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# Rates and potentials of soil organic carbon sequestration in agricultural lands in Japan: an assessment using a process-based model and spatially-explicit land-use change inventories

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## Abstract

In order to develop a system to estimate a country-scale soil organic carbon stock change (SCSC) in agricultural lands in Japan that enables to take account effect of land-use changes, climate, different agricultural activity and nature of soils, a spatially-explicit model simulation system using Rothamsted Carbon Model (RothC) integrated with spatial and temporal inventories was developed. Future scenarios on agricultural activity and land-use change were prepared, in addition to future climate projections by global climate models, with purposely selecting rather exaggerated and contrasting set of scenarios to assess system's sensitivity as well as to better factor out direct human influence in the SCSC accounting. Simulation was run from year 1970 to 2008, and to year 2020, with historical inventories and future scenarios involving target set in agricultural policy, respectively, and subsequently until year 2100 with no temporal changes in land-use and agricultural activity but with varying climate to investigate course of SCSC.

Results of the country-scale SCSC simulation have indicated that conversion of paddy fields to croplands occurred during past decades, as well as a large conversion of agricultural fields to settlements or other lands that have occurred in historical period and would continue in future, could act as main factors causing greater loss of soil organic carbon (SOC) at country-scale, with reduction organic carbon input to soils and enhancement of SOC decomposition by transition of soil environment to aerobic conditions, respectively. Scenario analysis indicated that an option to increase organic carbon input to soils with intensified rotation with suppressing conversion of agricultural lands to other land-use types could achieve reduction of $CO_2$ emission due to SCSC in the same level as that of another option to let agricultural fields be abandoned. These results emphasize that land-use changes, especially conversion of the agricultural lands to other land-use types by abandoning or urbanization accompanied by substantial changes in the rate of organic carbon input to soils, could cause





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a greater or comparable influence on country-scale SCSC compared with changes in management of agricultural lands.

A net-net based accounting on SCSC showed potential influence of variations in future climate on SCSC, that highlighted importance of application of process-based model for estimation of this quantity. Whereas a baseline-based accounting on SCSC was shown to have robustness over variations in future climate and effectiveness to factor out direct human-induced influence on SCSC. Validation of the system's function to estimate SCSC in agricultural lands, by comparing simulation output with data from nation-wide stationary monitoring conducted during year 1979–1998, suggested that the system has an acceptable levels of validity, though only for limited range of conditions at current stage. In addition to uncertainties in estimation of the rate of organic carbon input to soils in different land-use types at large-scale, time course of SOC sequestration, supposition on land-use change pattern in future, as well as feasibility of agricultural policy planning are considered as important factors that need to be taken account in estimation on a potential of country-scale SCSC.

## 1 Introduction

Soil organic carbon (SOC) sequestration in agricultural lands as an option to mitigate global climate change is considered to have significant technical potentials to reduce emission of $CO_2$ or to act as $CO_2$ sink at global scale (Lal, 2004; Smith et al., 2008). Given that this technique has potential to establish "win-win" solutions in a context of sustainable agriculture (Lal, 2004; Lehmann, 2009) with low abatement cost (Smith et al., 2008), and that Article 3.4 of Kyoto Protocol (KP) allows parties to include accounting on sinks or sources of $CO_2$ due to soil organic carbon stock-change (SCSC) in lands under cropland and grazing land management to meet their target to reduce emissions of green house gases (GHGs), the agricultural soil organic carbon sequestration (hereafter referred as ASCS) has been attracting interest from international society.

Establishing methodologies to ensure accurate measurement or estimation for ASCS at regional or country scale is amongst the most difficult challenges in implementation of ASCS. The regional scale ASCS is a complex system involving various factors such as climate, soil properties, land-use change (LUC), and agricultural practices on farm lands. Need or attempt to take account spatial and temporal variability of these factors often faces difficulties due to limited availability or insufficient temporal and spatial resolution of these data.

So far, significant efforts have been taken to estimate potential of ASCS at large spatial scale, such as adoption of spatially-explicit LUC data at global scale (Eglin et al., 2010; Houghton, 1999, 2003) or at country to regional scale (Houghton, 1999; Schulp et al., 2008), application of process-based model on SOC dynamics (Eglin et al., 2010; Janssens et al., 2005; Li et al., 2003; Piao et al., 2009; Sitch et al., 2008), realistic estimation of agricultural activity and organic amendment input to soils with ensuring mass-balance between production and consumption of manure (Mondini et al., 2012). Given that these items (i.e. LUC, biomass mass-balance, process-based model) have been identified as important factors to take account in large-scale ASCS estimation, each of these different but important effort or approach should be integrated into one framework of simulation to develop better simulation system with improved reliability and increased functionality, and not be applied solely. For example, Tian et al. (2011) demonstrated that lack of LUC data, as well as different modeling approaches and input data sources, could induce large discrepancy in C balance estimation by comparing estimates of terrestrial C balance in China from several different studies. In addition, it is important to ensure mass-balance between production and consumption of manure, by taking account changes in cropping area and manure application rate (consumption side) as well as live-stock number and treatment of live-stock waste (production side), as lack or insufficient attention on consistency among these factors would lead issues of deficiency or surplus of manure, especially for future scenario projection. However, only few study could achieve this with support from statistics or observations (Mondini et al., 2012). Ensuring completeness and comprehensiveness in a large-scale ASCS simulation will be required more when it is intended to assist policy making which in most cases requires to draw and setup realistic conditions in simulations in terms of policy implementation in a "real society", rather than simple hypothetical conditions or scenarios often involving inconsistencies.

In this study, we developed a system to perform comprehensive assessment on SCSC in agricultural lands in Japan with fulfilling the following conditions:

1. Use of spatially-explicit land-use change data, rather than statistics on land-use change only weakly associated with other geographical inventories on soil and climate.

2. Application of process-based model on SOC dynamics with future climate projections, rather than book-keeping model, e.g. stock-change factor.

3. Realistic estimation of the rate of organic matter input to soils with ensuring mass-balance between production and consumption of biomass (manure and plant residue).

4. Estimation of SCSC rate in both base year and reporting/commitment period in line with KP to allow net-net accounting with an intension to assist policy making.

Spatial and temporal inventory on soil, land-use change, and climate were prepared and used to apply process based model on SOC turnover over agricultural lands in Japan. Future scenarios of agricultural activity were selected from basic plan on agriculture policy compiled by the government, that we used and discussed in part on its feasibility. As to uncertainty analysis on the country-scale SCSC estimation, we performed only scenario analysis using different scenarios of future climate, land-use changes, and agricultural activity to acquire necessary information on system's sensitivity to select limited numbers of factors identified to have large influence on the estimation, prior to full implementation of uncertainty analysis employing creation of probability distribution functions on model input parameters and Monte Carlo simulations. Simulation output on SCSC for different types of soil and land-use was compared with





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that obtained from nation-wide stationary monitoring on agricultural soils conducted during year 1979–1998 to discuss validity of the system we developed.

## 2 Materials and methods

### 2.1 Basic framework of simulation system

The framework of simulation system we built consists of three major modules:

- Module 1: a set of spatial and temporal inventories comprised of database of soil, weather, agricultural activity, and land-use change that covers the entire regions of Japan.
- Module 2: SOC turnover simulation module, computes changes in SOC stock using RothC model (Jenkinson et al., 1990) with monthly time interval using the spatial-temporal inventory as input.
- Module 3: accounting module, performs accounting for $CO_2$ removal or emission due to SCSC for a given commitment period and base period (base year), in compliance with Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) established by The Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change, 2003), based on the simulation output of SCSC in combination with that of land-use change.

In this study, we employ only land-based accounting. Activity-based accounting employed in commitment of KP, defined in "Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol" in Chapter 4 of GPG-LULUCF, was not employed in this study to avoid any misleading interpretation on SCSC as this method allows to deal with unequal size of land area between base year and commitment period. Brief descriptions on each modules are explained in following sections. More details are described in the Supplement.





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## 2.2 Land-use change

A nation-wide, spatially explicit land-use change dataset for LULUCF or AFOLU (Agriculture, Forestry and Land Use) accounting was created by compiling different geographical data archives to serve an interpreted map product. Four different sources of geographical data on land-use and land-cover (see Supplement for details) were compiled and superimposed on a geographical grid system, that covers whole area of Japan. The grid system has spatial resolution of 1/1200 and 1/800° (3.0 and 4.5 s), along latitudinal and longitudinal lines, respectively. Size of individual cell of the grid equivalents to a parcel of a square land ca. 100 m on a side, with an area of ca. 10 000 $m^2$ (1 ha). A decision tree for land-use type identification was created and applied to individual or grouped map legend item(s) in these four different geographical data sources. As a result, each grid cell was classified into 9 land-use types based on six top-level land categories and their subdivisions in consistent with GPG-LULUCF; i.e. (1) paddy fields (PD), (2) upland crop fields (UP), (3) orchards (OC), (4) managed grasslands (MG), (5) unmanaged grasslands (UG), (6) forest lands (FL), (7) wetlands (WL), (8) settlements (ST), and (9) other lands (OT). In total, five of interpreted maps with different time period were created for year 1976, 1987, 1991, 1997, and 2006, as a database table with geographic references using PostgreSQL 9.0.13 (The PostgreSQL Global Development Group, 2013) and PostGIS 1.5.8 (Refractions Research Inc., 2012).

