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Assessment on the rates and potentials of soil organic carbon sequestration in agricultural lands in Japan using a process-based model and spatially explicit land-use change inventories – Part 2: Future potentials

Y. Yagasaki[1,*] **and Y. Shirato**[1]

[1]Natural Resources Inventory Center, National Institute for Agro-Environmental Sciences, 3-1-3 Kannondai, Tsukuba, 305-8604, Japan
[*]now at: Terrestrial Ecosystems Management, Hall of Global Environmental Research, Graduate School of Global Environmental Studies, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto, 606-8501, Japan

Correspondence to: Y. Yagasaki (yagasaki.yasumi.7n@kyoto-u.ac.jp)

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Abstract. Future potentials of the sequestration of soil organic carbon (SOC) in agricultural lands in Japan were estimated using a simulation system we recently developed to simulate SOC stock change at country-scale under varying land-use change, climate, soil, and agricultural practices, in a spatially explicit manner. Simulation was run from 1970 to 2006 with historical inventories, and subsequently to 2020 with future scenarios of agricultural activity comprised of various agricultural policy targets advocated by the Japanese government. Furthermore, the simulation was run subsequently until 2100 while forcing no temporal changes in land-use and agricultural activity to investigate duration and course of SOC stock change at country scale.

A scenario with an increased rate of organic carbon input to agricultural fields by intensified crop rotation in combination with the suppression of conversion of agricultural lands to other land-use types was found to have a greater reduction of CO_2 emission by enhanced soil carbon sequestration, but only under a circumstance in which the converted agricultural lands will become settlements that were considered to have a relatively lower rate of organic carbon input. The size of relative reduction of CO_2 emission in this scenario was comparable to that in another contrasting scenario (business-as-usual scenario of agricultural activity) in which a relatively lower rate of organic matter input to agricultural fields was assumed in combination with an increased rate of conversion of the agricultural fields to unmanaged grasslands through abandonment.

Our simulation experiment clearly demonstrated that net-net-based accounting on SOC stock change, defined as the differences between the emissions and removals during the commitment period and the emissions and removals during a previous period (base year or base period of Kyoto Protocol), can be largely influenced by variations in future climate. Whereas baseline-based accounting, defined as differences between the net emissions in the accounting period and the ex ante estimation of net business-as-usual emissions for the same period, has robustness over variations in future climate and effectiveness to factor out some of the direct human-induced effects such as changing land-use and agricultural activity.

Factors affecting uncertainties in the estimation of the country-scale potential of SOC sequestration were discussed, especially those related to estimation of the rate of organic carbon input to soils under different land-use types. Our study suggested that, in order to assist decision making of policy on agriculture, land management, and mitigation of global climate change, it is also important to take account of duration and time course of SOC sequestration, supposition on land-use change pattern in future, as well as feasibility of agricultural policy planning.

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1 Introduction

Sequestration of soil organic carbon (SOC) in soils in agricultural usages has been suggested to have large potentials to contribute to mitigate global climate change (Lal, 2004; Smith et al., 2008) with relatively low abatement cost (Smith et al., 2008). A current framework of international agreement to combat against global climate change had already decided to allow a member of the party, or a nation, to include reduction of carbon dioxide (CO_2) emission due to SOC stock change in croplands and grazing lands in their accounting on the emission of greenhouse gases (GHGs) for which reduction obligation is placed, as defined in Article 3.4 of Kyoto Protocol (KP) under United Nations Framework Convention on Climate Change (UNFCCC) (United Nations Framework Convention on Climate Change, 1998).

In order to support the decision making of policy makers at local or central governmental level and implementation of SOC sequestration on agricultural lands, it is essential to develop measures that enable them to provide a reliable estimation on future potential of SOC sequestration at large spatial scale. So far, previous studies have demonstrated that application of currently available process-based models of SOC turn-over is an effective approach to estimate temporal changes in SOC stock over several decades or centuries (Jenkinson et al., 1990; Kelly et al., 1997; McGill, 1996; Shirato and Yokozawa, 2005; Shirato et al., 2004; Skjemstad et al., 2004). In many of those studies, validation of the model was conducted based on observed changes in SOC stock in long-term field experiments, in which the rate of organic matter application to soils or soil initial conditions, key parameters determining SOC stock change, have had been known or well identified. In this context, with respect to such a model simulation approach to estimate SOC sequestration potentials on agricultural lands, it can be said that there is still a large research gap between plot-level study and the challenge to make estimation at country scale, unless variability in the availability of organic matter amendments including livestock waste composts and plant residues, as well as spatial variability of soil properties and climate, will be identified or well estimated. Also, findings from many of those long-term experiments at plot-scale were based on a certain land-use type, and thus may not be suitable to extend directory to a large geographical entity experiencing various types of land-use change.

Recently, Yagasaki and Shirato (accepted) developed a simulation system to conduct a comprehensive assessment on the size of future SOC sequestration potential in agricultural lands in Japan at country scale by combining a process-based model of SOC stock change with spatial and temporal inventories on soil, land-use change, agricultural activity, and climate. Validation of the predictive power of the system was conducted by comparing simulated SOC stock in a historical period with those observed in nation-wide monitoring program on soil properties in agricultural lands conducted during 1979–1998.

In this study, we conducted an assessment on the size of SOC sequestration potential in future using the simulation system developed by Yagasaki and Shirato (accepted). We elaborated future scenarios of agricultural activity and land-use changes to ensure consistencies in the area of different land-use types in a spatially explicit manner, as well as in the mass balance between production and consumption of organic matter amendment in agriculture in Japan, that could otherwise cause critical defect in the assessment of this sort.

We also conducted an investigation on important parameters that should be taken into account in the assessment of future SOC stock change potential at country-scale. Two future climate projections by global climate models (GCM) having a contrastingly high and low average of mean annual temperature were selected for the purpose of investigating sensitivity of the simulation system. Furthermore, based on the estimated potential of country-scale SOC stock change in the future, accounting of CO_2 removal or emission was conducted according to methodologies in technical guidelines created by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2003), to provide useful implications to policy makers, as well as to investigate robustness of the accounting methodologies and its ability to factor out the direct human-induced effect against varying temperature in future.

2 Materials and methods

2.1 Overview of the simulation experiment

The SOC stock change simulation system we developed recently (Yagasaki and Shirato, 2013) was used to simulate future SOC stock change in agricultural lands in Japan. Details on the basic framework of the simulation system, as well as spatial and temporal inventories of soil, climate, land-use change, and agricultural activity for a historical period, were described in Yagasaki and Shirato (2013). In this study, we created future scenarios of agricultural activity, land-use changes and, together with selected future climate projections by GCMs, applied them to run the simulation system to estimate future potential of SOC sequestration at country scale, as described below in detail. Schematic diagram of the system was shown in Fig. 1.

