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From research to policy: optimizing the design of a national monitoring system to mitigate soil nitrous oxide emissions

Stephen M Ogle1,2, Klaus Butterbach-Bahl3, Laura Cardenas4, Ute Skiba5 and Clemens Scheer3

Nitrous oxide (N2O) emissions from agricultural soils are a key source of greenhouse gas emissions in most countries. In order for governments to effectively reduce N2O emissions, a national inventory system is needed for monitoring, reporting and verifying emissions that provides unbiased estimates with the highest precision feasible. Inventory frameworks could be advanced by incorporating experimental research networks targeting key gaps in process understanding and drivers of emissions, with a multi-stage survey to collect data on agricultural management and N2O fluxes that allow for development, parameterization and application of models to estimate national-scale emissions. Verification can be accomplished with independent estimation of fluxes from atmospheric N2O concentration data. A robust monitoring system would provide accurate emission estimates, and allow policymakers to develop programs to more sustainably manage reactive N and target mitigation measures for reducing N2O emissions from agricultural soils.

Introduction
Climate shapes the world around us and has a profound impact on society. The anthropogenic influence of greenhouse gas (GHG) emissions on climate is growing with various lines of scientific evidence demonstrating regional impacts such as increased frequency of heat waves, droughts, and heavy precipitation events [1]. In turn, there has been sea level rise, greater risk of catastrophic fires, increased flooding episodes, impacts on food supplies, changes in species migrations and ranges, and increased health risk, among a variety of other impacts that vary regionally [1]. With growing recognition of impacts, there is the possibility of limiting warming by 2°C or possibly 1.5°C through the Paris Agreement [12].

Nitrous oxide (N2O) is one of three main GHGs emitted through anthropogenic activity, and more than half of global N2O emissions are from agricultural soil management associated with reactive forms of N [2]. These practices include applications of synthetic mineral N and livestock manure N; crop residue N inputs to soils; enhanced mineralization of N from soil organic matter due to continuous cultivation of land or change in land use to cropland from grassland, forest or wetlands; as well as increased cultivation of N-fixing legume species. There are opportunities to more sustainably manage reactive N in agricultural lands and reduce soil N2O emissions by optimizing nitrogen-use efficiency (NUE) of crops with a greater proportion of available mineral N incorporated into crop growth [3,4]. In fact, overapplication of N, which decreases NUE, has been shown to exponentially increase N2O emissions [5], although not all studies have found an exponential increase in emissions with higher application rates [6]. Moreover, the relationship between NUE and soil N2O emissions may vary due to the complexity of processes driving emissions [4]. For example, improving NUE may not always equate with less N2O emissions because a larger proportion of crop N uptake may be achieved by a reduction in other N losses, such as ammonia (NH3) volatilization and emissions of other nitrogen gases (NOx, N2), as well as leaching of nitrate and dissolved organic matter.

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Similarly, the system’s response to a combination of N sources, that is, (mineral and organic fertilizer N, and crop residue N), is also complex and not necessarily linear [7,8]. Nonetheless there are opportunities to reduce emissions by improved N management that targets N application rates, timing, placement and type of fertilizers [3,4,9].

With knowledge about ways to reduce N2O emissions from agricultural soils, there are opportunities to incorporate agricultural soil management into national mitigation plans [10]. However, robust monitoring, reporting and verification programs are needed to support climate change policy. In general, GHG inventories provide the basis for monitoring national emissions, and assessing progress in reducing emissions with mitigation programs. The Intergovernmental Panel on Climate Change (IPCC) has developed inventory guidelines for monitoring national emissions [11,12,13]. Improving inventories is largely predicated on developing country-specific emission factors (categorized as Tier 2 methods by the IPCC) or model-based approaches for deriving dynamic emission factors both spatially and temporally (categorized as Tier 3 methods by IPCC), as well as improving activity data collection [14,15]. Approximately half of Annex I countries (Table 1) and less than 10% of non-Annex I countries [15] are using country-specific emission factors (Tier 2) and/or model-based approaches (Tier 3) for reporting soil N2O emissions to the UN Framework Convention on Climate Change. Three Annex I countries have developed Tier 3 methods that are used in combination with Tier 1 and/or 2 methods to estimate soil N2O emissions, including Iceland [16], Switzerland [17], and USA [18].

