Soil Carbon Sequestration and Greenhouse Gas Mitigation in Agriculture

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Abstract

This paper summarizes mechanisms and the current status of carbon (C) sequestration in soils and greenhouse gas (N_2O and CH_4) emission from soils. In terrestrial ecosystems, C cycles among atmospheric, biomass and soil pools. Because the size of biomass C pool is constant in cropland, increasing soil C can decrease atmospheric CO_2. We can increase soil C by increasing C inputs into soils through the application of organic matter and by reducing decomposition through the use of no-tillage and reduced-tillage techniques. Soil C sequestration contributes to both climate change mitigation and sustainable agricultural production, a win–win relationship, along with the maintenance of soil fertility. Field observations from many valuable long-term experiments have supported the development of soil C modelling. The RothC soil C turnover model has been validated in Japan and modified for Andosols and paddy soils. Linking of RothC with spatial databases of weather, soil, land use and agricultural activities has allowed the development of a system for the calculation of soil C nationwide, which was adopted in the National Greenhouse Gas Inventory Report of Japan. The model also has been validated in other Asian countries with long-term field datasets. The mechanisms of CH_4 and N_2O emissions and options for their mitigation are being uncovered, and modelling studies have progressed, but further studies of N_2O in particular are needed. Collaboration between modelling and monitoring studies will become increasingly important. Because of a trade-off between CO_2 mitigation by soil C sequestration and increases in emissions of CH_4 and N_2O, the evaluation of all greenhouse gases by life-cycle inventory analysis is necessary. A web-based application to visualize greenhouse gas emissions provides a tool for supporting farmers' decisions on soil management to achieve sustainable food production and environmentally friendly agriculture.

Keywords: climate change, cropland management, life-cycle assessment, RothC model, soil organic matter

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1. Introduction

Climate change is one of the most important environmental issues of this century. The latest assessment report on climate change concluded that it is "extremely likely" that human influence has been the dominant cause of the observed global warming in the past 50 years (IPCC, 2013). This conclusion is an upgrade from "very likely" in the previous report (IPCC, 2007). It is therefore urgent that we reduce greenhouse gas (GHG) emissions as much as possible. Recently, adaptation to climate change has become important for many stakeholders; almost all economic sectors have already been affected by climate change, and agriculture is no exception. But at the same time, we have to practice mitigation of climate change by reducing GHG emissions. Developed countries, including Japan, have a particular responsibility.

The first priority for reducing GHGs applies to sectors such as energy and transport, because fossil fuel combustion is the major source of GHGs. But other sectors also emit GHGs. Notably, the "agriculture, forest and other land use" sector contributes about a quarter of global GHG emissions (Smith et al., 2014). Even in Japan, where its contribution is very small (GIO, 2015), we have to make efforts to reduce GHGs from this sector. As technologies to reduce GHGs from agriculture are no more expensive than those in other sectors (Smith and Martino, 2007), it is therefore possible and worth doing. Strategies include the sequestration of soil carbon (C) and the mitigation of methane (CH_4) and nitrous oxide (N_2O) emissions.

This paper introduces mechanisms and the current status of soil C sequestration in soils and N_2O and CH_4 emission from soils; emphasizes that the evaluation of total GHG emissions must consider a trade-off among those GHGs; and examines how to mitigate climate change without disturbing agricultural productivity.

2. Soil Carbon Sequestration

In terrestrial ecosystems, C cycles among atmospheric, biomass and soil pools (Fig. 1). In forest, the size of the biomass C pool increases with tree growth, and therefore forest is considered to be a sink of atmospheric CO_2. In cropland, on the other hand, the size of the biomass C pool can be considered to be constant on a scale of decades or centuries, because most crops are annual plants. Therefore, increasing soil C through the addition of organic matter (OM) in cropland can decrease atmospheric CO_2.

Soil C sequestration can additionally improve food security through improvement of soil quality, because soil C content is one of the basic soil productivity indices (Lal, 2004).

