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**The effect of organic matter application on carbon sequestration and soil fertility in upland
fields of different types of Andosols**

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Abstract

We evaluated the effect of long-term application of organic matter on soil organic carbon (SOC), and physico-chemical properties of different types of Andosols in the cool temperate zone. In 2012, a soil survey was conducted in 34 fields in Toya, Hokkaido, Japan, using reference data collected from 2001 to 2003 in the same fields. The region contains three groups of soil series (K1, K2, and HO), with soils of K1 (Vitric Andosols) being strongly affected by newly (1769–2000) erupted volcanic ash compared with K2 and HO (Silandic Andosols). The mean application rate of organic matter was $1.45 \pm 1.27 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Mean SOC contents in 2001–2003 and 2012 were 26.5 ± 8.1 and $25.7 \pm 5.7 \text{ g C kg}^{-1}$, respectively, and mean SOC stocks were 39.6 ± 10.2 and $37.9 \pm 7.4 \text{ Mg C ha}^{-1} \text{ 0.15 m}^{-1}$, respectively. There were no significant differences in either SOC content or stock. However, the rate of change in SOC between 2001–2003 and 2012 (ΔSOC) was significantly higher in K1 than in K2, and SOC decreased significantly in K2. There was a significant negative correlation between initial SOC and rate of ΔSOC : rate of ΔSOC content ($\text{g C kg}^{-1} \text{ yr}^{-1}$) = $-0.046 \times \text{Initial SOC content (g C kg}^{-1}) + 1.12$ and rate of ΔSOC stock ($\text{Mg C ha}^{-1} \text{ 0.15 m}^{-1} \text{ yr}^{-1}$) = $-0.052 \times \text{Initial SOC stock (Mg C ha}^{-1} \text{ 0.15 m}^{-1}) + 2.09$. The thresholds of initial SOC content and stock (intercept at the x-axis) were calculated as 24.3 g C kg^{-1} and $36.1 \text{ Mg C ha}^{-1} \text{ 0.15 m}^{-1}$, respectively. These values were higher than those obtained in previous studies conducted in croplands probably because of the specific features of Andosols. ΔSOC content was significantly negatively correlated

with Δ bulk density, Δ available phosphorus, and base saturation, but positively correlated with Δ total porosity, Δ phosphate absorption coefficient, and cation exchange capacity. These findings indicate that application of organic matter increases SOC and improves soil fertility when the initial SOC is lower than the threshold and highlight the difficulties in maintaining or accumulating SOC in Andosols because of the high SOC.

Keywords: Andosol, Organic matter application, physico-chemical properties, Soil organic carbon.

1. Introduction

The carbon (C) stored in the top 1 m of soil (1500 Pg C) is approximately three times that stored in the aboveground biomass, and twice that present as carbon dioxide (CO₂) in the atmosphere (Jobbágy and Jackson 2000; Janzen 2004). Therefore, changes in soil organic carbon (SOC) stock have a considerable influence on atmospheric CO₂ concentrations. The IPCC (2013) estimated a 33% contribution of land-use change to anthropogenic global carbon emissions (180 Gt C was emitted from 1750 to 2011). Although the change in SOC stock is likely to be one of the causes of these C emissions, the exact rate remains unclear. Bellamy *et al.* (2005) reported that in all land use in England and Wales, SOC was lost at a mean rate of 0.6% yr⁻¹ (relative to the existing soil carbon content) from 1973 to

2003. They also found a significant linear relationship between the rate of change in SOC and the initial SOC content (1973), indicating that the losses occurred in soils with SOC greater than a threshold level. Moreover, several researchers have reported a decrease in SOC in temperate and cool temperate zones, such as England and Wales, South Norway, France, Finland, and South Germany (Lark *et al.* 2006; Riley and Bakkegard 2006; Saby *et al.* 2008; Heikkinen *et al.* 2013; Capriel 2013). Significant negative correlations between initial SOC content and the rate of change in SOC content have also been reported in similar zones in South Norway, South Belgium, France, the Netherlands, and South Germany (Riley and Bakkegard 2006; Goidts and van Wesemael 2007; Saby *et al.* 2008; Hanegraaf *et al.* 2009; Capriel 2013). These studies provided no information on soil types; moreover, there have been no studies that have focused on in volcanic soils such as Andosols.

Although Andosols cover only approximately 0.84% of the world's land surface (Soil Survey Staff, 1999), they, including ancient to recent, cover more than 50% of the total upland crop field area in Japan. Moreover, Andosols often have high organic carbon content, mainly due to the formation of short-range ordered minerals and Al/Fe–humus complexes (Shoji *et al.* 1993; Takahashi and Dahlgren, 2016). Therefore, changes in the SOC of Andosols contribute significantly to calculations of CO₂ emission from soils (Shirato *et al.* 2004)

Soil organic matter (SOM) is a major binding agent that stabilizes soil aggregates, whereas soil aggregates protect organic matter and act as an important reservoir of C and other mineral nutrients

(Elliot 1986; Beare *et al.* 1994). SOM therefore affects the physico-chemical properties of soil (Matson *et al.* 1997; Bot and Benites 2005). Increases in SOM lower bulk density (BD) but improve aggregation, hydraulic conductivity, water-holding capacity, and total porosity (Celik *et al.* 2004; Papadopoulos *et al.* 2009; Celik *et al.* 2010; Liu *et al.* 2011). In addition, the cation exchange capacity (CEC) of soil is highly correlated with SOC content (Gruba and Mulder 2015).

In cropland, C sequestration is influenced by field management practices (Jobbágy and Jackson 2000; Jastrow *et al.* 2007). Management systems relying on chemical fertilizers have increased agricultural productivity, but their application may induce a decline in SOC and the leaching of environmental pollutants—for example, by soil erosion and nitrogen (N) leaching—to the aquasphere because of the lack of C input and excess amounts of N input to soils (Mäder *et al.* 2002; Pimentel *et al.* 2005). The application of organic matter is expected to increase SOC by means of the direct input of a C source and mitigate environmental pollution by the stabilization of soil aggregates and the reduction of chemical fertilizer application rates. Many studies have indicated a positive relationship between the amounts of C incorporated into soil and an increase in SOC content (Hao *et al.* 2003; Kundu *et al.* 2007, Naveed *et al.* 2014).

Andosols are noted for their good physical properties, including low BD, high porosity, high water-holding capacity, well drainage and aeration, good tilth and friability (Shoji *et al.* 1993; McDaniel *et al.* 2012; Takahashi and Dahlgren 2016). Consequently, Andosols have been widely used for

cultivation in Japan. However, the low BD results in low weight-bearing capacity and renders Andosols highly susceptible to wind erosion (McDaniel *et al.* 2012). Moreover, phosphorus deficiency caused by a high phosphate absorption coefficient (PAC) (Shoji *et al.* 1993; Takeda *et al.* 2009) is a major constraint on crop production in Andosols. Organic matter application has been expected to minimize the effect of wind erosion by facilitating aggregate stability (Bronick and Lal 2005; Arthur *et al.* 2013) and to improve P availability by enhancing organic P mineralization (Tsuji *et al.*, 2006; Takeda *et al.* 2009).

Management practices that influence SOC concentration may also affect soil BD. However, most previous studies have evaluated SOC stock using SOC content and soil BD associated with a specific soil depth (fixed-depth method) (Mikha *et al.* 2013; Lee *et al.* 2009), without considering changes in soil mass caused by changing BD. Consequently, changes in soil BD and its effect on unequal soil mass associated with a fixed depth have a confounding effect on the estimation of SOC mass (Mikha *et al.* 2013), illustrating the importance of reporting soil C using an equivalent soil mass (ESM) method (Ellert and Bettany 1995).

It is important to evaluate the effect of long-term application of organic matter in Andosols, not only from the perspective of C sequestration but also from that of soil fertility improvement.

Therefore, we conducted the present study in Toya, Hokkaido, Japan, where Andosols of different

ages are distributed in the same area and practices that encourages the efficient use of organic matter have been developed from the late 1990s.

This study had the following aims: firstly, to estimate the changes in SOC content and stock associated with long-term application of organic matter in upland fields of Andosols in the cool temperate zone by using an ESM method; secondly, to evaluate the effects of long-term applications of organic matter on soil physico-chemical properties; and, thirdly, to identify the factors that control SOC sequestration.

2. Materials and methods

2.1. Study site

The study was conducted in Toya, Central Hokkaido, Japan (42° 65'N, 140° 80'E), located on the north side of Lake Toya (Fig. 1). The site was characterized by a humid continental climate with cold winters and cool summers but without an apparent wet or dry season. The long-term (30 years) average annual precipitation and air temperature were 1179 mm and 7.5 °C, respectively, with a mean monthly temperature ranging from 24.5 °C in August to -4.2 °C in January.

The soil was classified as an Andosol (IUSS working Group WRB. 2015), and the parent materials were derived from Toya Caldera. Subsoils in the study area were derived from Mt. Yotei (Ya), and surface soils from Mt. Usu (Ua and Ub) (Miyabuchi *et al.* 2014). Eruptive activity at Usu Volcano

resumed in 1663, and since then seven eruptions have been recorded in 1769, 1822, 1853, 1910, 1943–1945, 1977–1978, and 2000 (Miyabuchi *et al.* 2014). Ua was derived from the volcanic ash produced by an eruption after 1769. Ub originated from the volcanic ash produced by the eruption in 1663. Four major soil series are distributed in this area (Fig. 1). Kagawa-1 (K1) was more affected by Ua and Ub than the other three soil series, since the K1 soil series is closer to Mt. Usu (Fig. 1). K1 is consequently an immature soil, which has low SOC content and soil physico-chemical fertilities (Table 1). Kagawa-2 (K2), Ohara (H), and Ohnishiyama (O) have thin Ua and Ub horizons. The soil series of H and O have high SOC content in whole profiles and are regarded as being of a similar soil series (Table 1). The K1 soil series is classified as a Vitric Andosol [IUSS Working Group WRB. 2015; Typic Udivitrands (Soil Survey Staff 2014)], whereas the K2, H, and O soil series are classified as Silandic Andosols [IUSS Working Group WRB. 2015; Typic Hapludands or Hydric Hapludands (Soil Survey Staff 2014)].

Major crops such as corn (*Zea mays*), sugar beet (*Beta vulgaris vulgaris*), potato (*Solanum tuberosum*), red bean (*Vigna angularis*), radish (*Raphanus sativus* var. *longipinnatus*), carrot (*Daucus carota* subsp. *sativus*), and burdock (*Arctium lappa*) are rotationally cultivated in this area.

2.2 Soil sampling

From 2001 to 2003, soil profiling surveys and physico-chemical property analyses were conducted in 34 upland fields [12 fields from K1, 18 fields from K2, two fields from H, and two fields from O

(Fig. 1)] with one replicate by the Hokkaido Central Agricultural Experiment Station. The average depth of the Ap horizon of the 34 fields was 0.23 ± 0.04 m (ranging from 0.15 to 0.32 m) in 2001–2003 and no changes have been reported since that time. Three replicates of both composite and undisturbed samples (100 mL) were taken from the top 0.15 m (the minimum depth of the Ap horizon) of the soils in the same fields in May 2012 to evaluate the effect of organic matter application on C stock change in the Ap horizon. As the H and O are regarded as similar soil series, these soil series are treated as one group (HO) in this study.

2.3 Sample preparation and analysis

2.3.1 Sample preparation

To measure the chemical properties of soil samples, composite samples were air dried and passed through a 2-mm mesh sieve that removed stones, roots, and other plant residues. Samples for C content estimation were sifted further using a 0.5-mm mesh. Samples were stocked in the laboratory until measurements of soil chemical properties could be conducted.

2.3.2 Soil physical properties

The same methods in 2001–2003 and 2012 were employed to determine the soil physical properties. Total porosity was measured using a three-phase meter (DIK-1110; Daiki Rika, Saitama, Japan). The

cores were then oven dried at 105 °C for 48 h to measure water content and BD. The saturated hydraulic conductivity was measured using both constant head and falling head methods, based on Darcy's law. Soil texture was determined using the pipette method.

2.3.3 Soil organic carbon (SOC) content

The wet oxidation method using $K_2Cr_2O_7$ was used to determine SOC content in 2001–2003. This method has been reported to give, on average, 6–7% lower SOC concentrations for mineral soil than the dry combustion method (Sippola 1982). Hence, 15 surface soil samples collected in 2012 were analyzed with both this method and the dry combustion method using an NC analyzer (NC-900; Sumika Chemical Analysis Service, Ltd., Osaka, Japan), to account for discrepancies between the methodologies. We accordingly obtained the following regression equation: SOC using the combustion method ($g\ C\ kg^{-1}$) = $1.04 \times$ SOC using the oxidation method ($g\ C\ kg^{-1}$) + 0.24 (1) ($R^2 = 0.99$, $P < 0.01$). Using this equation, we modified the values measured using the oxidation method in 2001–2003.

2.3.4 Soil chemical properties

Soil pH, available phosphorus (P), phosphate absorption coefficient (PAC), cation exchange capacity (CEC), exchangeable base cations, and available nitrogen (N) were measured using the same methods

in 2001–2003 and 2012.

Soil pH in 1:5 soil:water suspensions was measured using a pH meter (F-8 pH meter; Horiva, Japan).

Available P was measured using the Truog method. Soil samples were extracted with 0.001 M H₂SO₄,

and the concentration of P₂O₅ was determined with the ascorbic acid reduction method using a

spectrophotometer (UV mini-1240; Shimadzu, Kyoto, Japan). PAC was measured using the

ammonium phosphate method. The soil sample was extracted for 24 h with 13.44 mg P₂O₅ mL⁻¹

ammonium phosphate solution, and the concentration of P₂O₅ was determined using the

vanadomolybdate acid method using a spectrophotometer (UV mini-1240; Shimadzu, Kyoto, Japan).

CEC and exchangeable base cations were measured using the batch method. Exchangeable potassium

(K⁺), sodium (Na⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) were extracted with 1 M ammonium

acetate (pH 7). Concentrations of K⁺ and Na⁺ were measured using flame photometry (Z5010; Hitachi,

Tokyo, Japan), and concentrations of Ca²⁺ and Mg²⁺ were measured using atomic absorption

spectrophotometry (Z5010; Hitachi, Tokyo, Japan). To determine CEC, the residual soil, after the

extraction of exchangeable cations, was extracted further with 1 M KCl, and the concentration of

NH₄⁺-N was measured using the formol titration method. Base saturation (BS) was determined as the

proportion of exchangeable basic cations to CEC. Thermal extraction methods are used to assess the

availability of nitrogen in soil (Curtin *et al.* 2006; Chantigny *et al.* 2008), and in this study, available

N was measured using a simplified thermal extraction estimation method (Sakaguchi *et al.* 2010).

2.4 Management practice

Application of organic matter was conducted in all 34 fields in the area because of the practice developed in the late 1990s that encourages sustainable agriculture with proper fertilization, based on soil analyses, and the effective use of organic matter. Information on management practices was collected using questionnaires given to farmers. Application rates of manure, green manure, and combined organic and synthetic fertilizer during the period between 2001–2003 and 2012 were collected. In this study, combined organic and synthetic fertilizer was defined as the sum of chemical fertilizer, organic fertilizers such as dried bacterial cells and defatted rice bran, and a mixture of chemical and organic fertilizers.

2.5 Manure sampling and analysis

Manures in this region are produced intensively on several livestock farms, and farmers purchase these manures from the farms. According to the result of the questionnaire for the farmers, we chose representative farmers who used each of the different types of manure (field nos. 9, 10, 28, 29, and 31). Manure samples were collected with five replicates in October 2012. Manure samples were well homogenized, and their chemical properties were analyzed in the laboratory. Fresh samples of manure were air-dried and passed through a 1-mm mesh to determine total carbon (TC), total nitrogen (TN),

P₂O₅, and K₂O contents. TC and TN were measured using the dry combustion method (NC-900; Sumika Chemical Analysis Service, Ltd., Osaka, Japan). P₂O₅ and K₂O content were measured using the wet oxidation method with conc. H₂SO₄. Concentrations of P₂O₅, K⁺, and Mg²⁺ were determined with the vanadomolybdate acid method using spectrophotometry (UV mini-1240; Shimadzu, Kyoto, Japan), flame photometry, and atomic absorption spectrophotometry (Z5010; Hitachi, Tokyo, Japan), respectively. Each of these analyses was replicated three times.

2.6 Calculations

2.6.1 Carbon stock

The SOC stock (Mg C ha⁻¹) in 0–0.15 m of the soil in 2012 was calculated using the following equations:

$$M_{2012} = \rho_{b2012} \times 0.15 \times 10^4 \quad (2)$$

where M_{2012} represents the soil mass (Mg ha⁻¹ 0.15m⁻¹), ρ_{b2012} is the soil bulk density (Mg m⁻³) in 2012, 0.15 is the soil sampling depth (m) in 2012, and 10⁴ is a factor to adjust units.

$$C_{stock2012} = M_{2012} \times C_{conc2012} \times 10^{-3} \quad (3)$$

where $C_{stock2012}$ represents the SOC stock in 2012 (Mg C ha⁻¹ 0.15 m⁻¹), $C_{conc2012}$ is the SOC content (g C kg⁻¹) in 2012, and 10⁻³ is a factor to adjust units.