Our objective is to describe an inventory framework for monitoring soil N2O emissions at the national scale that meets the overarching goal of the IPCC guidance, that is, to produce accurate estimates that are as precise as feasible [19], and thus provide a basis for governments to develop and implement policy to more sustainably manage reactive N and reduce N2O emissions (Figure 1). The components of the framework include: a) an experimental research network; b) multi-stage survey of land use, management practices, and emissions measurements; c) model selection and parameterization using N2O measurements from the survey; d) model implementation to estimate emissions and uncertainties using land use and management data from the survey and scaling to the national level; and e) verification of emissions using atmospheric N2O concentration data or other independent measurements of N2O emissions. This framework is primarily focused on direct N2O emissions from agricultural soils although adding reactive N to agricultural lands creates a cascade effect where N2O is also emitted indirectly as reactive N is transferred to other locations in the environment [20].

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Soil N2O inventory methods that are used by Annex I Parties for reporting to the UN Framework Convention on Climate Change (Convention Reporting)</th>
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Inventory framework for monitoring N\textsubscript{2}O emissions from soils

**Experimental research network**

Experiments provide the basis for understanding the N cycle and microbial transformations that lead to soil N\textsubscript{2}O emissions, and inform the design of monitoring networks and model development. Experiments are also useful for evaluating feedbacks on N\textsubscript{2}O emissions associated with climate change that may require refinements to mitigation strategies and updates to inventory frameworks in the future. Field and laboratory experiments address questions about factors driving emissions [21]. For example, experiments can evaluate effects of microbial community composition and activity on N\textsubscript{2}O production and consumption, as well as trade-offs leading to different levels of gaseous N emissions (NH\textsubscript{3}, NO\textsubscript{X}, N\textsubscript{2}O, N\textsubscript{2}) related to management and soil conditions. In the field, automated static chamber systems or eddy-covariance techniques capture inherent temporal and spatial variability with ‘high-frequency’ measurements that have significantly improved flux estimates [22,23]. To characterize and quantify production and consumption processes of N\textsubscript{2}O, various tools have been developed, including flow-through methods to directly measure N\textsubscript{2}O emissions [24], use of inhibitors (e.g., acetylene), and different stable isotope techniques [25,26,27,28]. Portable highly sensitive laser spectroscopy and chamber technologies [29] have been used to explore spatial variability in N\textsubscript{2}O fluxes from sites to landscape scales [30]. Furthermore, field and laboratory methods have been combined to better understand processes and drivers of N\textsubscript{2}O emissions [31,32]. Generalizations can be made by analyzing experimental data from multiple studies via meta-analysis [33,82].

Experiments have demonstrated that soil N\textsubscript{2}O emissions are primarily generated by microbial processes of
Nitrous oxide emissions from soils exhibit pulses over time and space, referred to as hot moments and hot spots of emissions, respectively [36]. Emission pulses can occur following fertilization in agricultural fields [37], and with changing soil conditions associated with drying-wetting and freeze-thaw cycles [38,39]. The periodicity in emissions requires sufficient sampling frequencies to ensure pulses are not missed, with more continuous measurements using automated chambers or tower-based eddy covariance measurements [40,41].

Experimental research networks provide a basis for understanding how management influences N$_2$O emissions [42], and generate new technologies and management options for reducing emissions. Research networks span across national boundaries and through international collaboration among scientists (i.e. https://globalresearchalliance.org/GRA; https://nitrogen.org/), providing greater efficiency in making new discoveries about N$_2$O emissions, and should be encouraged through international organizations (e.g. IPCC, UN-FAO, UNEP, and OECD).

