Anonymous Comment Referee 1

General comment This manuscript presents interesting results showing soil compaction risk classes and risk map units based on relative porosity and relative bulk density in Dutch soils. It is relevant to SOIL and of interest to a wider audience. The manuscript require amendments and explanations that have been indicated below:

1. As soil samples were taken directly below the plough layer (subsoil) (P 5 L 5-6) suggest changing soil to subsoil. Also "subsoil" is frequently used in the text.

We agree with this point, and changed soil into subsoil at all places where it refers to our study.

2. Provide information about whether soil (subsoil) compaction affects crop yields and other soil function in the studied areas.

We did not register the crop yields at the selected sampling sites. Note that to study the effect of subsoil compaction on crop yields an experimental design is needed. For an observational study into the effect of subsoil compaction on crop yields a different sampling design is needed: selection of pairs of sites, with/without subsoil compaction, comparable with respect to other factors that control crop yield (such as nutrient and water availability). This was not the aim of this research.

3. P4, L 9-10 and some other places: change specific density to particle density.

Thanks, we replaced specific weight by particle density.

4. P 7 L 26 and some other places including captions to Figures: "soil" is used here. Does it mean "subsoil" from which soil cores for determination of bulk density and porosity were taken as indicated in P 5 L 5-6). It should be clarified.

See comment 1, so we replaced soil by subsoil where appropriate.

Minor points P 2, L 3 and elsewhere: Schjonnong > Schjønnong. P 9, L 30 and elsewhere: Hakansson > Håkansson.

We corrected the spelling of the Scandinavian authors (sorry, I did not know how to do this in LaTeX, now I know).

Anonymous Comment Referee 2

Dear Authors I appreciate the mammoth amount of effort a nationwide soil survey will have taken and the importance for such surveys. The data obtained is important and could be compared to surveys from other Nations. It is wise to get a baseline appreciation on the widespread nature of compaction, which perhaps is a chronic problem for yields in European soils. I agree with the other comments already highlighted by the other reviewers and suggest they are taken on board. However, I think the manuscript is of publishable quality and of a wide interest to the readership of this journal. Here are a few amendments

P1 L20: Do you mean the layer above.

The word below is correct. We are talking about the subsoil here (see first part of the sentence) , and the panlayer is at the top of the subsoil. The panlayer is less permeable than the soil below it.

P3 L28: do you mean particle density?

Density refers here to dry bulk density, so we replaced density by dry bulk density.

P8 L27: I think when you refer to just density here and elsewhere you are referring to bulk density, this may go against the comment by reviewer 1.

This is correct, relative density is relative dry bulk density.

Short comment by Florian Schneider

Dear authors,

the title of your manuscript grabbed my attention. Studying the areal extent of compacted agricultural land is of great importance. However, it is a challenging task and various approaches have been suggested to do so. While reading the present manuscript, the following issues came into my mind:

The ratio of bulk density (porosity) and respective threshold values served as indicators to classify subsoil as compacted or not compacted. The reported threshold values were underpinned with citations. However, when briefly screening the respective articles, I could not find information on how the threshold values were exactly derived and related to soil functions. I would therefore recommend to explain the origin of these threshold values in a revised version of this manuscript in greater detail.

The paper of van den Akker and Hoogland (2011), which is cited, gives details about the derivation of the threshold values; maube a problem was that the hyperlink in this paper of van den akker and Hoogland was not working anymore. For that reason we have added an updated hyperlink, as well as a reference to the reports I and V of the ENVASSO project, see p.5, lines 16 and 17.

The study concludes that about 45% of the soils in the Netherlands are overcompacted. However, this confused me a little because in the methods section it says that organic soils and naturally compacted soils were omitted from the present study (page 4, line 28). What's the areal percentage of organic and naturally compacted soils in the Netherlands? Furthermore, mentioning the existence of naturally compacted soils is an important point, which I believe would be interesting to be addressed in greater detail in a revised version of this manuscript. For example Gao et al. (2016) pointed out that bulk density (or the degree of soil compaction) typically increases with soil depth merely due to the overburden pressure exerted by the above soil column. Could the present results be used to distinguish between anthropogenic and natural soil compaction?

