Estimation of Soil Carbon Stock Changes in Japanese Agricultural Soils using National Resources Inventory

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Abstract: National soil inventory is a vital tool for estimating changes in soil carbon stocks in arable land. The Basic Soil-Environmental Monitoring Project has been conducted throughout Japan since 1979. This soil monitoring project has repeated 5-year interval on about 20,000 fixed points, and it has been contributing for understanding the changes of soil fertility status in Japan. In this report, changes in soil carbon stocks in Japanese agricultural land during 1979 to 1998 were estimated using this soil inventory. For categorical estimation, soil carbon content (g/kg) and bulk density (0-30 cm) was summarized by soil series group (60 soil series group in Japanese cultivated soil taxonomy) and land use type (paddy field, upland field, grassland, and orchard) in each 5-year interval. The mean residuals of the categorical soil carbon stock estimation showed negative values, and it overestimated of soil carbon stock. Furthermore, the mean residuals of the categorical carbon stock estimation were positively larger in cooler soil temperature zone than in "thermic" or "hyperthermic" soil temperature zone. The spatial pattern of the residuals was mapped using geostatistical method to correct the overestimated and climatic biased categorical estimation method. From this correction, the precision of the carbon stock estimation was increased about 10% in each interval. Soil carbon stock (0-30 cm) in paddy fields and orchard were gradually increased from 76 to 78 tC/ha and from 81 to 87 tC/ha, respectively. In the upland fields and grassland, soil carbon stock showed the peak at third interval. Moreover, total soil carbon stock was gradually increased from 88 to 90 tC/ha. Total soil carbon content in agricultural land was decreased from 469 (1984-1988) to 446 (1994-1998) Tg. During the same period, agricultural land area was decreased from 5.4 to 5.0 million hectares. These results indicated that a decline of carbon stocks in Japanese agricultural soil was mainly influenced by the fluctuation of agricultural land area.
Keywords: Soil carbon stock, Inventory, Hybrid-kriging, Soil classification, Land use

1. Introduction

Important benefits of soil organic matter are closely linked to the facts that it acts as a storehouse for nutrients, that it is a source of soil fertility, and that it contributes to soil aeration, thereby reducing soil compaction (Jones et al. 2003). From a global environmental perspective, soil organic matter of agricultural ecosystem is composed of a substantial part of terrestrial carbon stock (Janzen 1997). Therefore, the dynamics of soil organic matter content has important implications for agricultural production systems and the impacts of global climate change (Jones et al. 2003). A better understanding of spatial and temporal variation of soil carbon stock and the related factors is crusial for improving sustainable land use management and for providing a valuable base against on which subsequent and future managements can be evaluated (Huang 2007). In this report, spatial and temporal variation of soil carbon stocks in Japanese agricultural land during was estimated using soil inventories.

2. Soil Survey and Inventories using in this Report

1) Cultivated Soil Maps and soil area

Cultivated soil maps are basic components of agro-environmental soil inventory in Japan, and it was drawn in a 1: 50,000 scale during the Fundamental Soil Survey for Soil Fertility Conservation (1959-1979). After the survey, those soil maps were digitized, and updated using two versions on agricultural land-use maps (1992 and 2001 versions). The 1992 version of cultivated soil map was shown in Fig. 1 and cultivated soil area is listed in Table 1. Gray lowland soils was the largest cultivated soil area in Japanese agricultural land, and followed by Gley soils, Andosols, Brown forest soils, Brown lowland soils, and Wet Andosols. Urban sprawl and other changes in land use (including abandonment of cultivation) had caused a loss of agricultural land area by 922,700 hectares from 1973 to 2001. Gray Lowlands soils (Fluvisols), Gley soils (Fluvisols), and Andosols mainly had declined during the years. It was clear that urbanization was advanced at flat lowland area (paddy fields) where distributed Gray Lowlands soils and Gley soils. Additionally, declines in the Andosols with expanding urbanization were observed widely over the flat upland fields in Kanto and Touzan district. On the contrary, upland fields sited at steep slope in Kinki, Chugoku, and Shikoku district, where distributed Brown Forest Soils (Cambisols), were mainly changed to abandoned fields (Y. Takata et al. unpublished data).

