Controversy is brewing about the potential greenhouse gas (GHG) savings resulting from the displacement of fossil energy sources by bioenergy, which mostly hinges on the uncertainty on the magnitude of nitrous oxide (N$_2$O) emissions from arable soils occurring during feedstock production. The life-cycle GHG budget of bioenergy pathways are indeed strongly conditioned by these emissions, which are related to fertilizer nitrogen input rates but also largely controlled by soil and climate factors.

The IMAGINE project, funded by the ENERBIO/Tuck Foundation from January 2010 to December 2011 aimed at improving the estimation of N$_2$O emissions from local to regional scales using ecosystem models and measurements and modeling of atmospheric N$_2$O in the greater Paris basin, by using ecosystem models and measurements and modeling of atmospheric N$_2$O. Ground fluxes were measured in two locations to assess the effect of soil type and management, crop type (including lignocellulosics such as triticale, switchgrass and miscanthus), and climate on N$_2$O emission rates and dynamics. High-resolution maps of N$_2$O emissions were generated over the Ile-de-France region (around Paris) with a generic ecosystem model, O-CN, and an agro-ecosystem model, CERES-EGC, using geographical databases on soils, weather data, land-use and crop management. The models were tested against ground flux measurements, and the emission maps were fed into the atmospheric chemistry-transport model CHIMERE. The maps were tested by comparing the CHIMERE simulations with time series of N$_2$O concentrations measured at various heights in the planetary boundary layer in two locations in 2007.
The emissions of N2O, as integrated at the regional scale, were used in a life-cycle assessment of representative biofuel pathways: bioethanol from wheat and sugar-beet (1st generation), and miscanthus (2nd generation process); biodiesel from oilseed rape. Compared to the standard methodology currently used in LCA, based on fixed emissions for N2O, the use of model-derived estimates leads to a 10 to 40% reduction in the overall GHG emissions of biofuels. This emphasizes the importance of regional factors in the relationship between agricultural inputs and emissions (altogether with biomass yields) in the outcome of LCAs. When excluding indirect land-use change effects (iLUC), 1st generation pathways enabled GHG savings ranging from 50 to 73% compared to fossil-derived equivalents, while this figure reached 88% for 2nd generation bioethanol from miscanthus.

INTRODUCTION

Controversy is brewing about the greenhouse gas (GHG) intensity of biofuels and bioenergy chains in general. While there appears a consensus on the benefits of displacing fossil fuels with energy from biomass (Hill, 2007), the reported GHG savings may differ widely for seemingly similar pathways (Quirin et al., 2004). These results are usually based on the life cycle assessment (LCA) methodology, relying on the same ISO standards but different calculation hypotheses and scope, in particular regarding coproduct allocation methods, system boundaries, functional unit, or impact characterization. However, correcting for these differences to make these results commensurate only reduces part of their variability (Farrell et al., 2006). In fact, the source of input data used in the inventory step of the LCA plays a major role in its final outcome. In particular, the emissions occurring upon the cultivation of energy crops in the field have a strong influence on the energy and GHG balance of the whole chain.

In most LCAs of bioenergy chains, N2O emissions from soils are estimated with fixed emission factors (EFs), expressing a proportionality between N2O efflux and fertilizer N input rate. These factors have a wide range of uncertainty (Eggleston et al., 2006), and their worldwide median value has even been questioned recently based on the gap between bottom-up inventories of fertilizer-derived field emissions and the atmospheric build-up of N2O (Crutzen et al., 2008). The higher EFs proposed by the latter authors would negate the GHG benefits of most bioenergy pathways, including 2nd generation biofuels from lignocellulose. It thus appears crucial to obtain more reliable assessments of the level of N2O emissions attributable to bioenergy feedstock production.

The first objective of IMAGINE is to improve the current estimates of biogenic sources of N2O, in particular over the ecosystems in which biomass may be grown for energy purposes, and at the spatial scales relevant to the feedstock supply area of bioenergy projects. The approach combined a monitoring of N2O sources from crops at the field-scale and of atmospheric concentrations of N2O in Northern France to capture emissions on a larger scale. Ecosystem models of the carbon and nitrogen (N) cycles were parameterized to produce N2O emission maps over the same domain. The second goal of this project is to provide more realistic estimates of the GHG balance of bioenergy pathways, using the improved estimates of N2O fluxes obtained above, along with the net C exchanges simulated by the ecosystem models. The pathways included first-generation biofuels (ethanol and biodiesel from oilseed rape), and a 2nd generation pathway (ethanol from lignocellulose).
RESULTS

Ground fluxes of N\textsubscript{2}O were measured in two locations (Grignon and Orléans) to assess the effect of soil type and management (in particular drainage), crop type (including lignocellulosics such as triticale, switchgrass and miscanthus), and climate on emission rates and dynamics. The measurements emphasized the effect of rainfall patterns, drainage, fertilizer input rates and timing on N\textsubscript{2}O emissions. Measurements carried out over perennial lignocellulosic crops evidenced much smaller (up to an order of magnitude) N\textsubscript{2}O emission rates from these plants. The effect of fertilizer N inputs in spring were strongly conditioned by the weather pattern in the months following application. In the spring of 2011 fluxes were lower than in 2010 due to the climate being much drier. The data were used to test the predictions of by two ecosystem models: a generic model applicable on a large scale, O-CN, and a more specialized agro-ecosystem model, CERES-EGC. Both models compared well with measured ground fluxes in the dozen of cropland sites monitored in IMAGINE or previous projects. Overall, O-CN tended to over-estimate ground fluxes by c. 75 % whereas CERES-EGC was too conservative by c. 20 %. The models' root mean squared error ranged between 1.8 and 38 g N\textsubscript{2}O-N ha\textsuperscript{-1} d\textsuperscript{-1}, compared to an average observed flux of 4.5 g N\textsubscript{2}O-N ha\textsuperscript{-1} d\textsuperscript{-1}.