Good question! We understand the confusion. The 45% overcompacted soils refers to the target population, and so it will be slightly smaller for the entire Netherlands, see Figure 1 (grey area) which parts of the Netherlands were excluded. The target population excludes:

a. build-up areas, glasshouses, infrastructure (roads), water

b. soils with peat at about 20 to 25 cm below surface. So peat soils with a mineral topsoil (clay, sand) are NOT excluded.

c. naturally compact subsoils, such as boulder clay soils, 'knipkleigronden' and others

The area of the soils of category b, which are not overcompacted, is about 4.5%. The estimated total area (a, b and c) is about 5% to 6% of the area of the Netherlands. So correcton for this gives an estimate of about 43% instead of 45%. We corrected the percentage in the abstract and Conclusions, and added a sentence in the Results subsection 4.2 (first paragraph)

Finally, I was wondering at which depth soil samples were taken if no plough layer was present (if I understood correctly also uncultivated soils were sampled, right? page 4, line 28) and whether on cropland typically more compacted parts of the fields like traffic lanes or headland were sampled as well.

When it was not clear at what depth the subsoil was compacted, both in uncultivated and cultivated soils the decision was based on the penetration resistance as measured with a penetrometer. Sampling sites were randomly selected, and selected sites in traffic lanes and headlands of arable fields were NOT excluded. We added a sentence in subsection 3.2, second paragraph.

Best regards,

Florian Schneider

How serious a problem is ~~soil~~ subsoil compaction in the Netherlands? A survey based on probability sampling.

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Abstract. Although soil compaction is widely recognized as a soil threat to soil resources, reliable estimates of the acreage of overcompacted soil and of the level of soil compaction parameters are not available. In the Netherlands data on ~~soil~~ subsoil compaction were collected at 128 locations selected by stratified random sampling. A map showing the risk of ~~soil~~ subsoil compaction in five classes was used for stratification. Measurements of bulk density, porosity, clay content and organic matter content were used to compute the relative bulk density and relative porosity, both expressed as a fraction of a threshold value. A ~~soil~~ subsoil was classified as overcompacted if either the relative bulk density exceeds 1 or the relative porosity is below 1. The sample data were used to estimate the means of the two ~~soil~~ subsoil compaction parameters and the areal fraction overcompacted. The estimated global means of relative bulk density and relative porosity were 0.946 and 1.090, respectively. The estimated areal fraction of the Netherlands with overcompacted ~~soils was 45~~ subsoils was 43 %. The estimates per risk map unit showed two groups of map units, a ‘low risk ’ group (unit 1 and 2, covering only 4.6 % of the total area) and a ‘high risk’ group (unit 3, 4 and 5). The estimated areal fraction overcompacted ~~soil~~ subsoil was 0 % in the ‘low risk’ unit and 47 % in the ‘high risk’ unit. The map contains no information about where overcompacted ~~soils~~ subsoils occur. This was caused by the poor association of the risk map units 3, 4 and 5 with the ~~soil~~ subsoil compaction parameters and ~~soil~~ subsoil overcompaction. This can be explained by the lack of time for recuperation.

1 Introduction

Soil compaction is recognized as one of the major soil threats. Van Camp et al. (2004) recognized soil compaction as one of the eight soil threats requiring further attention. In 2006 the Thematic Strategy for Soil Protection was launched by the European Commission (European Commission, 2006). Subsoil compaction is of more concern than topsoil compaction, because of its persistency (Alakukku, 2000; Berisso et al., 2012, 2013). Subsoil compaction is defined as compaction of the soil below the cultivated layer. This compacted layer is referred to as the panlayer, hardpan or plow pan. The panlayer is often the bottleneck for the functioning of the subsoil, because it is denser and less permeable for roots, water and oxygen than the ~~soil~~ subsoil below this layer.

Lipiec and Hatano (2003) review indices and methods to quantify the effects of compaction on soil physical properties and crop growth. They concluded among others that yield decrease in overcompacted soil is frequently attributed to excessive mechanical impedance, reduced water infiltration and crop water use efficiency, insufficient aeration or their combination depending on weather conditions. Etana et al. (2013) stressed the impact of subsoil compaction on preferential flow of water in a sandy clay soil, which can result in a fast transport of nutrients and agrochemicals to deeper ~~sol~~ soil layers and ground water. Schjønning et al. (2015) present an overview of results of field experiments on crop yield reduction by subsoil compaction. Alblas et al. (1994) report average yield reductions of silage maize on sandy soils with a compacted subsoil of 15 % with a wheel load of 5 Mg and 4 % with a wheel load of 2.5 Mg. Håkansson and Reeder (1994) report 2.5 % permanent yield reductions in long term experiments with wheel loads of 5 Mg applied in the first year of the experiment. After this first year wheel loads were limited to 2 Mg to prevent further compaction. The same kind of long term experiments by Voorhees (2000), however, with wheel loads of 9 Mg resulted in permanent yield reductions of on average 6 %. It should be noted that in practice wheel loads of 5 to 9 Mg or even higher are commonly used in heavy mechanized agriculture during manuring and harvesting.

