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Using surface soil layer depth for determining soil quality index for evaluating productivity of potato (*Solanum tuberosum* L.) in Hokkaido, Japan

Running title:

Soil quality index to evaluate productivity

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ABSTRACT

A comprehensive quantification of soil quality is necessary for data-driven soil management, and numerous studies have sought to devise methods for determining the soil quality index (SQI) to assess soil productivity. However, most studies have focused on topsoil properties rather than deeper soil properties. Therefore, this study attempted to calculate the SQI by incorporating subsoil properties and surface soil layer depth and topsoil properties, targeting farms cultivating potatoes in Tokachi region, Hokkaido. The soil parent material in this region is primarily composed of a mixture of alluvial deposits, volcanic ash, and peat, which makes the comparison between the various soil properties difficult for evaluation by farmers. Principal component analysis (PCA) and regression analysis were used to select the minimum data set (MDS) representing the variance of the original data set: exchangeable Ca, K, pH, solid phase, and acid-soluble Cu in descending order of weight. Weights were allocated based on the eigenvalues of the principal components. This study selected MDS's parameters from properties with soil diagnosis criteria based on past research on productivity evaluation. The selected parameters contained both physical and chemical properties, which indicated that the soil quality was evaluated from both aspects. For surface soil layer depth consideration, the corrected SQI was calculated by reducing more when the depth was shallower. SQI considering subsoil properties did not correlate with yield ($r = 0.358$), but SQI considering surface soil layer depth was significant ($r = 0.515$ - 0.518) regardless of the soil type (parent material) and cultivar. Correlations between SQI considering depth and yield were stronger when considering a single cultivar with the greatest number of sites ($r = 0.620$ - 0.641). A deeper surface soil layer depth would provide more macropores to plant roots and improve the availability of air, greatly affecting soil quality in the Tokachi region, where precipitation is high during the growth season. Therefore, this study reveals the importance of considering the surface soil layer depth to evaluate soil productivity using the SQI.

Keywords:

surface soil layer depth, multivariate analysis, potato yield, productivity, soil quality index

1. INTRODUCTION

Soil quality is defined as ‘the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health’ (Doran and Parkin 1994).

To evaluate soil quality, a quantitative formula and conceptual framework have been proposed, which suggested that soil quality should be evaluated based on soil functions (Doran et al. 1996, Karlen et al. 1997). Subsequently, soil quality has been recognized as an important tool for evaluating various agricultural systems worldwide (Bouma and Droogers 1998, Andrews et al. 2002a, Armenise et al. 2013, Mukherjee and Lal 2014).

However, one of the limiting aspects of soil quality evaluation is the lack of a universally accepted method for developing soil quality indices. Currently, new indices are excessively developed, although they seem to be endemic and unjustified, which implies that researchers should evaluate the suitability of existing indices before developing them (Qi et al. 2009).

The soil quality index (SQI) is obtained by integrating different soil property indicators. It is important to consider all information about the study area and expert opinions to select indicators for the SQI (Andrews et al. 2004). However, it is necessary to develop evaluation methods that use a minimum number of indicators to reduce labor time, work efficiency, and expenses. A minimum data set (MDS) was selected from a total data set (TDS) using methods such as principal component analysis (PCA) (Mukherjee and Lal 2014, Armenise et al. 2013) and factor analysis (Shukla et al. 2006) and the high consistency of the two datasets (MDS and TDS) was highlighted for soil quality evaluation.

To date, most studies on soil quality evaluation have been based on topsoil horizon (less

than 30 cm depth) properties (Andrews et al. 2002b, Andrews et al. 2002a, Armenise et al. 2013, Rahmanipour et al. 2014, Liu et al. 2014). Studies that evaluate the SQI from the full soil profile are limited (Vasu et al. 2016, Zhijun et al. 2018, Santos-Francés et al. 2019, Zhou et al. 2022), but these studies imply the importance of considering subsoil properties for soil quality assessment. It is easy to measure the properties of the superficial soil layer. However, these properties provide incomplete information, because soil functions are driven by pedogenic processes in the soil control section. Soil quality evaluation using both topsoil and subsoil properties will help identify the soil properties that have the maximum influence on soil functions.

Crop growth and harvest volume depend on soil conditions for the extension of their roots. Surface soil layer depth may influence productivity both directly and indirectly. Depth suppresses root growth and prevents the uptake of water and nutrients directly, as a depth below horizon is very hard. Depth also indirectly restricts the total content of water and nutrients in the rhizosphere (Tsunekawa et al. 1997, Nakatsuka and Tamura 2016). The correlation between crop yield and SQI calculated using topsoil properties was significant for soil types with shallow surface soil layer depth, but not for deep soil depth (Yoshimura et al., 2022). Rhoton and Lindbo (1997) suggested surface soil layer depth as a single attribute to express soil quality, based on the relationship between yield and soil properties within a region with different surface soil layer depths. The productivity index (PI) was estimated as the sum of productivity in each soil horizon of the 0–100 cm profile corrected according to the depth (Pierce et al. 1983, Duan et al. 2009). However, the PI did not consider the weight of parameters, nutrient content, and surface soil layer depth. Therefore, the developing of SQI considering surface soil layer depth is necessary to assist farmers in soil management by assessing factors dedicated to SQI.

Tokachi District in Hokkaido is one of the largest upland field areas in Japan. The area of upland fields measures almost 254,600 ha, and the major crops are wheat, sugar beets, potatoes, and pulses, which are cultivated in rotation. Farmers in this region make decisions for soil management based on the results of soil property analysis, but they only compare these to soil diagnosis criteria, and it is difficult to judge which field or indicator requires more intense improvement. The soil parent material in this region is primarily composed of alluvial deposits, and volcanic ash and a mixture of these (Niwa et al. 2008), which makes soil properties varied and difficult to compare for evaluation by farmers. This region has a federation of agricultural cooperatives that undertakes soil analysis for farmers and manages the results linked to the locations. Therefore, it is necessary to develop a productivity evaluation method by developing a soil quality assessment and establishing a decision support system for effective soil management by comparing the contribution of soil properties to soil quality. The objectives of this study were: (1) to evaluate productivity using SQI considering surface soil layer depth and (2) to discuss which soil property including surface soil layer depth was more important to evaluate soil productivity. In this study, the soil quality was benchmarked by productivity.

2. MATERIALS AND METHODS

2.1. Site description

The study was carried out in Makubetsu Town (42° 54' 31" N, 143° 21' 21.9" E), located in the central part of Tokachi district, and the area of upland fields measured almost 22,500 ha. The climate was characterized as winter with little snow and summer with heavy rain, with climatological normal annual precipitation and annual average temperatures of 920 mm and 7.2°C, respectively. The precipitation during summer (July,

August, and September) and winter (December, January, and February) was 390 mm and 122 mm, respectively. The maximum soil frozen depth in this region has decreased since the late 1980s because of increasingly common early onset of deep snowpack inducing thermal insulation, which has made the maximum soil frozen depth less than 20 cm since 2000 (Hirota et al. 2006, Shimoda and Hirota 2018). Table 1 showed a summary of the research sites. The research was conducted at 23 sites cultivating potatoes (*Solanum tuberosum* L.), including three cultivars: Sayaka, Toyoshiro, and Waseshiro, in 2020. The study sites were divided into four types, depending on their parent materials, based on Niwa et al. (2008). The sites had Brown Lowland soils, Andosols with alluvial deposits (mainly Haplic Fluvisols in the World Reference Base for Soil Resources (WRB)), Andosols (mainly Umbric Andosols in the WRB), and peat soil (mainly Andic Histosols in the WRB). In soil diagnose, Andosols is defined as the soil with phosphate absorption coefficients exceeding 15,000 mg P₂O₅ kg⁻¹. None of the study sites had serious damage due to common scabs of potato.

2.2. Yield data

Yield data were obtained by interviewing the agricultural cooperative in Makubetsu city. The cooperative collects yield data on potatoes delivered per site. However, it is possible that in some cases, farmers may not deliver all potatoes harvested from a single site to the cooperative, but rather to other retailers. Therefore, we ensured that all targeted sites delivered all potatoes to the cooperative. Yield data was determined as the total weight of potatoes delivered to the cooperative, including imperfect potatoes intended for commercial use.

