Soil Carbon Stock Change Due to Afforestation in Japan by Paired-Sampling Method in an Equivalent Mass Basis

Shigehiro Ishizuka[1], Shoji Hashimoto[1], Shinji Kaneko[1], Kenji Tsuruta[1], Kimihiro Kida[1], Shuhei Aizawa[1], Toru Hashimoto[1], Eriko Ito[1], Mitsutoshi Umemura[1], Yoshiki Shinomiya[1], Tomoaki Morishita[1], Kyotaro Noguchi[1], Kenji Ono[2], Toru Okamoto[1], Takeo Mizoguchi[1], Atsushi Torii[1], Hisao Sakai[1], Yoshiyuki Inagaki[1], Koji Sichi[1], Jumpei Toriyama[1], Yoshimi Sakai[1], Masahiro Inagaki[1], Yasuhito Shirato[3], Hiroshi Obara[4], Kazunori Kohyama[4], Yusuke Takata[4], Nobuko Katayanagi[1], Takashi Kanda[4], Haruna Inoue[4], and Takashi Kusaba[5]

[1]Forestry and Forest Products Research Institute
[2]Tohoku Research Center, Forestry and Forest Product Research Institute, Japan
[3]National Institute for Agro-Environmental Science
[4]National Institute for Agro-Environmental Sciences
[5]Kyushu Okinawa Agricultural Research Center

November 22, 2022

Abstract

To identify the soil carbon stock change from cropland to forest land in Japan, we compared the soil carbon stock of a cropland and that of an adjacent forest land at 23 different sites. With regard to a 0–30 cm depth basis, the soil carbon stock in the cropland was greater than that in the forest land; however, it was less than that in the forest land when an equivalent mass basis was used. In less than an elapsed time of 20 years after a land-use change, the soil carbon stock after afforestation was less than that in the adjacent cropland at the same sites. However, after an elapsed time of 20 years, the soil carbon stock in the afforested site exceeded that in the adjacent cropland at the same sites. The ratio of the soil carbon stock in forest land to that in the cropland was 1.10 on average, which is comparable with the previous mass-corrected paired-sampling studies. The ratio in the conifer-planted forest was significantly greater than that in the hardwood re-generated forest. Some of the previous reviews, including those of the non-mass-corrected data, were possibly biased, and more studies using the paired-sampling method with equivalent mass basis need to provide more general ratios in the future.

Soil Carbon Stock Change Due to Afforestation in Japan by Paired-Sampling Method in an Equivalent Mass Basis

Enter authors here: Shigehiro Ishizuka[1], Shoji Hashimoto[1], Shinji Kaneko[1], Kenji Tsuruta[1], Kimihiro Kida[1], Shuhei Aizawa[1], Toru Hashimoto[2], Eriko Ito[2], Mitsutoshi Umemura[2], Yoshiki Shinomiya[3], Tomoaki Morishita[3], Kyotaro Noguchi[3], Kenji Ono[3], Toru Okamoto[4], Takeo Mizoguchi[4], Atsushi Torii[4], Hisao Sakai[5], Yoshiyuki Inagaki[5], Koji Sichi[5], Jumpei Toriyama[6], Yoshimi Sakai[6], Masahiro Inagaki[6], Yasuhito Shirato[7], Hiroshi Obara[7], Kazunori Kohyama[7], Yuusuke Takata[7], Nobuko Katayanagi[7], Takashi Kanda[7], Haruna Inoue[7], Takashi Kusaba[8]

[1]Affiliation for author 1. Forestry and Forest Products Research Institute, Tsukuba, Japan

[2]Affiliation for author 2. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan

[3]Affiliation for author 3. Tohoku Research Center, Forestry and Forest Products Research Institute, Morioka, Japan

[4]Affiliation for author 4. Kansai Research Center, Forestry and Forest Products Research Institute, Kyoto, Japan

[5]Affiliation for author 5. Shikoku Research Center, Forestry and Forest Products Research Institute, Kochi, Japan

[6]Affiliation for author 6. Kyushu Research Center, Forestry and Forest Products Research Institute, Kumamoto, Japan

[7]Affiliation for author 7.Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, Tsukuba, Japan

[8]Affiliation for author 8. Kyushu Okinawa Agricultural Research Center, National Agriculture and Food Research Organization, Kumamoto, Japan

Corresponding author: Shigehiro Ishizuka (ishiz03@ffpri.affrc.go.jp)

Key Points:

- The soil carbon stock due to land-use change from a cropland to a forest land increased 1.10 times on average.
- To obtain an appropriate ratio of land-use change factor, a paired-sampling method on an equivalent soil mass basis should be adopted.
- The annual average soil carbon stock change rate depends on the elapsed time after the land-use change.

Abstract

To identify the soil carbon stock change from cropland to forest land in Japan, we compared the soil carbon stock of a cropland and that of an adjacent forest land at 23 different sites. With regard to a 0–30 cm depth basis, the soil carbon stock in the cropland was greater than that in the forest land; however, it was less than that in the forest land when an equivalent mass basis was used. In less than an elapsed time of 20 years after a land-use change, the soil carbon stock after afforestation was less than that in the adjacent cropland at the same sites. However, after an elapsed time of 20 years, the soil carbon stock in the afforested site exceeded that in the adjacent cropland at the same sites. The ratio of the soil carbon stock in forest land to that in the cropland was 1.10 on average, which is comparable with the previous mass-corrected paired-sampling studies. The ratio in the conifer-planted forest was significantly greater than that in the hardwood re-generated forest. Some of the previous reviews, including those of the non-mass-corrected data, were possibly biased, and more studies using the paired-sampling method with equivalent mass basis need to provide more general ratios in the future.

1 Introduction

Soil carbon stock change is among the critical issues that give rise to climate change because the soil carbon stock is the largest carbon stock in the terrestrial system. Also, the carbon content in the atmosphere partly depends on whether it works as a source or a sink of carbon. The gross primary production is balanced by plant respiration and the decomposition of soil organic matter, while the loss of soil carbon stock due to land-use change is a significant carbon source to the atmosphere as 1.6 Pg C y^{-1} (Lal, 2008). The cumulative carbon emissions from land-use change are estimated to be greater than those from industrial processes since the preindustrial era (Lal, 2004).

In spite of the importance of the soil carbon stock change due to the land-use change, the evaluation of the soil carbon stock change is limited. Guo and Gifford (2002) reviewed the soil carbon stock change ratios in many types of land-use change, including afforestation, and they found that the soil carbon stock increased after the land-use change from a cropland to a plantation or a secondary forest and that it decreased after the land-use change from a pasture to a plantation and from a native forest to a plantation. Bárcena et al. (2014) also reviewed the land-use change effect on the soil carbon stock in northern European countries, and they concluded that the changes were relatively lower than the previous reports with tropical, temperate, and global data sets. A review of 31-site results (Deng et al., 2016) suggested that the soil carbon stock does not significantly change after the conversion from farmland to forest land. According to these reviews, the soil carbon stock change is obscure and that it might vary based on the climate, soil condition, and management practices of the croplands in each country.

The default method for calculating the soil carbon stock change due to land-use change in IPCC Guideline (IPCC, 2019) is simple, where the average soil carbon stock of the land-use before the land-use change changes into that of the land-use after the land-use change in a certain transition time, which is 20 years as a default value. This method is available for the countries in which land-use is equally dispersed and where the distribution does not depend on the location in the landscape. In such countries, the land-use tends to be determined by the soil fertility associated with the soil type, and the land-use itself should be the important parameter for the difference in the averaged soil carbon stocks among different land-use types. However, in some countries, including Japan, croplands are usually located on relatively flat terrains at relatively low altitudes. Otherwise forest lands are usually located on gentle or steep slopes in the mountains at relatively high altitudes. According to the difference in the dominant location of each land-use, the dominant soil properties affecting the soil carbon stock, such as the soil type, bulk density, and amount of volcanic deposits, are different in proportion to the land-use. In this case, because the soil carbon stock might not only depend on the land-use effect but also on the geographical distribution of the land-use, it is not appropriate to apply the difference in the nationwide average soil carbon stocks in each land-use to the land-use emission factor.

Additionally, the land-use factor in the IPCC Guideline (IPCC, 2019) is mainly targeted to supply the factor when forest land turns into other land types, such as cropland and grassland. Therefore, the land-use factor for afforestation has not yet been supplied, and the reciprocal value of the factor from forest land to other land types is used for afforested sites. There are not so many surveys for clarifying the justification of this factor for afforested sites. Since the rate of accumulation of soil carbon stock in afforested sites may be different from the rate of loss or gain of soil carbon stock in deforested sites, the land-use factor for afforestation can be ideal for use in the future so that the carbon sequestration at afforested sites can be precisely estimated.

The paired-sampling method is often used to determine the comparison before and after the land-use change (for example, Bárcena et al., 2014). The sequential monitoring method by repeated sampling in a fixed site, such as in Rothamsted Field Experiment (Jenkinson, 1991), is robust to explore the carbon stock change, but it requires a vast effort to perform continuous sampling for a relatively long time like at least several decades. For this reason, the plot number is very limited and needs a model to expand the nationwide estimate. The paired-sampling method requires some hypothesis, where the condition before the land-use change should be as much as possible similar to that of the reference adjacent land and that only the land-use effect should be mainly reflected on the difference in the soil carbon stocks between these lands. Therefore, the land history, geographical position, and soil condition need to be carefully considered in advance. Despite these conditions, there are some advantages to adopting the paired-sampling method, as it can be used to survey the nationwide variability in the carbon stock change after land-use change, as many pair sites can be prepared in a country, and less spatially or regionally biased data can be obtained.

