2O emissions in those agricultural systems (Hickman et al., 2011;Valentini et al., 2014). In N-rate trials in Western Kenya, an exponential response of N_2O to N input was observed (Hickman et al., 2015), similar to many studies in temperate systems (Hoben et al., 2011;Kim et al., 2012). Nevertheless, emissions as a percentage of N applied ranged between 0.01 and 0.11%, well below the average IPCC emission factor of 1% (Hickman et al., 2015). Likewise, simulations of intensification scenarios suggested a smaller environmental impact relative to productivity gains in Zimbabwe compared to Austria and China (Carberry et al., 2013). To meet the needs of the growing global population, there is an urgent need to investigate the sustainability of various intensification scenarios across the globe, through collaborations between agroecologists, agronomists, rural economists, nutrition specialists and sociologists. Soil scientists specializing in N_2O emissions could help address where and how intensification would have the largest impact on food and nutrition security with minimal environmental impact, by seeking out experiments in currently underrepresented geographic locations and cropping systems, e.g. by investing in climate-smart agricultural projects in developing countries (Marques de Magalhães and Lunas Lima, 2014;Steenwerth et al., 2014).

By “the stuffed”, we are referring to the overconsumption of calories worldwide (especially in the form of fats and refined sugars), which has contributed to a global epidemic of obesity and has been linked to increased risk of non-communicable diseases such as cardio-vascular diseases, several cancers, and diabetes (Lustig et al., 2012). The increasing consumption of these foods at unhealthy levels has become an undeniable public health issue, and has boosted many debates on policies such as sugar and fat taxes, diet education, and prevention campaigns to address the problem (Malik et al., 2013). Meanwhile, many of the sugar and oil crops are also on the table for bio-energy production. Yet, the net greenhouse gas benefit of biofuels remains controversial and tends to strongly depend on the feedstock used (Del Grosso et al., 2014) and regional adoption potentials (Yi et al., 2014). One of the largest uncertainties in life cycle analysis (LCA) of biofuels relates to direct and indirect N_2O emissions from soil (Benoist et al., 2012). Due to the lack of original data, many LCAs default to IPCC emission factors to estimate N_2O emissions from soil, and therefore fail to account for land-use, geographical, and management effects on N_2O emissions. For example, there is evidence that N_2O emissions from sugar cane cultivation might be larger than expected based on IPCC emission factors, which could change the picture on the greenhouse gas balance of sugarcane based biofuels (Lisboa et al., 2011). Meanwhile, there are great hopes that second-generation biofuels (e.g. conversion of lignocellulose rather than sugars) will help meet bioenergy targets. Feedstock production is expected to be less intensive and cause lower N_2O emissions from soil compared to first-generation biofuels (Bessou et al., 2011;Don et al., 2012). From a global perspective, sugar cane, sugar beet, maize, soybeans, rapeseed and palm oil accounted for over 20% of the harvested crop area and over 30% of the total crop production in the period 2009-2013 (FAOSTAT, 2015). Up to 20% of the harvested biomass is used for bio-energy production (FAO, 2013a). This fraction is expected to increase as various countries mandate an increasing share of bioenergy in the total energy consumption (Alexandratos and

Bruinsma, 2012). Clearly, interrelated trends in public health, energy and environmental policies could have a significant effect on the cultivated acreage of oil and sugar crops, the emergence of second-generation bioenergy crops, and the associated changes in N_2O emissions.

Feed, oil, sugar and bioenergy crops form an important share of the significant contribution of crop production to N_2O emissions. Soil scientists should take up responsibility in debates on the impact of forthcoming policies that directly or indirectly affect the cultivated acreage of these crops, backed by robust crop, region and management specific N_2O emission measurements. The examples above clearly illustrate the need to assess public interest and socio-economic feasibility in combination with biophysical effectiveness, in order to guide land-use decisions. This requires multi-directional collaborations between biophysical scientists and actors engaged in policy making, socio-economic assessments and livelihood enhancement of farmers. Furthermore, the highlighted land-use changes are heavily dependent on behavioural change of multiple actors, including producers and consumers. It is not clear how and at what rate such behavioural changes can take place. Step-wise policy implementation may be necessary, and a lag time in effectiveness can be expected. Dynamic modelling that takes into account transition phases can help achieve a more realistic map of projected changes in N_2O emissions.