Håkansson and Reeder (1994) also studied the recuperation of soil compaction in a clay loam soil. In the first 5 years the topsoil recuperated to a great extent. In the first 10 years also the upper part of the subsoil to a depth of about 40 cm recuperated considerably, however in the third layer below 40 cm depth the recuperation was almost zero and caused a permanent yield reduction of 2.5 %.

Soil compaction is estimated to be responsible for the degradation of an area of about 33 million ha in Europe (Van Ouwerkerk and Soane, 1994). About 32 % of the subsoils in Europe is highly vulnerable and another 18 % is moderately vulnerable to subsoil compaction (Fraters, 1996). However, these are very rough estimates and not the result of a thorough assessment. Jones et al. (2003) present a map of the vulnerability of subsoils to compaction. The authors concluded that at the moment on the basis of the existing information, any attempt to identify the vulnerability to compaction of subsoils in Europe, on a spatial basis, lends itself to fundamental improvement. Also the assessment of the compaction state of subsoils is scarce and incomplete and requires improvement (van den Akker et al., 2003).

Previous work by van den Akker and Hoogland (2011) was not conclusive about how serious the problem is in the Netherlands either. Two risk-assessment methods were used to map the vulnerability and susceptibility to soil compaction. These maps were compared to a map showing the probability that the subsoil is already compacted. The agreement of the vulnerability and susceptibility maps with the probability map was poor. The probability of compacted ~~soil~~ subsoil was mapped using legacy data on bulk density in the Dutch Soil Information System. The value of these data for assessing the current ~~soil~~ subsoil compaction is restricted because most of the measurements were done more than 20 years ago. Another problem was that the sampling locations were not selected by probability sampling. For that reason the only option was to construct the map and estimate the areal fraction overcompacted ~~soil~~ subsoil by a model-based approach, more specific space–time kriging. The available data for the calibration of the model were rather scarce, so that the quality of the geostatistical model is questionable. This together with the questionable quality of the legacy data was the motivation for a new, nationwide survey, specifically designed to quantify how serious the problem of current ~~soil~~ subsoil compaction is in the Netherlands.

The aim of this research was to design a sample for estimating ~~with quantified precision the means of soil~~ the current means of subsoil compaction parameters and the areal fraction where ~~soil~~ subsoil compaction has exceeded a critical threshold. These means and areal fraction must be estimated for the Netherlands in its entirety, as well as for the five units of the soil compaction risk map. The estimates must be accompanied with estimates of their accuracies.

The soil compaction risk map for the Netherlands of van den Akker et al. (2013) plays a central role in this study. Therefore we first describe how van den Akker et al. (2013) constructed this map. In the subsequent section we describe the methodology of this study.

2 Soil compaction risk classification and mapping

The risk of ~~soil~~ subsoil compaction is a function of wheel loads of machines which is related to landuse, and soil mechanical strength which is determined by various soil properties such as soil texture and water content. The map of soil compaction risk was constructed by combining information derived from the landuse database of the Netherlands (Hazeu et al., 2010), and from the Soil Map of the Netherlands 1:50,000 and associated database with descriptions of typical soil profiles (de Vries, 1999).

The landuse database was used to determine typical agricultural machinery and associated typical wheel loads, tyres and tyre inflation pressures for agricultural areas in The Netherlands. In this an inventory of Vermeulen et al. (2013) was used, in which typical, commonly used heavy machinery, wheel loads and tyres in 1980 and 2010 are compared. The SOCOMO model (van den Akker, 2004) was used to calculate for each of these wheel loads the soil stresses at several depths.