To compare the soil carbon stock in different land-use sites, the equivalent soil mass method has been sometimes used to avoid the soil mass change due to the impact of the land-use change and/or land management (Ellert and Bettany, 1995; Gifford and Roderick, 2003; Toriyama et al., 2011). To a certain soil depth, the soil mass changes in response to the management practices of the land-use change, such as uprooting forest vegetation, land leveling, and rain compaction, due to the disappearance of the cover of the tree canopy (Ellert and Bettany, 1995; IPCC, 2019). The comparison of the soil carbon stocks between cropland and forest land to the same depth involves the changes in the soil carbon stocks as a direct consequence of the changes in the soil bulk density (Ellert and Bettany 1995). Therefore, even in the case with the absence of any changes in the soil carbon content, it is possible to calculate a change in the soil carbon stock to a fixed depth due to the change in the bulk density. Therefore, it is more robust to calculate the soil carbon stock change on an equivalent mass basis rather than on a fixed-depth basis. The IPCC Guideline 2019 refinement introduces the recommendations for using the equivalent soil mass method to prepare the country-specific factor for the land-use change factor (IPCC, 2019).

In this study, we aim to clarify whether the soil carbon stock will increase or decrease when a land-use from cropland to forest land occurs. For this objective, we have compared the soil carbon stocks of a cropland and an adjacent forest land using two calculation methods, i.e., the conventional depth-based approach and the equivalent soil mass approach, using the paired-sampling method.

2 Materials and Methods

2.1 Background of Japanese land-use history

The history of land-use change in Japan drastically changed in the last five decades. There was substantial deforestation during World War II, followed by intensive reforestation during the 1950s to 1970s (Marten, 2005). To supply food, the Japanese government recommended the exploration of new cultivation areas, especially paddy fields. The agricultural land area was maximum in 1961 (6 million hectares) (Yamashita, 2016). Since the 1970s, to reduce the rice supply beyond consumption, the Japanese government prevented the land-use change to rice paddy fields, and the agricultural land area was reduced to 4.5 million hectares in 2016 (Yamashita, 2016). As a result, the agricultural population decreased with the increase in the industrial population from 1960 to 1975 (Shigeno, 1992), especially in mountainous areas. This change in population resulted in an increase in the abandoned cropland (Kimura, 1981). In these few decades, a part of the cropland turned into afforested land, grassland, or abandoned fields where natural vegetation regenerated, as the cropland was not maintained due to the aging of farmers and the lack of successors (Ishida, 2011). From 1990 to 2017, the land-use change from cropland to forest land is estimated to have a cumulative area of 35.4 k ha (National Inventory Report, 2019). However, it is unclear how cropland turns into forest land due to the lack of precise statistics.

2.2 Site preparation and measurement

The primary information of the location where the land-use change from cropland to forest land had occurred was obtained from the national inventory survey of land-use change, which was visibly identified by the change from 1990 (cropland, by aerial photograph) to 2011–2013 (forest land, by SPOT 5-HRV-P) in a 31 m circle area (0.3 ha, minimum area of forest in Japan) at every 500-m grid point all over Japan (Forestry Agency of Japan, 2015). Based on this information, we looked for the suitable candidate sites for our research by comparing the current satellite images (Google Maps) with the past aerial photo images (GSI Maps, Geospatial Information Authority of Japan). In total, we selected 112 pairs and conducted a preliminary field survey to identify the suitable pairs for our objectives. Then, we checked the following factors in the preliminary field survey. 1) The pair was on the same terrain, 2) the soil type was not different, 3) the period of land-use change can be identified using aerial/satellite images or by interviewing the landowner, 4) the availability of the land history and the management practices of both land types, and 5) the permissions of the landowners to use their soil. Finally, 27 sites were available for our objectives, and their details are listed in Table 1.

We measured the living and deadwood biomass of each forest. The living biomass was measured by the Bitterlich method (Bitterlich, 1947) using Omitooshi (Japan Forest Technology

Association) and Vertex (GIS supply), and the deadwood biomass was measured using the line intersect method (Kangas, 2006) for fallen logs and the belt transect method for standing dead trees and stumps (Ugawa et al., 2012).

2.3 Soil sampling

We took 6 replicate samples per one land-use from three pits, which were approximately 40 cm deep and 50 cm wide, except at SKK-AR01 and SKK-AR02, where we took 12 replicate samples per one land-use from six pits. The volumetric samples were taken using a 100 mL stainless cylindrical core (5 cm height, DIK-1801, Daiki Rika Kogyo Co., Ltd.) from every layer. Then, the samples for the chemical analysis were taken from every layer from the right and left sides of each pit. We also took a litter sample from the forest land from a 50 cm x 50 cm area in front of the pit (n = 3).

2.4 Soil analysis and calculation

The bulk density was determined by weighing the dry weight (24 h, 105°C) of the soil in the 100 mL cylindrical core mentioned above, and the litter amount was weighed the dry weight (48 h, 70°C). The carbon content of the soil and litter was measured using a dry combustion method by VarioMAX CN (Elementar, Germany). We analyzed the phosphate absorption coefficient (PAC), which is one of the indices of the mixture ratio of volcanic ash in soil, where its high value signifies a high concentration of volcanic ash. We adopted the comparison of PAC in the same equivalent soil mass of the soil profile between the cropland and forest land as an index to support the equality of the soils. The PAC was measured after a 24-h extraction of 13.44 g P_2O_5 L^{-1} $(NH_4)_2HPO_4$ solution (Nanzyo, 1997), the solution and soil weight ratio of which was 2:1. Then, the P concentration in the filtered extract was determined using an Auto Analyzer (SWAAT, BLTEC K.K., Japan).

2.5 Calculation methods

We calculated the soil carbon stock in two ways. The first way is the conventional method, which is done by comparing the soil carbon stock of the top 30 cm of the soil surface (excluding the litter layer) in each land-use. The other one is the equivalent soil mass method, which is done by calculating the soil carbon stock equivalent to the averaged 0–30 cm soil mass in the cropland. The calculation details are as follows (a little modification of Toriyama et al., 2011):

$$BD_{som}(i) = BD(i) \times TC(i) \times 1.724 \times 10^{-3} \quad (1)$$

$$BD_{mf}(i) = BD(i) - BD_{som}(i) \quad (2)$$

$$MF_{mass30} = \sum_{i=1}^{n} BD_{mf}(i) \times TH(i) \quad (3)$$

$$MF_{mass30\_Crop} = \sum_{j=1}^{6} MF_{mass30}(j)/6 \quad (4)$$

$$C_{ESM} = \sum_{i=1}^{n-1} BD_{mf}(i) \times TH(i) \times TC(i) + (MF_{mass30\_Crop} - \sum_{i=1}^{n-1} BDmf(i) \times TH(i)) \times TC(n) \quad (5)$$

where $BD_{som}(i)$ is the mass of the soil organic matter of fine earth (<2 mm) per volume in the ith layer (Mg m^{-3}), $BD(i)$ is mass of the soil fine earth (<2 mm) fraction per volume in the ith layer (Mg m^{-3}), $TC(i)$ is the carbon concentration in the ith layer (gC kg^{-1}), $BD_{mf}(i)$ is the mass of the soil mineral fraction of fine earth (<2 mm) per volume in the ith layer (Mg m^{-3}), MF_{mass30} is the cumulative mass of the soil mineral fraction of the nth layer to the 30-cm depth (Mg m^{-2}), $TH(i)$ is the thickness of the ith layer (m), MF_{mass30_Crop} is the average of six replicates of cumulative mass of the soil mineral fraction to the 30-cm depth on the cropland, and C_{ESM} (kgC m^{-2}) is the carbon stock equivalent to the soil mass of the 30-cm depth on cropland. The equivalent soil mass carbon stocks were calculated at both the cropland and the forest land, respectively.

As a soil carbon stock calculation, the cumulative PAC in the 0–30 cm equivalent soil mass of the cropland (PAC_{ESM}, MgP_2O_5 ha^{-1}) was calculated to check the soil equality between the cropland and the adjacent forest land as follows.

$$PAC_{ESM} = [\sum_{i=1}^{n-1} BDmf(i) \times TH(i) \times PAC(i) + (MF_{mass30\_Crop} - \sum_{i=1}^{n-1} BDmf(i) \times TH(i)) \times PAC(n)] / 10, \quad (11)$$

where $PAC(i)$ is the phosphate absorption coefficient in the ith layer (gP_2O_5 kg^{-1}), and 10 is the dimension factor.

2.6 Data compilation

Some data were excluded from the following analysis because of the following points. 1) The difference in the gravel content between the compared sites, 2) incomplete depth in one or both sites, 3) the difference in the PAC between the compared sites, and 4) the insufficient number of soil profiles relative to the high heterogeneity of the soil profiles, as explained in the results section.

2.7 Statistical analysis

We conducted multiple comparisons of the ratio of the soil carbon stock in the cropland to that in the forest land by using R (R Core Team, 2020) based on the following categories: former land-use, current vegetation, and soil.

3 Results

3.1 Land-use change from cropland to forest land

Most of the candidate sites were not large in terms of land area, and they were less than 1 hectare. Thus, these land-use changes were considered to be introduced by landowners. According to the 112 pre-survey points (Table 2), 60% of the sites were planted by common conifer plantation species, such as Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*), and larch (*Larix kaempferi*). The second most common site (13%) was a successional hardwood forest, which was naturally regenerated in the abandoned crop fields. When excluding the sites where the land history was unknown, 64% of these lands were human-induced tree plantation sites, 29% were naturally regenerated forest, and the remaining 7% were bare lands.