SOC stock in 2001–2003 ($C_{stock2001-03}$) was calculated using the equivalent soil mass (ESM) method

(Ellert and Bettany 1995; Mikha *et al.* 2013). This method is generally recommended for comparing soil C stocks (Palm *et al.* 2014) because it minimizes the error associated with the possible changes in soil BD between the two sampling times. The soil mass in 2001–2003 was adjusted to that in 2012, and $C_{\text{stock2001-03}}$ was calculated as follows:

$$C_{\text{stock2001-03}} = M_{2012} \times C_{\text{conc2001-03}} \times 10^{-3} \quad (4)$$

where $C_{\text{conc2001-03}}$ is SOC content (g C kg⁻¹) in 2001–2003, and 10⁻³ is a factor to adjust units.

2.6.2 Change of SOC and soil physico-chemical properties.

The amount of change in SOC stock (ΔC_{stock} , Mg C ha⁻¹ 0.15 m⁻¹) was estimated as follows:

$$\Delta C_{\text{stock}} = C_{\text{stock2012}} - C_{\text{stock2001-03}} \quad (5)$$

The SOC stock change rate ($\Delta C_{\text{stockrate}}$, Mg C ha⁻¹ yr⁻¹) was calculated as follows:

$$\Delta C_{\text{stockrate}} = \Delta C_{\text{stock}} / T \quad (6)$$

where T is the interval (years) between the two soil sampling times.

The same calculation procedure was used to obtain the rate of change in SOC content and other soil physico-chemical properties.

2.6.3 Application rate of organic matter

Annual average C application rates of manure, green manure, organic fertilizer (C_{org} , Mg C ha⁻¹ yr⁻¹)

¹), N, P, and K were calculated as follows:

$$C_{org} = (R \times DMC \times TC \times 100) / Y \quad (7)$$

where R is the application rate of fresh organic matter ($Mg\ ha^{-1}\ period^{-1}$), DMC is the dry matter content of applied organic matter ($kg\ kg^{-1}$), TC is the total carbon content of dry organic matter ($g\ C\ kg^{-1}$), 100 is a factor to adjust units, and Y is the number of years.

Heiotsu (*Avena sativa*) was used as a green manure and both succeeding crop green manure and fallow green manure were used in the study site. The Hokkaido Agricultural Department (2004) have cited values for the fresh and dry matter weight and nutrient contents of green manures. The application rate of C in combined organic and synthetic fertilizer was calculated from the application rate of N and the CN ratio of organic matter (Shiga et al. 1985; Noguchi 2001). Dried bacterial cells, feather meal, defatted rice bran, rapeseed meal, soybean meal, fish meal, meat-and-bone meal, hair meal, and dried cow dung were applied, the CN ratios of which were 4.1, 3.1, 10.5, 5.7, 4.3, 3.6, 4.2, 4.9, and 15.5, respectively.

2.7 Statistical analysis

Statistical analyses were performed using R (R Development Core Team 2014; version 3.1.0). The differences in manure, green manure, and fertilizer application rates among the soil series were determined using a one-way factorial analysis of variance (ANOVA) and the Tukey–Kramer test. The

1 difference in soil physico-chemical properties among the fields and in the different years was
 2 determined using a two-way ANOVA and the Tukey-Kramer test. When interactions between the fields
 3 and the years were observed, the difference between the years for each of the 34 fields was analyzed
 4 using a paired t-test. The difference in soil physico-chemical properties among the soil series was
 5 analyzed using a one-way ANOVA and the Tukey-Kramer test. The difference between the two
 6 regression equations was analyzed using an analysis of covariance (ANCOVA).

8 **3. Results**

9 *3.1 Management practice*

10 Table 2 shows the annual average application rates of fresh weight, C, N, P₂O₅, and K₂O of manure,
 11 green manure, and combined organic and synthetic fertilizer in the study fields. Manure was used in
 12 24 fields and was spread once every 2 to 5 years from April to May and/or September to October.
 13 Green manure was used in 26 fields and was grown as the succeeding crop green manure, once every
 14 2 to 5 years, after the harvest of cultivated crops, or cultivated as a fallow green manure. Combined
 15 organic and synthetic fertilizer were applied to 33 fields. The annual average fresh weight of applied
 16 manure, green manure, and combined organic and synthetic fertilizer was 6.8 ± 7.8 , 8.3 ± 6.1 , and 1.4
 17 ± 0.5 Mg ha⁻¹ yr⁻¹, respectively, and there was no significant difference between the soil series. The
 18 annual average input of C in K1, K2, and HO was 1.71 ± 1.22 , 1.33 ± 1.42 , and 1.21 ± 0.67 Mg C ha⁻¹

¹ yr⁻¹, respectively. The application rate for K1 was relatively higher compared with that for K2 and HO. However, there were no significant differences among the soil series. The annual average input of N, P₂O₅, and K₂O was 209 ± 112 Kg N ha⁻¹ yr⁻¹, 274 ± 168 kg P₂O₅ ha⁻¹ yr⁻¹, and 224 ± 100 kg K₂O ha⁻¹ yr⁻¹, respectively, and there were no significant differences among the soil series. The composition ratio of manure, green manure, and other organic matters was 65%, 32%, and 3% in C, 32%, 10%; 58% in N; 26%, 4%, and 70% in P₂O₅; and 32%, 19%, and 49% in K₂O, respectively.

3.2 SOC content and SOC stock

The results of the two-way ANOVA showed significant differences in SOC content ($P < 0.01$) between the fields (Table 3). Significant interactions between the fields and the years were also observed ($P < 0.01$), and the trend of increasing and decreasing SOC content differed in each field. Paired t-tests showed that SOC content increased, decreased, and was unchanged in 18%, 32%, and 50% of the fields, respectively. There were significant differences in SOC stock ($P < 0.01$) between the fields, but not in the different years (Table 3). Significant interactions between the fields and the years were observed ($P < 0.01$). SOC stock increased, decreased, and was unchanged in 10%, 35%, and 55% of the fields, respectively. In K2 soil series, SOC content and SOC stock decreased significantly. In HO soil series, those showed similar tendency, but in K1 soil series, there was a tendency of the increase (Table 4). The rates of Δ SOC content (0.24 ± 0.61 , -0.27 ± 0.38 , and $-0.33 \pm$

0.48 g C kg⁻¹ yr⁻¹, for K1, K2, and HO, respectively) and ΔSOC stock (0.44 ± 0.88 , -0.44 ± 0.59 , and -0.50 ± 0.70 Mg C ha⁻¹ 0.15 m⁻¹ yr⁻¹ for K1, K2, and HO, respectively), were significantly different in the soil series and ΔSOC content and ΔSOC stock were significantly higher in the K1 soil series in comparison with the K2 soil series. ΔSOC content and ΔSOC stock increased with increasing rates of manure C application; however, the correlations were not significant (Table 5). SOC content and SOC stock were negatively correlated with sand content and were positively correlated with silt content in 2001–2003 and 2012 ($P < 0.01$ and $P < 0.01$ for sand and $P < 0.01$ and $P < 0.01$ for silt in 2001–2003 and $P < 0.01$ and $P = 0.05$ for sand and $P < 0.01$ and $P < 0.01$ for silt in 2012) (Fig. 2). However, soil texture had no effect on the rates of ΔSOC content and ΔSOC stock. There was a significantly negative correlation between initial SOC content (in 2001–2003) and the rates of ΔSOC content ($P < 0.01$) (Fig. 3a) and between initial SOC stock (in 2001–2003) and the rate of ΔSOC stock ($P < 0.01$) (Fig. 3b).

3.3 Soil physical properties

Results of the two-way ANOVA showed that there were significant differences in BD and total porosity ($P < 0.01$) in the different fields and in both 2001–2003 and 2012, and that hydraulic conductivity was significantly different between the years ($P < 0.01$) and there was no interaction between the fields and the years in terms of physical properties (Table 6). BD decreased significantly in K1 and K2 soil series, and there was a tendency of decrease of BD in the HO soil series ($P = 0.1$)

(Table 4). K1 soil series showed a tendency of increase of total porosity ($P = 0.07$), no significant changes were observed in the K2 and HO soil series. A significantly negative correlation between SOC content and BD ($P < 0.01$), and positive correlations between SOC content and total porosity ($P < 0.01$) were found in both 2001–2003 and 2012 (Table 7). Similarly, we observed a significantly negative correlation between Δ SOC content and Δ BD ($P < 0.05$), and a positive correlation between Δ SOC content and Δ total porosity ($P < 0.05$) (Table 5).

3.4 Soil chemical properties

pH, available N, PAC, and available P were significantly different in each field and in both 2001–2003 and 2012 ($P < 0.01$), and significant interactions between the fields and the years were also observed ($P < 0.01$) (Table 8). Paired t-test results showed that pH increased, decreased, and remained unchanged in 52%, 27%, and 21% of the fields, respectively. Available N increased, decreased, and remained unchanged in 12%, 53%, and 35% of the fields, respectively. PAC increased, decreased, and remained unchanged in 54%, 9%, and 29% of the fields, respectively, whereas available P increased, decreased, and remained unchanged in 9%, 29%, and 62% of the fields, respectively. The trend of change for pH, available N, PAC, and available P differed among the soil series (Table 4). pH increased significantly only in the K1 soil series and a significantly higher Δ pH was observed in the K1 soil series than the K2 and HO soil series. The available N decreased significantly in the K1 and K2 soil

series, but no change was observed in the HO soil series, and the Δ available N was significantly lower in the K1 soil series than the K2 soil series. PAC increased significantly in the K1 and K2 soil series, but a significant decrease in available P was observed only in the K1 soil series. PAC increased significantly in the K1 and K2 series, but a significant decrease in available P was observed only in the K1 soil series. Δ PAC (787 ± 479 , 193 ± 341 , and 46 ± 272 mg P_2O_5 100 mg^{-1} , for K1, K2, and HO, respectively) was significantly higher in K1 soil series than K2 and HO soil series, while Δ available P (-19.5 ± 19.7 , -5.1 ± 9.7 , and -1.7 ± 2.5 mg P_2O_5 kg^{-1} , for K1, K2, and HO, respectively) was significantly lower in the K1 soil series than K2 and HO soil series. Changes in PAC and available P between 2001–2003 and 2012 were significantly positively and negatively correlated with Δ SOC content ($P < 0.01$), respectively, and there was a significant negative relationship between Δ available P content and Δ PAC ($P < 0.01$) (Table 5).

Exchangeable K^+ and Mg^{2+} , base saturation, and CEC were significantly different in each field and in 2001–2003 and 2012 ($P < 0.01$), but exchangeable Ca^{2+} was significantly different only between the fields ($P < 0.01$). However, there was a significant interaction between the fields and the years for all the properties ($P < 0.01$) (Table 9). Exchangeable K^+ increased, decreased, and was unchanged in 73%, 3%, and 24% of the fields, respectively; exchangeable Ca^{2+} increased, decreased, and was unchanged in 18%, 23%, and 59% of the fields, respectively; and exchangeable Mg^{2+} increased, decreased, and was unchanged in 44%, 9%, and 47% of the fields, respectively. Base saturation increased, decreased,

and was unchanged in 3%, 32%, and 65% of the fields, respectively. CEC increased, decreased, and was unchanged in 59%, 3%, and 38% of the fields, respectively. Among the soil series, there were no differences in the trend of change in exchangeable base cations and CEC. (Table 4). A significant increase in exchangeable Mg^{2+} was observed only in the K1 soil series, and the Δ exchangeable Mg^{2+} was significantly higher in the K1 soil series in comparison with the K2 soil series. There was a strong positive correlation between CEC and SOC content in both 2001–2003 and 2012 ($P < 0.01$) (Fig. 4), and a significant positive relationship between Δ SOC content and Δ CEC ($P < 0.01$) (Table 5).

4. Discussion

4.1 Possible causes of changes in SOC and soil physico-chemical properties

From 2001–2003 to 2012, we observed changes in SOC content and SOC stock, and several soil physico-chemical properties, such as significant improvement of soil physical properties (Table 6), and significant increases in PAC (Table 8) and CEC (Table 9). In the K1 soil series in particular, significant increases in SOC content and stock were observed in several fields (Table 3), and a significant increase in PAC and significant decrease in available P were also observed (Table 4). These changes can be attributed to the long-term application of organic matter and mixing with subsurface soil. The Ya horizon with high SOC content, PAC, and CEC, and low BD appeared only at a depth of below 0.77, 0.57, and 0.48 m in K1, K2, and HO (the average value of H and O) soil series, respectively,

and it was much deeper than the depth of plowing (Table 1). Additionally, the subsurface horizon of K1 is a mixture of Ua and Ub or Ub horizons, which has soil physico-chemical properties similar to the surface horizon (Table 1). We accordingly judged that long-term application of organic matter is the main cause of the changes in SOC and soil physico-chemical properties.

4.2 SOC content and SOC stock

The changes in SOC stock reflect the C balance in a field [the difference between C input (net primary production and organic matter application) and C output (organic matter decomposition, harvest, and erosion)]. Improved agricultural practices that could lead to reduced carbon losses, or even increased SOC stock, are highly desirable (West and Post 2002; Lal *et al.* 2004). In this study, the changes in both SOC content and SOC stock were not significant but decreased slightly during the study period (Table 3). This result indicated that organic matter application basically maintained the SOC content and SOC stock in this study area. Organic matter application is generally expected to increase SOC (Hao *et al.* 2003; Kundu *et al.* 2007; Naveed *et al.* 2014). Several studies have indicated a positive relationship between the amounts of C incorporated into the soil and SOC content (Hao *et al.* 2003; Kundu *et al.* 2007; Naveed *et al.* 2014). In this study, there were weak positive trends of increase in Δ SOC content and Δ SOC stock with increases in the application of manure C (Table 5).

Clay particles protect and stabilize SOM (Six *et al.* 2002; Bronick and Lal 2005), but in this study,

there was no significant correlation between SOC and clay content. However, there was a significant positive correlation between silt content and SOC (Fig. 2). This result may indicate that the SOC accumulates in fine pores inside aggregates formed by the orientation of silt particles rather than via chemical bonding with clay minerals. Heikkinen *et al.* (2013) reported that the cultivation of annual crops decreased SOC in coarse-textured soils more than in fine-textured soils. However, we could not detect a direct effect of texture on changes in SOC.

Table 10 shows a comparison of the regression equations between initial SOC content and rate of Δ SOC content obtained in previous studies in England and Wales (Bellamy *et al.* 2005), South Norway (Riley and Bakkegard 2006), the Netherlands (Hanegraaf *et al.* 2009), and South Germany (Capriel 2013). All of these studies were conducted in temperate or cool temperate zones, and the soil types were undisclosed. The threshold level of initial SOC content ranged from 0.35 to 63.7 g C kg⁻¹. Because all of these studies were undertaken in temperate or cool temperate zones, and the mean annual temperature (ranging from 5.6 to 9.7 °C) and the annual precipitation (ranging from 620 to 798 mm) are not so differ among the studies, we could not determine the effect of climate on the threshold. The threshold level in grassland or grassland and maize rotation (ranging from 22.3 to 63.7 g C kg⁻¹) appears to be higher than it is in cropland (15.8 and 17.2 g C kg⁻¹), with the exception of 0.35 g C kg⁻¹ in the grassland and maize rotation in the Netherlands (Hanegraaf *et al.* 2009). Agricultural practices such as tillage enhance SOM decomposition through the destruction of soil aggregate and an increase

in aerobic conditions (Balesdent *et al.* 2000; Grandy and Robertson 2006). Moreover, the export of C through the harvesting of crops also causes a reduction of SOC in cropland in comparison with other land uses such as natural forest or grassland (Gelaw *et al.* 2014; Wang *et al.* 2016). The threshold level that we obtained in this study (24.3 g C kg^{-1}) was higher than those in croplands in South Norway (Riley and Bakkegard 2006) and South Germany (Capriel *et al.* 2013) (15.8 and 17.2 g C kg^{-1} , respectively). This may be attributable to the specific feature of Andosols in this study area, which accumulate SOC by the formation of short-range-ordered minerals and Al/Fe–humus complexes (Shoji *et al.* 1993; Takahashi and Dahlgren, 2016).

Similar to previous studies, a significant negative relationship between initial SOC content (in 2001–2003) and the rate of Δ SOC content (Fig. 3a) and the rate of Δ SOC stock (Fig. 3b) were observed (Bellamy *et al.* 2005; Lark *et al.* 2006; Riley and Bakkegard 2006; Goidts and van Wesemael 2007; Saby *et al.* 2008, Hanegraaf *et al.* 2009; Capriel 2013). From the regression equations, the threshold level of initial SOC was estimated as $24.3 \text{ (g C kg}^{-1}\text{)}$ in SOC content and $36.1 \text{ (Mg C ha}^{-1} \text{ } 0.15 \text{ m}^{-1}\text{)}$ in SOC stock.

