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RESEARCH ARTICLE

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Temporal trends in Finnish agricultural soils: A comparative analysis of national and LUCAS soil monitoring datasets

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Abstract

Finnish agricultural soil conditions are regularly monitored both through national and European Union (EU)-wide LUCAS Soil sampling. In this study, we compare temporal trends and variability in organic carbon content (OC), pH, phosphorus (P) and potassium (K) in 2009–2018 across the two datasets. The national monitoring programme encompasses more monitoring plots (620 vs. 134 in 2018), while LUCAS sampling is repeated more frequently and in addition to 2009 and 2018, it also includes data from 2015. The temporal variability in all examined indicators was substantially higher in the LUCAS dataset compared to the national monitoring data. In mineral soils, Spearman's rank correlation coefficient between element contents measured in 2009 and 2018 ranged between 0.82 and 0.94 in the national dataset, and between 0.52 and 0.67 in the LUCAS dataset. The results for organic soils mirrored those of mineral soils. The higher variability in the LUCAS dataset may be attributed to less precise geolocation of sampling plots and/or variations in the sampling protocol such as greater sampling depth and the use of a spade instead of a core auger. The greater temporal variability, coupled with a smaller number of sampling plots in the LUCAS dataset, resulted in lower statistical power making the detection of trends with a realistic magnitude more challenging. Further, in LUCAS data, the confidence intervals of trends were of the same magnitude, regardless of whether the data from the year 2015 was included or not. The national dataset was found to be sufficient for detecting nationwide trends in element contents. Our results indicate that refining sampling protocols and improving the location accuracy of sampling plots are more cost-effective approaches to enhance the precision of temporal trend estimation than increasing the number of sampling plots.

KEYWORDS

sampling protocol, soil element content, soil monitoring, sources of uncertainty, temporal trend, variability

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1 | INTRODUCTION

The monitoring of agricultural soils is gaining momentum in Europe owing to the recent proposal for the European Union's (EU) soil monitoring and resilience directive (EU, 2023). Its implementation would involve national soil monitoring, complemented by parallel EU-scale monitoring conducted through the LUCAS Soil monitoring programme (Orgiazzi et al., 2018). The directive is linked to the promotion of sustainable soil use in general and to combatting soil organic matter loss in agricultural soils and harnessing their potential for carbon sequestration (Rumpel et al., 2020; Soussana et al., 2019). Simultaneously, monitoring of arable soils is constantly relevant for maintaining favourable soil nutrient balances and managing risks associated with pollutants (EEA, 2023).

In this context, the development of soil monitoring requires detailed understanding of how national and EU-level monitoring compare in terms of their performance. Comparing statistical distributions of variables produced by different monitoring programmes at a specific moment of time can be challenging due to differences in sampling design and procedures, as well as in laboratory analyses. However, regardless of possible methodological differences, comparison of temporal trends can highlight the relative efficiency of different study designs and can thus be utilized in optimizing data collection protocol. Having data from two independent monitoring programmes can also be useful in order to confirm any alarming trends that may be observed in a given dataset.

National arable soil monitoring in Finland has revealed long-term (1974–2018) trends in chemical soil fertility components (Keskinen et al., 2016) and microelement concentrations (Soinne et al., 2022). It has also provided evidence of a decline in topsoil carbon content (Heikkinen et al., 2013) and identified some of its environmental and agricultural drivers over the latest 10-year study interval (2009–2018; Heikkinen et al., 2022). The LUCAS Soil study was started in Finland in 2009, and data are available from then and the two subsequent field campaigns in 2015 and 2018. Apart from the study by De Rosa et al. (2024), LUCAS Soil data have not been used comprehensively for the study of temporal changes in soil properties in Europe, particularly in the context of agricultural soils of Finland.

The aim of this study is to compare temporal changes in soil pH, organic carbon (OC), phosphorus (P) and potassium (K) contents included in both national and LUCAS Soil data. Additionally, the study aims at investigating the temporal variability in repeated measurements in both datasets. Comparison of datasets facilitates the identification of potential error sources in measurements, enabling the development of soil monitoring protocols which are cost-effective yet reliable. The temporal alignment of the two monitoring studies in the years 2009 and 2018 makes the comparison of their results particularly relevant.

Highlights

- Comparison of soil monitoring data facilitates identifying the sources of uncertainty.
- Sampling protocol and location accuracy affect data quality.
- Temporal variability was higher in LUCAS Soil than in national data for all studied indicators.
- Optimized sampling reduces uncertainties in trends more efficiently than increasing sample size.

2 | MATERIALS AND METHODS

2.1 | National soil monitoring

The Finnish national soil monitoring is built on a general nationwide inventory of the nutrient status of agricultural soils carried out in 1974. At that time, soil samples were collected from 2042 field plots designed on a small-scale map and specified in the field according to predetermined crop, and distances from railroads, roads and electric power lines (see Keskinen et al., 2016). Thereafter, the plots have been revisited to a gradually reducing extent in 1987 ($n = 1362$), 1998 ($n = 720$) and 2009 ($n = 611$) principally abandoning sites no longer under cultivation or difficult to locate while ensuring comprehensive spatial coverage of the sampling network. For the latest sampling in 2018 ($n = 620$, Figure 1), 471 original plots were complemented by 149 new plots randomly positioned among the original network. Until 1998, the location of sampling plots was based on printed maps and written descriptions. Since 2009, the plots have been accurately located with Global Positioning System (GPS). Sampling date was available for the 2018 data, and the majority of samples were taken in July and August. The representativity of the soil monitoring network has been discussed in detail in Heikkinen et al. (2013).