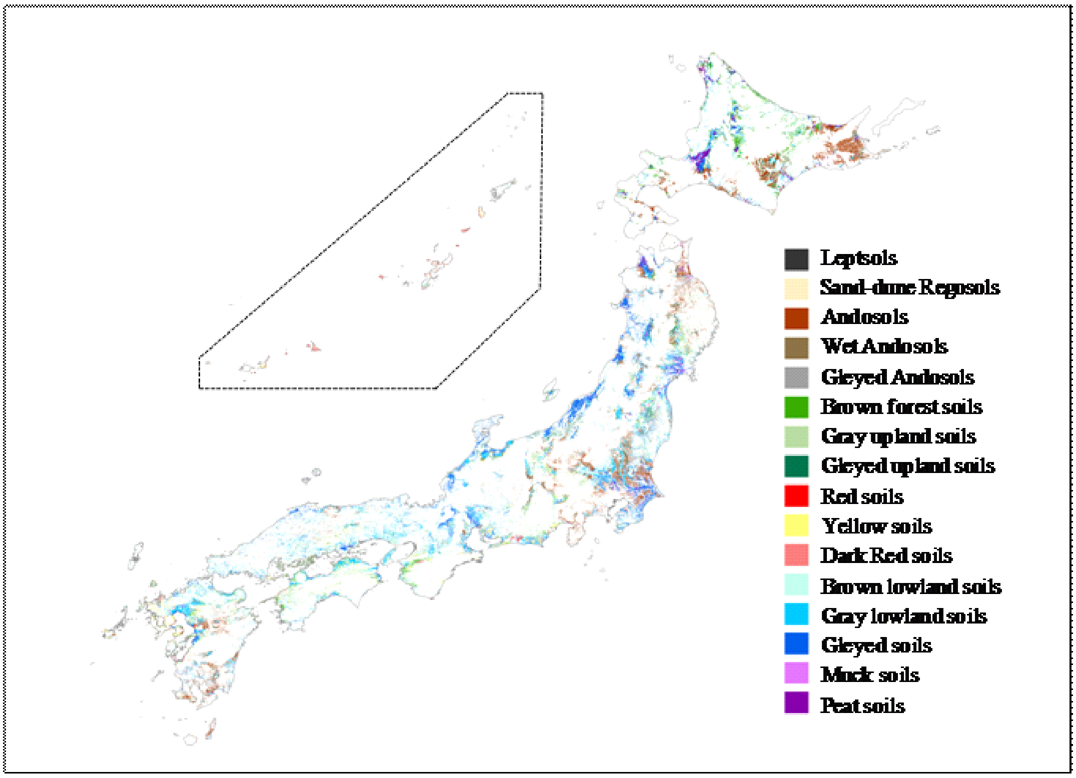

Fig. 1. The 1992 version of cultivated soil map (From Takata et al. 2009)

Table 1. Cultivated soil area in Japan

Soil Group (Japanese classification system)	No. of Soil Series Group	Soil Group (World Reference Base for Soil Resources)	Cultivated soil area (x1000 ha) 1973	1992	2001
Leptosols	1	Leptosols	18.1	5.5	4.4
Sand-dune Regosols	1	Regosols	25.4	20.3	18.7
Andosols	5	Andosols	1007.3	944.5	879.3
Wet Andosols	5	Gleyic Andosols	384.1	419.1	397.5
Gleyed Andosols	3	Gleyic Andosols	51.5	55.1	53.0
Brown Forest soils	3	Cambisols	483.1	426.0	361.9
Gray Upland soils	4	Gley soils, Planosols	181.7	157.2	144.4
Gley Upland soils	3	Gley soils, Planosols	86.2	71.7	61.9
Red soils	3	Cambisols, Acrisols, Alisols	48.7	41.2	36.2
Yellow soils	6	Cambisols, Acrisols, Alisols	360.9	316.1	271.4
Dark Red soils	2	Luvisols, Cambisols	42.3	41.0	37.2
Brown Lowland soils	6	Fluvisols	438.7	407.6	376.0
Gray Lowland soils	9	Fluvisols, Gley soils	1274.9	1157.3	1071.6
Gley soils	7	Fluvisols	1027.3	907.8	848.4
Muck soils	1	Histosols	87.1	71.6	66.6
Peat Soils	1	Histosols	158.0	160.1	161.2
Total			5675.2	5202.0	4789.8

2) Basic Soil-Environment Monitoring Project (Stationary Monitoring)

The Basic Soil-Environmental Monitoring Project has been conducted throughout Japan since 1979. This soil monitoring project has repeated 5-year interval on about 20,000 fixed points (Fig. 2). The following soil properties and agricultural activity are monitored at each location. It has been contributing for understanding the changes of soil fertility status in Japanese agricultural land (Obara 2000; Obara & Nakai 2004; Fig. 3).

a) Soil properties: soil classification, physic-chemical, nutrient, morphology, etc.

b) Agricultural activity: crop yield, manure and fertilizer application, crop rotation, etc.

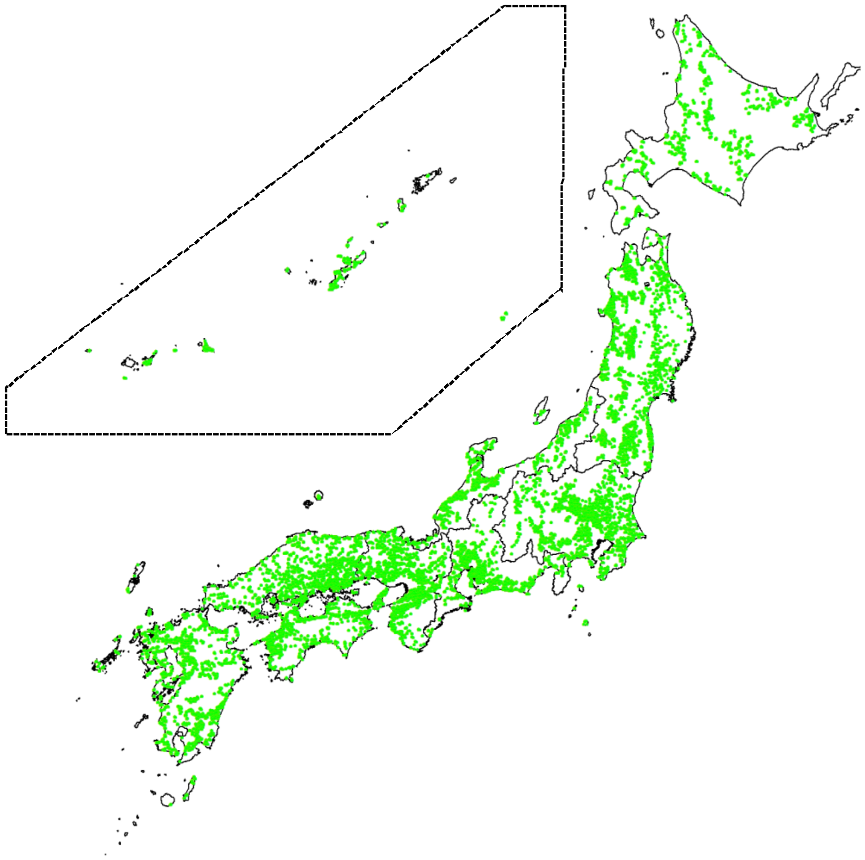

Fig. 2. Location of the monitoring sites of "Basic Soil-Environment Monitoring Project"