**National survey**
Based on experimental research, it is known that crop management affects the timing and magnitude of soil N$_2$O emissions (e.g. Refs. [9,42,43]). Therefore, collection of management activity data is a key component of a national monitoring system and can be accomplished with remote sensing data, questionnaires and expert knowledge [14]. Surveys can use remote sensing data in combination with questionnaires for management information, and can include measurements of N$_2$O emissions at survey locations. Surveys are cost-effective because data collection is focused on a subsample of locations that are randomly selected from the entire population of the agricultural land base, rather than ‘wall-to-wall’ data collection from the entire domain using a census approach. Data could be collected using a hierarchical framework with several stages in the survey to increase sampling efficiency and reduce costs.

First, data are needed on the managed land base and underlying area of land use and land use change [11]. Land use data should be collected at all survey locations as the first stage in the sample. Remote-sensing data are the most cost-effective approach for collecting these data, and the information would serve the broader GHG inventory for land use activities [11,12]. Data collection must also address uncertainty in the area estimation based on the underlying survey design [44].

Second, data need to be collected on management activities such as fertilizer management, livestock and manure management, tillage practices, crop selection (including legumes), cover crops, residue management, and other related activities. These data could be collected from a subsample of the survey locations in a second stage of sampling, and may include use of remote sensing technologies to reduce costs at least for some practices such as tillage management [45]. Other data may be collected through questionnaires to capture management information that cannot be collected with remote sensing technologies, such as the type, rate, timing and placement of fertilizer. For efficiency, the data collected through questionnaires may be a subset of the locations in the second stage of sampling (effectively another stage in the sample design). Data collection could also involve crowd-sourcing methods to reduce costs associated with personnel time to deliver a survey. It is likely that some training is needed when collecting data through crowdsourcing to ensure the responses are accurate, reflecting the information and classifications that are used in the inventory [46].

It may not be possible to collect all management data from the survey, and so supplemental data from a regional/national census or other surveys may be used in the inventory (e.g. UK countryside survey, https://countrysidesurvey.org.uk). However, it is important to recognize that this will introduce additional uncertainty. Ogle et al. [47] conducted an inventory by modeling emissions based on land use and management histories for survey locations that are tracked by the US Department of Agriculture (USDA) [48]. The USDA survey did not include all management practices needed for the inventory, but additional information was compiled in other datasets. To address uncertainty, Ogle et al. [47] used a Monte Carlo simulation approach to estimate emissions multiple times representing variation in the likely practices at each USDA survey location based on the supplemental datasets. Even though it is possible to combine data from different sources, collecting the majority of management data at the survey locations will
minimize uncertainty. Other data may be needed to model N₂O emissions, such as meteorological data and soil characteristics [14], which may be part of the survey, but could be based on other data sources introducing some additional uncertainty into the inventory.

Third, an optimal survey supporting the monitoring system would include measurements of N₂O emissions to select and parameterize the best model for the inventory. Data collection could also include other components of the N cycle, such as volatilization of other N gases, losses of N through leaching and overall water flows, plant N uptake and microbial immobilization, as well as N inputs from fertilization, N fixation and deposition. While experimental research will inform model development about key processes and management activities, emission measurements are often a limiting factor in developing and parameterizing models, leading to a large source of overall uncertainty in model predictions (e.g. Ref. [49]). Therefore, measurement data could be collected in a third stage of sampling, that is, a subsample of the second stage, with accepted protocols, for example, Global Research Alliance [81] or the ICOS network protocols [51].

Estimation of national emissions could be inferred directly from the measurements in the survey if there is sufficient spatio-temporal sampling resolution to represent the country’s geoclimatic variability, and if resulting estimates meet expected levels of precision under government policy programs. However, this level of sampling may be prohibitively expensive in which case a model can be used to scale the information in the measurement data from the third stage to the entire survey sample for estimation of national emissions. Models that are used to predict soil N₂O emissions for inventory assessments are either empirically based statistical models or process-based models. These models are typically designed to quantify the impact of management practices on N₂O emissions, such as application of nitrification inhibitors (e.g. Refs. [54,55]), which is critical for advancing mitigation strategies and verifying outcomes in policy frameworks.