2.2 Future agricultural activity scenario

Two future agricultural activity scenarios for 2009–2020 were created in this study, as described below in detail:

1. MAFF-BP: A scenario employing various agricultural policy targets in 2020, defined in the Basic Plan for Food Agriculture and Rural Areas (Ministry of Agriculture Forestry and Fisheries, 2005) advocated by the Ministry of Agriculture Fishery and Forestry (MAFF)

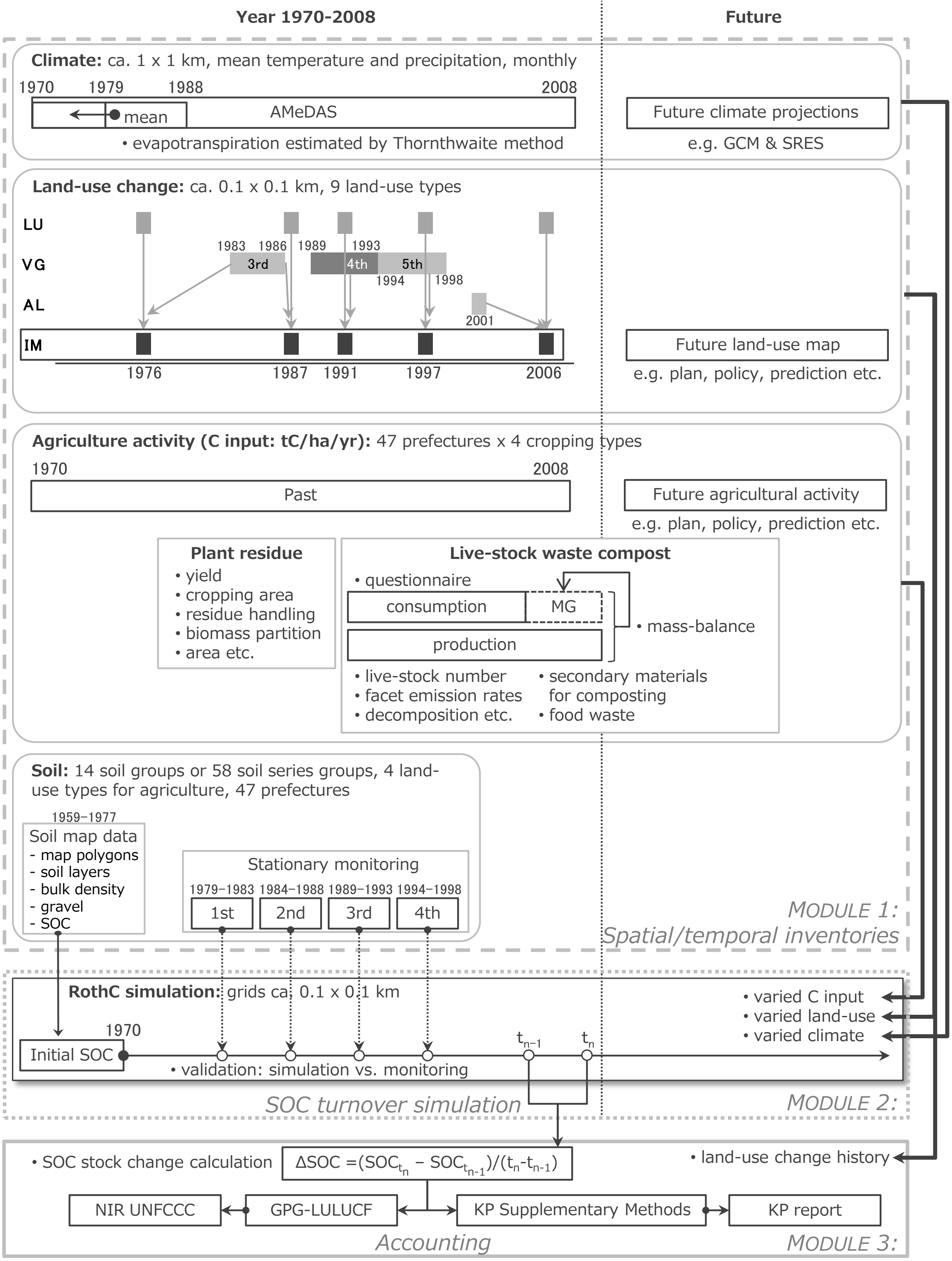


Figure 1. Schematic diagram of the system developed to simulate soil carbon stock change at country-scale using spatially explicit inventories on land-use change, climate, soil, and agricultural activity. The system is designed to be capable to simulate both historical and future soil organic carbon stock change, provided that spatial and temporal inventories are continuous or have appropriate time interval. See the text and Supplement for detail descriptions on other abbreviated text in figures; SOC: soil organic carbon: LU – land-use map, VG – vegetation map, AL – agricultural field map, IM – interpreted land-use/land-cover map, MG – managed grasslands, GCM – Global Climate Models, SRES – Special Report on Emission Scenarios of IPCC, KP – Kyoto Protocol, NIR – National Inventory Report.

of the government of Japan. This scenario employs intensified rotation as well as increase in cropping area as main strategies to increase food self-sufficiency rate of Japan. Other targets includes cropping area and yield of major crops, vegetables, fruits, and forages, as well as number of livestock. Whereas the rate of livestock waste compost applications in each cropping system during 2009–2020 was assumed to keep the same level as that in 2008. Conversion of agricultural fields to other land-use types was assumed to be suppressed and subject to occur only 18 000 ha in 2007–2020.

2. BAU: Business-as-usual scenario, assuming recent trend in the changes in cropping area, yields, livestock number, as well as area of agricultural lands, will also just continue in future. For this scenario, linear extrapolation was applied to set levels of cropping area and yields in each year between 2009 and 2020. In addition, this scenario assumes decline in the rate of livestock waste compost application in each cropping system since 2008 at a rate of $-1\,\%$ annually during 2009–2020. Conversion of agricultural fields to other land-use types in 2007–2020 was assumed to have occurred at a much greater extent compared with that assumed in MAFF-BP scenario, in total 404 000 ha (i.e. 8.7 % of agricultural fields in 2006).

For each of these scenario, average annual rates of organic carbon input to soils during 2009–2020 were estimated for four different land-use types of agricultural lands (paddy fields, upland crop fields, orchards, and managed grasslands) in each of 47 prefectures. For this estimation we used a calculation toolkit named DTK (after *Dojo tanso kun*, in Japanese), which was originally developed by Agricultural Production Bureau (APB) of MAFF, comprised of a collection of spread sheets with stratified calculation modules. The DTK contains data tables for national agricultural statistics (e.g. yields, cropping area, etc.), survey data on material flow including treatment of plant residue and livestock waste by farmers, and physicochemical properties of plant biomass including decomposition rate during composting. Various parameters related to details of organic matter cycling in agro-ecosystems, such as treatment of livestock waste or handling of plant residues, were taken into account in the calculation. Also, one of the modules in DTK has the function of estimating average annual rates of organic carbon input to soils based on future policy targets or predictions on above-mentioned quantities, though at country-level. In the DTK, shares of the country-level future targets or predictions on certain quantity (e.g. increased area of managed grasslands in 2020) had been allocated to different 47 prefectures by proportional distribution based on the level of this quantity in 2006 by simply assuming an equal rate of changes in each prefecture, instead of by assessing potentials and capabilities in each prefecture. Another module in DTK has a function to estimate the sum of the amount of produced and/or consumed organic amendments in Japan, such as livestock waste compost and plant residues, and to check the balance between the two. We used this module to check mass balance of organic matter in future agricultural activity scenarios, e.g. whether there will be enough amount of available livestock waste compost to be applied to a certain type of cropping, under a scenario to increase cropping area while keeping the level of application rate of livestock waste compost in this cropping system.