We observed various trends in Δ SOC content and Δ SOC stock in different soil series (Table 4). There was no significant difference between the soil series with regards to the total application rate of C via organic matter (Table 2). Therefore, difference of initial SOC content might be a reason for the different trend of Δ SOC content and Δ SOC stock, because there was a significant relationship between

initial SOC and Δ SOC content and stock (Fig. 3). Positive Δ SOC content and stock were found in K1 soil series where the initial SOC content and SOC stock (19.0 ± 8.2 g C kg⁻¹ for SOC content; 28.9 ± 9.5 Mg C ha⁻¹ 0.15 m⁻¹ for SOC stock) were lower than the threshold SOC (24.3 g C kg⁻¹ and 36.1 Mg C ha⁻¹ 0.15 m⁻¹, for SOC content and SOC stock, respectively). However, in fields in the K2 and HO soil series, where initial SOC content and SOC stock were higher than the threshold values (30.5 ± 3.9 and 31.2 ± 5.6 g C kg⁻¹ for SOC content, respectively, and 43.8 ± 6.9 , 45.1 ± 6.3 Mg C ha⁻¹ 0.15 m⁻¹ for SOC stock, respectively), we observed negative Δ SOC content and stock. These results indicate the strong effect of organic matter application on C sequestration in immature soils of K1, and indicate the difficulties in maintaining or accumulating SOC in fields where SOC is higher than the threshold level.

4.3 Soil physical properties

Similar to the findings of previous studies (Hati *et al.* 2007; Papadopoulos *et al.* 2009; Chen *et al.* 2010), the long-term application of organic matter significantly increased total porosity but decreased BD without significant interactions between fields and years. Bronick and Lal (2005) showed that organic amendment such as manure has a dilution effect that results in the lower BD and higher porosity of mineral soil. The mixing of organic materials, which have low BD and high macroporosity, with denser mineral fractions of soils leads to this reduction (Celik *et al.* 2004; Arthur *et al.* 2013;

Naveed *et al.* 2014). The strong negative relationship between Δ total porosity and Δ BD (Table 5) indicated that an increase in total porosity due to the long-term application of organic matter decreases BD. Additionally, research has shown that SOM is a major binding agent that stabilizes soil aggregates. An increase in SOM content results in a greater total porosity and lower BD in soil (Hati *et al.* 2007; Papadopoulos *et al.* 2009; Hemmat *et al.* 2010). As reported by Haynes and Naidu (1998), based on data including 21 soil types, 7 waste types, and 8 crop types, Khaleel *et al.* (1981) calculated a highly significant linear regression ($R^2 = 0.69$) between increases in SOC (as a result of waste applications) and the percentage reduction in soil BD. This phenomenon is a result of improved aggregation of individual soil particles and decreased BD concomitant with a high SOC content (Hati *et al.* 2007; Papadopoulos *et al.* 2009). In this study, we detected significant negative correlations between SOC content and BD (Table 7) and between Δ SOC content and Δ BD (Table 5). Significant positive correlations between SOC content and total porosity (Table 7), and between Δ SOC content and Δ total porosity, were also observed (Table 5). BD decreased and total porosity increased in most fields where the SOC content increased (Table 3, Table 6). Among soil series, there were no significant differences in Δ BD and Δ total porosity. However, an increasing trend in total porosity ($P = 0.07$) was observed only in the K1 soil series. The majority of the fields where SOC content increased significantly are located in the K1 soil series (Table 3) and a large decrease in BD and increase in total porosity were also observed in the same fields (e.g., field nos. 7 and 9, in Table 6). These results indicate that long-

term application of organic matter improves total porosity and decrease BD directly by the dilution effect of mixing of organic materials in all fields and indirectly by the increasing the SOC content in fields that had low initial SOC contents, particularly in the K1 soil series.

Saturated hydraulic conductivity showed significant differences between 2001–2003 and 2013 in all soil series. Saturated hydraulic conductivity is primarily determined by the continuities of macropores in soil. Therefore, increases in saturated hydraulic conductivity may be caused by the improved aggregation and increased total porosity of the soil, which results from the application of organic matter (Castellini and Ventrella 2012).

4.4 Soil chemical properties

4.4.1 pH

The application of organic matter resulted in a significant increase in soil pH (Table 8). This is consistent with the findings of Whalen *et al.* (2000) and Hati *et al.* (2008), who reported that cattle manure could increase the pH of soil. Continuous applications of inorganic fertilizers alone reduce soil pH (Hati *et al.* 2008, Tripathi *et al.* 2014) mainly because most of these fertilizers supply nitrogen as NH_4^+ , and then release H^+ ions via oxidation. There was a significant positive correlation between soil pH and base saturation (Table 7), probably because organic matter contains substantial amounts of base cations (Table 2). When these amendments are incorporated into the soil, the base cations

replace exchangeable Al^{3+} and H^+ at negatively charged sites in the soil and enhance the neutralization of soil exchangeable acidity (Masud *et al.* 2014). The application of organic matter can therefore reduce the application rate of chemical fertilizers, and act as a buffer against a marked reduction in soil pH caused by the deactivation of Al^{3+} and concomitant release of cations with its decomposition.

4.4.2 PAC and available P

Unlike previous studies, in which the application of organic matter increased available P via the decomposition of large inputs of P_2O_5 (Singh *et al.* 2007; Liu *et al.* 2010; Li *et al.* 2012), PAC increased, and available P decreased significantly in the present study (Table 8). We observed significant negative relationships between Δ available P and Δ SOC content or Δ PAC (Table 5), and the following regression equations were obtained: Δ available P ($\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$) = $-16.9 \times \Delta$ SOC content (g C kg^{-1}) - 65.0 ($R^2 = 0.34$; $P < 0.01$) and Δ available P ($\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$) = $-0.25 \times \Delta$ PAC ($\text{mg P}_2\text{O}_5 100 \text{ g}^{-1}$) - 45.1 ($R^2 = 0.60$; $P < 0.01$). These results indicate that available P decreases with increasing SOC content and PAC. There was also a significant positive relationship between Δ PAC and Δ SOC content (Table 5). These results indicate that changes in SOC content, caused by the long-term application of organic matter to the soil, are closely related to changes in PAC. The PAC increased significantly in the K1 and K2 soil series, whereas a significant decrease in available P was observed only in the K1 soil series, and the Δ PAC in the K1 soil series was significantly larger than that in the K2 and HO soil

series (Table 4). These results indicate that the increase in PAC in K1 was of sufficient magnitude to decrease available P.

The efficiency of applied P is typically low in Andosols rich in allophones and active Al (Lukito *et al.* 1998; Wickramatilake *et al.* 2010; Takahashi and Dahlgren 2016). Furthermore, the application of organic matter is expected to improve P availability by enhancing organic P mineralization (Tsuji *et al.*, 2006; Takeda *et al.* 2009). However, K1 had a relatively low initial PAC (1061 ± 389 mg P_2O_5 100 g^{-1} in 2001–2003), because this area is covered mainly by immature soil derived from Ua. Under such conditions, the long-term application of organic matter increased PAC because organic matter absorbs P. However, available P was higher than the critical level of the lower limit [$100\text{ mg } P_2O_5\text{ kg}^{-1}$ (Hokkaido agricultural department 2015)] in all but one of the fields (field no. 14; Table 8) in 2012.

4.4.3 CEC and exchangeable cations

As expected, the application of organic matter increased exchangeable cations and CEC in all soil series (Table 4, Table 9) (Hao and Chang 2002; Aranda *et al.* 2015). Edmeades (2003) reviewed the results from 14 field trials (six fields in the USA, five in England, and one each in Canada, Ireland, and Denmark), comparing the long-term (20 to 120 years) effects of fertilizers and manures on crop production and soil properties. He found that manured soils had higher K^+ , Ca^{2+} , and Mg^{2+} contents in their top soils than fertilized soils. Increases in exchangeable cations are probably attributable to the

continuous supply of high concentrations of K^+ and Mg^{2+} from organic matter as it decomposes (Liu *et al.* 2010).

Soil CEC is important in plant nutrient uptake and ion movement and is highly correlated with the organic carbon and clay content of soil (Hemmat *et al.* 2010; Gruba and Mulder 2015). In all soil series in the present study, CEC was mainly associated with SOC, as suggested by the intercept ($8.97 \text{ cmol}_c \text{ kg}^{-1}$ in 2001–2003 and $9.97 \text{ cmol}_c \text{ kg}^{-1}$ in 2012) of the liner relationship between SOC content and CEC (Fig. 4). We also found a significantly positive relationship between Δ SOC content and Δ CEC (Table 5). These findings indicate that the majority of CEC is determined by SOM and that changes in CEC are closely related to changes in SOC content (Hemmat *et al.* 2010).

Significant correlations between SOC content and CEC were observed in both 2001–2003 and 2012 (Fig. 4). The results of the ANCOVA showed that there was a significant difference in the slope (0.35 cmol_c of CEC per g SOC in 2001–2003 and 0.50 cmol_c CEC per g SOC in 2012) ($P < 0.05$) between the two regression equations, but no significant difference in the intercept ($8.97 \text{ cmol}_c \text{ kg}^{-1}$ in 2001–2003 and $9.97 \text{ cmol}_c \text{ kg}^{-1}$ in 2012). These results indicate that the contribution of the permanent charge of clay minerals for CEC did not change and there was a 43% increase in CEC per g SOC, which was attributable to changes in the quality of SOM because of the application of organic matter.

5. Conclusion

In this study, we evaluated the effects of long-term application of organic matter on the SOC sequestration and physico-chemical properties of soil in upland fields of different types (K1, K2, and HO) of Andosols in the cool temperate zone. In 2001–2003 and 2012, mean SOC content and SOC stock did not change significantly. However, changes in SOC were strongly related to the initial SOC, and most significant increases in SOC were obtained in the fields that had a low initial SOC in the K1 soil series, whereas they decreased significantly in the K2 soil series where the initial SOC was high. On the basis of the regression equation between initial SOC and Δ SOC, the threshold values of the initial SOC content and SOC stock were calculated as 24.3 g C kg⁻¹ and 36.1 Mg C ha⁻¹ 0.15 m⁻¹, respectively, and the threshold level of SOC content was higher than that recorded in previous studies in croplands probably because of the specific features of Andosols. Several soil physico-chemical properties, particularly BD, total porosity, saturated hydraulic conductivity, and CEC, improved significantly. However, where PAC increased significantly, available P decreased significantly. These changes were closely related to changes in SOC content. These findings indicate that the application of organic matter increases SOC and improves soil fertility when the initial SOC is lower than the threshold and highlight the difficulties in maintaining or accumulating SOC in Andosol croplands because of the high SOC.

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Figure legends

Fig. 1. Distribution of the soil series and location of the study fields.

Fig. 2. Relationship between soil texture and soil organic carbon (SOC). Present: 2012; Past, 2001–2003.

Fig. 3. Relationship between: (a) Initial soil organic carbon (SOC) content and rate of Δ SOC content; (b) Initial SOC stock and rate of Δ SOC stock.

Fig. 4. Relationship between soil organic carbon (SOC) content and cation exchange capacity (CEC). Present: 2012, Past: 2001–2003.

Tables

Table 1. Representative soil profile of each soil series of the study area in 2001–2003

Ap: Plow layer, BD: Soil bulk density, PAC: Phosphate absorption coefficient, CEC: Cation exchange capacity. The soil profile survey was conducted by Hokkaido Central Agricultural Experiment Station.

Table 2. Annual average application rate of manure, green manure, and combined organic and synthetic fertilizer in study fields

Different lower-case letters within the same column indicate significant differences among soil series. Values are the mean $\pm$ standard deviation. M: Manure, GM: Green manure, COS: Combined organic and synthetic fertilizer (sum of chemical fertilizer, organic fertilizer, and a mixture of chemical and organic fertilizer). Total application rate: sum of the application rate of manure, green manure, and combined organic and synthetic fertilizer.

Table 3. Comparison of soil organic carbon (SOC) content and stock between 2001–2003 and 2012

Different lower-case letters within the same row indicate significant differences between 2001–2003 and 2012. Different capital letters within the same column indicate significant differences among 34 sampling fields. Values are the mean $\pm$ standard deviation.

Table 4. Changes in soil organic carbon (SOC) content, SOC stock, and physico-chemical properties

in 2001–2003 and 2012 for three soil series

Different lower-case letters within the same row indicate significant differences between 2001–2003

and 2012. Different capital letters within the same column indicate significant differences among

soil series. Values are the mean $\pm$ standard deviation.

Table 5. Pearson's correlation matrix of C application rates and changes in soil physico-chemical

properties

M: Manure, GM: Green manure, COS: Combined organic and synthetic fertilizer (sum of chemical

fertilizer, organic fertilizer, and a mixture of chemical and organic fertilizer). Total C application

rate: Sum of application rate of manure C, green manure C and combined organic and synthetic

fertilizer C. *: Significant at the 0.05 level, **: Significant at the 0.01 level.

Table 6. Comparison of soil physical properties between 2001–2003 and 2012

Table 7. Pearson's correlation matrix of soil physico-chemical properties in both 2001–2003 and

2012

Table 8. Comparison of soil chemical properties between 2001–2003 and 2012.

- 1 Table 9. Comparison between exchangeable cations, base saturation, and cation exchange capacity
2 (CEC) in 2001–2003 and 2012.
- 3 Table 10. Comparison of regression equation between initial soil organic carbon (SOC) content and
4 rate of Δ SOC content.
- 5 Threshold level; x intercept of regression equation. *¹ If the original regression equation was
6 provided as a relationship between initial SOC content change in SOC content, the slope and
7 intercept of regression equation was divided by the year difference between two sampling times. *²
8 If the original regression equation was provided as SOM content, the intercept was divided by 1.724
9 to convert to SOC content.

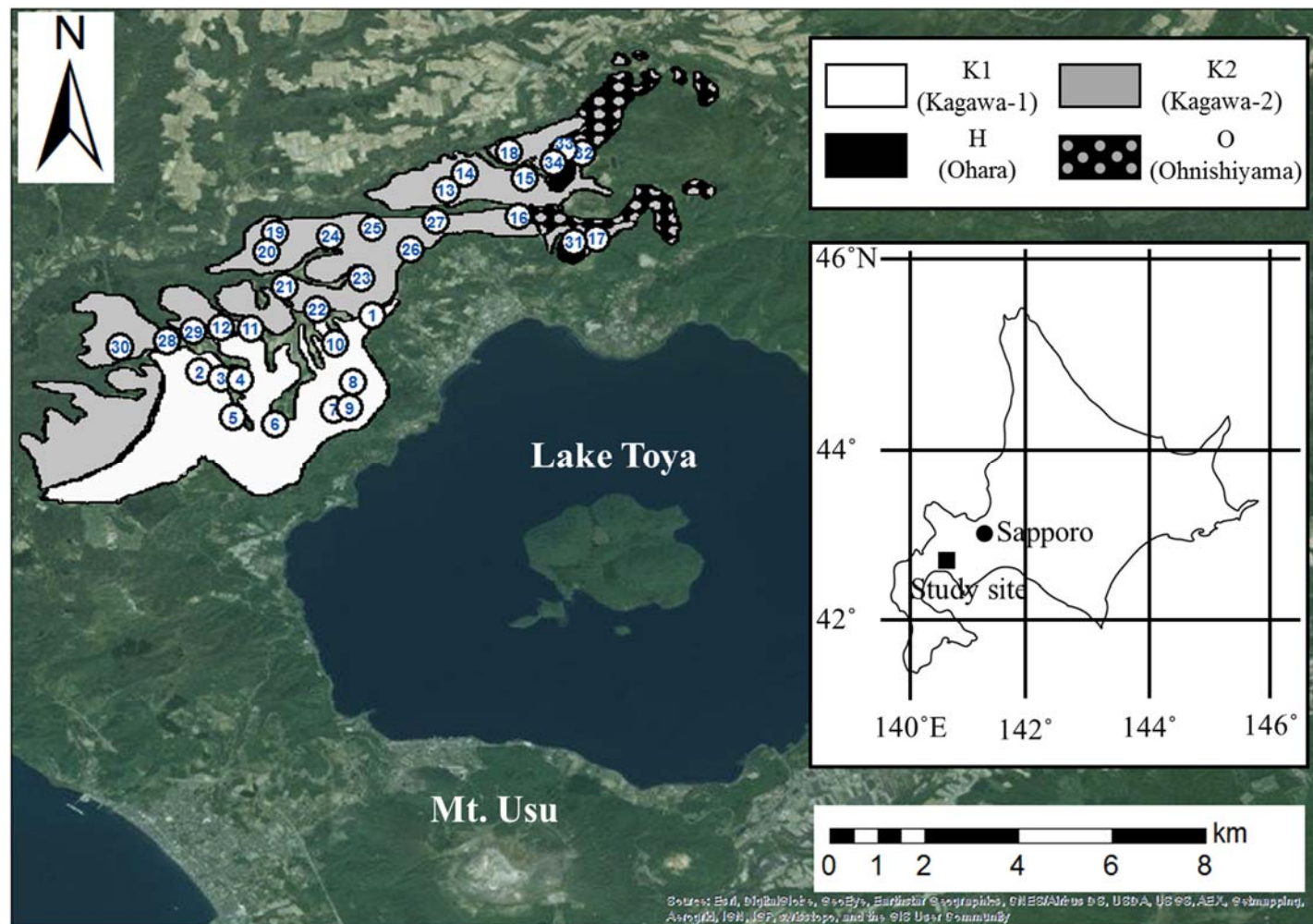


Fig. 1. Distribution of the soil series and location of the study fields.