2.3. Soil sampling and analysis

Soil samples were collected on 5–8 Oct. 2021, one year after harvest, at depth of 0–30 and 30–60 cm. These two depths were chosen because of the practicality of visit lots of farms and the difficulty in classifying soil layers in every farm. In this study, topsoil and subsoil were defined as 0–30 cm and 30–60 cm depth soil, respectively. Disturbed soil samples were air-dried and passed through 2 mm sieves before chemical analysis. The pH was determined using the glass electrode method (1:2.5 soil: water suspension). Available phosphate was determined using the Truog method (Truog 1930). The phosphate absorption coefficient was determined as the difference between the original phosphate solution concentration and that of the filtrate of the soil and di-ammonium hydrogen phosphate ((NH₄)₂HPO₄) suspension (Araki et al. 1986). The cation exchange capacity (CEC) and exchangeable cations (calcium (Ca), magnesium (Mg), and potassium (K)) were determined using the Schollenberger method (Schollenberger and Simon 1945). Hot-water dissolved boron (B) was determined as the concentration of filtrate of soil and hot-water suspension using the azomethine H method (Gaines and Mitchell 1979). Easily reducible manganese (Mn) was determined using 1 mol L⁻¹ ammonium acetate, including hydroquinone extraction (Sherman et al. 1942). Acid-soluble zinc (Zn) and copper (Cu) were determined using 0.1 mol L⁻¹ hydrochloric acid extraction. The soil texture was measured using the pipette method (Gee and Or 2002). Total carbon were determined using the dry combustion method (SUMIGRAPH NC-TRINITY, Sumika Chemical Analysis Service, Tokyo, Japan). Intact soil samples were subjected to physical analysis. Macropores were determined as pores with < -3.1 kPa. Available moisture was determined as the percentage difference between < -98.1 and < -3.1 kPa. The bulk density and solid phase were determined using a digital volumenometer (DIK-1110, Daiki Rika Kogyo, Saitama, Japan). The surface soil layer depth was defined as the depth until compacted layer with 10 cm or more. The compacted layer depth was defined as the depth with more than 1.5

MPa penetration resistance using a digital cone penetrometer (DIK-5532 i penetrometer, Daiki Rika Kogyo, Saitama, Japan).

2.4. Evaluation of the soil quality index

Indicators for SQI estimation were selected and weighted using principal component analysis (PCA) based on Klimkiewicz-Pawlas et al. (2019) and Mukherjee and Lal (2014). The dataset consisted of selected indicators defined as minimum data sets (MDS).

2.4.1. Minimum data set selection

Properties with criteria in the Hokkaido Fertilizer Recommendations 2020 were the candidates for MDS indicators, except for surface soil layer depth due to SQI, which were calculated for each soil depth (Hokkaido Government Department of Agriculture 2020). Indicators were selected using PCA to reduce information loss by integrating many indicators into a few principal components (PC). MDS selected PCs with eigenvalues greater than 1.0, and indicators with a maximum eigenvector of more than 90% in each PC (Wander and Bollero, 1999). However, in cases where indicators had significant correlations, the one with a lower eigenvalue or vector was removed to reduce dataset redundancy.

2.4.2. Indicator scores

Indicators were converted to unitless scores between 0–1, using scoring functions. The functions gave a lower score if the property was farther from the criterion. The functions were classified into three types: (1) ‘more is better’, (2) ‘less is better’ and (3) ‘optimum’. The ‘more is better’ function gave a score referencing Eq. (1):

$$Score = \begin{cases} \frac{X}{L} & X < L \\ 1 & L \leq X \end{cases} \quad (1)$$

where X is the observation of the property, L is the lower threshold of the property. The ‘less is better’ function gave a score referencing Eq. (2):

$$Score = \begin{cases} 1 & X < U \\ \frac{U}{X} & U \leq X \end{cases} \quad (2)$$

where U is the upper threshold of the property. The ‘optimum’ function gave a score referencing Eq. (3):

$$Score = \begin{cases} \frac{X}{L} & X < L \\ 1 & L \leq X < U \\ \frac{U}{X} & U \leq X \end{cases} \quad (3)$$

Table 2 shows the function type and threshold that were determined by referencing the soil diagnosis criteria in Hokkaido (Hokkaido Government Department of Agriculture 2020). Generally, the criteria of soil properties are applied only for topsoil. However, this study also applied subsoil to the criteria because it could contribute to crop growth in the same way as topsoil if it facilitates root growth. However, available phosphate was scored as a ‘more is better’ function because Takahashi et al. (1980) reported 3000–5000 mg P_2O_5 kg^{-1} available phosphate could cause excess symptoms, and the samples did not have high concentrations.

2.4.3. Weight allocation and soil quality index

The weight of each indicator was given as a percentage by dividing the eigenvalue of a PC by the total eigenvalue of the selected PCs in MDS, which means that the more variance the indicator had, the more weight it had. If several indicators were selected from the PC, the weights were divided equally.

SQI was calculated as the sum of weighted scores referencing Eq. (4):

$$SQI = \sum_{i=1}^n W_i N_i \quad (4)$$

where W_i is the weight of each indicator, N_i is the indicator score and n is the number of

indicators.

2.5. Consideration of surface soil layer depth on SQI

The field SQI was evaluated by integrating the SQIs in each horizon. In addition, it was assumed that a shallower surface soil layer depth results in less productivity because plant roots are less able to access essential resources such as air, water, and nutrition. Therefore, SQI was integrated at two depths and corrected by surface soil layer depth (depth-corrected SQI) to treat the deeper surface soil layer with better quality, as shown in Eq. (5):

Depth corrected SQI

$$= \begin{cases} \frac{SQI_{0-30} + SQI_{30-60}}{2} & 60 \leq D \\ \frac{SQI_{0-30} + SQI_{30-60} \left(\frac{D-30}{30}\right)}{2} & 30 \leq D < 60 \\ \frac{SQI_{0-30} \left(\frac{D}{30}\right)}{2} & D \leq 30 \end{cases} \quad (5)$$

where SQI_{0-30} and SQI_{30-60} are SQI at 0-30 and 30-60 cm depth, respectively, and D is the surface soil layer depth (cm).

Taking samples from the subsoil is labor-intensive for large-scale research, which could be a major hurdle in evaluating soil quality on a large scale. To address this challenge, a simplified version of the depth-corrected SQI (simple-corrected SQI) was calculated which did not require samples from the subsoil, using Eq. (6):

$$Simple\ corrected\ SQI = \begin{cases} SQI_{0-30} & 50 \leq D \\ SQI_{0-30} \left(\frac{D}{50}\right) & D < 50 \end{cases} \quad (6)$$

The SQI was corrected by referring to the threshold of the effective soil depth (50 cm) in the soil diagnosis criteria.

2.6. SQI relation to crop productivity

The yield was transformed to cultivar-adjusted yield, divided by the average of each cultivar, to remove the effect of cultivar on productivity. The ability of SQI to evaluate soil productivity was validated by calculating Pearson's correlation coefficient between SQI and cultivar-adjusted yield. This study applied SQI_{0-30} , the average of SQI_{0-30} and SQI_{30-60} (depth-averaged SQI), depth-corrected SQI, and simple-corrected SQI to validate productivity.

2.7. Statistical analysis

The R version 4.0.2 (R Core Team 2021) was used for statistical analyses. The impact of soil type or cultivar on yield was analyzed using two-way analysis of variance (ANOVA) and multiple comparison tests employing the Tukey-Kramer method. The influence of soil type and depth on soil properties, scores, and SQI was analyzed via repeated measures ANOVA with depth as a within-subject factor and soil type as a between-subject factor, with multiple comparison tests conducted using the Shaffer method. The effect of soil type on the depth of the surface soil layer was analyzed via ANOVA utilizing the Kruskal-Wallis method (a non-parametric test) due to the inclusion of depth data exceeding 60 cm. The data in Andosols with alluvial deposits was excluded from the analysis due to only one field in this study. All tests were conducted at a significance level of 5%.

3. RESULTS

3.1. Meteorological condition, yields, and soil properties

The cumulative precipitation in 2020 amounted to 716 mm, with a summer total of 292 mm (July, August, and September) representing 77.8% and 74.9% of the climatological normal, respectively. The monthly average temperature during the summer of 2020

remained consistent with the climatological normal except for August; it was 1.7 °C higher in 2020 than in the normal.

In Tokachi region, the average potato yield in 2020 was 3440 g m⁻², which was almost the same as the average of 2011-2020 (3459 g m⁻²). At the study sites, Sayaka yielded 3957 g m⁻², which was significantly higher than that of the other cultivars (Table 3). Soil type did not significantly affect yield.

The soil textural classes of the sites were classified as HC, LiC, CL, SCL, and L, referring to the soil particle range system of the International Soil Science Society (Table 1). Most of the soil was clayey soil (15-45% clay), regardless of the topsoil or subsoil. The total carbon content (average of two depths) was high in peat soils, with a large range in Andosols and a moderate range in others.