Furthermore, we created spatially explicit future land-use map at year 2020 in consistent with figures on areas of agricultural lands in future agricultural activity scenario (described in Sect. 2.6). A module comprised of functions written in PL/pgSQL, a procedural language for PostgreSQL, was developed to create future land-use map using (A) current (latest) land-use map, and (B) a land-use change matrix for future in consistent with target figures on land areas set in future agricultural scenarios. This module performed grouping grid cells on land-use map year 2006 by land-use type and agricultural commune to create unit geographic entity for LUC, sorting the entity by order of area of the entity (simply assuming the smaller entity under the higher pressure for land-use conversion), and proceed conversions of land-use until cumulated sum of converted area approaches figures prescribed in the LUC-matrix.

For the conversion of agricultural lands to non-agricultural lands, two different and rather exaggerated scenarios were assumed and adopted to LUC-matrix:

1. URB (urbanization): lands converted from agricultural lands were all converted to settlements

2. ABN (abandonment): lands converted from agricultural lands were all converted to unmanaged grasslands

As a result, two different future maps were created for each future agricultural scenario.

Different LUC-matrix was prepared for each three different group of lands under zoning regulations to control farmland conversion and urbanization. In addition, the LUC module was applied also to modify each of the five land-use maps created for year 1976–2006 with arbitrary formulated LUC-matrix so that area of paddy field, croplands, orchards, and managed grassland to be in a good agreement with corresponding figures in national agricultural statistics. Year of land-use conversion for each entity was set by random number generation, which led to interpolation of total area of each land-use in intermittent years between years of two consecutive but discontinuous maps. Details on each geographical data sources, method of land-use/land-cover interpretation and future land-use map creation are described in the Supplement.

### 2.3 Soil organic carbon dynamics

We used Rothamsted carbon model (RothC), or RothC-26.3 (Coleman et al., 1999; Jenkinson et al., 1990) to simulate turnover of SOC. This model simulates changes in SOC stock in a surface soil layer with monthly time interval under given environmental conditions and rate of organic matter input to soil. The model expresses the process of





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SOM decomposition and accumulation with five hypothetical SOC components having different intrinsic decomposition rate constant, namely Decomposable Plant Materials (DPM), Resistant Plant Materials (RPM), Microbial Biomass (BIO), Humus (HUM), and Inert Organic matter (IOM).

In addition to the original RothC-26.3, we used two other versions of RothC model with modifications to extend its functionality to be applicable to wider range of land-use and soil types (Table 1):

1. RothC-26.3: for all land-use types other than paddy fields (i.e. UP, OC, MG, UG, FL, ST, and OT) with soil types other than Andosols.

2. RothC-26.3_p: for paddy fields that hold water-logged conditions for some periods in a year (Shirato and Yokozawa, 2005).

3. RothC-26.3_v: for all land-use types excluding PD (i.e. UP, OC, MG, UG, FL, ST, and OT) with Andosols. A simple tuning on decomposition rate constant of HUM, expressed as a function of the size of pool of active aluminium bound to humus, had been introduced (Shirato et al., 2004). Another recent modification that employs phosphate adsorption coefficient, more commonly available data attribute in the soil database, as a single parameter for this tuning (Takata et al., 2011), was employed in this study to assure to run model simulation across entire country.

## 2.4 Climate

For climate input data, downscaled observations in Automated Meteorological Data Acquisition System (AMeDAS) (Seino, 1993) was used for period 1979–2009. Whereas for future period in year 2009–2099, global climate model (GCM) projections with SRES scenario downscaled by Okada et al. (2009) was used. Both datasets had been downscaled to a $1/120^\circ \times 1/80^\circ$ (30 s × 45 s), along latitudinal and longitudinal lines, respec-





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tively (Okada et al., 2009; Seino, 1993). The size of the grid cell equivalents to a parcel of a square land ca. 1 km on a side, with an area of ca. 1 $km^2$ (100 ha).

For year 2009–2099, we aimed to select two GCM climate projections holding highest and lowest mean annual temperature during year 2013–2020, respectively, among combinations of 12 GCMs (BCCR, GISS-AOM, INMCM3, MIROC-M, CGCM-T63, CGCM-T47, FGOALS, IPSL, MIROC-H, MRI, CSIRO-30, and GFDL-21) and 2 SRES scenarios (A1B and B1). We employed this strategy to tackle and highlight an issue of factoring out human direct effect in accounting of $CO_2$ emission or reduction, in addition to an assessment on sensitivity of the model and accounting system. As result, MIROC-H & A1B, and FGOALS & B1 were selected, with the mean annual temperature of the former ca. 1.0 °C higher than that of the latter.

Mean monthly air temperature, monthly precipitation, and monthly potential evapotranspiration were calculated or directly obtained from these data sources and used as input for RothC. For year 1979–2009, monthly potential evapotranspiration was estimated based on mean monthly temperature in the AMeDAS and latitude of each grid cell using a Thornthwaite equation (Thornthwaite, 1948). For year 1970–1978, means of year 1979–1989 in each grid cell were calculated and used.

### 2.5 Soil

For initial setup of total SOC levels of each geographic entity in simulation, representative values of total SOC ($Mg\,C\,ha^{-1}$) and clay content (%) for a top 0–30 cm layer were calculated for each soil series group with different land-use and prefecture, using three nation-wide soil inventories:

1. “Daihyou danmen chousa” (survey on representative soil profiles), a sub-program of “Chiryoku hozen kihon chousa” (basic survey for soil fertility conservation; BSSFC), year 1959–1977, that had collected data on attributes of soil horizons from ca. 20 000 soil profiles throughout agricultural soils in Japan, except Kyoto and Wakayama prefecture (hereafter referred as RS-BSSFC).





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2. "Kanni danmen chousa" (simplified survey on soil profiles), another sub-program of BSSFC, that had collected data on attributes of surface and sub-surface soil layers from ca. 25 000 soil profiles (referred as BS-BSSFC).

3. Basic Soil Environment Monitoring Project (BSEMP), Stationary Monitoring, conducted during year 1979–1998 (hereafter referred as "stationary monitoring") with a series of 4 waves with interval of 4–5 yr, had collected soil samples from ca. 20 000 survey points in agricultural lands (Agricultural Production Bureau, 2008).

Firstly, for each of all three datasets, soil horizons data records were sub-divided into a series of consecutive layers with 1 cm thickness and rearranged by order of layer depth, using ordinary functions of structured query language (SQL) on PostgreSQL. Next, using RS-BSSFC dataset, vertical distribution patterns of SOC (%), bulk density (BD) ($\mathrm{Mg\,m^{-3}}$), and clay content (%), expressed as relative proportion of the value of attributes in each 1 cm layer compared with those in a top 0–1 cm layer, were analyzed for each soil series group, land-use, and prefecture. Using this vertical distribution pattern dataset, soil attributes data of BS-BSSFC split into a bundle of layers with 1 cm interval were vertically interpolated or extrapolated in case data were missing down to depth of 30 cm. Estimates for SOC ($\mathrm{Mg\,C\,ha^{-1}}$) and clay content (%) for a top 0–30 cm layer were obtained as the sum and mean of each attributes through the 1st to 30th layers, respectively. Gravel content in each soil layer was not taken into consideration in calculation of the SOC stock due to limited data availability in these datasets, which becomes a source of error in the SOC stock estimation.

### 2.6 Agricultural activity

Average annual rates of organic carbon input to soil during year 1970–2008 were estimated for 4 land-use types of agricultural lands (PD, UP, OC, and MG) in 47 prefectures using a toolkit, named DTK (after Dojo-tanso-kun, in Japanese), comprised of a collection of spread sheets with stratified calculation modules, containing data tables for national agricultural statistics (e.g. yields, cropping area, etc.), survey data on material flow including treatment of plant residue and live-stock waste by farmers, and physicochemical properties of biomass including decomposition rate during composting, developed originally by Agricultural Production Bureau (APB), Ministry of Agriculture Forestry and Fishery (MAFF), Japan. Modifications with newly updated parameter set and calculation modules were added in the latest version of DTK developed for this study (version 3.0.0), including major update and revisions for older version of DTK (version 2.2.8 and older) developed by Shirato (Shirato and Yagasaki, 2012a, b, 2013).

As main strategy, DTK employs a mix of top-down approach based on national agricultural statistics table, and bottom-up approach based on results of questionnaire to farmers on their practices conducted in the stationary monitoring, in its framework of calculation to ensure a mass-balance between production and consumption of manure compost on annual base. Rates of annual application of manure compost for each cropping type in different group of prefectures were calculated based the farmer's questionnaire data collected in the stationary monitoring, which was then assembled for each agricultural land-use type with assuming variations in rotation, except MG which had no available data. Average manure compost application rate in MG was estimated at country level based on the mass-balance between production and consumption of manure, by subtracting sum of the manures applied to PD, UP, and OC, from the mass of total available manure, that was estimated by unit production of manure and the number of livestock in combination with a set of parameters on manure treatments including proportion of waste to be used for manure production against other usages such as disposal and incineration. Selected equations and parameters used in DTK are shown in the Supplement.

Two future agricultural activity scenarios were created using a function of DTK by setting target levels of crop yields, cropping area, manure application rate, and live-stock number at year 2020, based on corresponding targets or suppositions shown in the Basic Plan on Food, Agriculture and Rural Areas (MAFF-BP) and business-as-usual scenario (BAU) (Ministry of Agriculture Forestry and Fisheries, 2010). The MAFF-BP has various targets to increase cropping yield mainly by intensified rotation to meet





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target of food self-sufficiency rate at year 2020, with keeping levels of manure applications per cropping as same as year 2008. Whereas BAU employs linear extrapolation to predict future trend of changes in cropping area and assumes decline in the levels of manure application per cropping at a rate of −1 % annually. In BAU, in total 404 000 ha of agricultural fields (i.e. 8.7 % of agricultural fields in year 2006) were subject to be converted to other land-use types in year 2007–2020. Whereas in MAFF-BP, conversion of agricultural fields was much suppressed and subject to occur only 18 000 ha.