Table 2
The Vegetation Type of the Candidate Sites for Paired Sampling

Type of forest	Region						
	Hokkaido	Tohoku	Kanto	Kansai	Shikoku	Kyushu	Total
Deciduous conifer	5						5
Evergreen conifer	4	20	17	11	6	4	62
Old-growth hardwood	2	2	3	3		2	12
Successional hardwood	1	9	1	3		1	15
Bamboo		1	1	1			3
Abondoned		4		4			8
Unidentified		2		5			7
Total	12	38	22	27	6	7	112

3.2 Difference in the soil bulk density between cropland and forest land

By inspecting the profile data, we removed the data of the two sites (HKD-AR08 and SKK-AR02) for further analysis, as the forest land soil before the land-use change should not be in a similar condition to that of the adjacent cropland soil due to the following reasons. In the case of HKD-AR08, the gravel content of the surface soil (from 0 to 35 cm depth) in the cropland (10%) was larger than that in the forest soil (0%). As for SKK-AR02, the shallower soil layer of the forest land had a 90% gravel content, which was not observed in the cropland. If a part of the cropland had turned into forest land, the forest land would have properly contained the same amount of gravel at the same depth. In this sense, we considered that the soil of the adjacent forest and cropland in these cases were not comparable. Therefore, we did not use these sites in the further analyses. The soil bulk density in the cropland was mostly larger than that in the forest land (Table 3). Also, the soil bulk density of fine earth (<2 mm) at KNT-AR06 was relatively low (0.144) due to the high gravel content (below 20 cm depth). By excluding these sites, the bulk density ranges of the cropland and forest land were 0.45–1.26 and 0.43–1.11, respectively, and the average and median of the bulk density on the cropland (excluding KNT-AR06) were 0.86 and 0.85, respectively, while those on the forest land were 0.77 and 0.82, respectively. The ratio of the soil bulk density of the cropland to the forest land ranged from 0.82 to 1.50, the average and median of which were 1.12 and 1.10, respectively.

Table 3
Bulk Density at 0 - 30 cm in Each Pair

	Cropland		Forest land		
	(a) Average	SD	(b) Average	SD	(a)/(b)
	Mg m^{-3}	Mg m^{-3}	Mg m^{-3}	Mg m^{-3}	
HKD-AR01	1.003	0.047	0.937	0.056	1.07
HKD-AR02	1.061	0.077	1.041	0.111	1.02
HKD-AR03	0.907	0.040	0.946	0.055	0.96
HKD-AR06	1.236	0.069	1.076	0.140	1.15
HKD-AR07	1.262	0.032	1.112	0.091	1.14
HKD-AR09	0.908	0.096	0.854	0.115	1.06
HKD-AR10	1.150	0.063	0.979	0.042	1.17
HKD-AR11	0.849	0.033	0.700	0.067	1.21
THK-AR01	0.639	0.030	0.754	0.036	0.85
THK-AR02	0.583	0.050	0.464	0.028	1.26
THK-AR04	0.883	0.016	0.985	0.059	0.90
THK-AR07	0.763	0.115	0.933	0.053	0.82
THK-AR08	0.857	0.060	0.824	0.071	1.04
KNT-AR01	0.671	0.025	0.535	0.039	1.26
KNT-AR06	0.446	0.125	0.144	0.113	3.09
KNT-AR08	0.968	0.081	0.962	0.171	1.01
KAS-AR01	0.843	0.061	0.629	0.088	1.34
KAS-AR02	1.187	0.019	0.966	0.062	1.23
KAS-AR03	0.839	0.034	0.647	0.104	1.30
SKK-AR01	0.785	0.056	0.615	0.105	1.28
KYS-AR01	0.558	0.031	0.551	0.100	1.01
KYS-AR02	0.924	0.079	0.862	0.065	1.07
KYS-AR03	0.564	0.044	0.431	0.047	1.31
KYS-AR04	0.787	0.074	0.523	0.081	1.50
KYS-AR05	0.773	0.068	0.806	0.068	0.96

3.3 Cumulative phosphate absorption coefficient in 0–30 cm of equivalent soil mass to the cropland (PAC_{ESM})

The range of the PAC_{ESM} in the cropland and forest land was 7.7–55.7 and 7.1–58.9, respectively (Table 4). The PAC_{ESM} of the cropland was larger than that of the forest land in the six of the 25 sites. However, the average PAC_{ESM} of the cropland (33.7 MgP_2O_5 ha^{-1}) was less than that of the forest land (35.9 MgP_2O_5 ha^{-1}).

Table 4
Cumulative Phosphorous Absorption Coefficient (PAC) in the Equivalent Soil Mass to 0 - 30 cm Soil at Cropland

Site ID	Cropland MgP_2O_5 ha^{-1}	Forest land MgP_2O_5 ha^{-1}	Cropland/Forest land
HKD-AR01	34.1	41.8	0.82
HKD-AR02	42.7	38.9	1.10
HKD-AR03	34.6	31.1	1.11
HKD-AR06	33.2	43.2	0.77
HKD-AR07	34.4	39.7	0.87
HKD-AR09	36.3	39.1	0.93
HKD-AR10	55.7	58.9	0.95
HKD-AR11	50.9	43.0	1.18
THK-AR01	21.9	25.1	0.88
THK-AR02	23.9	39.2	0.61
THK-AR04	24.1	21.5	1.12
THK-AR07	25.9	26.4	0.98
THK-AR08	29.2	30.7	0.95
KNT-AR01	41.6	48.9	0.85
KNT-AR06	7.7	7.0	1.09
KNT-AR08	37.4	42.3	0.88
KAS-AR01	17.2	17.4	0.99
KAS-AR02	27.1	27.7	0.98
KAS-AR03	34.9	37.8	0.93
SKK-AR01	20.9	26.9	0.78
KYS-AR01	31.3	33.8	0.93
KYS-AR02	50.2	50.5	0.99
KYS-AR03	42.5	46.8	0.91
KYS-AR04	38.5	45.5	0.85

KYS-AR05	46.3	33.7	1.37

We excluded one site (KYS-AR05) from the soil carbon stock calculation due to the relatively large value of the PAC_{ESM} of the cropland corresponding to that of the forest land. Since the PAC_{ESM} is an index indicating the mixture ratio of volcanic ash in soil, we compared the cumulative PAC_{ESM} in the profile to verify the equality of the land history between the cropland and the forest land. The difference in the PAC_{ESM} between the cropland and the forest land in each site should be small if the land history is the same. According to (Mizota et al., 2008), a continuous phosphate application may reduce the PAC_{ESM}, as the exchange sites with the phosphate absorption capacity are occupied by excess phosphate. In contrast, the cease of phosphate application and continuous absorption of the excess phosphate by trees possibly increase the PAC_{ESM} after land-use change from cropland to forest land. For this reason, we defined an acceptance range of the PAC_{ESM} ratio of cropland to forest land as less than 1.2 (as same as Koga et al., accepted). According to these criteria, KYS-AR05 was out of the acceptance range, so we excluded this site from the comparison of the soil carbon stocks.

3.4 Comparison of the soil carbon stock between in the cropland and the forest land

Before the comparison, we excluded THK-AR02 from this analysis, as it is difficult to compare the cropland and forest land based on the different soil profiles' feature. One of three profiles in the cropland contained a coarse-textured and light yellow-colored Chuseri volcanic ash layer below 21 cm (Ishimura and Hiramine, 2020), the carbon content of which was relatively low (less than 10 g kg^{-1}), while two of the three profiles did not contain the layer. However, two of the three profiles in the forest land contained a Chuseri volcanic ash layer below 28 cm and 22 cm, respectively, while one of the three profiles did not contain a Chuseri volcanic ash layer. This difference means that the spatial heterogeneity of this site was high and that three pits are not enough for comparing the cropland and forest land of the sites. Therefore, we excluded this site from the comparison of the soil carbon stocks.

Overall, we could compare the soil carbon stock between the cropland and the adjacent forest land at 23 sites (Table 5). According to the conventional depth-based approach to calculate 0–30 cm depth of the cropland and forest land, the soil carbon stock range (average) in the cropland and forest land was 34.0–208.5 (77.4) MgC ha^{-1} and 11.7–209.8 (75.2) MgC ha^{-1}, respectively. Based on the equivalent soil mass approach, the average soil carbon stock in the cropland and forest land was 77.6 MgC ha^{-1} and 84.6 MgC ha^{-1}, respectively. The average ratio of the soil carbon stock of forest to cropland based on the equivalent soil mass approach was 1.10, whereas that based on depth based approach was 0.98. The average ratio of the equivalent soil mass approach to the depth approach in the forest land was 1.16.