Table S1 shows soil properties. Andosols had higher pH and more exchangeable K than peat soils and the least available phosphate of all. Peat soils had more exchangeable Ca than Andosols and most hot-water dissolved B of all. Solid phase and bulk density were higher in Brown Lowland soils but macropore was not different among soil types. Available moisture was the most in peat soils of all. Surface soil layer depth did not have significant difference among soil types.

In comparison of depth, the subsoil had higher solid phase, bulk density and fewer macropores. In Andosols, the subsoil contained more hot-water dissolved B compared to the topsoil, despite the fact that their average values were nearly equivalent.

3.2. Principal component analysis

The results obtained from PCA indicated presence of four PCs with eigenvalues greater than 1.0 (Table 4), and soil variables from each PC were considered for the MDS. These four PCs accounted for > 70% of the total variation (Table 4). The four PCs explained

33%, 18%, 15%, and 10% of the total variance, respectively. The soil parameters selected from PC 1 were exchangeable Ca and Mg. However, a significant correlation between these parameters was observed (Table 5), and only Ca, which had the highest factor loading, was retained in the MDS. Exchangeable K and pH values were chosen from PC 2, and after the correlation (Table 5), they were included in the MDS because they were independent of each other. From PC 3, the solid phase and macropores were selected, and only the solid phase was considered as an indicator based on correlation (Table 5). Acid-soluble Cu was selected as an indicator of PC 4. Finally, MDS included exchangeable Ca, K, pH, solid phase, and acid-soluble Cu, in the order of PC and their weights were 43.4, 11.9, 11.9, 19.4, and 13.4, respectively.

3.3. Weighted scores and SQI

Fig. 1 shows the distribution of the weighted scores in the MDS parameters. The highest variance in weighted scores was observed for Ca (60.3), followed by that of acid-soluble Cu (11.4). Less weighted values, such as pH and exchangeable K, had smaller variances in weighted scores (0.13, 2.05, respectively). Despite being the second most heavily weighted physical parameter in MDS, the weighted score of the solid phase had a relatively small variance (3.03). Repeated measures ANOVA revealed that depth did not have a significant impact on the weighted scores of all parameters of MDS and SQI, however, soil type had a significant effect on the weighted scores of pH and exchangeable K (Table 6). The score of pH in peat soils was the lowest among soil types though that of solid phase was not significantly different among soil types by multiple comparison.

Fig. 2 shows the SQI values calculated by different methods. Median SQI values of each soil type were higher in methods not considering surface soil layer depth (SQI in 0-30 cm and depth-averaged SQI), especially in Andosols with alluvial deposits and Brown

Lowland soils.

3.4. Relationship between yield and corrected SQI

Fig. 3 shows the relationships between SQI and the yield of all cultivars. The simple-corrected SQI and depth-corrected SQI had a significant positive correlation with yield ($r = 0.518, 0.515, p < 0.05$, respectively), although SQI_{0-30} and depth-averaged SQI did not ($r = 0.370, 0.358, p = 0.082, 0.093$, respectively).

Fig. 3 also shows the relationships between SQI and yield of Sayaka, which had the most sites of the three. In concordance with the results for all cultivars, SQI considering the surface soil layer depth (simple-corrected SQI and depth-corrected SQI) had a significant correlation with yield in Sayaka ($r = 0.641, 0.620, p < 0.05$, respectively) although SQI_{0-30} and depth-averaged SQI did not ($r = 0.524, 0.386, p = 0.054, 0.173$, respectively). Notably, these r values were higher than those of all cultivars.

4. DISCUSSION

4.1. Adequacy of productivity evaluation by MDS parameters

PCA has been used for the data reduction method (Armenise et al. 2013, Mukherjee and Lal 2014). However, it is risky to select parameters with large variances, even though they have no relationship with productivity, which could aggravate the accuracy of soil quality evaluation. In this study, MDS parameters were selected from properties with soil diagnosis criteria according to the Hokkaido Fertilizer Recommendations 2020 based on productivity studies, which would avoid any potential issues with evaluation. Parameters in the MDS included both chemical and physical properties, and soil quality was evaluated from both aspects. In this study, MDS was selected from the dataset merging topsoil and subsoil data, but the MDS including solid phase differed between the depths

(Table S1) and could consider the depth difference.

Ca plays a role not only in the elemental composition of the plant cell membrane and wall but also as a signaling molecule mediating plant responses to environmental stresses and hormones. Ca is regarded as a nutrient that contributes to potato yield and quality by improving cell wall rigidity and heat stress resistance (Palta 2010). The weighted scores of exchangeable Ca were deducted by exceeding the upper threshold except for two samples. The Hokkaido Fertilizer Recommendations 2020 recommends adjusting pH prior to exchangeable Ca content when farmers decide on the amount of lime application. It also recommends an acidic pH within the criteria for potatoes as a countermeasure for potato common scab in sites that are frequently affected. The average pH at all sites was 5.7, and the deduction of its weighted score was insignificant at most of the sites. These results indicated that most of these sites require a Ca supply with neutral soil agents, such as gypsum, for soil quality improvement.

The weighted scores of exchangeable K were deducted by falling below the lower threshold for only six samples. The scores for most of the sites were deducted by exceeding the upper one. The solid phase scores were deducted by exceeding the upper threshold, particularly in the subsoil. The acid-soluble Cu scores were deducted by falling below the lower threshold. Therefore, organic matter applied for soil physical property improvement could also be beneficial for enhancing soil quality by increasing Cu holding capacity, but K input needs to be adjusted to avoid exceeding the criteria.

Total carbon in soil is an important parameter because it determines many soil characteristics, such as nutrient application, aggregate stability, and suitable water retention (Doran et al. 1998). Many studies have evaluated soil quality improvement through various treatments as total carbon increases (Dewi et al. 2022, Jung et al. 2008, Mardegan et al. 2022, Tirol-Padre et al. 2005, Yajuan et al. 2022). Many previous studies

listed total carbon as a candidate SQI evaluation parameter (Bünemann et al. 2018). This study did not select total carbon as an MDS candidate; however, the criteria for exchangeable Ca was dependent on CEC values, which had a strong positive correlation with total carbon ($r = 0.947$, $p < 0.001$). In this study, the effect of total carbon on SQI might be substantial because the weight of exchangeable Ca was the highest of all parameters. Additionally, total carbon was defined as the lower threshold of acid-soluble Cu with the second highest variance, which considers the Cu decrease through sorption by humus (Agbenin and Olojo 2004). Therefore, total carbon would affect SQI indirectly through weighted scores of exchangeable Ca and acid-soluble Cu.

Although previous studies found that the soil quality of the subsoil was worse than that of the topsoil (Gozukara et al. 2022, Zhijun et al. 2018), this study did not show a significant difference in the SQI. This difference might be due to the definition of one horizon (every 10 cm or 30 cm depth) and the targeted depth range (0-100 cm or 0-60 cm). A thin horizon would easily reveal the difference between the surface and deeper horizons whereas a thick horizon could obscure the soil quality differences between the upper and lower parts. A shallower targeted depth range might have missed the soil quality difference between the surface and deeper horizons.

4.2. Productivity evaluation depended on SQI calculation methods

Previous studies have consistently demonstrated a positive correlation between yield and SQI in experimental plots with treatments such as different crops, organic matter management (Andrews et al. 2002a, de Paul Obade and Lal 2016), crop rotation (Armenise et al. 2013), and tillage intensity (Armenise et al. 2013, de Paul Obade and Lal 2016). However, the correlation within each treatment group was either weak or unknown. Therefore, SQI can evaluate treatment effects, but is less adept at assessing the impact of

site- specific differences. On the other hand, various factors (soil properties and management) are different in the farmers' fields, which have unconsidered factors to evaluate productivity by SQI, which would make the evaluation difficult.

This study suggested that SQI in the topsoil and subsoil was not sufficient for productivity evaluation; however, consideration of the surface soil layer depth made it possible. SQI not considering the depth might overestimate soil quality affected by the depth (Fig. 2). These might indicate that deep surface soil layer depth, including the subsoil, could contribute to improving soil quality, increasing nutrient mass, macropores, and aerobic conditions in the rhizosphere. Therefore, this would be one reason that simple-corrected SQI could evaluate productivity without subsoil SQI to some degree, which suggested that the depth measurement could omit subsoil sampling, saving labor, although the evaluation accuracy decreased slightly.