### 2.7 Experimental design of simulation

Simulation was run from year 1970 to 2008 using a set of spatial and temporal inventory on climate, agricultural activity, and land-use change, and subsequently until year 2099 using several different future scenarios of those data. At the start of simulation, year 1970, proportion and size of SOC model compartments in RothC (DPM, RPM, BIO, HUM, and IOM) as well as its total SOC level was assumed to be in equilibrium state and was obtained by executing a long-term simulation with a spin up period for 10 000 yr prior to starting year with conditions of weather, management, and organic matter input as same as those in year 1970. As this set up for initial SOC would cause an artifact in estimation of SCSC for some years following starting year, we used output of simulation only after year 1980 with assuming first 10 yr (year 1970–1979) is affected by the undesirable artifact.

During year 2009–2020, the simulation was run with future agricultural activity and land-use change scenario approaching to their target set at year 2020. After year 2020, they were set to have no further temporal changes to occur until year 2099. This was employed in order to highlight duration of SOC sequestration as well as effect of agricultural activity scenario implementation. To focus only on croplands and grazing lands, aggregations and accounting of $CO_2$ emission were performed only to a limited range of grid cells that would fall into categories of PD, UP, OC, and MG at least one year in a course of land-use change. Hereafter this extent of land will be referred as "agricultural lands", as employed in title of this paper, for purpose of simplicity.

The rate of organic carbon input to soils under UG and FL were assumed to be 3.8 and 2.0 $Mg C ha^{-1} yr^{-1}$ following Shirato et al. (2004), respectively, whereas those under ST and OL were assumed to be zero (Table 1).

### 2.8 Accounting $CO_2$ removal and emission due to SCSC

For accounting on $CO_2$ removal and emission due to SCSC, multiple periods were selected from year 2010 to 2090 to which future scenarios were applied in simulation, with dividing these period into a sequence of 8 decadal periods with 10 yr duration in each (e.g. yr 2010–2020, 2020–2030, etc.). The rate of SCSC for each period, in unit of $Mg C yr^{-1}$, was calculated by comparing changes in the size of SOC stock at the end of period with that in the beginning. Using the rate of SCSC, we applied the following two different methods for accounting $CO_2$ removal from or emission to the atmosphere due to SCSC, with differing objectives:

- Objective 1: To assess combined effect of climate, agricultural activity, land-use change in future scenario. With regarding year 1985–1995 as base period, a "net-net based" accounting as employed in Article 3.4 of KP (United Nations Framework Convention on Climate Change, 1998), by comparing net emissions and removals from all lands in agricultural lands in Japan (land-based) during a commitment period with emissions and removals during base period (Schlamadinger et al., 2007).

- Objective 2: Factoring out effect of measures. "Baseline based" accounting was employed with subtracting $CO_2$ emission or removal in "baseline scenario", compiled with premise of prospected business-as-usual trends, from those in target scenario involving measures to evaluate relative differences in $CO_2$ emission or removal between these two different activity scenarios, yet with same scenario of climate and land-use change.





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### 2.9 Validation of model simulation in year 1979–1998

Temporal changes in SOC stock predicted by simulation were compared with those observed in the stationary monitoring during year 1979–1998 to assess validity of model prediction in this period. For this comparison, eight major soil groups based on a Japanese soil classification system on cultivated lands (National Institute for Agricultural Sciences, 1983) were selected, which accounted 95 % of the total area of agricultural lands in Japan dealt in the simulation. For each waves of the monitoring survey (wave 1: 1979–1983; wave 2: 1984–1988; wave 3: 1989–1993; wave 4: 1994–1998), quartiles, median, minimum and maximum values of SOC stock in surface 0–30 cm layer in unit of $\mathrm{Mg\,C\,ha^{-1}}$ were calculated for different land-use types (excluding MG due to limited data availability) and 8 major soil groups using the stationary monitoring data. In order to obtain SOC stock at 0–30 cm depth, vertical interpolation or extrapolation of SOC concentration and bulk density was performed for the stationary monitoring dataset in a similar manner as employed for estimation of initial SOC stock for simulation using BSSFC dataset. For SOC stock in simulation output, mean SOC stock was calculated for collection of grid cells grouped by soil groups and land-use types at country scale. These two sets of SOC stock data were then compared with a generic boxplot approach.

## 3 Results

### 3.1 Land-use change

During year 1970–2006, changes in the area of different land-use types were characterized by a large decline in PD and OC occurred along with a large increase in the area of UG, ST, and UP (Fig. 2). From year 1970 to 2006, the area of PD and OC declined from 2.9 to 1.6 Mha, and from 0.6 to 0.3 Mha, respectively. Correspondently, the area of UG, ST, and UP, increased largely, from 1.0 to 1.5–1.6 Mha, from 0.06 to 0.4–





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0.5 Mha, and from 1.5 to 1.8 Mha, respectively. In addition, MG and OL were found to have increased, though relatively small, from 0.5 to 0.6 Mha, and from 0.08 to 0.2 Mha, respectively (Fig. 2).

Land-use change during year 2007–2020 with different scenarios on land-use changes and agricultural activity were summarized as land-use change matrices shown in Supplement. In BAU, from year 2007 to 2020, 166 000, 129 000, 58 000, and 51 000 ha of PD, CL, OC, and MG, respectively, were converted to ST or UG, depending on land-use change scenario URB and ABN, respectively. Whereas in MAFF-BP, 60 000 ha and 55 000 ha of CL were converted to PD and MG, respectively, from year 2007 to 2020. In addition, 4000 ha of OC was converted to MG. Another 18 000 ha of OC was converted to ST or UG depending on land-use change scenario URB and ABN, respectively.

### 3.2 Agricultural activity in year 1970–2008

Estimated overall input of organic carbon to unit area of soils (sum of plant residue, manure, slurry, and excreta) during year 1970–2008, expressed as weighted mean values for the entire country, for PD, CL, OC, and MG ranged 2.1–2.8, 2.1–3.1, 1.5–2.0, and 2.5–6.8 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$, respectively (Fig. 3a). In PD, the overall input rate gradually increased during year 1970–2008 due to relatively greater increase in plant residue input that overcomed decline in manure input (Fig. 3a). The increase in plant residue input in PD was explained mostly by increases in the proportion of farmers who employed rice straw incorporation into soils in preference to other treatments (e.g. compost production, roughage, livestock bedding, production of handicraft, and incineration), documented in a survey report on actual conditions of rice production practices (e.g. changed from 47 to 73 %, from year 1979 to 2008, as a mean of 5 regions, respectively).

In UP, the overall input rate declined with time due to decline in manure input (Fig. 3a). In OC, the overall input rate slightly increased with time characterized by a slight increase in input rate of both plant residue and manure found in mid-1990's





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(Fig. 3a). In MG, the overall input rate increased rapidly from year 1970 to mid-1990's, followed by a plateau continued until year 2008, due to changes in manure input (Fig. 3a).

The rapid and large increase in manure input rate from year 1970 to mid-1990's in MG was due to increase in production of livestock waste compost caused by an increase in the number of livestock (cattle, pig, and poultry) in combination with decline in consumption rate of livestock waste compost in three other types of agricultural lands (PD, UP, and OC). In PD and MG, relatively greater levels of plant residue input were estimated compared with those in UP and OC, reflecting application of rice straw to soils and turnover of below ground biomass of perennial grasses, in PD and MG, respectively (Fig. 3a).

### 3.3 Agricultural activity in year 2009–2020

In future agricultural activity scenario BAU, change in the rate of organic carbon input to unit area of soils, expressed as $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$, from year 2008 to 2020 was characterized by (1) increase in manure input in MG (130 % in year 2020 compared with year 2008), and (2) decrease in manure input in PD, UP, and OC (86–87 % in year 2020 compared with corresponding values in year 2008) (Fig. 3a), due to decline in manure application rate in PD, UP, OC assumed in this scenario which lead to an increase in manure application rate in MG by receiving surplus of produced manure as calculated by the mass-balance estimation.

In MAFF-BP scenario, the change was a direct antithesis of that in BAU and was characterized by (1) decrease in manure input in MG (49 % in year 2020 compared with year 2008), (2) increase in manure input in PD and UP (105–132 % in year 2020 compared with year 2008), and (3) no major change in OC (Fig. 3a). Intensification in cropping in PD and UP (i.e. increase in cropping area per unit area of agricultural field) was accompanied by an increase in annual rate of plant residue incorporation and that of manure application to soils. Increased use of manure in PD and UP lead to decline in manure application in MG as calculated by the mass-balance estimation.





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On a total mass basis, in year 2020 with future land-use change scenario URB, soils in agricultural area of Japan under MAFF-BP scenario received 1438 Gg of more organic carbon than that under BAU scenario (Table 2 and Fig. 4). Whereas those with future land-use change scenario ABN, difference in the organic carbon input between MAFF-BP and BAU was only very small. Greater input of organic carbon estimated for ABN compared with URB found in the future agricultural activity scenario MAFF-BP was due to difference in assumed input rate of plant residue per unit area of soils in UG and ST combined with difference in area of ST and UG between these two scenarios. Whereas for manure, amount of organic carbon input to soils were found to be in similar level in both MAFF-BP and BAU scenarios (see Supplement for details).