Details on the key quantities in future agricultural activity scenarios as well as the methodology employed in the DTK including equations used for the calculations, are shown in Supplement.

2.3 Future land-use change

Spatially explicit future land-use maps at 2020 were created to be consistent with the areas of lands under agricultural usages (paddy fields, upland crop fields, orchards, and managed grasslands) defined in the future agricultural activity scenario as either policy targets or predictions. As the information on the future changes in the area of these four land-use types in the future agricultural activity scenarios were not spatially explicit, we needed to make some assumptions on geographical location of the occurrence of land-use change and to create a set of computational programs for this operation. A module comprised of a set of functions written in PL/pgSQL, a procedural language for PostgreSQL (PostgreSQL Global Development Group, 2013), was developed to create a future land-use map using (A) a current (latest) land-use map in 2006, and (B) a set of land-use change matrices for 2006–2020 in future that were created to be consistent with the targets or predictions on the areas of those four land-use types defined in the future agricultural scenarios. This module can perform (1) grouping for grid cells in land-use map in 2006 by land-use type and agricultural commune to create unit geographic entity to be handled in generation of land-use change, (2) sorting the unit geographic entity by assigning an order as an index of the likeliness of land-use conversion to occur (pressure of land-use conversion) based on arbitrary properties of the unit geographical entity (e.g. distance from street or railway station, area, land price, zoning regulations, soil properties, etc.), and (3) proceeding conversions of land-use type by the assigned order until cumulative sum of converted area will have approached the figures prescribed in the land-use change-matrix. In this study, we used the area of unit geographic entity as index of land-use conversion pressure by simply assuming the smaller unit will have greater pressure of land-use conversion, for simplicity. Different land-use change matrices were prepared for each of three different groups of lands under different zoning regulations in Japan to control farmland conversion and urbanization.

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

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

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

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

In addition, the land-use change module was applied to modify each of the five land-use maps created for 1976, 1987, 1991, 1997, and 2006 in a historical period with arbitrary formulated land-use change matrices so that area of paddy fields, upland crop fields, orchards, and managed grasslands to be in a good agreement with corresponding figures reported in national agricultural statistics.

Year of land-use conversion was assigned for each of the unit geographic entities for land-use change by generating uniform random number, which was employed to lead interpolation of total area of each land-use in intermittent years between years of two consecutive but discontinuous maps.

The details on the method to create spatially explicit future land-use map with specified land-use area target, or predictions, we developed is shown in Supplement.

2.4 Future climate

For future climate data, global climate model (GCM) projections with SRES scenario for 2009-2099 was used. The data sets had been down-scaled to $1/120° \times 1/80°$ $(30\,\text{s} \times 45\,\text{s})$, along latitudinal and longitudinal lines, respectively (Okada et al., 2009; Seino, 1993). The size of the grid cell is equivalent to a parcel of land with an area of ca. $1\,\text{km}^2$ (100 ha).

For 2009–2099, we aimed to select two GCM climate projections holding highest and lowest mean annual temperature during 2013–2020 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 investigate methodological issue on how to factor out the direct human-induced effect (i.e. changes in agricultural activity and land-use) in the accounting of CO_2 emission or reduction due to SOC stock change, in addition, to assess sensitivity of the simulation system. As result, MIROC-H & A1B, and FGOALS & B1 were selected, with average of 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.

2.5 Experimental design of simulation

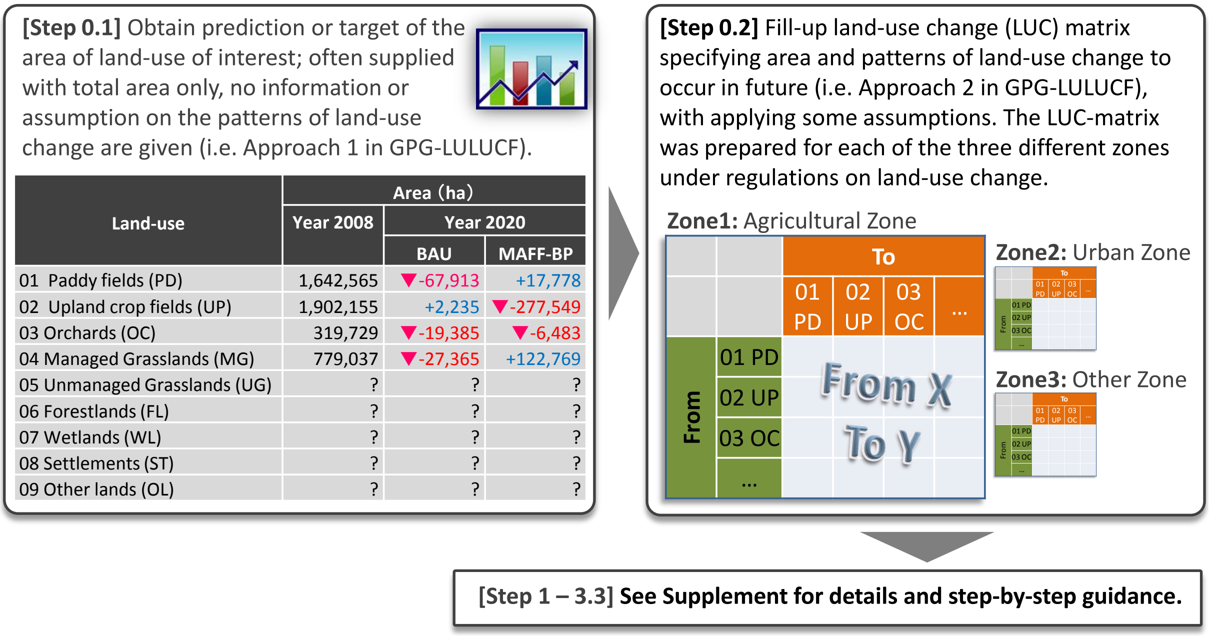
For 2009–2020, the simulation was run with the future scenario of agricultural activity and land-use change described earlier (Fig. 2). After 2020, a simulation was run while forcing no temporal changes in both agricultural activity and land-use occurring until 2099, that is, keeping the rate of organic matter input and land-use as same as those in 2020 (Fig. 2). This setting was employed in order to investigate duration and course of SOC sequestration in relation to assessment on the effect of agricultural policy implementation in future.