Poor drainage is suggested to be one of the limiting factors for plant growth in Tokachi region due to its high annual precipitation during the growing season (Niwa et al. 2008). This study chose the solid phase as the physical property in MDS, but the variance of the weighted score was less than that of the chemical ones (Fig. 1), which might indicate that the solid phase was an important property for SQI, and most of the sites had relatively favorable conditions. This finding is consistent with a previous study in Tokachi region that selected the solid phase as an MDS parameter with a small variance in its weighted score (Yoshimura et al. 2022).

The site with ID 14 had a low depth-corrected SQI (30.9), even though it had a high cultivar-adjusted yield (125.0). This site had a lower SQI at 0–30 cm (80.7) and SQI at 30–60 cm (78.3) than the average, but was not particularly low at all sites. The site with ID 14 had a shallow surface soil layer depth (23 cm), which reduced the depth-corrected SQI. The site contained little gravel content ($< 0.1\%$ of gravimetric percent, data not

shown) and gravel did not cause underestimation of the surface soil layer depth or SQI, so the evidence why this site had high productivity was not clear in this study. One potential explanation for this might be that the distribution of plant roots was not measured, leading to the possibility that roots did not decrease in proportion with depth. Therefore, correcting SQI for depth might not accurately reflect optimal or non-optimal root elongation. Hence, the SQI suggested by this study may not accurately evaluate productivity when yield is ensured by the root system concentrated in a shallow horizon, which is an issue for the future research.

SQI considering surface soil layer depth did not affect soil types and cultivars to evaluate productivity; however, sites cultivating Sayaka had stronger correlations than all sites (Fig. 3), which suggests that better evaluations would be conducted in the case of comparison among sites of the same single cultivar. Nonetheless, more studies are needed in the future because the relationships were compared using a limited number of samples.

4.3. Prospection for farmers' decision support by SQI

Because major crops are cultivated in upland fields in Tokachi region, a comprehensive evaluation of productivity by SQI requires more research on other crops, such as wheat, sugar beets, and pulses. Enhancing data collection efficiency must help build a dataset on a large scale and provide a better understanding of soil quality. Validating the MDS equation reduces the cost of laboratory analysis. An adequately sized dataset of soil properties of intact and disturbed soils could contribute to the development of a pedotransfer function that estimates soil physical properties from disturbed samples (Reidy et al. 2016). The function could save the cost of intact soil sampling that needed proficiency. Utilizing datasets from previous studies would help to reduce sampling costs to evaluate productivity by SQI.

Minimizing the number of parameters and samples could also motivate farming communities to evaluate soil quality. Accumulating soil data by the community would give recognition to the importance of practicing management judgment based on the data and accumulating the data.

It might be feasible to identify physicochemical properties of high priority for improvement in each field by obtaining a weighted score for each depth, considering the depth of the surface soil layer. Comparing which properties at which depths are particularly impactful in reducing SQI could aid in determining how to quantitatively improve soil properties. However, it is necessary to assume that there is no extreme excess or deficiency in the properties. In this study, soil samples were obtained from farmers' fields, indicating the need to verify whether yield increases when soil improvements are implemented based on weighted scores and surface soil layer depth data in a future experiment.

This research suggested that productivity could be evaluated by SQI within a surface soil layer depth; however, considering whole profile is still necessary for soil quality targeting waste recycling, environmental protection, or biodiversity.

CONCLUSIONS

The SQI considering the properties of both topsoil and subsoil was insufficient in evaluating productivity. However, by incorporating the depth of the surface soil layer into the SQI, it became possible to evaluate productivity without depending on subsoil properties. Additionally, this methodology was applicable to a variety of soils composed of different parent materials, thus highlighting the depth consideration is effective in comparing soil quality between various soil types. To expand the scope of research on

soil quality evaluation using the SQL, it is crucial to implement effective data sampling methods and to consider the depth of the surface soil layer.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

SUPPLEMENTAL DATA

Supplemental data for this article can be accessed online at <https://doi.org/10.1080/00380768.2023.2237992>

REFERENCES

- Agbenin JO and Olojo LA 2004: Competitive adsorption of copper and zinc by a Bt horizon of a savanna Alfisol as affected by pH and selective removal of hydrous oxides and organic matter. *Geoderma* **119**, 85-95. doi: [https://doi.org/10.1016/S0016-7061\(03\)00242-8](https://doi.org/10.1016/S0016-7061(03)00242-8)
- Andrews SS, Karlen DL and Cambardella CA 2004: The Soil Management Assessment Framework. *Soil Science Society of America Journal* **68**, 1945-1962. doi: <https://doi.org/10.2136/sssaj2004.1945>
- Andrews SS, Karlen DL and Mitchell JP 2002a: A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, Ecosystems & Environment* **90**, 25-45. doi: [https://doi.org/10.1016/S0167-8809\(01\)00174-8](https://doi.org/10.1016/S0167-8809(01)00174-8)
- Andrews SS, Mitchell JP, Mancinelli R *et al.* 2002b: On-Farm Assessment of Soil Quality in California's Central Valley. *Agronomy Journal* **94**, 12-23. doi: <https://doi.org/10.2134/agronj2002.1200>
- Araki S, Hirai H and Kyuma K 1986: Phosphate Absorption of Red and/or Yellow Colored Soil Materials in Relation to the Characteristics of Free Oxides. *Soil Science and Plant Nutrition* **32**, 609-616. doi: <https://doi.org/10.1080/00380768.1986.10557542>
- Armenise E, Redmile-Gordon MA, Stellacci AM, Ciccacese A and Rubino P 2013: Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. *Soil and Tillage Research* **130**, 91-98. doi: <https://doi.org/10.1016/j.still.2013.02.013>
- Bünemann EK, Bongiorno G, Bai Z *et al.* 2018: Soil quality – A critical review. *Soil Biology and Biochemistry* **120**, 105-125. doi: <https://doi.org/10.1016/j.soilbio.2018.01.030>
- Bouma J and Droogers P 1998: A procedure to derive land quality indicators for sustainable agricultural production. *Geoderma* **85**, 103-110. doi: [https://doi.org/10.1016/S0016-7061\(98\)00031-7](https://doi.org/10.1016/S0016-7061(98)00031-7)
- de Paul Obade V and Lal R 2016: Towards a standard technique for soil quality assessment. *Geoderma* **265**, 96-102. doi: <https://doi.org/10.1016/j.geoderma.2015.11.023>
- Dewi RK, Fukuda M, Takashima N, Yagioka A and Komatsuzaki M 2022: Soil carbon sequestration and soil quality change between no-tillage and conventional tillage soil management after 3 and 11 years of organic farming. *Soil Science and Plant Nutrition* **68**, 133-148. doi: <https://doi.org/10.1080/00380768.2021.1997552>
- Doran JW, Elliott ET and Paustian K 1998: Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. *Soil and Tillage Research* **49**, 3-18. doi: [https://doi.org/10.1016/S0167-1987\(98\)00150-0](https://doi.org/10.1016/S0167-1987(98)00150-0)
- Doran JW and Parkin TB 1994: Defining and Assessing Soil Quality. *Defining Soil Quality for a Sustainable Environment*, pp 1-21. doi: <https://doi.org/10.2136/sssaspecpub35.c1>