Table 5
Carbon Stock Calculated Using Conventional Method and Equivalent Mass Based Method

Site ID	Cropland		Forest land				
	(a) depth based MgC ha^{-1}	(b) mass based MgC ha^{-1}	(c) depth based MgC ha^{-1}	(d) mass based MgC ha^{-1}	(c)/(a)	(d)/(b)	(d)/(c)
HKD-AR01	48.8	48.7	77.6	81.5	1.59	1.67	1.05

HKD-AR02	109.0	108.8	101.2	100.6	0.93	0.92	0.99
HKD-AR03	92.7	92.7	78.0	72.0	0.84	0.78	0.92
HKD-AR06	132.3	132.9	119.7	134.5	0.91	1.01	1.12
HKD-AR07	74.5	74.5	79.1	87.2	1.06	1.17	1.10
HKD-AR09	57.3	57.7	71.9	78.2	1.25	1.36	1.09
HKD-AR10	85.1	85.2	58.1	69.0	0.68	0.81	1.19
HKD-AR11	109.3	109.5	89.8	101.4	0.82	0.93	1.13
THK-AR01	63.3	63.3	56.5	49.1	0.89	0.78	0.87
THK-AR04	85.9	85.9	98.8	91.0	1.15	1.06	0.92
THK-AR07	49.3	49.1	43.2	38.8	0.88	0.79	0.90
THK-AR08	66.6	66.1	62.5	63.9	0.94	0.97	1.02
KNT-AR01	90.3	90.3	86.9	100.2	0.96	1.11	1.15
KNT-AR06	34.0	31.8	11.7	28.8	0.34	0.91	2.47
KNT-AR08	63.5	63.6	72.8	74.2	1.15	1.17	1.02
KAS-AR01	38.2	38.2	43.3	51.4	1.13	1.35	1.19
KAS-AR02	56.3	56.4	50.4	60.2	0.89	1.07	1.19
KAS-AR03	59.3	59.3	65.2	90.7	1.10	1.53	1.39
SKK-AR01	58.8	59.2	52.8	57.4	0.90	0.97	1.09
KYS-AR01	71.4	71.3	79.0	84.6	1.11	1.19	1.07
KYS-AR02	66.6	67.2	50.1	53.3	0.75	0.79	1.06
KYS-AR03	208.5	214.1	209.8	278.0	1.01	1.30	1.32
KYS-AR04	59.6	59.7	70.2	99.4	1.18	1.66	1.42

3.5 Effect of the former land-use, forest type, and soil type on the ratio

Based on the multiple comparisons of the ratio of the soil carbon stock of the cropland to the forest land according to the former land-use, current vegetation, and soil type, the positive effect of the current vegetation on the soil carbon stock accumulation was identified at the conifer plantation site, while the negative effect was identified in the hardwood forest (Table 6). Although the ratio in the citrus orchard was negative, even though it was only one site, the former land-use did not affect the carbon stock ratio of the land-use change. Also, the soil type did not affect the carbon stock ratio of the land-use change.

Table 6
Results of Multiple Comparison of the Ratio of Soil Carbon Stock of Cropland to Forest Land in Each Category (Former Land-use, Current Vegetation, and Soil)

Category	n	Median	Mean

Fomer Land-use	Upland field	11	1.11	1.12	a
	Paddy field	8	1.02	1.08	a
	Grassland	3	0.93	1.13	a
	Orchard	1	0.91	0.91	
Current vegetation	Conifer	18	1.14	1.17	a
	Hardwood	5	0.81	0.85	b
Soil	Brown	13	1.17	1.18	a
	Black	6	1.04	1.03	a
	Gley+others	4	0.95	0.94	a

Note. Different letter following the value means significant difference from others ($P < 0.05$).

3.6 Age and various environmental effects on the ratio

The ratio of the soil carbon stock of the forest land, which is equivalent to 0–30 cm of soil mass of cropland to that of cropland, increased along with the elapsed time after the land-use change (Fig. 1). The ratio was less than 1 under an elapsed time of 20 years, even though there were only three sites. The ratio also had no correlation with the mean annual temperature, mean annual precipitation, PAC_{ESM}, and aboveground biomass, while the litter amount had a weak positive correlation with the ratio ($R^2 = 0.209$) (Fig 2).

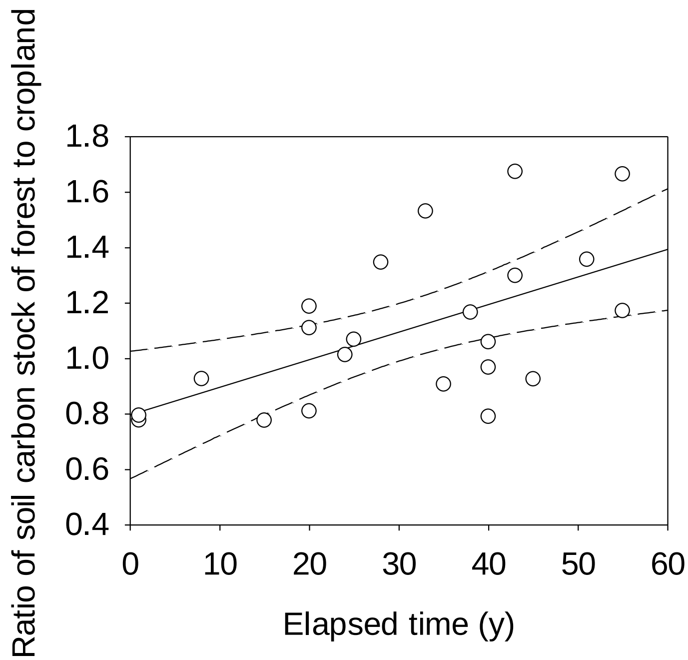

Fig. 1. The relationship between the elapsed time after the land-use change and the ratio of the soil carbon stock of the forest land to the cropland using the equivalent mass method (The solid line indicates the linear regression (R^2 = 0.329, Y = 9.95×10^{-3}X + 0.797), and the dashed lines indicate the ± 95% confidence interval of the regression, respectively.)

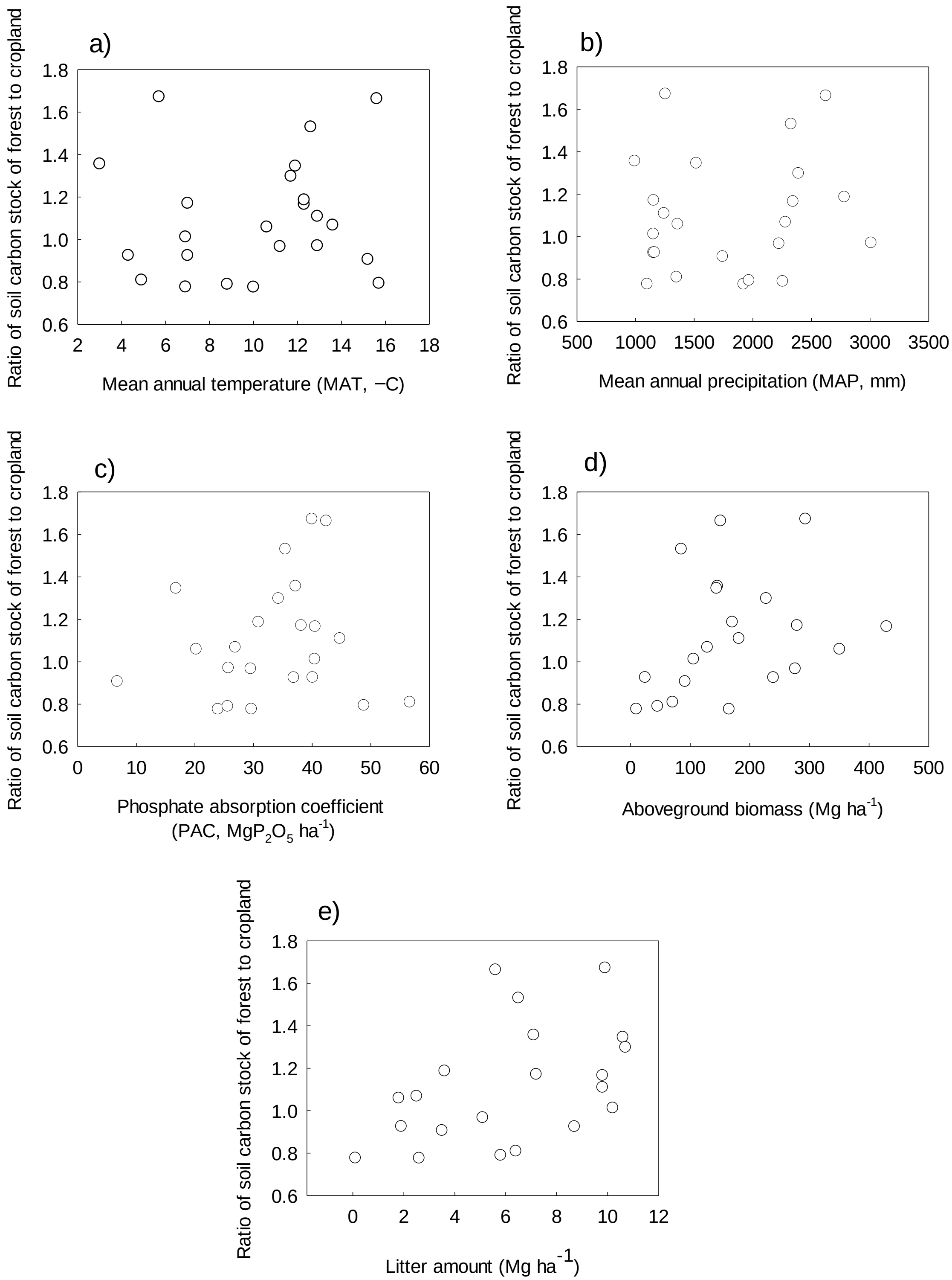

Fig. 2. Relationship between the ratio of the soil carbon stock of the forest to the cropland and other various factors: a) Mean annual temperature (MAT), b) Mean annual precipitation (MAP), c) Phosphate absorption coefficient (calculated using the equivalent soil mass approach), d) Aboveground biomass, e) Litter amount

4 Discussion

4.1. Effectiveness of the equivalent soil mass method for evaluating the soil carbon stock change due to the land-use change

It is well known that when a land-use change from forest land to cropland occurs, the soil in the cropland is usually compacted due to the heavy machine and raindrop compaction. However, the impact of the land-use change from cropland to forest land on the soil bulk density is less known. In this study, the bulk density in the forest land was lower than that in the adjacent cropland, meaning that the land-use change from cropland to forest land leads to loosening the soil, which is due to the behaviors of insects and/or invertebrates and the root system expansion of surface soils. Due to these activities, the amount of soil at 0–30 cm depth in the forest land is considered to be less than that at 0–30 cm depth in the cropland. As a result, when using the depth-based approach, the land-use change from cropland to forest land tends to underestimate the soil carbon stock due to the mass difference. Our results show that the ratio of the soil carbon stock of the forest land to the cropland is less than 1 with the depth approach (0.98), which is contradictory to the consensus that forest land accumulates more carbon in the soil by the more continuous biomass expansion and input of dead organic matter in comparison with the cropland (Guo and Gifford, 2002; Bárcena et al., 2014). However, the average of the soil carbon stock in the forest land calculated by the equivalent soil mass approach was greater than that in the cropland, the result of which is reasonable for the consensus mentioned above. Therefore, our result suggests that the equivalent soil mass approach is more reasonable and recommendable for comparing the land-use change effect of soil carbon stocks. A previous meta-analysis study in northern Europe (Bárcena et al., 2014) obtained the result that the mass-based comparison lowered the SOC stock effects in relative to the depth-based comparison. They hypothesized the relatively young age of the afforested plots, which led to a weak mass-correction effect. However, in this study, there was no correlation between the age of the trees and the ratio of the soil bulk density of the cropland to the forest land (Table 3). In any case, it is important to take the change in the bulk density into account when comparing the soil carbon stock in different land-use sites.