Atmospheric concentrations of N\textsubscript{2}O were monitored with high precision in 3 sites relevant to the Paris basin, using Radon tracing to produce source estimates. The latter ranged from 2.1 to 23.3 g N\textsubscript{2}O-N ha\textsuperscript{-1} d\textsuperscript{-1}, with similar source strength between the semi-urban site (Gif, in the vicinity of Paris) and the rural site (Trainou). Emissions were lower in wintertime and higher in spring through summer, a pattern evidencing the influence of spring fertilization on N\textsubscript{2}O emissions. Agricultural soils were estimated to contribute 50 to 60 % of the total emissions.

High-resolution maps of N\textsubscript{2}O emissions over France were simulated with the two ecosystem models for the year 2007, using geographical databases on soils, weather data, land-use and crop management. The spatial distribution of the N\textsubscript{2}O emissions differed markedly between the two models: O-CN simulated higher emissions in the west of France due to livestock farming whereas CERES-EGC emphasized the greater Paris basin with intensive cereal farming. This was partly due to variations in forcing such as N application rates, cropland area, and soil properties, but also to modelling concepts. In particular, the simulation of soil water balance and the response of N\textsubscript{2}O emissions to surface moisture follow different approaches in both models. The emission maps were fed into the atmospheric chemistry-transport model CHIMERE, and tested by comparing the CHIMERE simulations with time series of N\textsubscript{2}O concentrations measured at various heights in two locations in 2007. On an annual basis, N\textsubscript{2}O emissions from agricultural soils over France totalled 20, 56 and 69 Gg N\textsubscript{2}O-N with the CERES-EGC, O-CN, and EDGAR32 maps, respectively. In both atmospheric measurement sites (Gif and Trainou), the simulations with the regional atmospheric model CHIMERE showed best results with the emission maps generated by the ecosystem models. This confirms the benefits of using biophysical models capable of responding to short-term weather patterns as opposed to inventories based on fixed emission factors and temporal patterns. Inversion with the regional model CHIMERE made it possible to derive an estimate of the total emissions of N\textsubscript{2}O over France in 2007, using the modelled maps as a prior for biogenic emissions. The resulting range was 86 to 97 Gg N\textsubscript{2}O-N yr\textsuperscript{-1}, which is 50 % lower than reported by the EDGAR or CITEPA inventories (the latter being used for the national reporting of GHG emissions in France). Assuming industrial and transport-related emissions to be correctly estimated by the latter, this points to an over-
estimation of N₂O emissions by the IPCC Tier 1 methodology, at least for the conditions of 2007. Tier 1 emission factors for direct but mostly indirect emissions appear too high for France. Closing the gap with the top-down estimate implies that the lower end of the emission factor range is more probable, resulting in a value of 0.5 % rather than the 1 % Tier 1 value. This would have a large impact on the GHG balance of crops in France, but should be mitigated by the fact that it strictly applies to 2007. Similar estimates should be carried out for other climatic years to confirm this trend.

The emissions of N₂O, as integrated at the regional scale, were used in a life-cycle assessment of representative biofuel pathways (bioethanol from wheat, sugar-beet and miscanthus; biodiesel from oilseed rape). Compared to the standard methodology currently used in LCA, based on fixed emissions for N₂O, the use these estimates lead to a 10 to 40 % reduction in the overall GHG emissions of biofuels. This emphasizes the importance of regional factors in the relationship between agricultural inputs and emissions (altogether with biomass yields) in the outcome of LCAs. When excluding indirect land-use change effects (iLUC), 1st generation pathways enabled GHG savings ranging from 50 to 73 % compared to fossil-derived equivalents, while this figure reached 88 % for 2nd generation bioethanol from miscanthus. Including iLUC reduced the savings to less than 5 % for bio-diesel from rapeseed, 10 to 45 % for 1st generation bioethanol and to 60 % for miscanthus. These figures apply to the year 2007 and should be extended to a larger number of years, but the magnitude of N₂O emissions was similar between 2007, 2008 and 2009 over the Ile de France region.

CONCLUSIONS

IMAGINE allowed to gain new insight into the biogenic sources of N₂O in France and Europe, in particular regarding agricultural soils. A range of independent bottom-up and top-down methods were used to estimate the source strengths of the latter: bottom-up inventories using fixed emission factors (IPCC tier 1 methodology), measurements of ground fluxes or ecosystem models (CERES-EGC and O-CN) for bottom-up methods; inversion of atmospheric chemistry-transport models or Rn tracers combined with high-precision monitoring N₂O mixing ratios at several tower sites. Estimates varied across the methods, and pointed to a likely over-estimation of inventories resulting from the IPCC methodology.

This trend appeared consistent over the 3 years covered in this project, but this time span should be expanded to at least 10 years of historical weather data to result in a robust enough result. Nevertheless, the project showed the potential of the proposed methodology to provide more reliable estimates representative of regional conditions in France for the GHG balance of biofuels. This is compatible with the Tier 3 IPCC methodology for GHG emissions, with the advantage of validation via a top-down estimate of N₂O emissions, which is currently missing (A. Leip, JRC, pers. comm. in April 2011). However, some limitations with ecosystem modelling still need to be addressed to improve these estimates, as well as an update of forcing variables (such as weather data, fertilization practices or land-use). Also, the data on lignocellulosic crops is scant and should be supplemented, to confirm the potential of these crops for biofuel production with a high level of mitigation.

ACKNOWLEDGMENTS

The project was financially supported by the Enerbio fund of the Tuck foundation.
REFERENCES