Each sampling plot covers an area of 10 m × 10 m from which a composite soil sample is collected from the 0–15 cm layer. Since 1998, the sampling has been carried out using augers of 2 cm diameter and the samples have consisted of at least 10 subsamples to yield a sufficient sample size of ca. 0.5 L. Visible plant material and roots are removed during sampling or later while grinding the

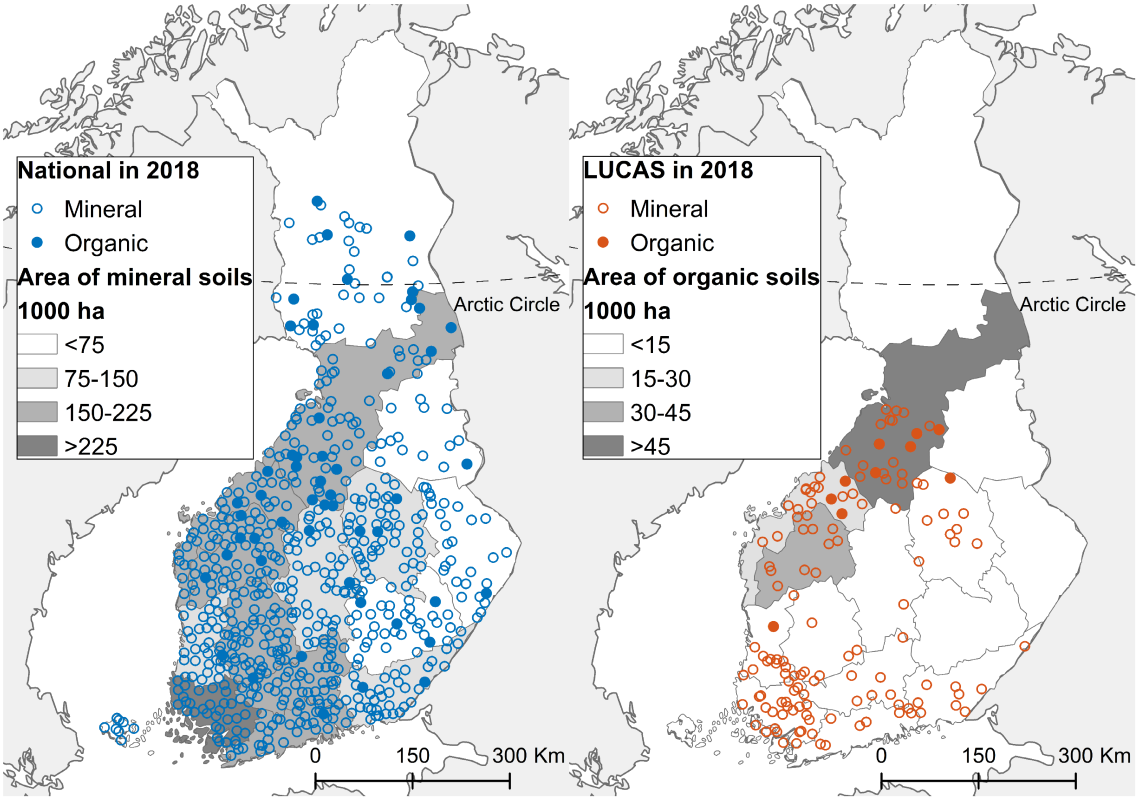

FIGURE 1 Location of arable sampling plots in Finnish national (left) and LUCAS Soil (right) monitoring networks in 2018. Sampling plots are classified into mineral and organic soils based on an OC-content threshold of 200 g kg^{-1}. The map also illustrates the cultivated area of mineral (left) and organic soils (right) within administrative districts used in the study.

samples through a 2-mm sieve following air-drying. Monitored parameters encompass macronutrients (P, K, Ca, Mg and S) in 0.5-M ammonium acetate–acetic acid (pH 4.65) extract, micronutrients and selected harmful elements (Cu, Fe, Mn, Al, Zn, Cd, Co, Cr, Mo, Ni, Pb) in 0.5-M ammonium acetate–acetic acid–0.02-M ethylenediaminetetraacetic acid extract, B in hot water extract, and pH and electrical conductivity in 1:2.5 soil–water suspension. The soil extractions are performed on a volumetric basis, but the weight of the sample is recorded for allowing mass-based conversion. Since 1987, inductively coupled plasma optical emission spectroscopy (ICP-OES) has been used in the analysis except for P, which is determined calorimetrically, and Mo, which is measured by graphite furnace (GF)-AAS. In addition, soil total C is analysed by dry combustion. Due to the general soil acidity, the total C is assumed to contain only OC. In 2018, soil bulk density at depths of 0–5 cm, 5–15 cm, 15–25 cm and 25–40 cm was determined from the 149 new sites. Particle size distribution has been analysed through sieving and sedimentation in 2009 and for the new sites in 2018. For a more detailed description of the methods see Heikkinen et al. (2013, 2021), Keskinen et al. (2016) and Soinne et al. (2022). The laboratory analyses excluding soil texture have been conducted throughout the survey in the soil laboratory of Natural Resources Institute Finland, LUKE (former Agrifood Research Finland, MTT). In 2018, separate samples were collected for partly outsourced analysis of DNA-based diversity of soil microbiome and occurrence of pesticide residues.

2.2 | LUCAS Soil

Soil monitoring under the European field survey programme LUCAS (Land Use/Land Cover Area Frame Survey) was launched in 2009 by the European Commission and, thereafter, the sampling has been repeated in the same plots in 2015 and 2018, while continuously extending both the spatial coverage of the network and the range of monitored parameters (Orgiazzi et al., 2018). The network design was based on a 2 × 2 km grid covering the territory of the EU, with the network consisting of a total of 18,984 sampling plots in 2018. The sampling plots comprise a representative subsample selected using multi-stage stratified random sampling from the subsample of general LUCAS georeferenced intersection points of the grid (Tóth et al., 2013a). The sampling plots are classified by land cover and the major classes are artificial land, bareland, cropland, grassland, shrubland, water, wetland and woodland. In Finland, the LUCAS survey includes 1143 sample plots in 2018, of which 134 are in cropland (Figure 1). Reaching the exact sampling plot is targeted, but according to the sampling instructions, samples can be taken within a maximum of 100 m distance from the LUCAS point (Fernández-Ugalde et al., 2017). Furthermore, samples should be preferably collected from the field where the LUCAS point is located but always within the fixed land cover class. Sampling dates were available for the 2018 sampling and varied between June and September.