4.2. Age effect of soil carbon stock change after land-use change

While there were only 3 points considered with a shorter elapsed time than 20 years after afforestation, the carbon stock in the forest land was lower than that in the adjacent cropland, indicating that the carbon stock in the cropland decreases just after the land-use change to forest land for certain years. This result is comparable with the meta-analysis of northern European countries, which indicates that the carbon stock in forest lands in less than 30 years after afforestation is sometimes lower than that of the previous cropland (Bárcena et al., 2014). Deng et al. (2016) reviewed the results of 160 sites in 29 countries and also found out that the soil carbon stock at afforested sites in less than 10 years after land-use change is lower than that of former farmland, while that of >11 years after land-use change is greater than that of former farmland. In young (10–20 years old) afforested sites, it is possible that the carbon input from aboveground biomass was reduced before the land-use change, which can not only be due to the lack of input from manure applications and/or crop residues but also due to the little carbon input from planted/regenerated trees because of the low productivity and stock of aboveground biomass in young age. Even though the carbon input with the management of former cropland affected the soil carbon stock ratio of the cropland to forest land, we did not supply the carbon input data in this study due to the lack or high uncertainty of data from the landowners' interviews.

The duration for achieving soil carbon stock equilibrium after land-use change is not well studied. Wei et al. (2013) suggested that the tree age does not affect the soil carbon stock in temperate and boreal forests in north eastern China, even though the tree biomass increases at more than 81 years. Marin-Spiotta and Sharma (2013) also suggested that there are no strong patterns between the forest age and the soil carbon stock in tropical reforested and afforested sites. These studies suggested that even though the tree biomass increases along with the tree age, the carbon stock in soils does not increase along with the tree age. In this study, the bulk density of the cropland was greater than that of the forest land, and if a depth-based approach was adopted, the soil carbon stock in the cropland would be greater than that of the forest land. With regards to the "no age effect" of the soil carbon stock, one possible hypothesis is that it is an artifact of using a depth-based approach that the increase in the carbon concentration of surface soil with the tree age coincides with the decrease in bulk density and that the soil carbon stock looks unchanged in old forests. For further progress, we need more studies to identify the carbon stock change when afforestation occurs by using equivalent soil mass approaches.

Although the decreasing rate of the soil carbon stock in deforested areas is not linear (Koga et al., accept), the duration for achieving soil carbon stock equilibrium should be different between afforestation/reforestation and deforestation. According to the two-species database of the Japanese cedar and cypress, the carbon input as a litterfall seems to be maximum at an elapsed time of 20–30 years after afforestation and slightly declines along with the age of the trees (Fig. 3, data from Osone et al., 2020). Also, the carbon input from twigs, cones, and branches seems to increase with the tree age (Fig. 3). The root biomass seems to be maximum at the age of around 20–30 years at the time of the canopy closure (Jagodzinski et al., 2016); however, the carbon input via roots likely increases along with the tree age (Børja et al., 2008). According to these studies, the carbon input derived from the above- and below-ground biomass linearly increases before the canopy closure and can reach equilibrium in around 30 years. Since the realization of soil carbon stock equilibrium should be delayed with respect to achieving the maximum carbon input, the necessary duration for the soil carbon stock equilibrium should be more than 30 years. Based on the above carbon input features and our result (Fig.1), the default value of 20 years, as defined by the 2019 Refinement of IPCC Good Practice Guidance (IPCC, 2019), is considered to be too short for the equilibrium duration. The increase in the soil carbon stock might continue even after 40 years after land-use change (Fig. 1). Also, the duration might be different based on the various climates, regions, management strategies in past croplands, planted species, and soil types. Thus, further studies are needed to make a general conclusion on the appropriate default values of the necessary durations to achieve equilibrium in afforested sites.

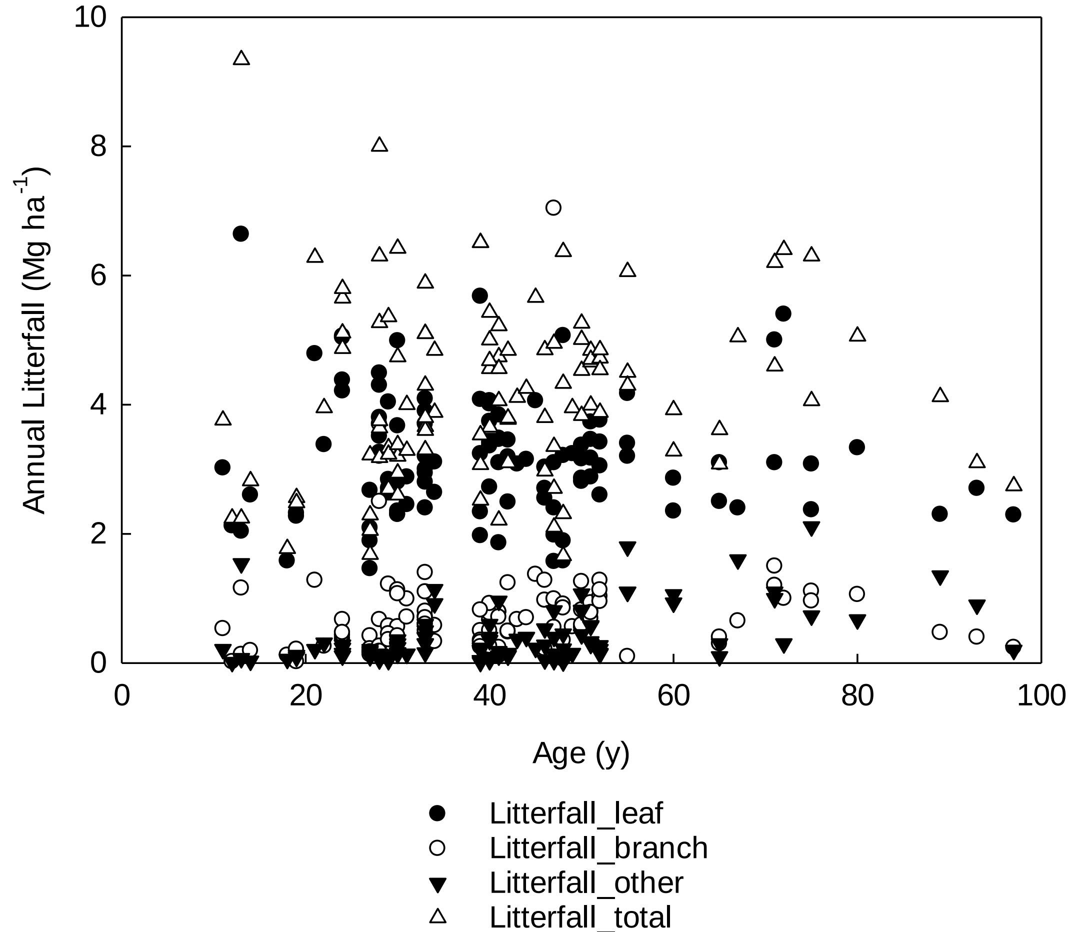

Fig. 3. The trend of the annual litterfall of *Cryptomeria japonica* and *Chamaecyparis obtusa* plantation forests along with the tree age from a dataset of Osone et al. 2020.

4.3. Does the accumulation of soil carbon depend on the soil, other environmental factors, and planted species?

The ratio of the soil carbon stock of forest to cropland had no correlation with the mean annual temperature, mean annual precipitation, and PAC (Fig.2). The soil type also did not affect the carbon stock ratio of the land-use change (Table 6). In general, Andic soil can strongly absorb carbon and promote the accumulation of soil carbon due to its storage of the recalcitrant Al-humus complex (Matus et al., 2014). Also, the C storage capacity was closely related to the oxalate-extractable Al (Matus et al., 2014). However, there is no correlation between the PAC, an index of the oxalate-extractable Al (Saigusa and Matsuyama, 1996), and the ratio of the soil carbon stock from cropland to forest land. These results suggest that carbon accumulation mainly depends on the carbon input rate rather than the accumulation properties of soils, and it might take more than several decades to exert the effect of volcanic soils on the accumulation. Although an early review showed that the annual precipitation of more than 2000 mm is the boundary of soil carbon accumulation (Guo and Gifford, 2002), there was no relationship between the precipitation and the ratio in this study. We only could identify a significant difference in the ratio with the forest type, where the ratio of the conifer plantation forest was greater than that of the hardwood forest (Table 6). Many previous studies showed that deciduous hardwood forests accumulate more carbon in soil than conifer forests (Deng et al., 2014; Guo and Gifford, 2002). In this study, the conifer forests were artificially planted ones, while the hardwood forests were naturally regenerated. Since the growth of conifer-planted forests usually exceeds that of hardwood forests in Japan (Matsumoto, 2001), the carbon input to the forest floor in conifer plantation forests should be greater than that in hardwood forests, which leads to a greater accumulation rate of soil carbon in conifer forests than in hardwood forests in Japan. However, Guo and Gifford (2002) concluded that pine plantation significantly reduces the soil carbon stock. Thus, overall, it is important to take into account the specific features of the tree species to properly estimate the effect on the soil carbon stock.