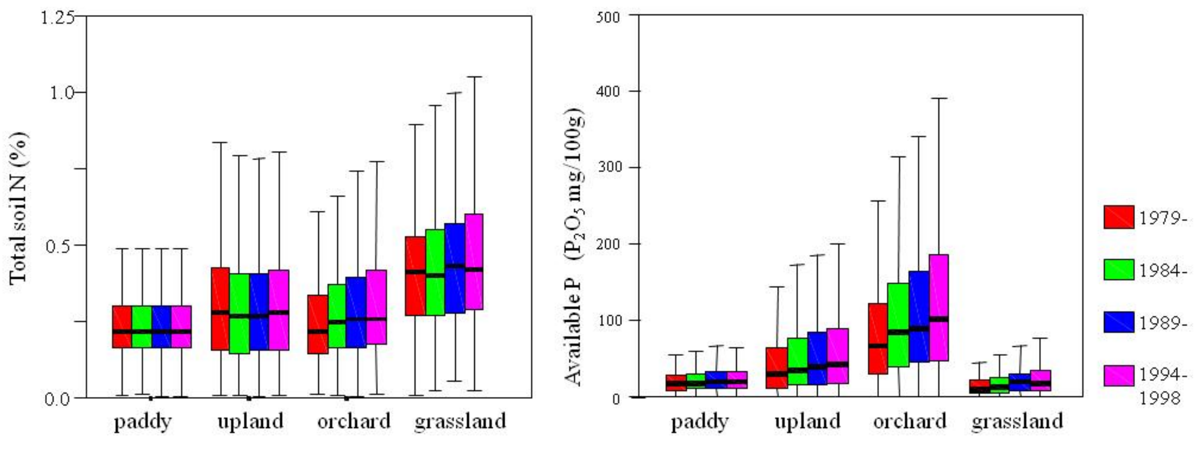

Fig. 3 Changes of total soil nitrogen (Left) and available phosphate (Right) of surface soils during 1979-1998 (From Obara 2000; Obara & Nakai 2004)

3) Cultivated Soil Classification System using in Soil Inventory

Agricultural soil inventories have been classified using Classification of cultivated soils in Japan, second approximation, 1982 (NIAS 1982). This soil classification system contained 16 soil groups, 60 soil series groups, and 320 soil series. Volcanic ash soils, referred to Andosols/Andisols (WRB/USDA) are divided into 3 soil groups in Japanese classification system, namely Andosols (dryer soil moisture types), Wet Andosols (referred to Episaturation aquic condition in USDA system), and Gleyed Andosols (referred to Endosaturation aquic condition in USDA system). Also, lowland soils, referred to Fluvisols/Entisols are classified to Brown lowland soils (dry condition), Gray lowland soils (Episaturation condition), and Gley soils (Endosaturation condition) in relation to aquic condition in Japanese system. Brown forest soils, referred to cambisols/Inceptisols widely occur in mountains and hills, but in Hokkaido and Tohoku districts, these soils also occur in Pleistocene terraces. Gray lowland soils, Gleyed soils, and Wet Andosols mainly are occurred in paddy fields. Andosols, Brown forest soils, and Brown lowland soils are occurred in upland, orchard, and grassland. These 7 soil groups covered about 82% of Japanese agricultural area (Table 1). Andosols and Wet Andosols are divided into 5 soil series groups by the difference in the thickness of humus layer and humus content. Brown forest soils, Brown lowland soils, Gray lowlands soils and Gley soils are divided into 3, 6, 9, and 7 soil series groups, respectively, by difference in texture, presence of gravel layers, presence of iron mottle and/or manganese concretions, depth of the top of gley horizons, etc. It is noteworthy that the Classification of cultivated soils in Japan, second approximation, 1982 is a topographically-aware classification system beased on parent material.

4) Soil Temperature Regime map (1 km-grid)

Soil temperature data supplied by the Ministry of Agriculture, Forestry, and Fisheries and the Meteorological Agency (1982) was used. During 1931 to 1970, the soil temperature at 50 cm depth (ST) was recorded at 95 meteorological stations throughout Japan (Fig. 1b). Since the length of ST recording period varied from one station to another, mean annual air temperature (AT) during ST recording period was recalculated one by one using climate statistical data (http://www.data.jma.go.jp/obd/stats/etrn/index). The difference between ST and AT (*Diff*_ST-AT) was calculated by subtracting AT from ST. Then, the *Diff* ST-AT map (resolution = 1 km) was computed by inverse distance weighting (weighting power = 2) using data from 95 stations (Fig. 1b). The AT map (resolution = 1 km) was provided by Japan Meteorological Agency (Mesh climatic data of Japan 2000), and then ST map (grid = 1 km) was calculated as the sum of the AT map and the *Diff* ST-AT map. Finally, definition of soil temperature regime by each pixel of ST map was followed by Soil Survey Staff (1999).

Soil temperature regime map was shown in Fig. 1c, and the area ratio of soil temperature regime and its elevation range were listed in Table 2. The “frigid” soil temperature regime mainly distributed in Hokkaido and high mountain zone in Tohoku and Kanto-Touzan districts. It is clear that the majority of the Japanese soils had a “mesic” soil temperature regime. The geophysical border between “mesic” and “thermic” regimes, i.e. 15ºC isothermic, in the main island of Japan (except for Tohoku) might be drawn along the altitude 150-300 m (Table 2). These results showed that “thermic” area was only distributed at low altitudes in southwest Japan.