The composite LUCAS Soil samples represent an area with a radius of 2 m such that one subsample is taken at the centre of the plot and four other subsamples at a distance of two metres from the centre to north, east, south and west (Fernández-Ugalde et al., 2017). A linear sampling pattern is allowed in case the radial arrangement is not possible. Each of the five subsamples is taken at 0–20 cm depth using a spade to collect a 3 cm thick soil slice along the side of a V-shaped hole. Residues of vegetation, litter and stones are removed, and samples are air-dried and sieved to <2 mm prior to analyses. The parameters which were originally monitored included coarse fragments (>2 mm), particle size distribution (laser diffraction), pH in water and 0.01 M $CaCl_2$ (1:5 V/V), organic carbon (dry combustion with correction for carbonates), carbonate content (Scheibler volumetric method), $NaHCO_3$-extractable P, total N (modified Kjeldahl method), ammonium acetate extractable K, multispectral properties (400–2500 nm) and effective cation exchange capacity ($BaCl_2$ extraction). Later the list of parameters has been extended to cover electrical conductivity (1:5 m/V), selected metals (As, Cd, Cr, Cu, Hg, Pb, Zn, Sb, Co and Ni; ICP-OES analysis following microwave-assisted aqua regia digestion) bulk density at 0–10 cm and 10–20 cm depths (volumetric metallic rings), soil biodiversity (DNA metabarcoding), thickness of organic horizon in peat soils and visual assessment of signs of soil erosion. For more detailed description of the methods see Orgiazzi et al. (2018) and references therein. All LUCAS Soil chemical and physical analyses are handled centrally by one laboratory. LUCAS Soil data for 2009 (Tóth et al., 2013b), 2015 (Jones et al., 2020) and 2018 (Fernandez-Ugalde et al., 2022) are openly accessible on the website of European Soil Data Center.

2.3 | Statistical analysis

In this study, soil OC, pH, P and K were selected for examination. These variables are important indicators of soil conditions, and they are measured in all sampling campaign years in both national and LUCAS Soil studies, and variables are openly accessible in LUCAS dataset.

The sampling plots were classified into mineral and organic soils based on an OC-content threshold of 200 g kg^{-1} (IPCC, 2014). A plot was classified as organic if its OC content exceeded the predefined threshold value in one or more sampling campaigns. The higher sensitivity for labelling a plot as organic rather than mineral is reasonable, as it is highly unlikely that actively cultivated mineral soil turns into organic soil, whereas the opposite occurs commonly (Heikkinen et al., 2022). Due to the different sampling depth used in LUCAS and in national monitoring (20 cm vs. 15 cm), the classification into organic and mineral soil is not fully comparable between the two datasets. In LUCAS data, there were a handful of zero values of P and K which were excluded from the analysis as they were interpreted to be missing, given that zero values should not occur in the data.

The consistency of successive measurements was explored by calculating Spearman's rank correlation coefficient r_s between the measurements in 2009 and 2018. Correlation coefficient was selected as a measure of 'goodness' of sampling as the changes in SOC stock are in the temporal scale of the study small in comparison to overall SOC stock and it is known that the uncertainty in SOC measurements is substantial both in space and time (Poeplau et al., 2022; Smith et al., 2020; Wuest & Durfee, 2024). Furthermore, Spearman's rank correlation coefficient does not assume linearity between two variables. Due to substantial differences between the geographical coverage of national sampling network and the LUCAS network (Figure 1), we used the administrative district-based division into 16 regions and calculated also the geographically weighted Spearman rank correlation coefficient r_{ws} with a bootstrapping approach. The weighting coefficients for mineral and organic soils were selected so that bootstrap replicates ($n = 1000$) contained sampling plots in each administrative region in proportions consistent with the geographical distribution of Finnish agricultural land (Figure 1). Cultivated areas were obtained by combining Finnish Soil Database (Lilja et al., 2017) with database of cultivated crop plants by the Finnish Food Authority. Geographical weighting based on administrative regions was employed to more accurately represent the nationwide situation on average and to enhance the comparability of the results between national and LUCAS datasets.

Temporal trends were estimated from the data using averages, with the approximate 95% confidence interval obtained using a non-parametric bootstrap approach (Efron & Tibshirani, 1994) where the data were resampled with replacement 100,000 times. The analyses were carried out for organic and mineral soils separately. For the national data (National), the analysis was based on the point-wise differences between 2018 and 2009. The analyses were done under the assumption that the national sample is a stratified simple random sample where the strata are administrative districts (Figure 1). The total change was calculated under this assumption, meaning that the sample weights were adjusted based on the area under cultivation in each administrative district. Since the geographical distribution of the sampling plots in the national and LUCAS monitoring differed, we also calculated the national results for OC and pH with the same geographical limitations as in LUCAS (National G) by removing the administrative districts from which there were no LUCAS points. As the sample sizes also differed, we also ran a geographically adjusted bootstrap analysis ($n = 100{,}000$ bootstrap replicates) using LUCAS sample sizes for organic and mineral soils in order to compare results with the same geographical limitations and sample size (National GS). The methodologies for K and P differed between the monitoring programmes, and thus the geographical adjustments were not done for these variables as the results are not directly comparable in any case. For the LUCAS data with measurements from three timepoints, we used two different approaches, both of which assumed that the sample was a stratified random sample where the strata were administrative regions analogously to the national data. This was done since there were significant differences in the averages between measurement years, and thus it was not obvious if including data from the year 2015 would improve the accuracy of the results or not. In the first approach (LUCAS I), the analysis was based on the point-wise differences between 2009 and 2018, as in for the national dataset. In the second approach (LUCAS II), we calculated the annual changes and their uncertainties between 2009 and 2015, and between 2015 and 2018 separately. The end result was then obtained as a weighted average of these two annualized changes, where the weights were inverse squared standard errors, which is the maximum-likelihood solution estimator in this case (see, e.g., Taylor (1997)). Differences in SOC contents at 2009 and 2018 between the LUCAS and national samples were tested using Wilcoxon's rank sum test for difference in means and Levene's test for difference in variance.