2.6 Accounting CO_2 removals and emissions

Accounting on CO_2 removal and emission due to SOC stock change was conducted for a sequence of eight periods with 10-year duration in each (e.g. year 2007–2017, 2017–2027, etc.) during 2007–2097. The rate of SOC stock change for each period, in $\text{Mg}\,\text{C}\,\text{yr}^{-1}$, was calculated by comparing changes in the size of SOC stock at the end of each period with that in the beginning. Using the rate of SOC stock change, we applied the following two methods for accounting CO_2 removal from or emission to the atmosphere due to SOC stock change, with different objectives:

> Objective 1: to assess combined effect of climate, agricultural activity, land-use change in future scenario. Regarding 1985–1995 as base period, a “net-net based” accounting employed in Article 3.4 of Kyoto Protocol (United Nations Framework Convention on Climate Change, 1998) was applied by comparing net emissions and removals from all agricultural lands in Japan (land-based) during a commitment period with emissions and removals during the base period (Schlamadinger et al., 2007).
>
> Objective 2: factoring out effect of measures (e.g. policy implementation). “Baseline based” accounting was employed by subtracting CO_2 emission or removal in “baseline scenario”, created with the 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 the same scenario of climate and land-use change.

Note that, in this study, we employed only land-based accounting for both net-net-based accounting and baseline-based accounting. Activity-based accounting employed in commitment of Kyoto Protocol, defined in “Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol” in Chapter 4 of GPG-LULUCF (Intergovernmental Panel on Climate Change, 2003), was not employed in this study to avoid any misleading interpretation on SOC stock change, as this method allows one to deal with an



[Step 0.1] Obtain prediction or target of the area of land-use of interest; often supplied with total area only, no information or assumption on the patterns of land-use change are given (i.e. Approach 1 in GPG-LULUCF).

Land-use	Area (ha)		
	Year 2008	Year 2020	
		BAU	MAFF-BP
01 Paddy fields (PD)	1,642,565	▼-67,913	+17,778
02 Upland crop fields (UP)	1,902,155	+2,235	▼-277,549
03 Orchards (OC)	319,729	▼-19,385	▼-6,483
04 Managed Grasslands (MG)	779,037	▼-27,365	+122,769
05 Unmanaged Grasslands (UG)	?	?	?
06 Forestlands (FL)	?	?	?
07 Wetlands (WL)	?	?	?
08 Settlements (ST)	?	?	?
09 Other lands (OL)	?	?	?

[Step 0.2] Fill-up land-use change (LUC) matrix specifying area and patterns of land-use change to occur in future (i.e. Approach 2 in GPG-LULUCF), with applying some assumptions. The LUC-matrix was prepared for each of the three different zones under regulations on land-use change.

[Step 1 – 3.3] **See Supplement for details and step-by-step guidance.**

Figure 2. Schematic illustration of the beginning part of the procedures developed to create spatially explicit future land-use map based on the latest land-use map and land-use change matrices that contains information on land-use conversions in the future.

unequal size of land area between base year and commitment period.

3 Results

3.1 Agricultural activity in 2009–2020

Land-use change during 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 2007 to 2020, 166 000, 129 000, 58 000, and 51 000 ha of paddy fields, upland crop fields, orchards, and managed grasslands, respectively, were converted to settlements or unmanaged grasslands, depending on land-use change scenario, urbanization, and abandonment, respectively (Fig. 3). Whereas in MAFF-BP, 60 000 ha and 55 000 ha of upland crop fields were converted to paddy fields and managed grasslands, respectively, from 2007 to 2020. In addition, 4000 ha of orchards was converted to managed grasslands. Another 18 000 ha of orchards was converted to settlements or unmanaged grasslands depending on land-use change scenario urbanization and abandonment, respectively (Fig. 3).

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 2008 to 2020 was characterized by (1) increase in manure input in managed grasslands (130 % in 2020 compared with 2008), and (2) decrease in manure input in paddy fields, upland crop fields, and orchards (86–87 % in 2020 compared with corresponding values in 2008) (Fig. 4a), due to the decline in manure application rates in paddy fields, upland crop fields, and orchards which led to an increase in the manure application rate in managed grasslands by receiving a surplus of produced manure as calculated by the mass-balance estimation.

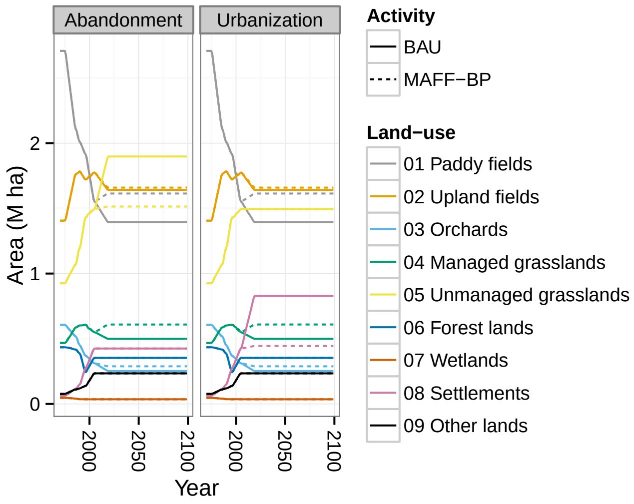


Figure 3. Temporal changes in the area of different land-use types in agricultural lands of Japan under different scenarios of future agricultural activity (indicated as different line type) and future land-use change (lined-up horizontally) employed in the simulation, in a historical (year 1970–2006) period, future scenarios with varying land-use change in 2007–2020, and subsequent future period in 2021–2099 with assuming no land-use change.