### 3.4 Soil organic carbon stock change

Total SOC stock in agricultural lands in Japan (sum of SOC stock among all land-use types) decreased continuously from year 1970 to 2008 (Fig. 5). This trend did not change even after year 2008 and continued until year 2099. From year 1980 to 2010, the simulation estimated that the total SOC stock has decreased from 602 to 556–559 Tg C. After year 2008 with future scenarios, relatively larger differences in SOC stock were found between future climate scenario FGOALS & B1 and MIROC-H & A1B compared with those found among different scenarios of future land-use change and agricultural activity with same climate scenario (Fig. 5). The SOC stock of 576 Tg C in year 2000 decreased to a level ranging from 474 to 493 Tg C and another level ranging from 424 to 440 Tg C in year 2090, under future climate scenario FGOALS & B1 and MIROC-H & A1B, respectively, with different scenarios on future land-use change and agricultural scenarios.

The rate of changes in the total SOC stock in agricultural lands in Japan evaluated with 10 yr interval were estimated to be $-1.11\,\mathrm{Tg\,C\,yr^{-1}}$ in period 1980–1990 (negative sign indicates loss of SOC with time) (Fig. 6). The rate of SOC loss continued to increase further until year 2000–2010 and reached to a level ranging from $-1.93$ to $-1.63\,\mathrm{Tg\,C\,yr^{-1}}$ (Fig. 6). The rate of SOC loss began to decline from year 2010–2020 with future scenario, except that of BAU-URB with FGOALS & B1 which began to decline from year 2020–2030 after an increase in year 2010–2020, to a level ranging from −1.47 to −0.44 $\text{Tg C yr}^{-1}$ and another level ranging from −2.17 to −1.33 $\text{Tg C yr}^{-1}$, under future climate scenario FGOALS & B1 and MIROC-H & A1B, with different scenarios on future land-use change and agricultural scenarios, respectively. The SOC stocks with future land-use change scenario ABN showed little differences between future agricultural scenario MAFF-BP and BAU (Fig. 6). Whereas those with future land-use change scenario URB showed large differences between these two future agricultural scenarios.

Rate of changes in SOC pool in different land-use with varying area with time, expressed as sum of SOC stocks in lands belonging to the same land-use type in a year (hereafter refereed as "apparent SOC loss (or gain)" for simplicity), evaluated with 10 yr interval, in year 1980–2010 was characterized by (1) a sharp increase in the rate of apparent SOC loss in UP (Fig. 7), due to increase in area (Fig. 2) combined with decline in manure input (Fig. 3a), (2) increase in the rate of apparent SOC loss in both ST and OL (Fig. 7) due to area expansion (Fig. 2) combined with no organic carbon input assumed for both of the land-use types, (3) decline in the rate of apparent SOC loss in PD (Fig. 7) due to a rapid and large decline in area (Fig. 2), and (4) a slight decline in the rate of apparent SOC gain in MG (Fig. 7), for which key factors controlling such change will be discussed later.

In period after year 2008 with future agricultural activity scenario MAFF-BP, changes in the rate of apparent SCSC were characterized by (1) a rapid decline in the rate of apparent SOC loss in UP (Fig. 7) due to decline in the area (Fig. 2) combined with increase in the annual organic carbon input rate (Fig. 3a), (2) decline in the rate of apparent SOC loss in both ST and OL (Fig. 7) due to termination in the area expansions of both land-use types that had been proceeding since year 1980 until year 2008 (Fig. 2), and (3) a sharp decline in the rate of apparent SOC gain in MG (Fig. 7) due to a sharp decline in annual input of organic carbon (Fig. 3a). Whereas the changes in the rate of apparent SCSC with future agricultural activity scenario BAU (Fig. 7) were char-





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acterized by (1) a rapid decline in the rate of apparent SOC loss in UP, similarly to that with MAFF-BP, (2) decline in the rate of apparent SOC loss in ST and OL began from year 2010–2020, except ST with future land-use change scenario URB that showed a negative greatest peak in year 2010–2020 followed by decline, and (3) a gradual decline in the rate of apparent SOC gain in MG affected by decline in the area despite of an increase in annual input of organic carbon (Fig. 3a).

### 3.5 Net-net accounting on SCSC

Emission of $CO_2$ due to SCSC in year 1985–1995 was found to be 4.47 Tg $CO_2$ $yr^{-1}$ (i.e. −1.22 Tg C $yr^{-1}$ SCSC; Fig. 6). With regarding this period as base period, a net-net accounting on $CO_2$ removal from or emission to the atmosphere due to SCSC in year 2010–2090 resulted in a net emission of $CO_2$ under future climate scenario MIROC-H & A1B, ranging from 0.41 to 3.47 Tg $CO_2$ $yr^{-1}$ (0.11–0.95 Tg C $yr^{-1}$; Fig. 6), regardless of differences in future scenarios of agricultural activity or land-use change. Whereas the net-net accounting with future climate scenario FGOALS & B1 in year 2010–2090 mostly resulted in removal from the atmosphere, ranging from 0.24 to 2.86 Tg $CO_2$ $yr^{-1}$ (0.06–0.78 Tg C $yr^{-1}$; Fig. 6), including a few cases with a net $CO_2$ emission ranging from 0.36 to 0.92 Tg $CO_2$ $yr^{-1}$ (0.10–0.25 Tg C $yr^{-1}$; Fig. 6).

### 3.6 Baseline accounting on SCSC

In baseline accounting relative reduction of $CO_2$ emissions were found only in cases with future land-use change scenario URB throughout the entire period regardless of different scenarios on future climate, due to greater rate of SOC loss in BAU defined as baseline scenario, compared with that in MAFF-BP (Fig. 8 and Table 3). Whereas in cases with future land-use change scenario ABN, baseline accounting resulted in relative $CO_2$ emissions of near zero or little size due to little or slightly lesser SOC loss rate found in BAU compared with that in MAFF-BP (Fig. 7 and Table 3). Differences in the relative reduction of $CO_2$ emission between two future climate scenarios were only





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small compared with differences found between two future land-use change scenarios (Fig. 8 and Table 3).

In cases with future land-use change scenario URB, a sharp increase in the relative reduction of $CO_2$ emissions were found in year 2000–2020, followed by the greatest relative reduction of $CO_2$ emission around 1.79 Tg $CO_2\,yr^{-1}$ in year 2010–2020, and subsequent gradual decline which continued until year 2080–2090. Compared with this greatest level of relative reduction of $CO_2$ emissions found in year 2010–2020, the relative $CO_2$ removal in subsequent periods declined continuously and substantially to 65–68 %, 23–26 %, and 5–15 %, in year 2020–2030, 2050–2060, and 2080–2090, respectively (Table 3).

### 3.7 Validation of model simulation in year 1979–1998

Results of comparison of temporal changes in SOC stocks between medians of observations in the stationary monitoring and means of the simulation outputs were summarized as followings:

1. For PD with Gray Lowland soils or Gley Lowland soils, and for UP with Andosols or Brown Forest soils, having large area distribution in common, little change or only small decline in medians and quartiles of SOC were found in the monitoring (Fig. 9). These soils and land-use types had means of the simulated SOC stock slightly greater than medians in stationary monitoring. In these entities excluding UP with Andosols, initial SOC set for the simulation were found in somewhat greater levels compared with those in the 1st wave of the monitoring.

2. In UP, all soil groups except Andosols and Yellow soils, means of the simulation were far greater than medians of the monitoring, with rather greater initial SOC levels set for the simulation.

3. In OC, all soil groups except Andosols mean of the simulation prediction decreased with time, with levels lower than those in medians of the monitoring, in

contrast to little changes or slight increases found in the monitoring. Whereas only Andosols both means of simulation prediction and medians of the monitoring observation showed little changes with time in common, with levels of SOC similar to each other.

4. In MG, means of the simulation had little change or increased with time. Whereas the medians of the monitoring were not obtained due to limited data availability.

## 4 Discussions

### 4.1 Historical and future changes in SOC stock in agricultural lands in Japan

Simulation outputs on emissions of $CO_2$ by SCSC in agricultural lands in Japan showed two different and contrasting trends in historical period (year 1980–2008) and future scenario projections (year 2020–2099), showing continuous increase and decline of $CO_2$ emissions, respectively (Fig. 6). Increase of $CO_2$ emissions in historical period was attributed to a large conversion of agricultural fields (PD, UP, OC, and MG) to ST or OL (Fig. 2) that lead to decline in the overall rate of organic carbon input to soils, as well as to conversion of PD to UP occurred from 1970's to year 2008 (Fig. 2) that lead to enhancement of SOM decomposition under aerobic conditions. On the other hand, decline in $CO_2$ emissions in period with future scenario projections was attributed mainly to termination of land-use conversions from agricultural fields to ST or OT (Fig. 2) as well as to decrease in the size of SOC stock with time. The fact that continuous decline of the $CO_2$ emissions were found not only for cases with enhanced organic matter input to soils (ABN with BAU or MAFF-BP, and URB with MAFF-BP) but also for cases with decreased organic matter input (URB with BAU) (Figs. 4 and 6) supports our interpretation that this decline is not due primarily to enhanced input of organic carbon to soils in agricultural fields in some of future scenarios in which such conditions were set.





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This suggests that conversion of agricultural fields to other land-use types have been playing major roles in country-scale SCSC in agricultural lands in Japan both in year 1980–2008, and would act so also in future.