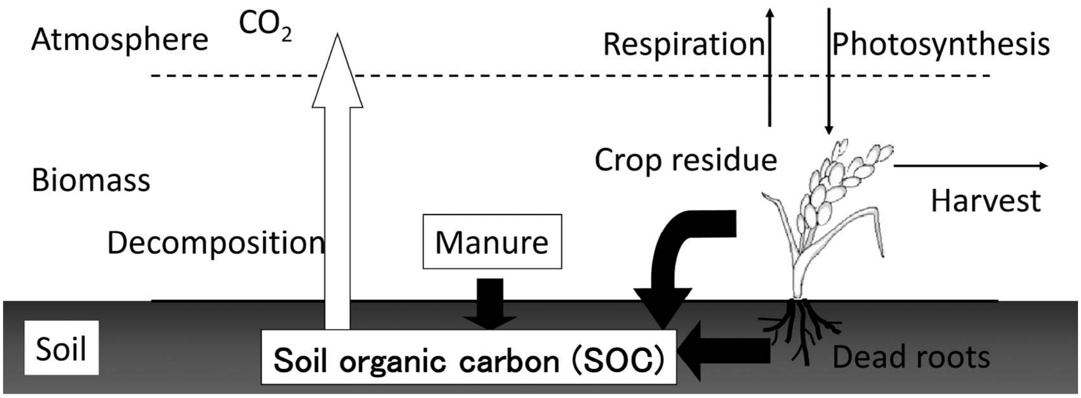

Fig. 1 Carbon cycling in cropland.

Historically, farmers all over the world have maintained their soils by the application of OM. This practice is now additionally recognized as a means to mitigate atmospheric CO_2. Appropriate OM management on agricultural land is therefore considered a win–win strategy, achieving both climate change mitigation and sustainable production.

We can increase soil C by increasing C inputs (black arrows in Fig. 1) or by reducing soil C decomposition by microorganisms (white arrow in Fig. 1). The application of OM can increase C inputs, while no-tillage or reduced-tillage practices can reduce C outputs due to decomposition. Much evidence shows that soil OM management is effective for increasing soil C (Lal, 2004; Smith and Martino, 2007; Smith et al., 2014).

Long-term datasets of field observations are valuable because changes in soil C are generally slow and difficult to detect in the short term. The longest-running field experiment in the world has been under way since 1843 at Rothamsted Research, UK (Jenkinson and Rayner, 1977). There are a number of such long-term experiments in Japan, too, but it is regrettable that some of them have been discontinued owing to lack of labor or funding. The importance of long-term field experiments (Richter et al., 2007) needs to be emphasized.

On the other hand, modelling approaches are effective for future projection or larger-scale evaluation of the effects of changes in agricultural management and climate. A number of soil OM models have been published (McGill, 1996). Among them, the RothC (Coleman and Jenkinson, 1996), CENTURY (Parton and Rasmussen, 1994) and DNDC (Li et al., 1992) models are widely used in Europe and the USA, although not in Asia.

The RothC model (Fig. 2), developed in the UK, was recently tested in Japan by using long-term experimental datasets and found to be applicable to non-volcanic upland soils (Shirato and Taniyama, 2003) (Fig. 3), but not to Andosols (Shirato et al., 2004). The model was modified for

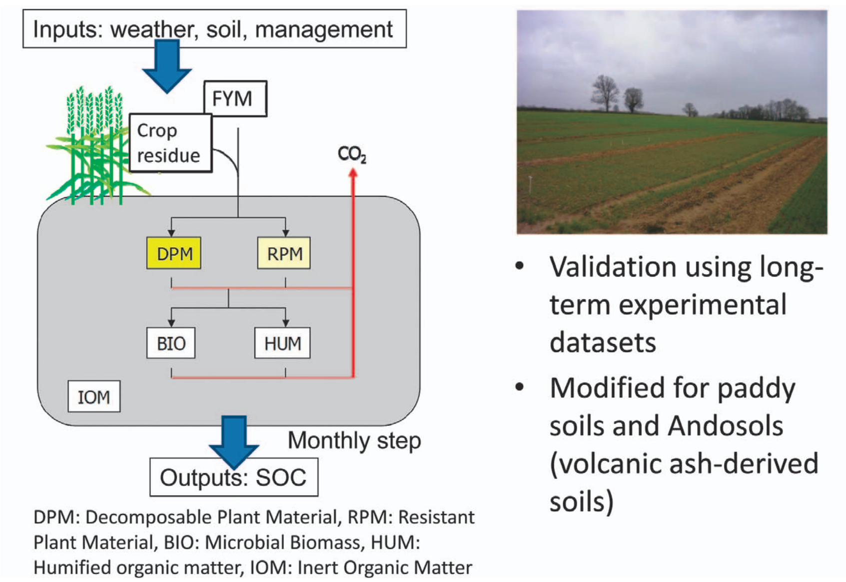

Fig. 2 Structure of the RothC model and photograph of long-term experiments at Rothamsted Research, UK.

