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Title	Factors controlling change in soil organic carbon stock in various land uses on different soil types under different climate
Author(s)	岩崎, 真也
Citation	北海道大学. 博士(農学) 甲第13152号
Issue Date	2018-03-22
DOI	10.14943/doctoral.k13152
Doc URL	http://hdl.handle.net/2115/73117
Type	theses (doctoral)
File Information	Shinya_Iwasaki.pdf

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Factors controlling change in soil organic carbon stock in various land uses on different soil types under different climate

(異なる気候、土壌のさまざまな土地利用における

土壌有機態炭素ストック変化の支配要因)

Hokkaido University Graduate School of Agriculture

Division of Environmental Resources Doctor Course

Shinya Iwasaki

Acknowledgements

First and foremost, I would like to express my deepest gratitude and immense indebtedness to my supervisor, Prof. Ryusuke Hatano, whose invaluable supervision, encouragement and infinite enthusiasm. I could not have made it without his mentorship, insights, and understanding. I am grateful to the members of the advisory committee, Prof. Munehide Ishiguro and Prof. Takashi Hirano for their constructive comments, suggestions and invaluable encouragement on this manuscript.

This study would not have been possible without guidance and support of many people.

I am thankful to the staff of the Toya branch of the Japan Agricultural Cooperatives for their work on the field measurements, and to the farmers of Toya region for allowing us to conduct the study on their farms. In particular, I thank Mr. Yasuhiko Endo for his coordination with farmers and kind support in various situations.

I would like to make a special reference to the Dr. Roman V. Desyatkin of the Institute for Biological Problems of Cryolithozone, Siberian Branch, Russian Academy of Science (IBPC) for his help in completing the study. With his variable advice, I improved this study. I also would like to express my gratitude to Dr. Aleksey R. Desyatkin of IBPC, who accompanied me to field sampling and his valuable suggestions throughout my study and manuscript writing. It is a pleasure to thank all other colleagues in IBPC, the Ammosov North-Eastern Federal University, Melnikov Permafrost Institute, Russian Academy of Science, and Yakutian Federation of Mountaineering and Sport Climbing, for their support, encouragement, and friendship during my study and life in Russia. In particular, I thank Ms. Tatiana V. Kyrbasova, Mr. Nikolai V. Filippov, and Dr. Pavel P. Fedorov for their support with fieldwork and sample analysis.

I am also very thankful to all staff members and students in the soil science laboratory from 2010 to 2018. I deeply appreciate Ms. Yoshino Nakamura, Ms. Kazumi Ishikawa, Ms. Atsumi Sawa, and Ms. Kaori Yamamoto for their kind support in dealing with various official matters related and their friendship. I also sincerely thank Dr. Kanta Kuramochi for his encouragement, helpful suggestions throughout my study. I particularly wish to thank Dr. Mariko Shimizu and Dr. Kiwamu Ishikura for giving me so much support for my research. With their help, I improved this study, and my scientific knowledge was enhanced. Special thanks to Dr. Nagaaki Sekiya, Dr. Yohei Hamada, Dr. Rui Jiang, Dr. Fengky Florante Adji, Dr. Chunying Wang, Dr. Xi Li, Dr. Atfritedy Limin, Dr. Mengjie Li, Dr. Arunrat Noppol, Dr. Ikabongo Mukumbuta, Ms. Miki Izumi, Mr. Naoya Kajihara, Mr. Kei Takizawa, Ms. Fuyuko Hazama, Ms. Sachiko Takahashi, Ms. Chihiro Naito, Ms. Hirono Kishimoto, Mr. Hitoshi Tsukasaki, Mr. Sho Saito, Mr. Shuntaro Hirasawa, Ms. Zaimire Abudushalamu, Mr. Yuta Nobuoka, Mr. Yosuke Morimitsu, Mr. Kentaro Horikawa, Mr. Hirokazu Nakamoto, Mr. Junki Tomohiro, Ms. Kayoko Ogura, Mr. Kentaro Okura, Mr. Arata Nagatake, Ms. Rina Kartikawati, Mr. Priyo Adi Nugroho, Mr. Kentaro Tanabe, Mr. Motohiro Yoshimura, Mr. Shunsuke Morita, Mr. Vecky Kuswandra Dwi, Ms. Yang Fu, Ms. Putri Oktariani, Mr. Daiki Kamei, Ms. Rina Shirataki, Mr. Yuma Michinobu, Ms. Dilin Rahaya Nataningtias, Ms. Mako Abe, Mr. Takuya Inadomi, Ms. Risa Sakaue, Mr. Sota Nishi, Ms. Kaho Yasuda, Ms. Iori Kasashima, Ms. Ayaka Kitahara, Ms. Chiho Sugiyama, Mr. Hiromichi Takahashi, and Mr. Takuto Nakayama.

I also would like to make a special reference to superiors and colleagues in Tsumura & Co. for their understanding and support for my work. I particularly appreciated the back up of Mr. Koin Toda: Executive officer, Head of the Botanical Raw Material (RBM) division, Mr. Takemi Hirate: Vice director of RBM division, Dr. Kazunori Hashimoto: Head of RBM

research laboratories, Mr. Kenji Kondo: Director of RBM research laboratories, Mr. Naoki Fujihara: Manager of RBM research laboratories.

I deeply thank my family for their support and understanding. Their encouragement kept me going even when things got tough.

Lastly, I offer my regards and blessings to all of those who supported me in many respects during the completion of the study.

Shinya Iwasaki

謝辞

本研究を行うにあたり，主査をしていただいた北海道大学大学院農学研究院土壌学研究室の波多野隆介教授には研究計画の立案から遂行，論文の執筆に至るまで多くのご指導･ご鞭撻を賜り，大変お世話になりました。ここに厚く御礼申し上げます。また，本論文の副査として適切なご指導･ご助言を賜りました同研究院土壌保全学研究室の石黒宗秀教授，生態環境物理学研究室の平野高司教授にも厚く御礼申し上げます。

調査の遂行にあたっては数えきれないほど多くの方々のご協力をいただきました。

洞爺地域での研究では，JA とうや湖の皆様には土壌調査にご協力いただくと共に多くの場面で便宜を図っていただきました。特に遠藤靖彦様には調査地の選定や分析に関するご助言をいただくと共に農家の方々との間を取り持っていただくなど多大なご支援をいただきました。洞爺地域の農家の皆様には土壌採取や聞き取り調査を快く引き受けていただき，貴重なデータを得ることができました。また現場での生の声を聞くことができ，私の研究生活にとって非常に良い経験となりました。洞爺地域での調査にご尽力いただいた皆様にここに厚く御礼申し上げます。

シベリアでの研究では，ロシア科学アカデミーシベリア支部･極寒地生物問題研究所の Roman V. Desyatkin 副所長には招聘状の発行，調査地の提供などで様々な便宜を図っていただき，研究についても多くのご助言をいただきました。同研究所の Aleksey R. Desyatkin 博士とは研究計画の立案，現地調査，データの解析に至るまで多くの苦楽を共にしました。また，論文の執筆活動においても多くの激励をいただきました。同研究所，北東連邦大学，ロシア科学アカデミーシベリア支部･永久凍土研究所のスタッフの皆様，及びヤクーツク登山･クライミング協会の皆様にはロシアでの長期滞在中，多くのご支援･ご協力をいただき，公私にわたり充実した生活を送ることができました。また，異国の文化に触れることができ，貴重な体験となりました。特に Tatiana V. Kyrbasova さん，Nikolai V. Filippov さん，Pavel P. Fedorov 博士とは

多くの現地調査で寝食を共にしました。ときに厳しい環境の中，調査を遂行することができたのは皆様のご協力があってこそだと感じています。また一緒にウォッカを飲める日を楽しみにしています。酪農学園大の澤本卓治教授，森林総合研究所の森下智陽博士，秋田県立大学の高階史章助教授，国際航業株式会社の小出隆広博士によるシベリアでの研究の立ち上げなくして本研究は無かったと思います。シベリアでの調査にご尽力いただいた皆様にここに厚く御礼申し上げます。

土壌学研究室の皆様には在籍中大変お世話になりました。中村芳野事務官，沢敦美事務官，石川和美事務官，山本香織事務官には多くの事務手続きを行っていただいたことで円滑に研究を進めることができました。倉持寛太講師には適切な土壌分析･データ解析法を指導していただきました。清水真理子博士，石倉究博士には学部生時代から様々な相談に乗っていただき，基礎的なデータの取り方から研究者としての姿勢まで，多くのことを学ばせていただきました。長竹新さんとは同じ博士課程の学生として苦楽を共有し、多くの有意義な議論ができました。関谷長昭博士，濱田洋平博士, Rui Jiang 博士, Fengky Florante Adji 博士, Chunying Wang 博士, Xi Li 博士, Atfritedy Limin 博士, Mengjie Li 博士, Arunrat Noppol 博士, Ikabongo Mukumbuta 博士の諸先輩方には様々なご指導･ご助言をいただきました。同期の齋藤翔さん，平澤俊太郎さん，延岡裕太さん, Zaimire Abudushalamu さんには多くの刺激をいただき、また在学中から変わらずに応援していただきました。泉弥希さん，梶原直哉さん，滝沢啓さん，間冬子さん，高橋幸子さん，内藤千尋さん，岸本紘乃さん，柄崎仁志さん，盛満陽介さん，堀川謙太郎さん，中本洋和さん，友広純貴さん，小倉加代子さん，大倉健太朗さん，Rina Kartikawati さん, Priyo Adi Nugroho さん，田邊健太郎さん，吉村元博さん，森田峻輔さん, Vecky Kuswandra Dwi さん, Yang Fu さん, Putri Oktariani さん，亀井大輝さん，白瀧吏奈さん，道信有真さん, Dilin Rahaya Nataningtias さん，阿部真子さん，稲富拓也さん，坂上里紗さん，西颯太さん， 安田花穂さん，笠島衣織さん，北原朱華さん，杉山千穂さん，高橋大道

さん，中山拓人さんには今まで大変お世話になりました。土壌学研究室で関わったすべての方々のおかげで学位論文をまとめることができたと感じています。

また、株式会社ツムラの上司·同僚の皆様のご理解·ご支援なくして本研究を完遂することはできませんでした。特に生薬本部長 戸田光胤様，同副本部長 平手豪己様，生薬研究所長 橋本和則様，栽培研究部長 近藤健児様，栽培基礎グループ長 藤原直樹様には多大なご支援をいただきました。この場を借りて厚く御礼申し上げます。

以上に述べた方々及び，ここに記しきれなかった多数の方々のご助力をいただくことにより，本研究をここまで進めることができました。全ての方々にこの場を借りて厚く御礼申し上げます。

最後になりましたが，学生生活を送るにあたり，経済面，精神面など様々な側面で支え続けてくれた家族に深く感謝しています。この場を借りて厚く御礼申し上げます。

岩崎真也

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1. General introduction

Atmospheric CO_2 increased by 40% from 278 ppm in 1750 to 391 ppm in 2011 (Ciais et al., 2013) with anthropogenic CO_2 emissions to the atmosphere of about 555 ± 85 Pg C, over the same period (Ciais et al., 2013; IPCC, 2013). Between 1970 and 2004, global emissions of greenhouse gases (GHG) increased by 70%, from 29 to 49 Gt CO_2-eq, with CO_2 as the largest source, representing an increase of approximately 80%. The rate of increase in atmospheric CO_2 concentration has been about 1.5 ppm (0.4%) per year over the past two decades (IPCC, 2013). Moreover, IPCC (2013) estimated a 33% contribution of land use change to anthropogenic global carbon (C) emissions (180 Gt C was emitted from 1750 to 2011). Carbon stored in the top 1 m of soil (1500 Pg C) is approximately three times greater than C stored in the aboveground biomass, and twice of the C, as carbon dioxide (CO_2), in the atmosphere (Janzen, 2004; Jobbágy and Jackson, 2000; Lal, 2004b) (Fig. 1.1).

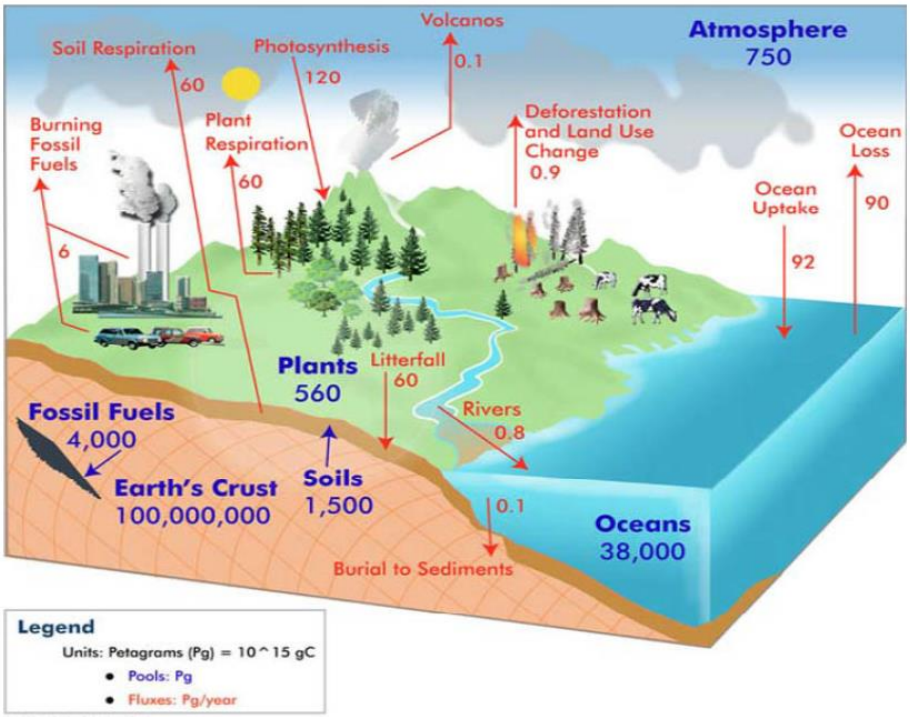

Fig. 1.1. The global carbon cycle showing carbon stocks in blue (in Pg C = Gt C) and carbon fluxes in red (in Gt C yr^{-1}) (Conijn and Lesschen, 2015).

Therefore, change in soil organic C (SOC) stock considerably influences atmospheric CO_2 concentrations and the stability of SOC is critical to the global C cycle and climate change (Li et al., 2013). A substantial amount of SOC is stored in the upper 10 to 20 cm of the soil, and the quantity and quality of C in the topsoil is often used as an indicator of soil quality and productivity (Johnston et al., 2009). Given the current attention to the potential of climate change mitigation through soil C sequestration, it is a quite importance that C stocks are estimated correctly.

Bellamy et al. (2005) reported that 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 suggested the climate change to be the driving factor behind the SOC losses because the loss occurred across the different types of land uses from natural forest to croplands. They also showed a significantly linear relationship between the rate of change in SOC and the initial SOC content (1973), the rate of change in SOC (g C kg^{-1} yr^{-1}) = -0.0187 × initial SOC content (g C kg^{-1}) + 0.6, indicating the threshold of initial SOC for the decrease of SOC (x-intercept). From the regression equation, the threshold value of initial SOC content was estimated at 32.1 g C kg^{-1}. And the loss occurred in the soils with initial SOC content greater than the threshold while soils with SOC content smaller than the threshold gained C. Moreover, a larger slope means there is a more vigorous change in the rate of change in SOC content with a change of initial SOC content. Therefore, the slope may be indicating the stability of SOC.

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 (Capriel, 2013; Heikkinen et al., 2013; Lark et al., 2006; Riley and Bakkegard, 2006; Saby et al., 2008).

Carbon sequestration on the soil surface is achieved by balancing the accumulation of C and the decomposition of organic matter in the ecosystem which is influenced by many factors, such as climate, topography, soil parent material, soil properties, land use, and anthropogenic management (Fernández-Romero et al., 2014; Jobbágy and Jackson, 2000; Khormali et al., 2009; Liu et al., 2011; Sun et al., 2015). Therefore, these factors can also affect the threshold SOC values and the slope of the regression equation.

Fig. 1.2 shows schematic diagram of C budget in the ecosystem. In the ecosystems, carbon enters the ecosystem through photosynthesis as the assimilation of atmospheric CO_2 (gross primary production; GPP), and most of C fixed as a GPP returns to the atmosphere by autotrophic and heterotrophic respiration (ecosystem respiration; RE). Net ecosystem exchange (NEE) is defined as a difference between these two processes -[(GPP - RE)]. Management practices such as harvest and manure application can affect the C budget. The difference of all C imports and exports [net biome production; NBP (-NEE + C input - C output)] equals the change in the C stock in the soil (Bernacchi et al., 2005; Randerson et al., 2002).

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 (Beare et al. 1994; Elliot 1986). SOM, therefore, affects the physico-chemical properties of soil (Bot and Benites 2005; Matson et al. 2002). Increases in SOM lower bulk density (BD) but improve aggregation, hydraulic conductivity, water-holding capacity, and total porosity (Celik et al. 2004; Celik et al. 2010; Liu et al. 2011; Papadopoulos et al. 2009). Also, the cation exchange capacity (CEC) of soil is highly correlated with SOC content (Gruba and Mulder 2015). Therefore, it is important to evaluate the change in SOC, not only from the perspective of C sequestration but also from that of soil fertility improvement.

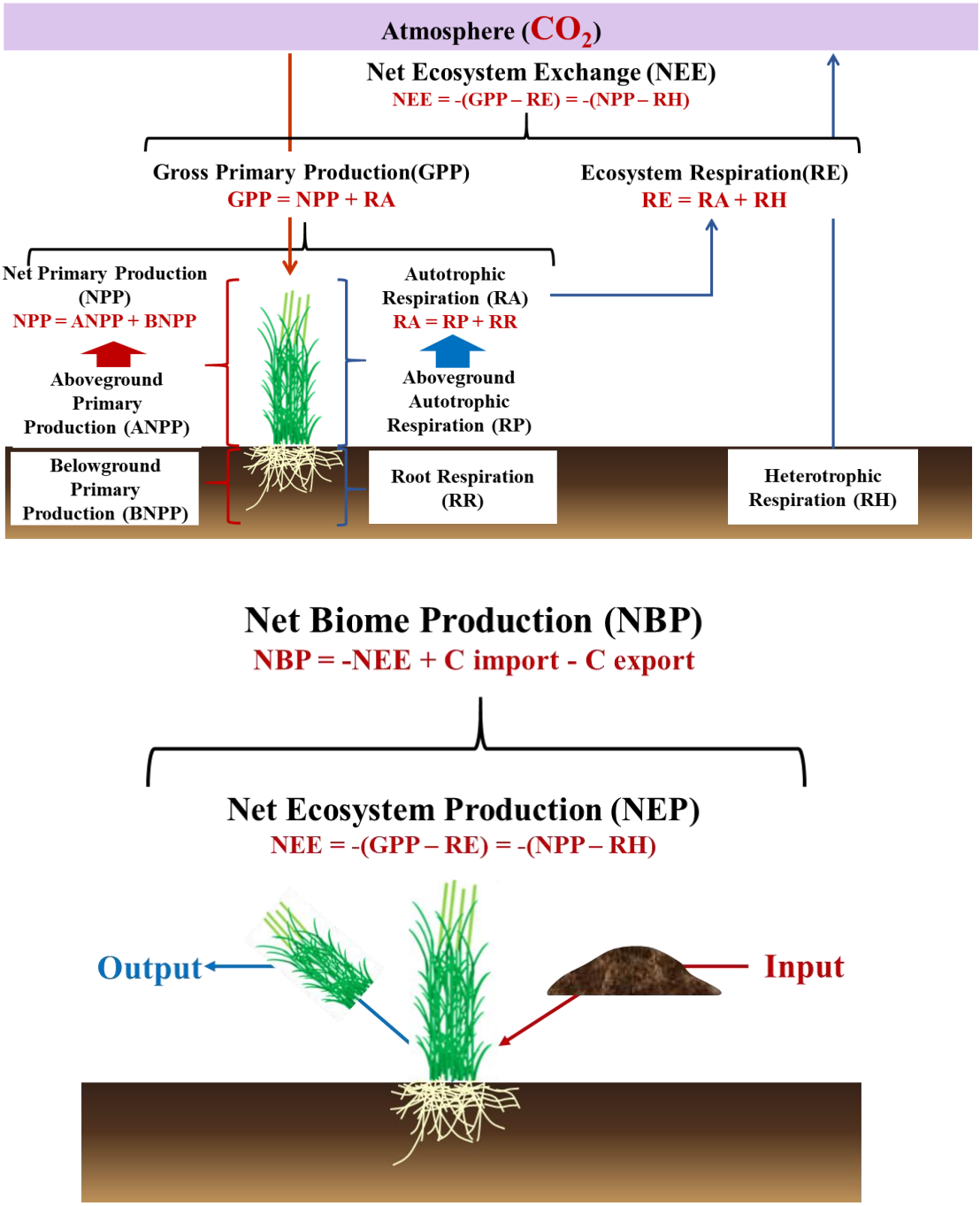

Fig. 1.2. Schematic diagram of carbon budget in the ecosystem.

In cropland, C sequestration is influenced by field management practices (Jastrow et al. 2007; Jobbágy and Jackson 2000). 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 through 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 the soil and an increase in SOC content (Hao *et al*. 2003; Kundu *et al*. 2007, Naveed *et al*. 2014).

Although Andosols cover only approximately 0.84% of the world's land surface (Soil Survey Staff, 1999), theycover more than 50% of the total upland crop field area in Japan. Moreover, Andosols often have a high SOC content, mainly due to the formation of short-range ordered (amorphous) minerals and Al/Fe–OH (Shirato et al., 2004; Shoji et al. 1993; Takahashi and Dahlgren, 2016). 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 (McDaniel et al., 2012; Shoji et al., 1993; 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 (Arthur et al., 2013; Bronick and Lal, 2005) and to improve P availability by enhancing organic P mineralization (Takeda et al., 2009; Tsuji et al., 2006).

In the northern circumpolar region, it is about 17.8 million km^2 occupied by the permafrost-affected soils (Hugelius et al., 2014). It is estimated that nearly one-third of the world's total SOC inventory of top 3m of the soil profile (approximately 1035 Pg C) is stored in arctic and boreal regions (Hugelius et al., 2014). This ecosystem accounts for more than 30% of total terrestrial organic C with the majority of this C residing in the soil environment and most of the C stored in high-latitude ecosystems with permafrost soils (Tarnocai et al., 2009). During a climate warming (IPCC, 2014), thawing of permafrost soils may cause remobilization of SOM previously protected by permafrost of this region (Schuur et al., 2008).

Global warming is expected to be most pronounced in northern high latitudes (Desyatkin et al., 2015; IPCC, 2014). Indeed, between 1961 and, 2010 the mean annual air temperature at Yakutsk increased by 2.5 ºC (Fedorov et al., 2014). Moreover, heavy precipitation events exceeding 20 mm d^{-1} significantly increased during 1936–1994 (Easterling et al., 2000) and unusual wet climate has occurred since 2005 (Iijima et al., 2014; Ohta et al., 2014;). Increase active layer depth and altered hydrological conditions can lead to increase of mineralization (Dutta et al., 2006; Koven et al., 2009; Schurr et al., 2015; Schuur and Bockheim, 2008). Therefore, changes in SOC stock in permafrost zone have a significant interest.

The central Yakutia region is a well-known as a thermokarst terrain (French, 1996). Thermokarst degradation occurs in four different stages, and finally forms a stable thermokarst depression, which is called an "alas" (Desyatkin and Desyatkin, 2006). Around 16,000 alases are located in the Central Yakutia lowland with a total area of 440,000 ha, which represents 17% of the total land area of Central Yakutia (Bosikov, 1991). SOC in alas soil is about 6 to 8-times higher than in surrounding typical taiga soils due to the accumulation of C during alas formation (Desyatkin and Desyatkin, 2006; Matsuura et al., 1994; Morishita et al., 2003). However, the exact amount of C stock in the thermokarst ecosystem is still unknown.

As a result of the climate change observed in this region, a significant increase in thermokarst activity has been observed since the early 1990th. Melting of the tops of ice wedges is causing subsidence of the ground surface, deepening and expansion of thermokarst depressions, and growth of thaw ponds to form larger lakes (Fedorov et al., 2014; Crate et al., 2017).

Therefore, the permafrost-affected soils in the northern circumpolar region are regarded as the hot spot of CO_2 emission. However, only a few studies about SOC dynamism have been conducted in this region.

This study had the following aims: firstly, to estimate the accumulated SOC stock and its change in various land uses on different soil types under different climate: secondly, to clarify the factors controlling SOC stock.

This dissertation is divided into seven chapters. The current chapter (Chapter 1) is a general introduction to the study. Chapter 2 provides a review of the relevant literature on the research topic. Chapter 3 describes the study sites, materials and the general methodology used in the study. Chapter 4 focuses on the effect of organic matter application on carbon sequestration and soil fertility in upland fields of Andosols in Toya, Hokkaido, Japan. Chapter 5 looks at the change in SOC associated with climate change in the Taiga-Alas landscape in Central Yakutia, Eastern Siberia, Russia. Chapter 6 looks at the effect of thermokarst activities, forest disturbances, and land use changes induced by human activities on soil C stock in Central Yakutia, Eastern Siberia, Russia. Chapter 7 is a general discussion of this study.

2. Literature review

2.1. Estimation of SOC stock

Situated the current attention to the potential of agricultural practices to climate change mitigation through C sequestration as SOC (Lal, 2004a), it is important that SOC stocks are estimated accurately. Most of the studies had calculated the SOC stock using SOC concentration and soil bulk density associated with a specific soil depth. Changes in SOC can be estimated by long-term field experiment (Hopkins et al., 2009), soil inventories based on historical records (Taghizadeh-Toosi et al., 2014), and simulation models (Gervois et al., 2008; Smith et al., 2005; Li et al., 2015). Extensive soil monitoring programs are valuable in providing information on temporal changes in SOC (Heikkinen et al., 2013). However, few studies have used repeated inventories for estimating changes in SOC at regional scales (Bellamy et al., 2005; Capriel, 2013; Chapman et al., 2013). Li et al., 2016 compared the changes in SOC stocks derived from estimation and using repeated inventory datasets for each individual land use type in Hokkaido, Japan. Since changes in SOC occur slowly, repeated samplings over decades are required to establish trends in SOC stocks (Saby et al., 2008). Moreover, the spatial variability of SOC can be considerable (Kinoshita et al., 2016) due to the complexity of physical, chemical and biological processes that influence C cycling in the soil (Jobbágy and Jackson, 2000; Sun et al., 2015). Therefore, soil samplings need to be sufficiently replicated to provide reliable estimates of SOC stocks.

2.2. Roles of SOC in the soil

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

(Beare et al., 1994). Therefore, it affects the physicochemical properties of soil (Bot and Benites 2005), and SOC decline is assumed to impose a threat to soil quality (Getahun et al., 2016; Johnston et al., 2009; Lal et al., 2004a). Increases in SOM lowers bulk density (BD) but improves aggregation, hydraulic conductivity, water holding capacity, and total porosity (Celik et al., 2004; Celik et al., 2010; Eibisch et al., 2015; Liu et al., 2011; Mahmoodabadi and Ahmadbeigi, 2013; Papadopoulos et al., 2009). In addition, the cation exchange capacity (CEC) of soil is highly correlated with SOC content (Gruba and Mulder, 2015). Hati et al., (2007) found a strong relationship between the improvement of the physical properties of soil and an increase in SOM. Moreover, as reported in Haynes and Naidu, (1998), based on the 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 increase rate in SOC (as a result of waste applications) and the reduction rate in soil BD was observed. This phenomenon is a result of the improved aggregation of individual soil particles and decreased BD with a high SOC content (Hati et al., 2007; Papadopoulos et al., 2009). This result consistent with Yang et al., 2014 and Celik et al., (2004), who also found that total soil porosity increased with the increase of SOC content as a result of the application of manure.

Hydraulic conductivity is one of the most important soil physical properties controlling infiltration rates in agricultural lands (Bayabil et al., 2015). In most agricultural soil, increase in the SOC enhances hydraulic conductivity by improving aggregate stability and porosity (Eibisch et al., 2015).

Cation exchange capacity (CEC) is the total sum of exchangeable cations (positively charged ions) that a soil can hold. Cation exchange capacity determines a soil's ability to retain positively charged plant nutrients, such as NH_4^+, K^+, Ca^{2+}, Mg^{2+}, and Na^+. As CEC increases for soil, it can retain more of these plant nutrients and reduces the potential for leaching. Soil CEC

consists of the permanent charge of clay particle and the variable charge of SOM (Gruba and Mulder, 2015). Therefore, CEC is highly correlated with SOC and clay content of the soil. Moreover, the percent contribution of SOM is greatest for soils with low clay content or where the clay fraction is dominated by minerals with a small charge (Gruba and Mulder, 2015; Hemmat et al., 2010).

2.3. Controlling factors of SOC accumulation

Accumulation of C in soil is achieved by balancing the accumulation of C and the decomposition of SOM in the ecosystem which is influenced by many factors, such as climate (Jobbágy and Jackson, 2000), topography (Khormali et al., 2009; Sun et al., 2015), soil properties (Jobbágy and Jackson, 2000), land use (Fernández-Romero et al., 2014; Sun et al., 2015), and anthropogenic management (Deng et al., 2016; Naveed et al., 2014).

Temperature has a large effect on both carbon accumulation and SOC decomposition (Lal, 2004a), and precipitation control plant growth (C input) and SOC decomposition (Jobbágy and Jackson, 2000).

Topography has been identified as an important variable for explaining SOC stocks since it influences the distribution of SOM and soil nutrient (Abrams et al., 1997), the rates of litter decomposition (Sariyildiz et al., 2005), the stability of SOC between landform positions as results of transport (Chaplot and Poesen, 2012; Nadeu et al., 2015). Accumulation of SOM is often favored at the bottom of hills. There are two reasons for SOC accumulation: conditions are wetter at the bottom of hills than at mid- or upper slope positions, and SOM is transported to the lowest point in the landscape through runoff and erosion (Bot and Benites 2005).

The type of land use is a key factor affecting SOC storage as the result of the different quantity and quality of OM input, the litter decomposition rates, and the processes of SOM stabilization

(Gelaw et al., 2014). For example, Schroth et al., (2002) found that SOC stocks in topsoil were lower in agricultural systems compared with the adjacent primary forest in Amazonia for less litter biomass input. Moreover, vegetation often determines the vertical distribution of SOC through root biomass differences with depth (Dorji et al., 2014; Jobbágy and Jackson, 2000). Thus, land use change may significantly impact SOC dynamics by changing the rates of OM inputs and decomposition of SOC in soil (Houghton, 2010; Kurganova et al., 2014).

Soil organic matter tends to increase with an increase of clay content. This increase depends on two mechanisms. First, bonds between the surface of clay particles and SOM retard the decomposition process. Second, soils with higher clay content increase the potential for aggregate formation (Bot and Benites 2005). Prasad and Power, (1997) showed the SOM content in fine-textured soils is two to four times that of coarse-textured soils under similar climate conditions. Don et al., (2007) examined the 440 soil core samples and showed that SOC stocks at the clay-rich site with Vertisols were almost twice as high (86 Mg C ha^{-1} 0.6 m^{-1}) as at the sandy site with Arenosols (48 Mg C ha^{-1} 0.6 m^{-1}).

The vertical distributions of the SOC content significantly affected by the root distribution (Fujisaki et al., 2017; Lai et al., 2017; Selim et al., 2016; Wang et al., 2016). Several studies have reported that root biomass plays an important role in soil C accumulation through fine root mortality in forest and arable land ecosystems (Asaye and Zewdie, 2013; Mazzilli et al., 2015). Mazzilli et al. (2015) analyzed changes in $\delta^{13}C$ natural abundance in OM, and found that belowground biomass contributed from 60 to almost 80% of the total new C present in the OM. Moreover, Limin et al. (2015) estimated the C budget of managed grassland using a combination of eddy covariance and the biometric method, and concluded that root litter might remain in the soil and is a significant contributor to the grassland soil C stock.

2.4. Changes in SOC

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. From the fact that the losses appear to be happening across both England and Wales irrespective of land use, authors assumed a link to climate change. Over the survey period, the mean temperature across England and Wales increased by about 0.5 ˚C, and there were also changes in rainfall distribution. Climate change will affect soil carbon turnover through various processes (Schuur et al., 2015). Increases in temperature will tend to increase rates of SOM decomposition by soil microbes. The effects of temperature will interact in a complicated way with changes in soil moisture brought about by changing rainfall and evapotranspiration patterns and changes in atmospheric CO_2 and nitrogen (N) deposition.

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 (Capriel, 2013; Heikkinen et al., 2013; Lark et al., 2006; Riley and Bakkegard, 2006; Saby et al., 2008).

Several C-climate models indicated that positive C-climate feedback would be triggered due to the acceleration of C release to the atmosphere as CO_2 under predicted future global climate change (Cox et al., 2000). According to the results of Smith et al., (2007) and Kirk and Bellamy, (2010), climate change accounts for about 10–20% of the observed SOC changes in England and Wales during the survey period 1978–2003 (Bellamy et al., 2005). Heikkinen et al., (2013) reported the decline of SOC from the agricultural soils in Finland where belongs to the cool temperate zone. According to the results, the SOC concentration has decreased in both mineral and organic soils across the Finland. The relative decline rate (0.2–0.4% yr^{-1}) is comparable

with some earlier studies in the northern part of Europe. In Norway, the mean relative decline rate was around 1% yr^{-1} in cultivated soils (Riley and Bakkegard, 2006).

Contrary to these findings, increasing SOC contents on a regional scale have been reported in Netherland where belongs to temperate zone (Hanegraaf et al., 2009; Reijneveld et al., 2009). Reijneveld et al., (2009) reported on changes in the mean SOC contents of the topsoils (0–5 cm) of grassland and the topsoil (0–25 cm) of arable land in the Netherlands during the period 1984–2004, using a database with 2 million data of SOC determinations from farmers' fields. They reported that SOC contents in mineral soils under grassland and arable land tended to increase by an average rate of 0.10 and 0.08 g C kg^{-1} yr^{-1}, respectively. These increases occurred for the dominant land use types, but with large regional differences. Hanegraaf et al., (2009) analyzed SOM content across Netherland using more than 20 thousand number of samples selected from grass, grass-maize rotation and maize fields in four adjacent provinces that had been sampled four to five times during the period 1984–2004. They found no single uniform trend in SOM content. Over the 20 years period, SOM declined in around 25% of all grassland and forage crops and increased in 40% of those.

Chen et al., (2015) revealed that SOC content exhibited an overall increase across the synthesized studies, with an average accumulation rate of 0.19% yr^{-1}. However, the rate of SOC changes showed large variability among individual cases, ranging from 1.67% yr^{-1} to 4.09% yr^{-1}. SOC content significantly increased in 43.1%, was stable in 31.4%, and decreased in 25.5% of all the synthesized cases, respectively.

In addition to decline in SOC, Bellamy et al., (2005) also found a significantly linear relationship between the rate of change in SOC and the initial SOC content (1973) as: the rate of change in SOC (g C kg^{-1} yr^{-1}) = -0.0187 × initial SOC + 0.6 (g C kg^{-1}), indicating that loss was greatest in soils with large carbon contents while soils with small carbon contents gained carbon.

Indeed, they found that the relative rate of carbon loss increased with soil carbon content and was more than 2% yr^{-1} in soils with SOC contents greater than 100 g C kg^{-1}. Significantly negative correlations between initial SOC content and the rate of change in SOC content were also reported also in temperate or cool temperate zone such as South Norway, South Belgium, France, Netherlands, and South Germany (Capriel, 2013; Goidts and van Wesemael, 2007; Hanegraaf et al., 2009; Riley and Bakkegard, 2006; Saby et al., 2008).

2.5. Effect of land use change on SOC stock

Land use changes significantly affect the amount of C stored in vegetation and soil, therefore, shifting the C balance in ecosystems (Don et al., 2011; Gelaw et al., 2014; Houghton, 2010). Don et al., 2011 made a global meta-analysis. In their study, 385 studies on land use changes were analyzed to estimate the SOC stock changes for all major land use change types and revealed the highest SOC losses were caused by the conversion of primary forest to cropland (-25%) and perennial crops (-30%), but forest conversion into grassland also reduced SOC stocks by 12%. Secondary forests stored less SOC than primary forests (-9%) underlining the importance of primary forests for C stores. Change of SOC is partly reversible, if agricultural land is afforested (+29%) or under cropland fallow (+32%) and with cropland conversion into grassland (+26%) (Fig. 2.1).

Deng et al. (2016) reviews the studies on the effects of land use change on SOCstocks, based on a synthesis of 103 publications, including 160 sites in 29 countries, with the aims of determining the factors responsible for soil C sequestration and quantifying changes in SOC from land use changes (Fig. 2.2). The results show that SOC stocks significantly increased after conversions from farmland to grassland (0.30 Mg ha^{-1} yr^{-1}) and forest to grassland

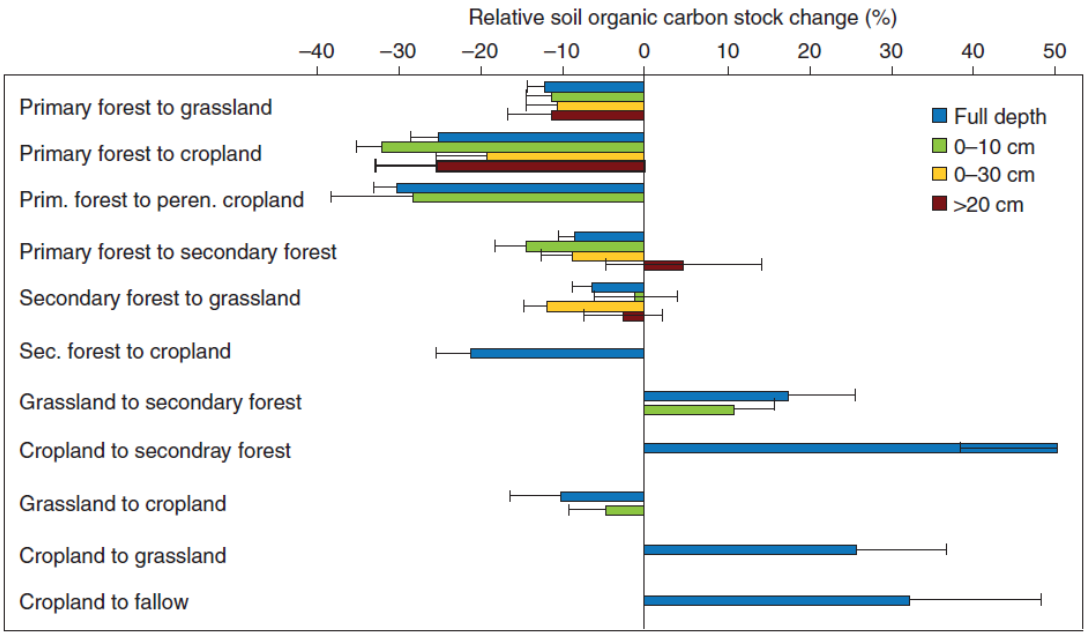

Fig. 2.1. Relative soil organic carbon (SOC) stock changes (Mg ha^{-1}) for different soil depth for different land use change types. The different depth increments are covered by different numbers of studies (Don et al., 2011).

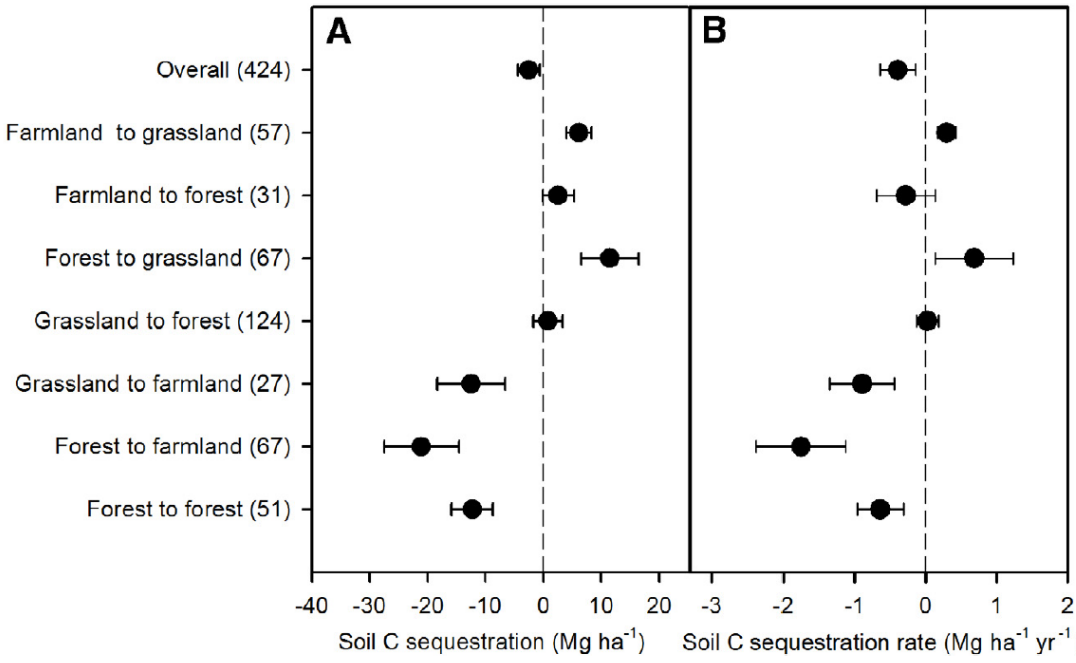

Fig. 2.2. The effects of the land use changes on soil C sequestration and soil C sequestration rate. Dots with error bars denote the overall mean values and the 95% confidence interval, and numbers of observations are in the parenthesis. The dash line indicates x = 0 (Deng et al., 2016).

(0.68 Mg ha^{-1} yr^{-1}), but significantly declined after conversion from grassland to farmland (0.89 Mg ha^{-1} yr^{-1}), forest to farmland (1.74 Mg ha^{-1} yr^{-1}), and forest to forest (0.63 Mg ha^{-1} yr^{-1}).

2.6. Effect of management practice on SOC

In general, agricultural utilization of soils has been found to decrease their SOC (Deng et al., 2016). In cropland, soil C sequestration is influenced by field management practices (Jastrow et al., 2007; Jobbágy and Jackson, 2000). Thus, cultivated mineral soils can be either sources or sinks of C depending on the environmental conditions and management (Lal, 2004a). Decrease of SOC is assumed to impose a threat to soil quality because of the roles mentioned above of SOC in mineral soils (Johnston et al., 2009).

After the Haber-Bosch process was invented, the global human population started growing rapidly. While there are many reasons for this, availability of food was an important factor. Today, more than half of the food eaten by the world's peoples is produced using N fertilizer from the Haber-Bosch process (Galloway and Cowling, 2002). However, management systems heavily relying on chemical fertilizers may have induced the decline of SOC and the leaching of environmental pollutants, for example, by soil erosion and N leaching to the aqua sphere because of the lack of C input and excess amounts of N input to soils (Mäder et al., 2002; Pimentel et al., 2005). Hu et al. (2004) evaluate the effect of cultivation and fertilization on the carbon balance in an onion field in Hokkaido, Japan. Soil respiration rate was measured by the closed chamber method and NBP was determined under fertilized treatments without organic matter input. The values ranged from -2.2 to -1.45 Mg C ha^{-1} yr^{-1}. These negative values indicate that C loss by OM decomposition in soil was not compensated by the amount of OM input into soil.

These background has led to a renewed interest in the use of OM such as manure, green manure, and organic fertilizers. The application of OM is expected to increase SOC by direct input of a C source. Moreover, it mitigates environmental pollution by the stabilization of soil aggregates and the reduction of chemical fertilizer application rates (Mahmoodabadi and Heydarpour, 2014; Yazdanpanah et al., 2016; Yuan et al., 2015).

Many studies have indicated a positive relationship between the amounts of C incorporated into the soil and an increase in SOC content (Hao et al., 2003; Kundu et al., 2007; Naveed et al., 2014). Naveed et al., (2014) show long-term fertilization resulted in significant differences in SOC increasing from 15.3 to 23.7 g C kg^{-1} with increasing amounts of OM and NPK fertilizers. Soil organic carbon linearly increased with the increase of OM input. This is mainly due to direct addition of organic C, and the higher amount of root residues and stubbles due to higher crop yields in well-fertilized plots.

However, also some results have indicated that increased in organic amendment application rate did not increase SOC stock (Kauer et al., 2013). The reason why the increased C input from fertilization did not influence the SOC content may have been that the higher N availability may have a positive impact on the SOC mineralization in conventional farming systems. In addition, N effect on mineralization depends on the chemical composition of OM (Sinsabaugh et al., 2002).

Several authors reported the effect of management practices on C budget on a field scale (Limin et al., 2015; Mu et al., 2008; Shimizu et al., 2013; Shimizu et al., 2015).

Mu et al. (2008) evaluate the C budget in soils under different cropping systems. The CO_2 flux from the soils was measured in a total of 11 upland crop fields within a small watershed in central Hokkaido, Japan over the no snow cover months for 3 years. The estimated carbon

budget value ranged from -7.34 to -0.78 Mg C ha^{-1} $period^{-1}$, except for a wheat site where a positive value of 4.9 Mg C ha^{-1} $period^{-1}$ because of a large input of C with OM (Table 2.1).

Table 2.1

Net primary production, crop residue and compost added to the soil, cumulative CO_2 emission from soil organic matte decomposition, and soil carbon budget under different cropping systems during the no snow cover months within each year (Mu et al., 2008).

Year	Site	Land use	Fertilized inorganic N (kg N ha^{-1})	NPP (kg C ha^{-1})	Carbon added in crop residue (kg C ha^{-1})	Carbon added in compost (kg C ha^{-1})	Cumulative CO_2 emission† (kg C ha^{-1})	Carbon budget‡ (kg C ha^{-1})
2003	A	Grass	32	2,177	665		5,381	−2,026
	B	Wheat	48	2,520	1,352		2,867	−1,515
	C	Maize	196	1,802	1,186		2,800	−1,614
	D	Wheat	140	2,940	1,578		5,282	−3,704
	E	Onion	220	3,490	444		3,302	−2,858
	F	Wheat	112	4,536	2,434		4,310	−1,876
	G	Soybean	36	3,036	1,775		4,370	−2,595
2004	A	Grass	50	2,767	846		7,642	−2,975
	D	Fallow	0	0	0		7,349	−7,349
	E	Onion	228	2,975	388		1,617	−1,229
	I	Wheat	120	3,364	1,807		6,916	−5,109
2005	A	Grass	100	2,306	705		7,271	−2,931
	D	Fallow	0	0	0		4,301	−4,301
	P	Onion	200	2,867	374		1,159	−785
	Q	Wheat	300	5,046	2,710	6543	4,352	4,901
	R	Potato	94	1,943	324		2,854	−2,530

†At site A, soil CO_2 emission was measured from planted plots and soil organic matter decomposition was assumed to account for half of the cumulative soil CO_2 emission for this site. ‡Negative values of carbon budget indicate net CO_2 emission from soils. NPP: net primary production.