3 | RESULTS

3.1 | Temporal variation in C, pH, P and K contents between 2009 and 2018

The temporal variability in all studied elements was higher in the LUCAS data compared to the national monitoring data. In mineral soils, the Spearman's rank correlation coefficient r_s between element contents and pH measured in 2009 and 2018 varied between 0.52 and 0.67 (Figure 2) in the LUCAS dataset. In the national dataset, r_s ranged from 0.82 to 0.94. Soil carbon had the highest correlation coefficient in national data whereas in LUCAS data, the correlation was highest for potassium. In both datasets, pH had the lowest r_s value. Geographical weighting with regional distribution of Finnish agricultural land slightly increased the correlation coefficients of all studied elements in the national data ($r_{ws} = 0.84$–0.95) whereas in LUCAS data, weighting tended to decrease the correlation coefficients ($r_{ws} = 0.51$–0.65) (Figure 2).

As was the case for mineral soils, there was significantly more variation in organic soil measurements in the LUCAS data than in the national data. In LUCAS data, Spearman's rank correlation coefficients (r_s) between 2009 and 2018 measurements were 0.51, 0.63, 0.65 and 0.13 for OC, pH, P and K, respectively (N.B. data not shown in Figure 2). In the national data, the corresponding correlation coefficients were 0.84, 0.81, 0.86 and 0.48. When the results were weighted by the geographical distribution of Finnish agricultural area, the correlation coefficients (r_{ws}) were 0.51, 0.79, 0.49 and 0.24 for OC, pH, P and K in LUCAS data and 0.79, 0.79, 0.87 and 0.56 for OC, pH, P and K in national data.

The overall levels of OC content and pH in 2018 were comparable between the national and LUCAS data. In mineral soils, median OC content was 29.8 g kg^{-1} in the national data and 30.6 g kg^{-1} in LUCAS data. The median pH in 2018 was 5.9 and 6.0 in national and LUCAS datasets, respectively. However, in 2009, the difference in mean pH between the national and LUCAS datasets was striking, the LUCAS data exhibiting a very low median value of 5.6 (Figure 2). Due to different analytical methods and different units, the nominal levels of P and K are not directly comparable between the national and LUCAS data. The mean or variance of SOC content in 2009 or 2018 did not differ in a statistically significant way between the national and LUCAS samples. Results for organic soils seemed consistent with those for mineral soils with respect to how the national and LUCAS results differ.

3.2 | Temporal trends in C, pH, P and K between 2009 and 2018

According to the national data, there were decreasing trends for all studied element contents as well as pH in mineral soils between 2009 and 2018 as can be seen in Figures 3–5. These decreases were statistically significant ($p = 0.002$ for P, $p < 0.001$ for C, pH and K). On the