4 Complex synergies and trade-offs challenge the path to sustainability

Sustainable management of agricultural systems evidently does not end at optimizing productivity and minimizing N_2O emissions. It includes, and is not limited to, improving the recycling of essential nutrients at the scale of management or policy-making, especially of those nutrients that come from finite reserves such as phosphorus; protecting of ground and surface waters from eutrophication and other toxicity induced by agrochemicals and fertilizers; restoring and conserving of biodiversity, including the safeguarding of pollination services and persistence of natural enemies for agricultural pests and disease control; preventing air pollution from agriculture by reducing indirect emissions of NO_x, NH_3, and dust particles; preventing unsustainable withdrawals of water for irrigation; protecting soil from depletion and degradation; and increasing the resilience of agricultural production systems, especially in the light of climate change (Schröder et al., 2011;Foley et al., 2011;Bindraban et al., 2012). In addition, social and economic aspects such as labour requirements and profitability cannot be disregarded (FAO, 2013b). Many solutions and interventions for several of these problems have been sought and applied at field, farm, landscape, national and global scales. Examples at the field and landscape scale include conservation agriculture, intercropping, agroforestry, precision agriculture, buffer strips, organic agriculture, recycling of organic waste streams for agricultural production, drip irrigation, and improved crop varieties, often assisted by advances in engineering and technological solutions such as genetic modification, novel machinery implements, and recently also drones. Mitigation actions at the national and global scale include environmental regulation and international collaborations. At present, interactions and conflicts between N_2O mitigation strategies and solutions proposed to address other agronomic, environmental or socio-economic problems remain insufficiently explored. Therefore, it is important to identify where synergies and trade-offs can be found, by collaborating with scientists that specialize in other aspects of agroecology, as well as with scientists that develop methods to facilitate transdisciplinary research and engage stakeholders, tools for trade-off analysis, and approaches to deal with complex systems (Klapwijk et al., 2014;van Mil et al., 2014;Jarvis et al., 2011). In practice, this could include combining management scenarios in field trials and modelling efforts; facilitating the transfer of the data they produce by collaborating on consistent data and reporting protocols, and standardized, centralized databases; contributing to build integrated bio-physical and socio-economic models; and conducting meta-studies placing N_2O-related outcomes among other environmental and socio-economic indicators, which in turn can feed back into the design of N_2O emission reduction research (Fig. 2).

Mitigating N_2O emissions is a complex issue embedded in the even more complex maze of improving the sustainability of agriculture and food systems. Therefore, finding the right denominator for assessing N_2O emissions is a challenging task. Yield-scaled emissions are practical for assessing the eco-efficiency of a particular field, but are problematic when it comes to absolute emission reductions at a global scale (Van Groenigen et al., 2010;Murray and Baker, 2011). Furthermore, yield-scaled emissions cannot accommodate impacts of systemic change and comparisons of land-use scenarios in which crops with very different nutritional, societal, and economic values are grown. Prior to the start of new experiments, soil scientists could reach out to policy makers, agricultural and resource economists, and industrial ecologists to identify what ancillary variables (e.g., use of the crop and its residues, yield, nutritional value, etc.) should be collected to accommodate a balanced comparison of different systems.

5 Inter- and transdisciplinary research: buzzword versus reality

While the terms inter- and transdisciplinary research are frequently dropped as buzzwords, especially in research evolving around real-world problems, challenges associated with working across scholarly disciplines, or collaborations between academic and non-academic actors, cannot be underestimated. So-called interdisciplinary projects often regress to research consortia that merely accommodate exchange of final research findings, rather than fostering true joint creation of new knowledge (Bruce et al., 2004). Common barriers to inter- and transdisciplinary research include: the high time commitment for coordination and communication; lack of recognition in traditional institutional reward systems; differences in attitudes, jargon, philosophies and publication protocols between disciplines; a lack of understanding of methods and outcomes of different disciplinary components; and difficulties in finding referees that appreciate and evaluate the quality of interdisciplinary projects (Campbell, 2005;Bruce et al., 2004). Many funding agencies and academic institutions are taking steps to overcome some of these barriers by opening calls for interdisciplinary research projects, by organizing meetings to explore potential new interdisciplinary partnerships, or by establishing competence centres tasked with bringing together knowledge and stakeholders relevant to addressing important national or global problems. Individual researchers committed to the cause of reducing N_2O emissions from soil could contribute by actively seeking out such opportunities. In this forum article, we presented a guiding framework for the N_2O researcher interested in inter- and transdisciplinary research, by conceptualizing links between major themes in sustainability of food and agricultural systems and N_2O emissions research across different scales (Fig. 1), and by drawing a map of relevant stakeholders and their potential interactions (Fig. 2).