Shimizu et al., (2009) clarify the C dynamics and the effect of fertilizer or manure management on the carbon budget in a managed grassland in Southern Hokkaido, Japan. The fertilizer, manure and control plots were established in the grassland, and carbon budgets were estimated for 2 years using an ecological technique. They revealed that the annual NBP in the fertilizer and control plots ranged from -3.9 to -2.9 Mg C ha^{-1} yr^{-1}, suggesting the loss of carbon in the field. On the other hand, NBP in the manure plot was 0.3 and 0.0 Mg C ha^{-1} $year^{-1}$ in 2005

and 2006, respectively. These results indicated that manure application is necessary to prevent carbon loss in the managed grassland.

Moreover, Limin et al. (2015) evaluated the C budget of managed grassland in Southern Hokkaido, Japan using a combination of eddy covariance and the biometric method for five years, to evaluate the effect of manure application. And they showed that the annual NBP in the manured plot (from 0.0 to 1.5 Mg C ha^{-1} yr^{-1}) was significantly higher than in the chemical fertilized plot (from -1.4 to 0.5 Mg C ha^{-1} yr^{-1}). These results indicated the long-term effect of manure application did not reduce grass production compared with chemical fertilizer only and long-term manure application enhanced the NBP.

2.7. Equivalent soil mass (EMS) method

The SOC stock is determined by both SOC concentration and BD. Management practices and land use change that influence SOC concentration may also affect soil BD (Naveed et al., 2014). However, the majority of previous research evaluated SOC stock using SOC content and soil BD associated with a specific soil depth (fixed depth method) without considering changes in soil mass caused by changing BD (Mikha et al., 2013). Ellert and Bettany, (1995) illustrated the importance of reporting SOC stock on an equivalent soil mass (ESM) basis, rather than fixed soil depth (Fig. 2.3). Equivalent soil mass is defined as the reference soil mass per unit area was chosen in a layer and equivalent C mass is C mass stored in an ESM.

Palm et al. (2014) summarized the several papers which treating ESM method. According to their report, Lee et al., (2009) compared the original ESM method against the fixed depth approach and concluded that fixed depth approach is not appropriate and can be less accurate than simply reporting SOC concentration. Wendt and Hauser, (2013) compared the cumulative mass coordinates and cubic spline function against the original ESM method (Ellert and Bettany,

1995) and found that these three gave the same soil C results. While any ESM method is better than the fixed depth method, there are still some advantages and disadvantages of all ESM methods. In recent years, several studies recognize the importance of comparing soil C stocks on the same soil mass per unit area (Oliveira et al., 2016; Poeplau and Don, 2013).

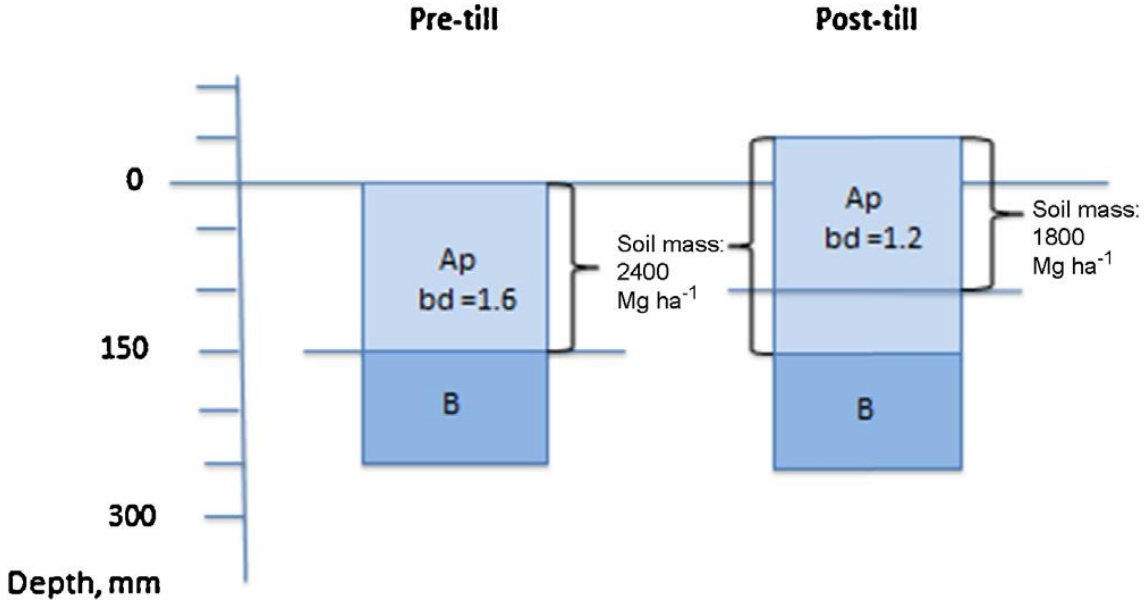

Fig. 2.3. Illustration showing the differences between sampling a soil that is tilled or not tilled to a fixed depth or an equivalent soil mass basis (Palm et al., 2014, edited from Ellert and Bettany,1995).

2.8. Permafrost and thermokarst

In the northern circumpolar region, it is about 17.8 million km^2 occupied by the permafrost-affected soils (Hugelius et al., 2014). Degradation of permafrost and ground ices due to thermokarst process may lead to dramatic distortions of terrain and changes in hydrology and vegetation. It is well known that permafrost contains ice complex, which estimated to be 76000 km^2 in Central Yakutia (Ivanov, 1984). These ice-complex or Yedoma deposits are characterized by more than 60% ground-ice content by volume, in which the ice-wedge volume alone is estimated to be about 50% of the total permafrost volume (Ivanov, 1984).

Fluctuations in climate conditions during the early- and mid-Holocene led to thermokarst formation caused by the degradation of ice complex (Bosikov, 1991; Katamura et al., 2006). The thermokarst depressions or drained thaw lake basins characterized by large areas of the subsided ground surface resulting from thawing of ice-rich permafrost is called “Alas.” Around 16,000 alases are located in Central Yakutia lowland with the total area of 440,000 ha. Alas, size varies from 0.1 to 15 kilometers in diameter and from 3 to 40 meters of depression depth (Bosikov 1991). Pollen analysis using has shown that the formation of thermokarst was initiated between 10,700–9,200 and 9,500–8,500 cal. years before present time (BP) in this region (Katamura et al., 2006). Desyatkin et al. (2013) summarized the specific feature, genesis, and dynamics of the thermokarst. Thermokarst formation process has four stages: bullar, dyede, tuumpu and alas - called alas formation (Fig. 2.4). Ice melting initiates small surface subsidence with the formation of rounded mounds of up to 1 m in height and several meters in diameter (the Bylar stage). Progressive melting of the ground ice results in the development of small lakes and the death of tree vegetation around their banks (the Dyuedya stage). Then, when the major part of ground ice is molten, typical thermokarst lake of rounded shape appear (the Tyympy stage). Under arid conditions, these lakes are partly dried, and meadow vegetation appears on their banks. This is a mature alas. The development of alases is accompanied by the considerable transformation of parent materials and soils. At the first stages, fallen trees from the banks enrich the sediments with the coarse organic material; bank erosion leads to the accumulation of the eroded fine earth. Then, under mature alas, bottom sediments enriched in the organic matter (lacustrine deposits, LD) accumulate in the alas. After partial drying of the lake, the upper horizons grow upward owing to peat (T) accumulation (T/LD) (Fig. 2.5).

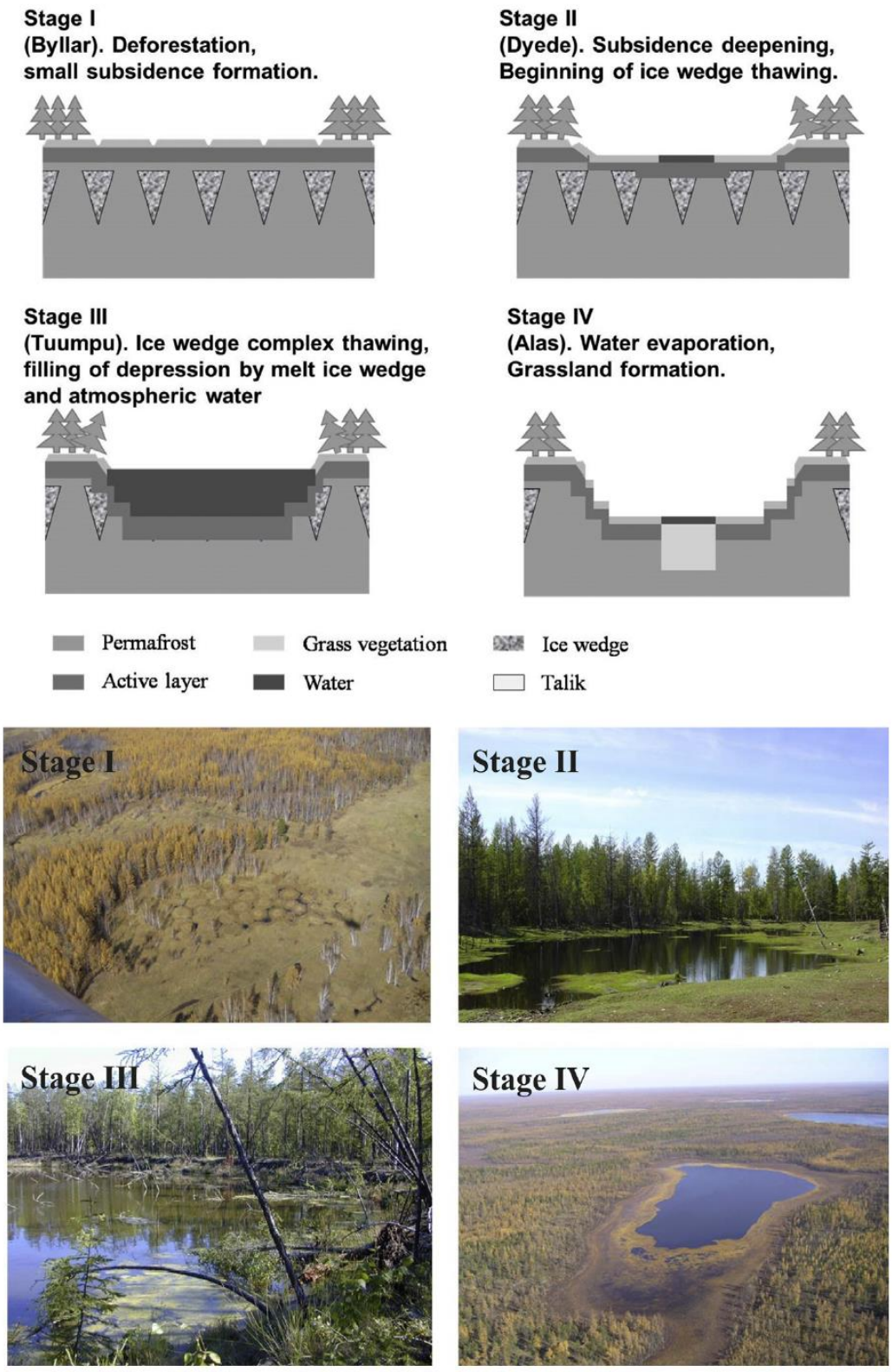

Fig. 2.4. Thermokarst stages in ice-rich permafrost in the boreal zone of Central Yakutia. For each stage corresponding pictures are shown below (Crate et al., 2017).

The deposits formed in thermokarst depressions drastically differ from the main surface (Desyatkin and Desyatkin, 2006; Desyatkin et al., 2013). As a result, stocks of C in Alas soils considerably increase compared with intact forest and C stock of alas soil is 7–10 times higher than intact forest soil surrounding alas. However, the exact rate of C stock in thermokarst ecosystem have not been studied well.

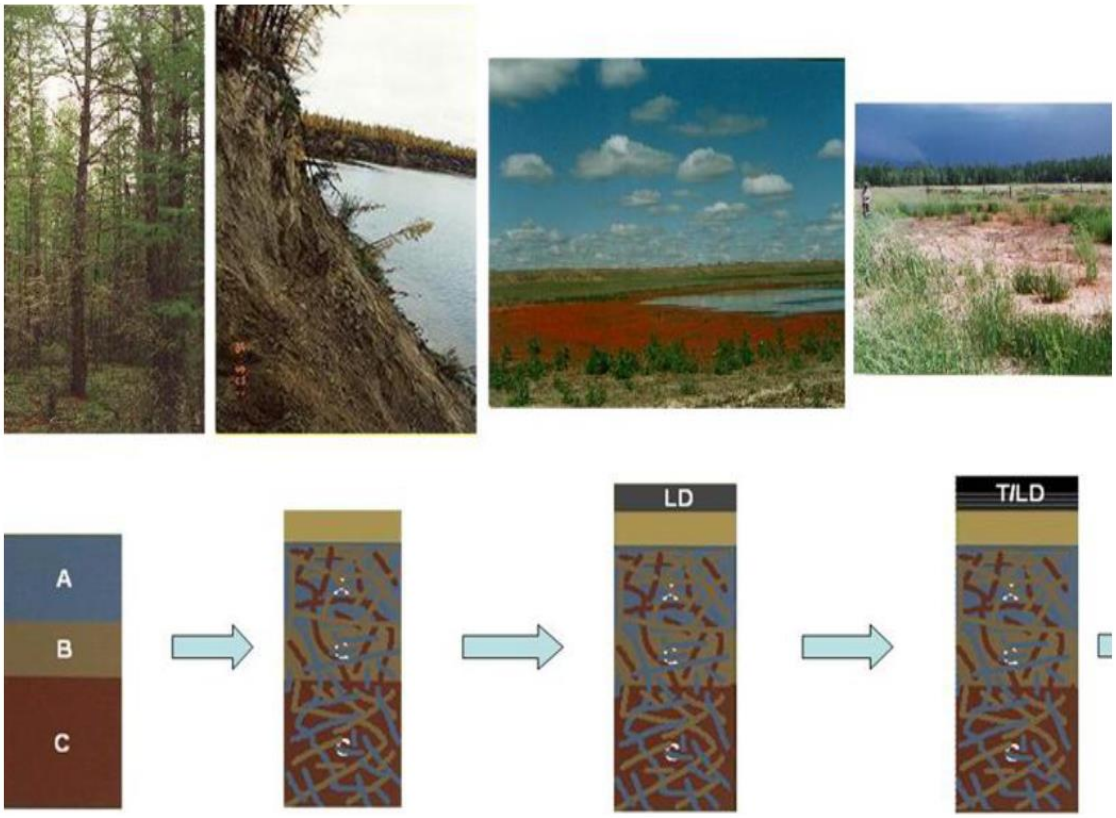

Fig. 2.5. Scheme of the transformation of the parent material upon the alas formation (Desyatkin et al., 2013). LD: lacustrine deposit, T/LD: peat and lacustrine deposit.

2.9. Recent dynamics of thermokarst activity in Central Yakutia, Eastern Siberia, Russia

Global warming is expected to be most pronounced in high northern latitudes (IPCC, 2014). Several studies reported a marked increase in the active layer depth and upper permafrost temperature (Crate et al., 2017; Fedorov et al., 2014; Iijima et al., 2010). During the period of

reliable direct records (1930 to present) the mean annual air temperature measured at the Yakutsk meteorological station increased by 0.03 ˚C per year. Concomitantly, the permafrost temperatures in the central and western lowlands of the Sakha Republic have increased by 0.02 ˚C per year (in 320 cm depth) (Crate et al., 2017). This contributed to an increase in the seasonal thawing depth (i.e., the active layer is usually up to 200 cm deep in forest-free areas) and subsequent melting of the upper parts of ice wedges on landscapes with ice-rich deposits (Crate et al., 2017). As a consequence, since the early 1980s, there has been a significant increase in thermokarst activity in the region. Melting of the tops of ice wedges is causing subsidence of the ground surface, deepening and expansion of thermokarst depressions, and growth of thaw ponds to form larger lakes (Fig. 2.6) (Fedorov et al., 2014). From 1980 to 2012, the area of thermokarst lakes on the Yukechi site increased four times with the bottom of these lakes deepening 2–2.5 m from 1992 to present and terrains with ice-wedge polygons turned into ponds (Fig. 2.6) (Crate et al., 2017). Additionally, from 2005 to 2007, sudden warming on landscapes with above-average amounts of snow cover in combination with increased summer precipitation, led to both a significant expansion of thermokarst lakes and to the extensive development of primary thermokarst landforms (Crate et al., 2017).

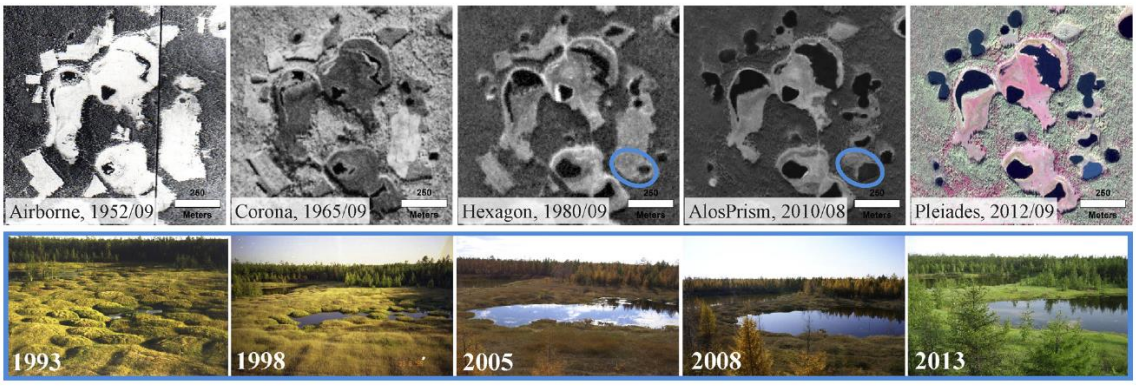

Fig. 2.6. Landscape change at Yukechi alas during recent years. Several thermokarst lakes around the Yukechi alas have developed rapidly in areas ploughed until the 1950s. The blue ellipse in the upper satellite image time series marks the view of the photographs below (Crate et al., 2017).

2.10. Abandonment of arable land in Russia

Central Yakutia is located one of the most northern agriculture areas on the world. The total area of agricultural land in Yakutia comprised 21802.8 thousand ha. Of this area, the land really used in agriculture was 885.6 thousand ha (4.16%), including 93.9 thousand ha of cropland, 482.5 thousand ha of hay fields, and 295.5 thousand ha of pastures (Desyatkin et al., 2013).

At the second half of 20th century, the Soviet government began the gradual establishment of the state farm system, with more collective farms amalgamated into large agricultural enterprises (Takakura, 2015). In the early 1990s, after the collapse of the Soviet collective farming system, the farmland area in all Russia decreased drastically (Ioffe and Nefedova, 2004). According to Lyuri et al. (2010), it was abandoned about 45.5 million ha of arable lands between 1990 and 2007. This area remained without changes up to 2011. This was the most widespread and abrupt land use change in the 20th century in the northern hemisphere (Lyuri et al., 2010). The spontaneous withdrawal of croplands in1990s caused several benefits for the environment including substantial C sequestration in abandoned arable landecosystems (Kurganova et al., 2015). Over the last decade, several studies (Kalinina et al., 2015; Kämpf et al., 2016; Kurganova et al., 2010; Kurganova et al., 2015) were aimed to estimate the total C sequestered in Russian soils due to the croplands abandonment. Kurganova et al. (2015) estimated the total extra C sink in abandoned arable land in Russia (45.5Mha) and Kazakhstan (12.9Mha) is estimated to be 155 ± 27 Mt C yr^{-1} and 31 ± 2Mt C yr^{-1}, respectively. This additional C sink could cover about 18% of the global CO_2 release due to deforestation and other land use changes or compensate annually about 36% and 49% of the current fossil fuel emissions in Russia and Kazakhstan, respectively.

3. Materials and Methods

3.1. Study sites information

The study sites are Toya, Central Hokkaido, Japan (42° 65'N, 140° 80'E) and Central Yakutia, Eastern Siberia, Russia (62° 00'N, 129° 70'E) (Fig. 3.1).

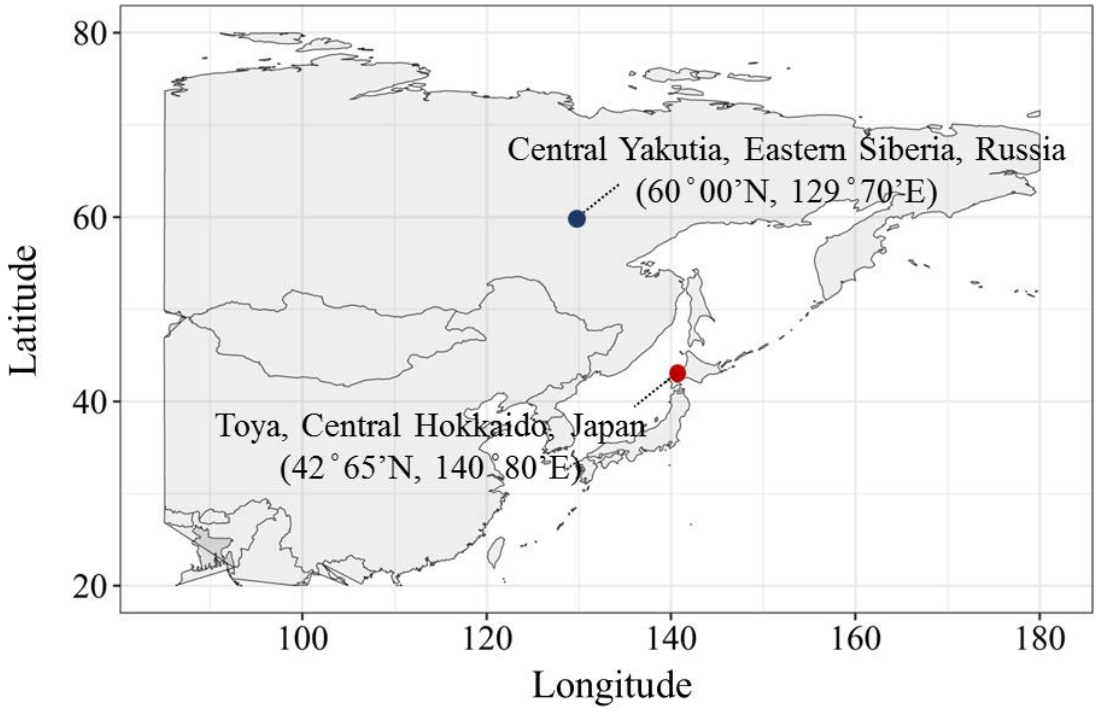

Fig. 3.1. Map of the research sites.

3.1.1. Toya, Hokkaido, Japan

3.1.1.1. Climate condition

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.

3.1.1.2. Soil information

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. 3.2). 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. 3.2). K1 is consequently an immature soil, which has low SOC content and soil physico-chemical fertilities (Table 3.1).

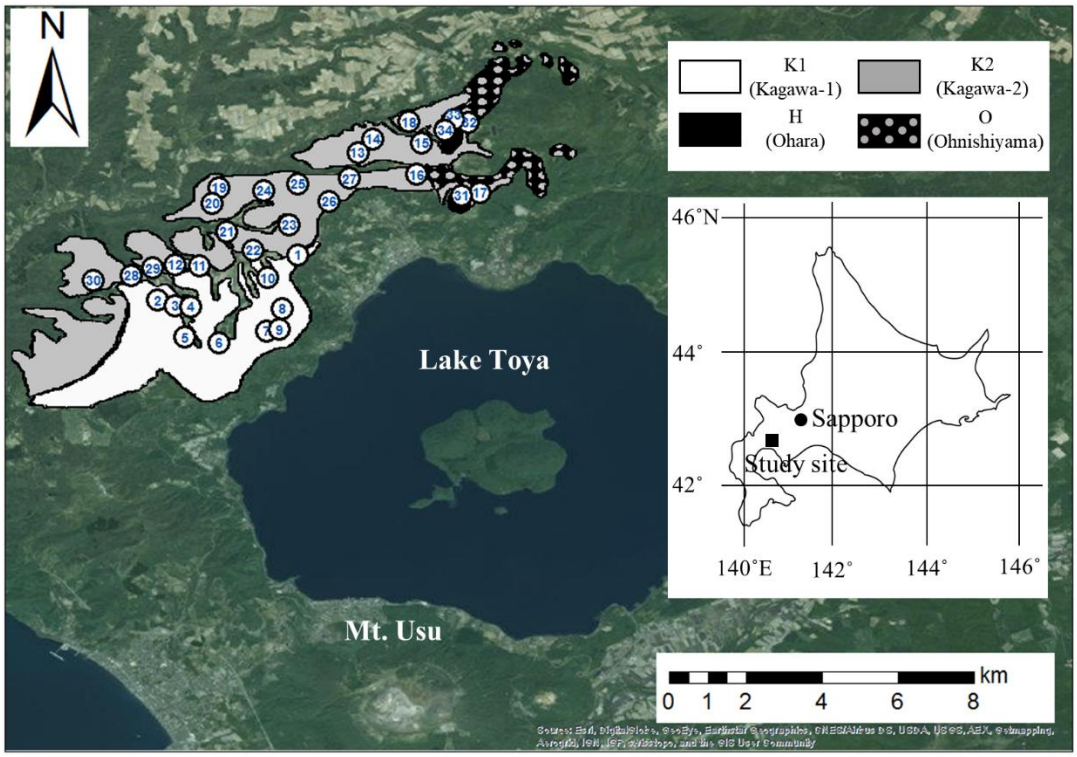

Fig. 3.2. Distribution of the soil series and location of the study fields in Toya region.

Table 3.1

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_2O_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_2O_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_2O_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_2O_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.

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 3.1). 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.

3.1.2. Central Yakutia, Eastern Siberia, Russia.

3.1.2.1. Climate condition

The study was carried out in the Lena-Amga river interfluve (Fig. 3.3). The climate of this region is extra-continental, characterized by severe and dry winters, and hot summers. Average annual temperature is -9.7°C for the past 100 years, with annual precipitation of 235 mm over the past 50 years. The territory has very high annual amplitude temperature. Recorded minimum and maximum temperatures are -63°C in January and 38.3°C in July, respectively. The maximum monthly average precipitation is 39 mm, which occurs in both July and August. The minimum monthly precipitation is 6 mm in March. The soil parent material in this region is composed mainly of Upper Pleistocene to Holocene alluvial deposits with continuous permafrost.

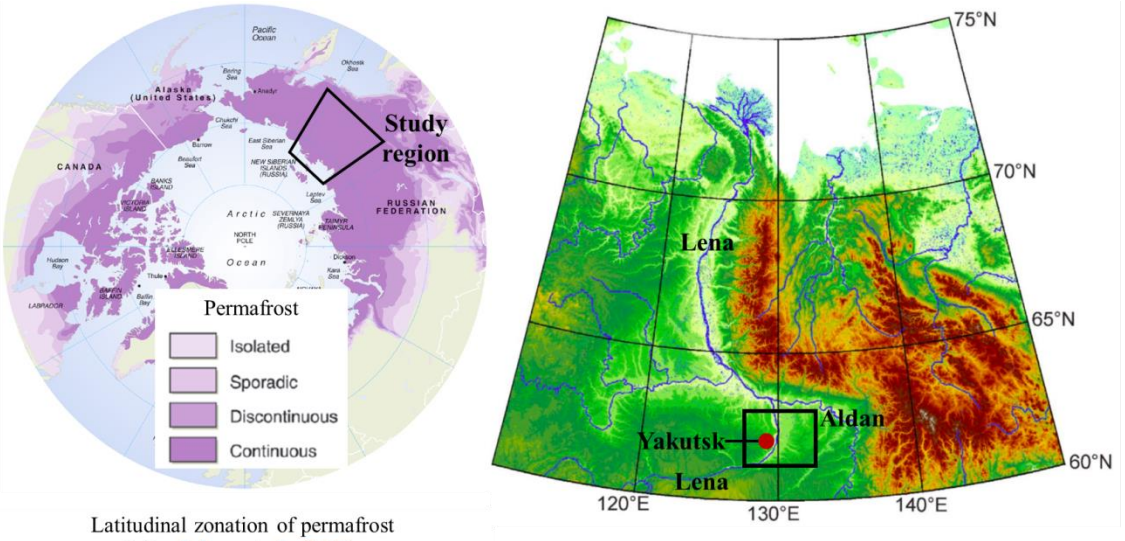

Fig. 3.3. Location of the study site in Eastern Siberia adapted from (http://www.ipf.tuwien.ac.at/permafrost/).

3.1.2.2. Typical land uses of study region

There are three ecosystems in this region: forest, arable land, and thermokarst.

The forest ecosystem can be subdivided into larch forest (LF), burned forest (BF), water-damaged forest (WF), and pine forest (PF) (Fig. 3.4). In the LF, the forest consists of larch *(Larix gmelinii)* trees that are mostly over 200 years old. In the BF, following the fire event, the dominant vegetation consisted of several species of grass, and fireweed (*Chamenearіom angustifolium*). Thermokarst lake expansion and a flood from a river damaged the surrounding forest (Iijima et al., 2014; Ohta et al., 2014). During this period, the ground vegetation composition changed from dense cowberry (*Vaccinium vitis-idaea*) to grasses and shrubs with a high water tolerance (Ohta et al., 2014). In some places in the WF, the dominant species has shifted from larch to white birch (*Betula platyphylla*). PF (*Pinus silvestris*) only grows in sandy soil, and the soil's high permeability and the acidic pine litter result in

podzolization. The active-layer thickness in the LF and BF is less than 2 m, and the soil is classified as Cambic Cryosol (IUSS Working Group WRB, 2015). However, the active-layer thickness in the WF and PF is deeper than 2 m, and the soils are classified as Cambic Fluvisol and Haplic Stagnosol, respectively (IUSS Working Group WRB, 2015).

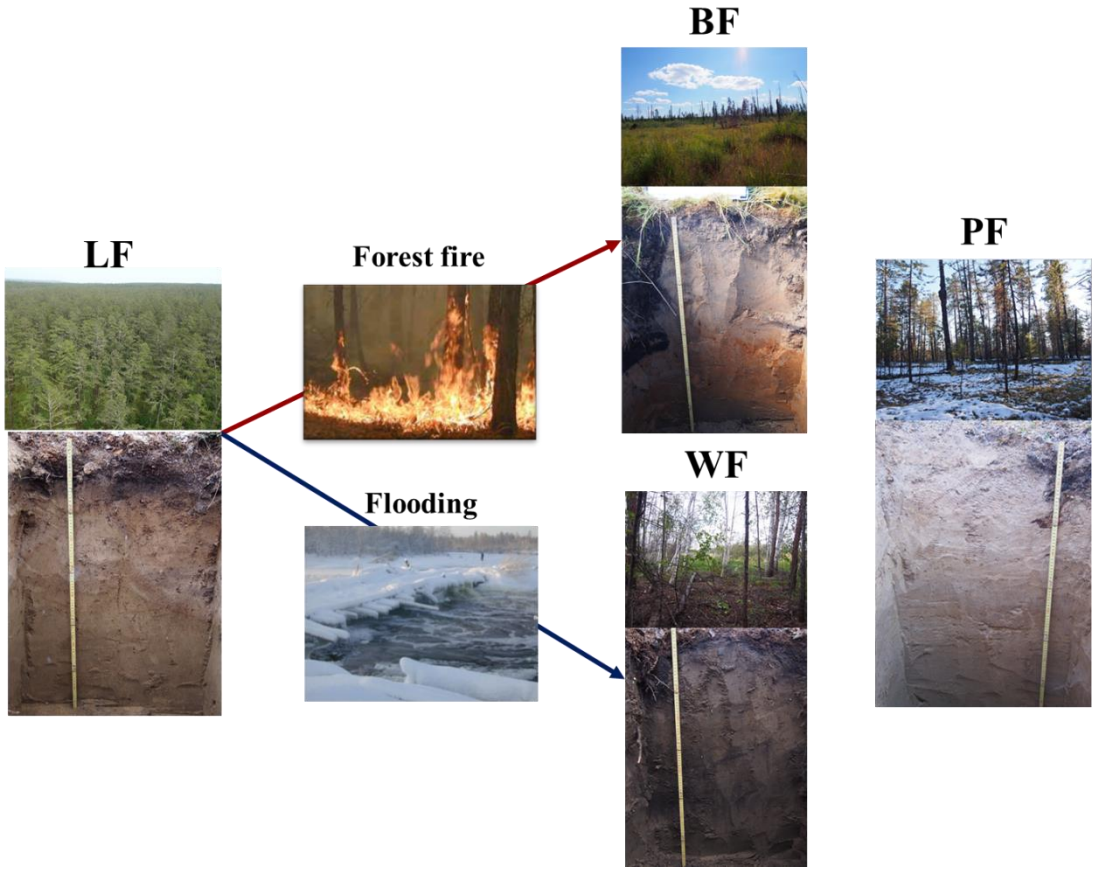

Fig. 3.4. Typical land uses in the forest ecosystem. LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest.

The arable land ecosystem can be subdivided into working arable land (WAL), abandoned arable land (AAL), and abandoned arable land invaded by new trees (NAL) (Fig. 3.5). Oats (*Avéna satíva*) are cultivated on the WAL. On the AAL, during self-recovery, the vegetation developed towards a steppe ecosystem, with *Stipa capillata*, *Chenopodium album*, and *Lappula squarrosa* being dominant. The grasses grow to around 40 cm tall. On the NAL, larch

dominates, and grows to 5–6 cm in diameter and 3–4 m in height. The active-layer thickness is deeper than 2 m, and the soil is classified as Umbric Cambisol (IUSS Working Group WRB, 2015).

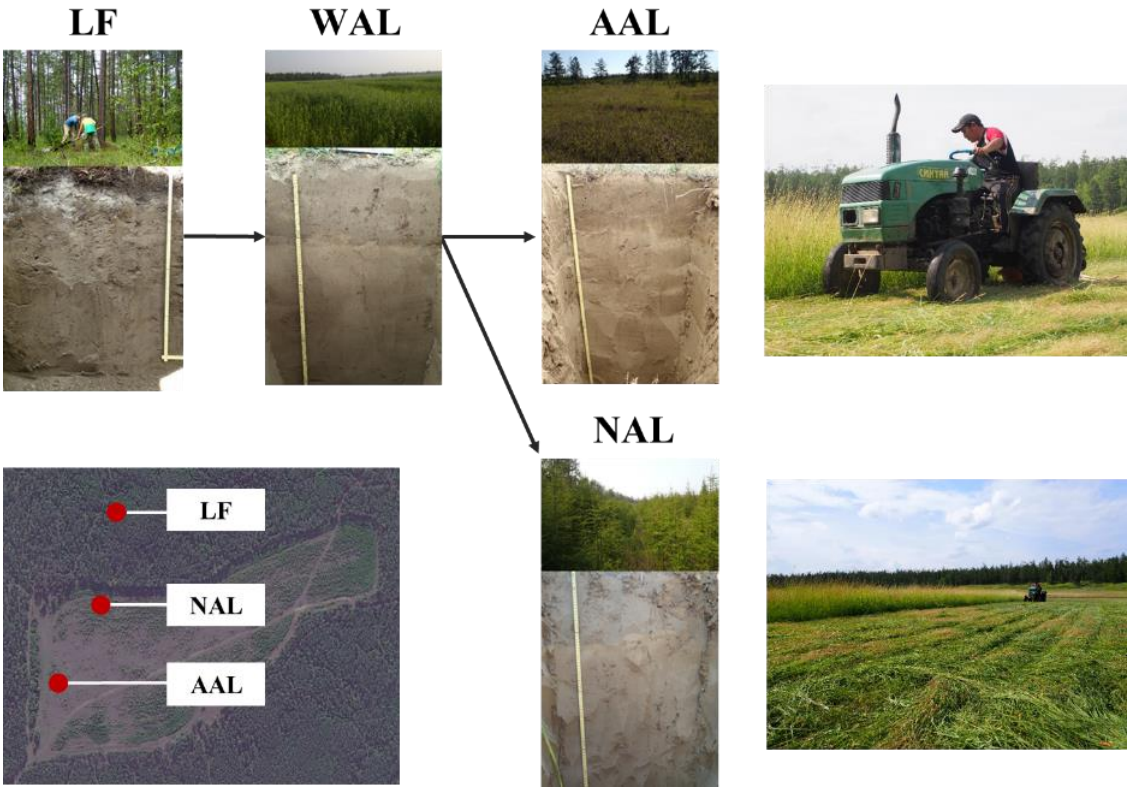

Fig. 3.5. Typical land uses in the arable land ecosystem. LF: Larch forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees

The thermokarst ecosystem can be subdivided into dry grassland (DG), moderately wet grassland (MG), wet grassland (WG), and pingo (PG) based on soil type, waterlogged status, vegetation, and topography (Fig. 3.6). DG is found on the elevated periphery of depressions, and the dominant species are *Puccine11ia tenuif1ora*, *Hordeum brevisubulatum*, and *Carex duriuscula*. MG and WG are characterized by lake deposit (LD) horizons. The relatively high soil moisture content of the MG promotes a high productivity of grassland vegetation, and *P. tenuif1ora*, *Po1ygonum aviculare*, and *C. duriuscu1a* dominate. WG is found on the lowest part of the depressions around the lakes, and the very high soil moisture content results in

gleying caused by anaerobic processes. The vegetation productivity is high, and the dominant species are *Carex wiluica meinsh*, *A1opecurus aruninaceus*, *Schoenoplectus lacustris*, and *Phragmites communis*. PG are round, alas deposition mounds, which form when water in the ponds refreezes (Desyatkin et al., 2013; Fitzpatrick, 1983). The dominant species are *Artemisia jacutica*, *Artemisia dracunculus*, and *Erysimum cheiranthoides*. The active-layer thickness is deeper than 2 m, and DG, MG, WG, and PG soils are classified as Endogleyic Stagnosol, Limnic Fluvisol, Limnic Histosol, and Umbric Cambisol, respectively (IUSS Working Group WRB, 2015). The thermokarst grasslands were used to feed livestock. Cattle were grazed for approximately two weeks in early June and late September, and hay was harvested for one week at the end of July or early August, depending on the highest above-ground biomass (Desyatkin et al., 2007). No C or nutrient source was added, through organic matter application (Desyatkin et al., 2007).

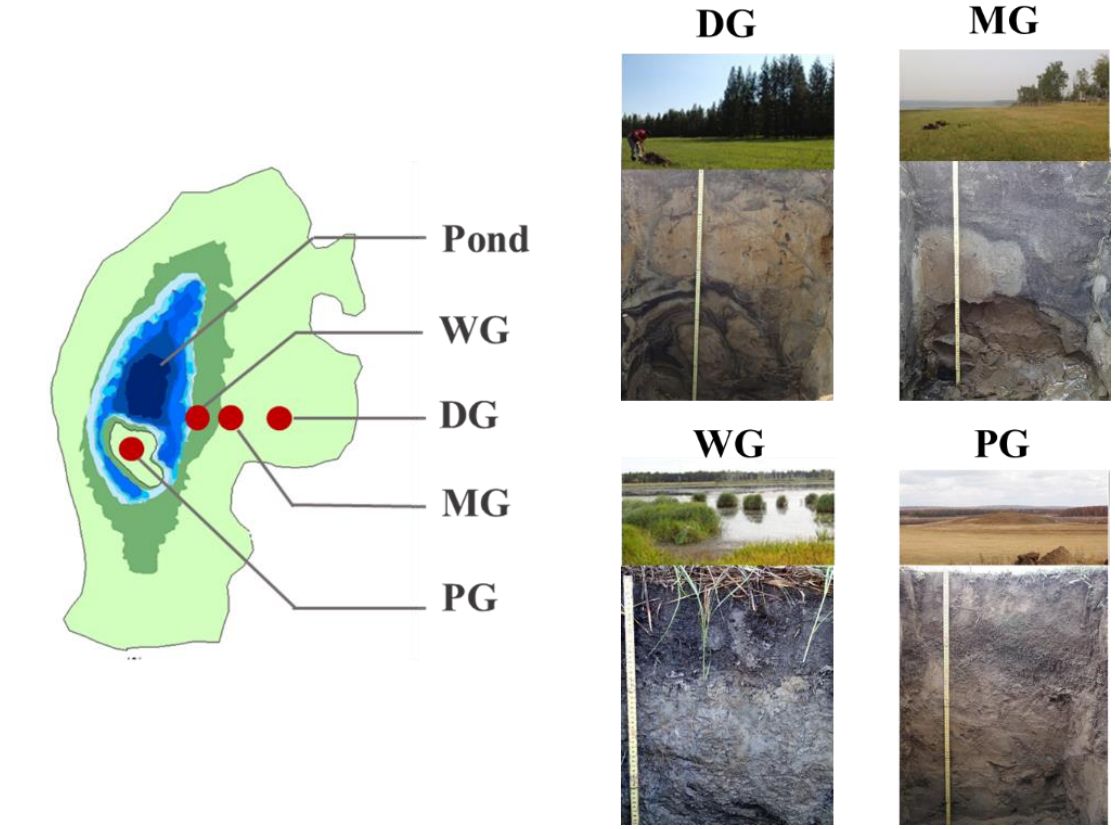

Fig. 3.6. Typical land uses in the arable land ecosystem. DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

3.2. Sample preparation and physico-chemical property analysis

Both composite and undisturbed (100mL of steel cylinder) samples were taken from each horizon. And after the sample preparation, soil physico-chemical properties were analyzed.

3.2.1. 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.

3.2.2. Carbon analysis

The loss on ignition (LOI) method (weight, %) at 550°C (for 6 h) was used to determine the OM content of the organic horizon. A van Bemmelen factor of 1.724, based on the assumption that organic matter is 58% carbon, was used to convert measured OM into estimated litter carbon (LIC). The LOI method has the potential to overestimate LIC compared with the dry combustion method (Campos, 2010). Hence, 15 organic horizon samples collected in 2014 in Central Yakutsk, Eastern Siberia, Russia were analyzed using both the LOI and dry combustion methods (Flash 2000 NC-soil, Thermo Fisher Scientific) to account for the discrepancy between these methodologies. We obtained a significant regression equation (Fig. 3.7) ($R^2 = 0.93$, $P < 0.01$).

LIC using the dry combustion method (g C kg^{-1}) = 0.931 × LIC using the LOI method (g C kg^{-1}) -14.7 (Eq. 3.1).

Using this equation, the values obtained using the LOI method was modified.

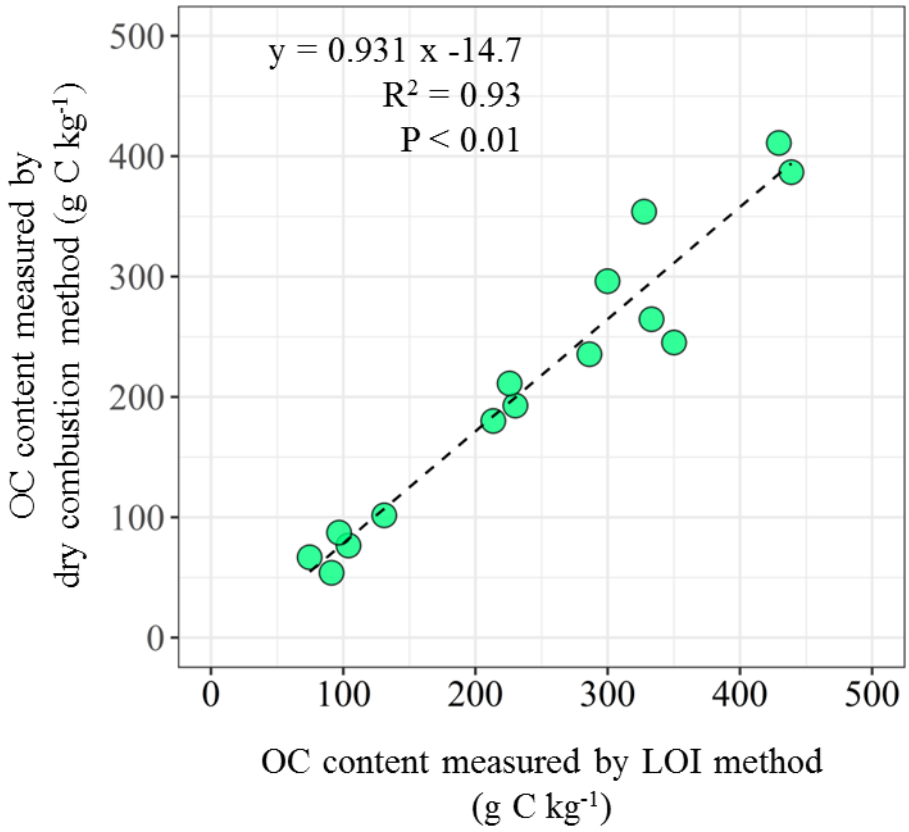

Fig. 3.7. The relationship between the organic carbon content measured by loss on ignition method and by dry combustion method. OC: Organic carbon, LOI: Loss on ignition.

To determine the SOC content of mineral soils, dry combustion method using a NC analyzer (NC-1000; Sumika Chemical Analysis Service, Ltd., Osaka, Japan; NC-1000; Sumika Chemical Analysis Service, Ltd., Osaka, Japan; Flash 2000 NC-soil, Thermo Fisher Scientific) and Tyurin (wet oxidation) method with $K_2Cr_2O_7$ was used.

Tyurin method has been reported to estimate SOC concentration of mineral soil, in average, 6–7% lower than the dry combustion method (Sippola, 1982) because of the incomplete oxidation of OM (Kingdom, 2009). Hence, 15 surface soil samples collected in 2012 in Toya were analyzed with both Tyurin 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 (Fig. 3.8).