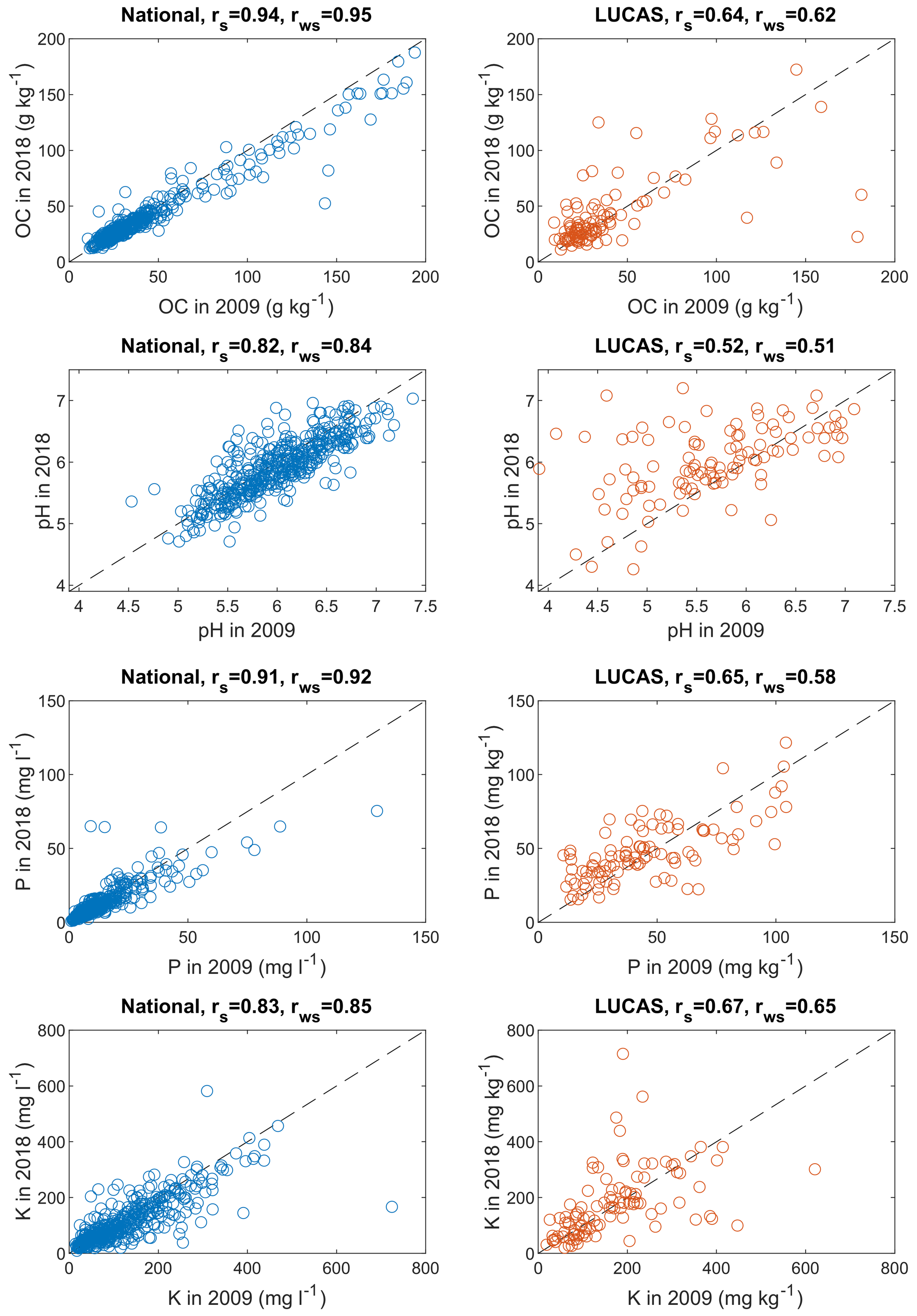

FIGURE 2 Observed soil OC, pH, P and K in 2009 and 2018 based on the Finnish national and LUCAS Soil monitoring networks on agricultural soils. Spearman's rank correlation coefficient between the values observed in 2009 and 2018 was calculated with (r_{ws}) and without (r_s) weighting the datasets to correspond to geographical distribution of Finnish agricultural land area (see Figure 1). LUCAS data had one outlier in P measurements (227 mg kg^{-1} in 2018) and both datasets had one observation of K with an exceptionally high value (1439 mg l^{-1} in national and 1079 mg kg^{-1} in LUCAS in 2009). For clarity, axis limits have been set in a way that the outlier observations are not visible in the figures. Notice the different units of P and K in national and LUCAS data.

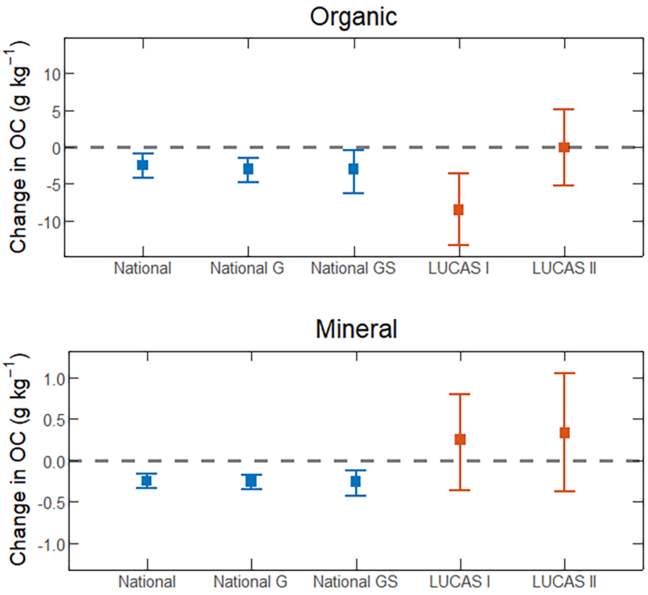

FIGURE 3 Mean annual change in soil OC between 2009 and 2018 with 95% confidence intervals. The national data are reported with weighting based on the geographical distribution of Finnish agricultural land (National), utilizing the same geographical restrictions as LUCAS by excluding administrative districts lacking LUCAS sampling plots (National G) and employing the same sample size and geographical constraints as LUCAS (National GS). LUCAS data were analysed in two different ways: using the data from years 2009 and 2018 (LUCAS I) similar to national data and using the data from years 2009, 2015 and 2018 (LUCAS II). Results are also given in numbers in the Supplementary material.

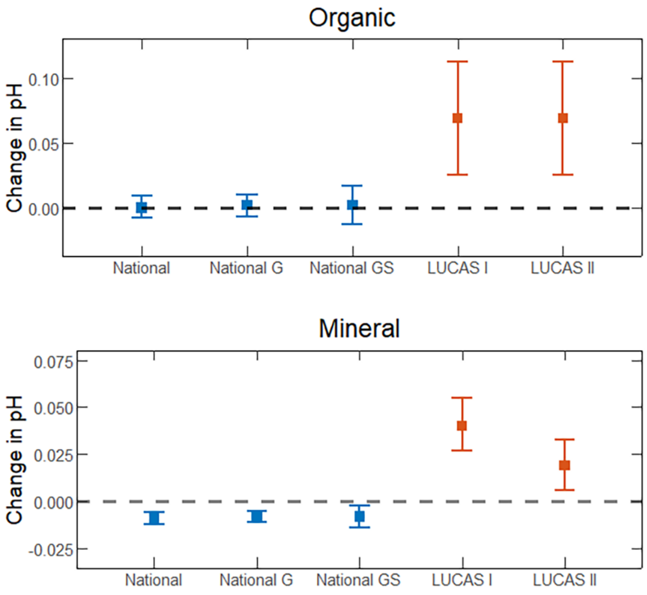

FIGURE 4 Mean annual change in soil pH between 2009 and 2018 with 95% confidence intervals. The national data are reported with weighting based on the geographical distribution of Finnish agricultural land (National), utilizing the same geographical restrictions as LUCAS by excluding administrative districts lacking LUCAS sampling plots (National G) and employing the same sample size and geographical constraints as LUCAS (National GS). LUCAS data were analysed in two different ways: using the data from years 2009 and 2018 (LUCAS I) similar to national data and using the data from years 2009, 2015 and 2018 (LUCAS II). Results are also given in numbers in Supplementary material.

contrary, in LUCAS data, the variables generally had an upward trend over time. However, apart from pH ($p < 0.001$), these changes were not statistically significant ($p = 0.39$ for OC, $p = 0.07$ for P and $p = 0.94$ for K, when taking into account only the years 2009 and 2018). When observations from 2015 were included in the analysis of LUCAS data (LUCAS II, Figures 3–5), the rate of change decreased for pH while additional data had only minor impact on change rate of OC, P and K concentrations. Confidence intervals were slightly broader when analyses were conducted using data also from 2015. This reflects the high variability in the absolute levels of element contents and especially high variation for pH between sampling years (Figure 6).