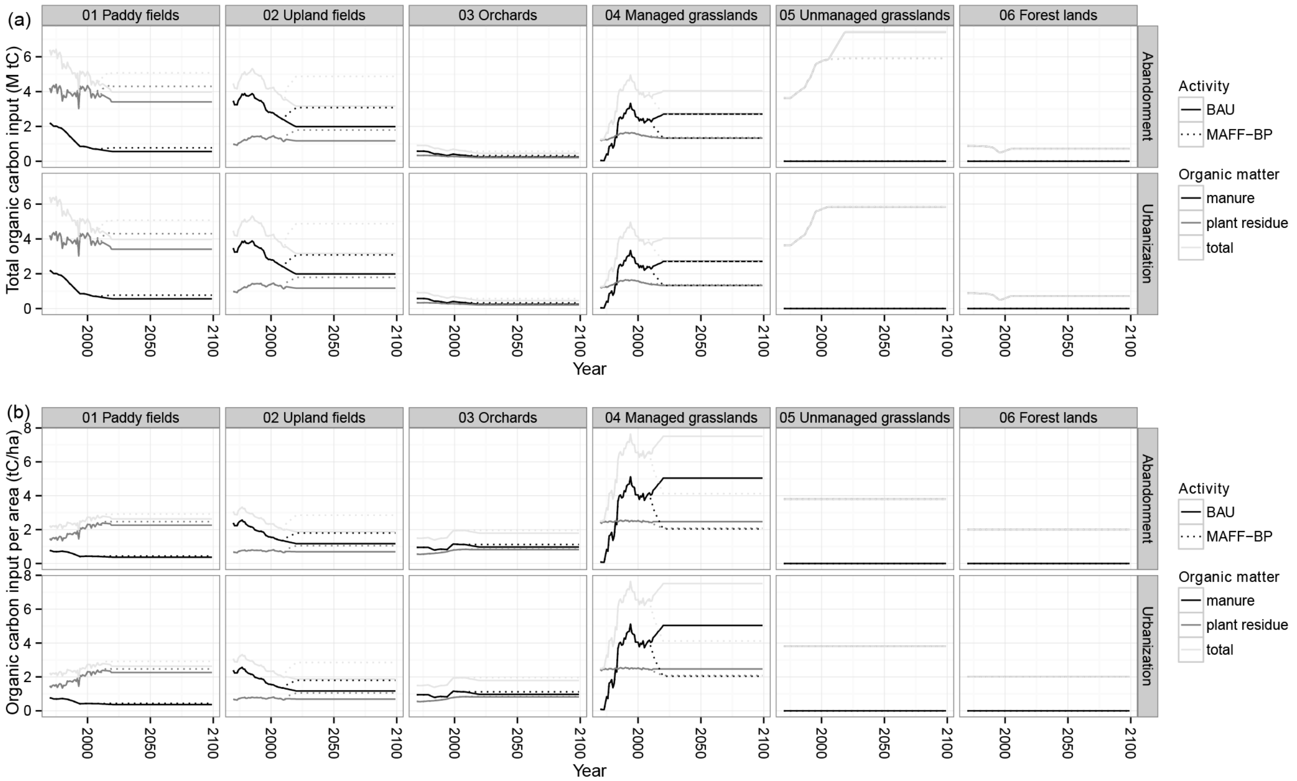


Figure 4. Input of organic carbon to soils expressed as annual total sum **(a)** and annual input rate per unit area of soils **(b)** in different land-use types (lined up horizontally) under different scenarios of future land-use change (abandonment and urbanization; lined-up vertically) in periods including historical (1970–2006), future scenarios during 2007–2020 with varying input rate toward target or predicted levels in 2020, and subsequent future period in 2021–2099 with assuming no change in input rate after 2020. Overall input (sum of plant residue, manure, slurry and excreta), plant residue, and sum of manure, slurry, and excreta are indicated in very light gray, light gray, and black colour, respectively. Solid and dashed line indicates future agricultural activity scenario BAU and MAFF-BP, respectively.

In MAFF-BP scenario, the change was a direct antithesis of that in BAU and was characterized by (1) a decrease in manure input in managed grasslands (49 % in 2020 compared with 2008), (2) increase in manure input in paddy fields and upland crop fields (105–132 % in 2020 compared with 2008), and (3) no major change in orchards (Fig. 4a). Intensification in cropping in paddy fields and upland crop fields (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 paddy fields and upland crop fields led to a decline in manure application in managed grasslands as calculated by the mass-balance estimation.

On a total mass basis, in 2020 with future land-use change scenario of urbanization, soils in agricultural area of Japan under MAFF-BP scenario received 1438 Gg of more organic carbon than that under BAU scenario (Table 1 and Fig. 5). Whereas those with future land-use change scenario of abandonment, difference in the organic carbon input between MAFF-BP and BAU was only very small. Greater input of organic carbon estimated for abandonment scenario compared with urbanization scenario found in the future agricultural activity scenario MAFF-BP was due to the difference in the assumed input rate of plant residue per unit area of soils in unmanaged grasslands and settlements combined with the difference in area of settlements and unmanaged grasslands between these two scenarios. Whereas for manure, the amount of organic carbon input to soils were found to be at a similar level in both MAFF-BP and BAU scenarios (see the Supplement for details).

3.2 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 1970 to 2008 (Fig. 6). This trend did not change even after 2008 and continued until 2099.

After 2008 with future scenarios, relatively larger differences in SOC stock were found between future climate projections FGOALS & B1 and MIROC-H & A1B compared with those found among different scenarios of future land-use change and agricultural activity with the same future climate projections (Fig. 6). The SOC stock with the amount of 467 Tg C in 2000 decreased to a level ranging from 399 to

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

							BAU[4]		MAFF-BP[4]	
	1970	1980	1990	2000	2008	LUC[3]	2020		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 2008.

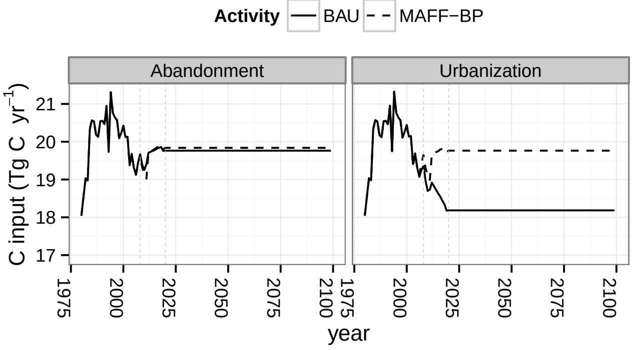


Figure 5. Input of organic carbon to soils expressed as annual total sum for all land-use types under different scenarios of future land-use change (abandonment and urbanization; lined-up horizontally) in periods including historical (1970–2006), future scenarios during 2007–2020 with varying input rate toward target or predicted levels in 2020, and subsequent future period in 2021–2099 with assuming no change in input rate after 2020. Solid and dashed line indicate future agricultural activity scenario BAU and MAFF-BP, respectively.

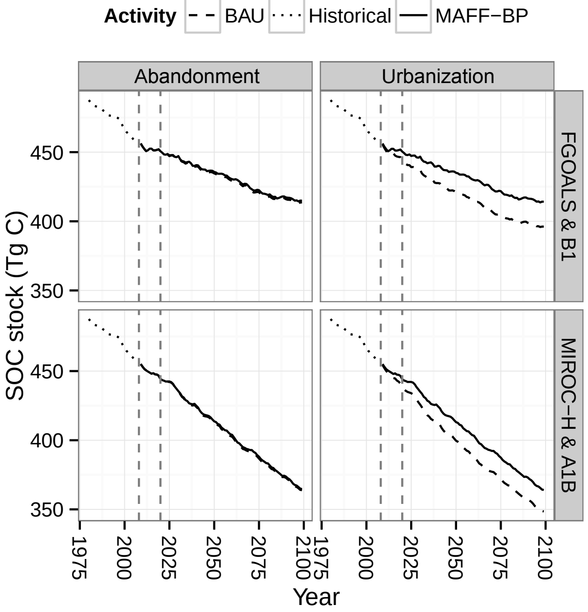


Figure 6. Simulation output on the changes in total soil organic carbon (SOC) stocks in agricultural lands in Japan under different future agricultural scenarios (BAU and MAFF-BP; indicated by different line type), future land-use change (abandonment and urbanization; lined up horizontally), and future climate projection (FGOALS & B1 and MIROC-H & A1B; lined up vertically), in periods including historical (1970–2006), future scenarios during 2007–2020 with varying input rate toward target or predicted levels in 2020, and subsequent future period in 2021–2099 with assuming no change in input rate after 2020. Vertical dashed line on the left and right indicate 2006 and 2020, respectively.