- Doran JW, Sarrantonio M and Liebig MA 1996: Soil Health and Sustainability. In: Sparks DL (ed) *Advances in Agronomy*, pp 1-54. Academic Press. doi: [https://doi.org/10.1016/S0065-2113\(08\)60178-9](https://doi.org/10.1016/S0065-2113(08)60178-9)
- Duan X-w, Xie Y, Feng Y-j and Yin S-q 2009: Study on the Method of Soil Productivity Assessment in Black Soil Region of Northeast China. *Agricultural Sciences in China* **8**, 472-481. doi: [https://doi.org/10.1016/S1671-2927\(08\)60234-5](https://doi.org/10.1016/S1671-2927(08)60234-5)
- Gaines TP and Mitchell GA 1979: Boron determination in plant tissue by the azomethine H method. *Communications in Soil Science and Plant Analysis* **10**, 1099-1108. doi: <https://doi.org/10.1080/00103627909366965>
- Gee GW and Or D 2002: 2.4 Particle-Size Analysis. In: Dane JH & Topp GC (eds) *Methods of Soil Analysis*, pp 255-293. Madison, Wisconsin, USA: Soil Science Society of America, Incorporated. doi: <https://doi.org/10.2136/sssabookser5.4.c12>
- Gozukara G, Acar M, Ozlu E, Dengiz O, Hartemink AE and Zhang Y 2022: A soil quality index using Vis-NIR and pXRF spectra of a soil profile. *CATENA* **211**, 105954. doi: <https://doi.org/10.1016/j.catena.2021.105954>
- Hirota T, Iwata Y, Hayashi M *et al.* 2006: Decreasing Soil-Frost Depth and Its Relation to Climate Change in Tokachi, Hokkaido, Japan. *Journal of the Meteorological Society of Japan. Ser. II* **84**, 821-833. doi: <https://doi.org/10.2151/jmsj.84.821>
- Hokkaido Government Department of Agriculture 2020: *Hokkaido Fertilizer Recommendations 2020 (Hokkaido Sehi Guide 2020)*, Hokkaido Sapporo, Japan: Department of Agriculture, Hokkaido Government.
- Jung WK, Kitchen NR, Sudduth KA and Kremer RJ 2008: Contrasting grain crop and grassland management effects on soil quality properties for a north-central Missouri claypan soil landscape. *Soil Science and Plant Nutrition* **54**, 960-971. doi: <https://doi.org/10.1111/j.1747-0765.2008.00314.x>
- Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF and Schuman GE 1997: Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial). *Soil Science Society of America Journal* **61**, 4-10. doi: <https://doi.org/10.2136/sssaj1997.03615995006100010001x>
- Klimkowicz-Pawlas, A., Ukalska-Jaruga, A., and Smreczak, B. 2019. "Soil quality index for agricultural areas under different levels of anthropopressure." *International Agrophysics*, **33**(4), 455-462. <https://doi.org/10.31545/intagr/113349>
- Liu Z, Zhou W, Shen J, Li S and Ai C 2014: Soil quality assessment of yellow clayey paddy soils with different productivity. *Biology and Fertility of Soils* **50**, 537-548. doi: <https://doi.org/10.1007/s00374-013-0864-9>
- Mardegan SF, de Castro AF, Chaves SSNF, dos Santos Freitas RS, Avelar MS and Filho FAOT

- 2022: Organic farming enhances soil carbon and nitrogen dynamics in oil palm crops from Southeast Amazon. *Soil Science and Plant Nutrition* **68**, 104-113. doi: <https://doi.org/10.1080/00380768.2022.2031285>
- Mukherjee A and Lal R 2014: Comparison of Soil Quality Index Using Three Methods. *PLOS ONE* **9**, e105981. doi: <https://doi.org/10.1371/journal.pone.0105981>
- Nakatsuka H and Tamura K 2016: Characterisation of soils under long-term crop cultivation without fertilisers: a case study in Japan. *SpringerPlus* **5**, 283. doi: <https://doi.org/10.1186/s40064-016-1917-y>
- Niwa K, Seino N, Yokobori J, Kikuchi K and Hongo C 2008: Effect of soil type on the time-course of changes in sugar beet (*Beta vulgaris* L.) productivity in Tokachi District, Hokkaido, Japan. *Soil Science and Plant Nutrition* **54**, 928-937. doi: <https://doi.org/10.1111/j.1747-0765.2008.00322.x>
- Palta JP 2010: Improving Potato Tuber Quality and Production by Targeted Calcium Nutrition: the Discovery of Tuber Roots Leading to a New Concept in Potato Nutrition. *Potato Research* **53**, 267-275. doi: <https://doi.org/10.1007/s11540-010-9163-0>
- Pierce F, Larson W, Dowdy R and Graham W 1983: Productivity of soils: assessing long-term changes due to erosion. *Journal of Soil and Water Conservation* **38**, 39-44. doi: Retrieved from <https://www.jswnonline.org/>
- Qi Y, Darilek JL, Huang B, Zhao Y, Sun W and Gu Z 2009: Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. *Geoderma* **149**, 325-334. doi: <https://doi.org/10.1016/j.geoderma.2008.12.015>
- R Core Team 2021: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rahmanipour F, Marzaioli R, Bahrami HA, Fereidouni Z and Bandarabadi SR 2014: Assessment of soil quality indices in agricultural lands of Qazvin Province, Iran. *Ecological Indicators* **40**, 19-26. doi: <https://doi.org/10.1016/j.ecolind.2013.12.003>
- Reidy B, Simo I, Sills P and Creamer RE 2016: Pedotransfer functions for Irish soils – estimation of bulk density (ρ_b) per horizon type. *SOIL* **2**, 25-39. doi: <https://doi.org/10.5194/soil-2-25-2016>
- Rhoton FE and Lindbo DL 1997: A soil depth approach to soil quality assessment. *Journal of Soil and Water Conservation* **52**, 66-72. doi: Retrieved from <https://www.jswnonline.org/>
- Santos-Francés F, Martínez-Graña A, Ávila-Zarza C, Criado M and Sánchez Y 2019: Comparison of methods for evaluating soil quality of semiarid ecosystem and evaluation of the effects of physico-chemical properties and factor soil erodibility (Northern Plateau, Spain). *Geoderma* **354**, 113872. doi: <https://doi.org/10.1016/j.geoderma.2019.07.030>
- Schollenberger CJ and Simon RH 1945: DETERMINATION OF EXCHANGE CAPACITY

- 572 AND EXCHANGEABLE BASES IN SOIL - AMMONIUM ACETATE METHOD. *Soil Science*
 573 **59**, 13-24. doi: <https://doi.org/10.1097/00010694-194501000-00004>
- 574 Sherman GD, McHargue JS and Hodgkiss WS 1942: Determination of active manganese in
 575 soil. *Soil Science* **54**, 253-257. doi: <https://doi.org/10.1097/00010694-194210000-00005>
- 576 Shimoda S and Hirota T 2018: Planned snow compaction approach (yuki-fumi) contributes
 577 toward balancing wheat yield and the frost-kill of unharvested potato tubers. *Agricultural*
 578 *and Forest Meteorology* **262**, 361-369. doi: <https://doi.org/10.1016/j.agrformet.2018.07.030>
- 579 Shukla MK, Lal R and Ebinger M 2006: Determining soil quality indicators by factor analysis.
 580 *Soil and Tillage Research* **87**, 194-204. doi: <https://doi.org/10.1016/j.still.2005.03.011>
- 581 Takahashi E, Yoshino M and Maeda M 1980: *Elemental Deficiency and Excess in Crops New*
 582 *Edition with colors(Gensyoku Sakumotsu no Yousoketsuboukajoushou)*, Nousan Gyoson
 583 Bunka Kyokai, Tokyo.
- 584 Tirol-Padre A, Tsuchiya K, Inubushi K and Ladha JK 2005: Enhancing Soil Quality through
 585 Residue Management in a Rice-Wheat System in Fukuoka, Japan. *Soil Science and Plant*
 586 *Nutrition* **51**, 849-860. doi: <https://doi.org/10.1111/j.1747-0765.2005.tb00120.x>
- 587 Truog E 1930: The Determination of the Readily Available Phosphorus of Soils1. *Agronomy*
 588 *Journal* **22**, 874-882. doi: <https://doi.org/10.2134/agronj1930.00021962002200100008x>
- 589 Tsunekawa A, Kar A, Yanai J, Tanaka U and Miyazaki T 1997: Influence of continuous
 590 cultivation on the soil properties affecting crop productivity in the Thar Desert, India.
 591 *Journal of Arid Environments* **36**, 367-384. doi: <https://doi.org/10.1006/jare.1996.0234>
- 592 Vasu D, Singh SK, Ray SK *et al.* 2016: Soil quality index (SQI) as a tool to evaluate crop
 593 productivity in semi-arid Deccan plateau, India. *Geoderma* **282**, 70-79. doi:
 594 <https://doi.org/10.1016/j.geoderma.2016.07.010>
- 595 Wander, M.M. and Bollero, G.A. 1999, "Soil Quality Assessment of Tillage Impacts in
 596 Illinois." *Soil Science Society of America Journal*, **63**, 961-971.
 597 <https://doi.org/10.2136/sssaj1999.634961x>
- 598 Yajuan W, Meiyang L, Ji W, Xiaohong D and Yanlong H 2022: The effects of vegetation
 599 communities on soil organic carbon stock in an enclosed desert-steppe region of northern
 600 China. *Soil Science and Plant Nutrition* **68**, 284-294. doi:
 601 <https://doi.org/10.1080/00380768.2022.2045847>
- 602 Yoshimura, M., Oka, N., Nagasawa, K., Maezuka, K., Morimoto, S. 2022. Estimation of the
 603 soil quality index for winter wheat productivity in Tokachi, Hokkaido. *Japanese*
 604 *Journal of Soil Science and Plant Nutrition*, **93**, 161-175. doi:
 605 https://doi.org/10.20710/dojo.93.4_161 (in Japanese with English summary)
- 606 Zhijun H, Selvalakshmi S, Vasu D *et al.* 2018: Identification of indicators for evaluating and
 607 monitoring the effects of Chinese fir monoculture plantations on soil quality. *Ecological*