The calculated soil stresses for 2010 were compared with the soil strengths in the same way as presented in van den Akker (2004) and van den Akker and Hoogland (2011). Also the same soil classification as in van den Akker (2004) and van den Akker and Hoogland (2011) was used. Based on the landuse map and the soil map 1 : 50 000 of The Netherlands for each parcel the exerted soil stresses on the subsoil by typical wheel loads for that land use were compared with the strength of that subsoil for a wet soil (at about field capacity) and a moist soil (a soil water suction of about -30 kPa). Five risk categories were considered: very high, high, moderate, low and very low. If the exerted soil stresses were higher than the strength of a moist soil, then the risk of subsoil compaction was considered to be "high". If the exerted soil stresses did not exceed the strength of the moist soil, however, exceeded the strength of the wet soil, then the subsoil compaction risk was "moderate". In case the exerted soil stresses didn't exceed the strength of the wet subsoil, then the subsoil compaction risk was "very low".

In a second step factors that increase or decrease the risk of subsoil compaction on the long term were taken into account. Factors that improve the resilience and natural recuperation of the compacted subsoil and in that way decrease the subsoil compaction risk are:

- The soil is well drained and in general dry, improving the resilience and the natural recuperation
- Clay content $>$ 17.5 %: improved natural recuperation by swelling and shrinkage and structure forming processes
- Organic matter content $>$ 4 %: improved rebound after loading, biological structure forming processes
- Coarse sand: hardly any increase in dry bulk density, water infiltration is never a problem
- Only a limited part of the parcel can be trafficked, so compacted: e.g. forests or orchards

Factors that increase the risk of subsoil compaction are:

- The soil is often wet
- The typical wheel loads of the land use will cause compaction at depths > 40 cm.

All positive and negative factors are added together and the risk class in the first step is increased or decreased with a maximum of one class. The change in class is limited to one step to account for the fact that overloading and compaction of the subsoil is cumulative in time and recuperation by shrinkage and biological processes is never complete, therefore the risk classification should be mainly determined as a function of the exerted stresses at a certain depth and the strength of the soil at that depth. Figure 1 shows the soil compaction risk map.

3 Sampling theory

3.1 Sampling design

For estimating means of ~~soil compaction parametersand to validate the soil compaction risk map~~subsoil compaction parameters, locations were selected by probability sampling, i.e. by random sampling with known inclusion probabilities which are > 0 for all locations in the study area (Särndal et al., 1992). With probability sampling model-free, design-based estimates of spatial means and their variances can be obtained, so that discussions on the validity of the results are avoided (de Gruijter and ter Braak, 1990; Brus and de Gruijter, 1997). Stratified simple random sampling was chosen as a design-type (de Gruijter et al., 2006). For stratification we used the map showing the risk of ~~soil~~ subsoil compaction in five classes (Figure 1). When the risk map units are related to the ~~soil~~ subsoil compaction parameters measured in this study (see hereafter), we expect a gain in precision of the estimated nationwide means compared to simple random sampling with the same sample size. Besides, a map showing the provinces of Zeeland, Noord-Brabant, Gelderland and remaining provinces was used for stratification This map was used to control the sample sizes in these administrative units. The three mentioned provinces contributed additional financial resources, so that these provinces claimed extra sampling locations. The assumption was that in the provinces of Gelderland, Noord-Brabant and Zeeland the problem of ~~soil~~ subsoil compaction is more serious, due to the intensive use of heavy machines in agriculture. The ultimate strata were obtained by overlaying the two maps. All five risk classes were present in all administrative units, so that the total number of strata became $5 \times 4 = 20$.

The total sample size was 128. The sample sizes in the provinces Gelderland, Noord-Brabant, Zeeland were 20, 39, 30, respectively, leaving 39 for the remaining provinces. These sample sizes were allocated proportionally to the area of the five risk map units within the provinces. The total sample sizes in the risk map units 1 (low risk) to 5 (high risk) were 4, 5, 56, 44 and 19, respectively. The small sample sizes for the risk map units 1 and 2 reflect the small areas of these two units: the sum of their areas is only 4.6 % of the total area.

The target population consists of all soils in the Netherlands, both cultivated and uncultivated soils, except soils with a low compaction risk due to peat layers, naturally compacted soils (‘knipkleigronden’) and soils in glasshouses.

3.2 Field sampling and laboratory measurements

The randomly selected locations were localized by differential GPS. If a randomly selected sampling location was unsuitable for collecting soil samples (no soil present, no permission, not part of the target population), the first point on a reserve list, in the same stratum as the omitted point, was added to the list of points to be visited.

