Integrated monitoring of carbon storage and loss through emerging isotope technology

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Abstract

The ability to trace carbon (C) in soil and the atmosphere is essential for optimizing soil management practices to foster soil organic carbon (SOC) sequestration for climate change adaptation and mitigation. Emerging isotope technology plays a major role in better understanding land and soil management impacts on SOC, including its stabilization and destabilization mechanisms. This paper highlights progress made at the Soil and Water Management & Crop Nutrition Laboratory (SWMCNL) of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture in the development of carbon-13 stable isotope technology for integrated monitoring of C storage in the soil and loss through CO_2, and how this technology can be used for *in situ* assessment of climate-smart soil management practices. An example is given of the use of stable isotope technology in monitoring SOC dynamics under mulch-based cropping systems.

Keywords: stable isotope technology, mulch, climate-smart soil management

Introduction, scope and main objectives

Agricultural soils have the most potential to store a large pool of C and, depending on the farming techniques applied, can either effectively store C belowground, or further release C, in the form of CO_2, into the atmosphere. Farming practices, such as mulch application, are frequently proposed to increase C content belowground and improve soil quality and can be used in efforts to reduce greenhouse gas levels, such as in the “4 per 1000” Initiative.

Soil organic C studies through conventional methods are often labor-intensive and time-consuming. As only total organic C stocks can be assessed, scientists cannot distinguish new from old C, or extract information to better understand the specific role of each crop or components in SOC storage or loss within a cropping system. Stable isotope technology, however, can help overcome most of these constraints.

For instance, depending on the source of the SOC present, the carbon-13 (^{13}C) stable isotope signature of SOC will range from about -10‰ until –30‰. The difference in ^{13}C signature of different organic carbon residues will allow tracing the source of C stored in the soil or lost through CO_2 or can assist in calculating proportions of new and old C and so estimate SOC stability. In addition, ^{13}C stable isotope studies can be based on the use of ^{13}C labelled or enriched plant materials. This allows more specifically targeting of certain processes within C storage or loss.

The scope of this paper is linked to the following themes of the Global Symposium on Soil Organic Carbon:

1. Measuring, mapping, monitoring and reporting SOC;

2. Maintaining and/or increasing SOC stocks (fostering SOC sequestration) for climate change mitigation and adaptation.

The objective is to demonstrate the latest development of isotope technology for monitoring C storage and loss and how this technology is envisaged to be used for *in situ* assessment of climate-smart soil management practices. Examples of recent highlights of research and development activities at the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture will be shown, with focus on the use of stable isotope technology in monitoring soil organic C dynamics under mulch-based cropping systems.

Methodology

1. Laser Isotope Spectroscopy for tracing CO_2 in cropping systems

Isotope analysis with laser spectroscopy is an emerging technology that is growing in scientific demand. Because this technology allows for real-time, *in situ* measurements of ^{13}C of CO_2, it is increasingly being used to monitor fluxes of CO_2. However, despite its potential to provide robust data to researchers, methods of calibration and data correction are still being developed and refined. Furthermore, standard reference gases are currently not available and researchers must make their own gases to ensure proper calibration and data correction. To improve quality of data and allow for comparison of data between studies, it is essential that standard CO_2 gases are accessible to researchers.

2. Quantitative isotopic tracing using homogeneously ^{13}C labelled plant material

Carbon-13 labelled plant material is increasingly being used to trace the fate of plant-derived C into the atmosphere, soil, water and organisms in many studies, including those investigating the potential of soils to store CO_2 belowground. However, accurate quantitative tracing of plant-derived C in such studies is only possible if plant material is labelled both homogeneously and in sufficient quantities. The SWMCNL has developed a method that achieves these two requirements for ^{13}C labelling by monitoring $^{13}CO_2$ labelling of plants in a $15m^3$ walk-in growth chamber with laser spectroscopy. This approach allows production of homogeneously labelled material at the intra-plant, inter-plant and metabolic level, which can be used for quantitative tracing.

3. Evaluating the effectiveness of mulch application to store carbon belowground

To test the effectiveness of mulch application to store carbon belowground in the short term and improve soil nutrient quality, we maintained agricultural soils with low and high organic carbon content in FAO/IAEA greenhouse mesocosms with controlled moisture for 4 years. Over the 4 years, maize and soybean were grown yearly in rotation and mulch was removed or applied to soils once plant material was harvested. After 4 years, we measured effects of mulch application on soluble soil and microbial carbon and nitrogen in the mesocosms and compared effects of mulch application versus no mulch on soils with low and high organic matter. We predicted that mulch would increase soil C and nitrogen (N) content and mulch application would have a greater effect on soils with low organic matter than soils with high organic matter.

Results and discussion

1. Laser Isotope Spectroscopy for tracing CO_2 in cropping systems

Within the SWMCNL, methods are being developed to make CO_2 gas standards on a universal gas mixing line that can both evacuate gas bottles and fill them with desired gas mixtures (Fig. 1). These gases are being isotopically labelled at natural isotope abundance levels as well as depleted and enriched isotope abundance levels so that they can be used in both natural abundance and tracer isotope studies. Furthermore, these gas mixtures will be produced at ambient and elevated concentration levels similar to those measured in natural environments and experiments. In addition to filling gas bottles to create larger volumes of standard gases, our universal gas mixing line can be used to produce mixed gases in small volume multi-layer foil gas sampling bags.

With use of standard CO_2 gases in laser isotope analysis studies we can improve confidence and accuracy in reported data and larger comparisons across studies. Once our methods for making gas standards for laser isotope analyzers are finalized, we plan to develop standard operating procedures for FAO and IAEA Member States to replicate our gas standards.