608 *Indicators* **93**, 547-554. doi: <https://doi.org/10.1016/j.ecolind.2018.05.034>
609 Zhou M, Xiao Y, Li YS *et al.* 2022: Soil quality index evaluation model in responses to six-
610 year fertilization practices in Mollisols. *Archives of Agronomy and Soil Science* **68**, 180-194.
611 doi: <https://doi.org/10.1080/03650340.2020.1827395>

1 Table 1. Summary of research sites.

ID	Cultivar	Soil type	Soil textural		Surface	Total C content (g kg ⁻¹)
			class		soil layer	
			0-30 cm	30-60 cm	depth (cm)	
1	Sayaka	Peat soils	LiC	HC	47	185
2	Sayaka	Andosols	LiC	LiC	> 60	76
3	Sayaka	Andosols	LiC	LiC	35	69
4	Sayaka	Andosols	LiC	CL	> 60	18
5	Sayaka	Andosols with alluvial deposits	LiC	LiC	18	57
6	Sayaka	Andosols	CL	CL	41	21
7	Sayaka	Andosols	LiC	CL	> 60	29
8	Sayaka	Brown Lowland soils	LiC	LiC	> 60	50
9	Sayaka	Andosols	LiC	LiC	50	49
10	Sayaka	Peat soils	LiC	LiC	> 60	147
11	Sayaka	Andosols	CL	CL	> 60	33
12	Sayaka	Andosols	LiC	CL	26	23
13	Sayaka	Andosols	LiC	CL	29	28
14	Sayaka	Andosols	LiC	L	30	21
15	Toyoshiro	Andosols	LiC	LiC	44	90
16	Toyoshiro	Peat soils	LiC	LiC	> 60	131
17	Toyoshiro	Andosols	LiC	CL	> 60	54
18	Toyoshiro	Brown Lowland soils	LiC	LiC	> 60	63
19	Toyoshiro	Brown Lowland soils	LiC	SCL	42	28
20	Waseshiro	Andosols	LiC	LiC	> 60	70
21	Waseshiro	Andosols	LiC	LiC	31	74
22	Waseshiro	Andosols	CL	CL	> 60	20
23	Waseshiro	Andosols	CL	SCL	32	19

2

3 Soil types were classified according to the mode of parent material deposition, as
4 suggested by Niwa et al. (2008). The soil texture was determined using the soil particle
5 range system of the International Soil Science Society.

6

7 Table 2. Soil diagnosis criteria in Hokkaido Japan.

Soil property	Criteria	Unit	Scoring function	Remarks
pH (H ₂ O)	5.5–6.5		optimum	
Available phosphate	100–300	mg P ₂ O ₅ kg ⁻¹	more is better	Determined by Troug method. This study defined the function as `more is better' function with 100 mg P ₂ O ₅ kg ⁻¹ lower threshold because of considering the effect on the productivity.
Exchangeable Ca content	1000–1700 (coarse textured soil)	mg CaO kg ⁻¹	optimum	applied when cation exchangealbe capacity (CEC) (cmol _c kg ⁻¹) is 7–12
	1700–3500 (medium textured soil)		optimum	applied when CEC (cmol _c kg ⁻¹) is 12–25
	3500–4900 (fine textured soil)		optimum	applied when CEC (cmol _c kg ⁻¹) is 25–35 This study also applied that function when CEC (cmol _c kg ⁻¹) is 35 or more.
Exchangeable Mg content	250–450	mg MgO kg ⁻¹	optimum	
Exchangeable K content	150–300	mg K ₂ O kg ⁻¹	optimum	
Mg / K	≥ 2		more is better	equivalent ratio
Ca / Mg	≤ 6		less is better	equivalent ratio
Lime saturation percentage	40–60	%	optimum	
Base saturation percentage	60–80	%	optimum	
Hot-water dissolved B content	0.5–1.0	mg kg ⁻¹	optimum	
Easily reducible Mn content	50–500	mg kg ⁻¹	optimum	
Acid-soluble Zn content	2–40	mg kg ⁻¹	optimum	
Acid-soluble Cu content	upper threshold: 8.0 lower threshold: refer the remarks	mg kg ⁻¹	optimum	total C content (g kg ⁻¹) < 86.2: 0.7
				total C content (g kg ⁻¹) 86.2–172.4: 0.5
				total C content (g kg ⁻¹) ≥ 172.4: 0.3
Solid phase	25–30 (volcanic ash soil)	× 10 ⁻² m ³ m ⁻³	optimum	applied when phosphate absorption coefficient (mg P ₂ O ₅ kg ⁻¹) is 15,000 or more
	≤ 40 (lowland and upland soil)		less is better	applied when phosphate absorption coefficient (mg P ₂ O ₅ kg ⁻¹) is less than 15,000
Bulk density	70–90 (volcanic ash soil)	× 10 ⁻² Mg m ⁻³	optimum	applied when phosphate absorption coefficient (mg P ₂ O ₅ kg ⁻¹) is 15,000 or more
	90–110 (lowland and upland soil)		optimum	applied when phosphate absorption coefficient (mg P ₂ O ₅ kg ⁻¹) is less than 15,000
Macropore	15–25	× 10 ⁻² m ³ m ⁻³	optimum	Macropore is defined as the air ratio of –3.1 kPa (pF1.5) .
Available moisture	≥ 10	× 10 ⁻² m ³ m ⁻³	more is better	Available moisture is defined as the difference of water contents between –98.1 kPa and –3.1 kPa (pF 1.5–3.0) .
Effective soil depth	≥ 50	cm	more is better	Effective soil depth is defined as the depth until gravel, pan or compacted layer with 10 cm or more. The compacted layer depth was defined as the depth with high penetration resistance (≥ 1.5 MPa) of cone penetrometer.

8

9 Based on the Hokkaido Government Department of Agriculture (2020), value ranges are shown as the lower threshold means the value or above, and the upper threshold means below.

10 Table 3. Potato yield comparison with cultivars or soil types in 2020.

	Number of sites	Yield g m ⁻²		
Sayaka	14	3957	± 608	a
Toyoshiro	5	3193	± 482	b
Waseshiro	4	2754	± 308	b
Andosols	16	3572	± 785	
Andosols with alluvial deposits	1	3479		
Brown Lowland soils	3	3277	± 577	
Peat soils	3	3970	± 647	

11 Values are shown as the mean ± standard deviation.

12 Different letters indicate significant differences among the cultivars ($p < 0.05$).

13 Table 4. Results of principal component analyses (PCA).

	PC1	PC2	PC3	PC4
Eigenvalue	5.59	3.07	2.49	1.73
Proportion of Variance	0.33	0.18	0.15	0.10
Cumulative Proportion	0.33	0.51	0.66	0.76
Weighted value	43.4	23.8	19.4	13.4
Eigenvector				
<u>pH (H₂O)</u>	0.099	<u>0.407</u>	0.151	-0.154
Available phosphate	-0.260	0.049	-0.247	0.180
<u>Exchangeable Ca content</u>	<u>-0.402</u>	0.007	-0.068	-0.162
Exchangeable Mg content	-0.387	0.094	-0.145	0.053
<u>Exchangeable K content</u>	0.081	<u>0.439</u>	-0.008	0.240
Mg/K	-0.336	-0.247	-0.059	0.091
Ca/Mg	-0.040	-0.193	0.086	-0.500
Lime saturation percentage	-0.306	0.312	0.024	-0.241
Base saturation percentage	-0.265	0.403	0.011	-0.117
Hot-water dissolved B content	-0.321	-0.099	-0.126	0.115
Easily reducible Mn content	0.028	0.347	-0.060	0.340
Acid-soluble Zn content	-0.321	0.067	-0.184	-0.014
<u>Acid-soluble Cu content</u>	0.016	-0.036	0.043	<u>0.564</u>
<u>Solid phase</u>	0.182	0.016	<u>-0.550</u>	-0.119
Bulk density	0.247	0.120	-0.462	-0.122
Macropore	-0.067	0.146	0.544	-0.030
Available moisture	-0.145	-0.317	0.110	0.224

14 PC shows the principal component.

15 The bold values under each component are highly weighted, and the underlined bold
16 values are selected in the minimum dataset.