### 4.2 Scenario analysis on SOC sequestration potential

One of the most important implications in the results of our country-scale simulation with different future scenarios is that there is a possibility that an option to let agricultural fields be abandoned (i.e. BAU with ABN) would archive same level of reduction of $CO_2$ emissions by SCSC compared with another option to pay effort to intensify crop rotations with preventing agricultural fields from conversion to other land-use types (i.e. MAFF-BP with ABN) (Figs. 6 and 7). Relative advantage of the MAFF-BP over BAU would be realized only in case large conversion of agricultural fields to ST is prevented, as shown with future land-use change scenario URB (Figs. 6 and 8).

In order to confirm order of superiority in reduction of $CO_2$ emission among these options, it must be emphasized that uncertainty analysis must be conducted as annual rates of organic matter input to soils in UG and ST this study employed were based on a single parameter taken from literature and simple assumption, respectively, rather than probability distribution function derived from a number of observations. This point will be further discussed later in sections on uncertainty in model simulation.

As to the maximum intensity of the relative reduction in $CO_2$ emissions estimated for MAFF-BP compared with BAU (1.79 Tg $CO_2\,yr^{-1}$ in year 2010–2020; Fig. 8 and Table 3), it is only 0.14 % of Japan's total anthropogenic emissions (1308 Tg $CO_2$ eq. in fiscal year 2011), and is still small compared to total GHGs emissions from agriculture sector (7.1 % of 25.4 Tg $CO_2$ eq. $yr^{-1}$ in fiscal year 2011, including methane ($CH_4$) and nitrous oxide ($N_2O$) estimated by the Tier 2 emission factors), but comparable to emissions of $CO_2$ from this sector (34 % of 5.3 Tg $CO_2\,yr^{-1}$) (Greenhouse Gas Inventory Office of Japan, 2013).





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Future agricultural activity scenario MAFF-BP used in this study does not include use of pyrolysed carbon (biochar), known as an effective option to sequestrate carbon in soils of arable lands, as an option to be employed. In addition, the most recalcitrant SOC model component, IOM, in RothC is completely “inert”, for which no decomposition is assumed to occur (Coleman et al., 1999). Thus, it is not a suitable to apply RothC to simulate decomposition of the pyrolysed carbon that are known to be rather recalcitrant but only slowly decomposable (Kuzyakov et al., 2009). With making use of such scenario and model in this study we rather aimed to investigate course of SOC sequestration, by assuming no temporal changes to occur in agricultural activity and land-use for a prolonged period after year 2020. Hence this study should be regarded as an assessment on the effect of implementation of intensified rotation as main driving factor enhancing organic matter input to soils. Obviously, seeking scenario having greater climate mitigation potential with an intention for policy implementation requires to estimate total GHGs budget including emission of $N_2O$ and $CH_4$ from agricultural activity to take account trade-off among emissions of these GHGs (Ceschia et al., 2010).

### 4.3 Factoring out direct human-induced influence

The fact that the baseline based accounting showed only small differences in relative SCSC between cases with different future climate projections (Fig. 8), despite that they were purpoqsely selected to have largest difference in temperature during year 2009–2020 among other climate projections, strongly suggests that this approach is robust over variations in future climate and effective to factor out direct human-induced influence. On the other hand, difference in land-use change is shown to have significant influence in this type of analysis. This has important implications for assessment on the effectiveness of measures implementing SOC sequestration in analysis of marginal abatement costs on various climate change mitigation options, as well as for discussions on institutions to issue credits for temporary carbon storage (Keeler, 2005; Marland and Marland, 2009; Marland et al., 2001; Sedjo and Marland, 2003). Although, a careful attention must to be paid on an issue that application of this approach alone is





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susceptible on methodologies on how to draw a baseline scenario, however, still potential of this approach to factor out direct human induced influence even at country-scale may deserve attention.

### 4.4 Course of SOC sequestration

In cases with future land-use change scenario URB, continuous decline in relative reduction of $CO_2$ emission due to SCSC found in period after year 2020 while keeping the same size of organic matter input enhancement (Fig. 8) should be regarded as a course of SOC approaching to a steady state. The decline in the relative reduction of $CO_2$ emission found in year 2020–2030 compared to that in year 2010–2020 ranged 0.57–0.63 Tg $CO_2$, equivalent to 32–35 % of the $CO_2$ emission reduction (Fig. 8 and Table 3).

Obviously, the course of SOC sequestration in which soils approaches to another new steady-state takes much longer time, e.g. from decades to near a century, than duration of a commitment period of international agreement, e.g. the first commitment period of KP (year 2008–2012). West and Six (2007) obtained estimates on the time to peak sequestration rate and the time to reach a new steady-state, based on measurements from many different experiments in croplands and grasslands with different duration, that ranged 5–10 yr and 40–45 yr, respectively.

Therefore, assessment on these quantitative properties of the course of SOC sequestration should be adequately performed and taken into consideration if policy maker or land-manager plans to include the SOC sequestration to meet assigned target to reduce GHGs emission, along with other measures of permanent reduction of GHGs emission (e.g. avoiding fossil fuel usage), as such decline will have to be replenished by other emissions reduction. In the case of our simulation, while agricultural lands in Japan would gain 1.79 Tg of $CO_2$ as peak emissions reduction in year 2010–2020, as maximum case with future land-use change scenario URB, other measures with GHGs reduction potential of 0.57–0.63 Tg $CO_2$ would inevitably need to be fully implemented by year 2020–2030.





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## 4.5 Feasibility of future scenario

It should be noted that the result of accounting on $CO_2$ removal from or emission to the atmosphere shown by net-net accounting or baseline based accounting is premised on a complete implementation of agricultural activity scenario MAFF-BP until its target year 2020, that might be rather challenging in terms of feasibility. For example, the goal of food self-sufficiency rate in year 2020 set in MAFF-BP is regarded as a premise on maximized effort of all stakeholders and is set as an aggressive target that would not be possible without it (Ministry of Agriculture Forestry and Fisheries, 2005, 2010). In other words, feasibility of MAFF-BP implementation, or timing of its complete implementation, is probably the most important factor that would have critical impact on the course of SOC sequestration presented in this study.

In MAFF-BP, increase in cropping area of major crops (Fig. 2) as well as intensification of annual cropping per unit area of fields in PD and CL with introducing efficient rotation is a major factor that lead to an increase in the rate of plant residue input to soils (Fig. 3a and b) and subsequent reduction in $CO_2$ emission from soils (Figs. 5 and 8). For these measures, any low level of achievements, if significantly far from the target, would cause inevitable decline in the reduction of $CO_2$ emission compared with the figures presented in this study.

Moreover, it should be noted that assumption on the extent of land-use change in both BAU and MAFF-BP scenario may need careful review as conversion of agricultural lands to ST or OL in future period year 2009–2020 were assumed to occur rather small extent compared with trend observed in recent decades (Fig. 2). With taking into account a major finding in our simulation study that conversion of agricultural lands to ST or OL would became a major cause of increased SOC loss rate found in recent and future period compared with that in period around year 1990 (Fig. 8), it is considered that any underestimation in this type of land-use conversion, if significant, would result in large overestimation of SOC stock in future period in Japan's case, particularly.





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It should be noted that this study did not deal with issues on non-permanency or risk of reversibility of temporary storage of carbon (Levasseur et al., 2012), and gave only estimate on potentials of SOC sequestration under the agricultural activity scenarios involving some challenging targets. For prediction of realistic levels of SCSC in future requires rather different approaches such as taking account risk of farmer's abandoning intensified rotation as well as estimation of land-use change after year 2020.

### 4.6 Uncertainties

With regard to sources of uncertainty in the system we developed to predict SCSCs at country scale, there are a number of factors to be paid attention involving variability of model input such as plant residue and manure input to soils, land-use change, initial soil conditions, climate as well as that in model formulations and parameters. In study on regional scale SCSC estimation for northern Japan agricultural lands by Koga et al. (2011), estimated advantage in SOC sequestration from utilization of cattle manure application to soils become ambiguous when uncertainties in climate and organic matter input to soils were taking into account by their Monte Carlo simulations. As estimation of organic carbon input to soils by DTK, which our simulation study relies on, employs a number of parameters and stratified calculation modules (see Supplement for details), a full assessment on its uncertainty needs to be implemented. As to variety in future climate projections, our simulation results only indicated a need to use process-based model in assessment of a country-scale SCSC, however, was not designed to fully assess influence of future climate uncertainty on country-scale SCSC estimation.

As to model application on lands with varying land-use, assumption that SOC in soils in ST and OL only continues declining with allowing no organic matter input to soils while keeping decomposition proceeding as same as CL, MG, or UG does not have enough support from evidence and thus may need further study. Several studies have argued that SOC stock in urban area are likely somewhat underestimated due to a lack of systematic measurements on this quantity (Edmondson et al., 2012). In our simulation, the rates of apparent SOC loss in ST and OL in year 2000–2010 were found to be the second and the third largest loss after that in CL among all land-use types, despite ST and OL had much smaller area than PD and CL. In such case, these land-use types should be regarded as "key category" in reporting on GHGs emissions in AFOLU sector. Uncertainties in key categories emission estimation need to be paid attention as this may apply also to other countries that have been facing a rapidly growing urbanization with a large-scale conversion of agricultural lands to ST or OL in recent decades.

Furthermore, predictive power of RothC_p application for PD needs further validation and refinement, as this subversion of RothC model, employing additional parameters to adjust SOC decomposition rate under submerged and drained yet rather moist soil conditions by simple tuning, has been tested with data from only limited numbers of long-term field experiments at this stage (Shirato and Yokozawa, 2005; Shirato et al., 2011). As PD has been holding one of the largest area among all land-use types in agricultural lands in Japan, even relatively small changes in prediction on the rate of SCSC per unit area basis in this land-use category may have large impact on overall figure of country level estimation of SCSC.