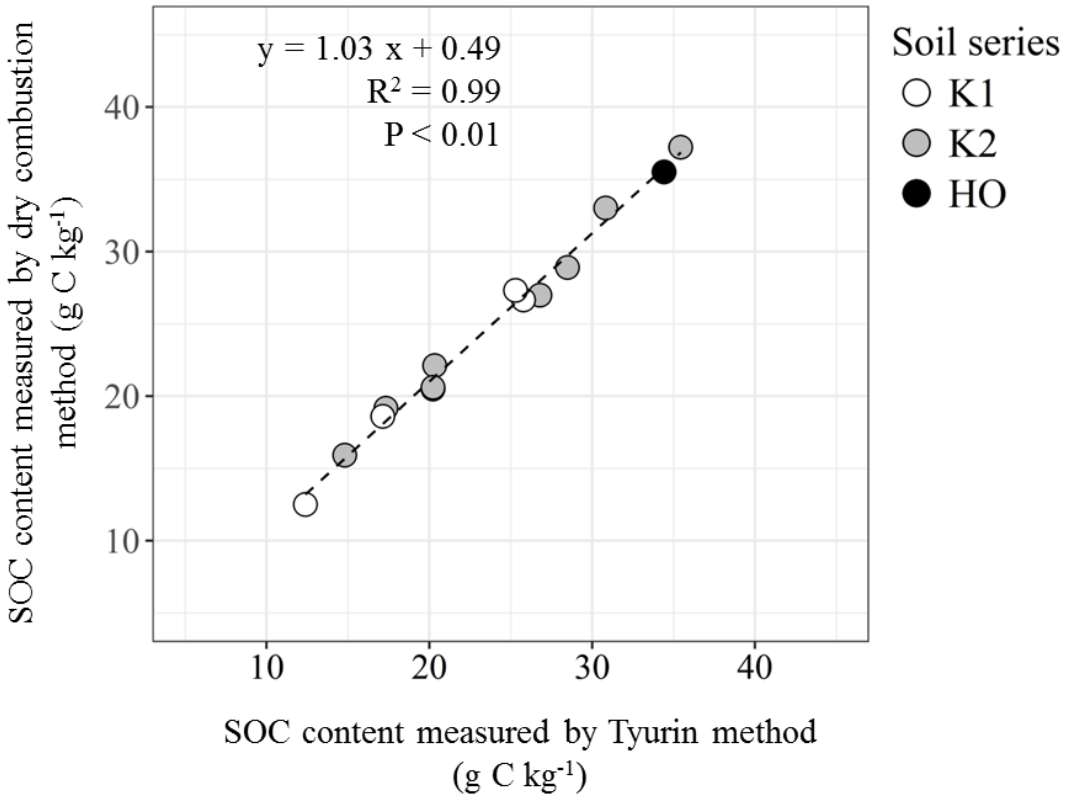

Fig. 3.8. The relationship between soil organic carbon (SOC) content measured by Tyurin method and dry combustion method.

The following regression equation was accordingly obtained:

SOC using the dry combustion method (g C kg^{-1}) = 1.03 × SOC using the Tyurin method (g C kg^{-1}) + 0.49 (R^2 = 0.99, P < 0.01) (Eq. 3.2)

Using this equation, the values measured using the Tyurin method was modified.

Soil carbonate carbon (SCC) content was calculated from the quantity of CO_2 produced by adding 10 mL 10% HCl (Wt/Wt) to 0.5–1.0 g dry soil sample. The volume of CO_2 produced was measured using an aqueous manometer. The weight of CO_2 was calculated from its volume at standard temperature and pressure, and was used to calculate the level of carbonate.

Total soil carbon (TSC) content was determined as a sum of LIC, SOC, and SCC content.

3.2.3. Soil physical properties

Air filled 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.

3.3.4. Soil chemical properties

Soil pH and electrical conductivity (EC) in 1:5 soil: water suspensions was measured using a pH meter (F-8 pH meter; Horiba, Japan) and EC meter (B-173 conductivity meter, Horiba, Japan), respectively.

Thermal extraction methods are used to assess the availability of nitrogen in soil (Chantigny et al. 2010; Curtin *et al*. 2006), and in this study, available N was measured using a simplified thermal extraction estimation method (Sakaguchi *et al*. 2010).

Available P was measured using the Truog method. Soil samples were extracted with 0.001 M H_2SO_4, and the concentration of P_2O_5 was determined with the ascorbic acid reduction method using a spectrophotometer (UV mini-1240; Shimadzu, Kyoto, Japan).

Phosphate absorption coefficient (PAC) was measured using the ammonium phosphate method. The soil sample was extracted for 24 h with 13.44 mg P_2O_5 mL^{-1} ammonium phosphate solution, and the concentration of P_2O_5 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 (Ca^{2+}), and magnesium (Mg^{2+}) 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 Ca^{2+} and Mg^{2+} 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 NH_4^+-N was measured using the formol titration method. Base saturation (BS) was determined as the proportion of exchangeable basic cations to CEC.

3.4. Data calculation

3.4.1. Carbon stock

The total profile SOC stock at each site and was calculated as the sum of the component soil horizon SOC stocks.

The SOC stock (Mg C $ha^{-1}horizon^{-1}$) of each horizon was calculated as follows:

$M = BD \times D \times 10^2$ (Eq. 3.3)

where M represents the soil mass (Mg ha^{-1} $horizon^{-1}$), BD is the soil bulk density (Mg m^{-3}), D is the soil sampling depth (m), and 10^4 is a factor to adjust units.

$SOC_{stock} = M \times SOC_{conc} \times 10^{-3}$ (Eq. 3.4)

where SOC_{stock} represents the SOC stock (Mg C ha^{-1} $horizon^{-1}$), SOC_{conc} is the SOC content (g C kg^{-1}), and 10^{-3} is a factor to adjust units.

The SCC stock and the C stock in the organic horizon (LIC) were calculated in the same method. The TSC stock was calculated as a sum of the SOC, SCC, and LIC stock.

SOC stock in past time ($SOC_{stockpast}$) 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 past time was adjusted to that in present time, and $SOC_{stockpast}$ was calculated as follows:

$SOC_{stockpast} = M_{present} \times SOC_{concpast} \times 10^{-3}$ (Eq. 3.5)

where $M_{present}$ is soil mass in present time, $SOC_{concpast}$ is SOC content (g C kg^{-1}) in past time, and 10^{-3} is a factor to adjust units.

3.4.2. Change in carbon

The amount of change in SOC stock (ΔSOC_{stock}, Mg C ha^{-1}) between present time and past time was estimated as follows:

$\Delta SOC_{stock} = SOC_{stockpresent} - SOC_{stockpast}$ (Eq. 3.6)

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

$\Delta SOC_{stockrate} = \Delta SOC_{stock} / T$ (Eq. 3.7)

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, LIC content and stock, and other soil physico-chemical properties.

3.5. Statistical analysis

Statistical analyses were performed using R (R Development Core Team 2016; version 3.3.3).

In chapter 4, 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 difference in soil physico-chemical properties among the fields and in the different years was determined using a two-way ANOVA and the Tukey-Kramer test. The difference in soil physico-chemical properties between the years for each of the 34 fields was analyzed using a paired t-test. The difference in soil physico-chemical properties among the soil series was analyzed using a one-way ANOVA and the Tukey–Kramer test.

In chapter 5, Two-way ANOVA and the Tukey-Kramer test were used to analyze the difference in LIC content and LIC stocks between year, depth, and land use. Three-way ANOVA and the

Tukey-Kramer test were used to analyze the difference in SOC content and SOC stocks between year, depth, and land use. A paired t-test was used to determine the difference in SOC content and LIC and SOC stocks between past and present sampling times. Analysis of covariance (ANCOVA) was used to determine the difference between the two regression equations.

In chapter 6, differences in soil physico-chemical properties and root C density among the ecosystems and depths were determined by conducting two-way ANOVA and Tukey-Kramer tests. Differences in SOC, SCC, LIC, and TSC stocks among the ecosystems and land use types were determined by conducting one-way ANOVA and Tukey-Kramer tests.

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

4. 1. Introduction

As mentioned in chapter 2, although Andosols cover only approximately 0.84% of the world's land surface (Soil Survey Staff, 1999), they cover more than 50% of the total upland crop field area in Japan. Moreover, Andosols often have high SOC content, mainly due to the formation of short-range ordered (amorphous) minerals and Al–OH complexes (Shoji et al. 1993; Takahashi and Dahlgren, 2016). Therefore, changes in the SOC of Andosols contribute significantly to the C budget (Shirato et al. 2004).

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) (Lee et al. 2009; Mikha et al. 2013), 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, this study was 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.

4. 2. Materials and methods

4.2.1. 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. 4.1)] 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.

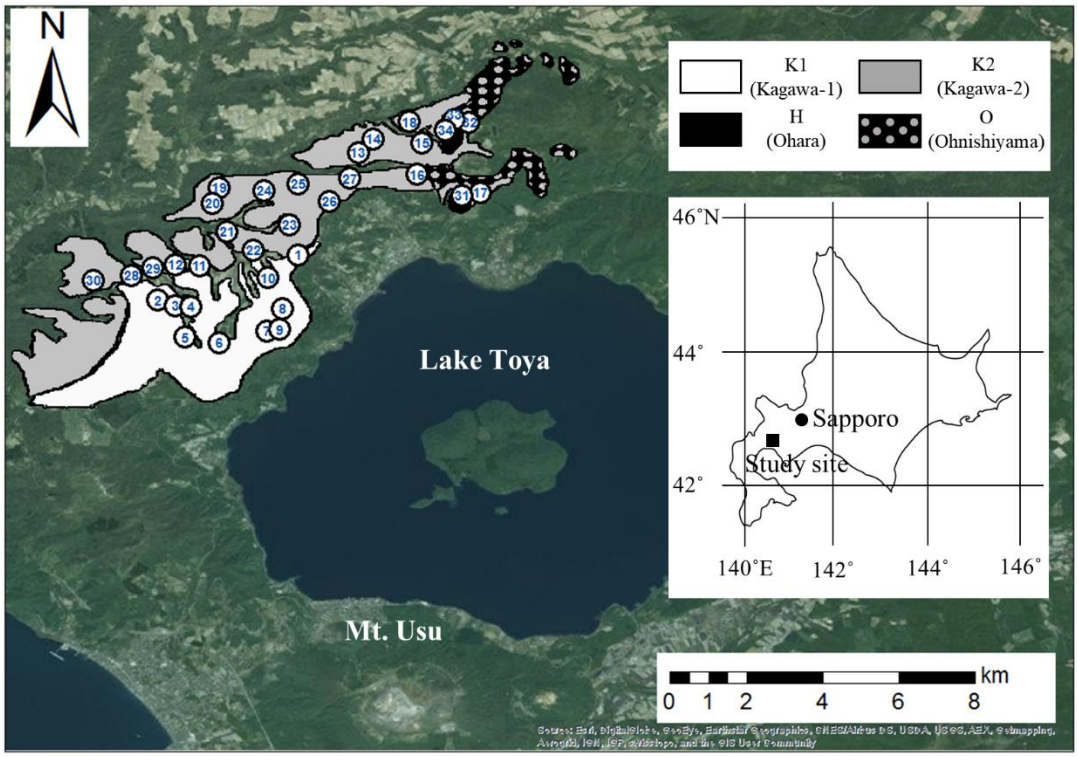

Fig. 4.1. Distribution of the soil series and location of the study fields.

4.2.2. SOC content

The dry combustion method was used to determined SOC content in 2012. On the other hand, the Tyurin method was used to determine SOC content in 2001–2003. Therefore, using Eq 3.2. in chapter 3, the values measured using the Tyurin method was modified.

4.2.3. Soil physical properties

Soil BD, total porosity, saturated hydraulic conductivity, and soil texture were measured based on the methodologies described in chapter 3.

4.2.4. 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 based on the methodologies described in chapter 3.

4.2.5. 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.

4.2.6. 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, representative farmers who used each of the different types of manure (field nos. 9, 10, 28, 29, and 31) were chosen. 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), P_2O_5, and K_2O contents. Total C and TN were measured using the dry combustion method (NC-900; Sumika Chemical Analysis Service, Ltd., Osaka, Japan). P_2O_5 and K_2O content were measured using the wet oxidation method with conc. H_2SO_4. Concentrations of P_2O_5, K^+, and Mg^{2+} 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.

4.2.7. Calculations

4.2.7.1. Carbon stock

The SOC stock (Mg C ha^{-1}) in 0–15 cm of the soil in 2012 was calculated using the Eq. 3.3 and Eq. 3.4 in chapter 3.

SOC stock in 2001–2003 was calculated using the ESM using the Eq. 3.5 in chapter 3.

4.2.7.2. Change of SOC and soil physico-chemical properties

The SOC stock change (ΔSOC, Mg C ha^{-1} 15 cm^{-1}) and the rate of SOC stock change (Rate of ΔSOC, Mg C ha^{-1} 15 cm^{-1} yr^{-1}) between 2001–2003 and 2012 was estimated using Eq.3.6 and

Eq. 3.7 in chapter 3, respectively.

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

4.2.7.3. Application rate of organic matter

Annual average C application rates of manure, green manure, organic fertilizer (C_{org}, Mg C ha^{-1} yr^{-1}), N, P, and K were calculated as follows:

$C_{org} = (R \times DMC \times TC \times 100) / Y$ (Eq. 4.7)

where R is the application rate of fresh organic matter (Mg ha^{-1} $period^{-1}$), DMC is the dry mater 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 (Noguchi 2001; Shiga et al. 1985). 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.

4.2.8. Statistical analysis

Statistical analysis applied in this chapter was described in chapter 3. 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

difference in soil physico-chemical properties among the fields and in the different years was determined using a two-way ANOVA and the Tukey-Kramer test. The difference in soil physico-chemical properties between the years for each of the 34 fields was analyzed using a paired t-test. The difference in soil physico-chemical properties among the soil series was analyzed using a one-way ANOVA and the Tukey–Kramer test.

4.3. Results

4.3.1. Management practice

Table 4.1 shows the annual average application rates of fresh weight, C, N, P_2O_5, and K_2O of manure, green manure, and combined organic and synthetic fertilizer in the study fields. Manure was used in 24 fields and was spread once every 2 to 5 years from April to May and/or September to October. Green manure was used in 26 fields and was grown as the succeeding crop green manure, once every 2 to 5 years, after the harvest of cultivated crops, or cultivated as a fallow green manure. Combined organic and synthetic fertilizer were applied to 33 fields. The annual average fresh weight of applied manure, green manure, and combined organic and synthetic fertilizer was 6.8 ± 7.8, 8.3 ± 6.1, and 1.4 ± 0.5 Mg ha^{-1} yr^{-1}, respectively, and there was no significant difference between the soil series. The 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} 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, P_2O_5, and K_2O was 209 ± 112 Kg N ha^{-1} yr^{-1}, 274 ± 168 kg P_2O_5 ha^{-1} yr^{-1}, and 224 ± 100 kg K_2O 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 P_2O_5; and 32%, 19%, and 49% in K_2O, respectively.

4.3.2. 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 4.2). 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 4.2). 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 4.3). The rates of ΔSOC content (0.24 ± 0.61, -0.27 ± 0.38, and -0.33 ± 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} 15 cm^{-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 4.4). 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. 4.2). 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. 4.3a) and between initial SOC stock (in 2001–2003) and the rate of ΔSOC stock ($P < 0.01$) (Fig. 4.3b).

Table 4.1

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

	Soil	Application rate (fresh weight)			Total application rate of each component				Composition ratio (%)											
		M	GM	COS	C	N	P_2O_5	K_2O	C			N			P_2O_5			K_2O		
			Mg ha^{-1} yr^{-1}		Mg C ha^{-1} yr^{-1}	kg N ha^{-1} yr^{-1}	kg P_2O_5 ha^{-1} yr^{-1}	kg K_2O ha^{-1} yr^{-1}	M	GM	COS	M	GM	COS	M	GM	COS	M	GM	COS
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, 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 4.2

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} 15 cm^{-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 IJK	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 4.3

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} 15 cm^{-1}	n	Mg C ha^{-1} 15 cm^{-1}	n	Mg C ha^{-1} 15 cm^{-1}	Mg C ha^{-1} 15 cm^{-1} yr^{-1}	
K1	12	19.0 ± 8.2 a A	12	21.7 ± 4.9 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	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	18	-2.7 ± 3.9 A	-0.27 ± 0.38 A	18	43.8 ± 6.9 b B	18	39.4 ± 6.7 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	4	-2.9 ± 4.3 AB	-0.33 ± 0.48 AB	4	45.1 ± 6.2 a B	4	40.5 ± 7.7 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
	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	9	-0.16 ± 0.21	-0.015 ± 0.019 A	9	51.0 ± 8.0 a A	12	56.8 ± 5.0 a	9	5.8 ± 8.5 A	0.53 ± 0.78 A	9	27.6 ± 43.2 a	12	1900 ± 1332	9	1880 ± 1319	172 ± 119 A
K2	18	1.09 ± 0.08 b	18	1.00 ± 0.11 a	18	-0.09 ± 0.11	-0.01 ± 0.012 A	18	59.3 ± 3.4 a B	18	61.4 ± 5.4 a	18	2.0 ± 5.3 A	0.23 ± 0.57 A	18	57.0 ± 85.5 a	18	2146 ± 1827	18	2089 ± 1846	214 ± 191 A
HO	4	1.12 ± 0.14 a	4	1.01 ± 0.08 a	4	-0.11 ± 0.09	-0.012 ± 0.01 A	4	59.0 ± 5.6 a B	4	61.1 ± 3.4 a	4	2.1 ± 3.6 A	0.23 ± 0.40 A	4	80.5 ± 140.2 a	4	3542 ± 2005	4	3462 ± 2134	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	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_2O_5 100 mg^{-1}	n	mg P_2O_5 100 mg^{-1}	n	mg P_2O_5 100 mg^{-1}	mg P_2O_5 100 mg^{-1} yr^{-1}
K1	12	5.46 ± 0.12 a	11	5.94 ± 0.14 b	11	0.46 ± 0.18 B	0.042 ± 0.016 B	12	56.4 ± 17.4 b	12	37.0 ± 9.4 a	12	-19.5 ± 19.7 A	-1.76 ± 1.79 A	12	1061 ± 389 a	12	1848 ± 294 b	12	787 ± 479 B	71.6 ± 43.5 B
K2	18	5.67 ± 0.26 a	18	5.70 ± 0.23 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	18	-5.1 ± 9.7 B	-0.52 ± 0.98 B	18	1555 ± 377 a	18	1748 ± 322 b	18	193 ± 341 A	19.1 ± 34.0 A
HO	4	5.97 ± 0.31 a	4	5.70 ± 0.16 a	4	-0.27 ± 0.21	-0.03 ± 0.023 A	4	41.0 ± 6.8 a	4	39.3 ± 4.4 a	4	-1.7 ± 2.5 AB	-0.19 ± 0.28 AB	4	1386 ± 290 a	4	1432 ± 325 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	2001-2003		2012		Δexchangeable Ca^{2+}	Rate of Δexchangeable
	n	mg P_2O_5 kg^{-1}	n	mg P_2O_5 kg^{-1}	n	mg P_2O_5 kg^{-1}	mg P_2O_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	12	-19.5 ± 19.7	-1.76 ± 1.79 A	12	1.04 ± 0.30 a	12	1.31 ± 0.22 b	12	0.27 ± 0.39 A	0.025 ± 0.036 A	12	7.07 ± 1.15 a	12	6.67 ± 2.51 a	12	-0.40 ± 3.26 A	-0.035 ± 0.297 A
K2	18	187 ± 100 a A	18	172 ± 45.0 a	18	-5.1 ± 9.7 B	-0.52 ± 0.98 B	18	0.79 ± 0.15 a	18	1.22 ± 0.27 b	18	0.43 ± 0.32 A	0.045 ± 0.033 A	18	6.57 ± 1.61 a	18	7.28 ± 3.22 a	18	0.71 ± 2.65 A	0.074 ± 0.267 A
HO	4	226 ± 147 a	4	322 ± 175 a	4	-1.7 ± 2.5 B	-0.19 ± 0.28 AB	4	0.76 ± 0.10 a	4	1.38 ± 0.09 b	4	0.62 ± 0.15 A	0.069 ± 0.017 A	4	6.53 ± 2.38 a	4	8.43 ± 3.03 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	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	12	2.40 ± 0.85 b	12	1.00 ± 0.79 B	0.091 ± 0.072 B	12	62.5 ± 16.8 a	12	52.4 ± 13.4 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	12	4.3 ± 5.1 A	0.39 ± 0.46 A
K2	18	1.18 ± 0.29 a	18	1.46 ± 0.47 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	18	-3.1 ± 11.2 A	-0.33 ± 1.13 A	18	19.5 ± 2.1 a B	18	24.2 ± 3.13 b	18	4.7 ± 3.8 A	0.49 ± 0.40 A
HO	4	1.07 ± 0.26 a	4	2.00 ± 0.73 a	4	0.92 ± 0.97	0.103 ± 0.108	4	45.3 ± 15.1 a	4	50.7 ± 14.9 a	4	1.24 ± 13.3 A	0.14 ± 1.48 A	4	18.7 ± 2.2 a	4	23.9 ± 2.28 b	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 4.4

Pearson's correlation matrix of carbon (C) application rates and changes in soil physico-chemical properties.

	M C application rate	GM C application rate	COS 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} 15 cm^{-1}	Mg m^{-3}	%	10^{-6} m s^{-1}		mg N kg^{-1}	mg P_2O_5 100g^{-1}	mg P_2O_5 kg^{-1}	$cmol_c$ kg^{-1}			%	$cmol_c$ kg^{-1}
M C application rate	-																	
GM C application rate	0.12	-																
COS 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, 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.

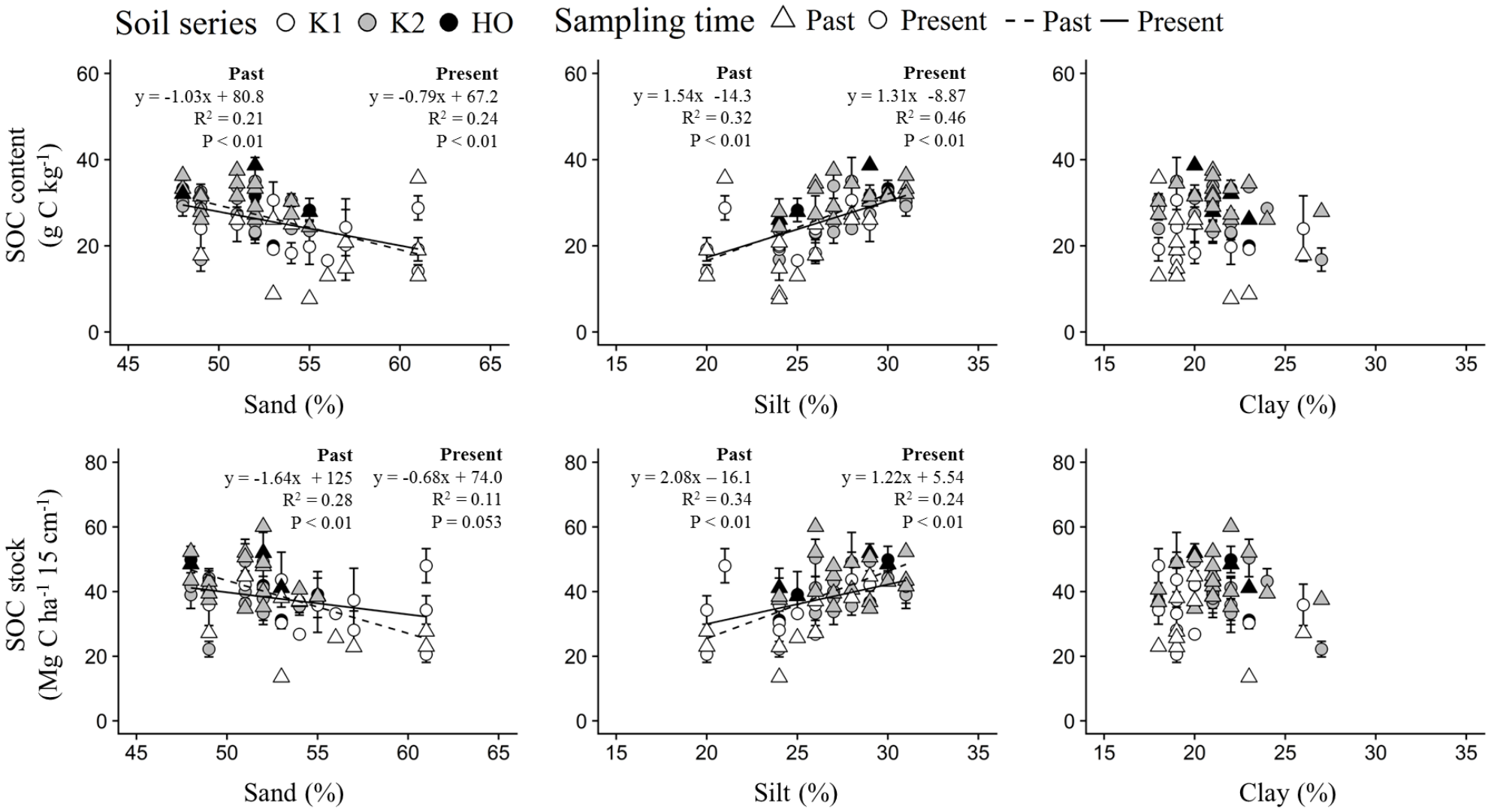

Fig. 4.2. Relationship between soil texture and soil organic carbon (SOC). Present: 2012; Past, 2001–2003.

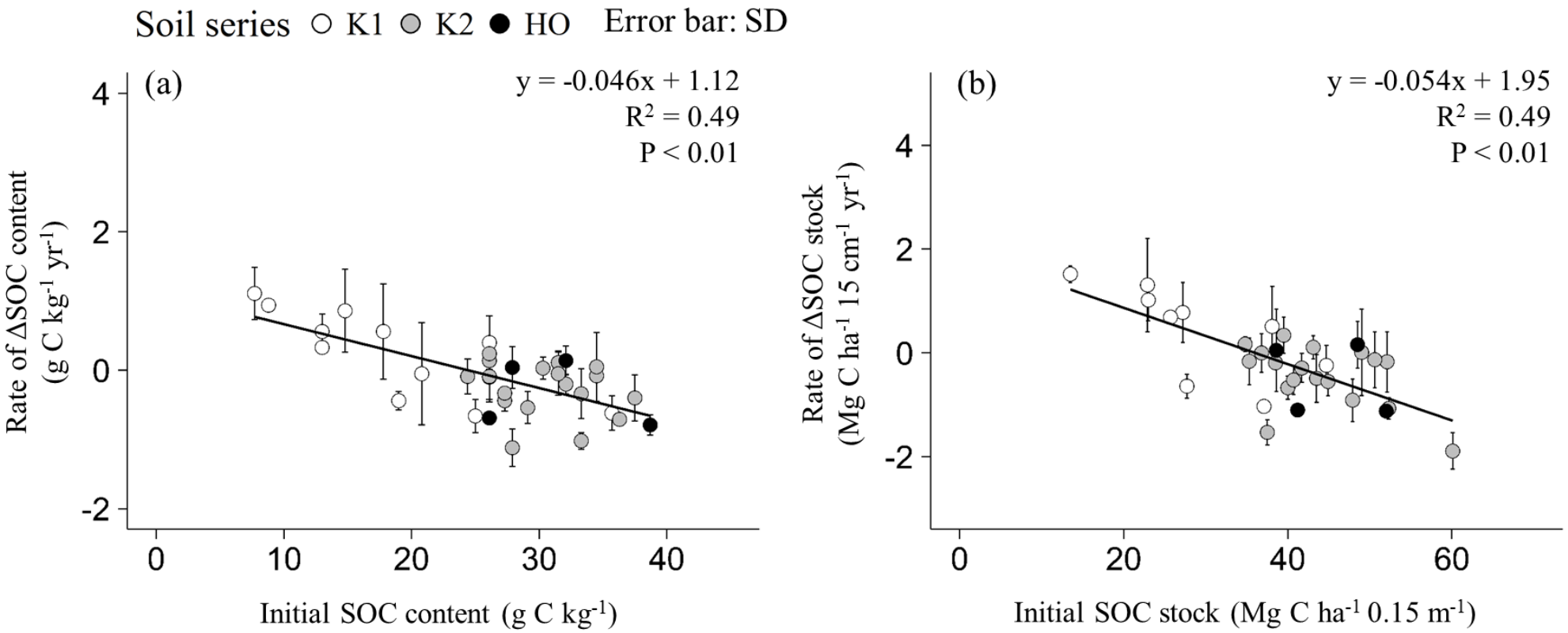

Fig. 4.3. Relationship between: (a) Initial soil organic carbon (SOC) content and rate of ΔSOC content; (b) Initial SOC stock and rate of ΔSOC stock.

4.3.3. 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 4.5). 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 4.3). 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 4.6). Similarly, a significantly negative correlation between ΔSOC content and ΔBD ($P < 0.05$), and a positive correlation between ΔSOC content and Δtotal porosity ($P < 0.05$) (Table 4.4) were observed.

4.3.4. 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 4.7). 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 4.3). pH increased significantly only in the K1

soil series and a significantly higher ΔpH 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 Δavailable 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. ΔPAC (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 Δavailable 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 ΔSOC content ($P < 0.01$), respectively, and there was a significant negative relationship between Δavailable P content and ΔPAC ($P < 0.01$) (Table 4.4).

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 4.8).

Table 4.5

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 4.6

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} 15 cm^{-1}		%		Mg m^{-3}	%	10^{-6} m s^{-1}		mg N kg^{-1}	mg P_2O_5 $100g^{-1}$	mg P_2O_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 4.7

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_2O_5 $100g^{-1}$			mg P_2O_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 4.8

Comparison of exchangeable cations, base saturation, and cation exchange capacity (CEC) between 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:	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.

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 4.3). A significant increase in exchangeable Mg^{2+} was observed only in the K1 soil series, and the Δexchangeable 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. 4.4), and a significant positive relationship between ΔSOC content and ΔCEC ($P < 0.01$) (Table 4.4).

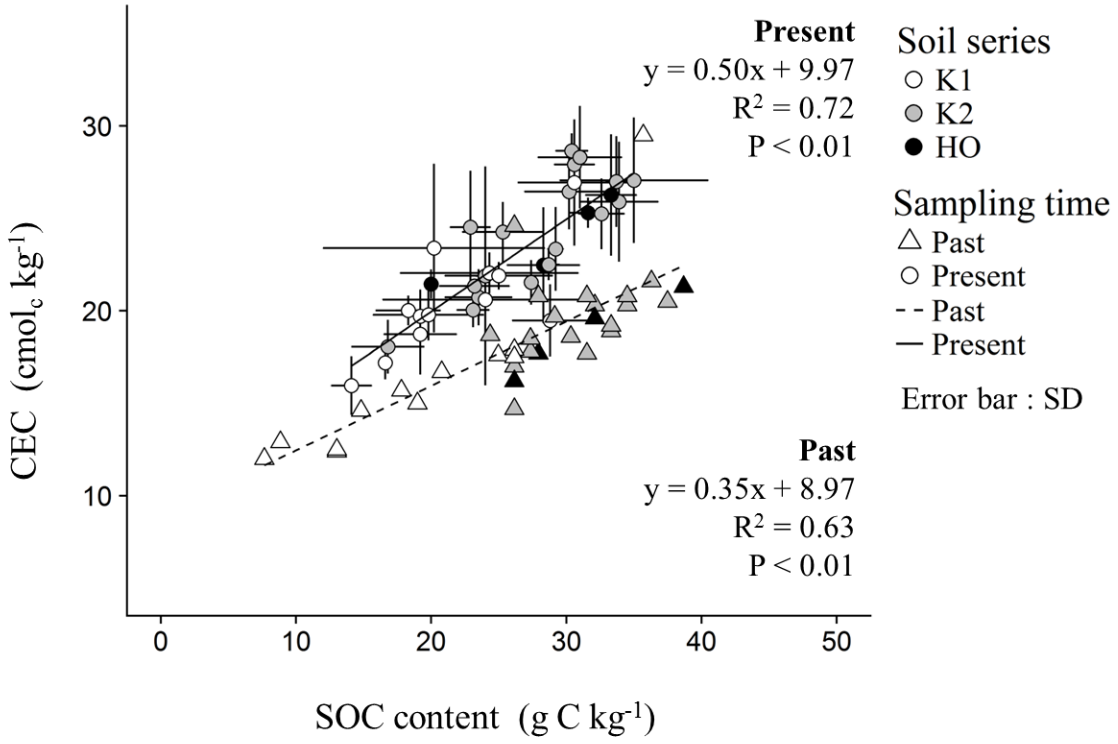

Fig. 4.4. Relationship between soil organic carbon (SOC) content and cation exchange capacity (CEC). Present: 2012, Past: 2001–2003.

4.4. Discussion

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

From 2001–2003 to 2012, changes in SOC content and SOC stock, and several soil physico-chemical properties, such as significant improvement of soil physical properties (Table 4.5), and significant increases in PAC (Table 4.7) and CEC (Table 4.8) were observed. In the K1 soil series in particular, significant increases in SOC content and stock were observed in several fields (Table 4.2), and a significant increase in PAC and significant decrease in available P were also observed (Table 4.3). 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 3.1). 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 3.1). Therefore, the long-term application of organic matter is the main cause of the changes in SOC and soil physico-chemical properties.

4.4.2. 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 (Lal et al. 2004b; West and Post 2002). In this study, the changes in both SOC content and SOC stock were not significant but decreased slightly during the study period (Table 4.2). 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 ΔSOC content and ΔSOC stock with increases in the application of manure C (Table 4.4).

Clay particles protect and stabilize SOM (Bronick and Lal 2005; Six et al. 2002), 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. 4.2). 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, there was a no direct effect of texture on changes in SOC.

Similar to previous studies, a significant negative relationship between initial SOC content (in 2001–2003) and the rate of ΔSOC content (Fig. 4.3a) and the rate of ΔSOC stock (Fig. 4.3b) were observed (Capriel 2013; Bellamy et al. 2005; Goidts and van Wesemael 2007; Hanegraaf et al. 2009; Lark et al. 2006; Riley and Bakkegard 2006; Saby et al. 2008,). From the regression equations, the threshold level of initial SOC was estimated as 24.3 (g C kg^{-1}) in SOC content and 36.1 (Mg C ha^{-1} 0.15 m^{-1}) in SOC stock.

Various trends in ΔSOC content and ΔSOC stock in different soil series (Table 4.3) was observed. There was no significant difference between the soil series with regards to the total application rate of C via organic matter (Table 4.1). Therefore, difference of initial SOC content might be a reason for the different trend of ΔSOC content and ΔSOC stock, because there was a significant relationship between initial SOC and ΔSOC content and stock (Fig. 4.3). Positive ΔSOC 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} 15 cm^{-1} for SOC stock) were lower than the threshold SOC (24.3 g C kg^{-1} and 36.1 Mg C ha^{-1} 15 cm^{-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} 15 cm^{-1} for SOC stock, respectively), negative ΔSOC content and stock was observed. 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.

4.4.3. Soil physical properties

Similar to the findings of previous studies (Chen et al. 2010; Hati et al. 2007; Papadopoulos et al. 2009), 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 (Arthur et al. 2013; Celik et al. 2004; Naveed et al. 2014). The strong negative relationship between Δtotal porosity and ΔBD (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; Hemmat et al. 2010; Papadopoulos et al. 2009). 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). A significant negative correlations between SOC content and BD (Table 4.6) and between ΔSOC content and ΔBD (Table 4.4) were detected. Significant positive correlations between SOC content and total porosity (Table 4.6), and between ΔSOC content and Δtotal porosity, were also observed (Table 4.4). BD decreased and total porosity increased in most fields where the SOC content increased (Table 4.2, Table 4.5). Among soil series, there were no significant differences in ΔBD and Δtotal 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 4.2) 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 4.5). 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 macro-pores 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).

4.4.4. Soil chemical properties

4.4.4.1. pH

The application of organic matter resulted in a significant increase in soil pH (Table 4.7). 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 4.6), probably because organic matter contains substantial amounts of base cations (Table 4.1). 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 $A1^{3+}$ and concomitant release of cations with its decomposition.

4.4.4.2. 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 (Li et al. 2012; Liu et al. 2010; Singh et al. 2007), PAC increased, and available P decreased significantly in the present study (Table 4.7). Significant negative relationships between Δavailable P and ΔSOC content or ΔPAC (Table 4.4), and the following regression equations were obtained: Δavailable P (mg P_2O_5 kg^{-1}) = - 16.9 × ΔSOC content (g C kg^{-1}) – 65.0 (R^2 = 0.34; P < 0.01) and Δavailable P (mg P_2O_5 kg^{-1}) = - 0.25 × ΔPAC (mg P_2O_5 100 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 ΔPAC and ΔSOC content (Table 4.4). 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 ΔPAC in the K1 soil series was significantly larger than that in the K2 and HO soil series (Table 4.3). 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; Takahashi and Dahlgren 2016; Wickramatilake et al. 2010). Furthermore, the application of organic matter is expected to improve P availability by enhancing organic P mineralization (Takeda et al. 2009; Tsuji et al., 2006). 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 mg P_2O_5 kg^{-1} (Hokkaido agricultural department 2015)] in all but one of the fields (field no. 14; Table 8) in 2012.

4.4.4.3. CEC and exchangeable cations

As expected, the application of organic matter increased exchangeable cations and CEC in all soil series (Table 4.3, Table 4.8) (Aranda et al. 2015; Hao and Chang 2002). 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 (Gruba and Mulder 2015; Hemmat et al. 2010). In all soil series in the present study, CEC was mainly associated with SOC, as suggested by the intercept (8.97 $cmol_c\ kg^{-1}$ in 2001–2003 and 9.97 $cmol_c\ kg^{-1}$ in 2012) of the liner relationship between SOC content and CEC (Fig. 4.4). A significantly positive relationship between ΔSOC content and ΔCEC (Table 4.4) was also observed. 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. 4.4). 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 $cmol_c\ kg^{-1}$ in 2001–2003 and 9.97 $cmol_c\ kg^{-1}$ 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.

4.5. Conclusion

In this Chapter, 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 was evaluated. 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 ΔSOC, 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} 15 cm^{-1}, respectively. 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.

4.6. Summary

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 was evaluated in this chapter. 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 ± 1.27 Mg C ha^{-1} yr^{-1}. Mean SOC contents in 2001–2003 and 2012 were 26.5 ± 8.1 and 25.7 ± 5.7 g C kg^{-1}, respectively, and mean SOC stocks were 39.6 ± 10.2 and 37.9 ± 7.4 Mg C ha^{-1} 15 cm^{-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 (g C kg^{-1} yr^{-1}) = -0.046 × Initial SOC content (g C kg^{-1}) + 1.12 and rate of ΔSOC stock (Mg C ha^{-1} 15 cm^{-1} yr^{-1}) = -0.052 × Initial SOC stock (Mg C ha^{-1} 15 cm^{-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 Mg C ha^{-1} 15 cm^{-1}, respectively. ΔSOC content was significantly negatively correlated with Δbulk density, Δavailable phosporus, and base saturation, but positively correlated with Δtotal porosity, Δphosphate 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.

5. Effect of global warming on soil carbon stock change in the Taiga-Alas landscape in Eastern Siberia

5.1. Introduction

As mentioned in chapter 1 and 2, several researchers have reported a decrease in SOC in temperate and cool temperate zones (Capriel, 2013; Heikkinen et al., 2013; Lark et al., 2006; Riley and Bakkegard, 2006; Saby et al., 2008). Significant negative correlations between initial SOC content and the rate of change in SOC content have also been reported (Capriel, 2013; Goidts and van Wesemael, 2007; Hanegraaf et al., 2009; Riley and Bakkegard, 2006; Saby et al., 2008; Stevens and Van Wesemael, 2008). Several authors have attributed this loss in SOC to global warming (Bellamy et al., 2005; Heikkinen et al., 2013). Other researchers have referred to changes in management practice in agricultural lands, such as decreased organic matter application (Capriel et al., 2013; Goidts and van Wesemael, 2007) and increased ploughing depth (Riley and Bakkegard, 2006).

Global warming is expected to be most pronounced in northern high latitudes (Desyatkin et al., 2015; IPCC, 2014). Indeed, between 1961 and, 2010 the mean annual air temperature at Yakutsk increased by 2.5 ºC (Fedorov et al., 2014). Consequently, increased depth of the active layer and altered hydrological conditions can lead to increased mineralization (Dutta et al., 2006; Koven et al., 2009; Schurr et al., 2015; Schuur and Bockheim, 2008).

Net biome production (NBP) is estimated as the carbon budget (gross primary production–ecosystem production–harvest) measured by combining micrometeorological and biometrical techniques, and is almost equal to the change in SOC stock (Bernacchi et al., 2005; Randerson et al., 2002). Desyatkin et al. (2007) estimated the NBP in the dry and wet grasslands of thermokarst in Central Yakutia. The NBP was positive in dry grassland (0.162 Mg C ha^{-1}), but negative in wet grassland (-1.21 Mg C ha^{-1}), and those authors stated that the larger SOC stock area resulted in a greater loss of C.

This chapter aimed: firstly, to estimate changes in the SOC content and stock by measuring SOC in forest and thermokarst ecosystems, where any land use changes and forest disturbances have been not recorded, at two different times. And the effect of global warming on the SOC stock was discussed: secondly, to identify factors controlling changes in SOC.

5.2. Materials and methods

5.2.1. Sampling point determination

The soil survey was conducted in 1992 (Matsuura et al., 1994) and 2000 (Kamide et al., 2001) totally at 18 sites (five LFs, one PF, six DGs, five WGs, and one PG) in two areas of the left bank and four areas of the right bank of Lena River (Fig. 5.1; Table 5.1). To estimate the change in litter carbon (LIC) and SOC, soil surveys and soil samplings were conducted in 2014 at the same sites. The sampling points were determined by considering the coordinate, topography, vegetation, maps, photos, and information obtained from the observers of soil survey in 1992 and 2000. And the soil survey in 2014 was conducted with the researchers who did the soil survey in the past time.

At the Neleger area the past time sampling points information were described by Morishita et al., (2003) and Takakai et al., (2008) with the satellite image. And the sampling points were on the FG-line in Morishita et al., 2003. At the Spasskaya-pad and Unakh area, the information of the past time sampling points was described by Matsuura et al., 1994. Moreover, the soil profiles at the soil survey in past time were found in the spasskaya-pad area. At the Ulakhan Sukkan area, the past time sampling points information were described in Desyatkin et al., (2007). And the sampling points corresponded to F, D, M plot in Desyatkin et al., (2007).

5.2.2. Soil sampling

To cover the variation of the SOC, three replications on the soil sampling was made in 2014. Soil sampling was conducted at the apex of the triangle with 10 to 30 m each side. Both composite and undisturbed (using 100 mL steel cylinders) samples were taken from each horizon in the 0–30 cm depth. At the LF and PF sites, each organic horizon was collected in 100 mL steel cylinders. During the soil survey, it was confirmed that the basic information of soil profile such as diagnostic horizons and soil texture were did not differ from the soil survey in the past time. And the any land use change and forest disturbance have been not observed in all sites.

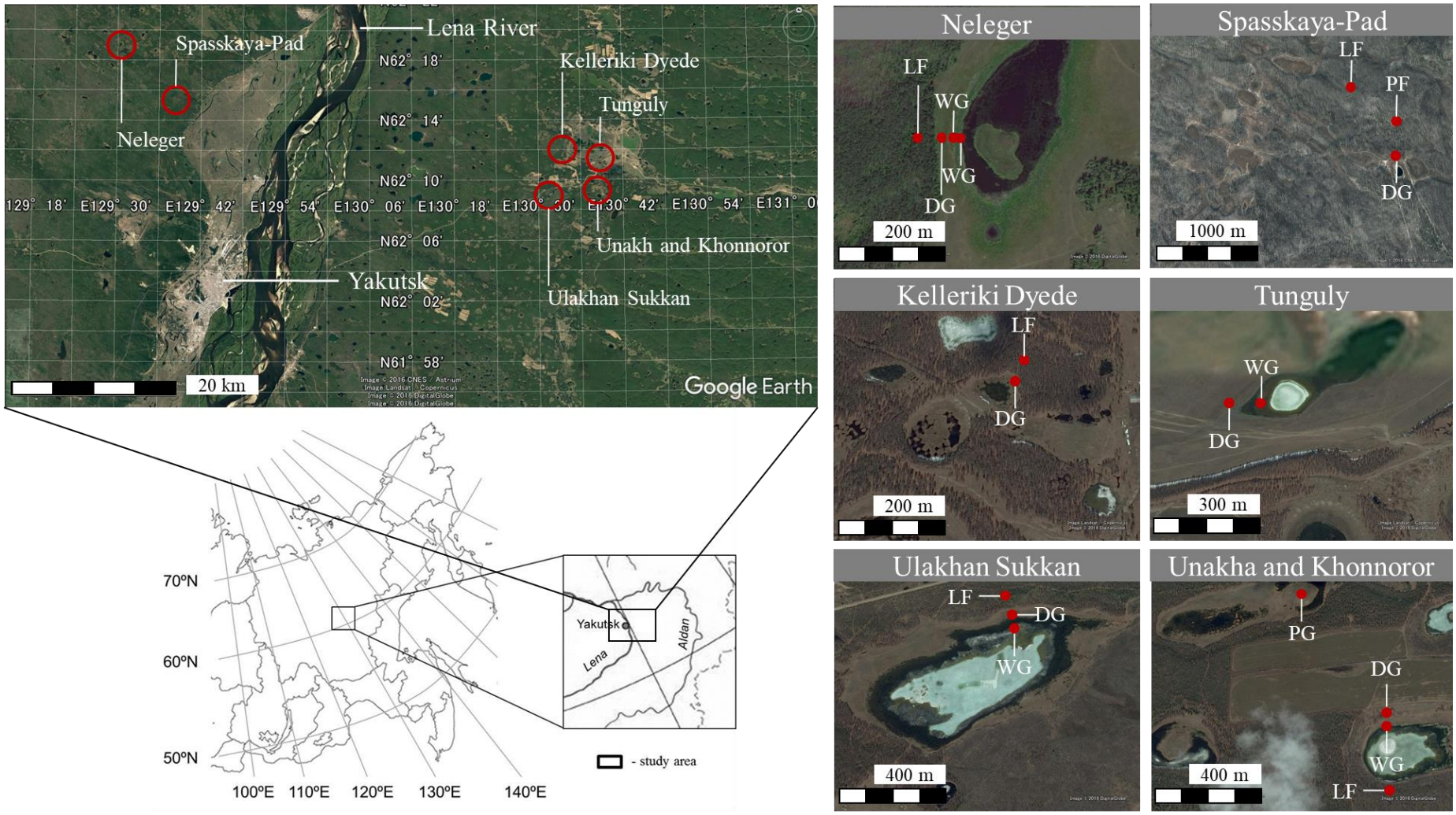

Fig. 5.1. Location of 18 study sites. LF: Larch forest, PF: Pine forest, DG: Dry grassland, WG: Wet grassland PG: Pingo.