6 Concluding remarks

Tremendous progress has been made during the last decennia with respect to the scientific understanding of N_2O emissions from soils: Various pathways and mechanisms have been elucidated (Butterbach-Bahl et al., 2013); molecular and isotopic tools to assess mechanisms have been advanced (Baggs, 2008;Baggs, 2011;Decock and Six, 2013); we have a general idea of temporal and spatial patterns of N_2O emissions (Groffman et al., 2009); micrometeorological methods are available to monitor spatially integrated N_2O emissions at high temporal resolution (Eugster and Merbold, 2015); various data sources have been synthesized in qualitative and quantitative reviews (Bouwman, 1996;Decock, 2014); and biogeochemical models have been developed and improved to predict N_2O emissions under various scenarios (Chen et al., 2008). These efforts have paved the way to identify the major causes of soil-derived N_2O and to isolate the strategies that have the greatest potential for reducing global N_2O emissions (e.g. increasing N efficiency in cropping systems and reducing meat and dairy consumption in developed countries) (Snyder et al., 2014;UNEP, 2013;Oenema et al., 2014). The time is ripe to reach across disciplines, not only to fine-tune crop and region-specific agronomic management strategies for instant mitigation action, but also to better integrate the issue of N_2O emissions in overarching debates on agricultural change. This will help steer transformative action for improving the social, economic and environmental sustainability of agricultural and food systems for many generations to come.

References

Alexandratos, N., and Bruinsma, J.: World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03., FAO, Rome, 2012.

Baggs, E. M.: A review of stable isotope techniques for N_2O source partitioning in soils: recent progress, remaining challenges and future considerations, Rapid Commun. Mass Sp., 22, 1664-1672, 2008.

Baggs, E. M.: Soil microbial sources of nitrous oxide: recent advances in knowledge, emerging challenges and future direction, Curr. Opin. Environmental Sustainability, 3, 321-327, 2011.

Benoist, A., Dron, D., Zoughaib, A.: Origins of the debate on the life-cycle greenhouse gas emissions and energy consumption of first-generation biofuels–A sensitivity analysis approach, Biomass Bioenerg., 40, 133-142, 2012.

Bessou, C., Ferchaud, F., Gabrielle, B., and Mary, B.: Biofuels, greenhouse gases and climate change. A review, Agron. Sustain. Dev., 31, 1-79, 2011.

Bindraban, P. S., van der Velde, M., Ye, L., Van den Berg, M., Materechera, S., Kiba, D. I., Tamene, L., Ragnarsdóttir, K. V., Jongschaap, R., and Hoogmoed, M.: Assessing the impact of soil degradation on food production, Curr. Opin. Environmental Sustainability, 4, 478-488, 2012.

Bouwman, A. F.: Direct emission of nitrous oxide from agricultural soils, Nutr. Cycl. Agroecosys., 46, 53-70, 1996.

Bruce, A., Lyall, C., Tait, J., and Williams, R.: Interdisciplinary integration in Europe: the case of the Fifth Framework programme, Futures, 36, 457-470, 2004.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, Philos. T. R. Soc. B: Biological Sciences, 368, 2013.

Campbell, L. M.: Overcoming obstacles to interdisciplinary research, Conserv. Biol., 19, 574-577, 2005.

Carberry, P. S., Liang, W.-l., Twomlow, S., Holzworth, D. P., Dimes, J. P., McClelland, T., Huth, N. I., Chen, F., Hochman, Z., and Keating, B. A.: Scope for improved eco-efficiency varies among diverse cropping systems, P. Natl. Acad. Sci. USA, 110, 8381-8386, 2013.