At each sampling location three volumetric ~~soil~~ subsoil samples were collected using a cylinder with a diameter of 7.6 cm. The length of the soil cores was 5 cm. The soil cores were collected directly below the plough layer (sandy soils below 35 cm, clay soils below 20 to 22 cm). If a plough layer was absent are unclear, the sampling depth was based on the penetration resistance as measured with a penetrometer. The clay content and soil organic matter content was estimated by the soil surveyor in the field. The dry bulk density and the actual moisture content was determined in the laboratory by weighing and drying of the samples. The porosity was calculated from the dry bulk density using a ~~specific weight~~ particle density of the mineral parts of 2.65 g.cm^{-3} and a specific weight of the soil organic matter of 1.47 g.cm^{-3}.

3.3 Soil compaction parameters

We used as ~~soil~~ subsoil compaction parameters the relative bulk density and relative porosity. The relative bulk density is defined as the actual bulk density as a fraction of the threshold value of the bulk density (van den Akker and Hoogland, 2011). For sand and loamy soils (clay content < 16.7 %) this threshold value is 1.6 g cm^{-3}; for soils with clay content > 16.7 % the threshold value is $1.75 - 0.009 \times clay$ g cm^{-3}. More information about the latter threshold value is presented in the reports I and V of the ENVASSO project (https://esdac.jrc.ec.europa.eu/content/envasso-environmental-assessment-soil-monitoring) in Huber et al. (2008) and Jones et al. (2008).

The relative porosity is defined as the actual porosity as a fraction of the threshold value of the porosity, which is 0.4 as determined in the ENVASSO project (Huber et al., 2008). In general this threshold value was only a problem in sandy and loamy soils with some organic matter.

If either the relative bulk density > 1 or the relative porosity < 1, the ~~soil~~ subsoil is classified as being overcompacted.

3.4 Estimation of means and areal fractions

The global means of the relative bulk density and relative porosity were estimated by design-based inference, more specifically by the usual estimator for stratified simple random sampling:

$$\hat{\bar{y}} = \sum_{h=1}^{H} w_h \hat{\bar{y}}_h$$
$$\hat{\bar{y}}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi} \quad (1)$$

with H total number of strata ($H = 20$), w_h the weight of stratum h quantified by the relative area, $\hat{\bar{y}}_h$ the estimated mean of stratum h, n_h the number of sampling points in stratum h, and y_{hi} the measurement of the target soil property at location i

in stratum h. The areal fraction overcompacted can be estimated by the same equations, replacing y_{hi} by an indicator having value 1 if the ~~soil~~ subsoil at that location is overcompacted and 0 else.

These estimators were also used to estimate the means of the two ~~soil~~ subsoil compaction parameters and the areal fraction overcompacted for the five units of the soil compaction risk map and for the three provinces. These subareas are unions of complete strata, i.e. they do not contain one or more strata which only partly belong to the subarea, so that estimation is straightforward.

3.4.1 Estimation of sampling variances

In all four strata of risk map unit 1 and three strata of risk map unit 2 only 1 point was selected. This complicates the estimation of the sampling variance of the estimated means. Following the approach of Cochran (1977), we collapsed all four strata of risk map unit 1, and all four strata of risk map unit 2. The total number of sampling points in the two collapsed strata were four (risk map unit 1) and five (risk map unit 2). After collapsing the total number of strata was $3 \times 4 + 2 = 14$. The sampling variance of the estimated means was then estimated by

$$\begin{aligned}
\widehat{V}(\hat{\bar{y}}) &= \sum_{c=1}^{C} w_c^2 \widehat{V}(\hat{\bar{y}}_c) \\
\widehat{V}(\hat{\bar{y}}_c) &= \frac{s_c^2}{n_c} \\
s_c^2 &= \frac{1}{n_c - 1} \sum_{i=1}^{n_c} (y_{ci} - \hat{\bar{y}}_c)^2 \qquad (2)
\end{aligned}$$

with C total number of strata after collapsing ($C = 14$), w_c the weight of (collapsed) stratum c quantified by the relative area, $\widehat{V}(\hat{\bar{y}}_c)$ the estimated sampling variance of the estimated mean of (collapsed) stratum c, s_c^2 the estimated spatial variance within (collapsed) stratum c, n_c the number of sampling points in (collapsed) stratum c, and $\hat{\bar{y}}_c$ the estimated mean in (collapsed) stratum c (the sample average in (collapsed) stratum c). Standard errors of the estimated means are computed by the square root of the estimated sampling variances.