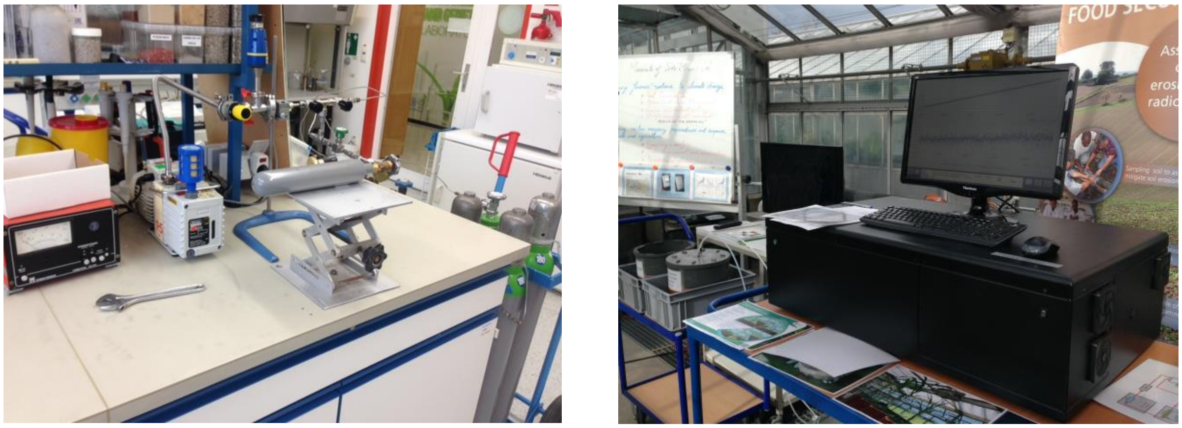

Fig. 1: Gas mixing line (left) linked to a vacuum pump, pressure gauge, CO_2 and synthetic air gas tanks for mixing of gases into desired containers, such as this 1L gas cylinder, to make standard reference gases for laser isotope analyzers; ^{13}C - CO_2 laser isotope analyzer (right) for measuring emissions of CO_2 from soils.

2. Quantitative isotopic tracing using homogeneously carbon-13 labelled plant material

Our initial labelling trials focused on maize due to its global importance as a crop and due to its potential to produce relatively large amounts of biomass, yielding one kilogram of dry plant material per run. With successful ^{13}C labelling of corn plants achieved, we are now further attempting to label other agricultural plants, such as soybeans, that can open more research avenues to better understand carbon dynamics. Additionally, we are attempting to create homogeneously labelled ^{13}C and ^{15}N plant material by supplying both labelled $^{13}CO_2$ and ^{15}N -labelled hydroponic nutrient solution during plant production. Dual labelling of plants is advantageous when studying agricultural greenhouse gas emissions, as it allows researchers to simultaneously account for plant-derived CO_2 as well as another greenhouse gas, N_2O.

In addition to homogenous ^{13}C and ^{15}N labelling of plant material, we also plan to produce heterogeneously labelled plant material. By performing incubation and field decomposition experiments using both types of labelled plant material, researchers will investigate the forms of plant material that more significantly contribute to greenhouse gas emissions and, conversely, store them belowground. Furthermore, a comparison between the two types of plant material should allow us to elucidate the error propagation that can occur from using heterogeneously labelled material and its effects on accuracy of estimating sequestration rates, emission rates as well as residence times.

In summary, the method developed at the SWMCNL for producing large amounts of homogeneous ^{13}C labelled plant material opens up new research pathways and assessment methods in the field of soil carbon dynamics and agricultural greenhouse gas emissions. Further development of homogenous ^{15}N labelled plant material will also help with research in the field of soil nitrogen dynamics and agricultural greenhouse gas emissions, as will the production of additional ^{13}C and ^{15}N labelled agricultural plants. This plant material will allow IAEA and FAO Member States to accurately quantify carbon storage and reduction of atmospheric greenhouse gas levels of various agricultural systems as well as assess the efficacy of different agricultural practices under local conditions, both via *in situ* and incubation experiments.

3. Evaluating the effectiveness of mulch application to store carbon belowground

To test the effectiveness of mulch application to store carbon belowground in the short term and improve soil nutrient quality, we maintained agricultural soils with low and high organic carbon content in greenhouse mesocosms with controlled moisture for 4 years. In soils with low organic C content and larger predicted potential to increase soil C, mulch application did not increase soluble soil or microbial C or N compared to the treatments without mulch application. However, mulch application significantly increased the $\delta^{13}C$ of both microbial and soluble soil C in these soils by 1 ‰ each, indicating a shift in belowground processes, such as increased decomposition coupled with increased C inputs. In soils with more organic content and lower potential to increase soil C, mulch application decreased microbial C by 0.01 mg C g soil-1 and increased soluble soil nitrogen by 0.01 mg N g $soil^{-1}$. Soluble soil C also decreased by 0.04 mg C g soil-1 and microbial N increased with mulch application by 0.006 mg N g soil-1, but only in 5-15 cm soil. Mulch application only decreased $\delta^{13}C$ of soluble soil carbon by 1.5 ‰, likely indicating a decrease in decomposition. Contrary to our initial predictions, mulch did not increase soil C content and only increased N content in soils that already had relatively higher organic matter content. These results suggest that mulch application (with only soil surface disturbance) may not play a significant role in increasing soil C content and overall soil quality, at least in a short 4-year term.

Conclusions

The development of isotope technologies is essential to improve the resilience of farming communities to climate change by optimizing soil management practices. These efforts are supported by a new generation of robust and affordable isotope techniques that can be used *in situ* at the plot (on-farm) and provide data in real-time.

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