It also should be noted that our attempt to give a reliable estimate on the base year emission, at current stage, largely relies on data on manure compost application rate based on farmer's questionnaire as well as that of soil carbon pools collected in the stationary monitoring. As the stationary monitoring did not employ stratified sampling in its design, use of this dataset to calculate national average might incur some degrees of bias. In a detail analysis of the stationary monitoring data by Leon et al. (2012), which documented important factors controlling application rate of organic amendments in Japanese paddy fields, they suggested to use weighted average to take account differences in proportions of types of those factors, i.e. paddy field use, livestock possession and/or part-/full-time farmers, between the samples in the stationary monitoring and entire population in country to calculate national average. The same situation applies also to SCSC data in the stationary monitoring. It should be noted that validity of our current estimate on base year emission is only conditional on an assumption that size and effect of the sampling bias in the stationary monitoring is negligible. For example, Leon et al. (2012) pointed out that simple arithmetic average on application rate of manure compost in the stationary monitoring was found to be greater than that shown in the results of statistical survey "Statistics on production cost of rice" conducted by Statistics and Information Department, MAFF, in year 1992, 1993, 1994, and 1995, in which 3000 commercial farmers were chosen through stratified sampling. Although, further study is needed to elucidate the degree of bias to calculate the national average, however, as to manure application rate, this only exert influence on its balance among different types of agricultural lands (i.e. PD, UP, OC, and MG), and not on total amount of manure applied in these lands, as mass-balance between manure production and consumption are ensured in our approach with adjusting application rate in MG. In our previous experience, simulations with recent older versions of DTK (version 2.2.8 and older) estimated much less manure production, owing primarily to employment of erroneously high parameter value for decomposition rate of secondary materials (e.g. saw dust, bark, etc.) utilized in live-stock waste composting, and correspondently, employed strong bias correction on the manure application rates (to be 36–51 %), resulted in rather different figures compared with that presented in this study, showing greater $CO_2$ emission by SCSC in historical period and much greater effect of MAFF-BP scenario to reduce $CO_2$ emission (or even to remove $CO_2$) with accordingly enhanced superiority of increased rate of organic matter input by intensified rotation in future scenario (data not shown) (Shirato and Yagasaki, 2012a, b, 2013). This highlights importance of double-checking on the amount of organic matter amendment from production side and consumption side, in a framework to ensure mass-balance between the two.

### 4.7 Performance and potential of simulation system to predict SCSC

The results that for some of soil groups and land-use types with relatively large area distributions the system's estimates on changes in SOC stock with time were found to be close to those found in the stationary monitoring (Fig. 9) suggest that the system has an acceptable level of validity, though in a limited range of conditions. On the





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other hand, for PD and UP with Gray Upland soils, Brown Lowland soils, Gray Lowland soils, and Gley Lowland soils, initial SOC levels set for simulation based on BSSFC dataset were found to be rather greater than those found in the 1st wave of the stationary monitoring (Fig. 9). Thus the nature of these soil inventories such as potential sampling bias as well as methodology to calculate representative values of SOC stock for each group of land-use, soil group, and spatial entity (prefecture or country) for both soil inventories needs review to explain this discrepancy. In addition, with regard to underestimation and decrease of SOC stock with time found in model predictions for 4 major soil groups in OC, settings of the concentration of organic carbon in plant residues in OC in DTK may need revision. The DTK employed the concentration organic carbon in plant residues in OC to be 40 %, as same as crop residues (Shirato and Yagasaki, 2012a, b, 2013), which is rather lower compared with figures reported for fruit trees in composition database for various biomass developed by Nakamura and Yuyama (2005) (e.g. leaves and pruned branches of chestnut and loquat, ranging 49–51 %). Furthermore, the simulation results that MG and ST could act as relatively large sink and source, respectively, of CO2 by SCSC, suggest there is remaining needs for validation of the model simulation on SOC stock-change in MG and ST including collection of data and evidences from fields.

## 5 Conclusions

Using spatially-explicit LUC dataset and process-based model in combination with rather exaggerated and contrasting settings on future scenarios of climate, agricultural activity, and land-use change, our simulation experiment indicated relative importance of conversions of agricultural fields to UG or ST to be taken account in assessment of a country-scale SCSC as key factors for a country facing growing urbanization and abandoning of agricultural fields. Scenario analysis indicated the possibility that option to increase the rate of organic matter input to soils in agricultural fields with intensifying crop rotation, with suppressing conversion of agricultural fields to other land-uses, may





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archive reductions of $CO_2$ emission due to SCSC in a level similar to that of another option to let agricultural field be abandoned. Application of a base-line based accounting showed robustness over future climate variations and good performance to factor out direct-human influence on a country-scale SCSC. In addition to uncertainties in estimation of the rate of organic carbon input to soils in different land-use types at large-scale, time course of SOC sequestration, supposition on land-use change pattern in future, as well as feasibility of agricultural policy planning are considered as important factors that need to be taken account in estimation on a potential of country-scale SCSC.

**Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/10/18359/2013/bgd-10-18359-2013-supplement.pdf.**

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**Table 1.** Settings in simulation as to model version and data source used to determine rate of organic carbon input to soils for plant residue and manure in different land-use types.

| Symbol[1] | Land-use | Model | Plant residue | Manure |
|---|---|---|---|---|
| 01 PD | paddy fields | RP[2] | estimation from stat.[5] | farmer questionnaire[8] |
| 02 CL | croplands | RO[3], RV[4] | estimation from stat.[5] | farmer questionnaire[8] |
| 03 OC | orchards | RO[3], RV[4] | estimation from stat.[5] | farmer questionnaire[8] |
| 04 MG | managed grasslands | RO[3], RV[4] | estimation from stat.[5] | mass-balance[9] |
| 05 UG | unmanaged grasslands | RO[3], RV[4] | $3.8\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$[6] | no manure input |
| 06 FL | forest lands | RO[3], RV[4] | $2.0\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$[7] | no manure input |
| 08 ST | settlements | RO[3], RV[4] | no residue input | no manure input |
| 09 OL | other lands | RO[3], RV[4] | no residue input | no manure input |
| 07 WL | wetlands | – | – | – |

[1] PD: paddy fields, CL: croplands; OC: orchards; MG: managed grasslands; FL: forest lands. WL: wetlands; ST: settlements; OL: other lands.
[2] RP: RothC26.3_p.
[3] RO: RothC26.3.
[4] RV: RothC26.3_v.
[5] Estimation based on various agricultural statistics such as yields, cropping area, and field area, etc. in combination with various parameters on agricultural management practices and crop characteristics taken from literatures.
[6] Estimation for grass lands employed in Shirato et al. (2004).
[7] Estimation for forest lands employed in Shirato et al. (2004).
[8] Estimation based on results of questionnaires to farmers archived by Basic Soil Environmental Survey Project, Stationary Monitoring.
[9] Estimation based on mass-balance calculation on supply (production) and demand (applications) of manure compost. Amount of manure applied in MG is calculated by subtracting the sum of amount of manure applied in PD, CL, and OC from total amount of produced manure in the same year.





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**Table 2.** Amount of organic carbon from different sources applied to soils in agricultural area of Japan, employed in simulation (unit: Gg C $yr^{-1}$).

| | 1970 | 1980 | 1990 | 2000 | 2008 | LUC[3] | BAU[4] 2020 | | MAFF-BP[4] 2020 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Manure | 6225 | 6869 | 7717 | 6497 | 5825 | | 5602 | (96) | 5462 | (94) |
| Slurry[1] | 64 | 67 | 75 | 66 | 58 | | 50 | (86) | 49 | (84) |
| Excreta[1] | 54 | 40 | 47 | 49 | 46 | | 43 | (93) | 44 | (96) |
| RSD[2] | 11 286 | 11 122 | 12 779 | 13 895 | 13 486 | URB | 12 674 | (94) | 14 252 | (106) |
| | | | | | | ABN | 14 254 | (106) | 14 327 | (106) |
| Total | 17 629 | 18 098 | 20 618 | 20 507 | 19 415 | URB | 18 369 | (95) | 19 807 | (102) |
| | | | | | | ABN | 19 949 | (103) | 19 882 | (102) |

[1] A conversion factor of 0.5 was applied for above listed values of slurry and excreta prior to determination of the annual input of farm-yard manure in RothC simulation to take account relatively fast decomposition of these organic matters compared to composted manure.

[2] RSD: plant residue.

[3] LUC: future scenarios on land-use change pattern. URB: urbanization, ABN: abandoning.

[4] Values in parentheses indicate relative changes expressed as percentage values compared with corresponding values in year 2008.