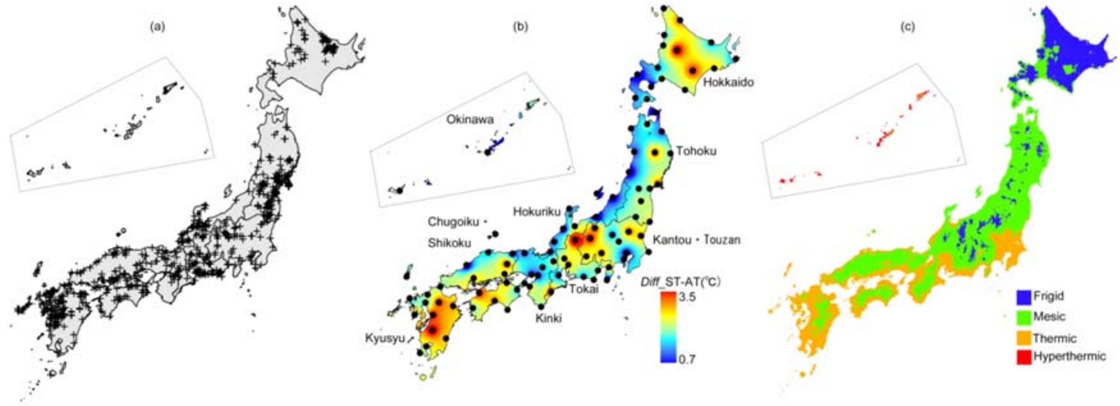

Fig. 4. Selected soil profiles as representative cultivated Brown forest soils (a), meteorological stations and the map of difference between air temperature and soil temperature (ºC) prepared by Inverse Distance Weighting method (b), and the map of soil temperature regime (Y. Takata et al. unpublished data).

Table 2. Area ratio of soil temperature regime (%), and it's elevation range between lower and upper 10 percentile (m).

	Frigid		Mesic		Thermic		Hyperthermic	
	Area	Elevation range	Area	Elevation range	Area	Elevation range	Area	Elevation range
Hokkaido	74.3	44 - 778	25.7	11 - 251	-		-	
Tohoku	7.3	765 - 1446	92.5	29 - 673	0.2	3 - 39	-	
Kanto・Touzan	10.0	1402 - 2260	54.1	233 - 1282	35.9	4 - 133	-	
Hokuriku	6.9	1230 - 2252	82.2	19 - 865	10.9	4 - 114	-	
Tokai	4.1	1439 - 2483	49.1	356 - 1172	46.7	4 - 286	-	
Kinnki	-		54.5	210 - 832	45.5	13 - 258	-	
Chugoku・Shikoku	-		51.8	259 - 899	48.2	10 - 314	-	
Kyushu	-		16.9	657 - 1206	80.8	32 - 706	2.3	15 - 154
Okinawa	-		-		9.0	164 - 293	91.0	6 - 128

Data source; Takata et al. (un-published data)

3. Estimation of Soil Carbon Stock (0-30 cm) Using Categorical method and Hybrid-Kriging Method

1) Categorical methods

Categorical method calculates the average of soil carbon content (%; 0-30 cm) and soil bulk density per soil series group and land use type (SSG_LU category) using “Basic Soil-Environmental Monitoring Project” data. Then, soil carbon stock (tC/ha) is calculated using average of soil carbon content and average of bulk density. “Basic Soil-Environmental Monitoring Project” data was divided into two groups namely parameterization dataset and validation dataset. The ratio of the number of sampling points in the two groups was 10:1. Average soil carbon stock was calculated per 1 cm layer from 0 to 30 cm depth in each 5-year interval. To extrapolate the deficit dataset, Pedo-transfer depth function was prepared in each soil groups and land use type (SG_LU category). Pedo-transfer depth function in this report was simple form, and it is an Increase/Decrease Ratio of each layer’s variable to the top layer’s variable. The target layer’s variable (deficit dataset) of the SSG_LU category is computed by Increase/Decrease Ratio by the top layer’s variable of the SSG_LU category (Fig 5).