417 Tg C and another level ranging from 358 to 374 Tg C in 2090, under future climate projections FGOALS & B1 and MIROC-H & A1B, respectively, with different scenarios on future land-use change and agricultural scenarios (Fig. 6).

In the period after 2008 with future agricultural activity scenario MAFF-BP, changes in the rate of apparent SOC stock change were characterized by (1) a rapid decline in the rate of apparent SOC loss in upland crop fields (Fig. 7) due to decline in the area (Fig. 3) combined with increase in the annual organic carbon input rate (Fig. 4a), (2) decline in the rate of apparent SOC loss in both settlements and other lands (Fig. 7) due to termination in the area expansions of both land-use types that had been proceeding since 1980 until 2008 (Fig. 3), and (3) a sharp decline in the rate of apparent SOC gain in managed grasslands (Fig. 7) due to a sharp decline in annual input of organic carbon (Fig. 4a). Whereas the changes in the rate of apparent SOC stock change with future agricultural activity scenario BAU were characterized by (1) a rapid decline in the rate of apparent SOC loss in

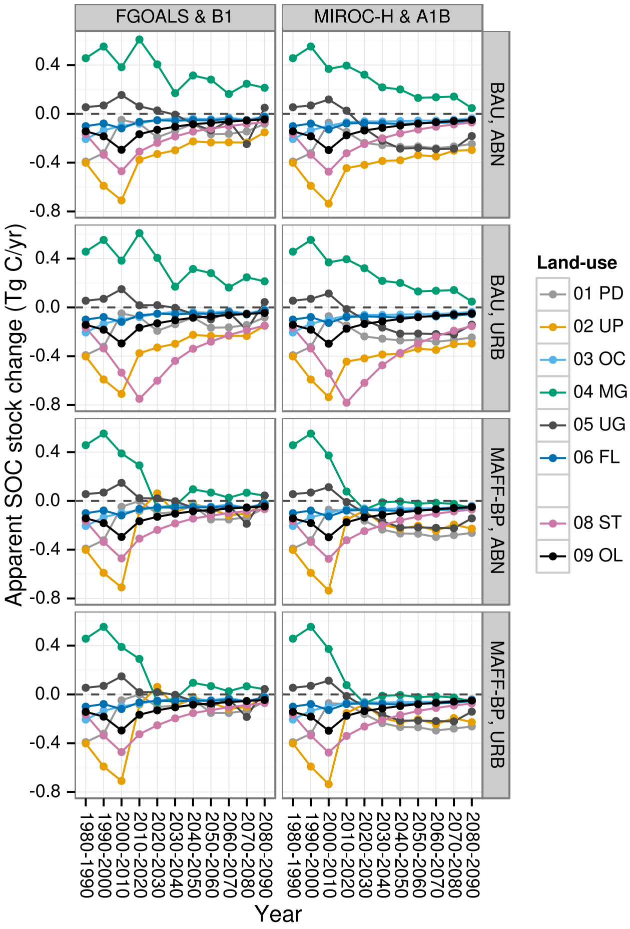


Figure 7. Rate of apparent soil organic carbon (SOC) stock changes in different land-use types under different future climate projections (FGOALS & B1 and MIROC-H & A1B; lined-up horizontally) and combinations of future agricultural activity scenarios (BAU and MAFF-BP) and future land-use change scenarios (ABN – abandonment, URB – urbanization) (lined-up vertically). Lines in different colour indicate different land-use types: PD – paddy fields, CL – upland crop fields, OC – orchards, MG – managed grasslands, FL – forest lands, WL – wetlands, ST – settlements, OL – other lands. Positive and negative values on vertical axis indicates gain and loss of SOC stock, which are equivalent to CO_2 removal from and emission to the atmosphere, respectively.

upland crop fields, similarly to that with MAFF-BP (Fig. 7), (2) decline in the rate of apparent SOC loss in settlements and other lands began from 2010–2020, except settlements with future land-use change scenario of urbanization that showed a negative greatest peak in 2010–2020 followed by decline (Fig. 7), and (3) a gradual decline in the rate of apparent SOC gain in managed grasslands (Fig. 7) affected by decline in the area despite of an increase in annual input of organic carbon (Fig. 4a).

3.3 Net-net accounting on SOC stock change

The rate of SOC stock change in 1985–1995 was found to be negative, around 0.72 $\mathrm{Tg\,C\,yr^{-1}}$ (Fig. 8) (i.e. emission of 2.64 $\mathrm{Tg\,CO_2\,yr^{-1}}$). In 2007–2097 (future period) under future climate scenario MIROC-H & A1B, the rate of SOC stock change ranged from -0.69–-1.72 $\mathrm{Tg\,C\,yr^{-1}}$, showing greater rate of SOC loss in most of the periods compared with the 1985–1995 regardless of differences in future scenarios of agricultural activity or land-use change. With regarding the 1985–1995 as base period, therefore, net-net accounting on CO_2 removal from or emission to the atmosphere due to SOC stock change in 2007–2097 mostly resulted in a net emission of CO_2 under future climate scenario MIROC-H & A1B. Whereas the net-net accounting with future climate scenario FGOALS & B1 in 2010–2090 mostly resulted in removal from the atmosphere, due to relatively smaller rate of SOC loss compared with the base period (Fig. 8).

The SOC stocks with a future land-use change scenario of abandonment showed little differences between future agricultural scenario MAFF-BP and BAU (Fig. 8). Whereas those with future land-use change scenario of urbanization showed large differences between these two future agricultural scenarios. Also, somewhat smaller levels of the rate of SOC loss were found in the latter period, compared with those in the earlier period, in common with all scenarios of future climate, future land-use change, and future agricultural activity (Fig. 8).

3.4 Baseline accounting on SOC stock change

In baseline accounting, relative reduction of CO_2 emissions were found only in cases with future land-use change scenario of urbanization throughout the entire period regardless of different scenarios of future climate, due to a greater rate of SOC loss in BAU defined as baseline scenario, compared with that in MAFF-BP (Fig. 9 and Table 2). Whereas in cases with a future land-use change scenario of abandonment, baseline accounting resulted in relative CO_2 emissions at around zero or a small size due to slightly smaller SOC loss rate found in BAU compared with that in MAFF-BP (Fig. 9 and Table 2). Differences in the relative reduction of CO_2 emission between two future climate scenarios were only small compared with differences found between two future land-use change scenarios (Fig. 9 and Table 2).