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**Table 3.** Accounting of $CO_2$ removal from or emission to the atmosphere due to changes in size of soil organic carbon pool evaluated with baseline method for a series of decadal period from year 1990 to 2090 under different future scenarios of climate, agricultural activity, and land-use change (unit: Tg $CO_2\,yr^{-1}$).

| | FGOALS & B1 | | | MIROC-H & A1B | | |
|---|---|---|---|---|---|---|
| year | URB | | ABN | URB | | ABN |
| 1990–2000 | 0.00 | | 0.00 | 0.00 | | 0.00 |
| 2000–2010 | 0.11 | | 0.00 | 0.11 | | 0.00 |
| 2010–2020 | 0.49 | (100) | −0.02 | 0.49 | (100) | −0.02 |
| 2020–2030 | 0.33 | (68) | −0.04 | 0.32 | (65) | −0.03 |
| 2030–2040 | 0.23 | (47) | −0.01 | 0.22 | (45) | 0.01 |
| 2040–2050 | 0.18 | (37) | 0.01 | 0.15 | (31) | 0.00 |
| 2050–2060 | 0.13 | (26) | 0.00 | 0.11 | (23) | 0.00 |
| 2060–2070 | 0.09 | (19) | 0.00 | 0.07 | (13) | 0.00 |
| 2070–2080 | 0.07 | (14) | 0.02 | 0.05 | (10) | 0.00 |
| 2080–2090 | 0.07 | (15) | −0.01 | 0.02 | (05) | 0.00 |

Numbers shown are differences in $CO_2$ removal from or emission to the atmosphere due to changes in size of soil organic carbon pool between BAU and MAFF-BP scenario (MAFF-BP minus BAU). Negative and positive value indicates relative $CO_2$ removal from or emission to the atmosphere due to changes in size of soil organic carbon pool in MAFF-BP scenario compared with those in BAU scenario. For land-use change scenario URB, numbers in parenthesis indicate percentage values compared with the level in year 2010–2020 that holds the greatest removal of $CO_2$ in entire period.

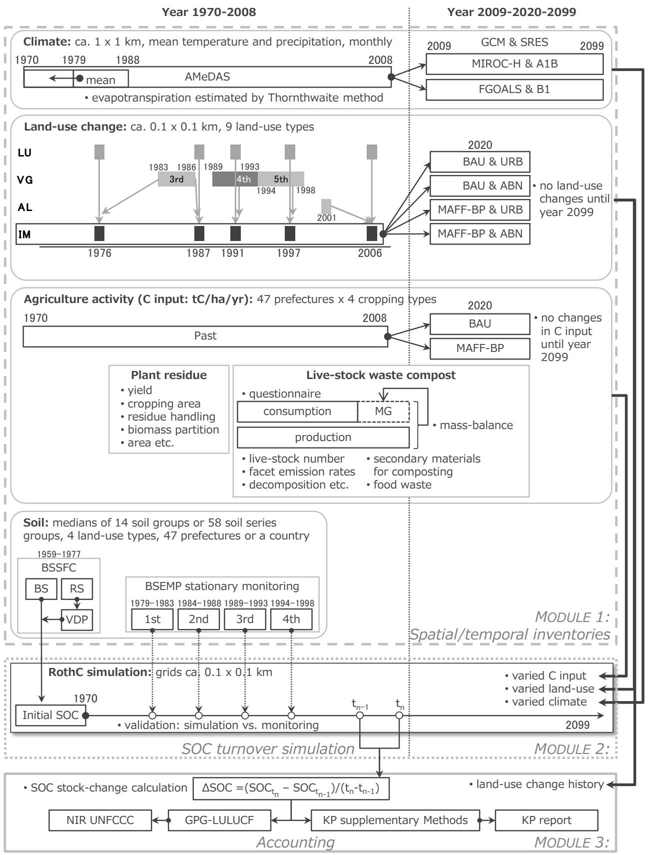


**Fig. 1.** Schematic diagram of the system developed to simulate soil carbon stock-change at country-scale using spatially-explicit inventories on land-use change, climate, soil, and agricultural activity. NIR: National Inventory Report. See body text and Supplement for detail descriptions on other abbreviated text in figures.





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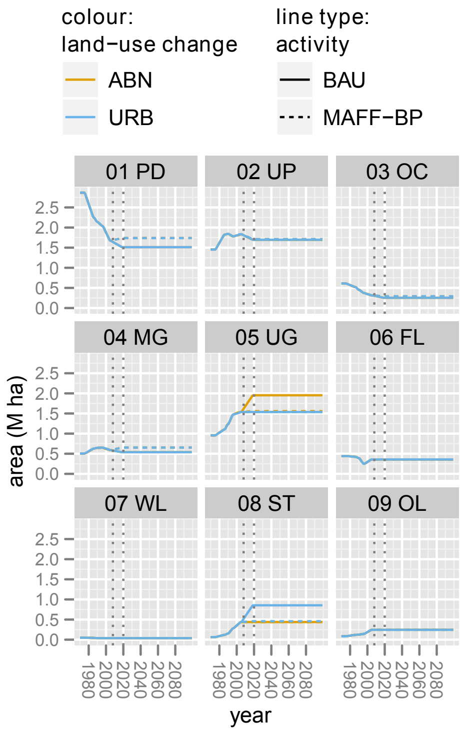


**Fig. 2.** Temporal changes in area of different land-use types in agricultural area of Japan used in simulation, including past (year 1970–2008), future scenarios with varying land-use change from year 2009 to 2020, and subsequent future period from year 2021 to 2099 with assuming no land-use change. PD: paddy fields, CL: croplands; OC: orchards; MG: managed grasslands; FL: forest lands. WL: wetlands; ST: settlements; OL: other lands. Ocher and light blue colour indicates, future land-use change scenario ABN (abandoning) and URB (urbanization), respectively. Solid and dashed line indicates future agricultural activity scenario BAU and MAFF-BP, respectively.





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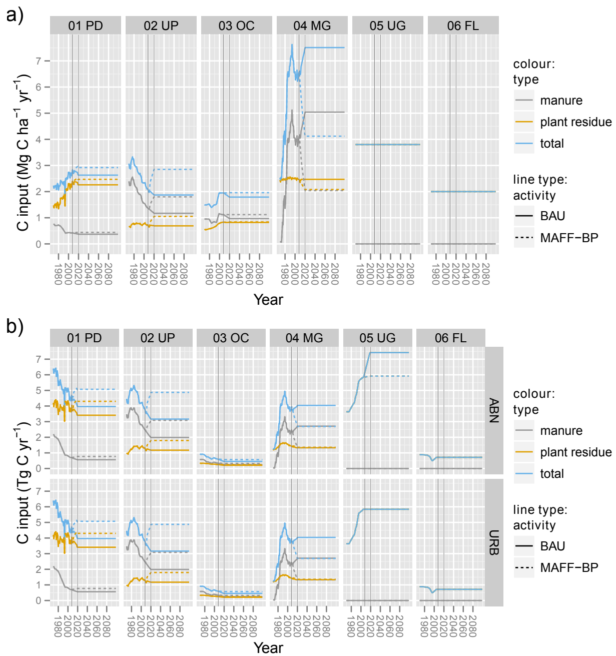


**Fig. 3.** Input of organic carbon to soils expressed as annual input rate per unit area of soils (**a**; upper) and annual total sum (**b**; bottom) in different land-use types (lined up horizontally) and periods including past (year 1970–2008), future scenarios during year 2009–2020 with varying input rate toward target levels in year 2020, and subsequent future period for year 2021–2099 with assuming no change in input rate after year 2020. Overall input (sum of plant residue, manure, slurry and excreta), plant residue, and sum of manure, slurry, and excreta are indicated in light blue, ocher, and gray colour, respectively. Solid and dashed line indicates future agricultural activity scenario BAU and MAFF-BP, respectively. PD: paddy fields, UP: upland fields; OC: orchards; MG: managed grasslands; FL: forest lands. Note that for annual total input of organic carbon (**b**; bottom) data with different scenarios on land-use change pattern, URB (urbanization) and ABN (abandoning), were shown and lined up vertically.

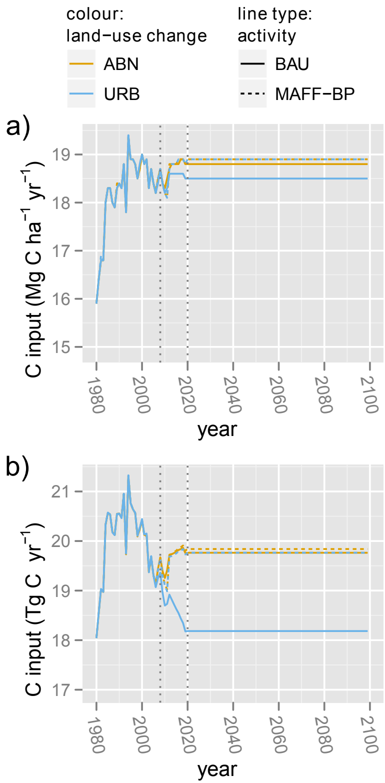


**Fig. 4.** Input of organic carbon to soils expressed as annual input rate per unit area of soils (**a**; upper) and annual total sum for all land-use types (**b**; bottom) in different periods including past (year 1970–2008), future (year 2009–2020) with scenarios on agricultural activity and land-use change, and subsequent future period (year 2021–2099) with assuming no change in input rate after year 2020. Solid and dashed line indicate future agricultural activity scenario BAU and MAFF-BP, respectively. Ocher and light blue colour indicate future scenarios on land-use change pattern ABN (abandoning) and URB (urbanization), respectively.