Table 5.1

Sampling sites information.

Region	Area	Soil type	Land use	Sampling date		Coordinate						Reference for the sampling points
						Latitude			longitude			
				Past	Present	Degree	Minute	Second	Degree	Minute	Second	
Left bank†	Neleger	Cambic Cryosol	LF	2000	2014	62	19	0.28	129	30	7.36	Morishita et al., 2003; Takakai et al., 2008
Left bank†	Neleger	Endogleyic Stagnosol	DG	2000	2014	62	18	59.02	129	30	12.5	Morishita et al., 2003; Takakai et al., 2008
Left bank†	Neleger	Limnic Histosol	WG	2000	2014	62	18	59.05	129	30	13.2	Morishita et al., 2003; Takakai et al., 2008
Left bank†	Neleger	Limnic Histosol	WG	2000	2014	62	18	58.9	129	30	14.37	Morishita et al., 2003; Takakai et al., 2008
Left bank†	Spasskaya-pad	Cambic Cryosol	LF	1992	2014	62	15	17.11	129	36	46.16	Matsuura et al., 1994
Left bank†	Spasskaya-pad	Distric Cambisol	PF	1992	2014	62	15	5.59	129	37	16.76	Matsuura et al., 1994
Left bank†	Spasskaya-pad	Umbric Cambisols	DG	1992	2014	62	14	53.5	129	37	21.32	Matsuura et al., 1994
Right bank ‡	Kelleriki Dyede	Cambic Cryosol	LF	2000	2014	62	12	2.58	130	33	50.99	
Right bank ‡	Kelleriki Dyede	Endogleyic Stagnosol	DG	2000	2014	62	11	59.49	130	33	50.11	
Right bank ‡	Khonnoror	Umbric Cambisols	PG	2000	2014	62	9	44.28	130	37	47.91	
Right bank ‡	Tunguly	Endogleyic Stagnosol	DG	2000	2014	62	11	23.9	130	38	22.46	
Right bank ‡	Tunguly	Cambic Fluvisol	WG	2000	2014	62	11	22.49	130	38	28.5	
Right bank ‡	Ulakhan Sukkan	Cambic Cryosol	LF	2000	2014	62	9	18.86	130	31	47.67	Desyatkin et al., 2007
Right bank ‡	Ulakhan Sukkan	Endogleyic Stagnosol	DG	2000	2014	62	9	14.11	130	31	46.51	Desyatkin et al., 2007
Right bank ‡	Ulakhan Sukkan	Cambic Fluvisol	WG	2000	2014	62	9	13.3	130	31	47.89	Desyatkin et al., 2007
Right bank ‡	Unakh	Cambic Cryosol	LF	1992	2014	62	9	12	130	38	21	Matsuura et al., 1994
Right bank ‡	Unakh	Endogleyic Stagnosol	DG	1992	2014	62	9	23.72	130	38	23.23	Matsuura et al., 1994
Right bank ‡	Unakh	Limnic Histosol	MG	1992	2014	62	9	23.72	130	38	23.23	Matsuura et al., 1994

LF: Larch forest, PF: Pine forest, DG: Dry grassland, WG: Wet grassland, PG: Pingo. The soil type in each study site was determined using the WRB soil classification system (IUSS working Group WRB. 2015). In this study, the active layer in the LF was less than 2 m thick, and the soil was classified as Cryosol. The active layer in the PF, DG, WG, and PG sites was deeper than 2 m. Soils of the PF site were classified as Cambisol. Soils of the DG, WG, and PG sites were classified as Stagnosol, Fluvisol, Histosol (or Fluvisol), and Spodosol, respectively.

5.2.3. Sample analysis

The same methods in 1992–2000 and 2014 were employed to determine the soil BD (Chapter 3).

In 2014, the LIC content of the organic horizon was determined by LOI method. On the other hand, in 1992 and 2000, dry combustion method was employed to determine the LIC content. Hence, the LIC content in 2014 was modified by using Eq. 3.1 (chapter 3) to fill the discrepancy between these methodologies.

In 2014, Tyurin (wet oxidation) method was used to determine the SOC content of mineral soil. Conversely, total carbon (TC) content was determined by dry combustion method in 1992 and 2000. In addition to the incomplete oxidation of OM described in chapter 3, the dry combustion method has been reported to give higher C content for mineral soil than the Tyurin method because of the existence of SCC (Kingdom, 2009) particularly in arid region where accumulation of the SCC is expected (Raheb et al., 2017). Indeed, Desyatkin and Desyatkin, (2006) and Matsuura et al., (1994) referred to the accumulation of the SCC in Central Yakutsk up to 50%. Therefore, the SOC content in samples from 1992 and 2000 was determined from the difference between TC and SCC content. SCC content of mineral soil was determined by the method described in chapter 3.

15 organic horizon samples and 38 mineral soil samples collected in 2014 were analyzed with both methods employed in 1992–2000 and 2014 evaluate the discrepancies between the methodologies. Combined with the data of organic horizon and organic soil, and mineral soil, one-on-one relation with the high coefficient of determination ($R^2 = 0.98$) (Fig. 5.2) was obtained.

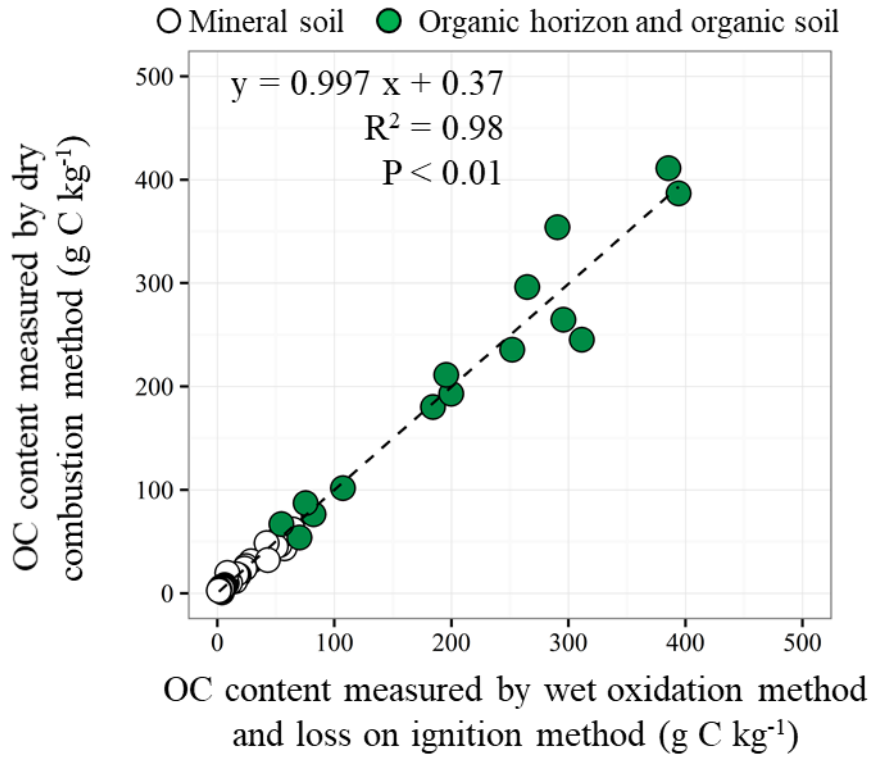

Fig. 5.2. Comparison of the organic carbon content between the methodologies. OC; Organic carbon. OC content measured by the loss on ignition method was modified by using Eq.3.1. OC content measured by the dry combustion method was determined from the difference between total carbon content (TC) and carbonate carbon (CC) content.

5.2.4. Data calculation

5.2.4.1. SOC and LIC stock

The total profile carbon stock at each site was calculated as the sum of the component soil horizon SOC stocks at depths of 0–5, 5–15, and 15–30 cm. The SOC stock (Mg C ha^{-1}) of each horizon was calculated by using Eq. 3.2 in chapter 3.

5.2.4.2. Weighted average SOC and LIC content

In this study, soil samples were taken from each horizon of the soil profile. Therefore, to evaluate the change in the LIC and SOC content among the same depth, the SOC content in the 0–5, 5–15, 15–30, 0–15 and 0–30 cm depths was calculated as a weighted average value obtained as SOC stock divided by soil mass at each depth. The weighted average LIC content was calculated in the same

manner.

5.2.4.4. Change in SOC and LIC

The SOC stock change rate (ΔSOC, Mg C ha^{-1} 15 cm^{-1} yr^{-1}) in 0–5, 0–15 and 0–30 cm soil layer between 1992–2000 and 2014 was estimated using Eq.3.6 and Eq. 3.7 in chapter 3.

The same calculation procedure was used to obtain the rate of change in SOC content, LIC content and LIC stock.

5.2.5. Statistical analysis

Statistical analysis applied in this chapter was described in chapter 3. Two-way ANOVA and the Tukey-Kramer test were used to analyze the difference in LIC content and LIC stocks between year, depth, and land use. Three-way ANOVA and the Tukey-Kramer test were used to analyze the difference in SOC content and SOC stocks between year, depth, and land use. A paired t-test was used to determine the difference in SOC content and LIC and SOC stocks between past and present sampling times. Analysis of covariance (ANCOVA) was used to determine the difference between the two regression equations.

5.3. Results

5.3.1. Changes in the LIC and SOC from 1992–2000 to 2014

Fig. 5.3 compares the BD, LIC content and stock, and SOC content and stock between 1992–2000 and 2014 in the organic horizon and 0–5, 5–15, and 15–30 cm soil layers. The mean BD in the organic horizon and in the 0–5, 5–15 and 15–30 cm soil layers in 1992–2000 was 0.10 ± 0.04, 0.96 ± 0.36, 1.19 ± 0.35, and 1.39 ± 0.26 Mg m^{-3}, respectively, and in 2014 was 0.11 ± 0.07, 1.09 ± 0.30, 1.22 ± 0.23, and 1.37 ± 0.17 Mg m^{-3}, respectively. The BD significantly differed between the depths, and was lowest in the organic horizon and highest in the 15–30 cm soil layer. There was no significant difference between sampling years at any depth.

The mean LIC and SOC content in the organic horizon and the 0–5, 5–15, and 15–30 cm soil in 1992–2000 was 437.0 ± 48.4, 64.7 ± 80.7, 42.9 ± 52.6, and 20.5 ± 35.9 Mg m^{-3}, respectively, and in 2014, 211.3 ± 81.9, 36.4 ± 30.8, 28.9 ± 27.3, and 11.7 ± 10.6 g C kg^{-1}, respectively. The LIC content in the organic horizon was significantly higher than the SOC content. Furthermore, the SOC content in the 0–5 cm soil layer was significantly greater than that in the 5–15 and 15–30 cm soil layers. There was a significant difference in LIC and SOC content between years in the organic horizon and 0–5 cm soil ($P < 0.01$, respectively). The mean LIC and SOC stock in the organic horizon and 0–5, 5–15, and 15–30 cm soil in 1992–2000 was 22.0 ± 12.0, 21.9 ± 15.1, 34.8 ± 31.3, and 30.7 ± 35.9 Mg m^{-3}, respectively, and in 2014, 19.1 ± 8.5, 17.1 ± 13.8, 30.8 ± 26.0, and 22.4 ± 18.1 Mg C ha^{-1}, respectively. The SOC stock in the 5–15 cm soil was significantly higher than that in the 0–5 cm soil. There was no significant difference between sampling years in LIC stock and SOC stock at any depth.

Table 5.2 compares the LIC stock, SOC content, and SOC stock between 1992–2000 and 2014 in the organic horizon and the 0–5, 0–15, and 0–30 cm soil samples. Two-way ANOVA revealed that LIC content significantly differed between years ($P < 0.01$). The LIC content significantly decreased in all sites. Among the different land uses, the mean ΔLIC content of LF and PF was

15.1 ± 6.7 and -12.9 ± 4.1 g C kg^{-1} yr^{-1}, respectively.

Three-way ANOVA showed that the SOC content differed significantly between year, depth, and land use ($P < 0.01$, respectively). The mean SOC content was significantly decreased at all depths. The SOC content at the 0–5 cm soil depth increased, decreased, and was unchanged in 17, 72, and 11% of the sites, respectively, The SOC content in the 0–15 cm soil depth increased, decreased, and was unchanged in 22, 67, and 11% of sites, respectively. The SOC content in the 0–30 cm soil depth increased, decreased, and was unchanged in 28, 55, and 17% of sites, respectively. Among the different land uses, the mean ΔSOC content in the 0–30 cm soil depths of the LF, PF, DG, WG, and PG sites was -0.04 ± 0.28, -0.20 ± 0.02, -0.43 ± 0.79, -1.84 ± 3.70, and -0.17 ± 0.29 g C kg^{-1} yr^{-1}, respectively.

Table 5.3 compares the LIC and SOC stocks between 1992–2000 and 2014 in the organic horizon and the 0–5, 0–15, and 0–30 cm soil depths. Two-way ANOVA showed that the LIC stock differed significantly only between the different land uses ($P < 0.01$). The LIC stock increased, decreased, and was unchanged in 17, 50, and 33% of sites, respectively. Among the different land uses, the mean ΔLIC stock in the LF and PF sites was -0.15 ± 0.88 and -0.29 ± 0.26 Mg C ha^{-1} yr^{-1}, respectively

Three-way ANOVA revealed a significant difference in the SOC stock between year, depth, and land use ($P < 0.05$ for depth and $P < 0.01$ for year and land use, respectively). Significant interactions were observed between year and land use ($P < 0.01$). The SOC stock in the 0–5 cm depth increased, decreased, and was unchanged in 17, 66, and 17% of sites, respectively. The SOC stock in the 0–15 cm depth increased, decreased, and was unchanged in 22, 56, and 22% of sites, respectively. The SOC stock in the 0–30 cm depth increased, decreased, and was unchanged in 28, 61, and 11% of sites, respectively. Among the different land uses, the mean ΔSOC stock in the 0–30 cm depth in the LF, PF, DG, WG, and PG sites was -0.05 ± 0.82, -0.58 ± 0.06, -1.52 ± 2.80, -2.10 ± 7.05, and -1.39 ± 1.24 Mg C ha^{-1} yr^{-1}, respectively.

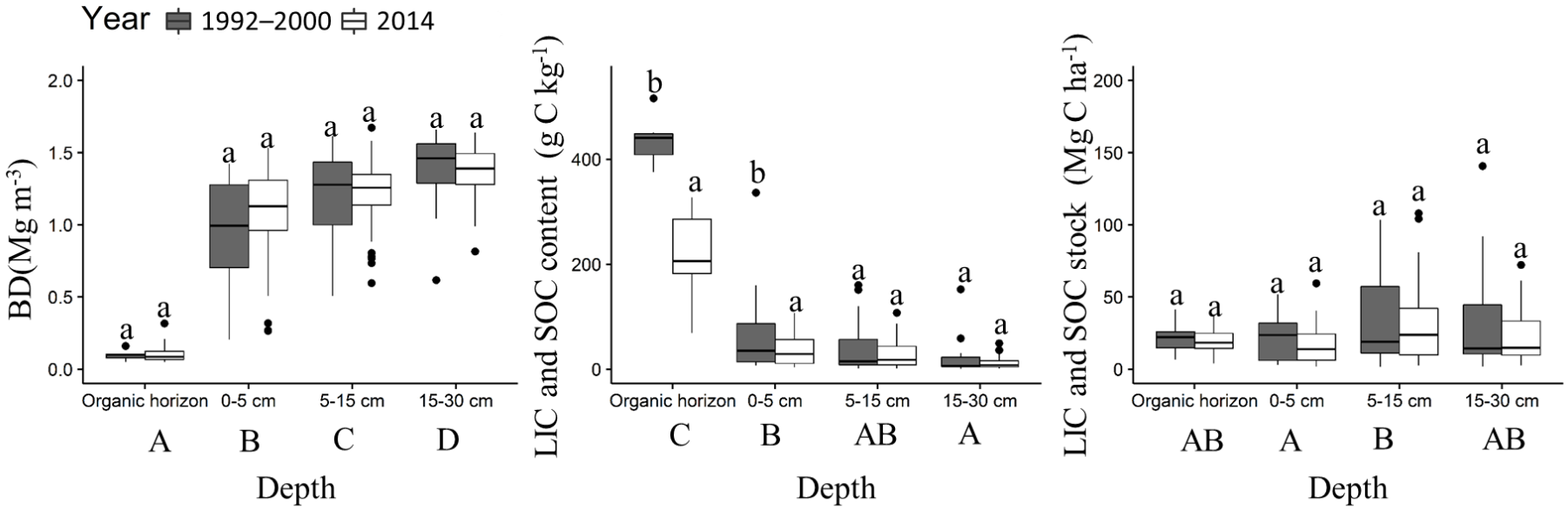

Fig. 5.3. Comparison of bulk density, carbon content, and carbon stock between 1992–2000 and 2014 at each depth. Different lower-case letters indicate significant differences between 1992–2000 and 2014. Different capital letters indicate significant differences between depths. SOC: Soil organic carbon, LIC: Litter carbon.

Table 5.2

Comparison of litter carbon (LIC) and Soil organic carbon (SOC) content between 1992–2000 and 2014.

Area	Soil sampling in past time	Land use	LIC content			SOC content								
			Organic horizon			0–5 cm mineral soil			0–15 cm mineral soil			0–30 cm mineral soil		
			g C kg^{-1}		g C kg^{-1} yr^{-1}	g C kg^{-1}		g C kg^{-1} yr^{-1}	g C kg^{-1}		g C kg^{-1} yr^{-1}	g C kg^{-1}		g C kg^{-1} yr-1
			1992–2000	2014	ΔLIC	1992–2000	2014	ΔSOC	1992–2000	2014	ΔSOC	1992–2000	2014	ΔSOC
Kelleriki dyede	2000	LF	450.7 b	243.0 ± 64.6 a	-14.8 ± 4.6	6.8 b	4.7 ± 0.8 a	-0.15 ± 0.06	6.0 b	4.7 ± 0.8 a	-0.09 ± 0.06	5.0 a	4.7 ± 0.8 a	-0.02 ± 0.06
Neleger	2000	LF	515.8 b	235.9 ± 72.0 a	-20.0 ± 5.1	18.7 b	9.5 ± 2.9 a	-0.66 ± 0.21	16.8 b	9.1 ± 0.5 a	-0.55 ± 0.03	15.2 b	8.6 ± 0.2 a	-0.47 ± 0.01
Spasskaya-pad	1992	LF	375.6 b	211.5 ± 72.3 a	-9.1 ± 4.0	9.5 b	3.9 ± 0.3 a	-0.31 ± 0.02	2.3 a	2.9 ± 0.7 a	0.03 ± 0.04	1.5 a	2.6 ± 1.0 b	0.06 ± 0.05
Unakh	1992	LF	440.4 b	297.6 ± 26.2 a	-7.9 ± 1.5	33.4 b	12.7 ± 3.6 a	-1.15 ± 0.20	18.6 b	11.7 ± 4.1 a	-0.38 ± 0.23	9.3 a	8.5 ± 2.2 a	-0.05 ± 0.12
Ulakhan Sukkan	2000	LF	441.5 b	114.0 ± 74.6 a	-23.4 ± 5.3	7.1 a	9.7 ± 1.6 b	0.18 ± 0.11	4.6 a	8.3 ± 0.9 b	0.26 ± 0.06	3.7 a	7.7 ± 0.4 b	0.29 ± 0.03
Spasskaya-pad	1992	PF	398 b	165.6 ± 72.9 a	-12.9 ± 4.1	12.8 b	4.8 ± 0.7 a	-0.44 ± 0.04	10.0 b	4.6 ± 0.5 a	-0.3 ± 0.03	7.5 b	4.0 ± 0.3 a	-0.2 ± 0.02
Kelleriki dyede	2000	DG	-	-	-	35.5 b	25.5 ± 8.9 a	-0.71 ± 0.64	17.8 b	11.5 ± 0.2 a	-0.45 ± 0.01	11.5 b	7.7 ± 0.1 a	-0.27 ± 0.01
Neleger	2000	DG	-	-	-	104 b	47.5 ± 19.8 a	-4.03 ± 1.41	72.2 b	35.4 ± 7.8 a	-2.63 ± 0.56	32.5 b	21.2 ± 3.1 a	-0.81 ± 0.22
Spasskaya-pad	1992	DG	-	-	-	336.1 b	81.5 ± 22.5 a	-14.15 ± 1.25	181.9 b	47.1 ± 13.2 a	-7.49 ± 0.73	40.3 b	24.6 ±4.7 a	-0.87 ± 0.26
Tunguly	2000	DG	-	-	-	7.0 a	13.5 ± 3.4 b	0.47 ± 0.24	5.5 a	12.6 ± 3.0 b	0.5 ± 0.25	5.8 a	9.5 ± 2.3 b	0.26 ± 0.16
Unakh	1992	DG	-	-	-	35.1 a	38.4 ± 14.3 a	0.18 ± 0.79	15.9 a	37.0 ± 11.8 b	1.17 ± 0.66	10.3 a	21.8 ± 2.8 b	0.64 ± 0.15
Ulakhan Sukkan	2000	DG	-	-	-	46.3 b	36.2 ± 10.0 a	-0.72 ± 0.71	46.3 b	26.4 ± 7.6 a	-1.42 ± 0.55	35.5 b	14.4 ± 4.7 a	-1.51 ± 0.34
Neleger	2000	WG	-	-	-	59.8 a	89.7 ± 15.3 b	2.13 ± 1.09	32.8 a	79.5 ± 12.4 b	3.33 ± 0.88	17.9 a	49.0 ± 9.6 b	2.22 ± 0.68
Neleger	2000	WG	-	-	-	120 b	85.4 ± 19.0 a	-2.47 ± 1.36	120 b	85.4 ± 19.0 a	-2.47 ± 1.36	78.9 b	50.7 ± 11.0 a	-2.01 ± 0.78
Tunguly	2000	WG	-	-	-	31 b	24.4 ± 4.0 a	-0.47 ± 0.28	31.0 b	24.4 ± 4.0 a	-0.47 ± 0.28	30.9 b	21.3 ± 3.3 a	-0.68 ± 0.24
Unakh	1992	WG	-	-	-	95.5 b	68.4 ± 14.6 a	-1.94 ± 1.04	95.5 b	68.4 ± 14.6 a	-1.94 ± 1.04	54.3 b	41.7 ± 6.7 a	-0.9 ± 0.48
Ulakhan Sukkan	2000	WG	-	-	-	160.2 b	62 ± 14.6 a	-7.01 ± 1.05	160.2 b	62 ± 14.6 a	-7.01 ± 1.05	156.2 b	46.4 ± 1.8 a	-7.84 ± 0.13
Khonnoror	2000	PG	-	-	-	45.4 a	37.5 ± 19.8 a	-0.56 ± 1.41	22.6 a	21.1 ± 9.9 a	-0.1 ± 0.70	14.4 a	12.1 ± 4.1 a	-0.17 ± 0.29
	LF		444.8 ± 49.7	220.4 ± 67.3	- 15.1 ± 6.7	15.1 ± 11.3	8.1 ± 3.9	-0.42 ± 0.51	9.7 ± 7.5	7.3 ± 3.7	-0.15 ± 0.32	6.9 ± 5.4	6.4 ± 2.7	-0.04 ± 0.28
	PF		398	165.6 ± 72.9	-12.9 ± 4.1	12.8	4.8 ± 0.7	-0.44 ± 0.04	10	4.6 ± 0.5	-0.30 ± 0.03	7.5	4.0 ± 0.3	-0.20 ± 0.02
	DG		-	-	-	94.0 ± 122.8	40.4 ± 25.1	-3.16 ± 5.62	56.6 ± 66.1	28.3 ± 15.2	-1.72 ± 3.13	22.6 ± 15.1	16.5 ± 7.2	-0.43 ± 0.79
	WG		-	-	-	93.3 ± 50.5	65.9 ± 26.9	-1.95 ± 3.34	87.9 ± 56.1	63.9 ± 25.0	-1.71 ± 3.73	67.6 ± 54.7	41.8 ± 12.7	-1.84 ± 3.70
	PG		-	-	-	45.4	37.5 ± 19.8	-0.56 ± 1.41	22.6	21.1 ± 9.8	-0.10 ± 0.70	14.4	12.1 ± 4.1	-0.17 ± 0.29
	Mean		437.0 ± 48.4 b	211.3 ± 64.2 a	-14.7 ± 6.1	64.7 ± 80.7 b	36.4 ± 30.8 a	-1.77 ± 3.66	47.8 ± 55.6 b	30.7 ± 27.6 a	-1.11 ± 2.61	29.5 ± 37.6 b	19.8 ± 16.5 a	-0.68 ± 2.00

Result of two-way ANOVA (LIC content)			
	d.f	F-value	p-value
Year	1	39.35	p < 0.01
Landscape	1	1.593	0.221
Year × Landscape	1	0.007	0.935
Residuals	20		

Result of three-way ANOVA (SOC content)			
	d.f	F-value	p-value
Year	2	8.89	< 0.01
Depth	1	14.7	< 0.01
Landscape	4	28	< 0.01
Year × Depth	2	12.8	0.28
Year × Landscape	8	1.04	0.41
Depth × Landscape	4	1.52	0.2
Year ×Depth × Landscape	8	0.38	0.93
Residuals	186		

SOC: Soil organic carbon, LF: Larch forest, PF: Pine forest, DG: Dry grassland, WG: Wet grassland, PG: Pingo. Different lower-case letters within the same row indicate significant differences between 1992–2000 and 2014. Values are the mean ± standard deviation.

Table 5.3

Comparison of litter carbon (LIC) and soil organic carbon (SOC) stock between 1992–2000 and 2014.

Area	Soil sampling in past time	Land use	LIC stock			SOC stock								
			Organic horizon			0-5 cm mineral soil			0-15 cm mineral soil			0-30 cm mineral soil		
			Mg C ha^{-1}		Mg C ha^{-1} yr^{-1}	Mg C ha^{-1}		Mg C ha^{-1} yr^{-1}	Mg C ha^{-1}		Mg C ha^{-1} yr^{-1}	Mg C ha^{-1}		Mg C ha^{-1} yr^{-1}
			1992–2000	2014	ΔLIC	1992-2000	2014	ΔSOC	1992-2000	2014	ΔSOC	1992-2000	2014	ΔSOC
Kelleriki dyede	2000	LF	6.8 a	19.5 ± 6.8 b	0.91 ± 0.48	4.7 b	3.4 ± 0.5 a	-0.09 ± 0.03	12.6 b	10.1 ± 1.4 a	-0.18 ± 0.10	21.3 a	19.8 ± 2.3 a	-0.11 ± 0.16
Neleger	2000	LF	41.3 b	20.4 ± 6.4 a	-1.49 ± 0.46	6.6 a	5.3 ± 2.3 a	-0.09 ± 0.16	25.1 b	16.5 ± 2.4 a	-0.62 ± 0.17	50.8 b	32.7 ± 2.8 a	-1.3 ± 0.20
Spasskaya-pad	1992	LF	21.0 b	14.2 ± 2.9 a	-0.38 ± 0.16	2.8 b	2.0 ± 0.1 a	-0.04 ± 0.004	4.4 a	5.9 ± 1.6 a	0.08 ± 0.09	6.3 a	11.3 ± 4.5 b	0.28 ± 0.25
Unakh	1992	LF	23.3 a	23.6 ± 1.6 a	-0.02 ± 0.09	11.9 b	7.8 ± 3.1 a	-0.23 ± 0.17	27.5 a	22.1 ± 9.8 a	-0.3 ± 0.55	34.3 a	32.6 ± 10.0 a	-0.10 ± 0.56
Ulakhan Sukkan	2000	LF	26.8 a	29.2 ± 8.6 a	0.18 ± 0.62	4.3 a	6.0 ± 0.7 b	0.12 ± 0.05	9.0 a	15.5 ± 1.5 b	0.46 ± 0.10	15.4 a	29 ± 0.5 b	0.97 ± 0.03
Spasskaya-pad	1992	PF	12.7 b	7.5 ± 4.8 a	-0.29 ± 0.26	5.8 b	3.2 ± 0.2 a	-0.15 ± 0.01	17.0 b	9.3 ± 0.7 a	-0.43 ± 0.04	27.2 b	16.7 ± 1.0 a	-0.58 ± 0.06
Kelleriki dyede	2000	DG	-	-	-	25.2 b	13.6 ± 3.6 a	-0.83 ± 0.26	41.5 b	22.7 ± 2.2 a	-1.34 ± 0.16	55.3 b	32.3 ± 2.8 a	-1.64 ± 0.20
Neleger	2000	DG	-	-	-	37.3 b	25.4 ± 10.7 a	-0.85 ± 0.76	95.1 b	61.8 ± 16.0 a	-2.38 ± 1.14	117.9 b	82.4 ± 12.8 a	-2.54 ± 0.92
Spasskaya-pad	1992	DG	-	-	-	34.3 b	11.4 ± 2.2 a	-1.27 ± 0.12	111.0 b	45.4 ± 12.1 a	-3.64 ± 0.67	123.4 b	64.7 ± 10.6 a	-3.26 ± 0.59
Tunguly	2000	DG	-	-	-	4.6 a	8.1 ± 1.5 b	0.25 ± 0.10	11.6 a	23.2 ± 4.6 b	0.83 ± 0.33	25.0 a	38.0 ± 7.3 b	0.93 ± 0.52
Unakh	1992	DG	-	-	-	22.1 a	24.5 ± 7.1 a	0.13 ± 0.39	33.4 a	71.3 ± 17.8 b	2.11 ± 0.99	45.0 a	90.3 ± 9.9 b	2.52 ± 0.55
Ulakhan Sukkan	2000	DG	-	-	-	27.6 b	21.5 ± 4.6 a	-0.43 ± 0.33	82.8 b	50.8 ± 11.4 a	-2.28 ± 0.82	133.6 b	62.1 ± 19.2 a	-5.11 ± 1.37
Neleger	2000	WG	-	-	-	32.3 a	50.4 ± 15.6 b	1.3 ± 1.12	64.0 a	141.7 ± 41.4 b	5.55 ± 2.95	78.8 a	190.8 ± 41.1 b	8.00 ± 2.94
Neleger	2000	WG	-	-	-	30.7 a	31.9 ± 3.1 a	0.09 ± 0.22	92.0 a	95.7 ± 9.3 a	0.27 ± 0.66	183.9 b	144.0 ± 15.6 a	-2.86 ± 1.12
Tunguly	2000	WG	-	-	-	20.4 b	16.4 ± 3.1 a	-0.28 ± 0.22	61.2 b	49.3 ± 9.3 a	-0.9 ± 0.66	112.9 b	86.8 ± 15.6 a	-1.86 ± 1.12
Unakh	1992	WG	-	-	-	43.0 b	36.2 ± 3.9 a	-0.48 ± 0.28	128.9 b	108.6 ± 11.8 a	-1.45 ± 0.84	182.1 b	155.7 ± 17.6 a	-1.89 ± 1.25
Ulakhan Sukkan	2000	WG	-	-	-	51.8 b	24.9 ± 5.8 a	-1.92 ± 0.42	155.4 b	74.8 ± 17.5 a	-5.75 ± 1.25	296.1 b	129.4 ± 14.2 a	-11.9 ± 1.02
Khonnoror	2000	PG	-	-	-	29.1 b	15 ± 6.2 a	-1.01 ± 0.44	48.7 a	35.5 ± 16.6 a	-0.94 ± 1.19	65 b	45.5 ± 17.4 a	-1.39 ± 1.24
	LF		23.8 ± 12.4	21.4 ± 5.5	-0.15 ± 0.88	6.1 ± 3.5	4.9 ± 2.6	-0.07 ± 0.12	15.7 ± 10.1	14.0 ± 7.0	-0.11 ± 0.41	25.7 ± 17.4	25.1 ± 9.7	-0.05 ± 0.82
	PF		12.7	7.5± 4.8	-0.29 ± 0.26	5.8	3.2 ± 0.3	-0.15 ± 0.02	17	9.3 ± 0.7	-0.43 ± 0.04	27.2	16.7 ± 1.0	-0.58 ± 0.06
	DG		-	-	-	25.2 ± 11.6	17.4 ± 8.5	-0.5 ± 0.6	62.6 ± 39.2	45.9 ± 21.3	-1.12 ± 2.17	83.4 ± 46.9	61.6 ± 23.8	-1.52 ± 2.80
	WG		-	-	-	35.6 ± 12.1	31.9 ± 13.6	-0.26 ± 1.16	100.3 ± 41.1	94.0 ± 37.1	-0.45 ± 4.05	170.7 ± 83.4	141.3 ± 40.3	-2.10 ± 7.05
	PG		-	-	-	29.1	15.0 ± 6.2	-1.01 ± 0.44	48.7	35.5 ± 16.6	-0.94 ± 1.18	65	45.6 ± 17.4	-1.39 ± 1.24
	Mean		22.0 ± 12.0 a	19.1 ± 7.5 a	-0.18 ± 0.79	21.9 ± 15.1 a	17.1 ± 13.8 a	-0.34 ± 0.94	56.7 ± 45.1 a	47.8 ± 39.4 a	-0.60 ± 2.34	87.5 ± 75.9 a	70.2 ± 53.6 a	-1.21 ± 3.85

Result of two-way ANOVA (LIC stock)

	d.f	F-value	p-value
Year	1	0.553	0.466
Landscape	1	8.442	p < 0.01
Year × Landscape	1	0.07	0.794
Residuals	20		

Result of three-way ANOVA (SOC stock)

	d.f	F-value	p-value
Year	2	87	< 0.01
Depth	1	6.58	< 0.05
Landscape	4	76.7	< 0.01
Year × Depth	2	0.82	0.44
Year × Landscape	8	10.3	< 0.01
Depth × Landscape	4	0.56	0.69
Year × Depth × Landscape	8	0.18	0.99
Residuals	186		

SOC: Soil organic carbon, LIC: Litter carbon, LF: Larch forest, PF: Pine forest, DG: Dry grassland, WG: Wet grassland, PG: Pingo. Different lower-case letters within the same row indicate significant differences between 1992–2000 and 2014. Values are the mean ± standard deviation

5.3.2. Factors controlling the change in LIC and SOC

Fig. 5.4 shows the relationship between initial C (LIC and SOC) content and ΔC (LIC and SOC) content, and between initial C stock and ΔC stock, for the organic horizon, and the 0–5, 0–15, and 0–30 cm soil depths. All regressions were significantly negative, except for that between the initial LIC content and the ΔLIC content ($P = 0.23$). The regression equations for SOC content revealed a determination coefficient greater than 0.77 ($P < 0.01$) for all depths; however, regression equations for SOC stock revealed a low determination coefficient of 0.22 ($P < 0.05$), 0.27 ($P < 0.05$), and 0.48 ($P < 0.01$). Results of the ANCOVA comparing the regression equations between initial SOC content and ΔSOC content revealed no significant difference in the slope and in the y-intercept among the depths, and between the initial SOC stock and the ΔSOC stock, showing that there was no significant difference in the slope, but a different trend ($P = 0.07$) in y-intercept among the depths. The slope was -0.041 to -0.048 for SOC content, and -0.024 to -0.036 for SOC stock. The slope of the regression equation between the initial LIC stock and the ΔLIC stock was -0.054.

From the regression equations, the threshold level of initial SOC content (x-intercept) was estimated as 23.3, 21.2, and 15.6 g C kg^{-1} in the 0–5, 0–15, and 0–30 cm depths, respectively, and that of the initial SOC stock was estimated as 8.3, 35.8, and 54.4 Mg C ha^{-1}, respectively. The threshold level of the initial LIC stock was estimated to be 18.7 Mg C ha^{-1}.

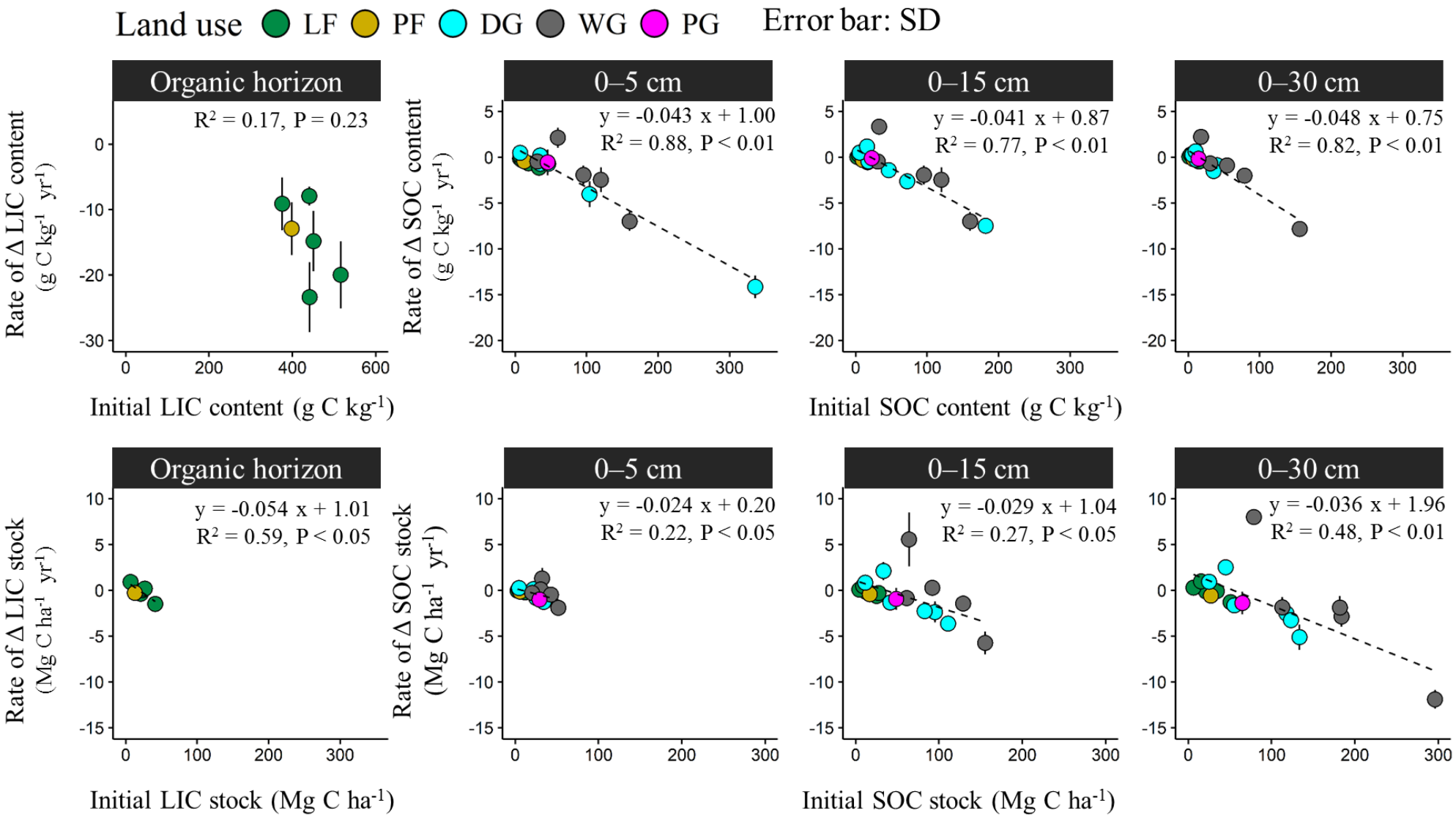

Fig. 5.4. Relationship between initial carbon and Δcarbon. SOC: Soil organic carbon, LIC: Litter carbon. LF: Larch forest, PF: Pine forest, DG: Dry grassland, WG: Wet grassland PG: Pingo

5.4. Discussion

5.4.1. Changes in SOC content and stock

A change in SOC stock reflects a change in C balance in the ecosystem, which is determined by the difference between C input (net primary production and organic matter application) and C output (organic matter decomposition, harvest, and erosion) (Jobbágy and Jackson, 2000).

The mean LIC content in the organic horizon decreased significantly from 437.0 ± 48.4 in 1992–2000 to 211.3 ± 64.2 g C kg^{-1} in 2014 (Table 6.2; Fig. 6.3). Furthermore, the mean SOC content in the 0–30 cm depth in 1992–2000 and 2014 was 29.5 ± 37.6 and 19.8 ± 16.5 g C kg^{-1}, respectively, and there was a significant difference between the years (Table 6.2). However, a significant decrease in the SOC content was observed only in the 0–5 cm depth, whereas no significant difference was observed between years in the deeper soil layers (Fig. 6.3). This indicates that LIC and SOC in the surface soil, which has a higher C content, were more sensitive to change. Gelaw et al. (2014) reported similar results and showed that the SOC in surface soil decreased, while that in the subsurface soil was more stable. In the present study, negative ΔSOC stocks in the 0–30 cm depth were observed in the DG and WG sites (-1.52 ± 2.80 and -2.10 ± 7.05 Mg C ha^{-1} 30 cm^{-1}, respectively). Desyatkin et al. (2007) reported that NBP (86 days) was 0.16 Mg C ha^{-1} in DG and -1.21 Mg C ha^{-1} in WG in 2006. Although the values were larger than those observed in the present study, a similar tendency was shown, whereby soil C loss was larger in WG than in DG. A larger C output than C input, due to harvest, resulted in a loss of soil C (negative ΔSOC stock or NBP). There was no C input via organic matter application, and the only C output was due to harvest in the DG and WG sites (Desyatkin et al., 2007). This may be the main reason for soil C loss. However, the much greater soil C loss in WG than in DG cannot be wholly explained by different management practices.

The increase in air temperature may increase the active layer depth and alter the hydrological conditions, which can lead to increased mineralization (Dutta et al., 2006; Koven et al., 2009; Schurr et al., 2015; Schuur and Bockheim, 2008). Indeed, marked increases in the active layer

depth and upper permafrost temperature (Iijima et al., 2010; Fedrov et al., 2014) triggered by an increase in air temperature (Fedrov et al., 2014; Desyatkin et al., 2015) were observed in this region. This may be one of the causes of the decrease in the SOC and negative NBP.

5.4.2 Factors controlling SOC change

The change in SOC stock differed significantly among the different land uses (Table 6.2). Mean ΔSOC stock (Mg C ha^{-1} 30 cm^{-1} yr^{-1}) was negative; and this change was greatest in WG (-2.10 ± 7.05) followed by DG (-1.52 ± 2.80), PG (-1.39 ± 1.2), PF (-0.58 ± 0.06), and LF (-0.05 ± 0.82). Similar to previous findings (e.g., Bellamy et al., 2005), there was a significant negative relationship between initial SOC (in 2001–2003) and the rate of ΔSOC (Fig. 6.4). This negative relationship revealed a threshold for no change in SOC stock, which indicated that ΔSOC is negative in the soil when the SOC exceeds the threshold, and ΔSOC stock is positive when the SOC is smaller than the threshold. This clearly explained the large negative ΔSOC in WG, which had a SOC level greater than the threshold (Table 6.2; Table 6.3). The SOC stocks in the 0–30 cm depth in DG and WG in 2014 were higher than the threshold level of 54.5 Mg C ha^{-1} 30 cm^{-1} (61.6 ± 23.8 and 141.3 ± 40.3 Mg C ha^{-1} 30 cm^{-1} in DG and WG, respectively). Therefore, the SOC stock in grasslands may decrease in the future. Conversely, the SOC stocks in the LF, PF, and PG sites in 2014 were lower than the threshold level (25.1 ± 9.7, 16.7 ± 1.0, and 45.6 ± 17.4 Mg C ha^{-1} 30 cm^{-1} in LF, PF, and PG, respectively). Therefore, SOC stock may increase in the future.

The initial threshold for SOC stock differed in soil of different depths on the regression, and was 8.3, 35.8, and 54.4 Mg C ha^{-1} in the 0–5, 0–15, and 0–30 cm depths respectively (Fig 6.4). This is due to variation in the BD and SOC content in soil with increasing depth; that is, SOC was lower but BD was higher at deeper depths.

The initial threshold of SOC content tended to decrease with increasing sampling depth (23.3, 21.2, and 15.6 g C kg^{-1} for 0–5, 0–15, and 0–30 cm depths, respectively). This was related to the

decrease in SOC content with increased soil depth at the study sites (Fig. 6.2), due to C input by litter fall and root turnover (Jabbagy and Jackson, 2000; Gelaw et al., 2014). The threshold value is varied with soil depth, in which data for the regression were corrected. Determination coefficients of the regression for SOC content were greater than 0.77 ($P < 0.01$) (Fig. 6.4). This indicates that a significant regression for SOC content can be obtained even when samples from 0 to 5 cm soil depths are used. However, in the case of SOC stock, the use of data from shallower depths (0–5 and 0–15 cm) resulted in low determination coefficients with $P < 0.05$. Therefore, using data from the 0–30 cm depth is recommended for the regression analysis.

As with the SOC, the initial LIC stock was significantly negatively correlated with ΔLIC stock. Furthermore, the initial threshold LIC stock was estimated at 18.7 Mg C ha^{-1}. The LIC stocks in LF (21.4 ± 5.5) in 2014 were higher than the threshold level. Therefore, the LIC stock in LF may decrease in the future. Conversely, the LIC stocks in PF (7.5 ± 4.8) in 2014 were higher than the threshold level. Therefore, the LIC stock in PF may increase in the future. Conversely, the initial LIC content was not significantly correlated with ΔLIC content. This might be due to the small number of sampling points ($n = 6$) and the small range of the initial LIC content in the field (ranging from 398.0 to 515.8 g C kg^{-1}).

5.5. Conclusion

The mean SOC stock in soil at 0–30 cm depth in 1992–2000 and 2014 was 87.5 ± 75.9 and 70.2 ± 53.6 Mg C ha^{-1} 30 cm^{-1}, respectively, and a non-significant decreasing trend was observed. The mean ΔSOC stock in the 0–30 cm soil of the LF, PF, DG, WG, and PG sites was -0.05 ± 0.82, -0.58 ± 0.06, -1.52 ± 2.80, -2.10 ± 7.05, and -1.39 ± 1.24 Mg C ha^{-1} 30 cm^{-1} yr^{-1}, respectively. The negative ΔSOC stock in the DG and WG sites was larger than the NBP estimated by Desyatkin et al. (2007) (0.16 and -1.21 Mg C ha^{-1} yr^{-1}, respectively), indicating that thermokarst grassland acts as a larger C source than expected. There was a significant negative correlation between the rate of ΔSOC and initial SOC content in soil at 0–30 cm depth. From the regression equation, the threshold level of initial SOC content (x-intercept) in the 0–30 cm depth was estimated as 15.6 g C kg^{-1}, which corresponds to the SOC stock of 54.4 Mg C ha^{-1} 30 cm^{-1}.