In cases with future land-use change scenario of urbanization, a sharp increase in the relative reduction of CO_2 emissions were found in 2000–2020. This reduction was followed by the greatest relative reduction of CO_2 emission around 0.44–0.45 $\mathrm{Tg\,CO_2\,yr^{-1}}$ in 2017–2027, and subsequent gradual decline which continued until 2087–2097. Compared with this greatest level of relative reduction of CO_2 emissions found in 2017–2027, the relative CO_2 removal in subsequent periods declined continuously and substantially to

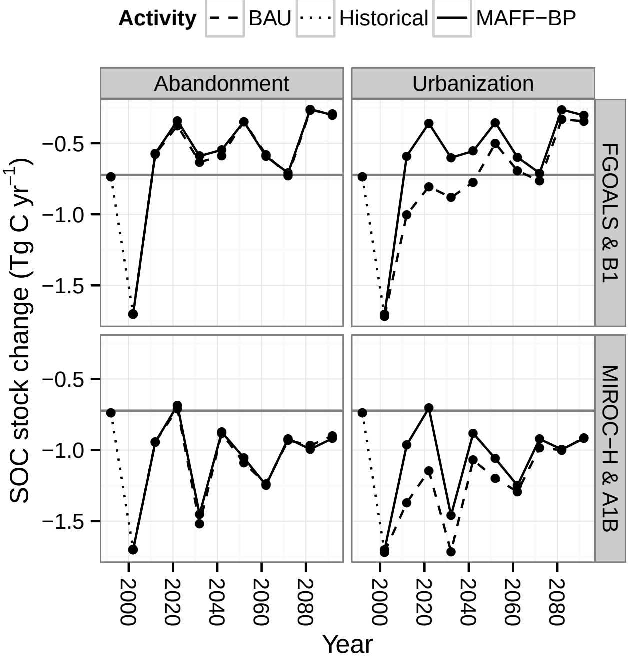


Figure 8. Changes in soil organic carbon (SOC) stock in agricultural lands in Japan under different future agricultural activity (BAU and MAFF-BP; indicated by different line types), future climate projections (FGOALS & B1 and MIROC-H & A1B; lined up vertically), and future land-use change scenarios (abandonment and urbanization; lined up horizontally). Solid and broken line indicates future agricultural activity scenario BAU and MAFF-BP, respectively. Gray horizontal line indicates the rate of SOC stock change in 1990 (mean of 1985–1995; $-0.72\,\mathrm{Tg\,C\,yr^{-1}}$).

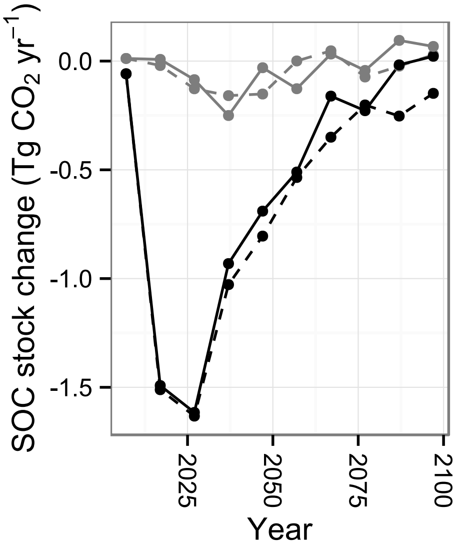


Figure 9. Relative changes in soil organic carbon (SOC) stock in agricultural lands in Japan obtained by baseline-based accounting defined as differences in estimated changes in SOC stock between two different future agricultural activity scenarios, MAFF-BP and BAU, with regarding BAU as baseline scenario (i.e. MAFF-BP minus BAU). Negative and positive value on vertical axis indicates relative removal and emission, respectively, of CO_2. Solid and dashed line indicates future climate projections, MIROC-H & A1B and FGOALS & B1, respectively. Gray and black colour indicates future land-use change scenario, abandonment and urbanization, respectively.

63–58 %, 32–33 %, and 12–14 %, in 2027–2037, 2047–2057, and 2067–2077, respectively (Table 2).

4 Discussions

4.1 Historical trend and future changes

The overall trend of the estimates on aggregate SOC stock in agricultural lands in the country showing continuous decrease both in historical and future periods (Fig. 6) indicates that (1) the changes in aggregate SOC stock act as a net source of CO_2 rather than a sink, and that (2) the magnitude of the emission of CO_2 will basically decrease over time at long timescale, despite different settings for organic matter input in future scenarios. The latter statement can also be supported by overall trend in SOC stock change estimated for a sequence of 10 periods (Fig. 8) showing a smaller rate of SOC loss in the later stage of the future period compared with that in the earlier period. In addition to these overall trends, in a shorter timescale, however, effects of changes in organic matter input to soils on the aggregate SOC stock change were found. In the historical period, an increase in the magnitude of aggregate loss of SOC was found, which was attributed to a large conversion of agricultural fields (paddy fields, upland crop fields, orchards, and managed grasslands) to settlements or other lands (Fig. 3) that led to decline in the overall rate of organic carbon input to soils, as well as to conversion of paddy fields to upland crop fields occurred from 1970s to 2008 (Fig. 3) that led to enhancement of SOM decomposition under aerobic conditions. Relatively rapid declines in the loss of SOC, found between 1997–2007 and 2007–2017 (Fig. 8) were considered to be attributed to termination of the land-use conversions from agricultural fields to settlements or other lands (Fig. 3).

4.2 Soil carbon sequestration potential under different future scenarios

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 abandonment) would archive the same level of reduction of CO_2 emissions by SOC stock change compared with another option to pay for an effort to intensify crop rotations with preventing agricultural fields from conversion to other land-use types (i.e. MAFF-BP with abandonment) (Figs. 8 and 9). Relative advantage

Table 2. Accounting of CO_2 removal from or emission to the atmosphere due to soil organic carbon stock change evaluated with baseline method for a sequence of 10 periods with 10-years duration in each from 2007 to 2097 under different future scenarios of climate and land-use change (unit: $\mathrm{Tg\,CO_2\,yr^{-1}}$). 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 urbanization (URB), numbers in parenthesis indicate percentage values compared with the level in 2017–2027 that held the greatest removal of CO_2 in entire period.

	FGOALS & B1[1]			MIROC-H & A1B[1]		
Year	ABN[2]	URB[2]		ABN[2]	URB[2]	
2007–2017	0.01	0.41		0.00	0.41	
2017–2027	0.03	0.45	(100)	0.02	0.44	(100)
2027-2037	0.04	0.28	(63)	0.07	0.25	(58)
2037–2047	0.04	0.22	(49)	0.01	0.19	(43)
2047–2057	0.00	0.15	(33)	0.03	0.14	(32)
2057–2067	−0.01	0.10	(21)	−0.01	0.04	(10)
2067–2077	0.02	0.06	(12)	0.01	0.06	(14)
2077–2087	0.01	0.07	(15)	−0.03	0.00	(1)
2087–2097	−0.01	0.04	(9)	−0.02	−0.01	(−1)

[1] Future climate projections by global climate models (GCMs) with future scenarios of greenhouse gases emission (SRES).
[2] Future land-use change scenario; ABN – abandoning, URB – urbanization. For details about each scenario, see the text.

of the MAFF-BP over BAU would be realized only in case when large conversion of agricultural fields to settlements is prevented, as shown with future land-use change scenario of urbanization (Figs. 7 and 9).

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 unmanaged grasslands and settlements 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 the model simulation.