4.4. The ratio of soil carbon stock change due to the land-use change from cropland to forest land

The ratio of the soil carbon stock of forest to cropland in this study is similar to those of previous studies (Table 7). Although many studies have been carried out using the chronosequence or landscape variation method, we picked up data carried out using the pair-sampling method in this table, as we could not make sure that the difference in the carbon stocks was derived from the land-use change by using the chronosequence and landscape method. In these methods, the control forest may be located in a specific area, such as areas that are not suitable for cultivation due to soil infertility, water deficiency, etc., and the differences in the soil carbon stocks could depend on such properties. The paired-sampling method is superior to minimize the bias due to its location variation when the pair sites are carefully chosen. According to our internet-based literature survey using the Web of Science (Clarivate Analytics), we could find out 6 studies that used the paired-sampling method to estimate the carbon stock difference in afforested sites with respect to adjacent croplands. The ratio of the soil carbon stock of forest to cropland ranged from 0.72 to 1.67 (Table 7) with a mean of 1.20. Two studies (Chia et al., 2017; Georgiadis et al., 2017) adopted an equivalent mass basis, and two other studies (DeGryze et al., 2004; Resh et al., 2002) can be re-calculated using the bulk density data as an equivalent mass basis. Only based on the data of the mass-corrected ratio, including our results, the range and mean of the ratio were 1.03–1.30 and 1.13, respectively. The value of 1.13 was very close to our result (1.10), even though the tree age was relatively younger than in our study. Overall, the number of researches is insufficient to obtain the general land-use factor, and more studies are needed to realize a valuable factor to the global scale.

4.5. Limitation of using the Tier1 method for the soil carbon stock change

In a Japanese forest soil survey, the average soil carbon stock of forest land was 69.4 MgC ha^{-1} (Ugawa et al., 2014), while that of cropland was 76.5 MgC ha^{-1} (Greenhouse Gas Inventory Office of Japan et al., 2019). When we adopted the Tier 1 method according to the IPCC Guideline, the calculated annual change of the soil carbon stock in the afforested site was −0.355 MgC ha^{-1} y^{-1} (i.e., (69.4–76.5)/20 years). The reason for this lower soil carbon stock in forest land may derive from 1) the relatively low bulk density in forest land, 2) relatively low frequency of Andisols, which relatively have high carbon stock, and 3) relatively high frequency on steep slopes in forest land, which accumulate less soil carbon than on the flat terrains. Therefore, in a country where the difference in the carbon stocks in different land-use areas is derived from not only the land-use effect but also from other factors of each land-use, such as the geographical location dominance, soil type, etc., we recommend using the country-specific factor based on a nationwide survey. Of course, it is also recommended that the survey covers the whole country as unbiased as possible (uniformly distributed), and the paired-sampling method should be adopted on an equivalent soil mass basis.

There are several issues to be solved for the future. One is the issue of the sampling bias. We selected the pair sites, the disturbance of which was minimum or ignorable when a change in the land-use occurred. However, in some cases, the surface soil was seriously disturbed when the land-use changed. In these cases, the effect of the land-use change was possibly greater or lower than the result of this survey. Therefore, our result of the comparison between the cropland and the adjacent forest land was obtained based on the ideal condition, and the factor may be over- or underestimated in the case that the disturbance of the land-use change was heavy. Unfortunately, we have no adequate methods to compare the carbon stock when the disturbance was heavy. In addition, in this study, the variation of the former land-uses was very limited. In previous studies, the ratio of the soil carbon stock of forest land to grassland in afforestation was less than 1 (Guo and Gifford, 2002; Bárcena et al., 2014). However, in this study, only three afforested sites with former grassland were surveyed, and the average ratio was greater than 1, although it was not statistically significant. Only one site was surveyed for the orchard. An additional survey for the sites with the various former land-use types will be needed for a more comprehensive estimation of the carbon stock change of the afforested sites.

Additionally, it is difficult to provide an average rate of the soil carbon stock change when a land-use change from cropland to forest land occurs, as our results and also other previous studies suggest that the carbon stock declines once after land-use change and begins to increase after an elapsed time of 5–20 years (see 4.2.). This result suggests that the annual average soil carbon stock change rate depends on the elapsed time after the land-use change. For example, the rate was lower (i.e., probably loss of carbon) when the elapsed time was less than 10 years after the land-use change, while the rate was greater with an elapsed time of more than 30 years. Therefore, the best estimation can be obtained by adopting the Tier 3 modeling approach to represent the decline and gain curves, as shown in Fig. 4, based on the results of the paired-sampling scheme in various age stands.

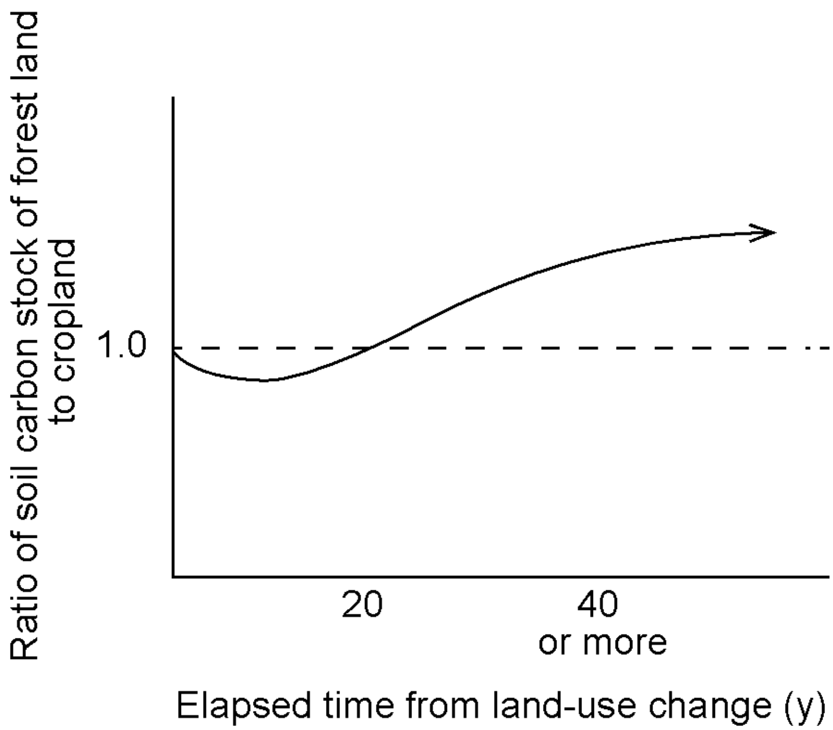

Fig. 4. Schematic diagram of the soil carbon stock change along with the elapsed time from the land-use change from cropland to forest land (The carbon stock ratio of 1 means the soil carbon stock in forest land is equal to that in cropland, and it becomes greater than that in cropland when the ratio is greater than 1.)

5 Conclusions

The soil carbon stock due to land-use change from a cropland to a forest land increased after the land-use change. The ratio of the soil carbon stock in forest land to that in the cropland was 1.10 on average in our study. Based on the data of the mass-corrected ratio in the literature and our study, the mean of the ratio were 1.13. Gathering the mass-corrected data is the key point to evaluate the adequate ratio. However, as our results and also other previous studies suggest that the carbon stock declines once after land-use change and begins to increase after an elapsed time of 5–20 years, an average rate of the soil carbon stock change when a land-use change from cropland to forest land occurs, this result suggesting that the annual average soil carbon stock change rate depends on the elapsed time after the land-use change. The best estimation can be obtained by adopting the Tier 3 modeling approach to represent the decline and gain curves, based on the results of the paired-sampling scheme in various age stands on the mass-corrected basis.

We recommend to obtain a country-specific factor of the soil carbon stock change ratio from a cropland to a forest land based on a nationwide survey for a country where the difference in the carbon stocks in different land-use areas is derived from not only the land-use effect but also from other factors of each land-use, such as the geographical location dominance, soil type, etc. To obtain an appropriate ratio, it is also recommended that the survey covers the whole country as unbiased as possible, and the paired-sampling method should be adopted on an equivalent soil mass basis.

Acknowledgments

This research was supported by the Environment Research and Technology Development Fund [grant numbers 2-1601 and 2-1909] of the Environmental Restoration and Conservation Agency of Japan. We thank so many landowners to permit us to take soil samples from their cropland and/or forest land. We also thank Drs. Ryusuke Hatano, Seiichi Ohta, and Nobuhisa Koga for their valuable comments to our study and Dr. Kazuyuki Atsumi for his help in the field work. We also thank Ms. Yumiko Okazaki, Ms. Akiyo Kawano, Ms. Yukari Yamamoto, Ms. Yoshiko Shimada, Ms. Yumiko Sakamoto, and Ms. Akane Sakumori for their laboratory assistance. Data used in this manuscript are publicly available on the website (see doi: 10.5281/zenodo.3873987).