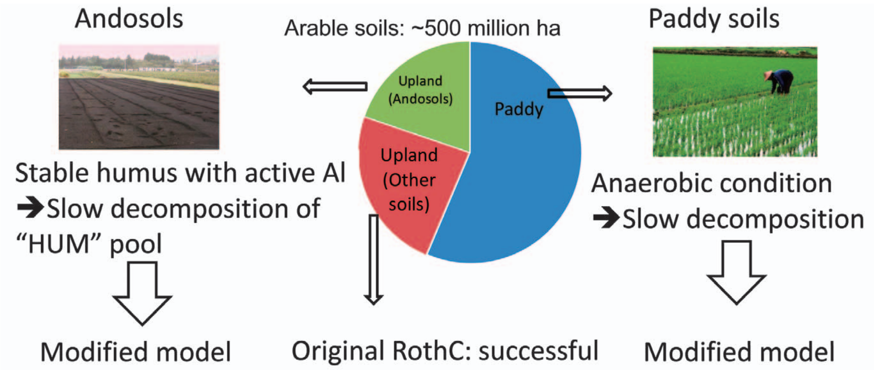

Fig. 3 Validation and modification of the RothC model for Japanese agricultural soils.

Andosols by slowing down the decomposition of the humus pool, taking into account the mechanisms that stabilize humus in Andosols (Shirato et al., 2004) (Fig. 3). It was also modified for paddy soils by slowing down all four active C pools to reflect the slower OM decomposition in submerged soils (Shirato, and Yokozawa, 2005) (Fig. 3). Collectively, these three versions of RothC can simulate soil C in all Japanese agricultural soils.

Because long-term experimental datasets are limited in Asia, and especially in the tropics, RothC has been tested against long-term experimental datasets only in China (Jiang et al., 2013) and Thailand (Shirato et al., 2005) (Fig. 4). RothC successfully simulated the changes in soil C with time, with some exceptions. For example, it omitted the significant contribution of soil fauna (e.g. termites) in decomposing OM in tropical Thailand. More study will be required to

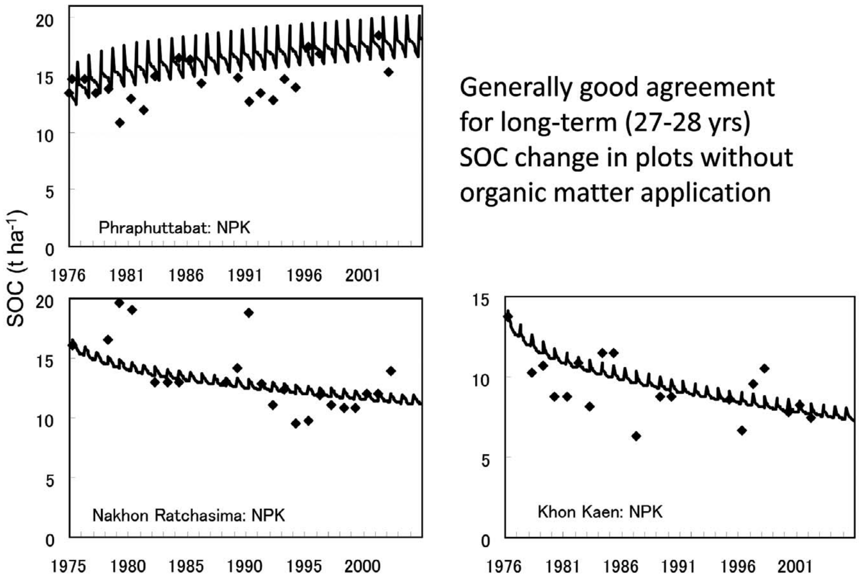

Fig. 4 Validation of the RothC against long-term experimental datasets in Thailand (from Shirato et al., 2005).

test the model with available long-term field data and to reveal the mechanisms of soil C dynamics in tropical Asia, and to modify the model if necessary. The search for long-term datasets is valuable and should be continued.