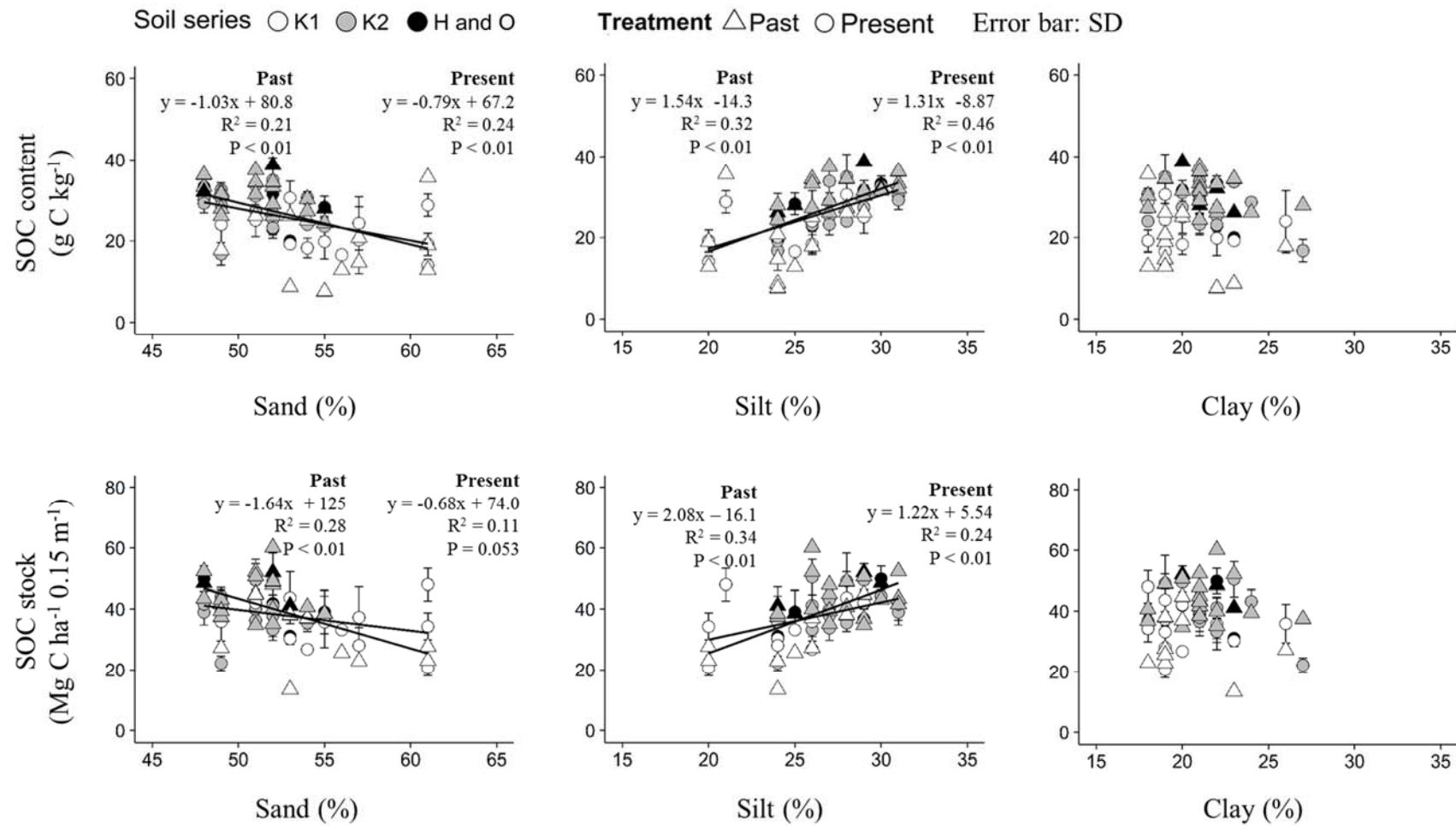


Fig. 2. Relationship between soil texture and soil organic carbon (SOC). Present: 2012; Past, 2001–2003.

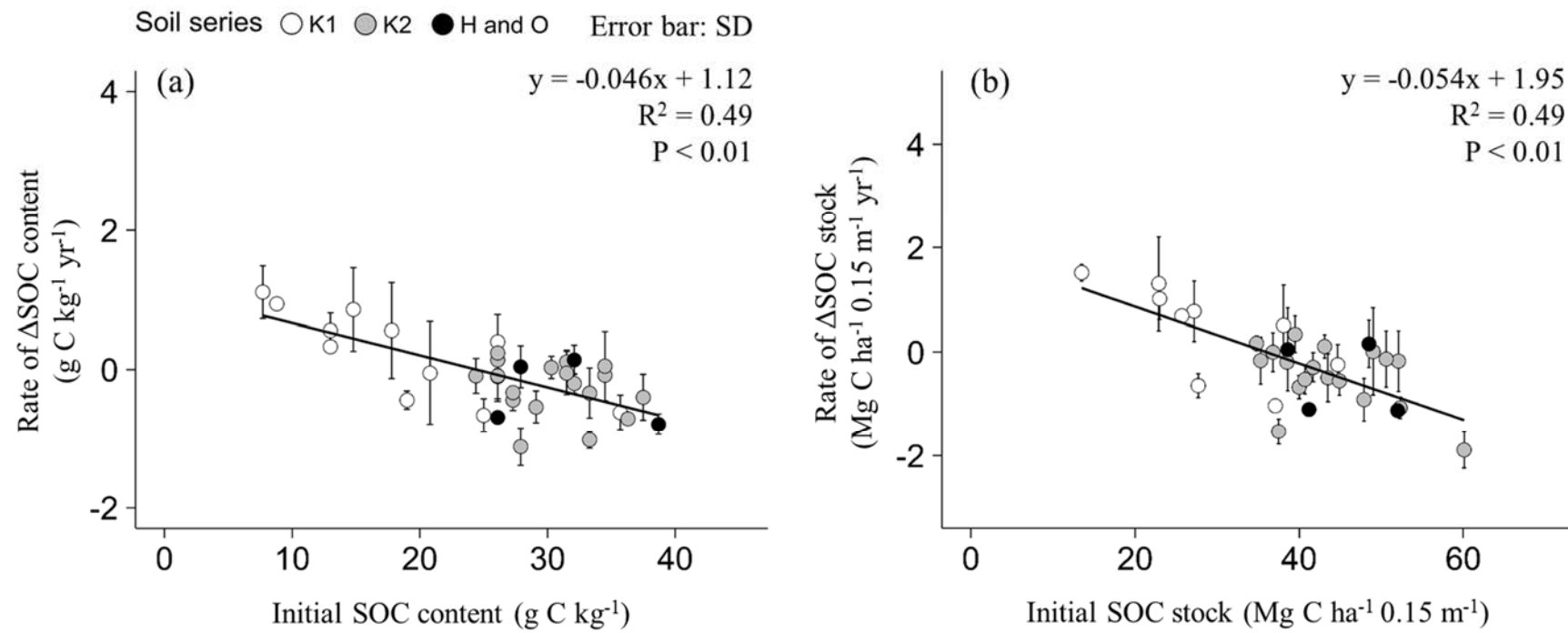


Fig. 3. Relationship between: (a) Initial soil organic carbon (SOC) content and rate of Δ SOC content; (b) Initial SOC stock and rate of Δ SOC stock.

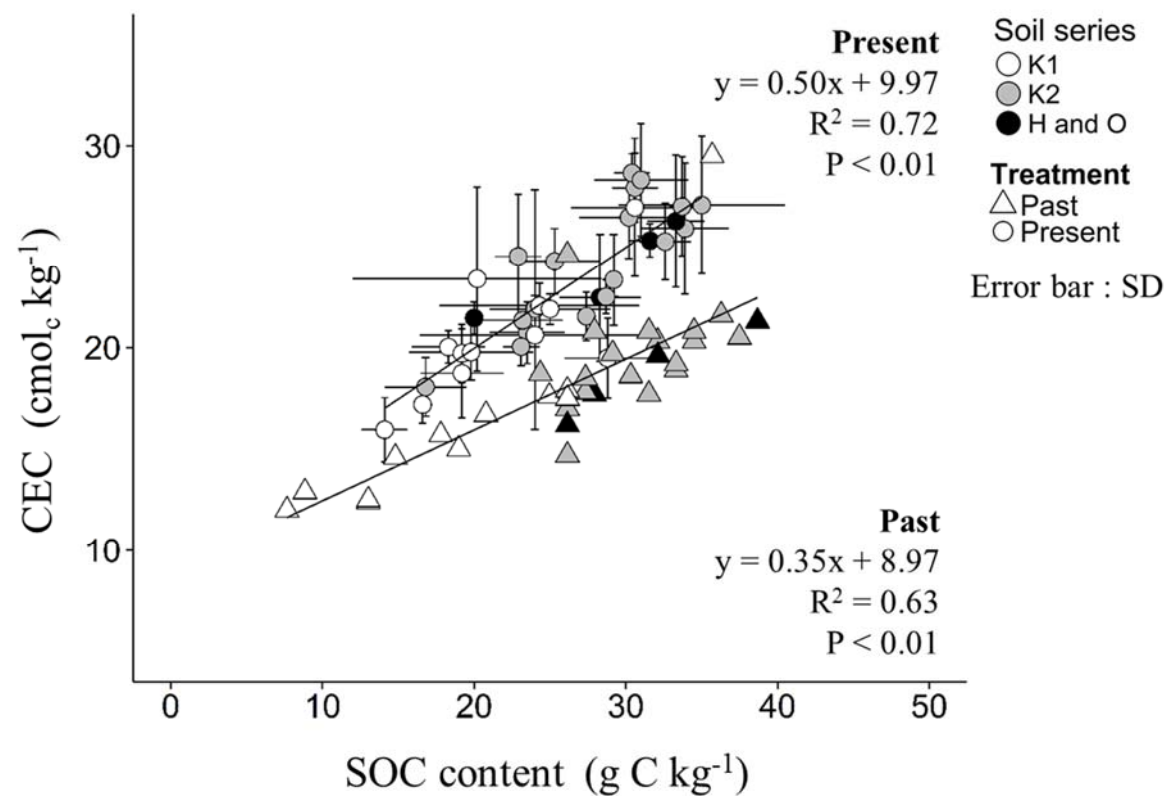


Fig. 4. Relationship between soil organic carbon (SOC) content and cation exchange capacity (CEC). Present: 2012, Past: 2001–2003.

Table 1
Representative soil profile of each soil series of the study area in 2001–2003

K1 (field no. 9)								
Horizon	Tephra	Depth	SOC content	BD	Total porosity	Hydraulic conductivity	PAC	CEC
		cm	g C kg ⁻¹	Mg m ⁻³	%	10 ⁻⁶ m s ⁻¹	mg P ₂ O ₅ 100g ⁻¹	cmol _c kg ⁻¹
1 (Ap)	Ua and Ub	0–27	13.0	1.47	43.8	1.0	821	12.5
2	Ua and Ub	27–46	-	1.55	41.1	0.08	758	12.6
3	Ub	46–77	-	1.40	48.1	1.4	1098	16.7
4	Ya	77–	-	0.70	73.6	58	2267	39.1
H (field no. 32)								
Horizon	Tephra	Depth	SOC content	BD	Total porosity	Hydraulic conductivity	PAC	CEC
		cm	g C kg ⁻¹	Mg m ⁻³	%	10 ⁻⁶ m s ⁻¹	mg P ₂ O ₅ 100g ⁻¹	cmol _c kg ⁻¹
1 (Ap)	Ua and Ub	0–20	32.1	1.21	54.0	0.27	1368	19.6
2	Ua and Ub	20–38	32.1	1.19	55.5	4.4	1359	18.3
3	Ub	38–54	30.4	1.11	60.3	21	1109	18.6
4	Ya	54–	60.2	0.64	76.8	31	2528	26.1

K2 (field no. 24)								
Horizon	Tephra	Depth	SOC content	BD	Total porosity	Hydraulic conductivity	PAC	CEC
		cm	g C kg ⁻¹	Mg m ⁻³	%	10 ⁻⁶ m s ⁻¹	mg P ₂ O ₅ 100g ⁻¹	cmol _c kg ⁻¹
1 (Ap)	Ua and Ub	0–21	36.3	1.15	56.2	34	1527	21.6
2	Ua and Ub	21–35	29.2	1.26	52.0	1.5	1191	19.6
3	Ub	35–57	25.0	0.98	63.0	17.0	1004	17.9
4	Ya	57–	57.8	0.62	78.6	13.0	2331	26.2
O (field no. 34)								
Horizon	Tephra	Depth	SOC content	BD	Total porosity	Hydraulic conductivity	PAC	CEC
		cm	g C kg ⁻¹	Mg m ⁻³	%	10 ⁻⁶ m s ⁻¹	mg P ₂ O ₅ 100g ⁻¹	cmol _c kg ⁻¹
1 (Ap)	Ua and Ub	0–22	38.7	0.91	67.1	290	1757	21.3
2	Ua and Ub	22–40	41.7	1.11	58.9	0.76	1790	22.8
3	Ya	40–62	54.9	0.66	76.3	1.7	2477	29.1
4	Ya	62–	40.5	0.73	73.9	14	2467	19.5

Ap: Plow layer, BD: Soil bulk density, PAC: Phosphate absorption coefficient, CEC: Cation exchange capacity. The soil profile survey was conducted by Hokkaido Central Agricultural Experiment Station.

Table 2
Annual average application rate of manure, green manure, and organic chemical fertilizer in study fields

Site	Soil	Application rate (fresh weight)			Total application rate of each components				Composition ratio (%)											
		M	GM	OCF	C	N	P ₂ O ₅	K ₂ O	C			N			P ₂ O ₅			K ₂ O		
		Mg ha ⁻¹ yr ⁻¹			Mg C ha ⁻¹ yr ⁻¹	kg N ha ⁻¹ yr ⁻¹	kg P ₂ O ₅ ha ⁻¹ yr ⁻¹	kg K ₂ O ha ⁻¹ yr ⁻¹	M	GM	OCF	M	GM	OCF	M	GM	OCF	M	GM	OCF
1	K1	6.7	16.3	1.2	1.71	260	285	281	49	50	1	23	16	61	14	7	79	29	31	40
2	K1	22.5	8.1	1.4	3.29	339	335	382	87	13	0	50	6	54	33	3	64	63	11	26
3	K1	7.5	8.1	1.1	1.38	202	233	217	69	31	0	13	11	76	16	4	80	37	20	43
4	K1	15.0	8.1	1.1	2.33	257	268	303	82	18	0	44	8	48	28	4	68	53	15	32
5	K1	0.0	0.0	1.4	0.07	154	187	118	0	0	100	0	0	100	0	0	100	0	0	100
6	K1	0.0	9.0	1.1	0.55	136	176	157	0	100	0	0	16	84	0	6	94	0	29	71
7	K1	0.5	0.0	0.0	0.10	18	40	6	100	0	0	100	0	0	100	0	0	100	0	0
8	K1	8.0	13.0	1.5	1.78	249	240	274	56	38	6	28	14	58	20	7	73	36	26	39
9	K1	5.0	8.1	1.9	1.08	274	292	256	57	40	3	16	8	76	10	3	87	24	17	59
10	K1	6.0	18.0	2.0	2.48	292	437	250	47	45	8	24	15	61	36	5	59	9	36	55
11	K1	18.0	22.0	3.6	4.09	481	755	402	68	30	2	57	12	31	64	3	33	32	29	39
12	K1	10.0	6.5	1.6	1.62	255	251	242	77	21	2	35	7	58	24	3	73	51	14	35
13	K2	5.0	6.5	1.3	1.02	149	260	205	63	33	4	25	11	64	10	3	87	26	17	57
14	K2	0.0	6.5	1.6	0.34	166	323	176	0	100	0	0	10	90	0	2	98	0	20	80
15	K2	4.0	0.0	1.6	0.70	170	221	168	73	0	27	18	0	82	9	0	91	25	0	75
16	K2	0.0	6.5	0.9	0.44	90	139	103	0	77	23	0	19	81	0	6	94	0	34	66
17	K2	0.0	15.0	1.1	0.92	132	182	180	0	100	0	0	28	72	0	10	90	0	42	58
18	K2	10.0	8.1	1.0	1.73	175	206	232	73	25	2	43	12	45	24	5	71	46	19	35
19	K2	25.0	0.0	1.2	3.24	298	289	343	98	0	2	64	0	36	43	0	57	78	0	22
20	K2	3.0	6.5	1.4	0.73	203	260	213	50	47	3	13	8	79	7	3	90	17	16	67
21	K2	5.0	8.1	1.2	1.07	191	248	223	58	40	2	23	11	66	12	4	84	27	20	53
22	K2	4.0	15.5	1.9	1.47	191	254	255	34	61	5	19	20	61	10	7	83	19	32	49
23	K2	8.0	6.5	1.1	1.40	200	218	226	73	24	4	30	9	61	18	4	78	38	15	47
24	K2	0.0	0.0	1.4	0.03	143	213	107	0	0	100	0	0	100	0	0	100	0	0	100
25	K2	0.0	0.0	2.1	0.06	141	291	132	0	0	100	0	0	100	0	0	100	0	0	100
26	K2	0.0	9.0	1.3	0.55	137	249	184	0	100	0	0	16	84	0	4	96	0	25	75
27	K2	0.0	19.5	1.3	1.14	164	261	227	0	89	11	0	31	69	0	9	91	0	46	54
28	K2	30.0	12.9	1.6	6.05	632	984	568	86	12	2	81	5	14	80	2	18	64	12	24
29	K2	12.5	8.1	1.1	2.33	191	255	271	80	18	2	58	11	31	19	4	77	52	16	32
30	K2	0.0	11.3	1.3	0.75	108	155	194	0	92	8	0	26	74	0	8	92	0	29	71
31	H	12.5	0.0	1.3	1.81	247	269	206	100	0	0	38	0	62	26	0	74	35	0	65
32	H	10.0	8.1	1.0	1.73	175	206	232	73	25	2	43	12	45	24	5	71	46	19	35
33	O	0.0	15.0	0.8	0.92	147	112	135	0	100	0	0	25	75	0	15	85	0	56	44
34	O	3.0	0.0	1.2	0.40	130	229	147	95	0	5	17	0	83	7	0	93	22	0	78
K1 (n=12)		8.3 ± 7.2 a	9.8 ± 6.6 a	1.5 ± 0.8 a	1.71 ± 1.22 a	243 ± 113 a	291 ± 174 a	240 ± 109 a	65	32	3	33	10	57	31	4	65	35	22	43
K2 (n=18)		5.9 ± 8.8 a	7.9 ± 5.7 a	1.4 ± 0.3 a	1.33 ± 1.42 a	193 ± 118 a	278 ± 182 a	222 ± 104 a	63	32	5	32	10	58	23	3	74	30	19	51
H (n=4)		6.4 ± 5.9 a	5.8 ± 7.2 a	1.1 ± 0.2 a	1.21 ± 0.67 a	175 ± 51 a	204 ± 67 a	180 ± 46 a	72	28	0	28	8	64	16	3	81	29	17	54
Mean (All sites, n = 34)		6.8 ± 7.8	8.3 ± 6.1	1.4 ± 0.5	1.45 ± 1.27	209 ± 112	274 ± 168	224 ± 100	65	32	3	32	10	58	26	4	71	32	19	49

Different lower-case letters within the same column indicate significant differences among soil series. Values are the mean ± standard deviation. M: Manure, GM: Green manure, OCF: Organic chemical fertilizer (sum of chemical fertilizer, other organic fertilizer, and a mixture of chemical and organic fertilizers). Total application rate: sum of the application rate of manure, green manure, and organic chemical fertilizer.