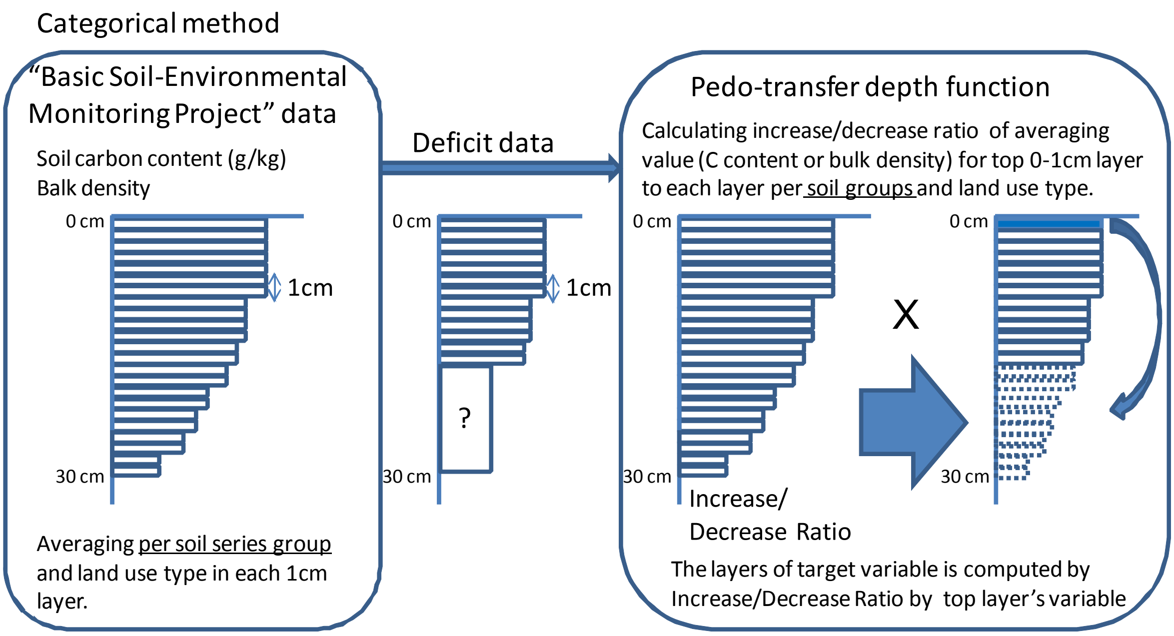

Fig. 5 The frame format of the categorical method

2) Hybrid-kriging method

The hybrid-kriging method (Liu et al. 2006; Zhang et al. 2010) combines categorical method and ordinary kriging. In the first step, categorical method of the carbon stock (tC/ha) in 5-layer groups (1-5 cm, 6-10 cm, 11-15 cm, 16-20 cm, and 21-30 cm) were used to create a spatial prediction $y(u_\alpha)$. The residuals of the categorical method $r(u_\alpha)$ can be obtained for the observed points $z(u_\alpha)$ as follows:

$$r(u_\alpha) = z(u_\alpha) - y(u_\alpha) \qquad \text{Eq. 1}$$

In the second step, ordinary kriging was applied to the residuals $r(u_\alpha)$. Ordinary kriging is a univariate interpolation method based on a weighting scheme to estimate the unknown primary target variable at unsampled locations by neighboring observation. Kriging minimizes the estimator variance and ensures the unbiasedness of the estimator (Webster & Oliver 2001). As the first step in applying ordinary kriging to residuals $r(u_\alpha)$, the spatial dependency of each residual $r(u_\alpha)$ was characterized by the semi-variogram $\gamma(h)$ using the following equation:

$$\lambda(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} [z(u_\alpha) - z(u_{\alpha+h})] \qquad \text{Eq.2}$$

where $\gamma(h)$ is the experimental semi-variogram value at distance interval h; $N(h)$ is the number of sample value pairs within the distance interval h; and $r(u_\alpha)$ and $r(u_{\alpha+h})$ are residual values at two points separated by the distance interval h. Spherical or exponential models were fitted to the experimental semi-variogram using geostatistical analyst (ESRI). In the third step, the spatially distributed categorical methods result and the kriged residuals are summed to estimate the target variable $Z^*_{\text{Hybrid-kriging}}$:

$$Z^*_{\text{Hybrid-kriging}}(u_\alpha) = y(u_\alpha) + r^*_{OK}(X_u) \qquad \text{Eq. 3}$$

3) Validation

Two validation indices were computed from the observed and predicted carbon stock (tC/ha) in 5-layer groups (1-5 cm, 6-10 cm, 11-15 cm, 16-20 cm, and 21-30 cm) as used by Odeh et al. (1995). As there are n sites belonging to the validation sample, the indices of validity computed from the observed values $z(s_j)$ and the predicted values $z^*(s_j)$ are the mean error (ME), and the root mean square error (RMSE). The mean error is defined as:

$$ME = 1/n\sum_{j=1}^{n}[z(s_j) - z^*(s_j)] \qquad \text{Eq. 4}$$

This measures the bias of prediction and it should be close to zero for unbiased methods.
The RMSE is expressed as:

$$RMSE = \{1/n\sum_{j=1}^{n}[z^*(s_j) - z(s_j)]^2\}^{0.5} \qquad \text{Eq. 5}$$

This is a measure of precision of prediction and should be as small as possible for precise prediction.

4) Changes of Soil Carbon Stock and Soil Carbon Content by Categorical Method

Categorical method showed that the average carbon stock of the Japanese cultivated soil was gradually increased from 1979 to 1998 (Table 3). In the major soil groups (>100 x 10^3 ha), most C stock increased soil groups was Gray upland soils, and it increased from 80 to 100 (tC/ha) during the period. Carbon stock of Brown lowland soils, Yellow soils, and Brown forest soils were also increased. However, Gray lowland soil and Andosols, both of them are the most common soil groups in Japanese cultivated soil, were decreased in carbon stock.

Relationship between the residuals of the categorical method and soil temperature regime were shown in Table 4. In each depth, almost layer groups showed negative values and it indicated that categorical method would overestimate of soil carbon stock. Categorical method separately calculated soil carbon content (%) and bulk density in each SSG_LU group. It means that all carbon content (bulk density) data were used to calculate the average of soil carbon content (bulk density) despite the missing data of bulk density (carbon content). However, the observed plots in the residuals calculation were selected from no-missing data of soil carbon content (%) data and bulk density. This difference processing would cause the whole overestimation of categorical method. The residuals of categorical method were remarkably lower in “Hyperthermic” soil temperature regime than in the other regime. Furthermore, cooler temperature regime was significantly higher than hotter temperature regime. It indicated that soil carbon stock was higher in cooler region than in hotter region. In general, soil organic matter content of the zonal soils tends to increase from a warmer to a cooler climate (Jones et al. 2003; McDaniel & Munn 1985). This relationship between soil temperature and SOC content is because the decomposition rate of soil organic matter increases in warm temperature, while it decreases in cool temperature region (Jones et al. 2003).