References

Alberti, G., Leronni, V., Piazzi, M., Petrella, F., Mairota, P., Peressotti, A., Piussi, P., Valentini, R., Gristina, L., La Mantia, T., Novara, & A., Ruhl, J. (2011). Impact of woody encroachment on soil organic carbon and nitrogen in abandoned agricultural lands along a rainfall gradient in Italy. *Regional Environmental Change*, *11*(4), 917-924. doi:10.1007/s10113-011-0229-6

Bárcena, T. G., Kiær, L. P., Vesterdal, L., Stefánsdóttir, H. M., Gundersen, P., & Sigurdsson, B. D. (2014). Soil carbon stock change following afforestation in Northern Europe: a meta-analysis. *Global Change Biology*, *20*(8), 2393-2405. doi:10.1111/gcb.12576

Bashkin, M. A., & Binkley, D. (1998). Changes in soil carbon following afforestation in HAWAII. *Ecology*, *79*(3), 828-833.

Børja, I., De Wit, H. A., Steffenrem, A., & Majdi, H. (2008). Stand age and fine root biomass, distribution and morphology in a Norway spruce chronosequence in southeast Norway. *Tree Physiology*, *28*(5), 773-784. doi:10.1093/treephys/28.5.773

Bitterlich, W., 1947. Die Winkelzahlmessung. *Allgemeine Forst- und Holzwirtschaftliche Zeitung*, *58* (11/12)

Chen, Z., Yu, G., & Wang, Q. (2020). Effects of climate and forest age on the ecosystem carbon exchange of afforestation. *Journal of Forestry Research*, *31*(2), 365-374. doi:10.1007/s11676-019-00946-5

Chia, R. W., Kim, D. G., & Yimer, F. (2017). Can afforestation with Cupressus lusitanica restore soil C and N stocks depleted by crop cultivation to levels observed under native systems? *Agriculture Ecosystems & Environment*, *242*, 67-75. doi:10.1016/j.agee.2017.03.023

DeGryze, S., Six, J., Paustian, K., Morris, S. J., Paul, E. A., & Merckx, R. (2004). Soil organic carbon pool changes following land-use conversions. *Global Change Biology*, *10*(7), 1120-1132. doi:10.1111/j.1529-8817.2003.00786.x

Deng, L., Liu, G., & Shangguan, Z. (2014). Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. *Global Change Biology*, *20*(11), 3544-3556. doi:10.1111/gcb.12508

Deng, L., Zhu, G., Tang, Z., & Shangguan, Z. (2016). Global patterns of the effects of land-use changes on soil carbon stocks. *Global Ecology and Conservation*, *5*, 127-138. doi:https://doi.org/10.1016/j.gecco.2015.12.004

Ellert, B. H., & Bettany, J. R. (1995). Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, *75*(4), 529-538. doi:10.4141/cjss95-075

Forestry Agency of Japan, 2015. The report of National Land-use Change Survey Project Fiscal Year 2014, 164pp (in Japanese, the title is personally translated in English).

Forest Soil Division. (1976) Classification of forest soils in Japan. *Bulletin of the Government Forestry Experiment Station*, *280*, 1-28.

Georgiadis, P., Vesterdal, L., Stupak, I., & Raulund-Rasmussen, K. (2017). Accumulation of soil organic carbon after cropland conversion to short-rotation willow and poplar. *Global Change Biology Bioenergy*, *9*(8), 1390-1401. doi:10.1111/gcbb.12416

Gifford, R. M., & Roderick, M. L. (2003). Soil carbon stocks and bulk density: spatial or cumulative mass coordinates as a basis of expression? *Global Change Biology*, *9*(11), 1507-1514. doi:10.1046/j.1365-2486.2003.00677.x

Greenhouse Gas Inventory Office of Japan (GIO), Center for Global Environmental Research (CGER), & National Institute for Environmental Studies (NIES) (2019) National Greenhouse Gas Inventory Report of JAPAN

Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, *8*(4), 345-360. doi:10.1046/j.1354-1013.2002.00486.x

IPCC. (2019). Change in carbon stocks in soils, In: E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, A. Osako, Y. Pyrozhenko, P. Shermanau, & S. Federici (Eds.), *2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories*, (pp. 2.33 - 2.52). IPCC, Switzerland.

Ishida, K. (2011) A study on factors and programs for abandoned cultivated land. *Japanese Journal of Farm Management*, *49*(1), 99-104.

Ishimura, D., & Hiramine, R. (2020). Proximal–distal fall deposit correlation of VEI-5 tephra (Towada-Chuseri) from Towada volcano, northeast Japan. *Journal of Quaternary Science*, *35*(1-2), 334-348. doi:10.1002/jqs.3161

Jagodzinski AM, Ziółkowski J, Warnkowska A, & Prais H (2016) Tree Age Effects on Fine Root Biomass and Morphology over Chronosequences of *Fagus sylvatica*, *Quercus robur* and *Alnus glutinosa* Stands. *PLoS ONE, 11*(2): e0148668. doi:10.1371/journal.pone.0148668

Jenkinson, D. S. (1991). The Rothamsted Long-Term Experiments: Are They Still of Use? *Agronomy Journal*, *83*(1), 2-10. doi:10.2134/agronj1991.00021962008300010008x

Kangas, A., (2006). Sampling rare populations, In: Kangas, A., & Maltamo, M. (Eds.), *Forest Inventory*. Springer, Dordrecht, Netherlands, pp. 119-139

Kimura, K. (1981) Degradation of mountain village farmland and its response -A case study in Namiai Village, Nagano Prefecture -. *Journal of the Japanese Society of Irrigation*

Drainage and Reclamation Engineering, *49*(4), 309-316. (The title was translated from original Japanese title)

Koga N., Shimoda S., Shirato Y., Kusaba T., Shima T., Niimi H., Yamane T., Wakabayashi K., Niwa K., Kohyama K., Obara H., Takata Y., Kanda T., Inoue H., Ishizuka S., Kaneko S., Tsuruta K., Hashimoto S., Shinomiya Y., Aizawa S., Ito E., Hashimoto T., Morishita T., Noguchi K., Ono K., Katayanagi N., & Atsumi K. (accepted). Assessing changes in soil carbon stocks after land use conversion from forest land to agricultural land in Japan, *Geoderma*

Lal, R. (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science, 304*(5677), 1623-1627.

Lal, R. (2008). Sequestration of atmospheric CO2 in global carbon pools. *Energy & Environmental Science*, *1*(1), 86-100. doi:10.1039/B809492F

Marín-Spiotta, E., & Sharma, S. (2013). Carbon storage in successional and plantation forest soils: a tropical analysis. *Global Ecology and Biogeography*, *22*(1), 105-117. doi:10.1111/j.1466-8238.2012.00788.x

Marten, G. G. (2005). Environmental Tipping Points: A New Paradigm for Restoring Ecological Security. *Journal of Policy Studies (Japan)*, *20*, 75-87.

Matsumoto, M. (2001) Carbon stock and carbon absorption by Japanese forests, *Shin-rin Kagaku*, *33*,30-36.

Matus, F., Rumpel, C., Neculman, R., Panichini, M., & Mora, M. L. (2014). Soil carbon storage and stabilisation in andic soils: A review. *CATENA*, *120*, 102-110. doi:https://doi.org/10.1016/j.catena.2014.04.008

Mizota, C., Tani, M., Li, X., Aiuchi, D., Niwa, K., Koike, M., & Kuromochi, K. (2008). Differences in soil profile morphology and thickness of layer between upland soil and adjacent virgin soil profiles in Tokachi district, *Pedologist 52*, 19-34.

Nanzyo, M. (1997). Phosphate absorption coefficient, In: Editorial Committee for Methods of Soil Environment Analysis (Dojyo-Kankyo-Bunsekihou-Henshu-Iinkai) (Ed.), *Methods of Soil Environment Analysis (Dojyo-Kankyo-Bunsekihou)*, pp. 262–264. Hakuyusha, Tokyo. (in Japanese).

Osone, Y., Hashimoto, S., Tanaka, K., Araki, M., Inoue, Y., Shichi, K., Toriyama, J., Yamashita, N., Tsuruta, K., Ishizuka, S., Nagakura, J., Noguchi, K., ONO, K., Sakai, H., Sakai, Y., Sano, T., Shigenaga, H., Shinohara, Y., & Yazaki, K. (2020). Plant trait database for *Cryptomeria japonica* and *Chamaecyparis obtusa* (SugiHinoki DB)—their physiology, morphology, anatomy and biochemistry, *Ecological Research*, *35*(1), 274-275. doi:10.1111/1440-1703.12062

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.

Resh, S. C., Binkley, D., & Parrotta, J. A. (2002). Greater soil carbon sequestration under nitrogen-fixing trees compared with Eucalyptus species. *Ecosystems*, *5*(3), 217-231. doi:10.1007/s10021-001-0067-3

Saigusa, M., & Matsuyama, N. (1996) Active aluminum of cultivated Andosols and some related soil chemical properties in Tohoku District, *Japanese Journal of Soil Science and Plant Nutrition*, *67* (2), 174-179.

Shigeno, R. (1992) Generation structure of farm labor force and employment behavior. *The Quarterly Journal of Agricultural Economy*, *46*, 1-132. (The title was translated from original Japanese title)

Toriyama, J., Kato, T., Siregar, C.A., Siringoringo, H.H., Ohta, S., & Kiyono, Y. (2011). Comparison of depth- and mass-based approaches for estimating changes in forest soil carbon stocks: A case study in young plantations and secondary forests in West Java, Indonesia, *Forest Ecology and Management*, *262*, 1659-1667.