Chen, D., Li, Y., Grace, P., and Mosier, A. R.: N_2O emissions from agricultural lands: a synthesis of simulation approaches, Plant Soil, 309, 169-189, 2008.

Davidson, E., Galloway, J., Millar, N., and Leach, A.: N-related greenhouse gases in North America: innovations for a sustainable future, Curr. Opin. Environmental Sustainability, 9, 1-8, 2014.

De Gryze, S., Lee, J., Ogle, S., Paustian, K., and Six, J.: Assessing the potential for greenhouse gas mitigation in intensively managed annual cropping systems at the regional scale, Agr. Ecosyst. Environ., 144, 150-158, 2011.

Decock, C., and Six, J.: How reliable is the intramolecular distribution of ^{15}N in N_2O to source partition N_2O emitted from soil?, Soil Biol. Biochem., 65, 114-127, 2013.

Decock, C.: Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps, Environ. Sci. Technol., 48, 4247-4256, 2014.

Del Grosso, S., Smith, P., Galdos, M., Hastings, A., and Parton, W.: Sustainable energy crop production, Curr. Opin. Environmental Sustainability, 9, 20-25, 2014.

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P. L., Wofsy, S. C., and Zhang, X.: Couplings Between Changes in the Climate System and Biogeochemistry, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Dobbie, K., McTaggart, I., and Smith, K.: Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons, key driving variables, and mean emission factors, J. Geophys. Res.-Atmos., 104, 26891-26899, 1999.

Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M. S., Drewer, J., Flessa, H., Freibauer, A., Hyvönen, N., and Jones, M. B.: Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon, Glob. Change Biol. Bioenergy, 4, 372-391, 2012.

Eugster, W., and Merbold, L.: Eddy covariance for quantifying trace gas fluxes from soils, SOIL, 1, 187-205, 2015.

Fang, Q., Ma, L., Halvorson, A. D., Malone, R., Ahuja, L., Del Grosso, S., and Hatfield, J.: Evaluating four N_2O emissions algorithms in RZWQM2 in response to N rate on an irrigated corn field., Environ. Modell. Softw., In Press, 2015.

FAO: FAO Statistical Yearbook 2013: World Food and Agriculture, Food and Agriculture Organization of the United Nations, Rome, 2013a.

FAO: SAFA Sustainability Assessment of Food and Agriculture systems guidelines version 3.0, Food and Agriculture Organization of the United Nations, Rome, 2013b.

FAO, IFAD, and WFP: The State of Food Insecurity in the World 2014. Strengthening the enabling environment for food security and nutrition., FAO, Rome, 2014.

Food and Agriculture Organization of the United Nations Statistics division. http://faostat3.fao.org, 2015.

Fitton, N., Ejerenwa, C., Bhogal, A., Edgington, P., Black, H., Lilly, A., Barraclough, D., Worrall, F., Hillier, J., and Smith, P.: Greenhouse gas mitigation potential of agricultural land in Great Britain, Soil Use Manage., 27, 491-501, 2011.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., and West, P. C.: Solutions for a cultivated planet, Nature, 478, 337-342, 2011.

Franks, J. R., and Hadingham, B.: Reducing greenhouse gas emissions from agriculture: avoiding trivial solutions to a global problem, Land Use Policy, 29, 727-736, 2012.

Frolking, S., Mosier, A., Ojima, D. S., Li, C., Parton, W. J., Potter, C., Priesack, E., Stenger, R., Haberbosch, C., Dörsch, P., Flessa, H., and Smith, K.: Comparison of N2O emissions from soils at three temperate agricultural sites: simulations of year-round measurements by four models., Nutr. Cycl. Agroecosys., 52, 77-105, 1998.

Groffman, P. M., Butterbach-Bahl, K., Fulweiler, R. W., Gold, A. J., Morse, J. L., Stander, E. K., Tague, C., Tonitto, C., and Vidon, P.: Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models, Biogeochemistry, 93, 49-77, 2009.

Hickman, J., Tully, K., Groffman, P., Diru, W., and Palm, C.: A potential tipping point in tropical agriculture: Avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya, J. Geophys. Res.-Biogeo., 120, 938–951, 10.1002/2015JG002913, 2015.