17 Weight value is calculated as: variance / total cumulative proportion (0.76).

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22 Table 5. Pearson correlation coefficients for all soil indicators.

<i>p</i> value	pH (H ₂ O)	Available phosphate	Exchangeable Ca content	Exchangeable Mg content	Exchangeable K content	Mg/K	Ca/Mg	Lime saturation percentage	Base saturation percentage	Hot-water dissolved B content	Easily reducible Mn content	Acid soluble Zn content	Acid soluble Cu content	Solid phase	Bulk density	Macropore
Available phosphate	< 0.05															
Exchangeable Ca content	1.00	< 0.05														
Exchangeable Mg content	1.00	< 0.05	< 0.05													
Exchangeable K content	0.34	1.00	1.00	1.00												
Mg/K	0.24	0.65	< 0.05	< 0.05	< 0.05											
Ca/Mg	1.00	1.00	1.00	1.00	0.28	1.00										
Lime saturation percentage	1.00	1.00	< 0.05	< 0.05	1.00	1.00	1.00									
Base saturation percentage	0.10	1.00	< 0.05	< 0.05	1.00	1.00	1.00	< 0.05								
Hot-water dissolved B content	1.00	0.20	< 0.05	< 0.05	1.00	< 0.05	1.00	1.00	1.00							
Easily reducible Mn content	1.00	1.00	1.00	1.00	< 0.05	1.00	1.00	1.00	1.00	1.00						
Acid-soluble Zn content	1.00	< 0.05	< 0.05	< 0.05	1.00	0.09	1.00	< 0.05	0.10	< 0.05	1.00					
Acid-soluble Cu content	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				
Solid phase	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00			
Bulk density	1.00	1.00	0.22	1.00	1.00	0.11	1.00	1.00	1.00	0.90	1.00	1.00	1.00	< 0.05		
Macropore	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	< 0.05	< 0.05	
Available moisture	1.00	1.00	1.00	1.00	0.89	< 0.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.46	1.00
<i>r</i> value																
Available phosphate	-0.501															
Exchangeable Ca content	-0.185	0.547														
Exchangeable Mg content	-0.151	0.625	0.896													
Exchangeable K content	0.424	0.133	-0.236	-0.038												
Mg/K	-0.439	0.396	0.725	0.744	-0.573											
Ca/Mg	-0.187	0.017	0.219	-0.186	-0.432	-0.016										
Lime saturation percentage	0.360	0.327	0.769	0.716	0.099	0.347	0.112									
Base saturation percentage	0.473	0.302	0.638	0.686	0.313	0.241	-0.123	0.959								
Hot-water dissolved B content	-0.330	0.447	0.707	0.660	-0.149	0.634	0.038	0.363	0.308							
Easily reducible Mn content	0.257	0.291	-0.135	0.033	0.504	-0.268	-0.298	0.157	0.278	-0.093						
Acid-soluble Zn content	-0.156	0.643	0.717	0.722	-0.004	0.477	0.097	0.537	0.471	0.605	-0.041					
Acid-soluble Cu content	-0.037	-0.011	-0.177	-0.072	0.071	0.093	-0.297	-0.184	-0.103	0.080	0.209	0.024				
Solid phase	-0.029	0.015	-0.282	-0.204	0.036	-0.261	-0.054	-0.239	-0.202	-0.208	0.037	-0.088	-0.085			
Bulk density	0.213	-0.144	-0.443	-0.351	0.185	-0.468	-0.110	-0.236	-0.159	-0.381	0.139	-0.216	-0.063	0.955		
Macropore	0.193	-0.046	0.041	-0.035	0.164	-0.102	0.133	0.270	0.264	-0.159	0.048	-0.035	0.012	-0.781	-0.651	
Available moisture	-0.265	0.050	0.248	0.196	-0.382	0.572	0.074	-0.060	-0.125	0.320	-0.213	0.049	0.242	-0.317	-0.411	-0.089

24 Table 6. Result of ANOVA on weighted scores and SQI value

	Factor	Sum of squares	Degree of freedom	Mean square	F-ratio	p-value
Exchangeable Ca	Soil type	370.71	2	185.36	1.984	0.164
	Depth	33.09	1	33.09	1.956	0.178
	Soil type x Depth	68.10	2	34.05	1.762	0.199
Exchangeable K	Soil type	15.98	2	7.99	3.837	0.040 *
	Depth	0.32	1	0.32	0.537	0.473
	Soil type x Depth	0.62	2	0.31	0.521	0.602
pH (H ₂ O)	Soil type	3.03	2	1.52	11.704	0.001 *
	Depth	0.00	1	0.00	0.021	0.887
	Soil type x Depth	0.03	2	0.02	2.076	0.153
Solid phase	Soil type	8.00	2	4.00	1.817	0.190
	Depth	2.67	1	2.67	1.020	0.325
	Soil type x Depth	11.69	2	5.85	2.235	0.134
Acid-soluble Cu	Soil type	49.82	2	24.91	1.213	0.319
	Depth	0.74	1	0.74	0.274	0.607
	Soil type x Depth	5.16	2	2.58	0.952	0.404
SQI	Soil type	409.35	2	204.68	1.797	0.193
	Depth	59.20	1	59.20	3.063	0.096
	Soil type x Depth	367.19	2	34.05	1.762	0.199

25 * indicates $p < 0.05$ by repeated measures ANOVA with depth as a within-subject factor and soil type as a between-subject factor

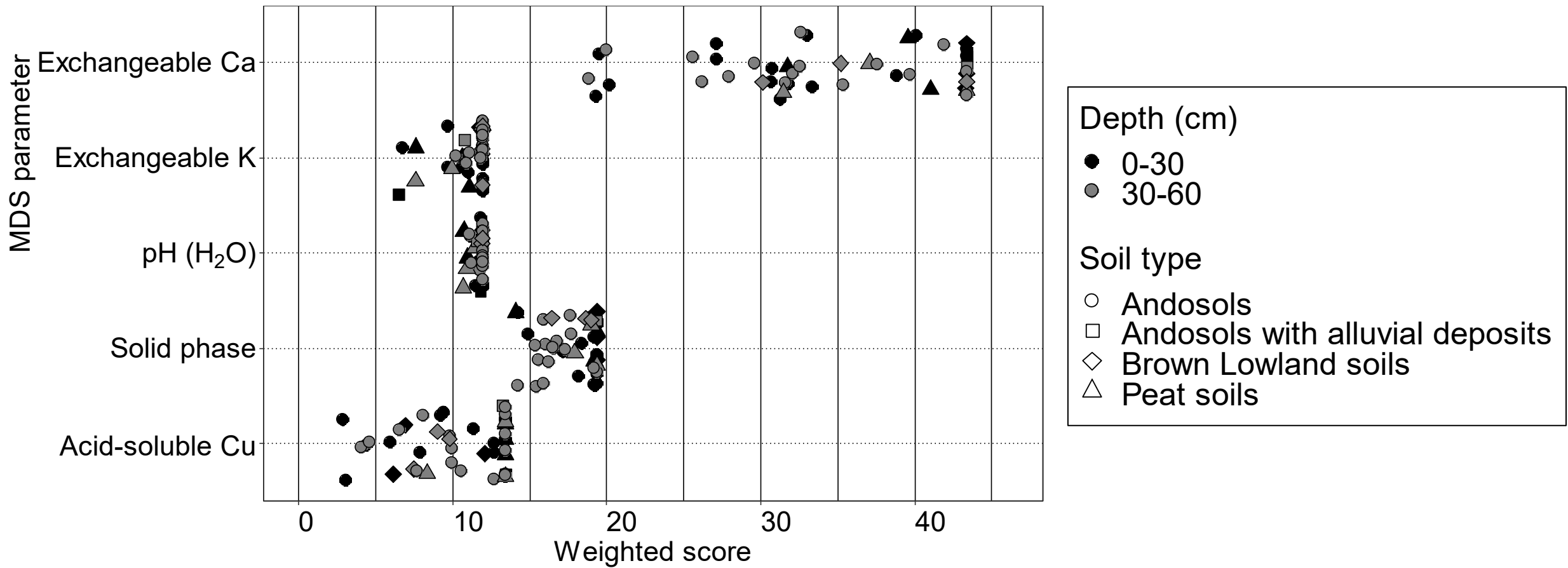


Figure 1.
Jitter plot showing weighted score of each minimum data set (MDS) parameters.