Table 3

Comparison of soil organic carbon (SOC) content and stock between 2001–2003 and 2012.

Field	Soil	Texture	SOC content			SOC stock		
			2001-2003	2012	Mean	2001-2003	2012	Mean
			g C kg ⁻¹			Mg C ha ⁻¹ 0.15 m ⁻¹		
1	K1	CL	25.0 b	18.3 ± 2.4 a	20.0 ± 3.8 AE	37.1 b	26.8 ± 0.7 a	29.4 ± 5.2 AE
2	K1	L	35.7 b	28.8 ± 2.8 a	30.5 ± 4.1 EFGHJK		48.0 ± 5.3	48.0 ± 5.3 EFGHJK
3	K1	CL	17.8 a	24.0 ± 7.6 a	22.4 ± 6.9 AHI	27.2 a	35.9 ± 6.4 a	33.7 ± 6.8 AHI
4	K1	L	14.8 a	24.3 ± 6.6 a	21.9 ± 7.2 AH	22.9 a	37.3 ± 9.9 a	33.7 ± 10.8 AH
5	K1	L	19.0 b	14.1 ± 1.5 a	15.3 ± 2.7 A	27.7 b	20.6 ± 2.5 a	22.4 ± 4.1A
6	K1	L	13.0 a	19.2 ± 2.7 b	17.6 ± 3.8 ABC	23.0 a	34.3 ± 4.4 b	31.5 ± 6.7 ABC
7	K1	CL	8.8 a	19.2 ± 0.1 b	16.6 ± 5.2 AB	13.5 a	30.3 ± 1.8 b	26.1 ± 8.5 AB
8	K1	CL	7.7 a	19.8 ± 4.1 b	16.8 ± 9.0 AB		35.8 ± 8.4	35.8 ± 8.4 AB
9	K1	L	13.0 a	16.6 ± 0.2 b	15.7 ± 1.8 A	25.7 a	33.2 ± 1.2 b	31.3 ± 3.9 A
10	K1	L	20.8 a	20.2 ± 8.2 a	20.3 ± 6.7 AF		28.1 ± 5.9	28.1 ± 5.9 AF
11	K1	CL	26.1 a	25.0 ± 4.0 a	25.3 ± 3.3 AHJK	44.7 a	42.1 ± 4.3 a	42.8 ± 3.7 AHJK
12	K1	L	26.1 a	30.6 ± 4.2 a	29.5 ± 4.1 DEFGHJK	38.1 a	43.7 ± 8.5 a	42.3 ± 7.5 DEFGHJK
13	K2	CL	33.3 a	30.2 ± 3.3 a	31.0 ± 3.1 GHJK	43.5 a	39.0 ± 4.2 a	40.1 ± 4.1 GHJK
14	K2	CL	37.5 a	33.9 ± 2.9 a	34.8 ± 3.0 K	44.9 b	40.0 ± 2.6 a	41.3 ± 3.2 K
15	K2	L	30.3 a	30.6 ± 1.5 a	30.5 ± 1.2 EFGHJK	36.8 a	36.8 ± 3.3 a	36.8 ± 2.7 EFGHJK
16	K2	CL	26.1 a	25.3 ± 3.0 a	25.5 ± 2.5 AHJK	35.3 a	33.8 ± 4.0 a	34.2 ± 3.4 AHJK
17	K2	CL	32.1 a	30.4 ± 1.2 a	30.8 ± 1.4 FGHJK	41.7 a	39.0 ± 2.6 a	39.7 ± 2.5 FGHJK
18	K2	CL	26.1 a	27.4 ± 0.3 b	27.1 ± 0.7 BEFGHJK	34.8 a	36.3 ± 1.2 a	35.9 ± 1.3 BEFGHJK
19	K2	CL	31.5 a	32.6 ± 1.7 a	32.3 ± 1.5 HK	43.1 a	44.2 ± 2.2 a	44.0 ± 1.9 HK
20	K2	CL	34.5 a	33.7 ± 0.8 a	33.9 ± 0.8 JK	52.1 a	50.4 ± 5.8 a	50.9 ± 4.8 JK
21	K2	CL	31.5 a	31.0 ± 3.1 a	31.1 ± 2.5 GHJK	50.6 a	49.4 ± 5.4 a	49.7 ± 4.5 GHJK
22	K2	CL	27.9 b	16.8 ± 2.7 a	19.6 ± 6.0 ABCD	37.5 b	22.2 ± 2.4 a	26.0 ± 7.9 ABCD
23	K2	CL	27.3 b	22.9 ± 1.5 a	24.0 ± 2.6 AHJ	40.0 b	33.3 ± 2.2 a	35.0 ± 3.8 AHJ
24	K2	CL	36.3 b	29.2 ± 0.6 a	31.0 ± 3.6 GHJK	52.3 b	41.6 ± 2.1 a	44.3 ± 5.6 GHJK
25	K2	L	27.3 b	24.0 ± 0.7 a	24.9 ± 1.8 AHJK	40.7 b	35.5 ± 2.8 a	36.8 ± 3.4 AHJK
26	K2	CL	24.4 a	23.5 ± 2.5 a	23.7 ± 2.1 AHJ	38.5 a	36.6 ± 1.3 a	37.1 ± 1.4 AHJ
27	K2	CL	33.3 b	23.1 ± 1.2 a	25.6 ± 5.2 AHJK	60.1 b	41.2 ± 3.5 a	46.0 ± 9.9 AHJK
28	K2	CL	26.1 a	28.7 ± 0.8 b	28.1 ± 1.5 CEFGHJK	39.5 a	43.2 ± 3.9 a	42.2 ± 3.7 CEFGHJK
29	K2	CL	29.1 b	23.2 ± 2.6 a	24.7 ± 3.6 AHJK	47.9 b	37.9 ± 4.5 a	40.4 ± 6.2 BCFI
30	K2	L	34.5 a	35.0 ± 5.5 a	34.9 ± 4.5 K	49.0 a	49.1 ± 9.2 a	49.1 ± 7.5 FGI
31	H	CL	27.9 a	28.3 ± 2.7 a	28.2 ± 2.2 CEFGHJK	38.6 a	39.1 ± 7.1 a	39.0 ± 5.8 BCFI
32	H	CL	32.1 a	33.3 ± 1.9 a	33.0 ± 1.7 UK	48.5 a	49.9 ± 4.1 a	49.6 ± 3.4 GI
33	O	CL	26.1 b	20.0 ± 0.5 a	21.5 ± 3.1 AG	41.2 b	31.2 ± 0.7 a	33.7 ± 5.0 ACF
34	O	CL	38.7 b	31.6 ± 1.4 a	33.4 ± 3.7 JK	52.0 b	41.9 ± 0.8 a	44.5 ± 5.1 CFI
Mean			26.5 ± 8.1 a	25.7 ± 5.7 a	25.9 ± 6.7	39.6 ± 10.2 a	37.9 ± 7.4 a	38.3 ± 8.7
			SOC content			SOC stock		
			Df	F	P	Df	F	P
Field			33	13.4	P <0.01	33	9.7	P <0.01
Year			1	1.6	0.21	1	3.1	0.09
Field: Year			33	2.2	P <0.01	30	2.3	P <0.01
Residuals			68			68		

Different lower-case letters within the same row indicate significant differences between 2001–2003 and 2012. Different capital letters within the same column indicate significant differences among 34 sampling fields. Values are the mean ± standard deviation.

Table 4
Changes in soil organic carbon (SOC) content, SOC stock, and physico-chemical properties in 2001–2003 and 2012 for three soil series

Soil series	SOC content							SOC stock						
	2001-2003		2012		ΔSOC content		Rate of ΔSOC content	2001-2003		2012		ΔSOC stock		Rate of ΔSOC stock
	n	g C kg ⁻¹	n	g C kg ⁻¹	n	g C kg ⁻¹	g C kg ⁻¹ year ⁻¹	n	Mg C ha ⁻¹ 0.15m ⁻¹	n	Mg C ha ⁻¹ 0.15m ⁻¹	n	Mg C ha ⁻¹ 0.15m ⁻¹	Mg C ha ⁻¹ 0.15m ⁻¹ yr ⁻¹
K1	12	19.0 ± 8.2 a A	12	21.7 ± 4.9 a A	12	2.7 ± 6.6 B	0.24 ± 0.61 B	9	28.9 ± 4.9 a A	12	34.7 ± 7.7 a A	9	4.9 ± 9.5 B	0.44 ± 0.88 B
K2	18	30.5 ± 3.9 b B	18	27.9 ± 4.9 a B	18	-2.7 ± 3.9 A	-0.27 ± 0.38 A	18	43.8 ± 6.9 b B	18	39.4 ± 6.7 a A	18	-4.4 ± 6.0 A	-0.44 ± 0.59 A
HO	4	31.2 ± 5.6 a B	4	28.3 ± 5.9 a AB	4	-2.9 ± 4.3 AB	-0.33 ± 0.48 AB	4	45.1 ± 6.2 a B	4	40.5 ± 7.7 a A	4	-4.5 ± 6.3 AB	-0.50 ± 0.70 AB
Mean	34	26.5 ± 8.1 a	34	25.7 ± 5.7 a	34	-0.8 ± 5.6	-0.10 ± 0.53	31	39.6 ± 10.2 a	34	37.9 ± 7.4 a	31	-1.7 ± 8.2	-0.19 ± 0.79

Soil series	BD							Total porosity							Hydraulic conductivity						
	2001-2003		2012		ΔBD		Rate of ΔBD	2001-2003		2012		Δtotal porosity		Rate of Δtotal porosity	2001-2003		2012		ΔHydraulic conductivity		Rate of ΔHydraulic conductivity
	n	Mg m ⁻³	n	Mg m ⁻³	n	Mg m ⁻³	Mg m ⁻³ yr ⁻¹	n	%	n	%	n	%	% yr ⁻¹	n	10 ⁻⁶ m s ⁻¹	n	10 ⁻⁶ m s ⁻¹	n	10 ⁻⁶ m s ⁻¹	10 ⁻⁶ m s ⁻¹ yr ⁻¹
K1	9	1.30 ± 0.2 b B	12	1.14 ± 0.12 a B	9	-0.16 ± 0.21 A	-0.015 ± 0.019 A	9	51.0 ± 8.0 a A	12	56.8 ± 5.0 a A	9	5.8 ± 8.5 A	0.53 ± 0.78 A	9	27.6 ± 43.2 a A	12	1900 ± 1332 b A	9	1880 ± 1319 A	172 ± 119 A
K2	18	1.09 ± 0.08 b A	18	1.00 ± 0.11 a A	18	-0.09 ± 0.11 A	-0.01 ± 0.012 A	18	59.3 ± 3.4 a B	18	61.4 ± 5.4 a A	18	2.0 ± 5.3 A	0.23 ± 0.57 A	18	57.0 ± 85.5 a A	18	2146 ± 1827 b A	18	2089 ± 1846 A	214 ± 191 A
HO	4	1.12 ± 0.14 a AB	4	1.01 ± 0.08 a AB	4	-0.11 ± 0.09 A	-0.012 ± 0.01 A	4	59.0 ± 5.6 a B	4	61.1 ± 3.4 a A	4	2.1 ± 3.6 A	0.23 ± 0.40 A	4	80.5 ± 140.2 a A	4	3542 ± 2005 b A	4	3462 ± 2134 A	385 ± 237 A
Mean	31	1.15 ± 0.16 b	34	1.05 ± 0.13 a	31	-0.11 ± 0.14	-0.011 ± 0.014	31	56.9 ± 6.5 a	34	60.0 ± 5.4 b	31	3.2 ± 6.3	0.32 ± 0.61	31	51.4 ± 83.1 a	34	2223 ± 1712 b	31	2176 ± 1728	219 ± 182

Soil series	pH							Available N							PAC						
	2001-2003		2012		ΔpH		Rate of ΔpH	2001-2003		2012		Δavailable N		Rate of Δavailable N	2001-2003		2012		ΔPAC		Rate of ΔPAC
	n		n		n			n	g N kg ⁻¹	n	g N kg ⁻¹	n	g N kg ⁻¹	g N kg ⁻¹ yr ⁻¹	n	mg P ₂ O ₅ 100 mg ⁻¹	n	mg P ₂ O ₅ 100 mg ⁻¹	n	mg P ₂ O ₅ 100 mg ⁻¹	mg P ₂ O ₅ 100 mg ⁻¹ yr ⁻¹
K1	12	5.46 ± 0.12 a A	11	5.94 ± 0.14 b B	11	0.46 ± 0.18 B	0.042 ± 0.016 B	12	56.4 ± 17.4 b B	12	37.0 ± 9.4 a B	12	-19.5 ± 19.7 A	-1.76 ± 1.79 A	12	1061 ± 389 a A	12	1848 ± 294 b A	12	787 ± 479 B	71.6 ± 43.5 B
K2	18	5.67 ± 0.26 a B	18	5.70 ± 0.23 a A	18	0.02 ± 0.34 A	0.001 ± 0.034 A	18	34.8 ± 7.6 b A	18	29.7 ± 6.8 a A	18	-5.1 ± 9.7 B	-0.52 ± 0.98 B	18	1555 ± 377 a B	18	1748 ± 322 b A	18	193 ± 341 A	19.1 ± 34.0 A
HO	4	5.97 ± 0.31 a B	4	5.70 ± 0.16 a AB	4	-0.27 ± 0.21 A	-0.03 ± 0.023 A	4	41.0 ± 6.8 a AB	4	39.3 ± 4.4 a AB	4	-1.7 ± 2.5 AB	-0.19 ± 0.28 AB	4	1386 ± 290 a AB	4	1432 ± 325 a A	4	46 ± 272 A	5.1 ± 30.2 A
Mean	34	5.63 ± 0.27 a	33	5.79 ± 0.22 b	33	0.14 ± 0.37	0.011 ± 0.037	34	43.2 ± 15.4 b	34	33.4 ± 8.4 a	34	-9.7 ± 15.2	-0.92 ± 1.41	34	1361 ± 430 a	34	1746 ± 328 b	34	385 ± 486	36.0 ± 45.2