The sampling variance of the estimated areal fractions was estimated by (Cochran, 1977)

$$\begin{aligned}
\widehat{V}(\hat{\bar{y}}) &= \sum_{c=1}^{C} w_c^2 \frac{\widehat{V}(\hat{\bar{y}}_c)}{n_c - 1} \\
\widehat{V}(\hat{\bar{y}}_c) &= \hat{\bar{y}}_c (1 - \hat{\bar{y}}_c) \qquad (3)
\end{aligned}$$

4 Results and Discussion

4.1 Descriptive statistics of data

Figure 2 shows boxplots of the relative bulk density and relative porosity for the five risk map units. The lower and upper side of the box represent the first and third quartile, the central line the median. Note that the boxplots for risk map unit 1 and 2 are based on 4 and 5 measurements only. For both ~~soil~~ subsoil compaction parameters the risk map units can be aggregated into two distinct groups, a group with relatively low ~~soil~~ subsoil compaction consisting of map units 1 and 2, and a group of relatively high ~~soil~~ subsoil compaction consisting of map units 3, 4 and 5. Differences between risk map units within the same group were small compared to differences between groups. In all three risk map units 3, 4 and 5 outliers occurred with a relatively small relative bulk density and relatively large relative porosity (dots in Figure 2).

4.2 Means of ~~soil~~ subsoil compaction parameters and areal fraction overcompacted

The estimated global mean of relative bulk density was 0.946 with an estimated standard error of 0.012. The estimated global mean of relative porosity was 1.090 with an estimated standard error of 0.020. The estimated areal fraction of the ~~Netherlands with overcompacted soils~~ target population with overcompacted subsoils was 0.446 with an estimated standard error of 0.053. Correcting the estimated areal fraction for the peat soils that were excluded from the target population (covering about 4.5% of the Netherlands), gives an estimated areal fraction overcompacted of about 43% of the Netherlands

Design-based estimates of the means of the two ~~soil~~ subsoil compaction parameters and of the areal fractions overcompacted per risk map unit are shown in Figure 3. The error bars represent the standard error of the mean. So for a 95 % confidence interval the length of the bars must approximately be doubled. The estimated means confirm what we have seen in the raw boxplots (Figure 2). Estimated means of relative bulk density were relatively low in map units 1 and 2 and relatively high in map units 3 to 5, and accordingly estimated means of relative porosity were relatively large in map units 1 and 2 and relatively small in maps units 3 to 5. The standard errors of the estimated means for map units 3 to 5 were acceptable; for map units 1 and 2 these were large compared to the estimated means due to the very small sample sizes. The error bars of map units within above mentioned groups clearly overlap, so that without statistical testing we can safely conclude that the means of risk map units within a group were not significantly different.

For map units 1 and 2 the estimated areal fractions overcompacted ~~soils~~ subsoils were both 0 (in both units no sampling points had a relative bulk density > 1 or a relative porosity < 1), whereas for map units 3 to 5 these varied from 0.34 (map unit 4) to 0.56 (map unit 3).

As differences between map units 1 and 2, and between the map units 3, 4 and 5 were small, we also estimated means and areal fractions for these two groups (Table 1). The sample sizes in these two groups were 9 (map units 1 and 2) and 119 (maps units 3, 4 and 5). The estimated mean relative bulk density in the 'high risk' group (units 3, 4 and 5) was 9.2 % larger than in the 'low risk' group. The difference in estimated mean relative porosity between the two groups was larger: 1.07 for the 'high risk' group of map units versus 1.42 for the 'low risk' group. Note that the mean relative porosity for the 'high risk' group exceeded value 1. The areal fraction overcompacted was about 47 % for the 'high risk' group, whereas it was 0 for the 'low risk' group. All differences were significant at a significance level of 0.01.

Finally, we estimated means of the two ~~soil~~ subsoil compaction parameters and areal fraction overcompacted for the 'high risk' group of map units inside the three provinces, to check the assumption that in these provinces the problem of ~~soil~~ subsoil compaction was more serious (Figure 4). The means of relative bulk density and relative porosity indicated more serious ~~soil~~ subsoil compaction problems in these provinces indeed, although the differences with the global means were not significant.