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 and Jenkinson, 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). By making use of such a 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 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 that has a greater climate mitigation potential with an intention of policy implementation requires estimating the total GHGs budget including emission of N_2O and CH_4 from agricultural activity to take account of 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 SOC stock change between cases with different future climate projections (Fig. 8), despite that they were purposely selected to have largest difference in temperature during 2009–2020 among other climate projections, strongly suggests that this approach is robust over variations in future climate and is effective to factor out some of direct human-induced influences (e.g. different agricultural activity and land-use change scenarios in our simulation study). 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, for example, analysis of marginal abatement costs on various climate change mitigation options, as well as 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 be paid on a methodological issue that application of this approach alone is susceptible on methodologies on how to draw a baseline scenario; nevertheless, the potential of this approach to factor out some of direct human-induced influences, even at country-scale with greater heterogeneity of soils, climate, and agricultural activities, still deserves attention.

4.4 Course of soil carbon sequestration

In cases with future land-use change scenario of urbanization, a continuous decline in relative reduction of CO_2 emission due to SOC stock change found in the period after 2017–2027 while keeping the same size of organic matter input enhancement (Fig. 9 and Table 2) should be regarded as a course of SOC approaching to a steady state. 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, for example, the first commitment period of Kyoto Protocol (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 years and 40-45 years, respectively. Therefore, assessment on these quantitative properties of the course of SOC sequestration should be adequately performed and taken into consideration if a policy maker or land-manager plans to include the SOC sequestration to meet an 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 with future land-use change scenario of urbanization, while agricultural lands in Japan would gain about 0.41–0.45 $\mathrm{Tg\,C\,yr^{-1}}$ (i.e. 1.50–1.65 Tg of $\mathrm{CO_2\,yr^{-1}}$) as peak emissions reduction in 2007–2017 and 2017–2027 by a full implementation of MAFF-BP scenario, other measures having GHGs reduction potential of 0.26–0.31 $\mathrm{Tg\,CO_2}$ would inevitably need to be fully implemented by 2047–2057.

4.5 Feasibility of future scenario

It should be noted that the result of accounting on $\mathrm{CO_2}$ 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 (2020) that might be rather challenging in terms of feasibility. For example, the goal of food self-sufficiency rate in 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 (MAFF, 2005, 2010). In other words, feasibility of MAFF-BP implementation, or timing of its completion, is probably the most important factor that would have a critical impact on the course of SOC sequestration presented in this study.

In MAFF-BP, increase in cropping area of major crops (Fig. 3) as well as intensification of annual cropping per unit area of fields in paddy fields and upland crop fields while introducing efficient rotation is a major factor that lead to an increase in the rate of plant residue input to soils (Fig. 4a and b) and subsequent reduction in $\mathrm{CO_2}$ emission from soils (Figs. 6 and 9). For these measures, any low level of achievements, if significantly far from the target, would inevitably cause decline in the reduction of $\mathrm{CO_2}$ emission compared with the figures presented in this study.

In addition, 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 settlements or other lands in the future period 2009–2020 were assumed to occur rather small extent compared with trend observed in recent decades (Fig. 3). With taking into account a major finding in our simulation study that conversion of agricultural lands to settlements or other lands would became a major cause of increased SOC loss rate found in recent and future periods compared with that in period around 1990 (Fig. 7), it is considered that underestimation in this type of land-use conversion, if any and significant, would result in large overestimation of SOC stock in the future period, particularly in Japan's case.

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 SOC stock change 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 2020.

4.6 Uncertainties

With regard to sources of uncertainty in the system, we developed to predict SOC stock changes 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 SOC stock change 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.

With regard to uncertainty of our estimation on the potential of future SOC sequestration, we performed only a limited number of simulations with scenarios of agricultural activity that were calculated while employing only mean, rather than probability distribution function, of each parameters. A lack of a full implementation of uncertainty analysis using Monte Carlo simulations may rate the assessment of our current study as preliminary, especially when the findings by Koga et al. (2011) are taken into consideration.

As for model application on lands with varying land-use, the assumption that SOC in soil in settlements and other lands only continues declining while allowing no organic matter input to soils and keeping decomposition proceeding the same as upland crop fields, managed grasslands, or unmanaged grasslands does not have enough support from evidence and thus may need to be further study. Several studies have argued that SOC stock in urban areas are likely to be 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 settlements and other lands in 2000–2010 were found to be the second and the third largest loss after that in upland crop fields among all land-use types, despite settlements and other lands had much smaller area than paddy fields and upland crop fields. In such case, emissions from these land-use types should be regarded as "key category" emission in reporting of GHGs emissions in the AFOLU sector. Uncertainties in estimation of key emissions categories need to be paid high attention. This may apply also to other countries that have been facing a rapidly growing urbanization with a large-scale conversion of agricultural lands to settlements or other lands in recent decades.

Furthermore, predictive power of RothC_p application for paddy fields 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 a limited numbers of long-term field experiments at this stage (Shirato and Yokozawa, 2005; Shirato et al., 2011). As paddy fields have been holding one of the largest area is among all land-use types in agricultural lands in Japan, even relatively small changes in prediction on the rate of SOC stock change per unit area basis in this land-use category may exert large impact on overall figure of country level estimation of SOC stock change.

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 data set 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 also applies to SOC stock change 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 the statistical survey "Statistics on production cost of rice" conducted by Statistics and Information Department, MAFF, in 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 exerts influence on its balance among different types of agricultural lands (i.e. paddy fields, upland crop fields, orchards, and managed grasslands), 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 managed grasslands.

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 the decomposition rate of secondary materials (e.g. saw dust, bark, etc.) utilized in livestock waste composting, and correspondingly, 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 SOC stock change in a historical period and a much greater effect of the MAFF-BP scenario to reduce CO_2 emission (or even to remove CO_2) at the same time enhanced superiority of increased rate of organic matter input by intensified rotation in a future scenario (data not shown) (Shirato and Yagasaki, 2012a, b, 2013). This highlights the importance of double checking on the amount of organic matter amendment from production side and consumption side to ensure mass balance between the two.

5 Conclusions

With respect to estimation of future potential of SOC sequestration in agricultural lands in Japan, our simulation study clearly demonstrated that it is not only management of or policy implementation for agricultural practices on the agricultural fields but also future land-use change, such as urbanization or abandonment of agricultural fields, which could exert significant influence on the potential of SOC sequestration at country-scale. Conversions of agricultural fields to unmanaged grasslands or settlements should be taken account in assessment of a country-scale future SOC stock change in Japan, facing growing urbanization and abandonment of agricultural fields. An 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-use types, may archive reductions of CO_2 emission due to SOC stock change comparable to that of another option to let agricultural field be abandoned. Application of a base-line-based accounting was found to have robustness over future climate variations and good performance to factor out direct-human influence (i.e. changes in agricultural activity and land-use) on a country-scale SOC stock change.

In addition to uncertainties in estimation of the rate of organic carbon input to soils in different land-use types, other factors, including time course of SOC sequestration, supposition on land-use change pattern in future, and feasibility of agricultural policy planning, were also considered to be taken into account in estimation on a potential of country-scale SOC stock change, especially when intended to assist decision making of policy on agriculture and mitigation of global climate change.

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