Soil series	Available P							Exchangeable K ⁺							Exchangeable Ca ²⁺						
	2001-2003		2012		Δavailable P		Rate of Δavailable P	2001-2003		2012		Δexchangeable K ⁺		Rate of Δexchangeable K ⁺	2001-2003		2012		Δexchangeable Ca ²⁺		Rate of Δexchangeable Ca ²⁺
	n	mg P ₂ O ₅ kg ⁻¹	n	mg P ₂ O ₅ kg ⁻¹	n	mg P ₂ O ₅ kg ⁻¹	mg P ₂ O ₅ kg ⁻¹ yr ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	cmol _c kg ⁻¹ yr ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	cmol _c kg ⁻¹ yr ⁻¹
K1	9	393 ± 150 b B	12	239 ± 87 a AB	12	-19.5 ± 19.7 A	-1.76 ± 1.79 A	12	1.04 ± 0.30 a A	12	1.31 ± 0.22 b A	12	0.27 ± 0.39 A	0.025 ± 0.036 A	12	7.07 ± 1.15 a A	12	6.67 ± 2.51 a A	12	-0.40 ± 3.26 A	-0.035 ± 0.297 A
K2	18	187 ± 100 a A	18	172 ± 45.0 a A	18	-5.1 ± 9.7 B	-0.52 ± 0.98 B	18	0.79 ± 0.15 a B	18	1.22 ± 0.27 b A	18	0.43 ± 0.32 A	0.045 ± 0.033 A	18	6.57 ± 1.61 a A	18	7.28 ± 3.22 a A	18	0.71 ± 2.65 A	0.074 ± 0.267 A
HO	4	226 ± 147 a AB	4	322 ± 175 a B	4	-1.7 ± 2.5 B	-0.19 ± 0.28 AB	4	0.76 ± 0.10 a AB	4	1.38 ± 0.09 b A	4	0.62 ± 0.15 A	0.069 ± 0.017 A	4	6.53 ± 2.38 a A	4	8.43 ± 3.03 a A	4	1.90 ± 2.83 A	0.211 ± 0.315 A
Mean	31	265 ± 155 b	34	213 ± 94 a	34	-9.7 ± 15.2	-0.92 ± 1.41	34	0.88 ± 0.24 a	34	1.27 ± 0.24 b	34	0.40 ± 0.34	0.041 ± 0.035	34	6.74 ± 1.53 a	34	7.20 ± 2.93 a	34	0.46 ± 2.91	0.052 ± 0.285

Soil series	Exchangeable Mg ²⁺							Base saturation							CEC						
	2001-2003		2012		Δexchangeable Mg ²⁺		Rate of Δexchangeable Mg ²⁺	2001-2003		2012		Δbase saturation		Rate of Δbase saturation	2001-2003		2012		ΔCEC		Rate of ΔCEC
	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	cmol _c kg ⁻¹ yr ⁻¹	n	%	n	%	n	%	% yr ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	n	cmol _c kg ⁻¹	cmol _c kg ⁻¹ yr ⁻¹
K1	9	1.41 ± 0.27 a A	12	2.40 ± 0.85 b B	12	1.00 ± 0.79 B	0.091 ± 0.072 B	12	62.5 ± 16.8 a B	12	52.4 ± 13.4 a A	12	-12.8 ± 23.7 A	-1.16 ± 2.16 A	12	16.2 ± 4.7 a A	12	20.5 ± 2.9 b A	12	4.3 ± 5.1 A	0.39 ± 0.46 A
K2	18	1.18 ± 0.29 a A	18	1.46 ± 0.47 a A	18	0.28 ± 0.57 A	0.028 ± 0.056 A	18	44.2 ± 9.5 a A	18	42.2 ± 14.7 a A	18	-3.1 ± 11.2 A	-0.33 ± 1.13 A	18	19.5 ± 2.1 a B	18	24.2 ± 3.13 b B	18	4.7 ± 3.8 A	0.49 ± 0.40 A
HO	4	1.07 ± 0.26 a A	4	2.00 ± 0.73 a AB	4	0.92 ± 0.97 AB	0.103 ± 0.108 AB	4	45.3 ± 15.1 a AB	4	50.7 ± 14.9 a A	4	1.24 ± 13.3 A	0.14 ± 1.48 A	4	18.7 ± 2.2 a AB	4	23.9 ± 2.28 b AB	4	5.2 ± 1.1 A	0.57 ± 0.12 A
Mean	31	1.25 ± 0.30 a	34	1.85 ± 0.78 b	34	0.61 ± 0.77	0.059 ± 0.074	34	50.8 ± 15.4 a	34	46.8 ± 4.28 a	34	-6.01 ± 17.2	-0.57 ± 1.62	34	18.2 ± 3.5 a	34	22.8 ± 3.4 b	34	4.6 ± 4.0	0.47 ± 0.40

Different lower-case letters within the same row indicate significant differences between 2001–2003 and 2012. Different capital letters within the same column indicate significant differences among soil series. Values are the mean ± standard deviation.

Table 5
Pearson's correlation matrix of C application rates and changes in soil physico-chemical properties

	M C application rate	GM C application rate	OCF C application rate	Total C application rate	ΔSOC content	ΔSOC stock	ΔBD	ΔTotal porosity	ΔHydraulic conductivity	ΔpH	ΔAvailable N	ΔPAC	ΔAvailable P	ΔExchangeable K ⁺	ΔExchangeable Ca ²⁺	ΔExchangeable Mg ²⁺	ΔBase saturation	ΔCEC
		Mg C ha ⁻¹ yr ⁻¹			g C kg ⁻¹	Mg C ha ⁻¹ 0.15 m ⁻¹	Mg m ⁻³	%	10 ⁻⁶ m s ⁻¹		mg N kg ⁻¹	mg P ₂ O ₅ 100g ⁻¹	mg P ₂ O ₅ kg ⁻¹		cmol _c kg ⁻¹		%	cmol _c kg ⁻¹
M C application rate	-																	
GM C application rate	0.12	-																
OCF C application rate	0.14	0.23	-															
Total C application rate	0.96 **	0.40 *	0.23	-														
ΔSOC content	0.17	-0.13	-0.09	0.00	-													
ΔSOC stock	0.23	-0.24	-0.29	0.13	0.99 **	-												
ΔBD	0.09	0.42 *	0.17	0.21	-0.44 *	-0.47 **	-											
ΔTotal porosity	-0.14	-0.46 **	-0.21	-0.26	0.44 *	0.47 **	-0.94 **	-										
ΔHydraulic conductivity	0.18	0.13	0.07	0.21	-0.14	-0.08	-0.28	0.29	-									
ΔpH	0.36 *	0.19	0.08	0.39 *	0.20	0.22	0.17	-0.08	-0.07	-								
ΔAvailable N	-0.17	0.03	0.05	-0.15	-0.25	-0.38 *	0.17	-0.20	0.00	-0.36	-							
ΔPAC	0.06	0.13	0.14	0.10	0.67 **	0.59 **	-0.18	0.20	-0.20	0.50 **	-0.40 *	-						
ΔAvailable P	0.09	0.20	0.02	0.14	-0.58 **	-0.55 **	0.28	-0.34	0.15	-0.25	0.41 *	-0.75 **	-					
ΔExchangeable K ⁺	-0.25	0.06	-0.09	-0.22	0.18	-0.03	0.05	-0.06	0.00	-0.34 *	0.51 **	-0.06	0.12	-				
ΔExchangeable Ca ²⁺	0.15	0.02	-0.26	0.13	-0.27	-0.16	-0.05	-0.09	0.06	0.05	0.30	-0.30	0.40 *	-0.08	-			
ΔExchangeable Mg ²⁺	-0.29	0.15	-0.19	-0.23	0.22	0.18	0.15	-0.09	-0.25	0.28	-0.17	0.38 *	-0.21	0.14	-0.20	-		
ΔBase saturation	0.24	0.07	-0.21	0.23	-0.54 **	-0.46 **	0.12	-0.23	0.18	0.08	0.17	-0.45 **	0.49 **	-0.31	0.90 **	-0.30	-	
ΔCEC	-0.36 *	-0.11	0.05	-0.36 *	0.51 **	0.48 **	-0.16	0.16	-0.18	-0.37 *	0.04	0.22	-0.2	0.6 **	-0.27	0.25	-0.57 **	-

M: Manure, GM: Green manure, OCF: Organic chemical fertilizer (sum of chemical fertilizer, the other organic fertilizer, and a mixture of chemical and organic fertilizer). Total C application rate: Sum of application rate of manure C, green manure C and organic chemical fertilizer C.

*: Significant at the 0.05 level, **: Significant at the 0.01 level.

Table 6
Comparison of soil physical properties between 2001–2003 and 2012.

Field	Soil	Texture	BD			Total porosity			Hydraulic conductivity		
			2001-2003	2012	Mean	2001-2003	2012	Mean	2001-2003	2012	Mean
				Mg m ³			%			10 ⁻⁶ m s ⁻¹	
1	K1	CL	1.01	1.04 ± 0.14	1.03 ± 0.12 ABC	62.6	59.5 ± 3.4	60.3 ± 3.2 BCD	29	1326 ± 331	1001 ± 702 A
2	K1	L		1.17 ± 0.11	1.17 ± 0.11 AD		54.3 ± 1.5	54.3 ± 1.5 AD		2393 ± 440	2392 ± 539 A
3	K1	CL	1.24	1.08 ± 0.16	1.12 ± 0.15 AD	53.2	58.8 ± 5.7	57.4 ± 5.5 AD	3.0	1578 ± 1279	1184 ± 1307 A
4	K1	L	1.43	1.09 ± 0.18	1.18 ± 0.22 AD	46.1	57.7 ± 7.7	54.8 ± 8.6 AD	1.8	1823 ± 2688	1367 ± 2376 A
5	K1	L	1.40	1.02 ± 0.02	1.12 ± 0.19 AD	47.1	61.7 ± 6.7	58.0 ± 9.1 AD	0.13	1511 ± 479	1133 ± 851 A
6	K1	L	1.28	1.26 ± 0.07	1.26 ± 0.06 CD	51.5	51.7 ± 2.4	51.7 ± 1.9 AC	12	70 ± 61	56 ± 58 A
7	K1	CL	1.63	1.11 ± 0.07	1.24 ± 0.27 BD	37.9	59.5 ± 2.0	54.1 ± 10.9 AD	0.03	3837 ± 2426	2877 ± 2757 A
8	K1	CL		1.26 ± 0.10	1.26 ± 0.10 BD		52.7 ± 5.6	52.7 ± 5.6 AD		719 ± 535	719 ± 535 A
9	K1	L	1.47	1.40 ± 0.05	1.42 ± 0.05 D	43.8	45.5 ± 3.0	45.1 ± 2.6 A	1.0	11 ± 12	8.3 ± 11.0 A
10	K1	L		1.03 ± 0.19	1.03 ± 0.19 ABC		62.8 ± 7.9	62.8 ± 7.9 BCD		3707 ± 2092	3707 ± 2092 A
11	K1	CL	1.08	1.19 ± 0.13	1.17 ± 0.12 AD	59.4	55.9 ± 5.4	56.8 ± 4.8 AD	120	3718 ± 2224	2819 ± 2556 A
12	K1	L	1.13	1.02 ± 0.25	1.04 ± 0.21 ABC	57.4	61.2 ± 10.6	60.3 ± 8.9 BCD	79	2113 ± 3376	1604 ± 2938 A
13	K2	CL	0.99	0.91 ± 0.05	0.92 ± 0.06 AB	64.1	66.4 ± 2.8	65.8 ± 2.6 CD	120	5259 ± 2278	3974 ± 3171 A
14	K2	CL	1.03	0.83 ± 0.05	0.88 ± 0.11 A	61.7	70.9 ± 7.5	68.6 ± 7.7 D	11	1141 ± 879	859 ± 913 A
15	K2	L	0.98	0.84 ± 0.04	0.88 ± 0.08 A	64.5	66.5 ± 1.8	66.0 ± 1.8 CD	91	2663 ± 1570	2020 ± 1816 A
16	K2	CL	1.18	0.94 ± 0.10	1.00 ± 0.14 ABC	56.0	62.6 ± 3.1	61.0 ± 4.2 BCD	8.9	579 ± 488	436 ± 490 A
17	K2	CL	1.03	0.90 ± 0.03	0.93 ± 0.07 ABC	62.6	30.3 ± 5.3	60.9 ± 4.5 BCD	51	1682 ± 648	1274 ± 972 A
18	K2	CL	1.28	0.93 ± 0.02	1.02 ± 0.18 ABC	51.9	66.9 ± 2.3	63.1 ± 7.7 BCD	0.44	3218 ± 1095	2414 ± 1841 A
19	K2	CL	1.08	0.95 ± 0.01	0.98 ± 0.06 ABC	59.5	64.1 ± 0.6	62.9 ± 2.3 BCD	11	2577 ± 1930	1936 ± 2032A
20	K2	CL	1.03	1.05 ± 0.11	1.04 ± 0.09 ABC	62.0	61.9 ± 6.5	62.0 ± 5.3 BCD	319	145 ± 232	188 ± 209 A
21	K2	CL	1.14	1.12 ± 0.02	1.12 ± 0.02 AD	57.6	56.2 ± 1.4	56.5 ± 1.3 AD	0.22	3.2 ± 4.3	2.4 ± 3.8 A
22	K2	CL	1.09	0.94 ± 0.07	0.97 ± 0.10 ABC	60.4	65.8 ± 0.5	64.4 ± 2.7 BCD	5.9	6859 ± 4175	5145 ± 4833 A
23	K2	CL	1.07	1.02 ± 0.02	1.04 ± 0.03 ABC	60.8	61.5 ± 2.8	61.3 ± 2.3 BCD	47	562 ± 841	433 ± 733 A
24	K2	CL	1.15	1.00 ± 0.03	1.03 ± 0.08 ABC	56.2	63.5 ± 1.2	61.6 ± 3.8 BCD	34	3332 ± 2031	2507 ± 2339 A
25	K2	L	1.04	1.04 ± 0.09	1.04 ± 0.07 ABC	60.6	58.9 ± 4.0	59.3 ± 3.4 AD	220	1020 ± 1403	820 ± 1214 A
26	K2	CL	1.18	1.10 ± 0.14	1.12 ± 0.12 AD	55.7	56.7 ± 6.3	56.4 ± 5.2 AD	16	3161 ± 4305	2374 ± 3851 A
27	K2	CL	1.19	1.25 ± 0.07	1.23 ± 0.06 BD	55.0	49.3 ± 2.0	50.7 ± 3.3 AB	15	61 ± 64	49 ± 57 A
28	K2	CL	1.13	1.05 ± 0.08	1.07 ± 0.08 ABC	57.3	55.5 ± 11.2	56.0 ± 9.2 AD	21	2397 ± 1276	1803 ± 1580 A
29	K2	CL	1.05	1.14 ± 0.04	1.12 ± 0.06 AD	60.6	54.2 ± 2.0	55.8 ± 3.6 AD	52	2375 ± 3766	1795 ± 3287 A
30	K2	L	0.98	0.98 ± 0.12	0.98 ± 0.10 ABC	61.6	63.8 ± 6.5	63.2 ± 5.4 BCD	3.4	1578 ± 1930	1191 ± 1764 A
31	HO	CL	1.15	0.96 ± 0.09	1.01 ± 0.12 ABC	58.0	61.7 ± 5.7	60.8 ± 5.0 BCD	28	3472 ± 1485	2611 ± 2106 A
32	HO	CL	1.21	1.05 ± 0.04	1.09 ± 0.09 ABC	54.0	60.3 ± 3.5	58.7 ± 4.2 AD	0.27	5707 ± 7319	4280 ± 6622 A
33	HO	CL	1.20	1.10 ± 0.05	1.12 ± 0.06 AD	57.0	57.2 ± 3.1	57.1 ± 2.5 AD	3.7	4105 ± 2983	3080 ± 3184 A
34	HO	CL	0.91	0.93 ± 0.03	0.92 ± 0.02 AB	67.1	65.4 ± 1.9	65.8 ± 1.8 CD	290	885 ± 663	736 ± 618 A
Mean			1.15 ± 0.16 b	1.05 ± 0.13 a	1.07 ± 0.16	56.9 ± 6.5 a	60.0 ± 5.4 b	59.1 ± 6.79	51.4 ± 83.1 a	2223 ± 1712 b	1712 ± 2404
			BD			Total porosity			Hydraulic conductivity		
			Df	F	P	Df	F	P	Df	F	P
Field			33	5.9	P <0.01	33	3.9	P <0.01	33	1.3	0.20
Year			1	31.1	P <0.01	1	9.1	P <0.01	1	20.6	P <0.01
Field: Year			30	1.6	0.06	30	1.2	0.28	30	0.4	0.99
Residuals			68			68			67		

Different lower-case letters within the same row indicate significant differences between 2001–2003 and 2012. Different capital letters within the same column indicate significant differences among soil series. Values are the mean ± standard deviation.

Table 7
Pearson's correlation matrix of soil physicochemical properties in both 2001–2003 and 2012.