5.6. Summary

Permafrost soils in the boreal zone, which possess a significant amount of soil organic carbon (SOC), are considered hot spots of CO_2 emission. This chapter was conducted in Eastern Siberia, Central Yakutia, Russia, to estimate the SOC stock and examine changes in this region, and to investigate factors controlling changes in SOC stock. In 2014, a soil survey was conducted in 18 sites, including five different types of land use: larch forest (LF), pine forest (PF), dry grassland (DG), wet grassland (WG), and pingo (PG) (round mount). A soil survey was conducted at the same sites in 1992 and 2000. The rate of change in SOC (ΔSOC) was calculated by dividing the difference between the present and past (initial) SOC stocks by the number of years. A negative ΔSOC value indicates decline in SOC. The mean SOC stock in soil at 0–30 cm depth in 1992–2000 and 2014 was 87.5 ± 75.9 and 70.2 ± 53.6 Mg C ha^{-1} 30 cm^{-1}, respectively. Although there was no significant difference between the average SOC stock, 28% of the study sites exhibited a significant increase in SOC stock, with 61% showing a significant decrease, and 11% showing no significant change. The mean ΔSOC stock in the 0–30 m soil layer of the LF, PF, DG, WG, and PG sites was negative, at -0.05 ± 0.82, -0.58 ± 0.06, -1.52 ± 2.80, -2.10 ± 7.05, and -1.39 ± 1.24, respectively. The negative ΔSOC stock in the DG and WG sites was larger than that previously estimated using the C budget method (0.16 and -1.21 Mg C ha^{-1} yr^{-1}, respectively). There was a significant correlation between ΔSOC and initial SOC. The initial threshold level of SOC content and stock (x-intercept of the regression equation) were 15.6 g C kg^{-1} and 54.4 Mg C ha^{-1} 30 cm^{-1}, respectively.

6. Carbon stock estimation and changes associated with thermokarst activity, forest disturbance, and land use changes in Eastern Siberia

6.1. Introduction

In chapter 5, the effect of global warming on the SOC stock was evaluated at the fields where any land use changes and forest disturbances were not recorded. In this chapter, the effect of thermokarst activity, forest disturbance, and land use change was accessed.

As mentioned in chapter 2, the central Yakutia region is a well-known example of a thermokarst terrain (French, 1996). Alas soils tend to have higher carbon (C) stock than in surrounding taiga soils (Desyatkin and Desyatkin, 2006; Matsuura et al., 1994). However, the exact amount of C stock in the thermokarst ecosystem is still unknown. Global warming, expected to be most pronounced in northern high latitudes (Desyatkin et al., 2015; IPCC, 2014), has been accelerate a significant increase in thermokarst activity since the early 1990th. The melting of the tops of ice wedges is causing subsidence, the deepening and expansion of thermokarst depressions, and the growth of thaw ponds that form larger lakes (Crate et al., 2017; Fedorov et al., 2014).

Forest disturbance affects the C budgets of Siberian forests (Kukavskaya et al., 2016). Recently, severe forest disturbances have been reported on the Siberian taiga as a result of forest fires (Conard et al., 2002; Isaev et al., 2002), which occur naturally on the eastern Siberian taiga and are essential for natural forest regeneration. However, forest fires may be becoming more frequent (Kukavskaya et al., 2016). The effects of fire on C stocks are highly variable, and mainly depend on the intensity of the fire (Cui et al., 2014).

The increased precipitation resulted in a warming and wetting of the active layer and near-surface permafrost, which persisted in subsequent years (Iijima et al., 2010, 2014), and the

larch forests in the central Lena River basin were gradually damaged. Flooding may change C budgets in forest ecosystems, but the effects of water damage on C stocks have not been extensively studied in boreal forests (Ohta et al., 2014).

Central Yakutia is one of the most northern agricultural centers in the world. During the second half of the 20th century, the Soviet government began the gradual establishment of the state farm system (Takakura, 2015). In the early 1990s, after the collapse of the Soviet collective farming system, the area of farmland drastically decreased in Russia (Ioffe and Nefedova, 2004). According to Lyuri et al. (2010), about 45.5 million ha of arable land were abandoned between 1990 and 2007, which was the most widespread and abrupt land use change in the 20th century in the northern hemisphere (Lyuri et al., 2010). Land use changes significantly affect the amount of C stored in the soil (Gelaw et al., 2014). The IPCC (2013) estimate that land use changes account for 33% of anthropogenic global C emissions (180 Gt C was emitted from 1750 to 2011). Changes in soil organic carbon (SOC) stocks are probably one of the main causes of C emissions. Converting natural forests into agricultural land results in the mineralization of soil organic matter (SOM), which leads to a decrease in SOC stocks (Don et al., 2011; Harris et al., 2012). In contrast, the abandonment of arable land and the recovery of natural vegetation result in SOC accumulation (Kalinina et al., 2015; Kurganova and Lopes de Gerenyu, 2009; Kurganova et al., 2015; Mao et al., 2010).

This chapter aimed to evaluate C stocks in the main land use types of Central Yakutia to estimate changes in C stocks associated with thermokarst activity, forest disturbance, and land use changes caused by anthropogenic activity, and to predict the change in the SOC stock in future.

6.2. Materials and methods

6.2.1. Soil sampling

Soil profile surveying and sampling were conducted in 2014 and 2015 in three areas on the left bank and 10 areas on the right bank of the Lena River (Fig. 6.1; Table 6.1). In total, 72 soil survey sites were included: 15, 3, 3, 4, 5, 14, 7, 8, 3, 5, and 4 sites in LF, BF, WF, PF, WAL, AAL, NAL, DG, MG, WG, and PG, respectively. Sampling sites were selected that represented the main vegetation types and geomorphology of the landscape. The forest was cultivated during two main periods. In the Nemmere area, cultivation started in 1965 and was abandoned in 1978 or 1994. In the Unakh and Tunguly areas, cultivation started in 1985 and was abandoned in 1994 and 2009, respectively (Table 6.1).

Using a 100-mL steel cylinder, two replicates of both composite and undisturbed samples were taken from each horizon at a depth of 50 cm, and one replicate was taken at a depth of 100 cm. Soil profiling survey data obtained by Desyatkin et al. (2013) in 2013 from nine other sites (six AAL, one DG, one MG, and one WG) were also used (Table 6.1). At the LF, BF, WF, PF, and NAL sites, three replicates from the organic horizon were sampled using a 100-mL steel cylinder.

6.2.2. Sample preparation and analysis

6.2.2.1 Organic carbon and carbonate carbon content of soils and organic horizon

To determine the SOC content of mineral soil, Tyurin (wet oxidation) method was used. SCC content of mineral soil was determined by the method described in chapter 3. LIC content of the organic horizon was determined by LOI method and modified by using Eq. 3.1 (in chapter 3).

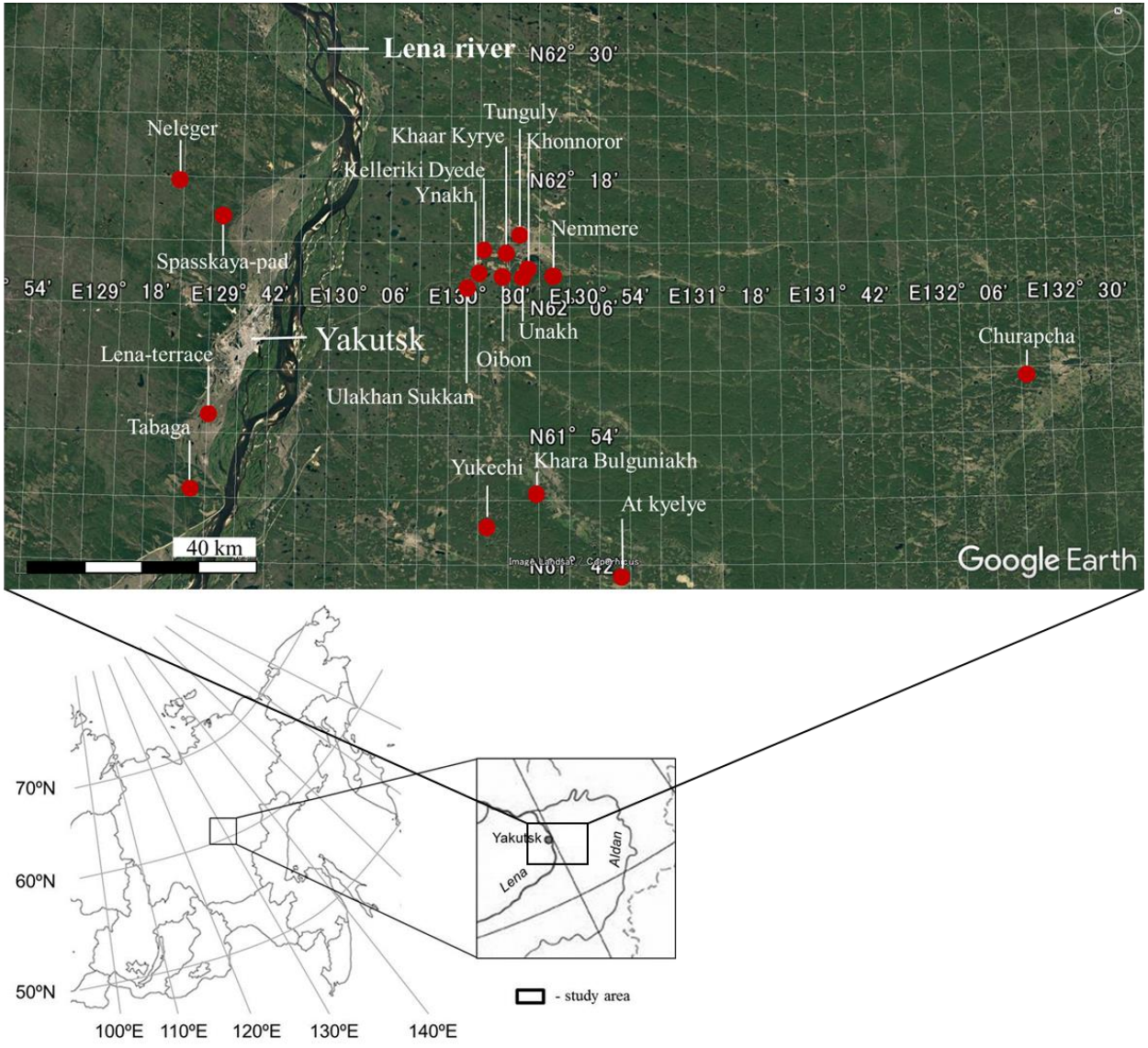

Fig. 6.1. Location of the study sites.

Table 6.1
Sampling point information.

Region	Area	Soil type	Landscape	Sampling date	Coordinate						Root sampling	Years after forest fire	Years as working arable land	Years after Abandonment
					Latitude			longitude						
					Degree	Minute	Second	Degree	Minute	Second				
Soil sampling conducted in 2014 and 2015														
Left bank†	Lena terrace	Umbric Cambisols	AAL	2014	61	55	00.4	129	33	45.27	○		Null	Null
Left bank†	Lena terrace	Umbric Cambisols	AAL	2014	61	54	56.19	129	34	00.33	○		Null	Null
Left bank†	Lena terrace	Umbric Cambisols	AAL	2014	61	54	57.13	129	34	02.14	○		Null	Null
Left bank†	Neleger	Cambic Cryosol	LF	2014	62	19	0.28	129	30	7.36				
Left bank†	Neleger	Endogleyic Stagnosol	DG	2014	62	18	59.02	129	30	12.5				
Left bank†	Neleger	Limnic Histosol	WG	2014	62	18	59.05	129	30	13.2				
Left bank†	Neleger	Limnic Histosol	WG	2014	62	18	58.9	129	30	14.37				
Left bank†	Spasskaya-pad	Cambic Cryosol	LF	2014	62	15	17.11	129	36	46.16				
Left bank†	Spasskaya-pad	Cambic Spodosol	PF	2014	62	15	5.59	129	37	16.76				
Left bank†	Spasskaya-pad	Umbric Cambisols	DG	2014	62	14	53.5	129	37	21.32				
Right bank ‡	Bestyakh terrace	Haplic Stagnosol	PF	2015	Null	Null	Null	Null	Null	Null				
Right bank ‡	Bestyakh terrace	Haplic Stagnosol	PF	2015	Null	Null	Null	Null	Null	Null				
Right bank ‡	Bestyakh terrace	Haplic Stagnosol	PF	2015	Null	Null	Null	Null	Null	Null				
Right bank ‡	Churapcha	Cambic Cryosol	LF	2015	61	57	38.46	132	08	59.54				
Right bank ‡	Churapcha	Cambic Cryosol	BF	2015	61	57	33.12	132	08	55.53		7		
Right bank ‡	Churapcha	Cambic Fluvisol	WF	2015	61	55	59.76	132	29	11.88				
Right bank ‡	Churapcha	Umbric Cambisols	AAL	2015	61	57	51.86	132	22	24			Null	Null
Right bank ‡	Churapcha	Umbric Cambisols	DG	2015	61	57	01.94	132	29	42.92				
Right bank ‡	Kelleriki Dyede	Cambic Cryosol	LF	2014	62	12	2.58	130	33	50.99	○			
Right bank ‡	Kelleriki Dyede	Endogleyic Stagnosol	DG	2014	62	11	59.49	130	33	50.11	○			
Right bank ‡	Khara Bulguniakh	Umbric Cambisols	PG	2014	61	49	58.11	130	38	34.11	○			
Right bank ‡	Khara Bulguniakh	Umbric Cambisols	PG	2014	61	50	21.12	130	40	06.88	○			
Right bank ‡	Khara Bulguniakh	Umbric Cambisols	PG	2014	61	50	16.8	130	39	38.76	○			
Right bank ‡	Khonnoror	Umbric Cambisols	PG	2014	62	9	44.28	130	37	47.91	○			
Right bank ‡	Nemmere	Cambic Cryosol	LF	2014	62	09	04.3	130	44	37.2	○			
Right bank ‡	Nemmere	Cambic Cryosol	LF	2014	Null	Null	Null	Null	Null	Null				
Right bank ‡	Nemmere	Cambic Cryosol	LF	2014	Null	Null	Null	Null	Null	Null				
Right bank ‡	Nemmere	Cambic Cryosol	LF	2014	62	09	11.99	130	45	2.47				
Right bank ‡	Nemmere	Cambic Cryosol	LF	2014	Null	Null	Null	Null	Null	Null				
Right bank ‡	Nemmere	Umbric Cambisols	WAL	2014	62	08	53.88	130	44	19.74	○		49	
Right bank ‡	Nemmere	Umbric Cambisols	AAL	2014	62	09	07	130	44	34.99	○		13	36
Right bank ‡	Nemmere	Umbric Cambisols	AAL	2014	Null	Null	Null	Null	Null	Null			13	36
Right bank ‡	Nemmere	Umbric Cambisols	AAL	2014	62	09	27.91	130	45	36.69			13	36
Right bank ‡	Nemmere	Umbric Cambisols	AAL	2014	Null	Null	Null	Null	Null	Null			13	36
Right bank ‡	Nemmere	Umbric Cambisols	AAL	2014	62	09	16.9	130	45	02.83			29	20
Right bank ‡	Nemmere	Umbric Cambisols	AAL	2014	Null	Null	Null	Null	Null	Null			29	20
Right bank ‡	Nemmere	Umbric Cambisols	NAL	2014	62	09	5.55	130	44	36.44	○		13	36
Right bank ‡	Nemmere	Umbric Cambisols	NAL	2014	Null	Null	Null	Null	Null	Null			13	36
Right bank ‡	Nemmere	Umbric Cambisols	NAL	2014	62	09	24.93	130	45	34.5			13	36
Right bank ‡	Nemmere	Umbric Cambisols	NAL	2014	Null	Null	Null	Null	Null	Null			13	36
Right bank ‡	Nemmere	Umbric Cambisols	NAL	2014	62	09	24.93	130	45	34.5	○		13	36
Right bank ‡	Nemmere	Umbric Cambisols	NAL	2014	Null	Null	Null	Null	Null	Null			13	36
Right bank ‡	Oibon	Endogleyic Stagnosol	DG	2014	62	9	30.2	130	35	28.66	○			
Right bank ‡	Oibon	Cambic Fluvisol	MG	2014	62	9	30.2	130	35	28.66	○			
Right bank ‡	Oibon	Limnic Histosol	WG	2014	62	9	30.2	130	35	28.66	○			
Right bank ‡	Tunguly	Cambic Cryosol	LF	2014	62	11	19.34	130	36	25.57				
Right bank ‡	Tunguly	Cambic Cryosol	LF	2014	Null	Null	Null	Null	Null	Null				
Right bank ‡	Tunguly	Cambic Cryosol	LF	2014	Null	Null	Null	Null	Null	Null				
Right bank ‡	Tunguly	Umbric Cambisols	WAL	2014	62	11	16	130	34	37.2	○		29	
Right bank ‡	Tunguly	Umbric Cambisols	WAL	2014	Null	Null	Null	Null	Null	Null			29	
Right bank ‡	Tunguly	Umbric Cambisols	AAL	2014	62	11	12.91	130	36	27.71	○		24	5
Right bank ‡	Tunguly	Umbric Cambisols	AAL	2014	Null	Null	Null	Null	Null	Null			24	5
Right bank ‡	Tunguly	Endogleyic Stagnosol	DG	2014	62	11	23.9	130	38	22.46	○			
Right bank ‡	Tunguly	Cambic Fluvisol	WG	2014	62	11	22.49	130	38	28.5	○			
Right bank ‡	Ulakhan Sukkan	Cambic Cryosol	LF	2014	62	9	18.86	130	31	47.67	○			
Right bank ‡	Ulakhan Sukkan	Cambic Cryosol	BF	2015	62	08	41.35	130	31	4.94		14		
Right bank ‡	Ulakhan Sukkan	Cambic Cryosol	BF	2015	62	08	38.76	130	31	52.19		14		
Right bank ‡	Ulakhan Sukkan	Endogleyic Stagnosol	DG	2014	62	09	14.11	130	31	46.51	○			
Right bank ‡	Ulakhan Sukkan	Cambic Fluvisol	MG	2014	62	09	13.3	130	31	47.89	○			
Right bank ‡	Ulakhan Sukkan	Limnic Histosol	WG	2014	62	09	12.95	130	31	48.5	○			
Right bank ‡	Unakh	Cambic Cryosol	LF	2014	62	9	12	130	38	21	○			
Right bank ‡	Unakh	Cambic Cryosol	LF	2014	Null	Null	Null	Null	Null	Null				
Right bank ‡	Unakh	Umbric Cambisols	WAL	2014	62	09	25.33	130	38	03.67	○		29	
Right bank ‡	Unakh	Umbric Cambisols	WAL	2014	Null	Null	Null	Null	Null	Null			29	
Right bank ‡	Unakh	Umbric Cambisols	AAL	2014	62	09	29.28	130	39	28.87	○		9	20
Right bank ‡	Unakh	Umbric Cambisols	AAL	2014	Null	Null	Null	Null	Null	Null			9	20
Right bank ‡	Unakh	Umbric Cambisols	NAL	2014	62	09	29.17	130	39	24.81	○		9	20
Right bank ‡	Unakh	Umbric Cambisols	NAL	2014	Null	Null	Null	Null	Null	Null			9	20
Right bank ‡	Unakh	Endogleyic Stagnosol	DG	2014	62	09	23.72	130	38	23.23	○			
Right bank ‡	Unakh	Limnic Histosol	MG	2014	62	09	23.72	130	38	23.23	○			
Right bank ‡	Yukechi	Cambic Fluvisol	WF	2015	61	45	56.48	130	27	44				
Right bank ‡	Yukechi	Cambic Fluvisol	WF	2015	61	45	43.08	130	28	08.4				

Region	Area	Soil type	Landscape	Sampling date	Coordinate						Root sampling	Years after forest fire	Years as working arable land	Years after Abandonment
					Latitude			longitude						
					Degree	Minute	Second	Degree	Minute	Second				
Cited from Desyatkin et al., 2013														
Left bank†	Lena terrace	Stagnic Chernozem	AAL	2013	61	55	0.6	129	33	45			Null	Null
Left bank†	Lena terrace	Mollic Solonetz	AAL	2013	61	54	57	129	34	02.2			Null	Null
Left bank†	Lena terrace	Hyposalic Solonetz	AAL	2013	61	54	56	129	34	00.7			Null	Null
Right bank ‡	Oibon	Endogleyic Stagnosol	DG	2013	62	09	30.2	130	35	28.66				
Right bank ‡	Oibon	Cambic Fluvisol	MG	2013	62	09	30.2	130	35	28.66				
Right bank ‡	Oibon	Limnic Histosol	WG	2013	62	09	30.2	130	35	28.66				
Right bank ‡	Tabaga	Stagnic Cambisol	AAL	2013	61	48	55.7	129	31	51.5			Null	Null
Right bank ‡	Tabaga	Luvic Phaeozem	AAL	2013	61	48	55.7	129	31	51.5			Null	Null
Right bank ‡	Tabaga	Mollic Solonetz	AAL	2013	61	48	55.7	129	31	51.5			Null	Null

† Located on the left bank of the Lena River; ‡ located on the right bank of the Lena River. The soil types at the study sites were classified by the WRB soil classification system (IUSS working Group WRB, 2015). In this study, the active-layer thickness in LF and BF was less than 2 m, and the soils were classified as Cryosol. However, the active-layer thickness in WF, PF, WAL, AAL, NAL, DG, MG, WG, and PG was deeper than 2 m. Soils of the WF and PF were classified as Fluvisol and Stagnosol (or Cambisol), respectively. Soils of the WAL, AAL, and NAL were classified as Cambisols, and soils of the DG, MG, WG, and PG were classified as Stagnosol (or Cambisol), Fluvisol, Histosol (or Fluvisol), and Cambisol, respectively. LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

6.2.2.2 Soil physico-chemical properties

Soil BD, texture, water content, pH, EC, and exchangeable cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) were measured based on the methodologies described in chapter 3.

6.2.3. Root sampling and analysis

Root sampling was conducted in 2014 at 31 sites (four, three, six, three, five, three, three, and four sites in LF, WAL, AAL, NAL, DG, MG, WG, and PG, respectively) (Table 6.1). Root samples were collected every 10 cm at a depth of 50 cm. Rectangular blocks of soil (25 × 25 × 10 cm) were washed with water through a 1-mm mesh sieve to separate the soil materials. Root samples were air-dried and crushed using a mill to pass through a 0.5-mm mesh sieve. The root samples (three replicates) were analyzed using the dry combustion method (Flash 2000 NC-Soil, Thermo Fisher Scientific) to determine their C and nitrogen (N) concentrations.

6.2.4. Data calculation

6.2.4.1. Carbon stock

The total profile SOC stock at each site and was calculated as the sum of the component soil horizon SOC stocks for a depth of 0–30 or 0–100 cm. The SOC stock (Mg C ha^{-1}) of each horizon was calculated by using Eq. 3.2 (in chapter 3). The same calculation procedure was used to obtain the SCC stock and the LIC stock. The TSC stock was calculated as a sum of the SOC, SCC, and LIC stock.

6.2.4.2. Carbon recovery rate after arable land abandonment

The annual average SOC stock recovery rate (SOC_{rec}, Mg C ha^{-1} 30 cm^{-1} yr^{-1}) after arable land abandonment was calculated using the equation suggested by Kurganova et al. (2014)

$SOC_{rec} = (SOC_{AAL\ (or\ NAL)} - SOC_{WAL}) / T$ (Eq. 6.1)

where $SOC_{AAL\ (or\ NAL)}$ and SOC_{WAL} are the SOC stocks at a depth of 0–30 cm at each AAL (or NAL) site and the mean at all WAL sites, respectively. T is the number of years after abandonment. C_{rec} was calculated based on the sites in Nemmere, Tunguly, and Unakh in which the number of years after cultivation was abandoned is known (Table 6.1). SCC_{rec} and TSC_{rec} were calculated in the same manner.

6.2.5. Statistical analysis

Statistical analysis applied in this chapter was described in chapter 3. Differences in soil physico-chemical properties and root C density among the ecosystems and depths were determined by conducting two-way ANOVA and Tukey-Kramer tests. Differences in SOC, SCC, LIC, and TSC stocks among the ecosystems and land use types were determined by conducting one-way ANOVA and Tukey-Kramer tests.

6.3. Results

6.3.1. Vertical distributions of SOC and SCC contents

Figs. 6.2 and 6.3 show the vertical distributions of SOC and SCC contents, respectively. In the forest and arable land ecosystems, the SOC content was highest in the surface soil, and gradually decreased with increasing depth. Among the forest ecosystems, a high SOC content was found in LF and WF surface soils, but not in the PF. Among the arable land ecosystems, the SOC content in the AAL tended to be higher than that in the WAL and NAL at a shallow depth. In the DG and PG, the SOC content was highest in the surface soil, and gradually decreased with increasing depth. At some MG and WG sites, a high SOC content was observed even at deep depths.

In contrast to the SOC content, the SCC content was almost constant, regardless of depth, or tended to be higher at deeper depths than at shallow depths. There were no clear differences between the ecosystems and land use types.

6.3.2. Soil physico-chemical properties

The two-way ANOVA revealed a significant difference in SOC and SCC contents among the ecosystems ($P < 0.01$ and $P < 0.05$ for the SOC and SCC contents, respectively) (Table 6.2). In 0–30 cm soil layer, the highest SOC and SCC contents were observed in the thermokarst ecosystem among the ecosystems. In the thermokarst ecosystem, there were no significant differences in SOC or SCC contents between the 0–30 and 30–100 cm soil layers. In the forest and arable land ecosystems, the SOC content was significantly higher in the 0–30 cm soil layer than in the 30–100 cm soil layer; in contrast, the SCC content was significantly higher in the 30–100 cm soil layer than in the 0–30 cm soil layer.

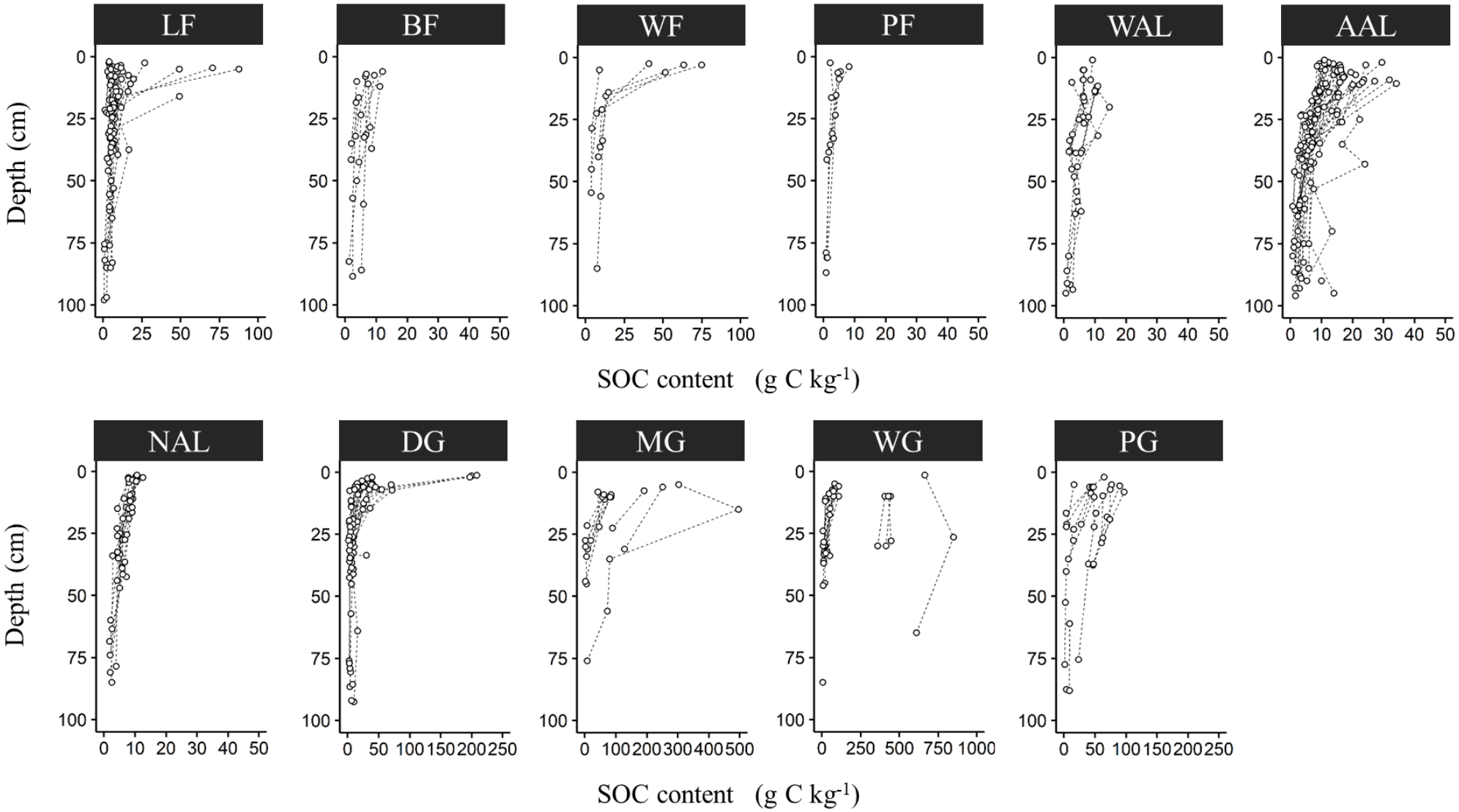

Fig. 6.2. Vertical distribution of soil organic carbon content. SOC: Soil organic carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

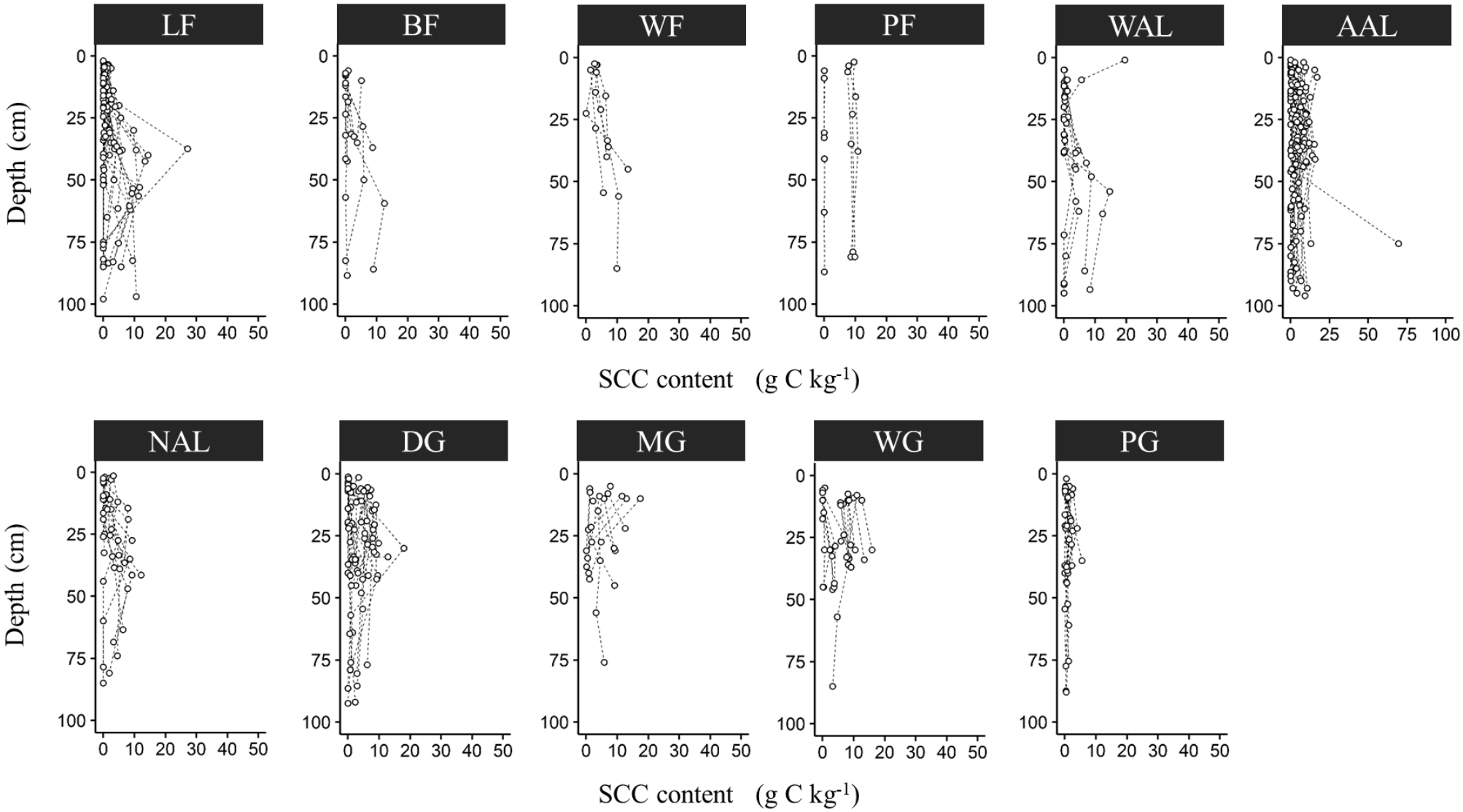

Fig. 6.3. Vertical distribution of soil carbonate carbon content. SCC: Soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table 6.2

Soil physico-chemical properties in the 0–30 and 30–100 cm soil layers.

Ecosystem	Landscape	SOC content (g C kg^{-1})				SCC content (g C kg^{-1})				BD (Mg m^{-3})				Water content (%, kg kg^{-1})				pH			
		n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm
Forest	LF	33	7.9 ± 3.8 a B	15	3.9 ± 1.4 b A	33	1.7 ± 1.8 a A	15	4.0 ± 2.8 a B	33	1.27 ± 0.16 a A	15	1.40 ± 0.10 a B	27	13.7 ± 3.9 b A	9	12.3 ± 3.9 b A	30	7.47 ± 0.75 b A	14	8.57 ± 0.69 B
Forest	BF	9	6.2 ± 3.5 a A	3	3.7 ± 1.9 ab A	9	1.3 ± 1.5 a A	3	3.8 ± 4.2 a A	9	1.31 ± 0.24 a A	3	1.40 ± 0.27 a A	9	13.4 ± 3.7 b A	3	13.2 ± 5.8 bc A	0	-	0	-
Forest	WF	5	15.1 ± 7.1 b A	3	5.6 ± 3.0 b A	5	3.5 ± 2.3 ab A	3	8.7 ± 3.5 a B	5	1.16 ± 0.19 a A	3	1.43 ± 0.17 a A	5	21.7 ± 1.3 c A	3	21.3 ± 1.9 c A	0	-	0	-
Forest	PF	6	3.7 ± 0.4 a B	4	1.3 ± 0.3 a A	6	4.5 ± 5.0 b A	4	7.0 ± 4.7 a A	6	1.38 ± 0.06 a A	4	1.43 ± 0.15 a A	6	3.9 ± 2.1 a A	4	3.0 ± 1.7 a A	3	5.50 ± 0.10 a A	1	5.7 A
Arable land	WAL	11	7.3 ± 2.1 a B	5	2.9 ± 0.9 a A	11	1.1 ± 1.6 a A	5	4.1 ± 3.2 a B	11	1.36 ± 0.09 a A	5	1.41 ± 0.07 a A	9	10.0 ± 2.2 ab A	3	9.7 ± 1.9 a A	11	8.22 ± 0.63 a A	5	8.74 ± 0.35 a A
Arable land	AAL	38	12.4 ± 4.4 b B	20	4.2 ± 2.1 a A	38	3.9 ± 3.3 b A	20	6.2 ± 8.4 a A	38	1.34 ± 0.10 a A	20	1.41 ± 0.10 a B	27	11.9 ± 3.6 b A	9	9.0 ± 5.3 a A	35	8.41 ± 0.85 a A	19	9.06 ± 0.58 a B
Arable land	NAL	13	7.5 ± 1.05 a B	7	3.0 ± 0.6 a A	13	2.2 ± 2.0 ab A	7	3.4 ± 1.8 a A	13	1.33 ± 0.06 a A	7	1.36 ± 0.09 a A	9	8.1 ± 2.4 a A	3	7.2 ± 1.8 a A	13	8.43 ± 0.38 a A	7	9.06 ± 0.14 a B
Thermokarst	DG	25	14.9 ± 6.8 a B	8	5.4 ± 3.5 a A	25	4.1 ± 3.2 ab A	8	3.0 ± 1.9 a A	25	1.30 ± 0.19 b A	8	1.45 ± 0.17 b B	24	12.5 ± 5.4 a A	7	14.5 ± 4.4 a A	22	8.90 ± 0.49 bc A	7	9.17 ± 0.19 a A
Thermokarst	MG	10	80.0 ± 58.3 ab A	3	14.9 ± 22.8 a A	10	5.3 ± 3.9 b A	3	2.4 ± 2.7 a A	10	1.12 ± 0.24 ab A	3	0.74 ± 0.48 a A	9	25.3 ± 8.7 b A	3	16.0 ± 1.0 a A	10	9.49 ± 0.22 c A	3	9.37 ± 0.25 a A
Thermokarst	WG	16	152.8 ± 207.5 b A	5	112.5 ± 202.4 a A	16	5.9 ± 4.0 b A	5	4.1 ± 3.2 a A	16	0.92 ± 0.43 a A	5	0.58 ± 0.54 a A	15	38.5 ± 19.1 c A	4	22.1 ± 12.0 a A	16	8.44 ± 0.96 ab A	5	8.72 ± 0.82 a A
Thermokarst	PG	12	42.7 ± 24.2 a B	4	12.0 ± 6.9 a A	12	1.3 ± 1.0 a A	4	0.6 ± 0.4 a A	12	1.05 ± 0.22 ab A	4	1.24 ± 0.23 ab A	12	11.2 ± 5.6 a A	4	10.1 ± 9.1 a A	12	7.98 ± 0.58 a A	4	8.53 ± 0.39 a A
Forest		53	7.8 ± 4.6 a B	25	3.7 ± 1.9 a A	53	2.1 ± 2.5 a A	25	5.0 ± 3.6 a B	53	1.28 ± 0.17 b A	25	1.41 ± 0.13 b B	47	13.2 ± 5.6 a A	19	11.9 ± 6.6 ab A	33	7.29 ± 0.92 a A	15	8.38 ± 1.00 a A
Arable land		62	10.5 ± 4.3 a B	32	3.7 ± 1.8 a A	62	3.1 ± 3.0 ab A	32	5.2 ± 6.9 a B	62	1.34 ± 0.09 b A	32	1.40 ± 0.09 b B	45	10.8 ± 3.5 a A	15	8.8 ± 4.2 a A	59	8.38 ± 0.73 b A	31	9.01 ± 0.49 b A
Thermokarst		63	65.6 ± 119 b A	20	34.7 ± 104 a A	63	4.2 ± 3.6 b A	20	2.7 ± 2.4 a A	63	1.13 ± 0.32 a A	20	1.09 ± 0.50 a A	60	20.6 ± 15.6 b A	17	15.4 ± 8.3 b A	60	8.69 ± 0.79 b A	19	8.95 ± 0.54 b A
ANOVA		d.f.	F-value		P-value	d.f.	F-value		P-value	d.f.	F-value		P-value	d.f.	F-value		P-value	d.f.	F-value		P-value
Depth		1	2.41		0.12	1	0.75		0.39	1	6.19		< 0.05	1	4.28		< 0.05	1	26.7		< 0.01
Ecosystem		2	17.7		< 0.01	2	3.57		< 0.05	2	22.8		< 0.01	2	16.4		< 0.01	2	37.2		< 0.01
Depth × Ecosystem		2	0.62		0.54	2	1.09		0.34	2	0.52		0.59	2	0.62		0.54	2	3.6		< 0.05

Ecosystem	Landscape	EC (m S m^{-1})				Exchangeable Na^+ (cmol$_c$ kg^{-1})				Exchangeable K^+ (cmol$_c$ kg^{-1})				Exchangeable Ca^{2+} (cmol$_c$ kg^{-1})				Exchangeable Mg^{2+} (cmol$_c$ kg^{-1})			
		n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm	n	0–30 cm	n	30–100 cm
Forest	LF	24	10.4 ± 5.2 b B	14	5.9 ± 6.0 a A	5	0.14 ± 0.17 a A	5	0.22 ± 0.18 a A	5	0.22 ± 0.08 a A	5	0.2 ± 0.07 a A	5	4.10 ± 1.80 a A	5	2.9 ± 0.64 a A	5	5.52 ± 1.32 a A	5	4.44 ± 1.35 a A
Forest	BF	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
Forest	WF	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
Forest	PF	3	0.8 ± 0.1 a A	1	0.5 a A	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
Arable land	WAL	9	9.5 ± 8.6 a A	5	5.6 ± 5.3 a A	3	0.20 ± 0.20 a A	3	0.40 ± 0.53 a A	3	0.13 ± 0.12 a A	3	0.10 ± 0.10 a A	3	3.63 ± 3.26 a A	3	1.63 ± 1.42 a A	3	3.87 ± 3.52 a A	3	2.60 ± 2.25 a A
Arable land	AAL	30	15.7 ± 11.6 a A	19	15.5 ± 13.5 a A	14	2.12 ± 3.49 a A	14	1.63 ± 1.77 a A	14	0.63 ± 1.46 a A	14	0.29 ± 0.61 a A	14	14.0 ± 13.3 a A	14	12.3 ± 25.4 a A	14	6.84 ± 1.97 a A	14	7.09 ± 4.78 a A
Arable land	NAL	9	9.6 ± 3.8 a A	7	4.9 ± 6.3 a A	3	0.07 ± 0.06 a A	3	0.03 ± 0.06 a A	3	0.23 ± 0.06 a B	3	0.10 ± 0.00 a A	3	5.30 ± 0.69 a B	3	1.97 ± 1.10 a A	3	6.77 ± 0.55 a B	3	3.07 ± 0.95 a A
Thermokarst	DG	22	18.8 ± 8.5 a A	7	20.8 ± 12.1 a A	3	0.13 ± 0.12 a A	2	0.40 ± 0.57 a A	3	0.27 ± 0.21 a A	2	0.25 ± 0.21 a A	3	5.90 ± 6.93 a A	2	8.20 ± 9.62 a A	3	7.27 ± 5.95 a A	2	5.60 ± 3.39 a A
Thermokarst	MG	10	67.8 ± 50.4 b A	3	19.4 ± 4.6 ab	3	4.13 ± 3.46 a A	2	0.80 ± 0.14 a A	3	0.13 ± 0.06 a A	2	0.30 ± 0.42 a A	3	7.27 ± 10.51 a A	2	9.80 ± 11.9 a A	3	23.5 ± 22.0 a A	2	8.10 ± 8.77 a A
Thermokarst	WG	16	62.2 ± 31.8 b A	5	31.4 ± 16.6 ab A	3	2.47 ± 0.38 a A	2	3.05 ± 1.34 a A	3	0.17 ± 0.12 a A	2	0.15 ± 0.07 a A	3	9.03 ± 11.59 a A	2	21.5 ± 29.3 a A	3	44.1 ± 39.6 a A	2	36.7 ± 41.9 a A
Thermokarst	PG	12	59.3 ± 70.7 b A	4	82.1 ± 63.7 b A	4	0.75 ± 0.64 a A	4	0.77 ± 0.73 a A	4	0.65 ± 0.33 a A	4	0.68 ± 0.43 a A	4	4.62 ± 3.61 a A	4	2.55 ± 1.36 a A	4	11.0 ± 9.3 a A	4	8.92 ± 8.70 a A
Forest		27	9.3 ± 5.6 a A	15	5.6 ± 6.0 a A	5	0.14 ± 0.17 a A	5	0.22 ± 0.18 a A	5	0.22 ± 0.08 a A	5	0.20 ± 0.07 a A	5	4.10 ± 1.82 a A	5	2.9 ± 0.64 a A	5	5.52 ± 1.32 ab A	5	4.44 ± 1.35 a A
Arable land		48	13.4 ± 10.4 a A	31	11.5 ± 12.1 a A	20	1.52 ± 3.04 a A	20	1.21 ± 1.62 a A	20	0.50 ± 1.23 a A	20	0.23 ± 0.52 a A	20	11.1 ± 11.9 a A	20	9.18 ± 21.6 a A	20	6.38 ± 2.27 a A	20	5.81 ± 4.5 a A
Thermokarst		60	46.6 ± 45.4 b A	19	36.3 ± 37.4 b A	13	1.78 ± 2.16 a A	10	1.16 ± 1.20 a A	13	0.33 ± 0.30 a A	10	0.41 ± 0.38 a A	13	6.55 ± 7.42 a A	10	8.92 ± 13.2 a A	13	20.7 ± 24.2 b A	10	13.6 ± 19.5 a A
ANOVA		d.f.	F-value		P-value	d.f.	F-value		P-value	d.f.	F-value		P-value	d.f.	F-value		P-value	d.f.	F-value		P-value
Depth		1	5.34		< 0.05	1	0.6		0.44	1	0.532		0.47	1	0.016		0.9	1	1.22		0.27
Ecosystem		2	30.6		< 0.01	2	1.51		0.23	2	0.182		0.83	2	0.918		0.4	2	6.47		< 0.01
Depth × Ecosystem		2	0.38		0.68	2	0.102		0.9	2	0.426		0.66	2	0.166		0.85	2	0.484		0.62

Different uppercase letters indicate significant differences between depths, and different lowercase letters indicate significant differences between land use types in the same ecosystem. SOC: Soil organic carbon, SCC: Soil carbonate carbon, BD: Bulk density, EC: Electrical conductivity. LF: Larch forest, BF: burned forest, WF: Water damaged forest, PF; Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: wet grassland, PG: Pingo

There were significant differences in BD, water content, pH, and EC among the ecosystems ($P < 0.01$), and between the 0–30 and 30–100 cm soil layers ($P < 0.05$ for BD, water content, and EC; $P < 0.01$ for pH) (Table 6.2). There was a significant interaction between soil depth and ecosystem for water content and pH ($P < 0.05$). The thermokarst ecosystems had the lowest BD, and in the forest and arable land ecosystems, BD was significantly lower in the 0–30 cm soil layer than in the 30–100 cm soil layer. The thermokarst ecosystems had the highest water content, with WG having the highest followed by MG. Among the forest ecosystems, WF had the highest water content. Soil pH was significantly lower in the forest ecosystems than in the other ecosystems, and LF had the highest soil pH. The EC was significantly higher in the thermokarst ecosystems than in the other ecosystems, and among the thermokarst ecosystems, DG had a significantly lower EC value than the others.