Hickman, J. E., Havlikova, M., Kroeze, C., and Palm, C. A.: Current and future nitrous oxide emissions from African agriculture, Curr. Opin. Environmental Sustainability, 3, 370-378, 2011.

Hillier, J., Brentrup, F., Wattenbach, M., Walter, C., Garcia-Suarez, T., Mila-i-Canals, L., and Smith, P.: Which cropland greenhouse gas mitigation options give the greatest benefits in different world regions? Climate and soil-specific predictions from integrated empirical models, Glob. Change Biol., 18, 1880-1894, 2012.

Hoben, J., Gehl, R., Millar, N., Grace, P., and Robertson, G.: Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest, Glob. Change Biol., 2011.

IPCC: Guidelines for National Greenhouse Gas Invertories, Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application, 2006.

IPCC: Climate Change 2007: Synthesis Report, in: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Pachauri, R. K., and Reisinger, A., IPCC, Geneva, 104, 2007.

IPCC: Climate Change 2013. The Physical Science Basis. Summary for Policymakers. Working Group I Contribution to the fifth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change, Switzerland, 2013.

Jarvis, A., Lau, C., Cook, S., Wollenberg, E., Hansen, J., Bonilla, O., and Challinor, A.: An integrated adaptation and mitigation framework for developing agricultural research: synergies and trade-offs, Exp. Agr., 47, 185-203, 2011.

Kim, D. G., Hernandez-Ramirez, G., and Giltrap, D.: Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis, Agr. Ecosyst. Environ., 168, 53-56, 2012.

Klapwijk, C., van Wijk, M., Rosenstock, T., van Asten, P., Thornton, P., and Giller, K.: Analysis of trade-offs in agricultural systems: Current status and way forward, Curr. Opin. Environmental Sustainability, 6, 110-115, 2014.

Linquist, B., Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., and Kessel, C.: An agronomic assessment of greenhouse gas emissions from major cereal crops, Glob. Change Biol., 18, 194-209, 2012.

Lisboa, C. C., Butterbach-Bahl, K., Mauder, M., and Kiese, R.: Bioethanol production from sugarcane and emissions of greenhouse gases–known and unknowns, Glob. Change Biol. Bioenergy, 3, 277-292, 2011.

Lustig, R. H., Schmidt, L. A., and Brindis, C. D.: Public health: The toxic truth about sugar, Nature, 482, 27-29, 2012.

Malik, V. S., Willett, W. C., and Hu, F. B.: Global obesity: trends, risk factors and policy implications, Nat. Rev. Endocrinol., 9, 13-27, 2013.

Marques de Magalhães, M., and Lunas Lima, D.: Low-Carbon Agriculture in Brazil: The Environmental and Trade Impact of Current Farm Policies, Issue Paper No. 54; International Centre for Trade and Sustainable Development, Geneva, Switzerland, http://www.ictsd.org., 2014.

Mérel, P., Yi, F., Lee, J., and Six, J.: A regional bio-economic model of nitrogen use in cropping, Am. J. Agr. Econ., 96, 67-91, 2014.

Murray, B. C., and Baker, J. S.: An output-based intensity approach for crediting greenhouse gas mitigation in agriculture: Explanation and policy implications, Greenhouse Gas Measurement and Management, 1, 27-36, 2011.

NOAA: Physical Sciences Division of the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL). http://www.esrl.noaa.gov/, 2015.

Oenema, O., Ju, X., de Klein, C., Alfaro, M., del Prado, A., Lesschen, J. P., Zheng, X., Velthof, G., Ma, L., and Gao, B.: Reducing nitrous oxide emissions from the global food system, Curr. Opin. Environmental Sustainability, 9, 55-64, 2014.

Popp, A., Lotze-Campen, H., and Bodirsky, B.: Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production, Global Environ. Chang., 20, 451-462, 2010.

Rochette, P., Worth, D. E., Lemke, R. L., McConkey, B. G., Pennock, D. J., Wagner-Riddle, C., and Desjardins, R.: Estimation of N_2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology, Can. J. Soil Sci., 88, 641-654, 2008.