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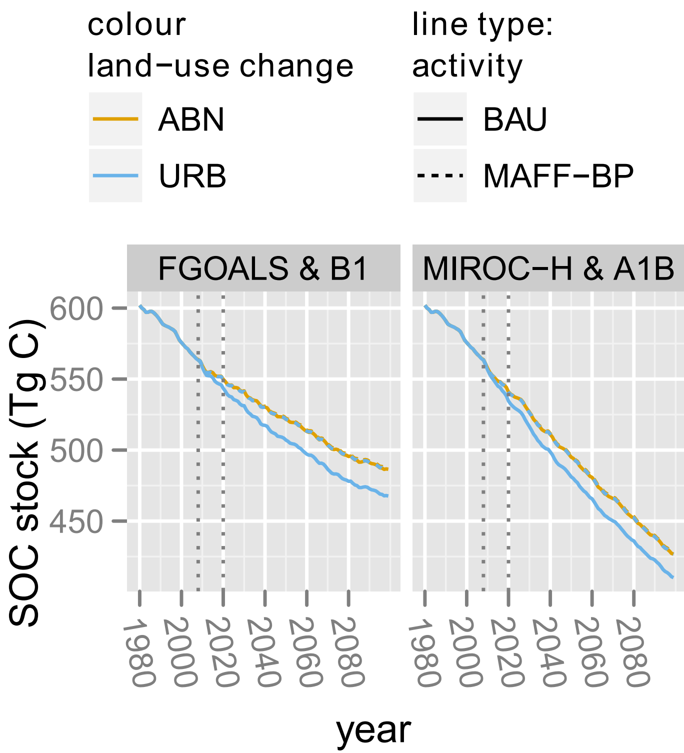


**Fig. 5.** Simulation output on changes in soil organic carbon stocks in agricultural lands in Japan with different scenarios on future agricultural activity, land-use change, and climate. Solid and dashed line indicate future agricultural activity scenario BAU and MAFF-BP, respectively. Ocher and light blue colour indicate scenarios on future land-use change pattern ABN (abandoning) and URB (urbanization), respectively. Results with different future climate scenarios, FGOALS & B1 and MIROC-H & A1B, are lined-up horizontally.





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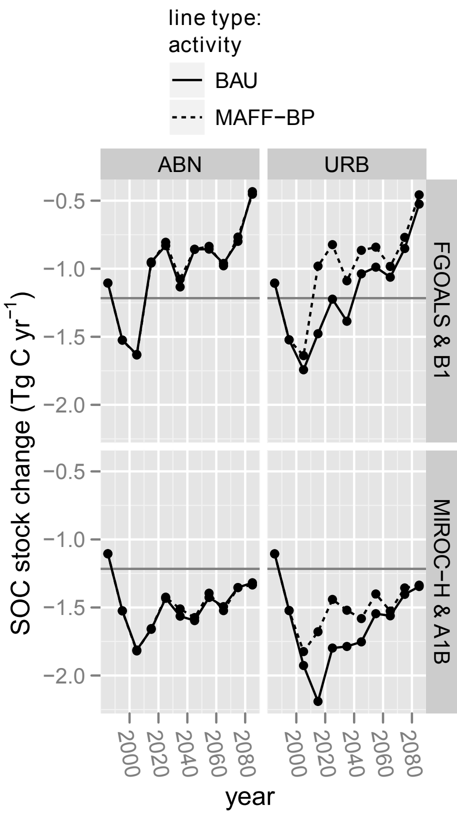


**Fig. 6.** Changes in SOC stock in agricultural area in Japan under different future climate projections (FGOALS & B1 and MIROC-H & A1B; lined up vertically) and future land-use change scenarios (ABN and URB; lined up horizontally). Solid and broken line indicates agricultural activity scenario BAU and MAFF-BP, respectively. Gray horizontal line indicates SOC stock change rate at year 1990 (mean of year 1985–1995; $-1.22\,\mathrm{Tg\,C\,yr^{-1}}$).





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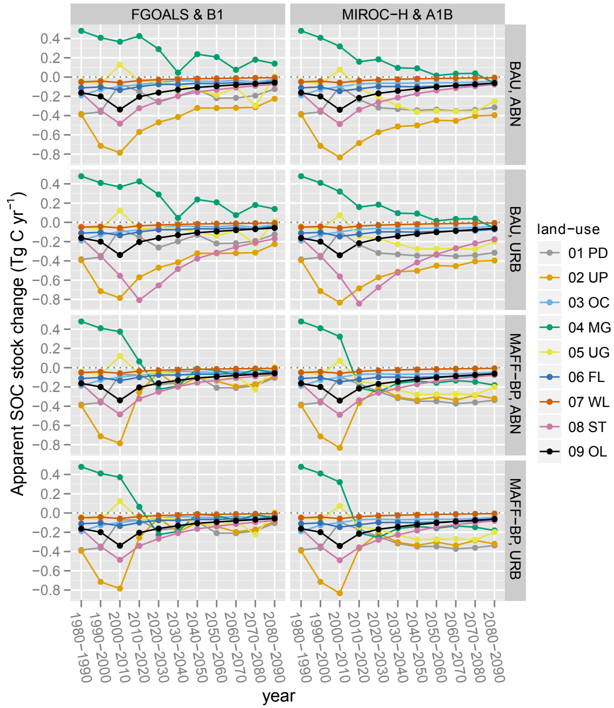


**Fig. 7.** Rate of apparent soil organic carbon stock changes in different land-use and period during year 1980–2008 and those projected for period after year 2008 with different future scenarios of climate (FGOALS & B1 and MIROC-H & A1B, lined-up horizontally) and combinations of agricultural activity (BAU and MAFF-BP) and land-use change pattern (ABN and URB) (lined-up vertically). PD: paddy fields, CL: croplands; OC: orchards; MG: managed grasslands; FL: forest lands. WL: wetlands; ST: settlements; OL: other lands. The rate is expressed as 10 yr mean value. Positive and negative values on vertical axis indicates gain and loss of soil organic carbon stock, which are equivalent to $CO_2$ removal from and emission to the atmosphere, respectively.

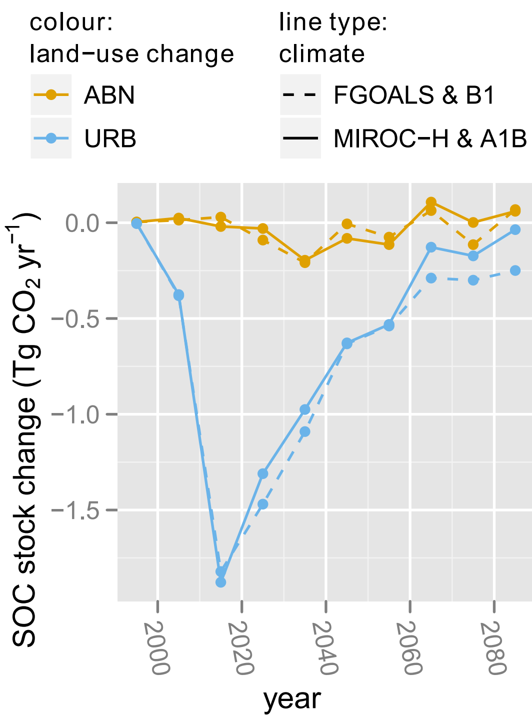


**Fig. 8.** Relative changes in SOC stock in agricultural lands in Japan obtained by baseline-based accounting defined as differences in estimated changes in SOC stock between two different future agricultural activity scenarios, MAFF-BP and BAU, with regarding BAU as baseline scenario (i.e. MAFF-BP minus BAU). Negative and positive value on vertical axis indicates relative removal and emission, respectively, of $CO_2$. Solid and broken line indicates the estimations with future climate scenario MIROC-H & A1B and FGOALS & B1, respectively. Ocher and light blue colour indicate results with future scenario on land-use change pattern ABN (abandoning) and URB (urbanization), respectively.

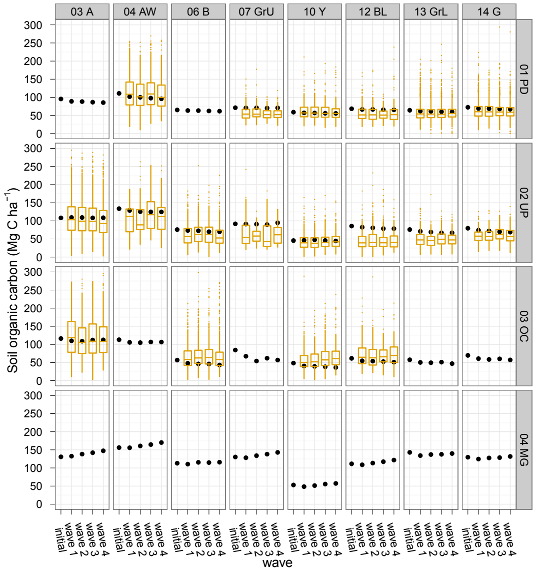


**Fig. 9.** Temporal changes in the stock of organic carbon in soils of 8 major soil groups (lined-up horizontally) with different land-use types (lined-up vertically) in agricultural lands in Japan. Means of prediction by simulation (black circle) were superimposed on observed data from the Basic Soil Environment Monitoring Project, Stationary Monitoring conducted during year 1979–1998 (ocher box plot). Edge of upward and downward whisker of box plot indicates minimum and maximum value, respectively. Upper and lower hinge indicates 25 % and 75 % percentile, respectively. Bar in middle of the box indicates median. Points above or below whisker indicate outlier values. PD: paddy fields; UP: upland fields; OC: orchards; MG: managed grasslands. Abbreviations and full names of soil groups and their relative area distribution (in parenthesis) are as follows, 03 A: Andosols (21 %); 04 AW: Wet Andosols (7 %); 06 B: Brown Forest soils (14 %); 07 GrU: Gray Upland soils (2 %); 10 Y: Yellow soils (5 %); 12 BL: Brown Lowland soils (7 %); 13 GrL: Gray Lowland soils (22 %); 14 G: Gley Lowland soils (17 %). Years of each survey wave (horizontal axis in each plot) are as follows: initial: 1970; wave 1: 1979–1983; wave 2: 1984–1988; wave 3: 1989–1993: wave 4: 1994–1998.





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