Only levels of exchangeable Mg^{2+} significantly differed among the ecosystems (Table 6.2), but exchangeable cation levels tended to be higher in the thermokarst ecosystems than in the forest or arable land ecosystems.

6.3.3. SOC, SCC, LIC, and TSC stocks

SOC and SCC stocks in the 0–30 and 0–100 cm soil layers are shown in Fig. 6.4. The SOC stock was significantly higher in the thermokarst ecosystems than in the forest or arable land ecosystems. The SOC stock in the 0–30 cm soil layer ranged from 15.3 ± 1.7 in PF to 248.7 ± 168.6 Mg C ha^{-1} 30 cm^{-1} in MG. Among the forest ecosystems, WF had a significantly higher SOC stock in the 0–30 cm soil layer than the others. Among the arable land ecosystems, AAL had a significantly higher SOC stock than the others. Among the thermokarst ecosystems, DG had a significantly lower SOC stock in the 0–30 cm soil layer than MG and WG. The SOC stock ranged from 27.0 ± 1.5 in PF to 520.8 ± 709.1 Mg C ha^{-1} 100 cm^{-1} in WG.

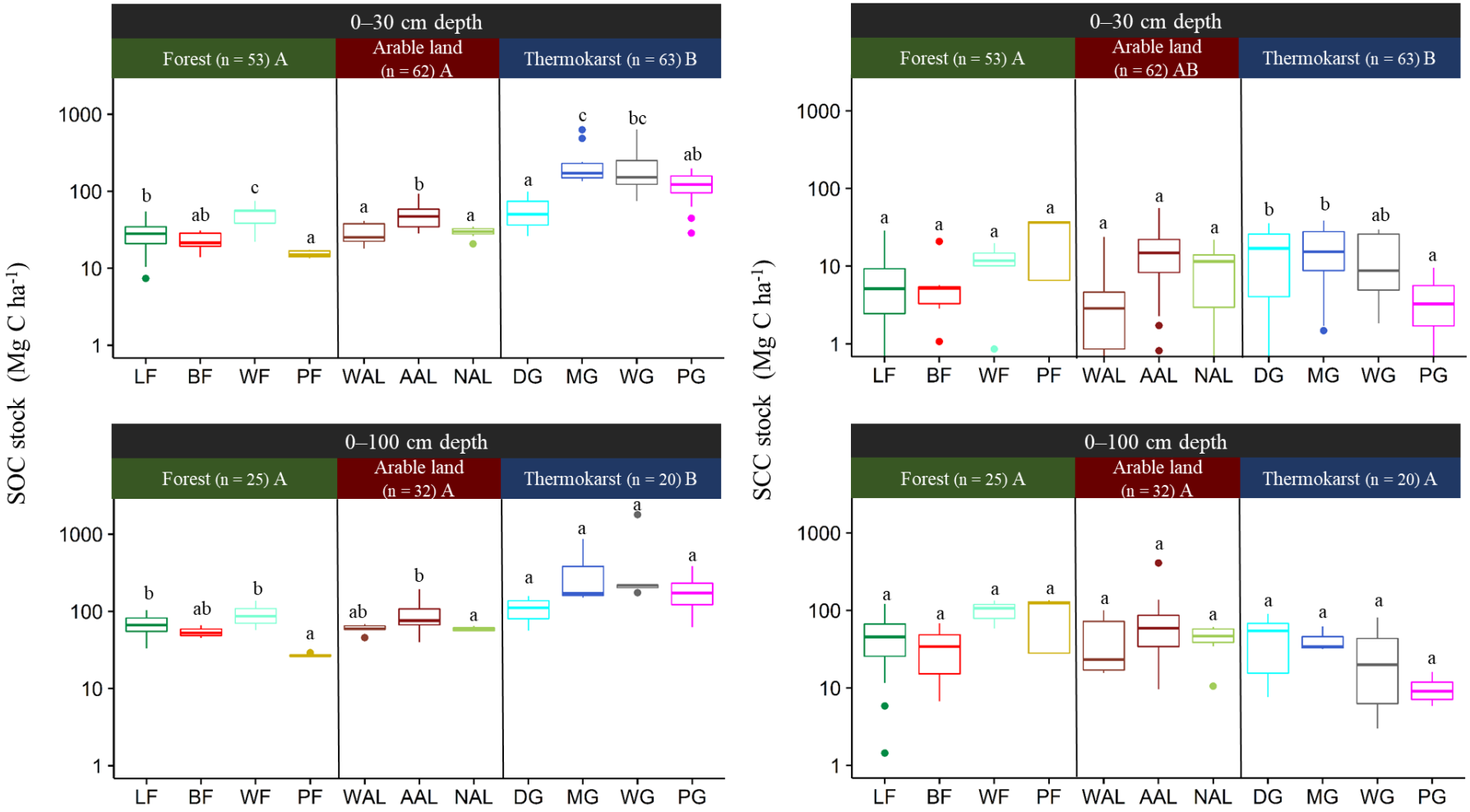

Fig. 6.4. Soil organic carbon and soil carbonate carbon stocks in the 0–30 and 0–100 cm soil layers. Box plots visualize the five-number summary of a data set (minimum, lower quartile, median, upper quartile and maximum) and points indicate outlier value. Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. SOC: Soil organic carbon, SCC: Soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

The SCC stock in the 0–30 cm soil layer ranged from 4.1 ± 3.1 in PG to 18.5 ± 20.2 Mg C ha^{-1} in PF, and in the 0–100 cm soil layer it ranged from 10.1 ± 4.5 in PG to 99.5 ± 38.3 Mg C ha^{-1} 100 cm^{-1} in WF.

Fig. 6.5 shows the LIC stocks in the forest ecosystems and NAL. LIC values in the LF, BF, WF, PF, and NAL were 18.5 ± 7.7, 8.5 ± 7.2, 8.7 ± 7.0, 6.5 ± 3.4, and 1.6 ± 0.6 Mg C ha^{-1}, respectively, and were significantly higher in LF than in the other sites.

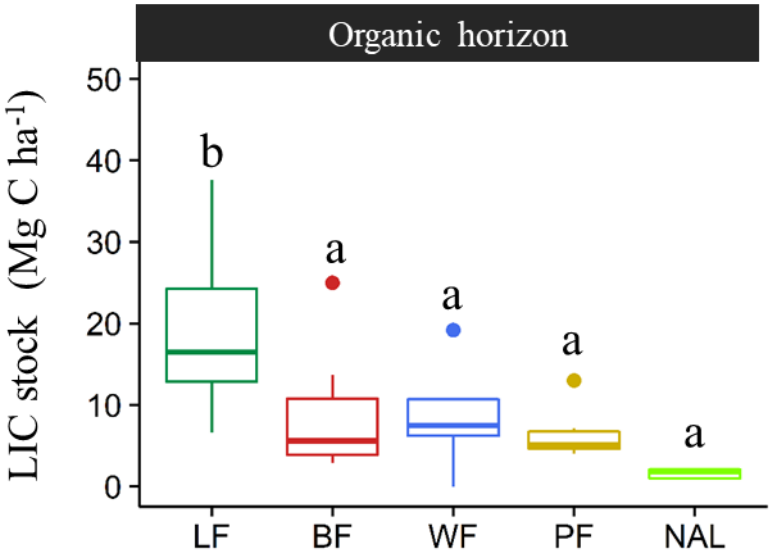

Fig. 6.5. Litter carbon stock in the organic horizon. Box plots visualize the five-number summary of a data set (minimum, lower quartile, median, upper quartile and maximum) and points indicate outlier value. Different lowercase letters indicate significant differences between land use types. LIC: Litter carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, NAL: Abandoned arable land invaded by new-growing trees.

The TSC stock was significantly higher in the thermokarst ecosystems than in the other ecosystems (Fig. 6.6). The TSC in the 0–30 cm soil layer ranged from 34.0 ± 13.1 in WAL to 266.9 ± 162.6 Mg C ha^{-1} 30 cm^{-1} in MG, and in the 0–100 cm soil layer it ranged from 96.9 ± 37.6 in BF to 551.5 ± 703.2 Mg C ha^{-1} 100 cm^{-1} in WG.

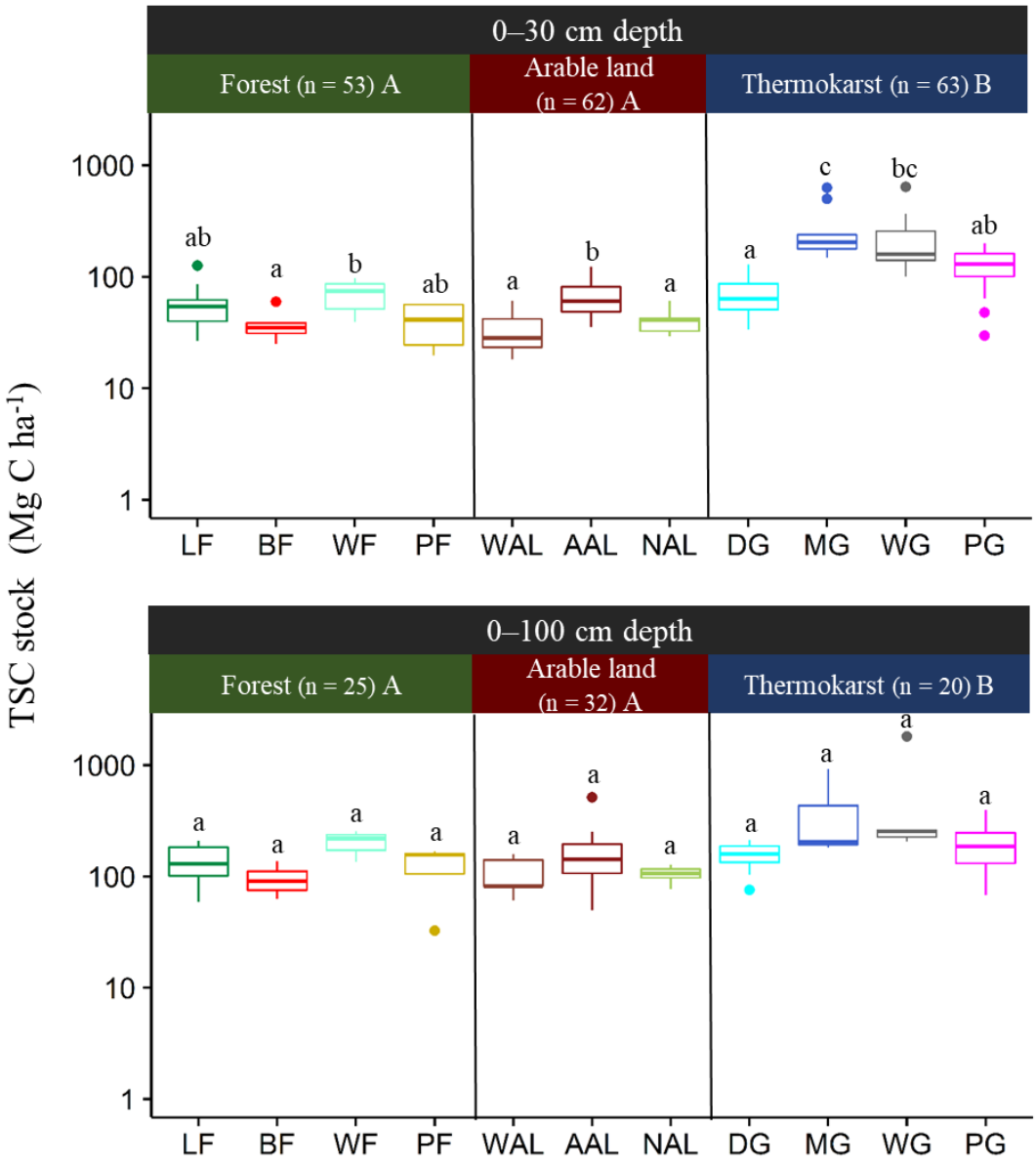

Fig. 6.6. Total soil carbon stock in the 0–30 and 0–100 cm soil layers. Box plots visualize the five-number summary of a data set (minimum, lower quartile, median, upper quartile and maximum) and points indicate outlier value. Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. TSC: Total soil carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

The composition ratios of the C stock in the 0–30 and 0–100 cm soil layers are shown in Fig. 6.7. The SOC stock was the main component of the TSC stock in both the 0–30 and 0–100 cm layers, but in PF, the SCC stock accounted for over 60% of the TSC stock in the 0–100 cm layer. The composition ratio of SCC stock was higher in the 0–100 cm layer than in the 0–30 cm layer. The percentage of SCC and LIC in the TSC in the 0–100 cm layer ranged from 6.2 ± 2.9% in PG to 60.0 ± 39.3% in PF, and from 3.3 ± 3.4% in NAL to 18.3 ± 7.5% in LF.

Fig. 6.8 shows the SOC stocks in the 0–30 and 0–100 cm soil layers. Several studies have estimated the SOC stock in permafrost (Cryosol) and permafrost-affected soils in the boreal and arctic regions. Although SOC values in grasslands of the thermokarst ecosystem were within the ranges found in previous studies, the forest and arable land ecosystem values were at the lower-end of those found in previous studies.

6.3.4. Vertical distributions of root C density and root C stock

Figs. 6.9 and 6.10 show the vertical distributions of root C density and root C stock, respectively. The root C density vertical distribution corresponded well with that of the SOC content (Fig. 6.2). Root C density was highest in the 0–10 cm layer in all plots, and gradually decreased with increasing depth. The root C stock in the 0–30 cm soil layer ranged from 0.14 ± 0.09 in DG to 1.04 ± 0.61 Mg C ha^{-1} 30 cm^{-1} in WG, and was significantly higher in the forest ecosystems than in the arable land ecosystems. Among the thermokarst ecosystems, WG had a significantly higher root C stock than DG.

6.3.5. Factors affecting SOC

Table 6.3 shows Pearson's correlation coefficients for SOC (or SCC) content and soil physico-chemical properties. In the forest ecosystems, the SOC content was significantly,

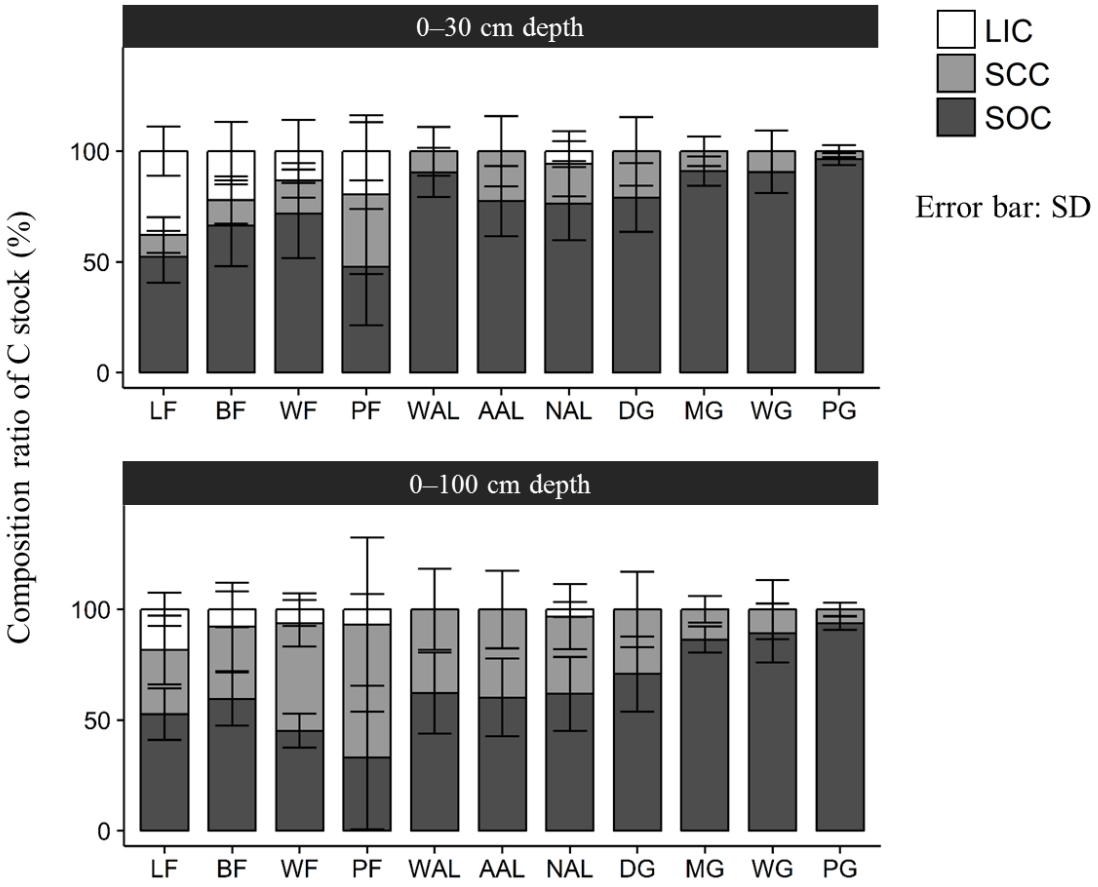

Fig. 6.7. Composition ratio of carbon stocks in the 0–30 and 0–100 cm soil layers. LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo

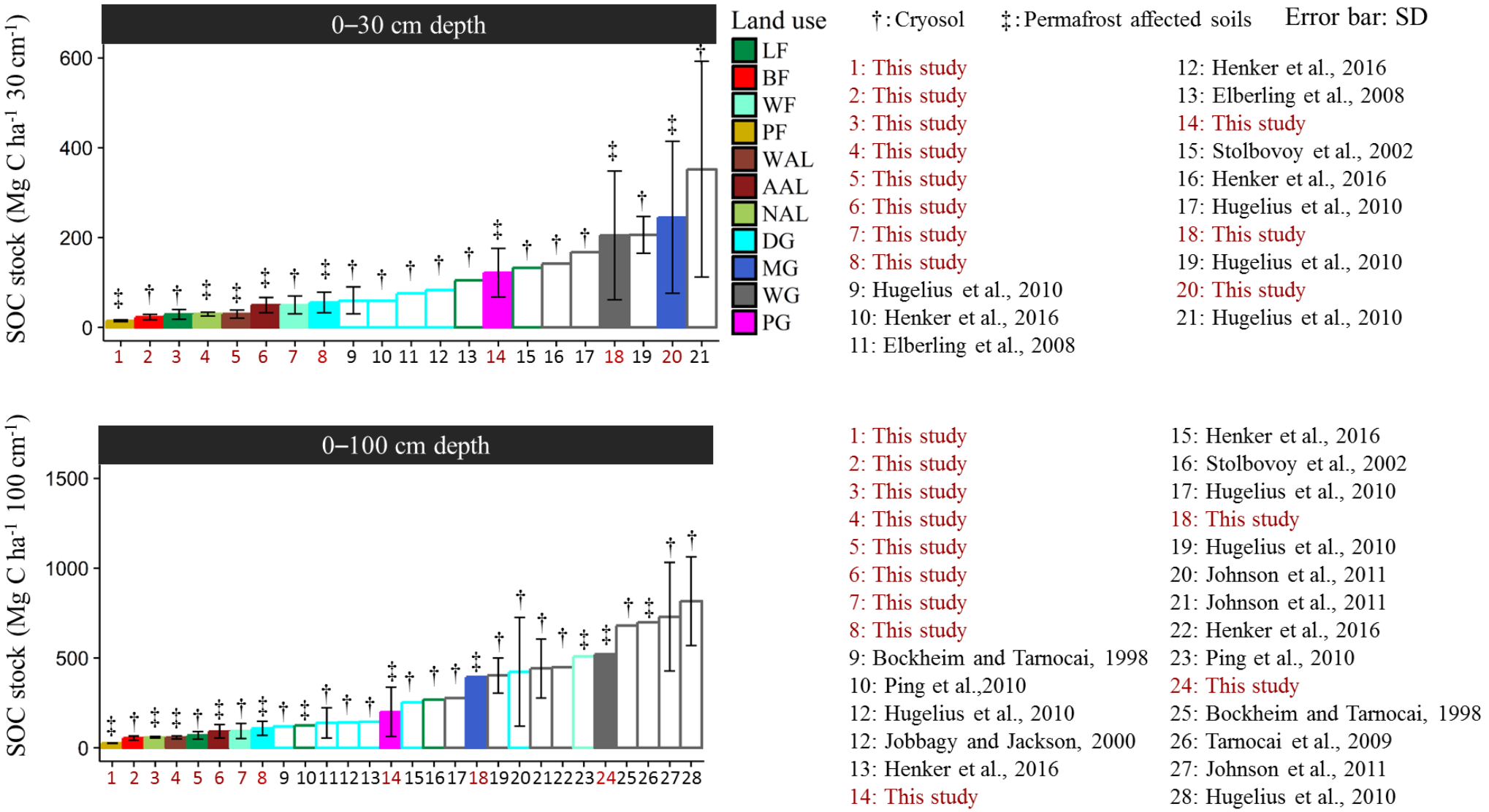

Fig. 6.8. Comparison of soil organic carbon (SOC) stocks in the 0–30 and 0–100 cm soil layers in permafrost and permafrost-affected soils.

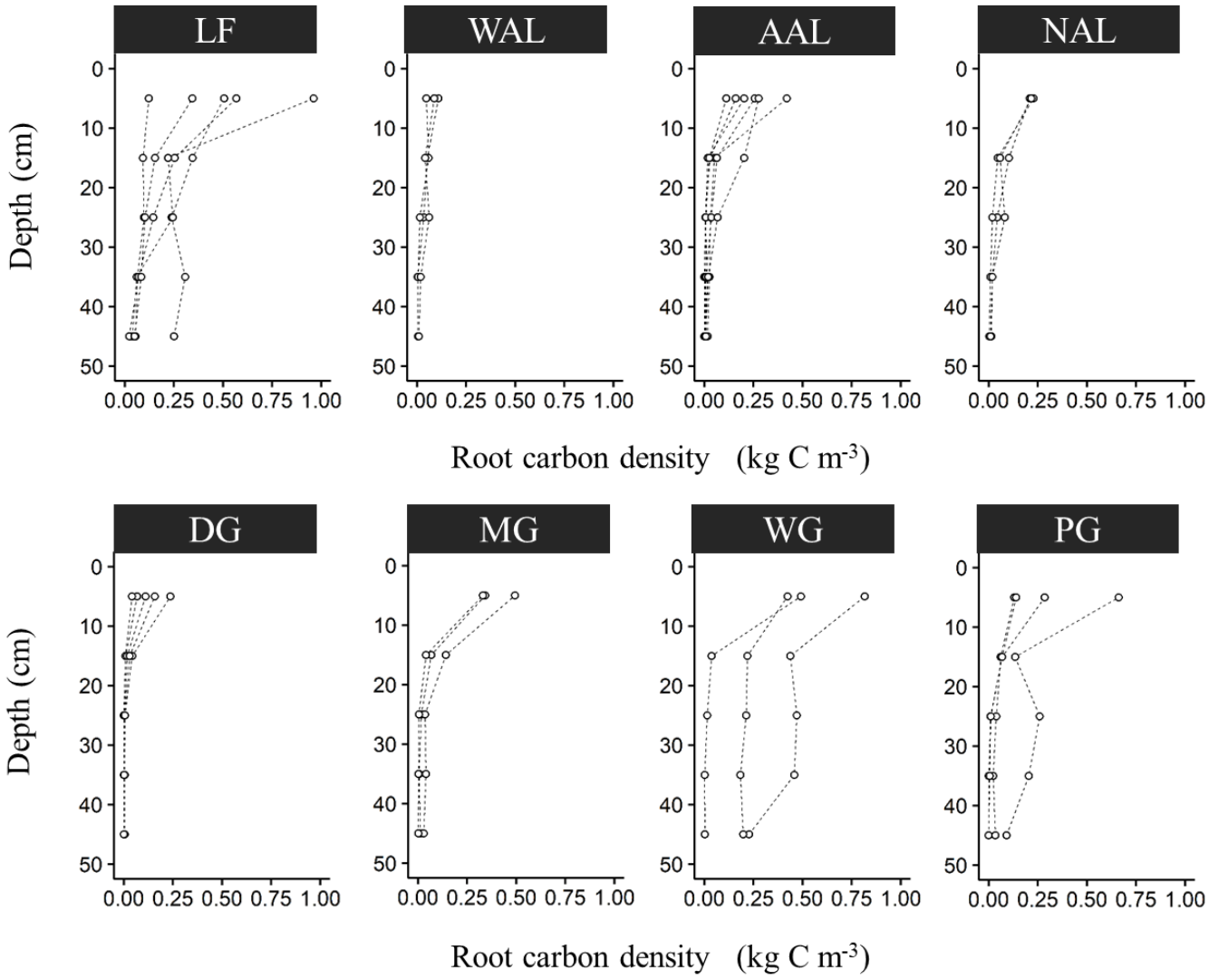

Fig. 6.9. Vertical distribution of root carbon density. LF: Larch forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

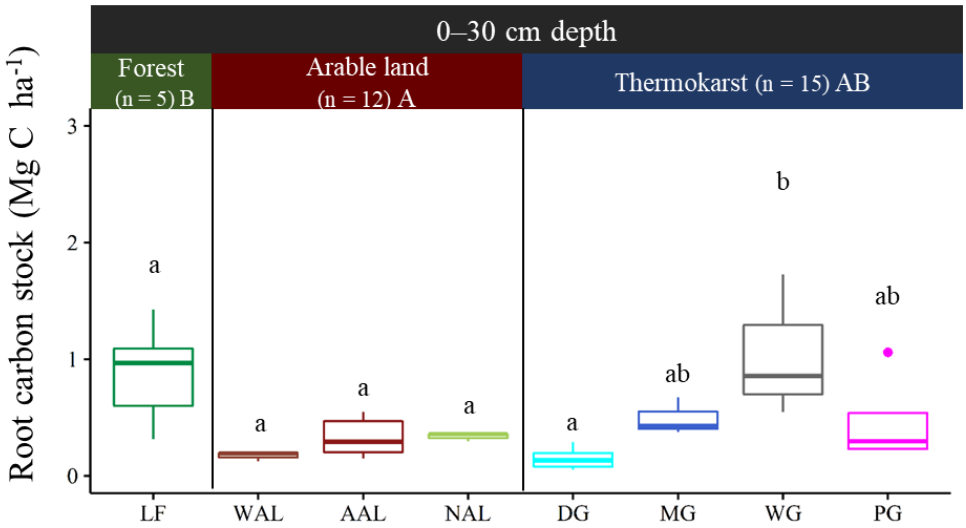

Fig. 6.10. Root carbon stock in the 0–50 cm soil layer. Box plots visualize the five-number summary of a data set (minimum, lower quartile, median, upper quartile and maximum) and points indicate outlier value. Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. LF: Larch forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

positively correlated with silt content, water content, EC, and exchangeable Ca^{2+} and Mg^{2+} ($P < 0.01$, $P < 0.01$, $P < 0.05$, $P < 0.01$, and $P < 0.01$, respectively), and negatively correlated with sand content, BD, and pH ($P < 0.01$). SCC content was significantly, positively correlated with pH and EC ($P < 0.01$). In the arable land ecosystems, SOC content was significantly, positively correlated with silt content and exchangeable K^+ ($P < 0.01$), and negatively correlated with sand content, BD, and pH ($P < 0.01$). SCC content was significantly, positively correlated with silt content ($P < 0.05$). In the thermokarst ecosystems, SOC content was significantly, positively correlated with SCC content, water content, EC, and exchangeable Na^+, Ca^{2+}, and Mg^{2+} ($P < 0.01$, $P < 0.01$, $P < 0.05$, $P < 0.01$, $P < 0.01$, and $P < 0.01$, respectively), and negatively correlated with BD and exchangeable K^+ ($P < 0.01$ and $P < 0.05$, respectively). The SCC content was significantly, positively correlated with SOC content, Sand content, water content, pH and exchangeable Mg^{2+} ($P < 0.01$, $P < 0.01$, P

< 0.01, P < 0.01 and P < 0.05, respectively), and negatively correlated with silt content and exchangeable K^+ (P < 0.01, respectively). For all ecosystems, SOC content was significantly, positively correlated with sand content, water content, EC, and exchangeable Na^+, Ca^{2+}, and Mg^{2+} (P < 0.05, P < 0.01, P < 0.01, P < 0.01, P < 0.05, and P < 0.01, respectively), and negatively correlated with BD and pH (P < 0.01). SCC content was significantly, positively correlated with pH (P < 0.01), and negatively correlated with exchangeable K^+ (P < 0.05).

Fig. 6.11 shows the relationship between root C density, soil BD, and SOC content. The root C density was negatively correlated with soil BD (P = 0.07 for the arable land, P < 0.05 for the forest, and P < 0.01 for the thermokarst), and positively correlated with the SOC content (P < 0.05 for the forest and P < 0.01 for the arable land and thermokarst).

6.3.6. C recovery rate after abandonment of arable land

Fig. 6.12 shows the annual average C recovery rate in AAL and NAL after the abandonment of arable land. The SOC recovery rate in AAL was 1.49 ± 1.26 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at five years after abandonment, which decreased to 0.85 ± 0.79 and 0.19 ± 0.28 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 20 and 36 years after abandonment, respectively. The SOC recovery rate in NAL was relatively slower than in AAL, which was 0.11 ± 0.57 and 0.11 ± 0.27 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 20 and 36 years after abandonment, respectively. The SCC recovery rate was slower than the SOC recovery rate, which was 0.80 ± 0.63, 0.16 ± 0.26, and 0.45 ± 0.43 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 5, 20, and 36 years after abandonment, respectively, in AAL, and 0.32 ± 0.18 and 0.07 ± 0.28 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 20 and 36 years after abandonment, respectively, in NAL. Consequently, the TSC recovery rate was higher in AAL than in NAL, and was 2.30 ± 1.31, 1.01 ± 0.76, and 0.64 ± 0.43 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 5, 20, and 36 years after abandonment, respectively, in AAL, and 0.42 ± 0.58 and 0.17 ± 0.36 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 20 and 36 years after abandonment, respectively, in NAL.

Table 6.3

Pearson's correlation coefficients for soil organic carbon and soil carbonate carbon contents and soil physico-chemical properties.

	Forest						Arable land						Thermokarst						All land uses					
	SOC content (g C kg^{-1})			SCC content (g C kg-1)			SOC content (g C kg^{-1})			SCC content (g C kg^{-1})			SOC content (g C kg^{-1})			SCC content (g C kg^{-1})			SOC content (g C kg^{-1})			SCC content (g C kg^{-1})		
	n	r	P-value	n	r	P-value	n	r	P-value	n	r	P-value	n	r	P-value	n	r	P-value	n	r	P-value	n	r	P-value
SOC content (g C kg^{-1})	218	1		163	-0.05	0.52	242	1		242	-0.02	0.80	177	1		177	0.20	P < 0.01	637	1		600	0.03	0.47
SCC content (g C kg^{-1})	163	-0.05	0.52	163	1		242	-0.02	0.80	244	1		177	0.20	P < 0.01	193	1		600	0.03	0.47	600	1	
Sand content (%)	83	-0.33	P < 0.01	83	0.00	0.98	110	-0.39	P < 0.01	110	-0.17	0.07	52	0.25	0.09	52	0.40	P < 0.01	245	0.15	P < 0.05	245	-0.04	0.53
Silt content (%)	83	0.41	P < 0.01	83	-0.01	0.93	110	0.43	P < 0.01	110	0.19	P < 0.05	52	-0.24	0.10	52	-0.37	P < 0.01	245	-0.12	0.06	245	0.05	0.48
Clay content (%)	83	0.19	0.09	83	0.01	0.91	110	0.15	0.12	110	0.07	0.47	52	-0.15	0.30	52	-0.08	0.59	245	-0.12	0.07	245	0.01	0.84
Water content (%, kg kg^{-1})	202	0.57	P < 0.01	163	0.11	0.19	169	0.15	0.06	169	0.04	0.64	177	0.80	P < 0.01	189	0.34	P < 0.01	560	0.65	P < 0.01	560	0.07	0.14
BD (Mg m^{-3})	218	-0.82	P < 0.01	163	-0.04	0.64	242	-0.84	P < 0.01	244	-0.03	0.67	177	-0.69	P < 0.01	193	-0.09	0.20	637	-0.77	P < 0.01	600	-0.01	0.76
pH	143	-0.61	P < 0.01	143	0.49	P < 0.01	240	-0.52	P < 0.01	240	0.08	0.25	177	-0.09	0.27	189	0.46	P < 0.01	572	-0.34	P < 0.01	572	0.16	P < 0.01
EC (m S m^{-1})	112	0.25	P < 0.05	112	0.44	P < 0.01	187	-0.03	0.72	187	0.08	0.31	177	0.15	P < 0.05	189	0.01	0.87	488	0.16	P < 0.01	488	0.02	0.60
Exchangeable Na^{+} ($cmol_c$ kg^{-1})	20	-0.08	0.73	20	0.42	0.07	90	0.01	0.92	90	-0.01	0.92	46	0.57	P < 0.01	46	0.20	0.20	156	0.34	P < 0.01	156	0.02	0.83
Exchangeable K^{+} ($cmol_c$ kg^{-1})	20	0.26	0.28	20	-0.15	0.53	90	0.37	P < 0.01	90	-0.13	0.23	46	-0.31	P < 0.05	46	-0.39	P < 0.01	156	-0.08	0.31	156	-0.18	P < 0.05
Exchangeable Ca^{2+} ($cmol_c$ kg^{-1})	20	0.47	P < 0.01	20	-0.14	0.55	90	0.12	0.27	90	0.03	0.80	46	0.66	P < 0.01	46	0.22	0.14	156	0.19	P < 0.05	156	0.04	0.59
Exchangeable Mg^{2+} ($cmol_c$ kg^{-1})	20	0.47	P < 0.01	20	0.01	0.97	90	0.07	0.51	90	0.08	0.47	46	0.89	P < 0.01	46	0.34	P < 0.05	156	0.88	P < 0.01	156	0.06	0.47

SOC: Soil organic carbon, SCC: Soil carbonate carbon, BD: Bulk density, EC; Electrical conductivity.

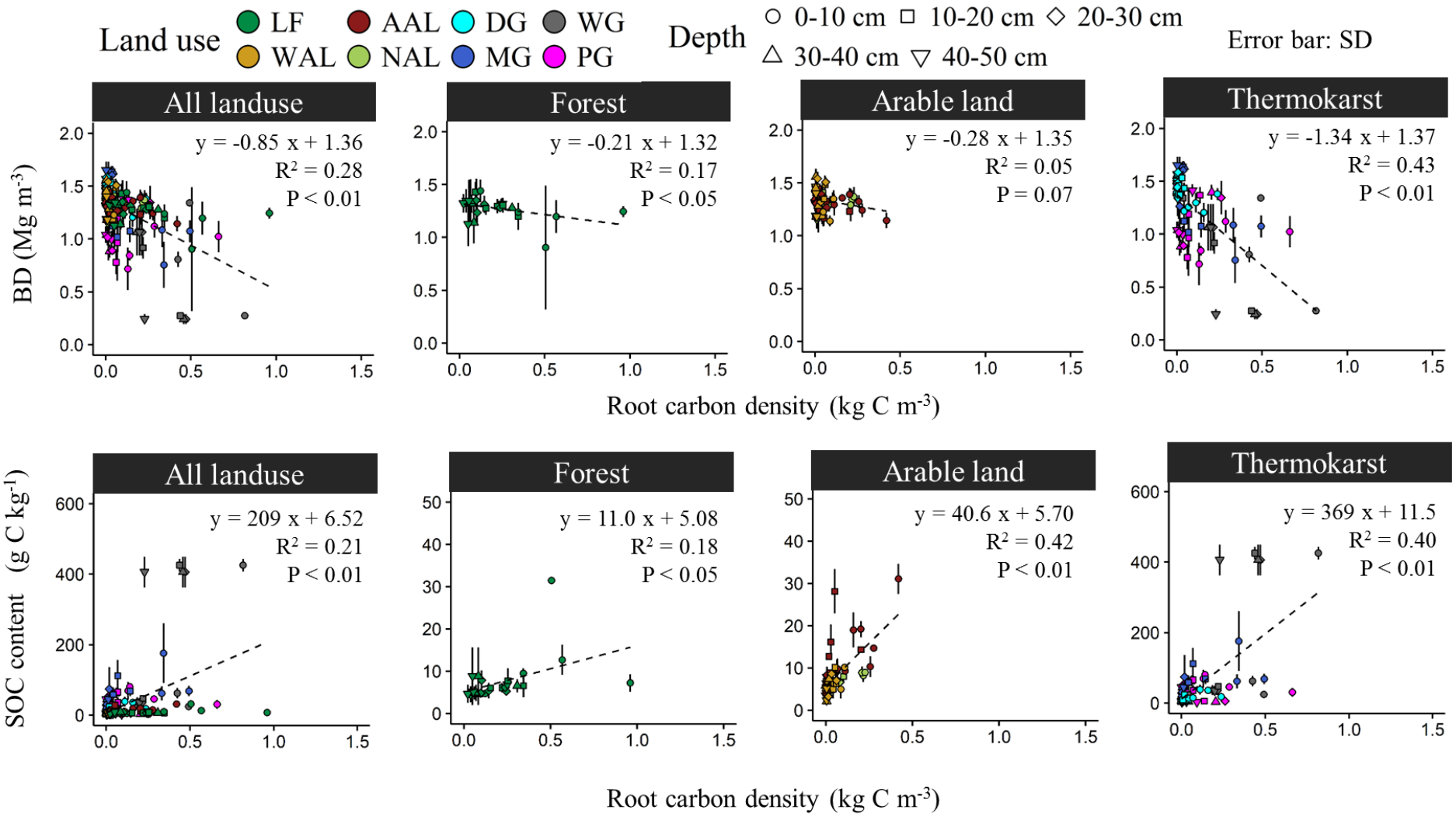

Fig. 6.11. Relationships between root carbon density and bulk density and between root carbon density and the soil organic carbon content. SOC: Soil organic carbon, BD: Bulk density. LF: Larch forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: wet grassland, PG: Pingo.

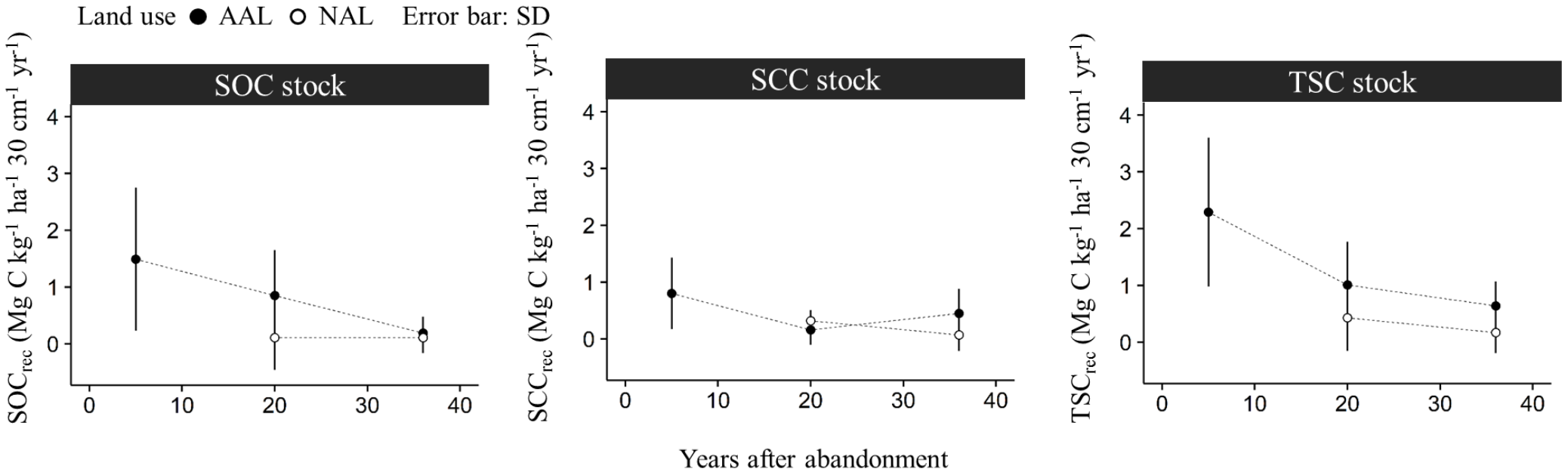

Fig. 6.12. Annual average carbon recovery rate on abandoned arable land and new-growth arable land after abandonment. SOC_{rec}: annual average rate of soil organic carbon stock recovery after the abandonment of working arable land. SCC_{rec}: annual average rate of soil carbonate carbon stock recovery after the abandonment of working arable land. TSC_{rec}: annual average rate of soil total carbon stock recovery after the abandonment of working arable land. SOC_{rec}, SCC_{rec}, and TSC_{rec} were calculated based on Kurganova et al. (2014). AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees.

6.4. Discussion

6.4.1. Factors affecting SOC

The vertical distributions of the SOC content and root C density exhibited similar trends, i.e., both decreased with increasing depth (Figs. 6.2 and 6.9), which agrees with the results of previous studies (Fujisaki et al., 2017; Lai et al., 2017; Selim et al., 2016; Wang et al., 2016). A significant, positive correlation between root C density and SOC content was also found, regardless of the ecosystem (Fig. 6.11). Several studies have reported that root biomass plays an important role in soil C accumulation through fine root mortality in forest and arable land ecosystems (Asaye and Zewdie, 2013; Mazzilli et al., 2015). Mazzilli et al. (2015) analyzed changes in $\delta^{13}C$ natural abundance in OM, and found that belowground biomass contributed from 60 to almost 80% of the total new C present in the OM. Moreover, Limin et al. (2015) estimated the C budget of managed grassland using a combination of eddy covariance and the biometric method, and concluded that root litter might remain in the soil and is a significant contributor to the grassland soil C stock. Our results clearly support those of these previous studies.

A significant effect of soil texture on SOC accumulation in the forest and arable land ecosystems was found (Table 6.3). The SOC content is usually high in fine-textured soils and low in coarse-textured soils (Barre et al., 2017; Gonçalves et al., 2017), because of the association between clay particles and soil C that forms clay-humic complexes that play a fundamental role in C protection against microbial oxidation (Bronick and Lal, 2005; Six et al., 2002). However, the SOC content was not as strongly correlated with the clay content ($P = 0.09$ and $P = 0.12$ for the forest and arable land ecosystems, respectively) as it was with the silt content in both the forest and arable land ecosystems ($P < 0.01$). This suggests that SOC accumulates in fine pores inside aggregates formed by the orientation of silt particles, rather

than by chemically bonding with clay minerals (Barré et al., 2014; Blanco-Moure et al., 2016; Li and Shao, 2014).

The SOC content in the thermokarst ecosystems was not affected by soil texture but by water content (Table 6.3), and a strong, positive correlation between water content and SOC content was also observed in the forest ecosystems and all land use types (Table 6.3). SOC accumulation reflects the C balance in a field [the difference between C input (net primary production) and C output (OM decomposition)] (Jobbágy and Jackson, 2000). Soil moisture affects OM decomposition by affecting oxygen diffusion into the soil and substrate availability for soil microorganisms (Tang et al., 2017; Xu et al., 2016). Consequently, a high SOC content is observed in wet rather than dry conditions in the boreal region (Henkner et al., 2016).

6.4.2. C stocks in the thermokarst ecosystems

Significantly higher SOC and TSC stocks were observed in the thermokarst ecosystems than in the forest or arable land ecosystems (Figs. 6.4 and 6.6), which agrees with previous studies conducted in this region (Desyatkin and Desyatkin, 2006; Matsuura et al., 1994; Morishita et al., 2003). This result indicates C accumulation during alas formation (Desyatkin and Desyatkin, 2006), when surface soils in the alas depression are buried by the LD horizon (Desyatkin and Desyatkin, 2006). After a long period, grassland vegetation on the bottom of the depression increases C stocks (Matsuura et al., 1994). In the thermokarst ecosystems, SOC, the main component of TSC (Fig. 6.7), was affected by soil water content and root C density (Table 6.3; Fig. 6.11). The SOC stock order corresponded well with the water content order (Table 6.2; Fig. 6.4), and the significantly higher root C stock explained the higher SOC stock in the WG (Figs. 6.4 and 10). Moreover, soil temperature has a large effect on SOM decomposition: SOM decomposition increase exponentially with increase in soil temperature (Limin et al., 2015;

Shimizu et al., 2009). Takakai et al., 2008 showed soil temperature tended to be higher in DG and PG than WG. These results may indicate that high water content in MG and WG kept soil temperature low and suppressed SOM decomposition.

Field studies have reported that thermokarst activity is significantly increasing and the permafrost underneath is thawing, a process caused by both the warming described above and shifting hydrological processes (Crate et al., 2017; Ulrich et al., 2017). For example, from 1980 to 2012, the area covered by thermokarst lakes at the Yukechi site in this region has increased four-fold (Crate et al., 2017). These results suggest that thermokarst formation accumulates OM, and further flooding increases the C stock. However, Desyatkin et al. (2014) reported, based on four years' field observations, that under future global climate change, thermokarst depressions in Central Yakutia have the potential for lake expansion, causing a significant increase in methane emission in the region. Therefore, to consider the effect of recent thermokarst activity on regional C budgets, each component should be carefully considered.

6.4.3. Effect of forest disturbance on C stocks

Wildfires are one of the main disturbances that affect the C budgets of Siberian forests (Kukavskaya et al., 2016), and forest degradation caused by a recent wet climate (Iijima et al., 2010, 2014) can also change C budgets (Ohta et al., 2014). In this study, the LIC stock was significantly decreased by forest disturbance, from 18.5 ± 7.7 Mg C ha^{-1} in the LF to 8.5 ± 7.2 and 8.7 ± 7.0 Mg C ha^{-1} in the BF and WF, respectively, at average rates of 54 ± 61 and 53 ± 60%, respectively (Fig. 6.5).

The effects of forest fires on the LIC stock are highly variable, and mainly depend on the fire's intensity (Cui et al., 2014). Hatano et al. (2006) reported that 51% of LIC (8.6 Mg C ha^{-1}) has been lost due to forest fires in Central Yakutia. The value that obtained in this study was similar,

and comparable to moderate-intensity surface fire values as proposed by Conard et al. (2002).

The effect of water damage on boreal forest C stocks has been little-studied (Ohta et al., 2014). In this study, water damage decreased LIC stocks almost as much as a moderate-intensity forest fire. According to Ohta et al. (2014), the number of living larch trees decreased by 15% from 1998 to 2011, and gross primary production was significantly reduced by waterlogging. These results indicate that a significant decline in LIC may decrease C input.