Empirical models are derived from measurement data using statistical methods and can be as simple as a single emission factor derived from the survey measurement data, or can be more complicated functions such as regression models [56–59]. Empirical models are useful in estimating emissions at regional and national scales, and in some cases are more accurate than more complex process-based models [60]. However, well-tested process-based models are likely to capture more drivers of emissions leading to greater accuracy [61]. In addition, process-based models can be applied to predict emissions for mitigation and future climate scenarios, while empirical models may not be adequate for this purpose if future conditions are different from conditions that were used to derive the empirical functions. Several process-based models have been developed and are currently used to estimate soil N₂O emissions at regional and larger scales, such as DayCent [62], DNDC [63], LandscapeDNDC [64], Dynamic Land Ecosystem Model [65], and SPACSYS [66]. Recent inter-comparisons of process-based models have been conducted to assess predictability of N₂O emissions [67,68].

A subset of measurement data from the survey can be used to derive an empirical model with statistical methods, or to parameterize a process-based model using optimization [69] or Bayesian methods [70,71–73]. Models can be evaluated with independent measurement data from the survey that are not used in model development and parameterization. Final model selection can be made using objective evaluation criteria including conventional statistics, such as root mean square error and bias statistics, or Bayesian model selection [74].

Model selection and parameterization

Estimation of national emissions could be inferred directly from the measurements in the survey if there is sufficient spatio-temporal sampling resolution to represent the country’s geoclimatic variability, and if resulting estimates meet expected levels of precision under government policy programs. However, this level of sampling may be prohibitively expensive in which case a model can be used to scale the information in the measurement data from the third stage to the entire survey sample for estimation of national emissions. Models that are used to predict soil N₂O emissions for the activity data on land use and management practices from the survey, possibly with supplemental datasets. For example, a process-based model simulates the histories over the inventory time period given the crop types, fertilization management, residue management, tillage practices, and other relevant management information. The uncertainty in estimates can be derived by applying the model several times with multiple iterations in a Monte Carlo analysis [19,47,49,75]. In each iteration, model parameters are randomly selected given parameter distributions, possibly from a Bayesian analysis, and a random selection of survey weights that can be estimated based on the survey design. If an empirical model
approach is used for the inventory, then uncertainty can be propagated using a Monte Carlo analysis based on probability distribution functions for the emission factors or parameters in the empirically derived functions [19].

Verifying national emissions
National emissions could be verified with N₂O emission measurements from a subsample of sites in the monitoring survey. However, this would only be valid if the subsample of measurement sites were not used in the development or parameterization of the model that was used to estimate national emissions. Alternatively, national GHG emission inventories could be verified using atmospheric N₂O concentrations and associated isotopic signatures from tall towers, aircraft campaigns and possibly remote sensing in the future [76,77]. Globally, atmospheric concentration samples are available through the National Oceanic and Atmospheric Administration Carbon Cycle Cooperative Global Air Sampling Network and the Commonwealth Scientific and Industrial Research Organization Network) [78**], and at regional scales from large tower measurements (i.e. TV towers) [79**]. Combining these data with atmospheric inversion approaches enables comparisons of ‘top down’ atmospheric measurements with ‘bottom-up’ GHG emissions inventories [80**]. Such an analysis has shown good agreement between the two methods for UK N₂O emissions [79**]. At the global scale, inverse modelling results identified increasing trends of N₂O emission from 2000 to 2015 for countries such as China and Brazil, whereas emissions from Europe and the USA remained stable [78**]. Although inverse modelling methods are still under development, the results can already provide useful information for verifying N₂O emission inventories, leading to improved confidence that reported emissions are accurate, provided that estimated emissions are consistent between the two approaches. Furthermore, inconsistencies in emission estimates can lead to identification of errors and improvements in the inventory.