In the national data of organic soil, the element contents tended to decrease, mirroring the trend observed in mineral soils (Figures 3–5). However, only for OC, the decrease was statistically significant ($p < 0.001$). In LUCAS data, OC and K tended to decrease in organic soils whereas pH and P increased. Confidence intervals were wide and only the increase in pH was statistically significant regardless of whether data from 2015 was included or not. As was the case in mineral soils, including the data from 2015 in the statistical analyses increased the uncertainty of the results.

Restricting the analyses of national data to those administrative regions with LUCAS plots (National G) had only a minor impact on the estimated mean change in OC and pH in mineral soils (Figures 3 and 4). Negative change in OC increased by 0.01 g kg^{-1} from -0.25 g kg^{-1} to -0.26 g kg^{-1} and the negative change in pH decreased by 0.001 unit from -0.009 to -0.008 in comparison to results using all sampling plots (National). In organic soils, the mean change in OC was 2.99 g kg^{-1} with (National G) and 2.47 g kg^{-1} without geographical restriction (National). Restriction increased the change in pH from 0.000 to 0.002 although confidence intervals are wide in both cases. As expected, analysing the national data using the same sample size and geographical restriction as in LUCAS (National GS) did not have an impact on the estimated mean changes in OC and pH in comparison to National G (Figures 3 and 4). However, reduced sample size increased the width of the confidence intervals by 1.8–2.0-fold in mineral soils and 1.7–1.8-fold in organic soils. In the Supplement, these results are given in numerical form.

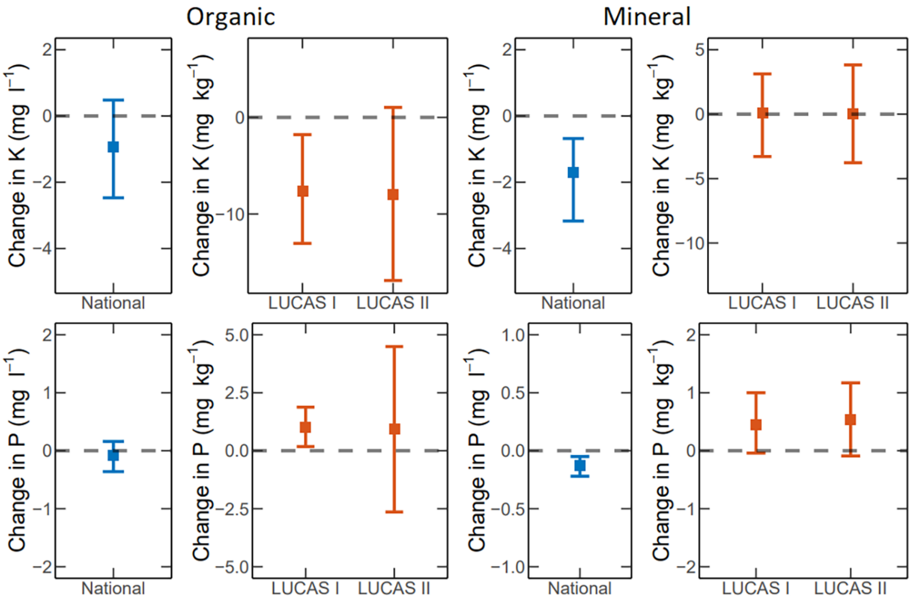

FIGURE 5 Mean annual change in soil K and P between 2009 and 2018 with 95% confidence intervals. LUCAS data were analysed in two different ways: using the data from years 2009 and 2018 (LUCAS I) similar to national data and using the data from years 2009, 2015 and 2018 (LUCAS II). Results are also given in numbers in Supplementary material.

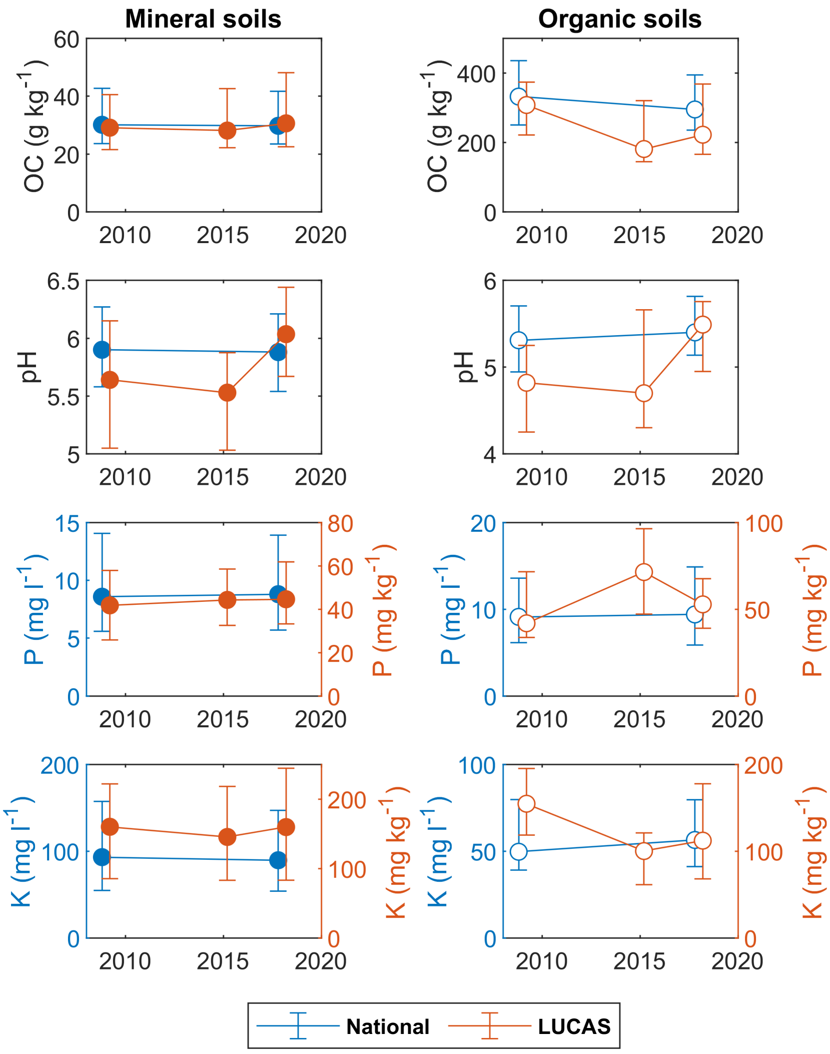

FIGURE 6 Median soil OC, pH, P and K of Finnish agricultural soils according to national (2009 and 2019) and LUCAS datasets (2009, 2015 and 2018). The bottom and top edges of the uncertainty bars indicate the lower and upper quartiles, respectively.