Forest fires did not change the SOC stock, but waterlogging significantly increased it (28.8 ± 11.2, 23 ± 5.9, and 49.8 ± 20.1 Mg C ha^{-1} 30 cm^{-1} in LF, BF, and WF, respectively) (Fig. 6.4). The effects of forest fire on the SOC are also mediated by the fire's intensity (Cui et al., 2014). Fernández et al. (1999) reported SOC losses greater than 50% in the upper 0–10 cm layer of a Cambisol caused by a high-intensity forest fire. In contrast, low- or moderate-intensity fires can increase SOC in surface soils by 10 to 30% (Certini et al., 2011; Cui et al., 2014). Cui et al. (2014) reported that there was no significant difference in SOC stocks after low- and moderate-intensity fires in the Daxingan Mountains, China. No significant change in the SOC stock in this study suggests that the loss of SOC by direct combustion in a fire and the C input from dry leaves and partially burnt plant materials is balanced after a moderate-intensity fire (Cui et al., 2014).

The SOC stocks in the forest ecosystems were strongly affected by the soil water content, as discussed in the previous section, because waterlogging significantly increased the soil water content, which significantly increased the SOC stock (Table 6.3).

Consequently, no significant change in the TSC stock was caused by any type of forest disturbance (54.4 ± 20.7, 36.4 ± 10.0, and 69.9 ± 24.1 Mg C ha^{-1} 30 cm^{-1} in LF, BF, and WF, respectively); however, forest disturbances altered the composition ratio of the C stock (Fig. 6.7).

6.4.4. Effects of forest cultivation and abandonment of arable land on C stocks

Conversion of the LF to the WAL did not change the SOC or SCC stocks in either the 0–30 or 0–100 cm soil layers (Figs. 6.4); however, 18.5 ± 7.7 Mg C ha^{-1} of the LIC stock that was originally stored in the organic horizon of the LF was diminished (Fig. 6.5), which as a consequence, significantly decreased the TSC stock in the 0–30 cm soil layer from 54.4 ± 20.7 to 34.0 ± 13.1 Mg C ha^{-1} 30 cm^{-1} (Fig. 6.6) at an average rate of 37 ± 47%. Converting forest to arable land results in OM mineralization, and a 50% decrease in the total C stock (Don et al., 2011; Harris et al., 2012) is common (Guo and Gifford, 2002). In the midwestern United States, the majority of soils that have been converted from natural to agricultural systems have lost 30–50% of their original C stock (Lal, 2002). The TSC reduction rate observed in the present study was similar to that found in previous studies, but there was no significant difference in SOC stock between LF and WAL. Many studies have shown that the conversion of natural forest to cropland often leads to a decrease in SOC stocks, because of a decrease in litter input and an increase in the soil C mineralization rate (Ajami et al., 2016; Assefa et al., 2017; Fujisaki et al., 2017). Assefa et al. (2017) reported that deforestation and agriculture have resulted in a significant 48.2% decrease in the SOC stock in the 0–30 cm soil layer in northwest Ethiopia under a tropical climate. Fujisaki et al. (2017) evaluated the effects of deforestation on SOC stocks in the 0–30 cm soil layer in Amazonia under a humid tropical climate, and showed that five years after deforestation, the SOC stock had decreased by -17.8% compared to that in the original forest. Previous studies have found that the reduction rate is highly variable. Victoria et al. (2012) showed that the SOC stock reduction rate associated with forest conversion depends upon the climate, and is more intense and rapid in tropical ecosystems (with losses of up to 60% in a few years) than in humid temperate ecosystems (with losses of less than 30% in 60 years of cultivation). This may be attributed to the difference in the C turnover rate associated with land

use changes, which is mainly affected by temperature and moisture (Chen et al., 2013). In this study, the extremely low annual air temperature (-9.7 ºC) and precipitation (235 mm) under an extracontinental climate might have prevented SOC mineralization caused by deforestation.

In contrast to deforestation, arable land abandonment leads to SOC accumulation (Kalinina et al., 2015; Kurganova and Lopes de Gerenyu, 2009; Kurganova et al., 2015), which was estimated as 64 to 861 Tg C for Russia in the period 1990–2009 (Kurganova et al., 2014; Schierhorn et al., 2013). Kalinina et al. (2015) investigated post-agrogenic plant succession and C stocks in Podzols, Albeluvisols, Chernozems, and Calcisols-Solonetzes in Russia, and found that during self-restoration, the vegetation and soil develop towards their natural condition. The abandonment of arable land significantly increased the SOC stock in the 0–30 cm layer and the TSC stock from 34.0 ± 13.1 Mg C ha^{-1} 30 cm^{-1} in WAL to 65.4 ± 22.1 Mg C ha^{-1} 30 cm^{-1} in AAL (Figs. 6.4 and 6.6). As a consequence, the TSC stock in AAL had almost recovered to the same level as in LF (Fig. 6.6). In AAL, during self-restoration, the vegetation developed towards a steppe. The continuous presence of vegetation provided the SOM protection, and contributed to C accumulation (Soussana et al., 2004).

In the arable land ecosystems, there was a strong correlation between root C density and SOC content (Fig. 6.11, $P < 0.01$, $R^2 = 0.42$). As discussed in the previous section, root C density significantly contributed to SOC accumulation. The root C density in the AAL tended to be higher than that in WAL (Fig. 6.11), and could be one of the causes for the larger SOC stock in AAL than WAL. However, in NAL, there was no significant C accumulation compared with that in WAL (Figs. 6.4 and 6.6). In the case of boreal arable land restoration, the dynamics of vegetation recovery and C stocks are closely related (Ryzhova et al., 2014), and a study conducted on the southern taiga found that meadow succession after arable land restoration inputs more C than young forest succession (Ryzhova et al., 2014).

The time period after abandonment was closely related to the C accumulation rate. The highest rate of SOC stock recovery (SOC_{rec}) was observed in the earliest stage of the abandonment (1.49 ± 1.26 Mg C ha^{-1} 30 cm^{-1} yr^{-1} for the first five years), before decreasing in the latter period (0.85 ± 0.79 and 0.19 ± 0.28 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at 20 and 36 years after abandonment, respectively) (Fig. 6.12). This result supports those of studies conducted in post-agrogenic ecosystems in Russia and Kazakhstan by Kurganova et al. (2014) and Kurganova et al. (2015), and in forest steppe to sub-taiga ecosystems in western Siberia by Belelli Marchesini et al. (2007). Kurganova et al. (2014) reported that the average SOC accumulation rate in the 0–20 cm soil layer was 0.96 ± 0.08 Mg C ha^{-1} 20 cm^{-1} yr^{-1} for the first 20 years after abandonment and 0.19 ± 0.10 Mg C ha^{-1} 20 cm^{-1} yr^{-1} during the next 30 years. Belelli Marchesini et al. (2007) reported that the average SOC accumulation rate in the 0–5 cm soil layer of abandoned cropland was 0.66 Mg C ha^{-1} 5 cm^{-1} yr^{-1}, and there was a tendency towards SOC saturation on abandoned land, as sequestration rates were much higher on recently abandoned land (1–10 years old, 1.04 Mg C ha^{-1} 5 cm^{-1} yr^{-1}) than on earlier-abandoned crop fields (11–20 years old, 0.26 Mg C ha^{-1} 5 cm^{-1} yr^{-1}). Our calculated SOC recovery rates were comparable to values reported by previous studies on Russian soils, but at an early stage of abandonment, the highest rate of SOC accumulation was observed in this study. Our estimation was based on the upper 30 cm of the soil profile, whereas Belelli Marchesini et al. (2007) and Kurganova et al. (2014) based their estimations on the upper 5 and 20 cm, respectively. This suggests that the effects of arable land abandonment and the self-restoration of natural vegetation on SOC accumulation occur not only in the topsoil but also in soils as deep as 30 cm, as reported by several studies that investigated the effect of land use changes on C stocks (Liu et al., 2017; Poeplau and Don, 2013; Sheng et al., 2015).

Net ecosystem production (NEP) is estimated as the C budget (gross primary production -

ecosystem respiration), which almost equals the change in the SOC stock in natural ecosystems (Bernacchi et al., 2005; Randerson et al., 2002). Positive NEP values indicate that the ecosystem is a C sink, while negative ones indicate that the ecosystem is a source of C (Kurganova et al., 2015). Kurganova et al. (2015) estimated the NEP during the first 20 years after cropland abandonment in Asian Russia, and summarized NEP values that had been reported in Russia and Kazakhstan (Belelli Marchesini et al., 2007; Kurganova et al., 2007; Perez-Quezada et al., 2010). The NEP values ranged from 1.47 to 2.96 Mg C ha^{-1} yr^{-1}, and the average value was 2.23 ± 0.42 Mg C ha^{-1} yr^{-1}. These values are comparable to the SOC accumulation rate, but slightly higher (Kurganova et al., 2015).

6.4.5. Future prediction of SOC stock in Central Yakutsk

In this chapter it is revealed that LIC, SOC, and SCC stock of the three different ecosystems were significantly different (Fig. 6.4; Fig. 6.5; Fig. 6.6). And SOC stock is the main component of TSC stock in both 0–30 and 0–100 cm depth except with the PF (Fig. 6.7). This result indicated that changes in SOC stock might have the largest effect on the global C budget (Ciais et al., 2013; Lal, 2004a). In chapter 5, the effect of global warming on the SOC stock change was evaluated and factor controlling SOC stock change was discussed. And there was a significant correlation between ΔSOC and initial SOC (Fig. 5.4): ΔSOC stock (Mg C ha^{-1} 30 cm^{-1} yr^{-1}) = -0.036 × Initial SOC stock (Mg C ha^{-1} 30 cm^{-1}) + 1.96 (Eq. 6.2). From the regression equation, the threshold level of initial SOC stock was estimated at 54.4 Mg C ha^{-1} 30 cm^{-1}. The relationship observed regardless of the land use. Therefore, future prediction of SOC stock in Central Yakutsk can be estimated by using the threshold level combined with estimated SOC stock in this chapter (Fig. 6.13). The SOC stocks in the 0–30 cm depth in land uses belong to the forest, and arable land ecosystem in 2013, 2014 and 2015 was lower than the threshold level of

54.4 Mg C ha^{-1} 30 cm^{-1}. Therefore, the SOC stock may increase in the future. Conversely, the SOC stocks in the land uses belong to the thermokarst ecosystem in 2013, 2014 and 2015 were higher than the threshold level. Therefore, SOC stock may decrease in the future.

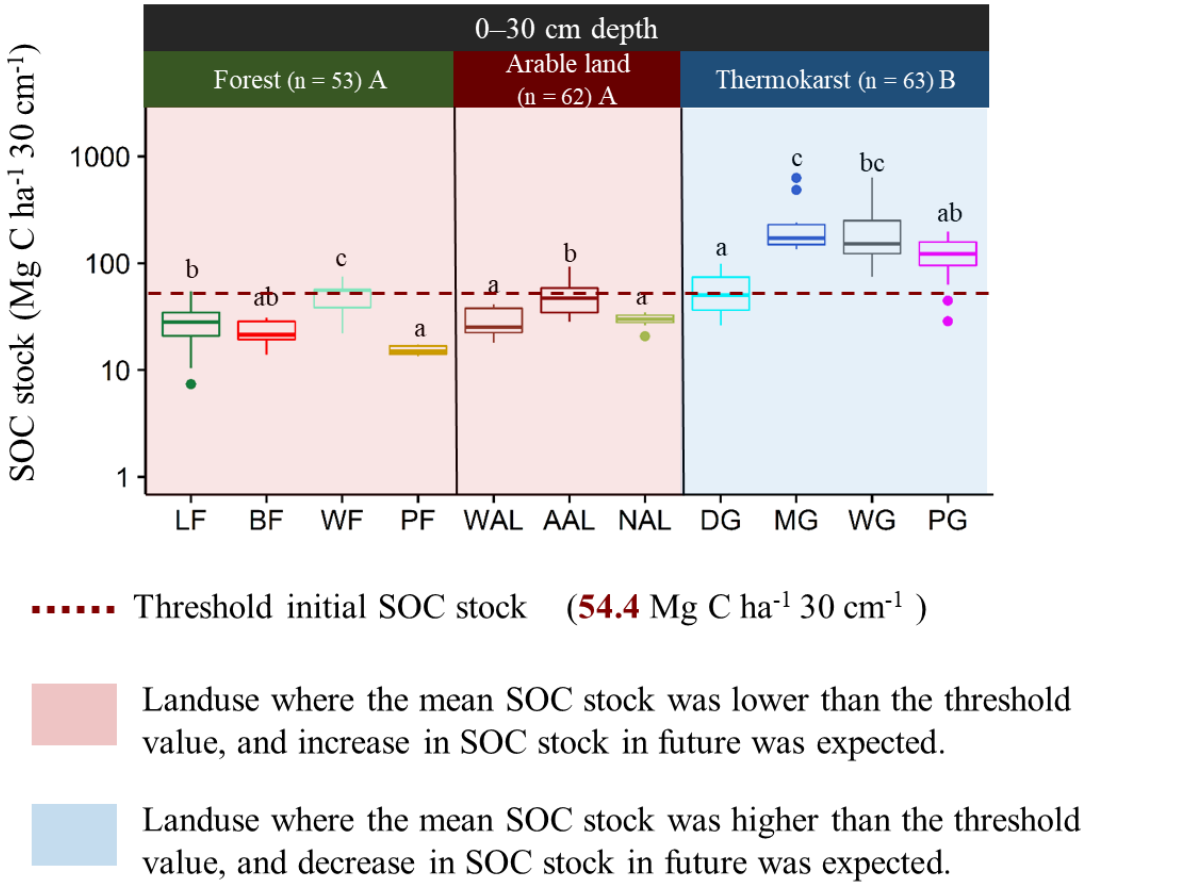

Fig. 6.13. Future prediction of soil organic carbon (SOC) stock in Central Yakutia. Box plots visualize the five-number summary of a data set (minimum, lower quartile, median, upper quartile and maximum) and points indicate outlier value. Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between landscape types in the same ecosystem. SOC: Soil organic carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Moreover, the significant correlation between ΔSOC and initial SOC also indicating that magnitude of the change in SOC in future is dependent on the initial SOC level (Bellamy et al., 2005), and a vigorous decline in the SOC stock will be predicted in the sites where SOC stock in 2013, 2014, and 2015 is high. By using the regression Eq. 6.2, the predicted rate of change in SOC stock in 0–30 cm depth was calculated (Fig. 6.14).

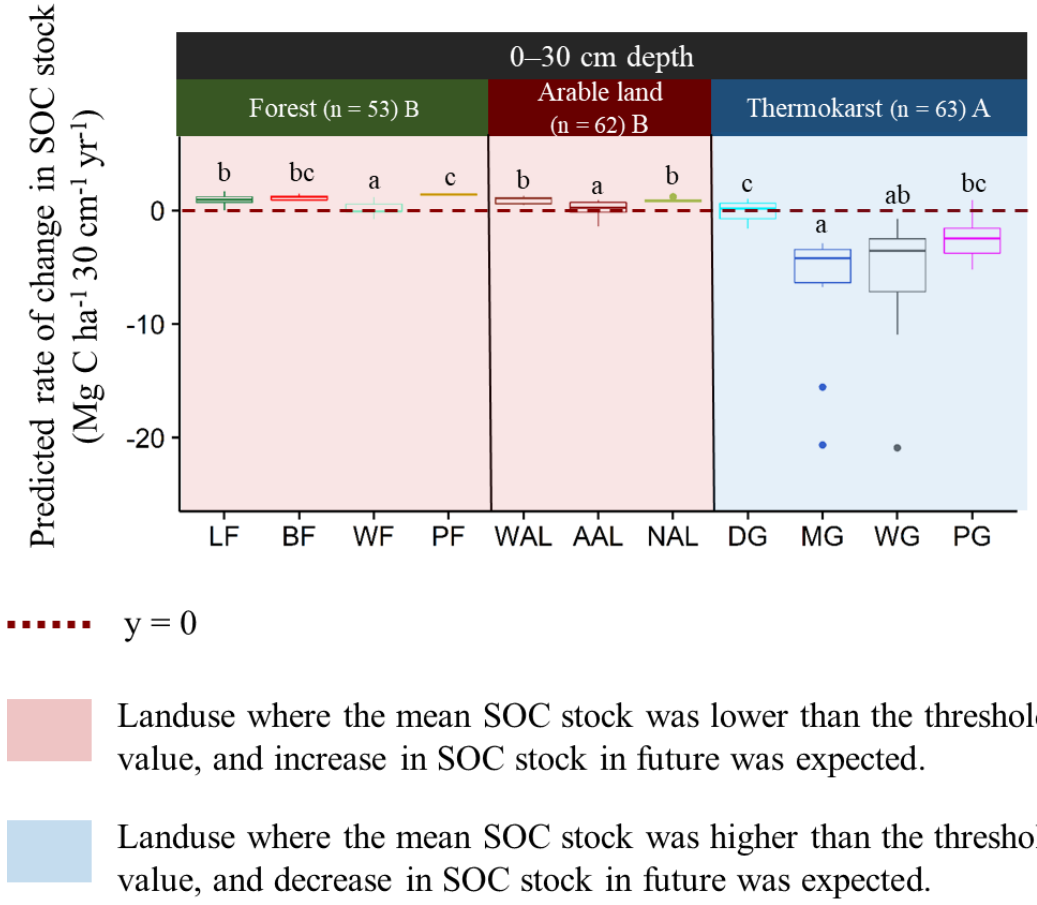

Fig. 6.14. Predicted rate of change in soil organic carbon (SOC) stock in Central Yakutia. Box plots visualize the five-number summary of a data set (minimum, lower quartile, median, upper quartile and maximum) and points indicate outlier value. Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. SOC: Soil organic carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

The positive value means C sink and the negative value means C source. Mean predicted rate of change in SOC stock (Mg C ha^{-1} 30 cm yr^{-1}) significantly differed between the ecosystems, and the values in the forest, arable land, and thermokarst ecosystem were 0.94 ± 0.49, 0.45 ± 0.61, and -2.98 ± 4.52, respectively. In the forest ecosystem, mean predicted rate of change in SOC stock were all positive and largest in PF (1.41 ± 0.06) followed by BF (1.13 ± 0.21) and LF (0.92 ± 0.40) and smallest in WF (0.17 ± 0.72). In the arable land ecosystem, the values were also all positive and the largest in WAL (0.89 ± 0.32) followed by NAL (0.89 ± 0.14) and smallest in AAL (0.18 ± 0.61). In the thermokarst ecosystem, the values were also all negative and the largest in MG (-6.99 ± 6.07) followed by WG (-5.43 ± 5.18) and PG (-2.43±1.95) and smallest in DG (-0.06 ± 0.81).

In this chapter, it is shown that thermokarst formation accumulates organic matter and further flooding increases C stock. However, the substantial decline in the SOC stock is also expected in the thermokarst ecosystem especially in the MG and WG where much SOC has been accumulated. Consequently, increase in the thermokarst activity might cause a net C loss in the future. Although in the forest and the arable land ecosystem, soil texture strongly controlled SOC content, water content was the main controlling factor of the SOC accumulation in thermokarst ecosystem (Table 6.3). The relationship between the soil texture and SOC content in each ecosystem were shown in Fig. 6.15. In the thermokarst ecosystem, high SOC content was observed in MG and WG despite high sand content and low silt and clay content because of the flooded condition which may prevent lake deposit from mineralization and accelerated the accumulation of dead plant materials (Desyatkin and Desyatkin, 2006). It is well known that fine particle such as silt and clay stabilize SOM depends on two mechanisms: first, bonds between the surface of clay particles and OM retard the decomposition process. Second, soils with higher fine particle increase the potential for aggregate formation (Barre et al., 2017; Bot

and Benites 2005; Gonçalves et al., 2017). These results indicating that not only because of the high SOC but also because of the low stability of the SOM, soils in the thermokarst ecosystem is more sensitive to the environmental change and exhibited the large C loss.

6.4.6 Possible causes of changes in recovery rate of SOC after arable land abandonment

In this chapter, the effect of arable land abandonment on SOC accumulation was evaluated. After the abandonment of arable land, SOC restored significantly, but the recovery rate of SOC decreased gradually (Fig. 6.4; Fig. 6.12). This decline in the recovery rate was in line with several previous studies (Kurganova et al., 2014; Kurganova et al., 2015; Belelli Marchesini et al., 2007). After the change in the environment such as land use, vegetation, and management practice, new stationary level of the SOC is established in the soils (Deng et al., 2016; Gelaw et al., 2014). In addition to this reason, the relationship between the initial SOC and ΔSOC obtained in chapter 6 may controlled the recovery rate in SOC. The SOC stock in the WAL (29.8 ± 8.9 Mg C ha^{-1} 30 cm^{-1}) was much lower than the threshold initial SOC stock (54.4 Mg C ha^{-1} 30 cm^{-1}). After the abandonment of the arable land, the SOC stock gradually increased, and the recovery rate might decrease gradually as the SOC stock got closer to the threshold.

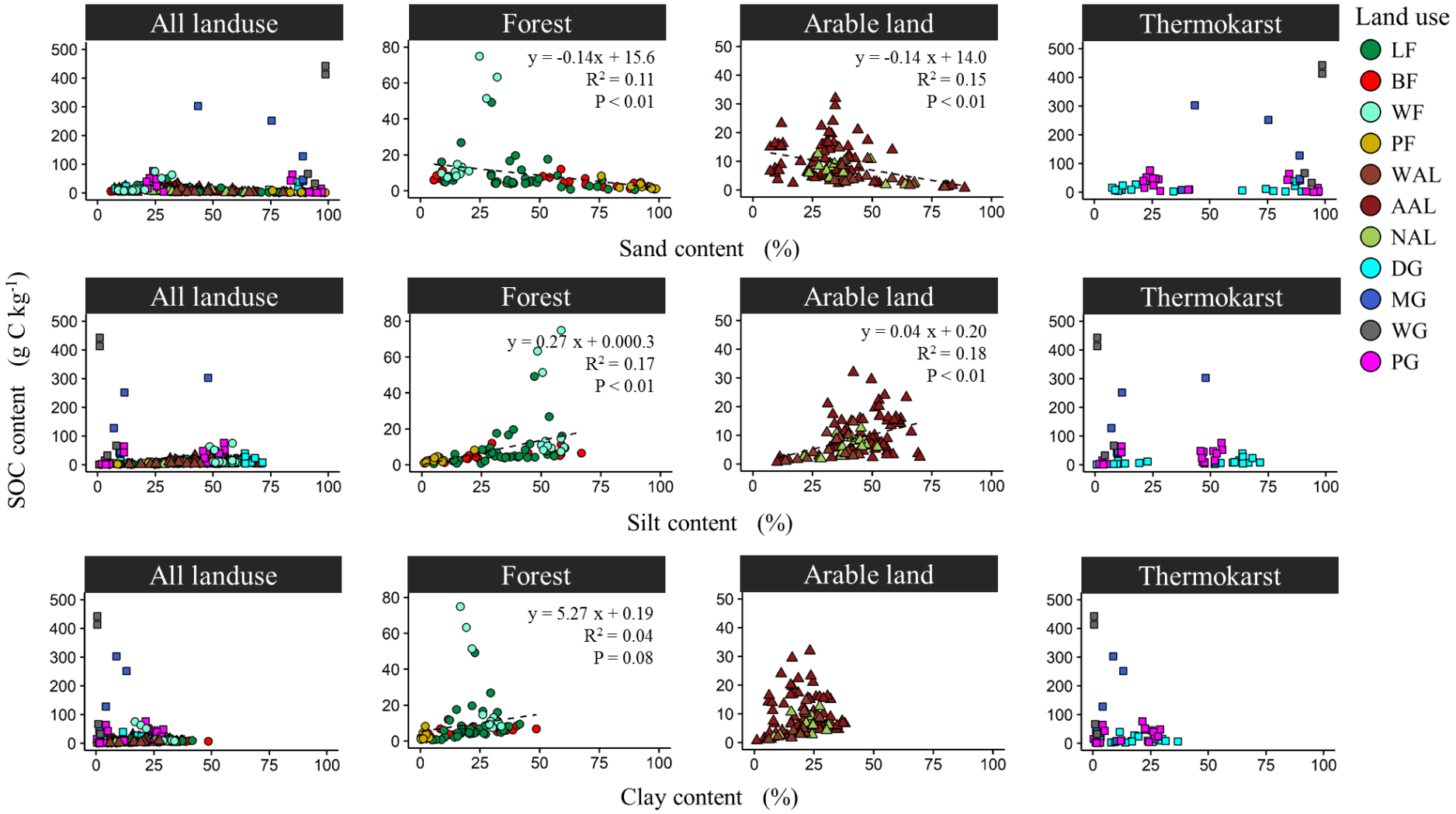

Fig. 6.15. The relationship between the soil texture and soil organic carbon (SOC) content. SOC: Soil organic carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

6.5. Conclusion

Litter and soil organic and inorganic C stocks (LIC, SOC, and SCC, respectively) of the three ecosystems (forest, arable land, and thermokarst) were significantly different. Significantly higher SOC and TSC stocks were found in the thermokarst ecosystem, suggesting that thermokarst formation accumulates OM and further flooding increases C stocks. Forest disturbance significantly changed the C balance in the forest ecosystem. Forest fire did not decrease SOC or SCC stocks, but significantly reduced LIC by 54 ± 61%, and waterlogging damage may have increased the SOC stock but reduced LIC by 53 ± 60%. In the arable land ecosystem after the abandonment of arable land, SOC was significantly restored, but its restoration rate gradually decreased. SOC content was significantly, positively correlated with the root C content in all ecosystems. In the forest and arable land ecosystems, soil texture strongly affected SOC content, whereas water content was the main factor that affected SOC accumulation in the thermokarst ecosystem.

Under the climate change, the SOC stock in forest and arable land ecosystem may increase in the future. Conversely, the SOC stock in the thermokarst ecosystem may decrease in the future.

6.6. Summary

This study was conducted to evaluate the change in total soil carbon [TSC = soil organic carbon (SOC) + soil carbonate carbon (SCC) + litter carbon (LIC)] associated with recent thermokarst activity, forest disturbance, land use change from forest to arable land, and arable land abandonment in a permafrost-affected area of Central Yakutia, Russia. TSC data from 81 sites [72 sites in 2014 and 2015, and 9 sites in 2013 from Desyatkin et al. (2013)] in three types of ecosystem were analyzed: forests [larch forest (LF), burned forest (BF), water-damaged forest (WF), and pine forest (PF)], arable land [working arable land (WAL), abandoned arable land (AAL), and abandoned arable land invaded by new trees)], and thermokarst [dry grassland (DG), moderately wet grassland (MG), wet grassland (WG), and pingo (PG) (round mount)]. The SOC stock was low in forest sites and high in thermokarst sites. Among the forest sites, SOC stock at 0–100 cm depth (Mg C ha^{-1} 100 cm^{-1}) was highest in WF (93.6 ± 40.6) followed by LF (69.7 ± 20.5) and BF (54.7 ± 10.7), and lowest in PF (27.0 ± 1.5). In BF, LIC was almost half of that in LF. Burning mainly decreased LIC. In WF, the SOC stock at 0–30 cm depth was significantly higher than in LF, although LIC decreased to around half of that in LF. Arable land sites had similar SOC stocks to the forest sites. The SOC stock at 0–100 cm depth was higher in AAL (91.8 ± 36.6) than in WAL (59.4 ± 8.7) and NAL (59.2 ± 3.7). SOC accounted for around 55% of TSC. It is clear that the abandonment of cultivation increased SOC. Thermokarst sites had significantly higher SOC stocks than forests and arable land. The SOC stock at 0–100 cm depth was highest in WG (520.8 ± 709.1) followed by MG (393.8 ± 404.2) and PG (199.6 ± 136.8), and lowest in DG (108.8 ± 38.7). SOC accounted for over 60% of TSC. Thermokarst formation accumulated organic matter, and further flooding increased SOC especially in surface soil. The SOC content was significantly, positively correlated with root C content, in all ecosystems. In the forest and arable land ecosystems, soil texture strongly affected SOC content,

but water content was the main factor in SOC accumulation in the thermokarst ecosystem.

Combined with the results of chapter 5, the future prediction of the SOC stock was conducted. The SOC stocks in the 0–30 cm depth in land uses belong to the forest, and arable land ecosystem in 2013, 2014 and 2015 was lower than the threshold level of 54.4 Mg C ha^{-1} 30 cm^{-1}. Therefore, the SOC stock may increase in the future. Conversely, the SOC stocks in the land uses belong to the thermokarst ecosystem in 2013, 2014 and 2015 were higher than the threshold level. Therefore, SOC stock may decrease in the future.

7. General discussion

In chapter 4 and chapter 5, the significant correlation between the initial SOC and ΔSOC was obtained. As shown in previous studies (Bellamy et al., 2005; Capriel, 2013; Goidts and van Wesemael, 2007; Hanegraaf et al., 2009; Riley and Bakkegard, 2006; Saby et al., 2008), the initial SOC level significantly controlled SOC change both in Toya, Hokkaido, Japan and Central Yakustk, Eastern Siberia, Russia.

The relationship indicated the threshold of initial SOC for the decrease of SOC (x-intercept): the C loss occurred in the soils with initial SOC greater than the threshold while soils with SOC smaller than the threshold gained C. Moreover, a larger slope means there is a more vigorous change in the rate of change in SOC content with a change of initial SOC content. Therefore, the slope may be indicating the stability of SOC. Acumulation of SOC is achieved by balancing input C and output C which is influenced by climate, soil type, land use and anthropogenic management. However, the effect of those factors on the threshold level and slope of the regression equation between initial SOC and ΔSOC has not been studied.

In chapter 5, it is showed that soil sampling depth has a significant effect on the threshold initial SOC: the threshold initial SOC content tended to decrease with increasing sampling depth, while, the threshold initial SOC stock increases with increasing sampling depth. On the other hand, the sampling depth has no obvious effect on the slope.

In this chapter, the effect of climate, soil type, land use, disturbance, and management on the slope and threshold initial SOC was evaluated using 7 regression equations obtained in chapter 4 and 5 combined with 12 regression equations from 7 reference studies conducted in temperate (Bellamy et al., 2005; Capriel, 2013; Hanegraaf et al., 2009; Stevens and van Wesemael, 2008), cool temperate (Riley and Bakkegard, 2006) and tundra zones (Chen et al., 2017).

7.1. Factors controlling the slope of the regression equations between initial SOC and ΔSOC

In chapter 4 and 5, the significant negative correlation between initial SOC and ΔSOC was obtained for both SOC content and SOC stock. Most of the previous studies which obtained the relationship only evaluated for the SOC content because of the lack the BD measurement (Bellamy et al., 2005; Capriel, 2013; Hanegraaf et al., 2009; Riley and Bakkegard, 2006). However, the relationship for the SOC content does not evaluate the variation and change in the soil BD. The uncertainties in the change in SOC is dependent not only on the SOC content but also on the BD (Goidts et al., 2009). And it has been recommended to evaluate the change in SOC using data of SOC stock (Hanegraaf et al., 2009; Zhang and Hartemink, 2017). Therefore, in this section, the factors controlling the slope of the regression equations between initial SOC stock and ΔSOC stock was explored. The slope was negative in both sites, and tended to be larger in Toya than Central Yakutsk (-0.054 and -0.029, respectively). Table 7.1 compares the regression equations between the initial SOC stock and the rate of ΔSOC stock obtained in previous studies in Northeast China (Li et al., 2016) and Tibetan Plateau (Chen et al., 2017). In the present study in chapter 5, there was no obvious trend in the slope between soil depths. Therefore, the slope was compared among regression equations regardless of the sampling depth. The slope was the smallest in the Central Yakutsk (-0.024 in 0–5 cm depth) and the largest in the Toya (-0.054) among the eight regression equations. Moreover, a positive correlation between mean annual temperature and the slope ($P = 0.08$) and between annual precipitation and the slope ($P < 0.01$) (Fig. 7.1) were obtained. This result is suggesting that the slope is controlled by the climatic condition. The slope of the regression equation between the initial SOC and ΔSOC indicates the stability of SOC. And the slope probably determined the speed of both OM accumulation via C input and OM decomposition by microbial activity. It is

known that climate condition can affect SOC turnover: temperature has a large effect on both carbon accumulation and SOC decomposition (Lal, 2004a), and precipitation control plant growth [NPP (C input)] and SOC decomposition (Jobbágy and Jackson, 2000). Chen et al. (2017) found large SOC loss occurred in the place where mean annual precipitation was high because of the high rate of OM decomposition. In Central Yakutsk, Sawamoto et al. (2003) and Desyatkin et al. (2007) reported lower NPP and slower OM decomposition rate characterized by low temperature and precipitation, and short growing season. The smallest slope (high stability of SOC) in the Central Yakutsk may be attributed to this reason. On the other hand, Koide et al., (2010) evaluated the effect of heavy precipitation event (20 mm day^{-1} for six days) on CO_2 fluxes in the taiga-forest soil in Central Yakutsk. They revealed that heavy precipitation events would increase both soil temperature and moisture, and accelerate microbial activities (organic matter decomposition). These results are indicating that there is a possibility, under the climate change, to change in the slope in future.

Table 7.1

Comparison of regression equations between initial soil organic carbon (SOC) stock and rate of change (Δ) in SOC stock.

Study region	Climate	Mean annual temperature (°C)	Annual precipitation (mm)	Land use	Soil type	Study period	Duration (Year)	Sampling depth (cm)	Regression equation	Threshold (Mg C kg^{-1})	Reference
Yakustk, Russia	Cold	-9.7	235	Grassland and forest	Cryosol and permafrost affected soils	1992 (2000)–2014	14–22	0–5	Δ SOC stock = -0.024 × Initial SOC stock + 0.20	8.3	Chapter 5
Yakustk, Russia	Cold	-9.7	235	Grassland and forest	Cryosol and permafrost affected soils	1992 (2000)–2014	21	0–15	Δ SOC stock = -0.029 × Initial SOC stock + 1.04	35.9	Chapter 5
Hokkaido, Japan	Cool temperate	7.5	1179	Cropland	Andosols	2001 (2003)–2012	9–11	0–15	Δ SOC stock = -0.054 × Initial SOC stock + 1.95	36.1	Chapter 4
Northeast China		2.6	437	Dry cropland and paddy	Chernozem and Phaeozem	1981–2011	30	0–20	Δ SOC stock = -0.030 × Initial SOC stock + 1.10†	36.6	Li et al., 2016
Northeast China		2.4	547	Dry cropland and paddy	Phaeozem	1981–2011	30	0–20	Δ SOC stock = -0.042 × Initial SOC stock + 2.79†	66.4	Li et al., 2016
Northeast China		4.4	488	Dry cropland and paddy	Phaeozem and Luvisol	1981–2011	30	0–20	Δ SOC stock = -0.036 × Initial SOC stock + 2.24†	62.2	Li et al., 2016
Yakustk, Russia	Cold	-9.7	235	Grassland and forest	Cryosol and permafrost affected soils	1992 (2000)–2014	14–22	0–30	Δ SOC stock = -0.036 × Initial SOC stock + 1.96	54.4	Chapter 5
Tibetan Plateau, China	Tundra	Various	Various	Alpine grassland	Cambisols	2002–2011	9	0–30	Δ SOC stock = -0.032 × Initial SOC stock + 1.37†	42.8	Chen et al. 2017

Threshold level; x-intercept of the regression equation. †: If the original regression equation was provided as a relationship between initial SOC stock and change in SOC stock, the slope and intercept of the regression equation was divided by the difference in years between two sampling times.

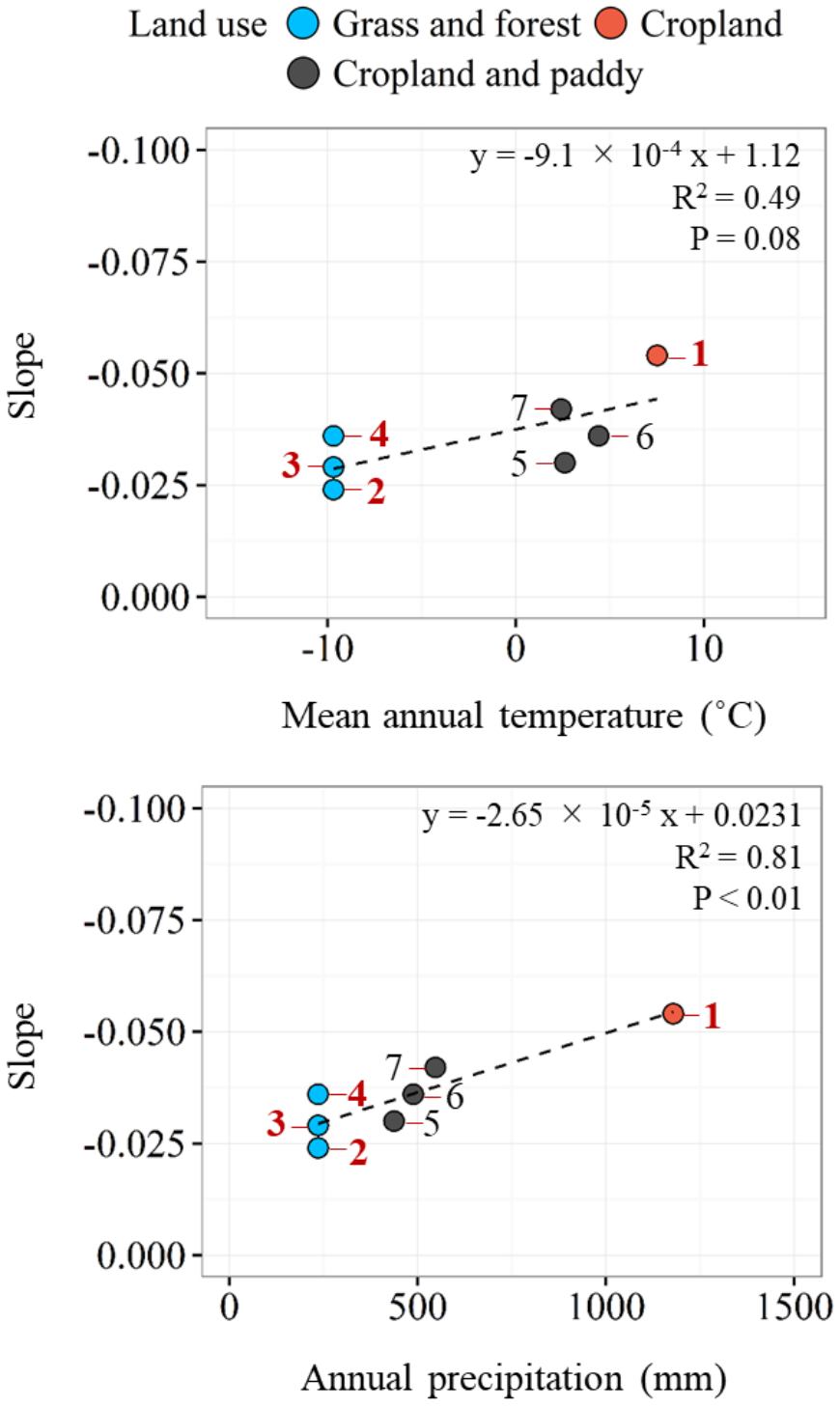

Fig. 7.1 The relationship between climate condition and the slope of the regression equation between initial soil organic carbon (SOC) stock and rate of change (Δ) in SOC stock. 1: Cropland (Chapter 4), 2, 3, and 4: Grassland and forest (Chapter 5), 5, 6, and 7; Cropland and paddy (Li et al., 2016).

7.2. Factor controlling threshold initial SOC of the regression equations between initial SOC content and ΔSOC content

As with the slope, it might be appropriate to be discussed using the relationship for the SOC stock. However, for a better understanding of the dynamics of SOC, in this section, the factors controlling the threshold initial SOC of the regression equations between initial SOC and ΔSOC was explored using both SOC content and stock.

The threshold initial SOC stock was 36.1, and 35.9 Mg C ha^{-1} in Toya and Central Yakutsk, respectively. Both threshold initial SOC content and stock were almost same level.

Table 7.1 compares the regression equations between the initial SOC stock and the rate of ΔSOC stock obtained in previous studies. The threshold level of the initial SOC stock in ranged from 8.3 to 66.4 Mg C ha^{-1} (Table 7.1). Because of the limited number of the regression and variation of the land use type, the factor controlling threshold initial SOC stock was not found. Hence, the regression equations between the initial SOC content and the rate of ΔSOC content was compared in Table 7.2. The threshold level of the initial SOC content ranged from 15.6 to 63.7 g C kg^{-1}. The initial threshold SOC content (and stock), so threshold values should be compared between the same sampling depths. Fig. 7.2 shows the comparison of threshold initial SOC content at same sampling depth. Comparing the threshold values at a sampling depth of 0–15 cm that shows highest number of the results, the threshold value was highest in grassland (63.7 g C kg^{-1}) (Capriel et al., 2013), followed by grassland and corn (Mean ± SD: 39.7 ± 17.0 g C kg^{-1}) (Hanegraaf et al., 2009) various land uses (32.1 g C kg^{-1}) (Bellamy et al., 2005) and cropland in Toya (24.3 g C kg^{-1}) (in Chapter 4), and was lowest in Forest and grassland in Central Yakutsk (21.2 g C kg^{-1}) (in chapter 5). Various land uses were reported by Bellamy et al. (2005), including cropland, grassland, forest, and peatland. At sampling depths of 0–25 and 0–30 cm, the threshold value was highest in the forest (35.4 g C kg^{-1}) (Stevens and van Wesemael et al., 2008), followed by cropland (15.8 g C kg^{-1}) (Riley and Bakkegard et al., 2006), and was lowest in the Central Yakutsk (15.6 g C kg^{-1}) (in chapter 5).

Table 7.2

Comparison of regression equations between initial soil organic carbon (SOC) content and rate of change (Δ) in SOC content

Study region	Climate	Mean annual temperature (°C)	Annual precipitation (mm)	Land use	Soil type	Study period	Duration (Year)	Sampling depth (cm)	Regression equation	Threshold (g C kg^{-1})	Reference
Yakustk, Russia	Cold	-9.7	235	Grassland and forest	Cryosol and permafrost affected soils	1992 (2000)–2014	14–22	0–5	Δ SOC content = -0.043 × Initial SOC content + 1.00	23.3	Chapter 5
South Germany	Temperate	4.0–9.0	550–2000	Cropland	Null	1986–2008	21	0–10	Δ SOC content = -0.053 × Initial SOC content + 0.91	17.2	Capriel et al. 2013
Yakustk, Russia	Cold	-9.7	235	Grassland and forest	Cryosol and permafrost affected soils	1992 (2000)–2014	14–22	0–15	Δ SOC content = -0.041 × Initial SOC content + 0.87	21.2	Chapter 5
Hokkaido, Japan	Cool temperate	7.5	1179	Cropland	Andosols	2001 (2003)–2012	9–11	0–15	Δ SOC content = -0.046 × Initial SOC content + 1.12	24.3	Chapter 4
England and Wales	Temperate			Various	Null	1978–2003	25	0–15	Δ SOC content = -0.019 × Initial SOC content+ 0.60	32.1	Bellamy et al. 2005
South Germany	Temperate	4.0–9.0	550–2000	Grassland	Null	1986–2007	21	0–15	Δ SOC content = -0.081 × Initial SOC content + 5.16	63.7	Capriel et al. 2013
South Norway	Cool temperate			Cropland	Null	1991–2001	10	0–25	Δ SOC content = -0.036 × Initial SOC content + 0.57†[1]	15.8	Riley and Bakkegard 2006
Yakustk, Russia	Cold	-9.7	235	Grassland and forest	Cryosol and permafrost affected soils	1992 (2000)–2014	14–22	0–30	Δ SOC content = -0.048 × Initial SOC content + 0.75	15.6	Chapter 5
Belgium	Temperate	8.0	1100	Forest	Null	1947 (1962)–2003 (2006)	41–59	0–30	Δ SOC content = -0.015 ×Initial SOC content + 0.531	35.4	Stevens and van Wesemael et al. 2008
Netherlands	Temperate		800	Grassland and maize	Null	1984–2004	20	15*	Δ SOC content = -0.043 × Initial SOC content + 0.96‡	22.3	Hanegraaf et al. 2009
Netherlands	Temperate		800	Grassland and maize	Null	1984–2004	20	15*	Δ SOC content = -0.035 ×Initial SOC content + 1.97‡	56.3	Hanegraaf et al. 2009
Netherlands	Temperate		800	Grassland and maize	Null	1984–2004	20	15*	Δ SOC content = -0.042 × Initial SOC content + 1.70‡	40.4	Hanegraaf et al. 2009

Threshold: x-intercept of the regression equation. *: 0–5 cm for grassland fields and 0–25 cm for maize fields and the value was shown as a mean. †: If the original regression equation was provided as a relationship between initial SOC content and change in SOC content, the slope and intercept of the regression equation was divided by the difference in years between two sampling times. ‡: If the original regression equation was provided as the soil organic matter content, the value was converted to SOC content by dividing by 1.724.