Conclusions
Implementation of policy to reduce N₂O emissions needs a robust inventory monitoring framework that is developed and adapted over time with the latest scientific findings from an experimental research network. A survey approach with application of a model is an optimal, cost-effective design for collecting data through remote sensing, questionnaires, crowd-sourcing, as well as N₂O measurements and related data to constrain N budgets. With the reliable, useful and credible soil N₂O data emission, the monitoring system could inform development of mitigation programs for reducing soil N₂O emissions, and be used to monitor emissions ensuring mitigation targets are met. This would give national governments the confidence to include more sustainable management of reactive N as part of their national GHG mitigation plans under the Paris agreement [10]. In turn, this would lead to a larger portfolio of mitigation strategies that is likely needed to achieve the goal of limiting warming to 2°C or less.

Conflict of interest statement
Nothing declared.

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References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

34 Climate change, reactive nitrogen, food security and sustainable agriculture


This publication presents a method to better quantify the reduction of N2O to N2 in soils based on a ‘mapping approach’ with isotopic ratios of 15N to 14N. This is an example of ongoing research to improve models with the latest experimental research.


30. Hensen A, Groot TT, Van Den Bulk WCM, Vermeulen AT, Olesen JE, Schelde K: Dairy farm CH4 and N2O emissions, from one square metre to the full farm scale. Agric Ecosyst Environ 2006, 112:146-152.


This review summarizes current knowledge on N2O emissions from urine patches. It also highlights the need for better metadata and uncertainty reporting in the published studies, in addition to the limited geographical extent of investigations in general, which are mostly in temperate regions. This study implies that systematic measurements throughout a domain of interest is critical for estimating soil N2O emissions.


39. Congresses KA, Wagner-Riddle C, Si BC, Clough TJ: Nitrous oxide emissions and biogeochemical responses to soil freezing-thawing and drying-wetting. *Soil Biol Biochem* 2018, 117:5-15. This publication presents key mechanisms driving pulses of emissions during the freeze-thaw and dry-wet cycles that are critical to predicting annual emissions of soil N2O. The authors highlight key differences in the drivers of emissions between the freeze-thaw and dry-wet cycles and discuss key uncertainties that need further research. Understanding the drivers of these cycles is critical for modeling N2O emissions as part of a monitoring system.


54. Ehrhardt F, Soussana J-F, Bellocci G, Grace P, McAuliffe R, Recous S, Såndor R, Smith P, Snow V, de Antoni Migliorati M et al.: Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N2O emissions. *Global Change Biol* 2018, 24:e603-e616. This article presents an approach and results for an intercomparison of models that are used to predict soil N2O emissions for crop and grassland ecosystems. The findings show that model ensembles could produce accurate results for N2O emissions by applying 3 models in an ensemble although the actual ensembles vary depending on the crop types and grassland.


soil N\textsubscript{2}O emissions. The results are for the period 1861–2016 and used a standard simulation protocol with seven process-based terrestrial biosphere models to predict N\textsubscript{2}O emissions.


This study presents a Bayesian calibration of the Landscape-DNDC model with the Metropolis-Hastings algorithm, and reduced uncertainty in model predictions of soil N\textsubscript{2}O emissions by 33%. Bayesian parameterization methods are a key method for integrating measurements with models that is needed for monitoring soil N\textsubscript{2}O emissions.


This publication shows that global N\textsubscript{2}O emissions in the last decade increased much faster than estimated by the IPCC emission factor approach. It also highlights that East Asia was a driver of the observed acceleration of global atmospheric N\textsubscript{2}O increases. Moreover, the authors point out that the global emission factor as calculated by atmospheric inversion is 2.3 ± 0.6% rather than 1.375% as indicated by the IPCC Tier 1 approach.


This publication presents an ambitious study to utilize atmospheric greenhouse gas concentration measurement data for estimating greenhouse gas fluxes in the United Kingdom. The study incorporates data from a variety of sensors, transport models and inverse modeling methods, and provides a basis for other countries to develop atmospheric-based flux estimates.


This publication recommends using atmospheric greenhouse gas measurements as the basis for reporting greenhouse gas emissions under the Paris agreement. The inversions would be informed by simple Tier 1 method developed by the IPCC with more complex Tier 2 or 3 methods where there are hotspots of emissions.