Ugawa, S., Takahashi M., Morisada K., Takeuchi M., Matsuura Y., Yoshinaga S., Araki M., Tanaka N., Ikeda S., Miura S., Ishizuka S., Kobayashi M., Inagaki M., Imaya A., Nanko K., Hashimoto S., Aizawa S., Hirai K., Okamoto T., & Kaneko S. (2012) Carbon stocks of dead wood, litter, and soil in the forest sector of Japan: general description of the National Forest Soil Carbon Inventory. *Bulletin of Forestry and Forest Products Research Institute*, *11*, 207–221.

Wei, Y., Li, M., Chen, H., Lewis, B. J., Yu, D., Zhou, L., Zhou1, W., Fang, X., Zhao, W., & Dai, L. (2013). Variation in Carbon Storage and Its Distribution by Stand Age and Forest Type in Boreal and Temperate Forests in Northeastern China. *PLOS ONE*, *8*(8), e72201. doi:10.1371/journal.pone.0072201

Yamashita K. (2016) Making agriculture an attractive place to work. *The monthly journal of the Japan Institute of Labour*, *675*, 33-46. (The title was translated from original Japanese title)

Table 1
Site Information

Region	Site ID	Latitude	Longtitude	MAT[a] (°C)	MAP[a] (mm)	Altitude (m)	Soil type[b]	Former land use	Current vegetation	Tree age	AB[c] (Mg ha^{-1})	Deadwood (MgC ha^{-1})	Litter (MgC ha^{-1})
Hokkaido	HKD-AR01	43.6	142.18	5.7	1253	240	Brown forest soil	Upland field (buckwheat)	Conifer	43	293.4	ND	9.9
Hokkaido	HKD-AR02	43.1	141.85	7.0	1152	90	Black soil	Upland field (potato, bean, wheat)	Conifer	45	239.5	1.8	8.7
Hokkaido	HKD-AR03	43	141.39	6.9	1099	170	Black soil	Upland filed (corn, soybean, sunflower)	Conifer	1	9.7	0.0	0.1
Hokkaido	HKD-AR06	43.1	141.85	6.9	1153	90	Black soil	Upland field (potato, wheat, beans)	Conifer	24	105.7	0.6	10.2
Hokkaido	HKD-AR07	43	141.87	7.0	1154	70	Brown forest soil	Upland field (wheat)	Conifer	55	279.4	3.7	7.2
Hokkaido	HKD-AR08	43.1	141.86	7.0	1176	80	Black soil	Upland field (potato, wheat, beans)	Conifer	48	163.7	5.8	8.7
Hokkaido	HKD-AR09	44.2	142.62	3.0	993	270	Brown forest soil	Upland field (buckwheat and potatoes)	Conifer	51	145.8	7.7	7.1
Hokkaido	HKD-AR10	44.6	142.59	4.9	1350	330	Brown forest soil	Upland field (sunflower, potato, cow grazing)	Hardwood	20	70.7	0.1	6.4
Hokkaido	HKD-AR11	44.4	142.70	4.3	1161	300	Anthrosols	Pasture	Hardwood	8	24.5	0.0	1.9
Tohoku	THK-AR01	39.5	140.27	10.0	1921	60	Brown forest soil	Paddy field	Conifer	15	165.3	ND	2.6
Tohoku	THK-AR02	40.3	140.78	8.4	1502	270	Black soil	Upland field	Hardwood	15	219.5	ND	2.4
Tohoku	THK-AR04	38.8	140.90	10.6	1360	70	Black soil	Upland field	Conifer	40	350.8	ND	1.8
Tohoku	THK-AR07	38.5	140.10	8.8	2255	390	Grey soil	Paddy field	Hardwood	40	45.2	ND	5.8
Tohoku	THK-AR08	38.7	139.97	11.2	2224	70	Grey soil	Paddy field	Conifer	40	276.3	ND	5.1
Kanto	KNT-AR01	36.3	140.34	12.9	1243	30	Black soil	Upland field (buckwheat)	Conifer	20	181.7	ND	9.8
Kanto	KNT-AR06	34.8	137.51	15.2	1743	30	Brown forest soil	Orchard (citrus)	Hardwood	35	91.4	0.2	3.5
Kanto	KNT-AR08	36.8	136.91	12.3	2344	150	Brown forest soil	Upland field (bean)	Conifer	38	429.4	1.3	9.8
Kansai	KAS-AR01	35.1	134.49	11.9	1518	380	Brown forest soil	Paddy field	Conifer	28	144.1	0.5	10.6
Kansai	KAS-AR02	36.3	136.27	13.6	2279	40	Grey soil	Paddy field	Conifer	25	128.8	0.5	2.5
Kansai	KAS-AR03	36.1	136.13	12.6	2326	280	Brown forest soil	Paddy field	Conifer	33	85.2	1.2	6.5
Shikoku	SKK-AR01	33.7	133.55	12.9	3009	410	Brown forest soil	Paddy field	Conifer	38	170.8	8.0	3.6
Shikoku	SKK-AR02	33.7	133.56	12.9	2991	420	Brown forest soil	Paddy field	Conifer	46	348.4	11.5	11.4

Kyushu	KYS-AR01	33.2	130.81	12.3	2781	510	Brown forest soil	Paddy field	Conifer	20	218.7	ND	13.2
Kyushu	KYS-AR02	32.8	130.74	15.7	1967	80	Brown forest soil	Grassland	Hardwood	1	ND	0.0	0.0
Kyushu	KYS-AR03	33	131.28	11.7	2390	670	Black soil	Upland field (corn)	Conifer	43	227.6	0.0	10.7
Kyushu	KYS-AR04	31.7	131.07	15.6	2623	170	Brown forest soil	Grassland (fallow)	Conifer	55	151.0	1.5	5.6
Kyushu	KYS-AR05	33.3	130.26	15.5	1993	10	Brown forest soil	Grassland	Conifer	40	77.6	0.7	2.0

Note . [a] Mean annual temperature (MAT) and mean annual precipitation (MAP) are averaged value for 1971-2000 (Japan Meteorological Agency)

[b] Soil type is classified by Japanese local classification system (Forest Soil Division, 1976)

[c]Aboveground biomass of forest

Table 7. Comparison of Soil Carbon Stocks Between Cropland to Forest Land Using Pair-Sampling Method

country	site	Precipitation (mm)	Temp. (˚C)	Altitude(m a.s.l)	LU pre.	LU post	Age (y)	Cpre (Mg/ha)	Cpost (Mg/ha)	ESM*	Coefficient (Forest/ Cropland)	Ref. No. (see footnote)
Italy	Zafferana Etnea	1100	14	750	Cropland	Shrubland	15	41.1	29.5	no	0.72	*1*
Italy	Maletto	900	12.5	1000	Cropland	Shrubland	15	57.7	74.7	no	1.29	*1*
Italy	San Martino	750	14.5	750	Cropland	Shrubland	11	98.3	102	no	1.04	*1*
Italy	Giacalone	750	14.5	750	Cropland	Shrubland	30	76.6	92.7	no	1.21	*1*
Italy	Misilmeri	700	18	250	Cropland	Shrubland	35	59.8	97.7	no	1.63	*1*
Italy	Santa Ninfa	654	17	450	Cropland	Shrubland	25	53.3	89	no	1.67	*1*
Italy	Trappeto	650	17.5	150	Cropland	Forest (Maquis)	15	31.1	47.6	no	1.53	*1*
Ethiopia	5year	1200-1244	19.5	1860	Cropland	Forest	5	74.3	79.5	yes	1.07	*2*
Ethiopia	8year	1200-1244	19.5	1849	Cropland	Forest	8	74.3	82.9	yes	1.12	*2*
Ethiopia	17year	1200-1244	19.5	1848	Cropland	Forest	17	74.3	77.4	yes	1.04	*2*
USA	Michigan	890	9.7	ND	Cropland	Forest	10	34.9	35.8**	no/yes	1.03**	*3*
USA	Michigan	890	9.7	ND	Cropland	*Quercus* (successional)	10	34.9	45.5**	no/yes	1.30**	*3*
USA	Hawaii, Kamae	4000	21	ND	Fallow sugarcane	*Eucalyptus* plantation	15	108.9	131.3**	no/yes	1.21**	*4*
USA	Hawaii, Kamae	4000	21	ND	Fallow sugarcane	*Albizia* plantation	15	108.9	140.8**	no/yes	1.29**	*4*
Denmark & Sweden	26 sites	ND	ND	ND	Cropland	willow and poplar plantation	4-29	81.2	84.9	yes	1.04	*5*
USA	Hawaii	3000-4600	21	30-400	Cropland	*Eucalyptus* plantation	21-14	74.1	79.6	no	1.07	*6*
Japan	23 sites	1000-3000	3.0-15.7	10-670	Cropland, Grassland	Conifer plantation, Hardwood	1-55	77.6	84.6	yes	1.10	*this study*

Note . *ESM: "no" means no data available for the ESM recalculation, "yes" means calculated by ESM method in the literature, and "no/yes" means that the soil carbon stock was calculated by depth-based method in the original paper but we recalculated the soil carbon stock by ESM method using the data of bulk density and carbon concentration in the paper.

**re-calculated by equivalent soil mass basis using the bulk density and soil carbon content data in the literature

Reference number: *1* Alberti, G., et al. (2011), *2* Chia, R. W., et al. (2017), *3* DeGryze, S., et al. (2004), *4* Resh, S. C., et al. (2002), *5* Georgiadis, P., et al. (2017). *6* Bashkin & Binkley (1998)