Table 3. Changes of soil carbon stock and soil carbon content in each 5 years interval, estimating by categorical method

Soil Group	First interval (1979-1983) Area (×10³ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Second interval (1984-1988) Area (×10³ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Third interval (1989-1993) Area (×10³ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Fourth interval (1994-1998) Area (×10³ha)	Carbon stock (tC/ha)	Carbon content (Tg)
Leptosols	5	73	0	4	79	0	4	64	0	4	70	0
Sand-dune	21	27	1	21	34	1	20	33	1	20	39	1
Andosols	947	138	131	961	127	122	943	129	122	909	127	115
Wet Andosols	432	131	57	427	141	60	418	150	63	410	132	54
Gleyed Andosols	58	112	6	57	122	7	55	120	7	55	109	6
Brown Forest soils	433	78	34	442	87	39	425	91	39	386	84	32
Gray Upland soils	162	80	13	161	86	14	158	91	14	151	100	15
Gley Upland soils	78	65	5	75	68	5	72	66	5	65	62	4
Red soils	46	59	3	45	57	3	42	59	2	41	57	2
Yellow soils	354	63	22	337	66	22	318	66	21	294	71	21
Dark Red soils	42	49	2	36	54	2	36	45	2	28	50	1
Brown Lowland	421	60	25	418	70	29	403	70	28	388	71	28
Gray Lowland soils	1235	70	87	1199	68	81	1157	67	78	1116	73	82
Gley soils	962	70	68	937	71	66	908	72	65	878	71	62
Muck soils	75	78	6	73	123	9	72	131	9	70	106	7
Peat Soils	158	188	30	161	174	28	160	165	26	165	179	30
Total	5428	90	489	5355	91	488	5191	93	482	4980	93	461

Area (×10³ha) are used 1981, 1986, 1991, and 1996 sensus data

Table 4. Compalison between the average of residuals of the 1st interval and soil temperature regime

ST Regime \ Layer groups	0-5 cm N	Residuals (tC/ha)	6-10 cm N	Residuals (tC/ha)	11-15 cm N	Residuals (tC/ha)	16-20 cm N	Residuals (tC/ha)	21-30 cm N	Residuals (tC/ha)
Hyperthermic	85	-5.63	85	-5.63	84	-5.46	74	-5.31	39	-6.71
Thermic	4959	-2.22	4959	-2.19	3986	-2.25	2152	-2.87	1225	-4.77
Methic	3419	-1.04	3419	-1.10	3121	-0.91	1480	-1.15	885	-1.39
Frigid	232	1.06	232	-0.12	152	0.26	125	0.63	31	5.99

5) Accuracy Comparison of Estimating Soil Carbon stock Between Categorical Method and Hybrid-Kriging Method

To correct the overestimation and spatially biased of the categorical method, hybrid-kriging method was applied for valid carbon stock estimation. The results of the validation were shown in Table 5. The lower absolute values of ME were shown in the hybrid-kriging than in the categorical method. This data indicated that hybrid-kriging method could overcome the whole overestimation of categorical method. Moreover, the RMSE values were almost 10 to 15% lower in hybrid-kriging than in categorical method. It suggested that the precision of hybrid-kriging method was increased from categorical method. The RMSE values of total layer groups was ranged from 35.7 (third interval) to 38.1 (first interval) tC/ha, and most valid estimation was the third interval. However, the ME value of the total layers groups in third interval was -3.13 tC/ha, and it was the lowest ME value (overestimation) in the all intervals. On the contrary, the first interval was shown the largest RMSE values and lowest biased (ME=-0.66) in the all intervals. Additionally, the ME and the RMSE values of all layers group in the second and the forth intervals showed similar values of the third interval. It might imply that the estimation of the soil carbon stock in the second, the third, and the forth intervals are comparable in this report.

Table 5. Validation of the estimation of carbon stock in cultivated soil (0-30)cm

	Method	Layer groups 0-5 cm			6-10 cm			11-15 cm			16-20 cm			21-30 cm		
		N	RMSE	ME	N	RMSE	ME	N	RMSE	ME	N	RMSE	ME	N	RMSE	ME
First interval	Categorical	935	6.70	-1.72	901	6.63	-1.78	657	7.05	-2.01	389	7.13	-2.20	222	13.90	-2.75
(1979-1983)	Hybrid-kriging	935	6.06	-0.02	901	5.95	0.00	657	6.31	-0.06	389	6.45	0.03	222	13.33	-0.62
Second interval	Categorical	817	5.86	-0.79	801	5.60	-1.83	562	6.25	-0.95	327	6.72	-1.66	185	15.40	-3.18
(1984-1988)	Hybrid-kriging	817	5.38	-0.13	801	4.90	-0.15	562	5.52	-0.22	327	6.05	-0.40	185	14.63	-0.99
Third interval	Categorical	825	5.71	-1.24	802	5.71	-1.25	579	6.05	-1.54	334	7.18	-1.89	178	13.87	-2.89
(1989-1993)	Hybrid-kriging	825	5.24	-0.33	802	5.32	-0.34	579	5.22	-0.48	334	6.26	-0.45	178	13.66	-1.54
Fourth interval	Categorical	607	5.84	-1.17	592	5.82	-1.09	386	6.25	-0.90	212	6.80	-0.84	102	14.28	-2.50
(1994-1998)	Hybrid-kriging	607	5.29	-0.03	592	5.28	0.06	386	5.71	0.27	212	6.34	0.36	102	13.72	-1.64

6) The Changes of Japanese Cultivated Soil Carbon stock and Carbon Content

Soil carbon stock and whole soil carbon content, estimating by hybrid-kriging method, was listed in Table 6 and Table 7. Corrected soil carbon stock and soil carbon content was lower than in the categorical estimation method. In the second interval, whole soil carbon stock was decreased from 91 (categorical method) to 88 (Hybrid-kriging method) tC/ha, and whole soil carbon content was also decreased from 488 (categorical method) to 469 (Hybrid-kriging method) Tg. Soil carbon stock of Peat soils was the highest in the Japanese cultivated soil groups. Wet Andosols and Andosols were also high soil carbon stock, and the carbon stock of these soils showed the peaks at the third intervals. Same fluctuation was observed in Brown forest soils. Andosols and Brown forest soils were mainly observed in upland fields and grassland, and these types of land use were also showed the peaks of soil carbon stock at the third interval (Table 6). In the paddy fields, soil carbon stock was gradually increased from 76 to 78 tC/ha during 1984-1998. Gray lowland soils and Gley soils, which are the main soil groups in the paddy fields, showed the increasing of carbon stock at the same period. Distribution pattern of soil carbon stock (0-30 cm) in the third interval was shown in Fig. 6. In the Andosols, carbon stock was higher in Hokkaido district (frigid-mesic soil temperature zone) than in Kanto, Touzan, and Kyusyu districts (thermic soil temperature zone). Peat soils-grassland combination in Hokkaido district showed the highest value of soil carbon stock. Soil carbon stocks of Red soils and Yellow soils, where distributed in thermic or hyperthermic soil temperature zone, were lower soil carbon stock than in the other soil groups.