Schröder, J. J., Smit, A. L., Cordell, D., and Rosemarin, A.: Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use, Chemosphere, 84, 822-831, 2011.

Snyder, C., Davidson, E., Smith, P., and Venterea, R.: Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions, Curr. Opin. Environmental Sustainability, 9, 46-54, 2014.

Springborn, M., Yeo, B.-L., Lee, J., and Six, J.: Crediting uncertain ecosystem services in a market, J. Environ. Econ. Manag., 66, 554-572, 2013.

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., Hatfield, J. L., Henry, K., Hopmans, J. W., and Horwath, W. R.: Climate-smart agriculture global research agenda: scientific basis for action, Agriculture & Food Security, 3, 11, 2014.

Stehfest, E., and Bouwman, L.: N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions, Nutr. Cycl. Agroecosys., 74, 207-228, 2006.

Stehfest, E., Bouwman, L., van Vuuren, D. P., den Elzen, M. G., Eickhout, B., and Kabat, P.: Climate benefits of changing diet, Climatic change, 95, 83-102, 2009.

UN: World Population Prospects: The 2012 Revisions, Key Findings and Advance Tables, United Nations, Department of Economic and Social Affairs, Population Division. Working Paper No. ESA/P/WP.227, 2013.

UNEP: Drawing down N_2O to protect climate and the ozone layer. A UNEP Synthesis Report, United Nations Environment Programme (UNEP), Nairobi, Kenya, 2013.

Valentini, R., Arneth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., Ciais, P., Grieco, E., Hartmann, J., Henry, M., Houghton, R. A., Jung, M., Kutsch, W. L., Malhi, Y., Mayorga, E., Merbold, L., Murray-Tertarolo, G., Papale, D., Peylin, P., Poulter, B., Raymond, P. A., Santini, M., Sitch, S., Vaglio Laurin, G., van der Werf, G. R., Williams, C. O., and Scholes, R. J.: A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities, Biogeosciences, 11, 381-407, 2014.

Van Groenigen, J., Velthof, G., Oenema, O., Van Groenigen, K., and Van Kessel, C.: Towards an agronomic assessment of N_2O emissions: A case study for arable crops, Eur. J. Soil Sci., 61, 903-913, 2010.

van Mil, H., Foegeding, E., Windhab, E., Perrot, N., and van der Linden, E.: Using a complex system approach to address world challenges in Food and Agriculture, arXiv preprint arXiv:1309.0614, 2013.

Venterea, R. T., and Stanenas, A. J.: Profile analysis and modeling of reduced tillage effects on soil nitrous oxide flux, J. Environ. Qual., 37, 1360-1367, 2008.

Verhoeven, E., Decock, C., Garland, G., Kennedy, T., Periera, P., Fischer, M., Salas, W., and Six, J.: (University of California, Davis) N_2O Emissions from the Application of Fertilizers in Agricultural Soils, California Energy Commission. Publication number: PIR-08-004, 2013.

Vogeler, L., Giltrap, D., and Cichota, R.: Comparison of APSIM and DNDC simulations of nitrogen transformations and N_2O emissions, Sci. Total Environ., 465, 147-155, 2013.

Westhoek, H., Lesschen, J. P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M. A., and Oenema, O.: Food choices, health and environment: effects of cutting Europe's meat and dairy intake, Global Environ. Chang., 26, 196-205, 2014.

Yi, F., Mérel, P., Lee, J., Farzin, Y., and Six, J.: Switchgrass in California: where, and at what price? , Glob. Change Biol. Bioenergy, 6, 672-686, 2014.