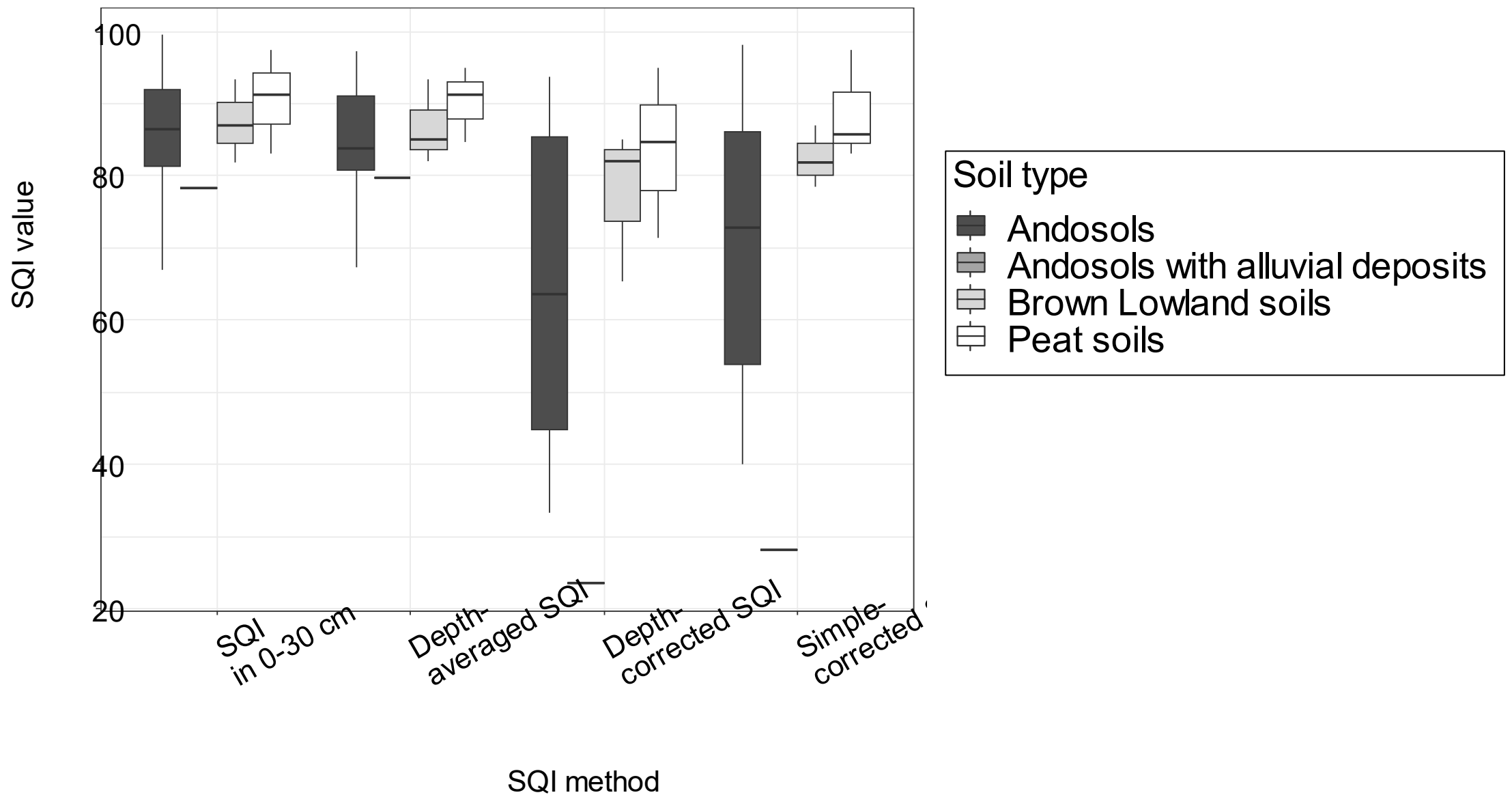


Figure 2.

Box plots showing SQL value difference depended on calculation methods.

Depth averaged SQL is the average SQL of 0-30 cm and 30-60 cm depth.

Simple corrected SQL is the SQL in 0-30 cm corrected by surface soil layer depth.

Depth corrected SQL is the SQL considering 0-30 cm and 30-60 cm depth and corrected by surface soil layer depth.

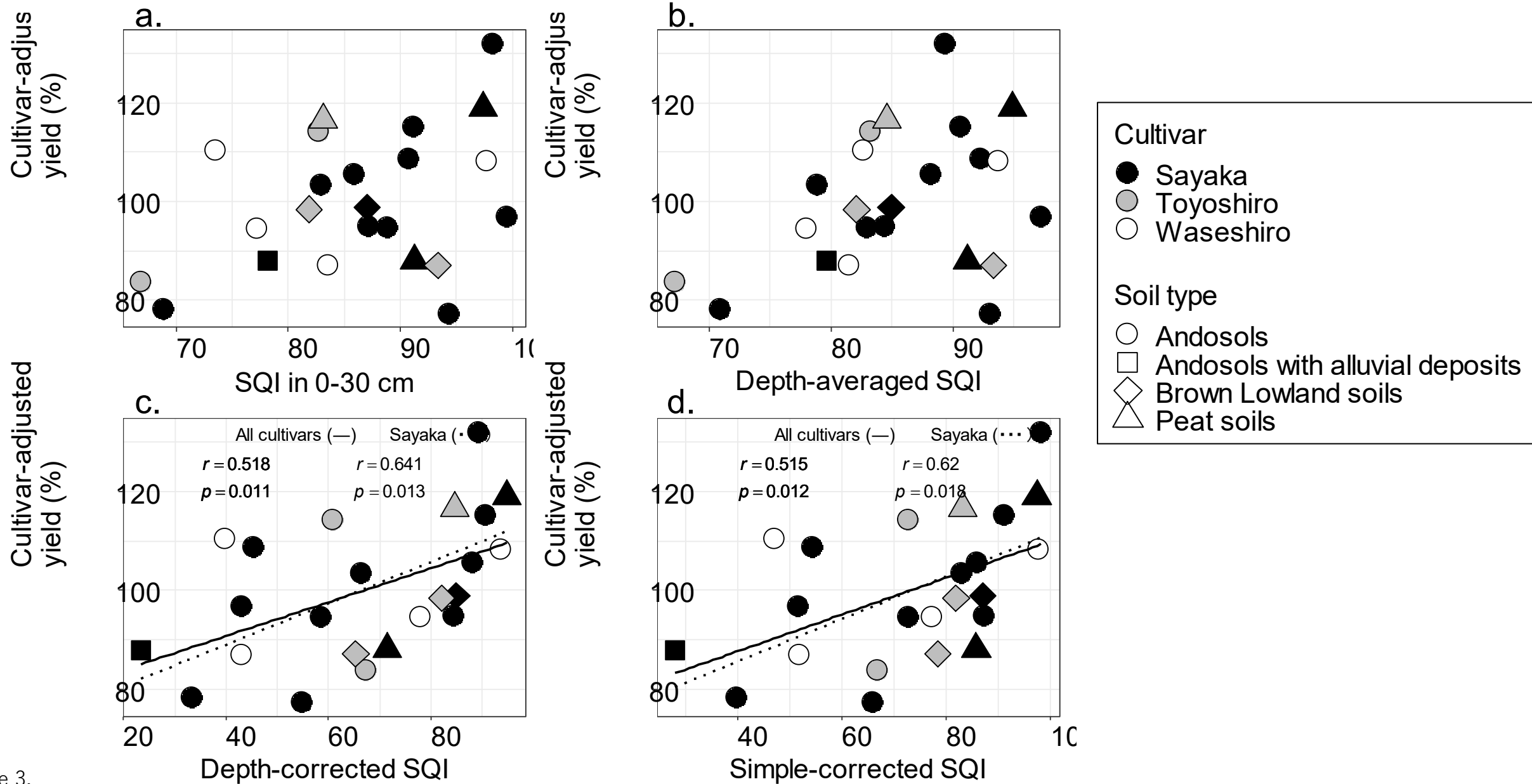


Figure 3. Scatter plots showing relationship between yield and SQI calculated by different methods: a) SQI in 0-30 cm, b) average of SQI in 0-30 cm and 30-60 cm (depth-averaged SQI), c) considering SQI in 0-30 cm and 30-60 cm and the surface soil layer depth (depth-corrected SQI), and d) considering SQI in 0-30 cm and the surface soil layer depth (simple-corrected SQI). Cultivar adjusted yield was obtained as the percentage of the yield to the average yield of the cultivar. Solid and dotted lines show significant correlation in all cultivars and Sayaka, respectively.