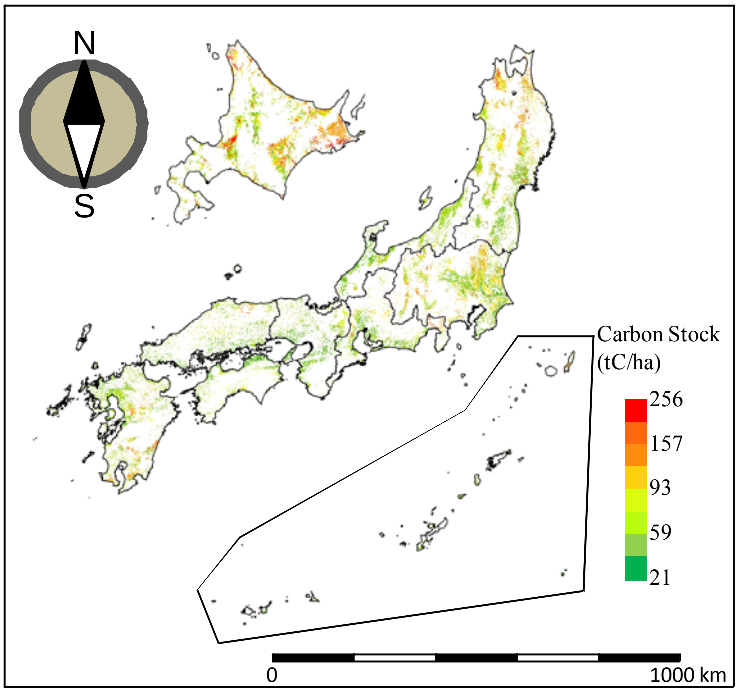

Fig. 6 Cultivated soil carbon stock ratio (0-30cm) in the third intervals

Table 6. Changes of soil carbon stock and soil carbon content in each land use type, estimating by hybrid-kriging

	First interval (1979-1983)			Second interval (1984-1988)			Third interval (1989-1993)			Fourth interval (1994-1998)		
	Area (x10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Area (x10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Area (x10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Area (x10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)
Paddy field	3026	71	216	2920	76	222	2826	77	216	2722	78	212
Upland fields	1245	89	111	1270	89	112	1257	91	115	1207	86	104
Grassland	577	129	74	629	146	92	647	151	98	659	146	96
Orchard	580	74	43	535	81	43	463	84	39	391	87	34
Agricultual land	5427	82	445	5354	88	469	5193	90	468	4979	90	446

Table 7. Changes of soil carbon stock and soil carbon content in each 5 years interval, estimating by hybrid-kriging method

	First interval (1979-1983)			Second interval (1984-1988)			Third interval (1989-1993)			Fourth interval (1994-1998)		
Soil Group	Area (×10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Area (×10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Area (×10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Area (×10^{3}ha)	Carbon stock (tC/ha)	Carbon content (Tg)
Leptosols	5	66	0	4	72	0	4	60	0	4	68	0
Sand-dune Regosols	21	24	0	21	34	1	20	33	1	20	38	1
Andosols	947	128	121	961	125	120	943	127	120	909	123	112
Wet Andosols	432	123	53	427	140	60	418	150	63	410	132	54
Gleyed Andosols	58	104	6	57	120	7	55	119	7	55	108	6
Brown Forest soils	433	73	31	442	84	37	425	89	38	386	81	31
Gray Upland soils	162	76	12	161	83	13	158	90	14	151	98	15
Gley Upland soils	78	59	5	75	66	5	72	64	5	65	63	4
Red soils	46	48	2	45	49	2	42	51	2	41	51	2
Yellow soils	354	53	19	337	59	20	318	60	19	294	66	19
Dark Red soils	42	44	2	36	55	2	36	44	2	28	47	1
Brown Lowland soils	421	54	23	418	69	29	403	69	28	388	68	27
Gray Lowland soils	1235	61	76	1199	62	75	1159	63	74	1116	70	78
Gley soils	962	62	60	936	66	62	908	68	61	877	68	60
Muck soils	75	66	5	73	119	9	72	125	9	70	101	7
Peat Soils	158	185	29	161	177	28	160	167	27	165	178	29
Total	5427	82	445	5354	88	469	5193	90	468	4979	90	446

Area (×10^{3}ha) are used 1981, 1986, 1991, and 1996 sensus data

In spite of the gradually increasing whole soil carbon stock, total soil carbon content decreased from 469 (second interval) to 446 (third interval) Tg. During the same period, agricultural land area was decreased from 5.4 to 5.0 million hectares. Distribution area of Andosols was decreased by 52,000 ha, and 8 Tg of soil carbon were lost. The declines in the Andosols with expanding urbanization were observed widely over the flat upland fields in Kanto and Touzan district. Additionally, the declines of paddy fields and orchard were observed in the whole country. Total carbon content in the paddy fields and orchards was remarkably decreased. These results indicated that a decline of soil carbon content in Japanese agricultural land, which was mainly influenced by the fluctuation of agricultural land area.