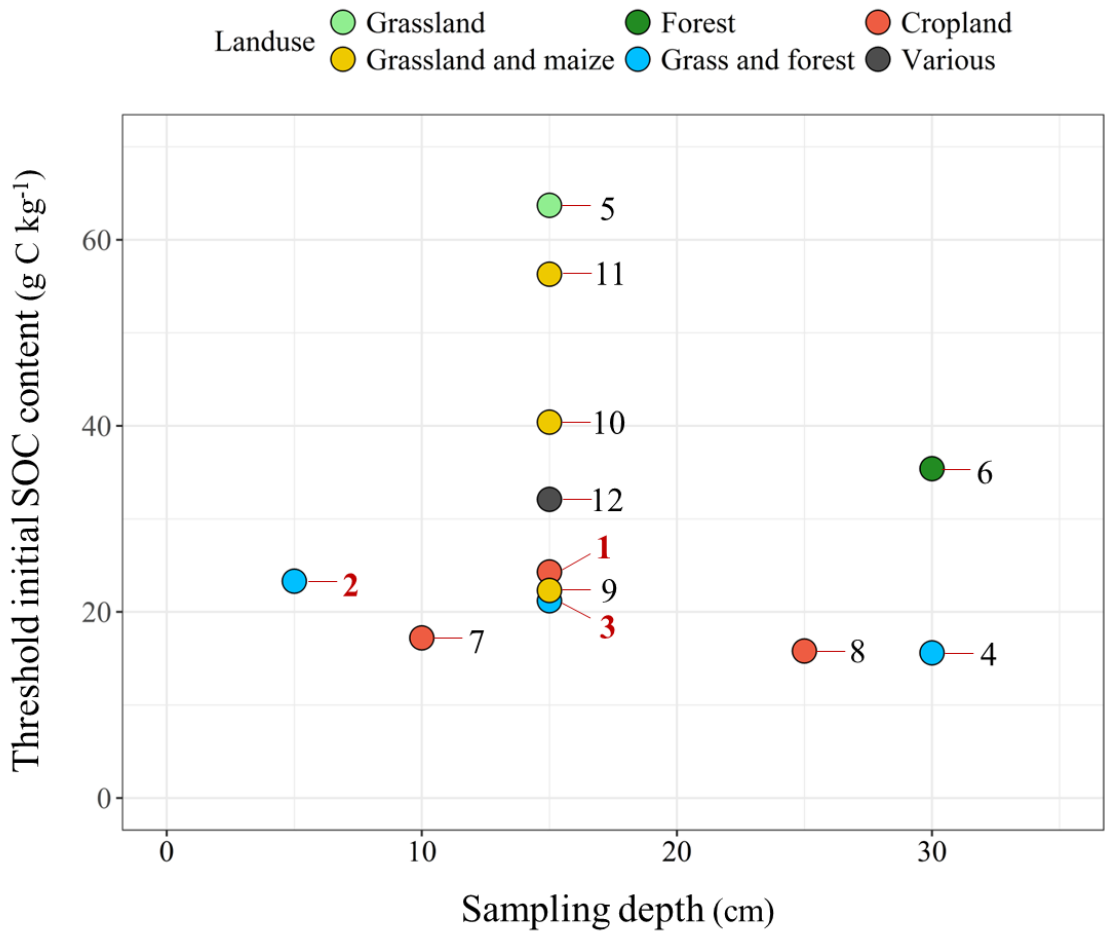

Fig. 7.2. Comparison of threshold initial soil organic carbon (SOC) content. The sampling depth of 10, 11, and 12 (Hanegraaf et al., 2009) was estimated as a mean value of grass land and maize field (0–5 cm for grassland fields and 0–25 cm for maize fields). 1: Cropland (Chapter 4), 2, 3, and 4: Grassland and forest (Chapter 5), 5; Grassland

These results suggested that land use had an effect not only on the accumulated amount of SOC but also on the threshold initial SOC. And the threshold initial SOC content in the cropland tended to be lower than that in the grassland or forest.

The type of land use is a key factor affecting SOC storage as the result of the different input quantity and quality of OM, the litter decomposition rates, and the processes of humification in soils (Gelaw et al., 2014). Indeed, in the present study, chapter 6 showed that the C stock significantly differed among land uses: significantly higher C stock was observed in grasslands

in thermokarst ecosystem than forest and arable land ecosystem (Figs. 6.4 and 6.6). Moreover, the TSC stock in the 0–30 cm soil layer in LF was significantly decreased from 54.4 ± 20.7 to 34.0 ± 13.1 Mg C ha^{-1} 30 cm^{-1} in WAL at an average rate of 37 ± 47% (Fig. 6.6). And this result was consistent with several previous studies (Ajami et al., 2016; Assefa et al., 2017; Fujisaki et al., 2017) which have shown that the conversion of natural forest to cropland often leads to a decrease in SOC stocks, because of a decrease in litter input and an increase in the soil C mineralization rate. Moreover, Agricultural practices, such as tillage, enhance SOM decomposition through the destruction of soil aggregates and increased aerobic conditions (Balesdent et al., 2000; Grandy and Robertson, 2006).

In chapter 5, the present study in Central Yakutsk was conducted in the grassland (DG, WG, and PG) and forest (LF and PF). Therefore, the threshold initial SOC content obtained in chapter 5 expected to be higher than those in the cropland. However, at the all depth (0–5, 0–15, 0–30 cm soil layer), the threshold initial SOC content in chapter 5 was smaller than those in grassland, grassland and maize, and forest (Fig.7.2) and almost similar level with croplands (Table 7.2; Fig. 7.2). The reason may be as follows; as described in chapter 3 and 5, the thermokarst grasslands were used to feed livestock. There was no C input via OM application, and the only C output was due to harvest in the DG, WG, and PG sites (Desyatkin et al., 2007). It decreased SOC stock (Chapter 5). Lower threshold initial SOC in chapter 5 was also may attributed to the same reason. Furthermore, a significant increase in air and soil temperature and precipitation (unusual wet climate) has been reported in this study region (Iijima et al., 2010; Fedlov et al., 2013; Desyatkin et al., 2015). Climate change will affect soil carbon turnover through various processes (Schuur et al., 2015). Increases in temperature and precipitation tend to increase OM decomposition by soil microbes, while it also tends to enhance the plant growth (NPP). Overall effects of climate change depend on whether the enhanced growth is large enough to counteract the increased decomposition (Heikkinen et al., 2013). Several C-climate models indicated that positive C-climate feedback would be triggered due to the acceleration of

C release to the atmosphere as CO_2 under predicted future global climate change especially in the permafrost soils (Cox et al., 2000; Schuur et al., 2015; Smith et al., 2007). Moreover, Chen et al., 2017 carried out a repeated soil sampling to assess the changes in SOC stocks (ΔSOC stock) in the 41 sites of alpine grasslands across the Tibetan Plateau. And a significant negative correlation between the mean annual precipitation and ΔSOC was found. They concluded that the increase in precipitation increased OM decomposition (Chen et al., 2017). Our result may also indicate that effect of the increase in the OM decomposition was greater than the increase in the C input through the plant growth and it decreased the threshold.

Among the croplands, the threshold level that obtained in Toya (24.3 g C kg^{-1}) was higher than those in South Germany (Capriel et al. 2013) (17.2 g C kg^{-1}) despite the deeper sampling depth. Andosols often have a high SOC content, mainly due to the formation of short-range ordered (amorphous) minerals and Al/Fe–OH (Shirato et al., 2004; Shoji et al. 1993; Takahashi and Dahlgren, 2016). Additionally, continuous application of the OM (1.45 ± 1.27 Mg C ha^{-1} yr^{-1} in average) (Table 4.1) has been conducted during the study period (from 2001 to 2012) In chapter 4, only a weak positive correlation was found between C application rate and ΔSOC content and stock (r = 0.17 and 0.23, respectively). However, many previous studies have indicated management practices have a significant effect on C budget at the field scale, and OM application is necessary to prevent C loss in the agricultural land (Limin et al., 2015; Mu et al., 2008; Shimizu et al., 2013; Shimizu et al., 2015). In this study, andic properties and OM application might increased threshold initial SOC content.

Fig. 7.3 shows factors controlling threshold initial SOC. In this section, it is shown that climate change, soil type, land use, and management affect the threshold initial SOC. Moreover, in chapter 6, it is identified that thermokarst activity, forest disturbance, land use change was significantly changed the SOC stock. This may also change the threshold initial SOC stock.

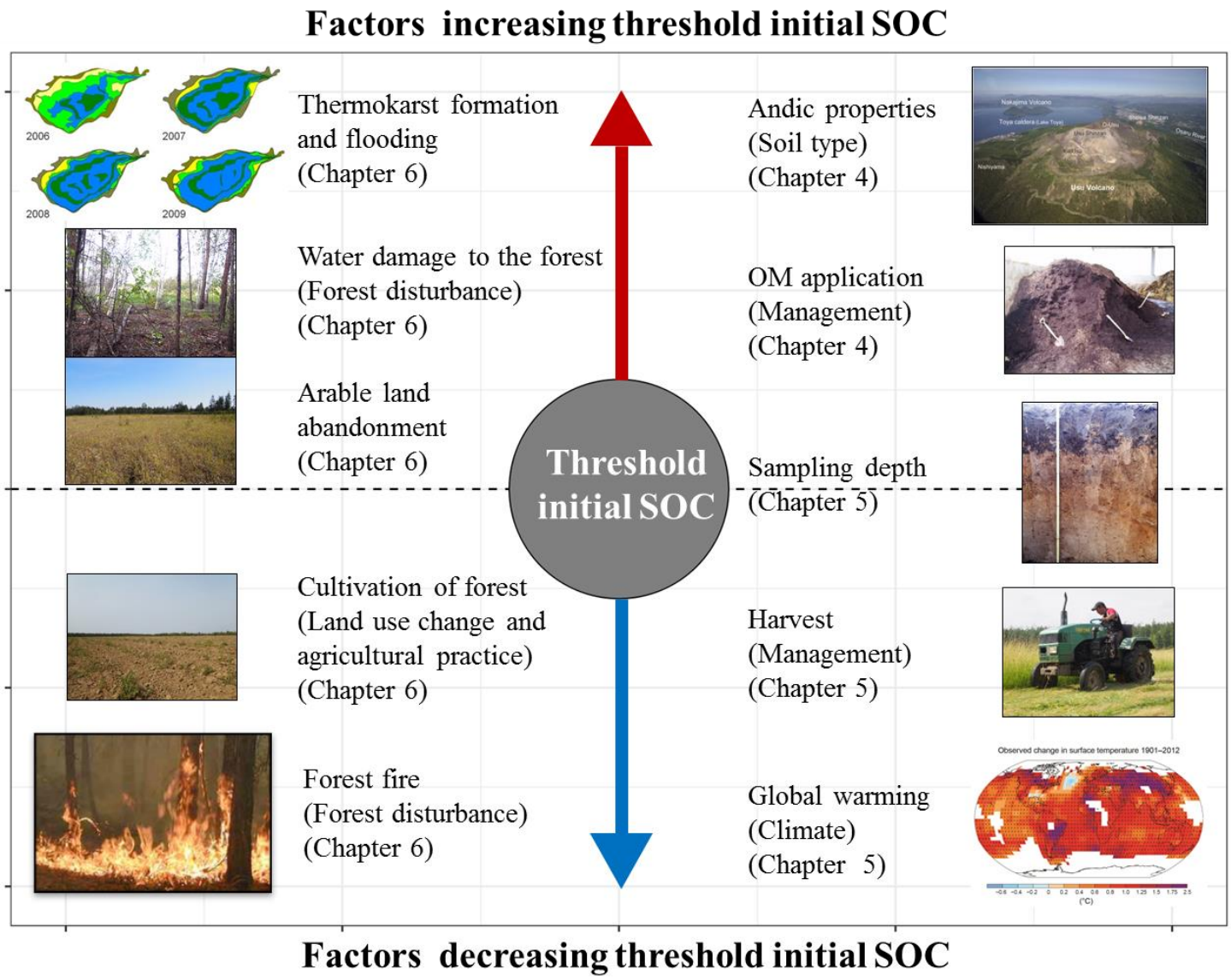

Fig. 7.4. Factors controlling threshold initial SOC. Phots were cited from Desyatkin et al., 2014, IPCC, 2013, and Miyabuchi et al., 2014.

7.3 Conclusion

Initial SOC level significantly controlled SOC change in both Toya and Central Yakutsk. The relationship showed the threshold of initial SOC for the decrease of SOC (x-intercept) and the stability of SOC (slope). The slope was controlled by the climate condition. A positive correlation between the mean annual temperature or annual precipitation and the slope ($P = 0.08$ and $P < 0.01$, respectively) indicating that the smallest slope in Central Yakutsk indicated the high stability of SOC characterized by the lower NPP and slower OM decomposition under the low temperature and precipitation. And the threshold initial SOC was controlled by the sampling depth, land use, management practice, and soil types. Thermokarst activity, forest disturbance, land use change may also change the threshold initial SOC.

Summary

1. Introduction

Soil stored 1500 Pg carbon (C) as soil organic carbon (SOC) in the top 1 m, which is the largest C pool on the land. Several studies have reported a decrease in SOC in temperate or cool temperate zones. Moreover, the significant negative correlation between initial SOC and SOC change rate (ΔSOC) was also reported. The relationship indicated the threshold of initial SOC for the decrease of SOC (x-intercept): the C loss occurred in the soils with initial SOC greater than the threshold while soils with SOC smaller than the threshold gained C. Moreover, a larger slope means there is a more vigorous change in the rate of change in SOC content with a change of initial SOC content. Therefore, the slope may be indicating the stability of SOC. SOC accumulation is achieved by balancing input C and output C which is influenced by climate, soil type, land use and anthropogenic management. However, the effect of those factors on the threshold level and slope of the regression equation between initial SOC and ΔSOC has not been studied. The SOC stock change was estimated as the difference between the stocks measured at two different times divided by the number of years, and net biome production (NBP) reflects SOC stock change.

Andosols cover more than 50% of the total upland crop field area in Japan. And Andosols often have a high SOC content due to Andic properties (e.g. Al-OH complex).

It is estimated that nearly one-third of the world's SOC is stored in arctic and boreal regions. However, during a climate warming, thawing of permafrost soils may cause remobilization of soil organic matter (SOM) previously protected by permafrost.

These regions is considered as a hot spot of C emission. This study had the following aims: firstly, to estimate the accumulated SOC stock and its change in various land use on different soil types under different climate: secondly, to clarify the factors controlling SOC stock.

2. Materials and methods

The effect of long-term application of organic matter (OM) on SOC and physico-chemical properties of different types of Andosols in Toya, Hokkaido, Japan (Mean annual temperature: 7.5℃, Annual precipitation: 1179 mm) was evaluated. 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 from Mt. Usu. And K2 and HO (Silandic Andosols) are characterized by volcanic ash from Mt. Yotei, and Mt. Usu which produced by the eruption in 1663. In 2012, a soil survey was conducted in 34 fields using reference data collected from 2001 to 2003 in the same fields.

The effect of global warming on the change in the SOC stock was evaluated in the permafrost-affected area of Central Yakutsk, Eastern Siberia, Russia (Mean annual temperature: -10℃, Annual precipitation: 230 mm). A baseline soil survey was conducted in 1992 and 2000 from five different types of land uses; Larch forest (LF), pine forest (PF), dry grassland (DG), wet grassland (WG), and pingo (PG). From these sampling sites, 18 sites where any land use change and disturbance have been recorded were selected, and soil samples were recollected in 2014.

Moreover, the change in total soil carbon [TSC = SOC + soil carbonate carbon (SCC) + litter carbon (LIC)] associated with thermokarst activity, forest disturbance, land use change in Central Yakutsk was evaluated. TSC data from 81 sites [72 sites in 2014 and 2015 and 9 sites in 2013 (Desyatkin et al. 2013)] in three types of ecosystem were analyzed: forests [LF, burned forest (BF), water-damaged forest (WF), and PF], arable land [working arable land (WAL), abandoned arable land (AAL), and abandoned arable land invaded by new trees (NAL)], and thermokarst [DG, moderately wet grassland (MG), WG, and PG] was analyzed.

The SOC stock was calculated by using equivalent soil mass method (ESM) to account for the

change in soil bulk density (BD). ΔSOC stock was estimated form the difference between the SOC stocks measured at two different times divided by the number of years. And a negative ΔSOC indicates the decline in SOC stock. The threshold initial SOC was estimated as an intercept at x-axis of regression equation between initial SOC and ΔSOC.

The effect of climate, soil type, land use, and management on the slope and threshold initial SOC was evaluated using 12 regression equations from 7 reference studies conducted in temperate, cool temperate, and tundra zones.

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

The mean application rate of OM was 1.45 ± 1.27 Mg C ha^{-1} yr^{-1}. There were no significant differences in SOC stock between 2001–2003 and 2012. However, 10% of the study sites exhibited a significant increase in SOC stock, with 35% showing a significant decrease, and 55% showing no significant change. The ΔSOC stock was significantly higher in K1 than in K2 and HO, and the SOC stock significantly decreased in K2. There was a significant negative correlation between initial SOC stock and ΔSOC stock: ΔSOC stock (Mg C ha^{-1} 15 cm^{-1} yr^{-1}) = -0.052 × Initial SOC stock (Mg C ha^{-1} 15 cm^{-1}) + 2.09. The thresholds of initial SOC stock were calculated as 36.1 Mg C ha^{-1} 15 cm^{-1}. The SOC stock in the K1 in 2012 (34.7 ± 7.7 Mg ha^{-1} 15 cm^{-1}) was lower than the threshold level. Therefore, the SOC stock may increase in the future. Conversely, the SOC stocks in the K2 and HO in 2012 (39.4 ± 6.7 and 40.5 ± 7.7 Mg ha^{-1} 15 cm^{-1}, respectively) were higher than the threshold level. Therefore, SOC stock may decrease in the future. ΔSOC content was significantly negatively correlated with Δbulk density, Δavailable phosphorus, and base saturation, but positively correlated with Δtotal porosity, Δphosphate 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.

4. Effect of global warming on soil carbon stock change in the Taiga-Alas landscape in Eastern Siberia

There was no significant difference in SOC stock between 1992–2000 and 2014. However, 28% of the study sites exhibited a significant increase in SOC stock, with 61% showing a significant decrease, and 11% showing no significant change. The mean ΔSOC stock in the 0–30 m soil layer of the LF, PF, DG, WG, and PG sites was negative, at -0.05 ± 0.82, -0.58 ± 0.06, -1.52 ± 2.80, -2.10 ± 7.05, and -1.39 ± 1.24, respectively. In this study region, the significant increase in the mean annual temperature at 2.5 ℃ has been reported from 1961 to 2010. Increased in the OM decomposition triggered by the global warming may be one of the causes of the decline in the SOC stock. Desyatkin et al. (2007) reported that NBP was 0.16 Mg C ha^{-1} in DG and -1.21 Mg C ha^{-1} $period^{-1}$ (period: 86 days) in WG in 2006. Although the values were larger than those observed in the present study, a similar tendency was shown, whereby soil C loss was larger in WG than in DG. There was no C input via OM application, and the only C output was due to harvest in the DG, WG, and PG sites. This may be the main reason for the large C loss. There was a significant correlation between ΔSOC stock and initial SOC stock for 0–15 and 0–30 cm soil layer: ΔSOC stock (Mg C ha^{-1} 15 cm^{-1} yr^{-1}) = -0.029 × Initial SOC stock (Mg C ha^{-1} 15 cm^{-1}) + 1.04 and ΔSOC stock (Mg C ha^{-1} 30 cm^{-1} yr^{-1}) = -0.036 × Initial SOC stock (Mg C ha^{-1} 30 cm^{-1}) + 1.96, respectively. The thresholds of initial SOC stock were calculated as 36.1 Mg C ha^{-1} 15 cm^{-1} and 54.4 Mg C ha^{-1} 30 cm^{-1}, respectively. This result explained the reason why the largest SOC loss was observed in the WG where initial SOC stock was the heist among the land uses.

5. Carbon stock estimation and changes associated with thermokarst activity, forest disturbance, and land use changes in Eastern Siberia

Thermokarst ecosystem had significantly higher SOC stocks than forests and arable land ecosystem. Among the forest sites, SOC stock at 0–100 cm depth (Mg C ha^{-1} 100 cm^{-1}) was highest in WF (93.6 ± 40.6) followed by LF (69.7 ± 20.5) and BF (54.7 ± 10.7) and lowest in PF (27.0 ± 1.5). In BF, SOC and SCC stock in 0–30 cm soil layer was almost same with LF, but LIC was almost half of that in LF. This result indicated that burning mainly decreased LIC. In WF, the SOC stock at 0–30 cm soil layer was significantly higher than in LF, although LIC decreased to around half of that in LF. In the arable land ecosystem, the SOC stock at 0–100 cm depth was higher in AAL (91.8 ± 36.6) than in WAL (59.4 ± 8.7) and NAL (59.2 ± 3.7). In 0–30 cm soil layer, the SOC stock in the AAL was significantly higher than that in WAL. It is clear that the arable land abandonment restores SOC, but its restoration rate gradually decreases. In the thermokarst ecosystem, the SOC stock at 0–100 cm depth was highest in WG (520.8 ± 709.1) followed by MG (393.8 ± 404.2) and PG (199.6 ± 136.8), and lowest in DG (108.8 ± 38.7). Thermokarst formation accumulated organic matter, and further flooding increased SOC. The SOC content was significantly, positively correlated with root C content, in all ecosystems. In the forest and arable land ecosystems, soil texture strongly affected SOC content, but water content was the main factor in SOC accumulation in the thermokarst ecosystem.

The SOC stocks in the 0–30 cm depth in land uses belong to the forest and arable land ecosystem in 2013, 2014, and 2015 was lower than the threshold level of 54.4 Mg C ha^{-1} 30 cm^{-1}. Therefore, the SOC stock may increase in the future. Conversely, the SOC stocks in the land uses belong to the thermokarst ecosystem in 2013, 2014, and 2015 were higher than the threshold level. Therefore, SOC stock may decrease in the future.

6. General discussion

The initial SOC level significantly controlled SOC change in both Toya and Central Yakutsk. The slope of the relationship between initial SOC stock and the ΔSOC stock in Toya and Central Yakutsk was higher and lower, respectively, than those estimated in previous studies. A positive correlation between the mean annual temperature or annual precipitation and the slope ($P = 0.08$ and $P < 0.01$, respectively) indicating that the smallest slope in Central Yakutsk indicated the high stability of SOC characterized by the lower NPP and slower OM decomposition under the low temperature and precipitation.

The threshold initial SOC content tended to decrease with increasing sampling depth, on the other hand, the threshold initial SOC stock increase with increasing sampling depth. Therefore, the comparison of the threshold initial SOC should be conducted in same soil sampling depth. Comparison with previous studies shows the threshold initial SOC content in the cropland tended to be lower than those in forest and grassland, indicating that land use affects the threshold level. It is identified that thermokarst activity, forest disturbance, land use change was significantly changed the SOC stock in this study. This may also change the threshold initial SOC stock. Among the cropland, the threshold initial SOC content that we obtained in Toya was the highest. This may be attributable to the specific feature of Andosol (humus accumulation by Al-OH complex) and continuous application of the OM in this region.

7. Conclusion

These results were indicating that the slope was controlled by the climate condition. And the threshold initial SOC was controlled by the sampling depth, land use, management practice, and soil types.

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Appendix

Table A.1

Description of the soil profiles of representative sites in 11 different types of land use in Central Yakutsk.

(a) Larch forest (LF), Soil type: Cambic Cryosol

				Coordinate:	62˚ 09’ 18.86” N, 130˚ 31’ 47.67” E		Site:	Ulakhan Sukkan, LF			Date:	2014/10/07
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Oi	-11	S, C	-----	None	-----	-----	-----	-----	-----	
2		Oae	-7	S, C	-----	None	-----	-----	-----	-----	-----	
3		A/Btk	10	S, G	-----	None	SiL	W, F, SBK	FR	SS	SP	
4		Btk	25	W C	-----	None	SiL	W, F, PL	FR	MS	MP	
5		Bt/Bk	50	W, G	-----	None	L	M, F, PL	FR	SS	SP	Whiter than the other horizons
6		BwC	100+		-----	None	SL	W, VF, PL	VFR	SSS	NP	
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	-----	-----	-----	
2	None	None	None	-----	-----	-----	
3	None	Clay conc.	None	M, VF~C, T	M, F~VF, VE & DTU	-	
4	None	Clay conc.	None	M, VF~M, T	M, F~VF, VE & DTU	++	
5	None	None	None	C, VF, P	M, VF, IR & DTU	++	
6	None	None	None	F, VF, P	M, VF, IR	-	
7							

(b) Burned larch forest (BF), Soil type: Cambic Cryosol

				Coordinate:	62˚ 08’ 38.76” N, 130˚ 31’ 52.19” E		Site:	Ulakhan Sukkan BF			Date:	2015/08/18
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	OaeA	4 2~7	IR –A	10YR 1.7/1	None	-----	-----	-----	-----	-----	
2		Bw	37	W, C	10YR 4/4	None	LS	VW, VF, PL	FR	SS	SP	
3		BgC	77	S, A	10YR 5/8	None	SL	VW, VF, PL	VFR	NS	NP	
4		Cg (G)	100		10YR 4/4	None	LS	NO	VFR	SS	SP	
5												
6												
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	M, VF~M, M	NO	-	
2	None	None	None	C, F, P	IR (Sand)	±	
3	Present (conc.)	Fe^{3+} conc.	None	VF, VF, P	IR (Sand)	-	
4	Present (conc. & dep.)	None	None	None	IR (Sand)	-	
5							
6							
7							

(c) Water damaged larch forest (WF), Soil type: Cambic Fluvisol

				Coordinate:	61˚ 55’ 59.76” N, 132˚ 29’ 11.88” E		Site:	Churapcha, WF			Date:	2015/08/15
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Oae	-4.5	S, A	10YR 4/4	None	-----	-----	-----	-----	-----	Could not divide into Oi and Oae
2		A	6	S, A	10YR 2/2	None	CL	W, F, GR	FR	MS	MP	
3		BwA	25	S, G	10YR 3/4	None	CL	M, F, PL	FR	MS	MP	
4		Bk	42	S, G	10YR 4/4	None	CL	M, F, PL	FR	MS	MP	
5		BkC/L	70	S, D	10YR 3/4	None	SiC	S, F, PL	FR	MS	MP	
6		C	100+		10YR 4/3	None	SiC	S, F~M, PL	FR	MS	MP	
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	M, VF, T		-	
2	None	None	None	C, F~M, T	M, F~VF, DT & VE	-	
3	None	None	None	C, F~M, T	M, F~VF, VE & DT	±	
4	None	None	None	F, M, T; F, F, P	M, VF, VE	++	
5	None	None	None	VF, F~VF, P	VM, VF, VE	++	
6	None	None	None	None	M, M, VF	±	
7							

(d) Pine forest (PF), Soil type: Cambic Spodosol

					Coordinate:	62˚ 15’ 5.59” N, 129˚ 37’ 16.76” E	Site:	Spasskaya-pad, PF		Date:	2014/10/16
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Matrix Color Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Consistence Stk ,	Consistence Pls	Notes
1	Small pit	Oi	-4	S, A	2.5Y 6/8	None	-----	-----	-----	-----	-----	
2		Oae	-3	S, C	2.5Y 3/2	None	-----	-----	-----	-----	-----	
3		E	31	S, C	2.5Y 6/3	None	LS	W, F, SBK & PL	-----	SS	SP	
4		Bw	52	S, C	2.5Y 5/4	None	LS	W F, PL	-----	SSS	SSP	
5		BwC	74	S, C	2.5Y 5/6	None	SL	VW, F, PL	VFR	NS	NP	
6		C	100+		2.5Y 5/2	None	S	SG	VFR	NS	NP	
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	-----	-----	-----	
2	None	None	None	-----	-----	-----	
3	None	None	None	M, F~C, T	M, VF, IR	±	
4	None	None	None	F, VF~F, T	M, VF, IR	-	
5	None	None	None	F, VF~F, T	M, VF, IR	-	
6	None	None	None	VF, VF, T	M, VF, IR	-	
7							

(e) Working arable land (WAL), Soil type: Umbric Cambisol

				Coordinate:	62˚ 09’ 25.33” N, 130˚ 38’ 03.67” E		Site:	Unakh, WAL			Date:	2014/08/18
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Ap1	20	S, C	10YR 4/3	None	SiL	W, F~M, SBK	FR	SS	MP	
2		AP2	22	S, C	10YR 4/3	None	SiL	M, F, SBK	FR	SS	MP	
3		Eb	35	S, C	10YR 6/3	None	SiL	W, F, SBK	FR	SS	SP	
4		Bw	42	S, C	10YR 5/4	None	SiL	W, F, SBK & PL	FR	MS	MP	
5		BwC	82	S, G	10YR 5/3	None	SiL	W, F, PL	FR	SSS	SSP	
6		C	100+		10YR 6/3	None	SL	SG	L	NS	NP	
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	M, F, T	M, F, VE	-	
2	None	None	None	C, F, T	C, F, VE & DTU	±	
3	None	None	None	F, VF, T	M, VF, VE & DTU	-	
4	None	None	None	VF, VF, P	M, VF, VE & DTU	-	
5	None	None	None	VF, VF, P	M, VF, VE	+	
6	None	None	None	Absent	M, VF, IR	±	
7							

(f) Abandoned arable land (AAL), Soil type: Umbric Cambisols

				Coordinate:	62˚ 09’ 29.28” N, 130˚ 39’ 28.87” E		Site:	Unakh, AAL			Date:	2014/08/19
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Ap1	7	S,C	10YR 5/3	None	SiL	W, F~M, SBK	FR	SS	SP	
2		AP2	22	S,C	10YR 5/3	None	SiL	W, F, SBK	M	SS	SP	
3		Bw1	30	W,C	10YR 6/6	None	SiL (SiCL)	W, F, SBK	FR	SS	MP	
4		E	39	S,G	10YR 7/2	None	SiL	W, VF, SBK & PL	FR	SSS	SSP	
5		Bkw	76	S,C	10YR 5/4	None	SiL	W, VF, PL	FR	SSS	SSP	
6		BwC	100+		10YR 6/4	None	SL	W, VF, PL	VFR	NS	NP	
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	Charcoal 2%	M,VF, T	M, VF, VE	-	
2	None	None	Charcoal 5%	C, VF, T	M, F, VE & DTU	-	
3	None	None	Charcoal 2%	F, VF, T	M, F, DTU	±	
4	None	None	None	F, VF, P	C, F, DTU	++	
5	None	None	None	Absent	M, VF, VE & DTU	++	
6	None	None	None	Absent	M, VF, IR	+	
7							

(g) Abandoned arable land invaded by new-growing trees (NAL), Soil type: Umbric Cambisols

					Coordinate:	62˚ 09’ 29.17” N, 130˚ 39’ 24.81” E	Site:	Unakh, NAL			Date:	2014/08/19
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Matrix Color Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Consistence Stk ,	Consistence Pls	Notes
1	Small pit	Oi	-2	S, A	2.5Y 4/3	None	-----	-----	-----	-----	-----	
2		AP1	6	S, G	10YR 5/3	None	SiL	W, VF, GR	M	SS	SP	
3		AP2	24	S, C	10YR 5/3	None	SiL	W, F, SBK	FR	SS	P	
4		Bw/E	31	S, C	10YR 5/6	10YR 7/3	SiL	W, F, SBK	FR	SS	SP	
5		Bwk	57	S, G	10YR 6/4	None	SiL	W, F, SBK	FR	SSS	SSP	
6		BwC	100+		10YR 6/4	None	SL	W, VF, PL	VFR	NS	NP	
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	-----	-----	-----	
2	None	None	None	M, F, T	M, VF, VE	+	
3	None	None	Charcoal 2~3%	C, VF~F, T	M, F, DTU & VE	+	
4	None	None	None	F, VF, P	M, VF, DTU & VE	+	
5	None	None	None	F, VF, P	M, VF, DTU & VE	++	
6	None	None	None	VF, VF, P	M, VF, VE	+	
7							

(h) Dry grassland (DG), Soil type: Endogleyic Stagnosol

					Coordinate:	62˚ 09’ 14.11” N, 130˚ 31’ 46.51” E		Site:	Ulakhan Sukkan, DG			Date:	2014/08/17
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes	
1	Small pit	Root mat	2	S, C	10YR 3/2	None	SL	W, VF,GR	VFR	NS	NP		
2		A	10	W,G	10YR 3/2	None	SL	W,F, SBK	VFR	NS	NP		
3		Bk/A	45	W, C	7.5YR 6/6	10YR 6/3	SL	M, F, PL	VFR	NS	NP		
4		Bgk/L	84	W, C	10YR 5/3	10YR 2/1	SL (SiL)	W, F, PL	FR	NS	NP		
5		Btk	100		10YR 4/4	None	SiL	VW, VF, PL	VFR	SS	SP		
6													
7													

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	M, VF~F, M	M, VF~F, IR	-	
2	None	None	None	M, VF, T	M, VF~F, IR	-	
3	Present (conc.)	Fe^{3+} conc.	None	C, VF~F, T	M, VF~F, IR	+++	
4	Present (conc. & dep.)	Fe^{3+}, Mn conc.	None	VF, VF, T	M, VF~F, IR	+++	
5	Present (conc. & dep.)	Clay, Fe^{3+}, Mn conc.	None	VF, VF, T	-----	++	
6							
7							

(i) Moderately wet grassland (MG), Soil type: Cambic Fluvisol

				Coordinate:	62˚ 09’ 13.3” N, 130˚ 31’ 47.89” E		Site:	Ulakhan Sukkan, MG			Date:	2014/08/17
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Root mat	2	S, C	10YR 2/1	None	SiL	W, VF, GR	VFR	SS	SP	
2		A	16	S, G	10YR 2/1	None	SiL	W,F, SBK	FR	SS	SP	
3		ABkw	28	IR, C	10YR 3/2	None	SL	W, F, SBK	VFR	NS	NP	
4		Bg (G)	60	IR, G	10YR 6/3	None	SL	-----	VFR	NS	NP	
5		BgC	100		-----	-----	S	-----	-----	-----	-----	
6												
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	M, VF, M	M, VF, IR & VE	±	
2	None	None	None	M, VF, T	M, VF,IR & VE	±	
3	Slightly present (conc.)	Fe^{3+} conc. (Slightly)	None	C, VF, T	M, VF, IR & VE	++	
4	Present (conc. & dep.)	Fe^{3+} conc.	None	VF, VF, T	-----	+	
5	Present (conc. & dep.)	-----	-----	-----	-----	-----	
6							
7							

(j) Wet grassland (WG), Soil type: Limnic Histosol

				Coordinate:	62° 09’ 12.95” N, 130° 31’ 48.5” E		Site:	Ulakhan Sukkan, WG			Date:	2014/08/17
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Root mat	3	S, C	10YR 2/1	None	L ~ SL	W, VF, GR	FR	SS	SSP	
2		A (L1)	15	S, G	10YR 2/1	None	L ~ SL	W, VF, GR	FR	SS	SSP	
3		AB (L2)	50		10YR 3/1	None	SL	VW, F, SBK	-----	NS	NP	
4												
5												
6												
7												

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	Slightly present (conc.)	None	None	M, F~VF, T	M, VF, IR	+	
2	Present (conc. & dep.)	None	None	F, F~VF, T	M, VF, IR	++	
3	Present (conc. & dep.)	None	None	VF, VF, T	-----	++	
4							
5							
6							
7							

(k) Pingo (PG), Soil type: Umbric Cambisols

				Coordinate:	62˚ 09’ 44.28” N, 130˚ 37’ 47.91” E		Site:	Khonnoror, PG			Date:	2014/08/16
	Obser. Method	Horizon	Depth (cm)	Bnd	Matrix Color Main	Sub	Texture	Structure Grade , Sz , Type	Consistence Mst ,	Stk ,	Pls	Notes
1	Small pit	Root mat	4	S, A	10YR 2/3	None	-----	M, VF, GR	-----	-----	-----	
2		A	8	W, A	10YR 2/3	None	SL	W, VF, GR	FR	SS	SP	
3		Bw1	25 (15~35)	IR, C	10YR 5/6	None	LS	VW, VF, GR	VFR	NS	NP	
4		Bk1	30 (20~40)	IR, C	10YR 4/4	None	LS	VW, VF, GR	VFR	NS	NP	
5		Bw2	50 (45~55)	W, C	10YR 5/6	None	LS	VW, VF, GR	VFR	NS	NP	
6		Bk2	55 (50~60)	W, C	10YR 6/3	None	LS	VW, VF, GR	VFR	NS	NP	
7		BkC	100+		10YR 5/4	None	LS	SG	L	NS	NP	

	Redoximorphic features	Concentrations	Ped / V. Surface Features	Roots Qty, Sz , Loc	Pores Qty , Sz , type	Reaction for 10 % HCL	Notes
1	None	None	None	M, F, T	M, VF, IR	-----	
2	None	None	None	M, VF~F, T	M, VF, IR	-----	
3	None	None	None	M, VF~F, T	M, VF, IR	±	
4	None	Presence of shell	None	M, VF~F, T	M, VF, IR	++	
5	None	None	None	M, VF, T	M, VF, IR	++	
6	None	Presence of shell	None	C, VF, T	M, VF, IR	+++	
7	None	None	None	C, VF, T	M, VF, IR	++	

Description of profiles and abbreviations were described based on the field book for describing and sampling soils ver. 3.0 (Schoeneberger et al., 2012). (a): Larch forest, (b): Burned larch forest, (c): Water damaged larch forest, (d): Pine forest, (e): Working arable land, (f): Abandoned arable land, (g): Abandoned arable land invaded by new-growing trees, (h): Dry grassland, (i): Moderately wet grassland, (j): Wet grassland, (k): Pingo.

Table A.2

Soil organic carbon stocks in the 0–30 30–100, and 0–100 cm soil layers in Central Yakutsk.

Ecosystem	Land use	SOC stock (Mg C ha^{-1})											
		0–30 cm				30–100 cm				0–100 cm			
		n	Mean	SD		n	Mean	SD		n	Mean	SD	
Forest	LF	33	28.8	11.2	b	15	37.8	12.2	b	15	69.7	20.5	b
	BF	9	23	5.9	ab	3	33.6	9.9	ab	3	54.7	10.7	ab
	WF	5	49.8	20.1	c	3	54.6	23.8	b	3	93.6	40.6	b
	PF	6	15.3	1.7	a	4	12.2	2.3	a	4	27	1.5	a
Arable land	WAL	11	29.8	8.9	a	5	28.3	7.3	a	5	59.4	8.7	ab
	AAL	38	49.5	17	b	20	41.4	22.4	a	20	91.8	36.6	b
	NAL	13	29.8	3.9	a	7	28.5	4.1	a	7	59.2	3.7	a
Thermokarst	DG	25	56.1	22.5	a	8	52	27.1	a	8	108.8	38.7	a
	MG	10	248.7	168.6	c	3	128.5	212.9	a	3	393.8	404.2	a
	WG	16	205.3	143.9	bc	5	283.2	486.9	a	5	520.8	709.1	a
	PG	12	121.9	54.2	ab	4	86.8	89	a	4	199.6	136.8	a
Forest		53	28.3	13.5	A	25	35.2	16.8	AB	25	64	27.6	A
Arable land		62	41.9	16.9	A	32	36.5	19	A	32	79.6	33	A
Thermokarst		63	137.1	125.5	B	20	128.2	255.6	B	20	272.7	396.9	B
Mean		178	71.5	89.8		77	59.9	135		77	124.6	218.9	

Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. SOC: Soil organic carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A.3

Soil carbonate carbon stock in the 0–30 30–100, and 0–100 cm soil layers in Central Yakutsk.

Ecosystem	Land use	SCC stock (Mg C ha^{-1})											
		0–30 cm				30–100 cm				0–100 cm			
		n	Mean	SD		n	Mean	SD		n	Mean	SD	
Forest	LF	33	6.2	6.7	a	15	39.1	29.2	a	15	48.2	32.5	a
	BF	9	5	6.3	a	3	32.2	31.3	a	3	36.4	30.7	a
	WF	5	11.4	6.9	a	3	89.3	42.4	a	3	99.5	38.3	a
	PF	6	18.5	20.2	a	4	68.5	45.8	a	4	96.2	64.1	a
Arable land	WAL	11	4.2	6.7	a	5	40.1	31.5	a	5	45.6	38.4	a
	AAL	38	15.8	13.5	a	20	60.8	85.7	a	20	77.1	85.9	a
	NAL	13	8.7	7.8	a	7	33	18.6	a	7	44.5	17.7	a
Thermokarst	DG	25	15.5	11.7	b	8	30.9	21.1	a	8	47.3	30.9	a
	MG	10	18.2	12.9	b	3	18.1	26.4	a	3	42.7	16.8	a
	WG	16	14	10.8	ab	5	17.7	20	a	5	30.7	32.2	a
	PG	12	4.1	3.1	a	4	4.8	2.3	a	4	10.1	4.5	a
Forest		53	7.9	9.7	A	25	49	36.8	A	25	60.6	43.6	A
Arable land		62	12.3	12.3	AB	32	51.5	69.6	A	32	65.1	70.9	A
Thermokarst		63	13.4	11.4	B	20	20.4	20.6	A	20	35	28.5	A
Mean		178	11.4	11.4		77	42.6	51.8		77	55.8	54.9	

Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. SCC: Soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A.4
Litter carbon stock in the organic horizon in Central Yakutsk.

LIC stock (Mg C ha^{-1})					
Ecosystem	Land use	Organic horizon			
		n	Mean	SD	
Forest	LF	27	18.5	7.7	b
	BF	9	8.5	7.2	a
	WF	5	8.7	7	a
	PF	6	6.5	3.4	a
Arable land	WAL	0	0	0	0
	AAL	0	0	0	0
	NAL	9	1.6	0.6	a
Thermokarst	DG	0	0	0	0
	MG	0	0	0	0
	WG	0	0	0	0
	PG	0	0	0	0
Forest		-	-	-	-
Arable land		-	-	-	-
Thermokarst		-	-	-	-
Mean		-	-	-	-

Different lowercase letters indicate significant differences between land use types in the same ecosystem. LIC: Litter carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A.5
Total soil carbon stock in the 0–30 30–100, and 0–100 cm soil layers in Central Yakutsk.

Ecosystem	Land use	TSC stock (Mg C ha^{-1})											
		0–30 cm				30–100 cm				0–100 cm			
		n	Mean	SD		n	Mean	SD		n	Mean	SD	
Forest	LF	33	54.4	20.7	ab	15	76.9	34.7	a	15	139.4	47.2	a
	BF	9	36.4	10	a	3	65.8	40.2	a	3	96.9	37.6	a
	WF	5	69.9	24.1	b	3	143.9	53	a	3	203.1	61.8	a
	PF	6	40.3	17.9	ab	4	80.7	47.7	a	4	128.7	64.3	a
Arable land	WAL	11	34	13.1	a	5	68.4	29.8	a	5	105	42.5	a
	AAL	38	65.4	22.1	b	20	102.2	92	a	20	168.9	97.8	a
	NAL	13	40.4	9.3	a	7	61.5	17.7	a	7	105.8	17.2	a
Thermokarst	DG	25	71.5	26.5	a	8	82.8	28.2	a	8	156.2	48.2	a
	MG	10	266.9	162.6	c	3	146.6	239.1	a	3	436.5	421	a
	WG	16	219.4	138.9	bc	5	300.8	485.7	a	5	551.5	703.2	a
	PG	12	125.9	54.5	ab	4	91.6	90.4	a	4	209.7	137	a
Forest		53	51.2	21.1	A	25	84.2	43.3	A	25	140.2	54.8	A
Arable land		62	54.6	23.1	A	32	88	75.6	A	32	145.1	84.4	A
Thermokarst		63	150.5	123.9	B	20	148.7	256.7	A	20	307.7	395.6	B
Mean		178	87.5	88.7		77	102.5	142		77	185.7	220	

Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. TSC: Total soil carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A.6

Composition ratio of carbon stocks in the 0–30, 0–100 and 0–100 cm soil layers in Central Yakutsk.

Ecosystem	Land use	0–30 cm depth							30–100 cm depth							0–100 cm depth						
			LIC (%)		SOC (%)		SCC (%)			LIC (%)		SOC (%)		SCC (%)			LIC (%)		SOC (%)		SCC (%)	
		n	Mean	SD	Mean	SD	Mean	SD	n	Mean	SD	Mean	SD	Mean	SD	n	Mean	SD	Mean	SD	Mean	SD
Forest	LF	31	37.9	11.1	52.3	11.7	9.8	8.1	13	0.0	0.0	61.8	23.1	38.2	23.1	13	18.3	7.5	52.8	11.7	28.9	15.5
	BF	9	22.0	13.2	66.5	18.5	11.5	10.7	3	0.0	0.0	60.1	26.9	39.9	26.9	3	7.8	8.1	59.5	12.0	32.7	19.9
	WF	5	13.1	14.2	71.8	20.0	15.1	7.9	3	0.0	0.0	38.9	11.3	61.1	11.3	3	6.2	7.4	45.2	7.7	48.6	10.5
	PF	6	19.5	13.2	47.7	26.3	32.8	35.9	4	0.0	0.0	33.6	41.9	66.4	41.9	4	6.8	6.9	33.1	32.4	60.0	39.3
Arable land	WAL	11	0.0	0.0	90.5	11.0	9.6	11.0	5	0.0	0.0	48.4	21.4	51.6	21.4	5	0.0	0.0	62.3	18.3	37.7	18.3
	AAL	38	0.0	0.0	77.5	15.8	22.5	15.8	20	0.0	0.0	50.8	21.9	49.2	21.9	20	0.0	0.0	60.2	17.6	39.8	17.6
	NAL	10	5.7	4.4	76.3	16.4	18.0	14.8	4	0.0	0.0	59.7	26.3	40.3	26.3	4	3.3	3.4	61.9	16.7	34.8	14.7
Thermokarst	DG	25	0.0	0.0	79.1	15.5	20.9	15.5	9	0.0	0.0	63.3	19.6	36.7	19.6	9	0.0	0.0	70.8	17.0	29.2	17.0
	MG	10	0.0	0.0	91.0	6.7	9.0	6.7	4	0.0	0.0	79.4	26.4	20.6	26.4	4	0.0	0.0	86.4	6.0	13.6	6.0
	WG	16	0.0	0.0	90.6	9.4	9.4	9.4	6	0.0	0.0	86.0	17.5	14.0	17.5	6	0.0	0.0	89.3	13.4	10.7	13.4
	PG	12	0.0	0.0	96.4	2.7	3.6	2.7	4	0.0	0.0	92.1	4.3	7.9	4.3	4	0.0	0.0	93.8	2.9	6.2	2.9

LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A.7

Root carbon stock in 0–30, 30–50, and 0–50 cm soil layer in Central Yakutsk.

Ecosystem	Land use	Root carbon stock (Mg C ha^{-1})											
		0–30 cm				30–50 cm				0–50 cm			
		n	Mean	SD		n	Mean	SD		n	Mean	SD	
Forest	LF	5	0.88	0.43		5	0.20	0.20		5	1.08	0.52	
	BF	0	-	-		0	-	-		0	-	-	
	WF	0	-	-		0	-	-		0	-	-	
	PF	0	-	-		0	-	-		0	-	-	
Arable land	WAL	3	0.17	0.04	a	3	0.02	0.01	a	3	0.19	0.05	a
	AAL	6	0.33	0.17	a	6	0.02	0.02	a	6	0.35	0.18	a
	NAL	3	0.34	0.04	a	3	0.03	0.01	a	3	0.36	0.05	a
Thermokarst	DG	5	0.14	0.09	a	5	0.01	0.00	a	5	0.15	0.10	a
	MG	3	0.49	0.16	ab	3	0.03	0.03	a	3	0.52	0.19	ab
	WG	3	1.04	0.61	b	3	0.36	0.34	a	3	1.4	0.94	b
	PG	4	0.47	0.4	ab	4	0.09	0.14	a	4	0.56	0.53	ab
Forest		5	0.88	0.43	B	5	0.20	0.20	A	5	1.08	0.52	B
Arable land		12	0.29	0.14	A	12	0.02	0.01	A	12	0.31	0.15	A
Thermokarst		15	0.48	0.45	AB	15	0.10	0.20	A	15	0.58	0.64	AB
Mean		32	0.47	0.40		32	0.09	0.16		32	0.56	0.54	

Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. TSC: Total soil carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.