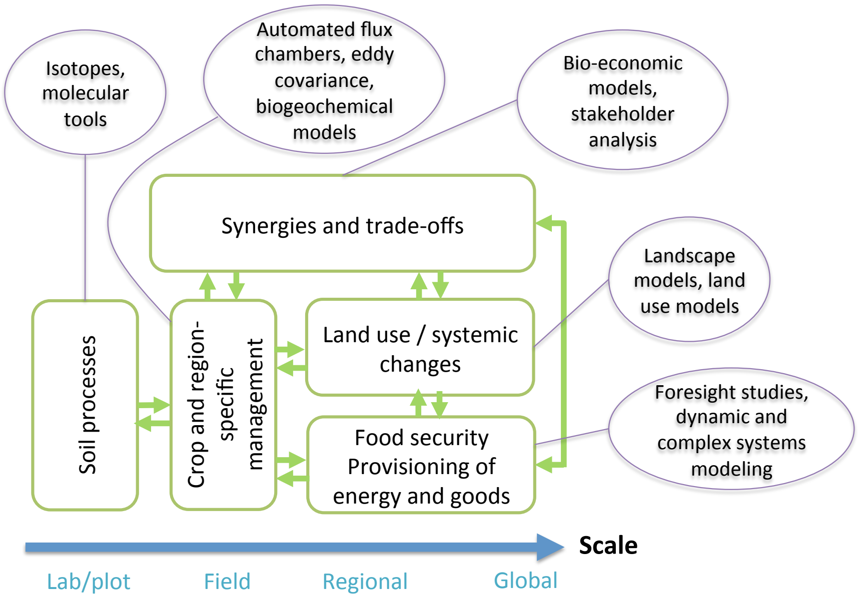

Figure 1. Illustration of interactions between major themes relevant for N_2O mitigation from patching leaks to transformative action. Examples of research tools commonly associated with the different themes are shown in the purple text balloons.

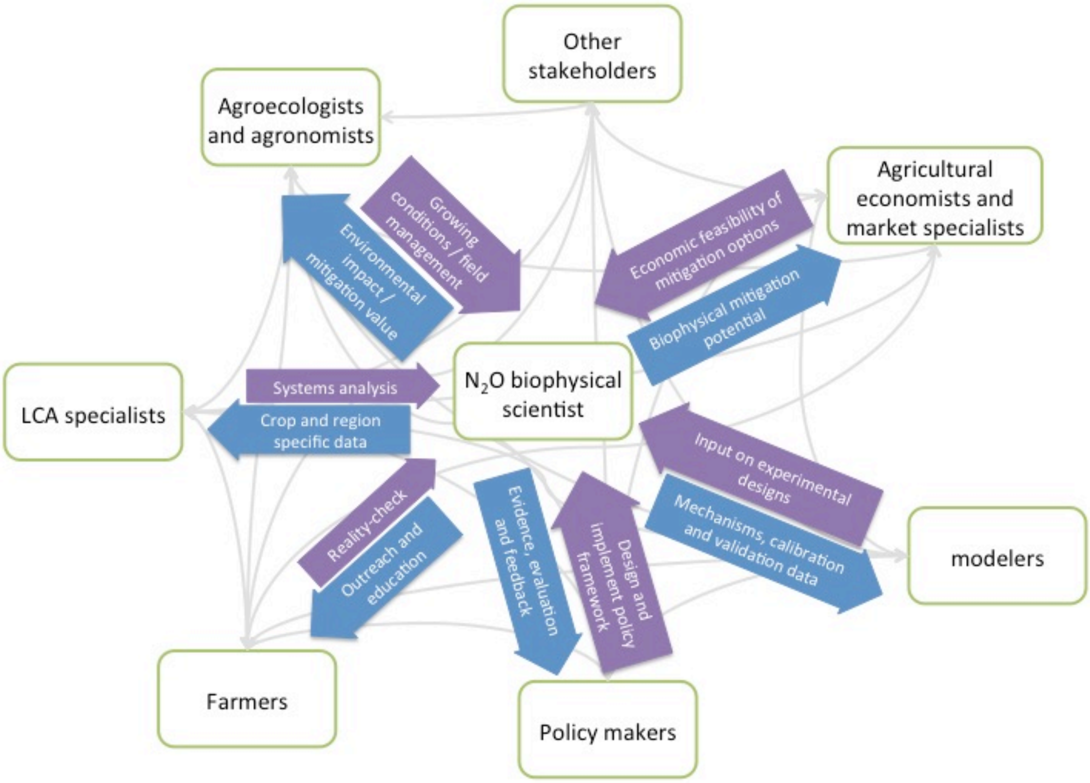

Figure 2. Stakeholder map with examples of knowledge exchange, interactions and opportunities for active collaborations between biophysical scientists in N_2O research and specialists in other disciplines.