	SOC content	SOC stock	Sand content	Silt content	Clay content	BD	Total porosity	Hydraulic conductivity	pH	Available N	PAC	Available P	Exchangeable K ⁺	Exchangeable Ca ²⁺	Exchangeable Mg ²⁺	Base saturation	CEC
	g C kg ⁻¹	Mg C ha ⁻¹ 0.15 m ⁻¹		%		Mg m ⁻³	%	10 ⁻⁶ m s ⁻¹		mg N kg ⁻¹	mg P ₂ O ₅ 100g ⁻¹	mg P ₂ O ₅ kg ⁻¹		cmol _c kg ⁻¹		%	cmol _c kg ⁻¹
SOC content	-	0.91† **	-0.46† **	0.57† **	-0.03†	-0.83† **	0.82† **	0.39† *	0.26†	-0.28†	0.83† **	-0.82† **	-0.16†	-0.18†	-0.43† *	-0.77† **	0.80† **
SOC stock	0.86‡ **	-	-0.53† **	0.58† **	0.04†	-0.72† **	0.70† **	0.37† *	0.20†	-0.43† *	0.73† **	-0.81† **	-0.47† **	-0.07†	-0.24†	-0.62† **	0.75† **
Sand content	-0.49‡ **	-0.33‡	-	-0.81† **	-0.59† **	0.44† *	-0.43† *	-0.10†	-0.24†	0.45† **	-0.42† *	0.39† *	0.51† **	0.12†	0.15†	0.40† *	-0.26†
Silt content	0.68‡ **	0.49‡ **	-0.81‡ **	-	0.04†	-0.55† **	0.53† **	0.26†	0.20†	-0.38† *	0.47† **	-0.48† **	-0.47† **	-0.17†	-0.20†	-0.44† **	0.27†
Clay content	-0.11‡	-0.14‡	-0.59‡ **	0.04‡	-	0.03†	0.00†	-0.14†	0.23†	-0.24†	-0.01†	0.02†	-0.29†	0.10†	0.04†	-0.02†	0.06†
BD	-0.51‡ **	0.00‡	0.41‡ *	-0.47‡ **	-0.09‡	-	-0.99† **	-0.50† **	-0.08†	0.36† *	-0.67† **	0.71† **	0.34†	0.22†	0.33†	0.71† **	-0.74† **
Total porosity	0.45‡ **	-0.03‡	-0.38‡ *	0.40‡ *	0.09‡	-0.94‡ **	-	0.51† **	0.12†	-0.38† *	0.65† **	-0.70† **	-0.36† *	-0.22†	-0.33†	-0.71† **	0.72† **
Hydraulic conductivity	0.00‡	-0.16‡	-0.32‡	0.15‡	0.33‡	-0.32‡	0.37‡ *	-	0.11†	-0.07†	0.42† *	-0.32†	-0.13†	0.03†	-0.08†	-0.20†	0.31†
pH	-0.41‡ *	-0.19‡	0.41‡ *	-0.46‡ **	-0.03‡	0.45‡ **	-0.44‡ *	-0.09‡	-	-0.34† *	0.03†	-0.13†	-0.48† **	0.50† **	0.02†	0.16†	0.00†
Available N	-0.22‡	-0.03‡	0.20‡	-0.27‡	0.10‡	0.35‡ *	-0.34‡	0.10‡	0.67‡ **	-	-0.19†	0.41† *	0.69† **	0.07†	0.27†	0.21†	0.03†
PAC	0.32‡	0.43‡ *	0.04‡	0.04‡	-0.21‡	0.14‡	-0.08‡	-0.28‡	0.03‡	-0.24‡	-	-0.83† **	-0.06†	-0.19†	-0.25†	-0.66† **	0.70† **
Available P	-0.36‡ *	-0.30‡	0.16‡	-0.27‡	0.17‡	0.15‡	-0.17‡	0.36‡ *	0.38‡ *	0.71‡ **	-0.58‡ **	-	0.25†	0.33†	0.43† *	0.73† **	-0.65† **
Exchangeable K ⁺	0.16‡	0.17‡	-0.08‡	0.12‡	-0.01‡	0.02‡	0.06‡	0.21‡	0.15‡	0.40‡ *	0.06‡	0.20‡	-	-0.13†	0.19†	-0.02†	0.27†
Exchangeable Ca ²⁺	-0.11‡	-0.11‡	0.09‡	-0.20‡	0.20‡	-0.04‡	-0.05‡	-0.02‡	0.48‡ **	0.43‡ *	-0.48‡ **	0.43‡ *	0.13‡	-	0.62† **	0.72† **	-0.19†
Exchangeable Mg ²⁺	-0.38‡ *	-0.21‡	0.42‡ *	-0.34‡ *	-0.26‡	0.44‡ **	-0.35‡ *	-0.22‡	0.20‡	0.14‡	0.24‡	-0.04‡	0.26‡	-0.32‡	-	0.66† **	-0.25†
Base saturation	-0.56‡ **	-0.41‡ *	0.46‡ **	-0.62‡ **	0.13‡	0.33‡	-0.33‡	-0.04‡	0.67‡ **	0.55‡ **	-0.43‡ *	0.50‡ **	0.11‡	0.82‡ **	0.07‡	-	-0.74† **
CEC	0.85‡ **	0.63‡ **	-0.52‡ **	0.73‡ **	-0.10‡	-0.58‡ **	0.51‡ **	-0.02‡	-0.46‡ **	-0.31‡	0.22‡	-0.31‡	0.23‡	-0.08‡	-0.23‡	-0.57‡ **	-

*, Significant at the 0.05 level, **, Significant at the 0.01 level, †: Pearson's correlation coefficient in 2001–2003, ‡: Pearson's correlation coefficient in 2012.

Table 8
Comparison of soil chemical properties between 2001–2003 and 2012.

Field	Soil	Texture	pH			Available N			PAC			Available P		
			2001-2003	2012	Mean	2001-2003	2012	Mean	2001-2003	2012	Mean	2001-2003	2012	Mean
						mg N kg ⁻¹			mg P ₂ O ₅ 100g ⁻¹			mg P ₂ O ₅ kg ⁻¹		
1	K1	CL	5.40 a	5.70 ± 0.05 b	5.63 ± 0.16 BC	23.0 a	30.2 ± 1.5 b	28.4 ± 3.8 AB	1243 a	1337 ± 184 a	1314 ± 157 AC	248 a	256 ± 52 a	254 ± 43 AC
2	K1	L	5.39 a	6.27 ± 0.14 b	6.05 ± 0.46 AC	80.0 b	49.4 ± 4.2 a	57.0 ± 15.7 C	1791 a	1755 ± 137 a	1765 ± 113 AC	120 a	285 ± 90 a	244 ± 110 AC
3	K1	CL	5.45 a	5.93 ± 0.05 b	5.80 ± 0.24 BC	55.0 b	36.0 ± 3.4 a	40.1 ± 9.9 AC	1132 a	2000 ± 188 b	1783 ± 460 AC	430 b	230 ± 57 a	280 ± 110 AC
4	K1	L	5.26		5.26 AB	63.0 b	26.7 ± 6.6 a	35.8 ± 19.0 AC	900 a	2059 ± 466 b	1770 ± 694 AC	530 b	217 ± 89 a	295 ± 172 AC
5	K1	L	5.54 a	5.86 ± 0.05 b	5.78 ± 0.17 BC	59.0 b	33.2 ± 0.8 a	39.7 ± 12.9 AC	1191 a	1521 ± 109 b	1439 ± 187 AC	320 a	253 ± 34 a	270 ± 43 AC
6	K1	L	5.31 a	5.89 ± 0.03 b	5.75 ± 0.29 BC	54.0 b	29.5 ± 6.8 a	35.7 ± 13.5 AC	753 a	2026 ± 186 b	1708 ± 655 AC	550 b	98 ± 37 a	211 ± 228 AC
7	K1	CL	5.63 a	5.94 ± 0.04 b	5.86 ± 0.16 BC	54.0 a	54.7 ± 4.7 a	54.5 ± 3.8 BC	771 a	1624 ± 94 b	1410 ± 433 AC	590 b	423 ± 52 a	465 ± 93 C
8	K1	CL	5.48 a	6.02 ± 0.05 b	5.88 ± 0.27 BC	43.0 a	41.8 ± 2.6 a	42.1 ± 2.2 AC	268 a	1778 ± 179 b	1401 ± 769 AC	490 b	232 ± 46 a	296 ± 134 AC
9	K1	L	5.67 a	5.92 ± 0.03 b	5.86 ± 0.13 BC	43.0 b	36.5 ± 0.9 a	38.1 ± 3.3 AC	821 a	1632 ± 40 b	1430 ± 407 AC	450 b	230 ± 24 a	285 ± 112 AC
10	K1	L	5.51 a	5.99 ± 0.07 b	5.87 ± 0.25 BC	52.0 b	32.7 ± 4.3 a	37.5 ± 10.3 AC	1248 a	2056 ± 456 a	1855 ± 550 AC	280 a	209 ± 47 a	227 ± 52 AC
11	K1	CL	5.53 a	5.98 ± 0.08 b	5.87 ± 0.23 BC	60.0 b	47.1 ± 4.9 a	50.3 ± 7.6 AC	1436 a	1985 ± 223 a	1848 ± 330 AC	220 a	325 ± 85 a	299 ± 87 AC
12	K1	L	5.35 a	5.86 ± 0.08 b	5.73 ± 0.26 BC	91.0 b	25.6 ± 7.5 a	42.0 ± 33.3 AC	1178 a	2407 ± 394 b	2100 ± 693 BC	490 b	106 ± 38 a	202 ± 195 AB
13	K2	CL	5.50 a	5.49 ± 0.11 a	5.49 ± 0.09 AB	31.0 b	25.7 ± 0.8 a	27.1 ± 2.7 AB	1691 a	1620 ± 198 a	1638 ± 165 AC	147 a	200 ± 43 a	187 ± 44 AB
14	K2	CL	5.80 b	5.42 ± 0.03 a	5.51 ± 0.19 AB	37.0 b	18.0 ± 1.9 a	22.8 ± 9.6 A	1758 a	2089 ± 32 b	2006 ± 167 AC	122 a	78 ± 21 a	89 ± 28 A
15	K2	L	5.60 a	5.51 ± 0.04 a	5.54 ± 0.05 AB	32.0 b	22.2 ± 0.8 a	24.7 ± 4.9 A	1415 a	1796 ± 65 b	1701 ± 198 AC	244 a	186 ± 24 a	200 ± 35 AB
16	K2	CL	6.20 b	5.75 ± 0.08 a	5.87 ± 0.23 BC	38.0 a	44.6 ± 22.4 a	43.0 ± 18.7 AC	1039 a	1298 ± 180 a	1234 ± 196 AB	280 a	231 ± 29 a	243 ± 34 AC
17	K2	CL	6.10 b	5.78 ± 0.08 a	5.86 ± 0.17 BC	44.0 b	37.4 ± 1.4 a	39.0 ± 3.5 AB	1568 b	1271 ± 13 a	1370 ± 172 AC	108 a	245 ± 14 b	211 ± 70 AC
18	K2	CL	5.70 b	5.59 ± 0.01 a	5.62 ± 0.05 AB	31.0 a	27.5 ± 2.3 a	28.4 ± 2.6 AC	1359 a	1631 ± 24 b	1563 ± 137 AC	209 a	187 ± 21 a	192 ± 20 AB
19	K2	CL	5.70 a	5.66 ± 0.06 a	5.67 ± 0.05 BC	31.0 a	36.3 ± 2.1 b	35.0 ± 3.2 AC	2280 b	1726 ± 41 a	1864 ± 279 AC	180 a	170 ± 36 a	173 ± 30 AB
20	K2	CL	5.90 b	5.60 ± 0.04 a	5.67 ± 0.15 BC	37.0 b	25.4 ± 2.4 a	28.3 ± 6.1 AB	2306 b	1862 ± 51 a	1974 ± 226 AC	113 a	136 ± 39 a	130 ± 34 A
21	K2	CL	5.50 b	5.28 ± 0.06 a	5.33 ± 0.12 B	23.0 a	22.7 ± 2.8 a	22.8 ± 2.3 A	1608 a	2007 ± 107 b	1908 ± 218 AC	78 a	103 ± 21 a	97 ± 21 A
22	K2	CL	5.70 a	5.60 ± 0.09 a	5.62 ± 0.09 BC	32.0 a	24.4 ± 4.2 a	26.3 ± 5.1 A	1267 a	1383 ± 33 b	1353 ± 64 AC	328 b	159 ± 5 a	201 ± 85 AB
23	K2	CL	5.80 a	6.32 ± 0.09 b	6.19 ± 0.27 C	23.0 a	43.6 ± 6.8 b	38.5 ± 11.7 AC	1292 a	1683 ± 314 a	1585 ± 323 AC	193 a	229 ± 32 a	220 ± 31 AC
24	K2	CL	5.50 a	5.93 ± 0.14 b	5.83 ± 0.25 BC	38.0 b	27.0 ± 0.4 a	29.8 ± 5.5 AC	1527 a	1579 ± 147 a	1566 ± 123 AC	261 b	144 ± 22 a	173 ± 61 AB
25	K2	L	5.80 a	5.73 ± 0.03 a	5.75 ± 0.04 BC	32.0 b	29.0 ± 0.3 a	29.7 ± 1.5 AC	1255 a	1458 ± 98 a	1408 ± 129 AC	221 a	185 ± 29 a	193 ± 30 AB
26	K2	CL	5.60 a	5.72 ± 0.01 b	5.69 ± 0.06 BC	34.0 a	37.3 ± 2.1 a	36.5 ± 2.4 AC	903 a	1458 ± 151 b	1320 ± 303 AC	447 b	228 ± 35 a	283 ± 113 AC
27	K2	CL	5.90 a	5.79 ± 0.22 a	5.82 ± 0.08 BC	25.0 a	32.5 ± 2.3 b	30.7 ± 4.2 AC	1424 a	1874 ± 64 b	1761 ± 231 AC	129 a	168 ± 22 a	158 ± 26 A
28	K2	CL	5.27 a	5.90 ± 0.04 b	5.75 ± 0.32 BC	50.0 b	36.1 ± 3.7 a	39.6 ± 7.6 AC	1496 a	2219 ± 86 b	2039 ± 369 AC	190 a	171 ± 37 a	176 ± 31 AB
29	K2	CL	5.26 a	5.81 ± 0.07 b	5.67 ± 0.28 BC	41.0 a	23.6 ± 7.7 a	27.9 ± 10.7 AB	1825 a	2165 ± 85 b	2079 ± 183 BC	80 a	131 ± 49 a	118 ± 47 A
30	K2	L	5.32 a	5.72 ± 0.02 b	5.62 ± 0.20 AB	47.0 a	34.7 ± 6.6 a	37.8 ± 8.2 AC	1982 a	2352 ± 245 a	2259 ± 272 C	50 a	154 ± 48 a	128 ± 65 A
31	H	CL	6.40 b	5.91 ± 0.06 a	6.03 ± 0.25 AC	51.0 b	45.6 ± 0.2 a	47.4 ± 3.2 AC	1048 a	1349 ± 71 b	1274 ± 161 AB	423 a	420 ± 68 a	420 ± 55 BC
32	H	CL	6.00 b	5.60 ± 0.02 a	5.70 ± 0.20 BC	36.0 a	35.5 ± 1.8 a	35.7 ± 1.5 AC	1368 a	1527 ± 49 b	1487 ± 89 AC	256 a	245 ± 34 a	248 ± 28 AC
33	O	CL	5.80 a	5.76 ± 0.08 a	5.77 ± 0.07 BC	40.0 a	39.0 ± 5.8 a	39.2 ± 4.8 AC	1372 b	1038 ± 68 a	1122 ± 176 A	131 a	508 ± 73 b	414 ± 198 BC
34	O	CL	5.70 b	5.55 ± 0.06 a	5.58 ± 0.09 AB	37.0 a	37.2 ± 10.1 a	37.2 ± 8.3 AC	1757 a	1813 ± 141 a	1799 ± 119 AC	97 a	115 ± 0 b	111 ± 9 A
Mean			5.63 ± 0.27 a	5.79 ± 0.22 b	5.74 ± 0.25	43.2 ± 15.4 b	33.4 ± 8.4 a	36.1 ± 12.1	1361 ± 430 a	1746 ± 328 b	1653 ± 412	265 ± 155 b	213 ± 94 a	226 ± 118
			pH			Available N			PAC			Available P		
			Df	F	P	Df	F	P	Df	F	P	Df	F	P
field			33	27.1	P <0.01	33	8.3	P <0.01	33	9.4	P <0.01	33	15.2	P <0.01
Year			1	102.0	P <0.01	1	66.9	P <0.01	1	110.0	P <0.01	1	33.0	P <0.01
Field: Year			32	23.5	P <0.01	33	5.4	P <0.01	33	5.1	P <0.01	33	9.7	P <0.01
Residuals			66			67			67			68		

Different lower-case letters within the same row indicate significant differences between 2001–2003 and 2012. Different capital letters within the same column indicate significant differences among soil series. Values are the mean ± standard deviation.

Table 9
Comparison between exchangeable cations, base saturation, and CEC in 2001–2003 and 2012.