4 | DISCUSSION

Depending on the studied variable, standard errors of mean (and thus 95% confidence intervals) in LUCAS mineral soil data were 2.6 to 6.9 times larger compared to the national monitoring programme between the years 2009 and 2018. Organic soils displayed a similar pattern with 2.5 to 5.2 times larger standard errors though the low number of organic soil sampling plots limits reliable comparison. In addition to the actual change in soil element contents over time, the variability in measurements between the two sampling periods can be attributed to various factors related to the accuracy of locating the sampling plot, soil sampling protocol and/or laboratory analysis. Since changes in OC stock are small compared to the large background stock (Smith et al., 2020), the pointwise variation in OC content between two sampling periods can be considered a good indicator of how successful the sampling has been. The SOC measurements are known to be highly variable, and measurements can have substantial temporal variation even if the repeated measurements from the same site are taken within a short period of time (Wuest & Durfee, 2024).

It is likely that higher temporal variation in LUCAS data is associated with location accuracy. Soil parameters can have high variability even within distances of less than 1 m (Poeplau et al., 2022). The greater the number of subsamples per sampling plot, the more likely it is that the sampling will capture variability at the sampling plot scale. In LUCAS sampling, five subsamples are taken per plot whereas in national monitoring, the number of subsamples typically ranges from 10 to 20. Furthermore, in LUCAS, the diameter of a sampling area is 4 m in contrast to the 10 m × 10 m used in national monitoring. As the accuracy of GPS is some metres, it is likely that a greater proportion of subsamples in LUCAS are collected outside the previous sampling area. It is also noteworthy that in national monitoring, the sampling plots are located using exact GPS coordinates whereas in LUCAS, the tolerance of location accuracy is less strict and the soil samples can be taken within a maximum of 100 m distance of the exact plot location (Fernández-Ugalde et al., 2017). Importance of the location accuracy with respect to data quality is clearly demonstrated in previous sampling campaigns of national monitoring (Heikkinen et al., 2013): when sampling plots were located using maps, there was considerably greater variation in the data compared to GPS-based locating used in the more recent sampling campaigns (Heikkinen et al., 2022). Based on the studies by Jauhiainen et al. (2008) and Nykänen et al. (2008) in Finnish agricultural fields, the resampling for soil properties or factors associated with soil, such as soil total C and P contents, and crop yield should be performed preferably with an accuracy of a few metres. Jauhiainen et al. (2008) demonstrated that for crop yield, a spatial dependence exhibits only up to 40 m. Furthermore, Nykänen et al. (2008) showed that for micronutrients and P, the spatial dependence has a range of 30–50 m and for macronutrients about 75 m. This means that all the advantages gained by resampling the same sites are lost if the relocation accuracy is worse than the range of spatial variation. For example, with the 100 m accuracy allowed by LUCAS Soil field protocol, the collected samples may, for all practical purposes, be statistically independent.

Another major source of uncertainty is the sampling protocol. Soil samples collected in the national monitoring programme might be more consistent as samples are taken with an auger of constant thickness whereas in LUCAS, samples are collected using spade. The elemental content of soil exhibits a vertical gradient even in mixed agricultural soils (Crozier et al., 1999), and in Finnish arable soils, the gradient steepens rapidly below 200 kg m^{-2} soil layer (corresponding approximately to 15 cm) (Heikkinen et al., 2021). Consequently, soil samples collected with a spade may be biased due to a potential imbalance between the share of the surface or the bottom part in the collected sample, although comparison made by Fernández-Ugalde et al. (2020) suggested that spade and gouge auger sampling results do not differ for various soil properties. Due to vertical gradient, the LUCAS samples collected from the 0–20 cm soil layer are also more sensitive to possible variation in actual sampling depth. Thirdly, as tillage depth is typically from 15 to 25 cm, the sampling depth of 20 cm used in LUCAS leads to an increased likelihood of including subsoil into the sample, which would influence the observed elemental concentration in the sample. On the other hand, in the lower sampling depth, applied in the national monitoring, changes in tillage practices which alter the stratification of elements are likely to impact element contents in the sampling layer. In both cases, the collected soil sample (about 0.5 L in national and 0.5 kg in LUCAS) is so small that it is unlikely to affect the results of subsequent sampling campaigns although pit hole sampling with spade, as used in LUCAS, might transport more subsoil to the soil surface compared to the auger sampling. Finally, it should be noted that the sampling protocols of both national and LUCAS monitoring are based on fixed depth (FD) sampling rather than the use of the equivalent soil mass (ESM) method. The fixed depth method is known to be sensitive to changes in soil bulk density (Ellert & Bettany, 1995), and therefore, it is not an ideal way for monitoring temporal trends in element contents.

For the P and K contents, the national monitoring programme uses mg l^{-1} as a unit while the LUCAS results are given in units of mg kg^{-1}. However, the volumetric dosing involves homogeneous ground samples and considering mineral soils, the difference to gravimetric dosing remains small (estimated mean volume weights for the samples were 0.9 kg l^{-1} for clay, 1.0 kg l^{-1} for fine-textured soils and 1.2 kg l^{-1} for coarse-textured soils), whereas in organic mull (0.7 kg l^{-1}) and peat soils (0.5 kg l^{-1}), this difference is more pronounced (Keskinen et al., 2016). Additionally, as different extraction methods are employed to analyse P and K contents in the two monitoring programmes, any statistics, possibly including the overall variation, are not directly comparable. However, one can expect that the average bulk density of pre-treated soil remains essentially constant over time, and, therefore, the direction of the trends should be the same regardless of which unit is used. This expectation is supported by the rank correlation coefficients of P and K between 2009 and 2018 aligning with those of OC and pH, which are determined using the same standard methods and units in both datasets.