A country-scale calculation system was developed in Japan (Yagasaki and Shirato, 2014a; b) (Fig. 5), using the unmodified version of RothC for non-volcanic upland soils (Shirato and Taniyama, 2003), the Andosol version (Shirato et al., 2004) and the paddy soil version (Shirato and Yokozawa, 2005) (Fig. 3). This system links the models with spatial datasets of weather, soil, land use and agricultural activity. The spatial resolution of the simulated unit of soil C stock change is 100 m over the whole country. Soil and land use information was compiled at a spatial scale of 100 m. Weather data had a spatial resolution of 1 km. The amount of C input into soils as crop residue and farmyard manure was calculated for each of the 47 prefectures for every year since 1970 and for four land uses (paddy field, upland crop field, orchard and grassland) separately. Future projections used two soil management scenarios: “business as usual” (BAU), in which current agricultural management continues; and “mitigation” (C sequestration), in which C inputs from crop residue increase with increased yields or cover crop usage and increased application of farmyard manure. Several future climate change scenarios were used.

By comparing CO_2 emission or removal derived from soil C stock change between 1990 and each commitment period (e.g. 2008 to 2012 is the first commitment period), this calculation system can be used for accounting under the Kyoto Protocol. It was adopted in the National Greenhouse Gas Inventory Report (NIR) of Japan (GIO, 2015) from 2015 in reporting CO_2 emissions derived from soil C stock change in cropland and grassland soils. This is the most

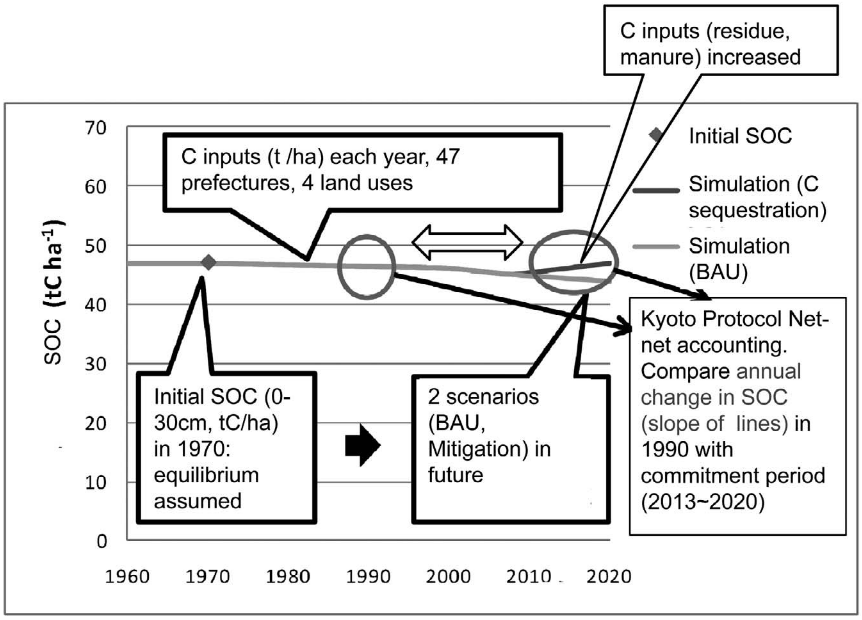

Fig. 5 Spatial calculation of soil C in Japanese agricultural land. BAU = business as usual.

advanced tier 3 approach (modelling), as recommended by the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006).

3. CH_4 and N_2O

CH_4 is produced in paddy fields where soils are submerged during the rice cropping period and are thus in a reduced condition. Water management and OM management are important for the mitigation of its emission because, for example, increasing OM inputs may increase CH_4 emissions; and continuous flooding may result in more emissions than intermittent flooding due to midseason drainage and intermittent irrigation.

Global CH_4 emissions were estimated by using emission factors, as was the potential for their mitigation through water and OM management (Yan et al., 2009). At the field scale, extending the period of midseason drainage was found to be effective for reducing CH_4 emissions (Itoh et al., 2011) in Japanese paddy fields. This result was based on field measurements at 10 experimental sites in Japan. We expect this cheap and easy method to be widely applicable in Japan and elsewhere in Asia. Since Japan's area is small, its mitigation potential is small, too. It is therefore important to think about extending mitigation technologies throughout Asia where similar paddy field-based agriculture is predominant.

Modelling of CH_4 has made progress, too. The DNDC-Rice model (Fumoto et al., 2008) was developed and tested against field data. Emission factors derived from a country-scale simulation using DNDC-Rice (Hayano et al., 2013; Katayanagi et al., 2016) were adopted in the NIR of Japan from 2015 (GIO, 2015).