Field	Soil	Texture	Exchangeable K ⁺			Exchangeable Ca ²⁺			Exchangeable Mg ²⁺			Base saturation			CEC		
			2001-2003	2012	Mean	2001-2003	2012	Mean	2001-2003	2012	Mean	2001-2003	2012	Mean	2001-2003	2012	Mean
			cmol _c kg ⁻¹			cmol _c kg ⁻¹			cmol _c kg ⁻¹			%			cmol _c kg ⁻¹		
1	K1	CL	0.72 a	1.05 ± 0.07 b	0.97 ± 0.17 A	5.81 a	7.09 ± 0.76 a	6.77 ± 0.89 AD	0.96 a	1.60 ± 0.23 b	1.44 ± 0.37 ABC	42.6 a	48.8 ± 6.7 a	47.3 ± 6.3 ACG	17.6 a	20.0 ± 0.8 b	19.4 ± 1.4 AC
2	K1	L	1.84 b	1.29 ± 0.16 a	1.43 ± 0.30 A	5.63 a	12.7 ± 4.4 a	10.9 ± 5.0 CDE	1.10 a	1.09 ± 0.03 a	1.09 ± 0.02 ABC	29.0 a	79.2 ± 30.1 a	66.7 ± 35.1 FG	29.5 b	19.5 ± 2.0 a	22.0 ± 5.3 AC
3	K1	CL	0.84 a	1.44 ± 0.15 b	1.29 ± 0.32 A	6.84 a	8.90 ± 0.61 b	8.38 ± 1.14 AD	1.21 a	2.05 ± 0.30 b	1.84 ± 0.48 ABC	56.7 a	60.6 ± 9.2 a	60.0 ± 7.6 CG	15.7 a	20.6 ± 2.0 b	19.4 ± 2.9 AC
4	K1	L	1.32 a	1.30 ± 0.10 a	1.30 ± 0.08 A	5.35 a	8.95 ± 5.07 a	8.04 ± 4.51 AD	1.2 a	1.97 ± 0.72 a	1.78 ± 0.70 ABC	53.8 a	56.2 ± 26.1 a	55.6 ± 21.3 ACG	14.6 a	22.1 ± 1.1 b	20.2 ± 3.8 AC
5	K1	L	1.02 a	0.86 ± 0.09 a	0.90 ± 0.11 A	8.70 a	6.85 ± 0.97 a	7.31 ± 1.22 AD	1.30 a	2.48 ± 0.52 a	2.19 ± 0.73 AD	73.4 a	64.0 ± 6.9 a	66.3 ± 7.4 EG	15.0 a	16.0 ± 1.6 a	15.7 ± 1.4 A
6	K1	L	1.11 a	1.24 ± 0.32 a	1.21 ± 0.27 A	5.85 a	5.32 ± 0.77 a	5.45 ± 0.68 AB	1.29 a	4.56 ± 1.15 b	3.74 ± 1.88 D	66.6 a	59.3 ± 8.9 a	61.2 ± 8.1 CG	12.4 a	18.7 ± 2.2 b	17.2 ± 3.6 AC
7	K1	CL	0.89 a	1.54 ± 0.05 b	1.37 ± 0.32 A	8.24 b	6.28 ± 0.22 a	6.77 ± 0.99 AD	1.56 a	2.30 ± 0.52 b	2.12 ± 0.57 ABC	82.8 b	51.5 ± 3.0 a	59.3 ± 15.9 BCG	12.9 a	19.7 ± 1.4 b	18.0 ± 3.6 AC
8	K1	CL	0.77 a	1.62 ± 0.15 b	1.41 ± 0.44 A	7.56 a	5.00 ± 0.48 a	5.64 ± 1.34 AB	1.56 a	2.85 ± 0.27 b	2.53 ± 0.68 BD	82.5 b	48.0 ± 3.2 a	56.6 ± 17.4 ACG	12.0 a	19.8 ± 1.4 b	17.8 ± 4.1 AC
9	K1	L	0.93 a	1.18 ± 0.13 a	1.12 ± 0.16 A	7.88 b	5.40 ± 0.34 a	6.02 ± 1.27 AD	1.67 a	2.37 ± 0.18 b	2.20 ± 0.38 AD	83.9 b	52.2 ± 1.5 a	60.1 ± 15.9 CG	12.5 a	17.2 ± 0.9 b	16.0 ± 2.5 AB
10	K1	L	0.93 a	1.53 ± 0.21 b	1.38 ± 0.35 A	7.99 b	5.37 ± 0.55 a	6.03 ± 1.38 AD	1.84 a	2.93 ± 0.33 b	2.66 ± 0.61 CD	64.3 a	43.2 ± 9.1 a	48.5 ± 12.9 ACG	16.7 a	23.4 ± 4.6 a	21.8 ± 5.0 AC
11	K1	CL	0.96 a	1.40 ± 0.16 b	1.29 ± 0.26 A	7.88 b	5.06 ± 0.36 a	5.76 ± 1.44 ABC	1.59 a	2.52 ± 0.67 a	2.29 ± 0.72 AD	58.2 b	41.1 ± 4.1 a	45.4 ± 9.2 ACG	17.9 a	21.9 ± 0.7 b	20.9 ± 2.1 AC
12	K1	L	1.17 a	1.30 ± 0.06 a	1.27 ± 0.08 A	7.09 b	3.14 ± 0.90 a	4.13 ± 2.11 A	1.60 a	2.12 ± 0.23 a	1.99 ± 0.32 ABC	56.4 b	24.9 ± 6.6 a	32.7 ± 16.7 ACD	17.5 a	26.9 ± 3.4 b	24.6 ± 5.5 AC
13	K2	CL	0.91 a	1.35 ± 0.11 b	1.24 ± 0.24 A	3.43 a	4.11 ± 0.59 a	3.94 ± 0.59 A	0.81 a	1.55 ± 0.03 b	1.37 ± 0.37 ABC	27.2 a	26.8 ± 4.5 a	26.9 ± 3.7 A	18.9 a	26.5 ± 2.0 b	24.6 ± 4.1 AC
14	K2	CL	0.65 a	1.22 ± 0.13 b	1.08 ± 0.31 A	6.06 b	3.92 ± 0.24 a	4.45 ± 1.09 AB	0.92 a	0.91 ± 0.18 a	0.92 ± 0.15 A	37.3 b	23.6 ± 2.7 a	27.0 ± 7.2 AB	20.5 a	25.9 ± 3.2 a	24.6 ± 3.8 AC
15	K2	L	0.73 a	1.14 ± 0.12 b	1.03 ± 0.22 A	6.22 a	6.51 ± 0.60 a	6.44 ± 0.51 AD	1.37 b	1.06 ± 0.07 a	1.14 ± 0.17 ABC	44.7 b	31.3 ± 3.5 a	34.6 ± 7.3 ACEF	18.6 a	27.9 ± 1.7 b	25.6 ± 4.9 AC
16	K2	CL	0.56 a	0.73 ± 0.07 b	0.69 ± 0.10 A	8.09 a	8.91 ± 0.61 a	8.7 ± 0.64 AD	1.28 a	1.45 ± 0.05 b	1.41 ± 0.09 ABC	58.4 b	45.8 ± 4.2 a	49.0 ± 7.2 ACG	17.0 a	24.3 ± 1.6 b	22.5 ± 3.9 AC
17	K2	CL	0.67 a	1.65 ± 0.20 b	1.41 ± 0.52 A	7.75 a	10.1 ± 1.22 a	9.51 ± 1.54 BD	1.22 a	2.12 ± 0.43 a	1.90 ± 0.57 ABC	47.5 a	48.4 ± 6.3 a	48.2 ± 5.2 ACG	20.3 a	28.7 ± 1.0 b	26.6 ± 4.3 C
18	K2	CL	0.65 a	1.30 ± 0.16 b	1.14 ± 0.35 A	4.25 a	6.01 ± 0.28 b	5.57 ± 0.91 AB	0.58 a	1.07 ± 0.02 b	0.95 ± 0.25 A	37.3 a	39.1 ± 3.9 a	38.6 ± 3.3 ACEF	14.7 a	21.5 ± 1.2 b	19.8 ± 3.6 AC
19	K2	CL	0.90 a	1.55 ± 0.10 b	1.38 ± 0.33 A	8.14 a	8.22 ± 0.21 a	8.20 ± 0.17 AD	1.83 b	1.19 ± 0.22 a	1.35 ± 0.37 ABC	52.2 b	43.5 ± 2.5 a	45.7 ± 4.8 ACG	20.8 a	25.3 ± 1.9 b	24.1 ± 2.7 AC
20	K2	CL	0.70 a	1.03 ± 0.07 b	0.94 ± 0.18 A	8.99 b	6.94 ± 0.51 a	7.45 ± 1.11 AD	1.36 a	1.32 ± 0.11 a	1.33 ± 0.09 ABC	54.4 b	34.7 ± 4.9 a	39.6 ± 10.6 ACEF	20.3 a	27.0 ± 2.5 b	25.3 ± 3.9 AC
21	K2	CL	0.67 a	1.37 ± 0.25 b	1.19 ± 0.41 A	6.39 a	6.27 ± 0.47 a	6.30 ± 0.39 AD	1.04 a	1.96 ± 0.22 b	1.73 ± 0.50 ABC	45.8 b	34.0 ± 3.2 a	37.0 ± 6.4 ACEF	17.7 a	28.3 ± 2.8 b	25.7 ± 5.8 BC
22	K2	CL	1.11 a	1.12 ± 0.08 a	1.12 ± 0.06 A	7.39 a	8.18 ± 0.09 b	7.98 ± 0.40 AD	1.48 a	1.42 ± 0.12 a	1.44 ± 0.10 ABC	48.1 a	59.7 ± 6.1 a	56.8 ± 7.7 ACG	20.8 a	18.1 ± 1.5 a	18.8 ± 1.8 AC
23	K2	CL	0.73 a	1.52 ± 0.03 b	1.33 ± 0.40 A	7.63 a	17.8 ± 3.7 b	15.3 ± 5.94 E	1.14 a	1.44 ± 0.15 a	1.37 ± 0.20 ABC	53.4 a	85.9 ± 21.0 a	77.8 ± 23.7 ACG	17.8 a	24.5 ± 3.1 a	22.8 ± 4.2 AC
24	K2	CL	0.85 a	1.17 ± 0.07 b	1.09 ± 0.17 A	7.78 a	7.79 ± 0.21 a	7.79 ± 0.17 AD	1.21 a	1.31 ± 0.33 a	1.29 ± 0.27 ABC	45.5 a	44.3 ± 5.1 a	44.6 ± 4.2 ACEF	21.6 a	23.4 ± 2.3 a	22.9 ± 2.0 AC
25	K2	L	1.04 a	0.88 ± 0.10 a	0.92 ± 0.11 A	6.50 a	6.78 ± 0.71 a	6.71 ± 0.60AD	1.31 a	1.42 ± 0.17 a	1.40 ± 0.15 ABC	47.8 a	43.1 ± 10.0 a	44.3 ± 8.5 ACEF	18.5 a	21.9 ± 5.9 a	21.0 ± 5.1 AC
26	K2	CL	0.83 a	1.56 ± 0.10 b	1.38 ± 0.37 A	7.68 a	7.90 ± 0.74 a	7.84 ± 0.62 AD	1.16 a	1.04 ± 0.09 a	1.06 ± 0.09 AB	51.8 a	50.7 ± 3.0 a	51.0 ± 2.5 ACG	18.7 a	20.7 ± 1.5 a	20.2 ± 1.6 AC
27	K2	CL	0.62 a	1.00 ± 0.15 b	0.91 ± 0.23 A	7.63 a	8.37 ± 0.36 a	8.18 ± 0.48 AD	1.32 a	1.37 ± 0.06 a	1.36 ± 0.05 ABC	49.8 a	53.8 ± 4.7 a	52.8 ± 4.3 ACG	19.2 a	20.0 ± 0.9 a	19.8 ± 0.9 AC
28	K2	CL	0.92 a	0.75 ± 0.15 a	0.80 ± 0.15 A	4.10 a	5.46 ± 0.50 b	5.12 ± 0.79 AB	1.07 b	0.80 ± 0.05 a	0.87 ± 0.14 A	24.7 a	31.3 ± 4.0 a	29.6 ± 4.6 AC	24.6 b	22.5 ± 0.8 a	23.0 ± 1.3 AC
29	K2	CL	0.79 a	1.21 ± 0.11 b	1.11 ± 0.23 A	4.71 a	3.65 ± 0.82 a	3.91 ± 0.85 A	1.28 a	2.44 ± 0.16 b	2.15 ± 0.59 ABC	34.4 a	34.2 ± 2.9 a	34.3 ± 2.4 ACE	19.7 a	21.3 ± 0.3 b	20.9 ± 0.8 AC
30	K2	L	0.94 a	1.46 ± 0.16 b	1.33 ± 0.29 A	5.56 b	4.19 ± 0.40 a	4.53 ± 0.76 AB	0.80 a	2.35 ± 0.19 b	1.96 ± 0.79 ABC	35.1 a	29.8 ± 3.0 a	31.1 ± 3.6 AC	20.8 a	27.1 ± 3.4 a	25.5 ± 4.2 AC
31	H	CL	0.77 a	1.48 ± 0.09 b	1.31 ± 0.36 A	9.83 a	11.6 ± 1.63 a	11.1 ± 1.6 DE	1.17 a	1.29 ± 0.11 a	1.25 ± 0.10 ABC	66.5 a	64.1 ± 3.9 a	64.7 ± 3.4 DEG	17.7 a	22.5 ± 3.1 a	21.3 ± 3.5 AC
32	H	CL	0.82 a	1.39 ± 0.04 b	1.24 ± 0.29 A	6.53 a	7.03 ± 0.81 a	6.91 ± 0.71 AD	1.33 a	1.67 ± 0.43 a	1.59 ± 0.39 ABC	44.3 a	38.9 ± 6.4 a	40.3 ± 5.9 ACEF	19.6 a	26.3 ± 3.3 a	24.6 ± 4.3 AC
33	O	CL	0.82 a	1.25 ± 0.10 b	1.15 ± 0.23 A	4.31 a	10.2 ± 0.55 b	8.74 ± 2.99 AD	1.09 a	2.03 ± 0.32 b	1.80 ± 0.54 ABC	38.4 a	63.1 ± 5.2 b	56.9 ± 13.1 ACG	16.2 a	21.5 ± 0.8 b	20.1 ± 2.7 AC
34	O	CL	0.62 a	1.38 ± 0.06 b	1.19 ± 0.39 A	5.44 a	4.89 ± 0.74 a	5.03 ± 0.67 AB	0.71 a	3.00 ± 0.61 b	2.42 ± 1.24 AD	31.8 a	36.6 ± 3.8 a	35.4 ± 3.9 ACEF	21.3 a	25.3 ± 0.8 b	24.3 ± 2.1 AC
Mean			0.88 ± 0.24 a	1.27 ± 0.24 b	1.17 ± 0.31	6.74 ± 1.53 a	7.20 ± 2.93 a	7.09 ± 2.82	1.25 ± 0.30 a	1.85 ± 0.78 b	1.7 ± 0.77	50.8 ± 15.4 b	46.8 ± 4.28 a	47.8 ± 16.2	18.2 ± 3.5 a	22.8 ± 3.4 b	21.7 ± 4.3
			Exchangeable K ⁺			Exchangeable Ca ²⁺			Exchangeable Mg ²⁺			Base saturation			CEC		
			Df	F	P	Df	F	P	Df	F	P	Df	F	P	Df	F	P
	Field	33	8.0	P <0.01		33	10.1	P <0.01	33	11.0	P <0.01	33	7.6	P <0.01	33	6.4	P <0.01
	Year	1	221.2	P <0.01		1	2.5	0.12	1	72.1	P <0.01	1	4.7	P <0.05	1	99.8	P <0.01
	Field: Year	33	4.9	P <0.01		33	2.9	P <0.01	33	3.4	P <0.01	33	2.7	P <0.01	33	2.2	P <0.01
	Residuals	68				68			68			68			68		

Different lower-case letters within the same row indicate significant differences between 2001–2003 and 2012. Different capital letters within the same column indicate significant differences among soil series. Values are the mean ± standard deviation.

Table 10Comparison of regression equation between initial soil organic carbon (SOC) content and rate of Δ SOC content.

Study region	Climate	Landuse	Mean annual temperature (°C)	Annual precipitation (mm)	Study period	Duration (year)	Regression equation	Threshold (g C kg ⁻¹)	Reference
England and Wales	Temperate	Various	7.6	611	1978-2003	25	Rate of Δ SOC = $-0.019 \times \text{Initial SOC} + 0.60$	32.1	Bellamy <i>et al.</i> 2005
South Norway	Cool temperate	Cropland	5.6	763	1991-2001	10	Rate of Δ SOC = $-0.036 \times \text{Initial SOC} + 0.57$ ^{† 1}	15.8	Riley and Bakkegard 2006
Netherlands	Temperate	Grassland and maize	9.7	798	1984-2004	20	Rate of Δ SOC = $-0.035 \times \text{Initial SOC} + 1.97$ [‡]	56.3	Hanegraaf <i>et al.</i> 2009
Netherlands	Temperate	Grassland and maize	9.7	798	1984-2005	20	Rate of Δ SOC = $-0.042 \times \text{Initial SOC} + 1.70$ [‡]	40.4	Hanegraaf <i>et al.</i> 2009
Netherlands	Temperate	Grassland and maize	9.7	798	1984-2006	20	Rate of Δ SOC = $-1.551 \times \text{Initial SOC} + 0.55$ [‡]	0.35	Hanegraaf <i>et al.</i> 2009
Netherlands	Temperate	Grassland and maize	9.7	798	1984-2007	20	Rate of Δ SOC = $-0.043 \times \text{Initial SOC} + 0.96$ [‡]	22.3	Hanegraaf <i>et al.</i> 2009
South Germany	Temperate	Grassland	9.7	620	1986-2007	21	Rate of Δ SOC = $-0.081 \times \text{Initial SOC} + 5.16$	63.7	Capriel <i>et al.</i> 2013
South Germany	Temperate	Cropland	9.7	620	1986-2008	21	Rate of Δ SOC = $-0.053 \times \text{Initial SOC} + 0.91$	17.2	Capriel <i>et al.</i> 2013
This study	Cool temperate	Cropland	7.5	1179	2001 (2003)-2012	9~11	Rate of Δ SOC = $-0.046 \times \text{Initial SOC} + 1.12$	24.3	

Threshold level; x intercept of regression equation. ^{*1} If the original regression equation was provided as a relationship between initial SOC content change in SOC content, the slope and intercept of regression equation was divided by the year difference between two sampling times. ^{*2} If the original regression equation was provided as SOM content. the intercept was divided by 1.724 to convert to SOC content.