Some soil properties, such as nutrient status or acidity, can exhibit intra-annual variability either due to natural reasons or as a result of management practices such as liming and fertilization (Soinne et al., 2008; Tate et al., 1991). Different extraction methods used in soil testing are also known to have different sensitivities in discerning seasonal and management-induced changes in the nutrient pools (Soinne et al., 2008). Although intra-annual variation is not technically classified as a measurement error, as is the case with, for example, localization and sampling protocol-related errors, it can result in additional plot-wise variation in long-term monitoring. As the soil sampling in 2018 in LUCAS monitoring was conducted over a time period nearly twice as long as in national monitoring, it is likely that LUCAS's results contain more seasonal variation. However, as depicted in Figure 2, the correlation coefficients for pH, P and K are comparable to the seasonally highly stable OC content (Smith et al., 2020), indicating that intra-annual variation is not a major source of uncertainty in LUCAS data when compared to national monitoring.

In addition to the greater variation associated with individual plots in the LUCAS data, the sample size is smaller than in national monitoring. With roughly four times as many plots in the national programme, one can expect the 95% confidence intervals to be twice as large for the LUCAS data since the accuracy of the average as an estimator of the mean is proportional to the square root of the number of independent samples. However, if we look at the results adjusted for geography and sample size, the confidence intervals are still much wider for the LUCAS data. For example, the confidence interval (and thus the standard error) for mineral soils is 3.77 times wider than for LUCAS I than National GS. This indicates that there could be much potential for eliminating some of the uncertainty in the LUCAS dataset without increasing the number of sampling plots.

While the national sample has been shown to be representative of Finnish agricultural soils (Heikkinen et al., 2013), the original sampling network was not established with formal randomization of sampling locations. However, 149 new randomized sampling plots were measured in 2018 and in the Supplementary material, the subset of 2018 data is compared with the complete national sample used in this study to show that the national sample is comparable to a random sample. It should be stressed that all population mean estimates and confidence intervals have been calculated under the assumption of a stratified simple random sample though the data were not collected strictly in this way. However, Nykänen et al. (2008) and Jauhiainen et al. (2008) have shown that in Finnish agricultural soils, the spatial autocorrelation of soil variables is limited to a range measured in tens of metres, while the sampling plots are kilometres apart in both soil monitoring datasets. Variograms for soil OC change in mineral soils for the national sample are presented in Supplementary material and show no clear spatial autocorrelation between sampling points. If clear autocorrelation existed, this information could be used to improve the accuracy of the national estimates with a model-based approach (Lohr, 2019). However, when spatial autocorrelation is assumed to be zero between the points, the model-based variance estimates are similar to those obtained by assuming that the points represent a simple random sample with a similar sample size. In any case, the confidence intervals calculated here are conservative estimates, as using a model-based approach that utilizes correlation information would always narrow the confidence interval assuming positive autocorrelation (Lohr, 2019).

Early and accurate detection of trends in key variables related to soil productivity or environmental impacts is essential when considering the need for future interventions and success of current correcting measures in soil management and policies. In the present assessment, the national soil monitoring distinguished unwanted decreases in mean OC and K contents, and in pH that need to be communicated to farmers and accounted for in policy recommendations. On the other hand, a decreasing trend in topsoil P in arable fields has been long aimed for to reduce the eutrophication of surface waters (Uusitalo et al., 2007) and the current result from national monitoring signals success in these efforts. LUCAS Soil data distinguished none of these key trends and, in contrast, merely discerned a significant increasing trend in soil pH. This result suggested an unrealistically high increase from remarkably low mean pH values in 2009 and 2015 to 2018 and was opposite to that recorded in the national data. Increasing trend in pH is not supported by the national production and import statistics for liming materials (Finnish Food Authority, 2022). In the present case, national soil monitoring programme appears essential for reliable detection of agronomically and environmentally important trends in agricultural topsoil properties.

This study focused on identifying potential sources of uncertainty in measurements and their impact on temporal trends in soil monitoring. Trends are also influenced by various agronomic and ecological factors. Changes in the content of the studied elements in Finnish agricultural soils have been attributed to various agricultural management practices, historical land use and climate change. However, these topics are beyond the scope of this paper, and for more information, we refer the reader to previous articles by Heikkinen et al. (2013, 2022) for C, Soinne et al. (2022) for pH and Keskinen et al. (2016) for other studied elements.

5 | CONCLUSIONS

The LUCAS Soil survey of the EU serves as a valuable database, offering a harmonized collection of soil data spanning across Europe. Nevertheless, its utility in discerning nationwide trends, particularly in countries and land-use types characterized by a relatively few sampling plots, such as Finnish agricultural soils, is constrained by the significant temporal variability in measurements. This study compared results between LUCAS Soil and the Finnish national monitoring programmes in order to identify sources of uncertainty and to offer insights for the development of cost-effective and reliable soil monitoring practices. The results indicate that the major source of uncertainty in Lucas Soil monitoring is related to the repeated measurements of individual sampling plots and that the quality of monitoring data could be substantially increased by improving geolocation accuracy and by adopting different sampling protocols. While these changes may require some additional resources, it is likely to be more cost-efficient than increasing sample size. This case study focussed on comparing LUCAS Soil and national dataset performance, but the simultaneous utilization of the datasets in statistical analyses of soil development could prove useful and reveal new perspectives on the topic.

AUTHOR CONTRIBUTIONS

Jaakko Heikkinen: Methodology; conceptualization; writing – original draft; investigation; visualization; formal analysis; writing – review and editing. **Joel Kostensalo:** Formal analysis; methodology; writing – original draft; investigation; visualization; writing – review and editing. **Riikka Keskinen:** Investigation; writing – original draft; writing – review and editing. **Helena Soinne:** Investigation; writing – original draft; writing – review and editing. **Visa Nuutinen:** Conceptualization; investigation; writing – original draft; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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