As mentioned above, the Classification of cultivated soils in Japan, second approximation, 1982 is parent material based topographically-aware classification system. Hence, the categorical method for estimating soil carbon stock could take into account the soil classification, topography, parent material, and human activity. Furthermore, the hybrid-kriging method could consider the climate condition (including spatial variation) and spatial position of the soil sampling sites. Therefore, the hybrid-kriging method was similar to the scorpan model, which is proposed by McBratney et al. (2003). The scorpan model predicts a soil property S,

$$S = f(s, c, o, r, p, a, n) + e$$

Where:
s: soil, other properties, or prior knowledge of the soil at points,
c: climate, climatic properties of the environment at a point,
o: organisms, vegetation or fauna or human activity,
r: topography, landscape attributes,
p: parent material, lithology,
a: age, the time factor,
n: space, relative spatial position,
e: autocorrelated random spatial variation, predicted with a variogram and kriging
(McBratney et al. 2003).

The scorpan model is a raster based prediction method, while the hybrid-kriging method is a hybrid between polygon based (categorical method) and raster based (residuals mapping) calculation. Moreover, the output map of the soil carbon stock is a polygon format so that it easily compares with the other agricultural-industrial census data. Therefore, hybrid-kriging methods for estimating soil carbon stock in agricultural land might be the extensible method to assess the past-to-ongoing agro-environmental policy, landscape planning, and land conservation policy.

7) Cultivated Soil Carbon Stock at Different Soil Depth

For calculating the soil carbon stock at different depth (30-50 cm and 30-100 cm) per SSG_LU category in each 5-year interval, the numbers of sample were limited. Therefore, the SSG_LU dataset in each interval were merged, and then calculated the average soil carbon stock in each 1-cm layers (30-50 cm and 30-100 cm) per soil groups. These carbon stocks were summed up to the third interval's surface soil carbon stock, which was estimated using hybrid-kriging method (Table 8). Soil carbon stock (0-100cm) was ranged from 70 (Sand-dune Regosols) to 573 (Peat soils) tC/ha, and it was two to three times higher than in the upper 30 cm.

Table 8. Cultivated Soil Carbon Stock Rate at Different Soil Depth

Soil Group	Soil Group (World Reference Base for Soil Resources)	Area ($x10^3$ha)	Carbon stock (tC/ha)	Carbon stock (tC/ha)	Carbon stock (tC/ha)	Carbon content (Tg)	Carbon content (Tg)	Carbon content (Tg)
			0-30cm	0-50cm	0-100cm	0-30cm	0-50cm	0-100cm
Leptosols	Leptosols	4	60	64	76	0	0	0
Sand-dune Regosols	Regosols	20	33	45	70	1	1	1
Andosols	Andosols	943	127	193	341	120	182	321
Wet Andosols	Gleyic Andosols	418	150	211	361	63	88	151
Gleyed Andosols	Gleyic Andosols	55	119	179	328	7	10	18
Brown Forest soils	Cambisols	425	89	114	171	38	48	73
Gray Upland soils	Gley soils, Planosols	158	90	128	218	14	20	35
Gley Upland soils	Gley soils, Planosols	72	64	84	134	5	6	10
Red soils	Cambisols, Acrisols, Alisols	42	51	69	101	2	3	4
Yellow soils	Cambisols, Acrisols, Alisols	318	60	79	122	19	25	39
Dark Red soils	Luvisols, Cambisols	36	44	70	139	2	3	5
Brown Lowland soils	Fluvisols	403	69	93	151	28	37	61
Gray Lowland soils	Fluvisols, Gley soils	1159	63	94	171	74	109	198
Gley soils	Fluvisols	908	68	105	197	61	95	179
Muck soils	Histosols	72	125	192	366	9	14	26
Peat Soils	Histosols	160	167	251	457	27	40	73
Total		5193	90	131	230	468	682	1195

Area ($x10^3$ha) are used 1991sgricultural sensus data

The total soil carbon content in forest soils at difference depth in Japan was estimated by Morisada et al. (2004), and it was 2180 and 4570 Tg for the upper 30 and 100 cm depth, respectively. The soil carbon stock of Japanese forest soil was 90 and 188 tC/ha for the upper 30 and 100 cm depth, respectively (Morisada et al. 2004). Surface soil carbon stock (0-30 cm) was coincided between cultivated soils and forest soils. In the upper 100 cm depth, soil carbon stock was higher in cultivated soils than in the forest soils. This result would be suggested that the difference of landscape position between agricultural land and forest causes the difference of soil carbon stock at the upper 100 cm depth. In Japan, forest mainly distributed at mountainous and hilly area, which is characterized un-stable slope position, and major part of forest soil is constantly exposed to high pressure of soil erosion. This situation might be difficult to develop the carbon accumulation at the deeper horizons. On the contrary, agricultural land mainly distributed flat to gentle slope site, and this stable landscape condition was suitable for carbon accumulation at the deeper horizons.

4. Conclusion

Changes of soil carbon stock and soil carbon content in Japanese agricultural land was estimated using national soil inventories including digital cultivated soil maps and the Basic Soil-Environmental Monitoring Project dataset. Categorical method for estimating soil carbon stock in each SSG_LU category was wholly overestimated. To correct this overestimation, hybrid-kriging method was applied in this report. The hybrid-kriging method could overcome the overestimation of categorical method, and it took account the climate condition and spatial position of the soil sampling points for soil carbon stock estimation. Accuracy of the soil carbon stock estimation was increased in hybrid-kriging method by about 10% compared to categorical method. Total soil carbon stock was gradually increased from 88 to 90 tC/ha during 1984-1998. Total soil carbon content in agricultural land was decreased from 469 (1984-1988) to 446 (1994-1998) Tg. During the same period, agricultural land area was decreased from 5.4 to 5.0 million hectares. These results indicated that a decline of carbon stocks in Japanese agricultural soil was mainly influenced by the fluctuation of agricultural land area.

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