N_2O is produced from soil nitrogen (N), which is derived from fertilizers and crop residues. The application of less N is therefore a simple way to reduce N_2O emissions. The application of appropriate rates of N fertilizer and OM is therefore important, although the rates should be calculated primarily to ensure crop yield and quality. This approach will also reduce fertilizer costs and other environmental impacts such as the leaching of N to groundwater. Other techniques, such as a change in fertilizer type or the use of a nitrification inhibitor, are also effective for mitigation (Akiyama et al., 2009). The mechanism of N_2O emission is complicated, and more research is still needed to fully understand it. The combination of field monitoring and modelling approaches is essential.

4. Mitigation of Total Global Warming Potential: Life-cycle Inventory Analysis

Although soil C sequestration promotes sustainable agricultural production, increasing OM input into soils creates a trade-off between CO_2 mitigation by soil C sequestration and increased CH_4 and N_2O emissions. It is therefore important to evaluate these three GHGs together by using the global warming potential (GWP) of each gas (Fig. 6). This can be achieved by combining the RothC model (Yagasaki and Shirato, 2014a; b) for soil C, DNDC-Rice (Fumoto et al., 2008; Hayano et al., 2013; Katayanagi et al., 2016) for CH_4, and an empirical N_2O model (Mu et al., 2009) combined with RothC, with the support of field observations.

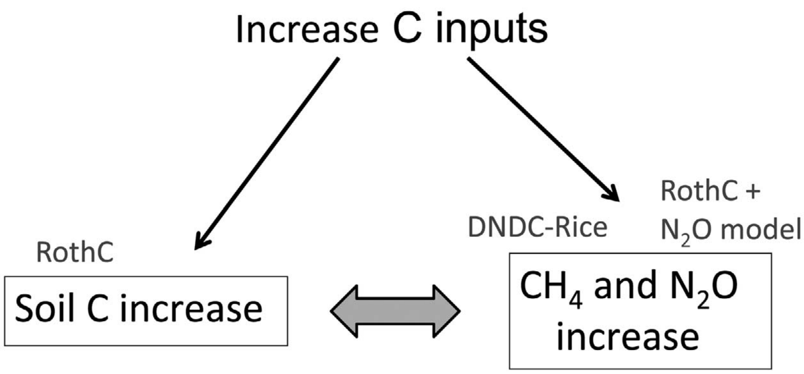

Fig. 6 Evaluating total GWP (Global warming Potential) by using models at country scale considering trade-off between soil carbon sequestration and emission of other greenhouse gases.

Fossil fuel consumption derived from agricultural machinery, plastic film, fertilizer, pesticides etc. should be included in the total GWP. This is the role of life-cycle inventory analysis. However, there are still only a few examples of life-cycle inventory analysis of GHGs in agriculture in Japan (Koga et al., 2006; Harada et al., 2007). In addition, other environmental impacts such as acidification and eutrophication, and other factors such as biodiversity, should be included for the evaluation of the total environmental impact. Future research on the total evaluation of environmental impacts and benefits is necessary.

A web-based decision support tool called “Visualization of CO_2 absorption by soils” (Fig. 7, available at: http://soilco2.dc.affrc.go.jp/) allows users to easily calculate changes in soil C, CH_4

Fig. 7 Decision-support tool “Visualization of CO_2 absorption by soil” on the web

and N_2O emissions, and fossil fuel consumption. With this tool, farmers can see how to improve the environmental sustainability of their products. The development of such user-friendly tools may help spread mitigation options widely.

5. Conclusion

Soil C sequestration can help achieve climate change mitigation and sustainable agricultural production with the maintenance of soil fertility. Field observations from many valuable long-term experiments have supported the development of modelling approaches. The mechanisms of CH_4 and N_2O emission and options for their mitigation are being uncovered, and modelling studies have progressed, but further studies of N_2O in particular are needed. Collaboration between modelling and monitoring studies will be a key. To achieve the mitigation of total GWP, the evaluation of all GHGs with a life-cycle inventory analysis is necessary. The inclusion of other environmental impacts will be required. The development of a web-based application to visualize GHG emissions provides a tool for supporting farmers' decisions on soil management to achieve sustainable food production and environmentally friendly agriculture. The development of such user-friendly tools may help spread mitigation options widely and achieve both sustainable agricultural production and reduced environmental impacts in soils.

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