The estimated areal fraction overcompacted was larger than the global areal fraction for the provinces of Noord-Brabant and Gelderland, but not for Zeeland.

The aggregated map unit ‘high risk’ covers 95.4 % of the Netherlands. About 47 % of the subsoils within this aggregated map unit are overcompacted, but the map contains no information about where these overcompacted subsoils occur, as the risk map units 3, 4 and 5 are not associated with the subsoil compaction parameters and subsoil overcompaction~~. The 47 % of the area with ‘high risk’~~ , i.e. differences between the map units 3, 4 and 5 of the current means of subsoil compaction ~~that has indeed an overcompacted subsoil is in good agreement with the 50 % overcompacted subsoils predicted for 2010 in van den Akker and Hoogland (2011). This prediction was based on legacy data mainly collected before 1988, whereas the data of this paper were collected in 2013.~~

~~The poor association~~ parameters were small.

A possible explanation is the poor quality of the soil compaction risk map. The soil compaction risk class as depicted on the map will not correspond everywhere with the risk class in the field, i.e. the risk class as based on the soil profile characteristics observed in the field. We estimated the purity of the five map units, i.e. the areal fractions of the map units where the soil compaction risk class as depicted on the map corresponds with the risk class in the field (Brus et al., 2011). For map units 1 and 2 the estimated purity was 1, but these estimates were based on a few sampling points only, and therefore are very inaccurate. For map units 3, 4 and 5 the estimated purities were 0.80, 0.71 and 0.84, respectively. This indicates that the small differences in subsoil compaction parameters between the map units cannot be attributed to low map unit purities. This was confirmed by the estimated means of the subsoil compaction parameters for the risk classes in the field 5. The patterns are very similar to those for the risk map units (3. Again the differences between the risk classes ~~and~~ 3, 4 and 5 in the field were small.

A second explanation could be a poor performance of the SOCOMO model. However, comparisons between modeled and measured stresses showed good agreement (van den Akker, 2004; **?**). It should also be noted that in general the calculated stresses were much higher than the strength of the subsoil (van den Akker et al., 2013), and also much higher than the strength threshold value of 40 kPa for the subsoil determined by **?**.

A third possible explanation is the ~~current means of soil compaction parameters can be explained by the~~ lack of time for natural recuperation of subsoil compaction. Due to the intensive agricultural land use the subsoil is overloaded every second or third year, so ~~the~~ considering a recuperation time of about 10 years of the upper subsoil up to a depth of 40 cm (Håkansson and Reeder, 1994), the expected natural recuperation in clay subsoils or sandy subsoils with a soil organic matter content > 4 % can only be very limited and temporally.

The 47 % of the area with ‘high risk’ of subsoil compaction that has indeed an overcompacted subsoil is in good agreement with the 50 % overcompacted subsoils predicted for 2010 in van den Akker and Hoogland (2011). This prediction was based on legacy data mainly collected before 1988, whereas the data of this paper were collected by probability sampling in 2013.

5 Conclusions

- About ~~45~~43% of the ~~soils~~ subsoils in the Netherlands are overcompacted.

- The map of risk ~~for~~ of subsoil compaction of van den Akker et al. (2013) provides only very rough information about where these overcompacted subsoils occur in the Netherlands.

- In terms of the ~~soil~~ subsoil compaction parameters relative bulk density and relative porosity, and in terms of the areal fraction overcompacted ~~soil~~ subsoil only two risk classes and risk map units can be distinguished: ‘low risk’ (risk classes/map units 1 and 2) and ‘high risk’ (risk classes/map units 3, 4 and 5).

- Lack of time for natural recuperation can be an explanation for the fact that, despite the good quality of the risk map in terms of map unit purity and class representation, no differences in subsoil compaction can be distinguished between the map units 3, 4 and 5.

Disclaimer. TEXT

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Table 1. Design-based estimates of means of two ~~soil~~ subsoil compaction parameters and of areal fraction overcompacted, for the groups ‘low risk’ (map units 1 and 2) and ‘high risk’ (map units 3, 4 and 5). Between brackets: standard error

	low risk	high risk	p-value
relative bulk density	0.858 (0.0276)	0.950 (0.0125)	1.3E-3
relative porosity	1.42 (0.0666)	1.07 (0.0206)	2.9E-7
areal fraction overcompacted	0.00 (0.000)	0.467 (0.0551)	1.1E-17

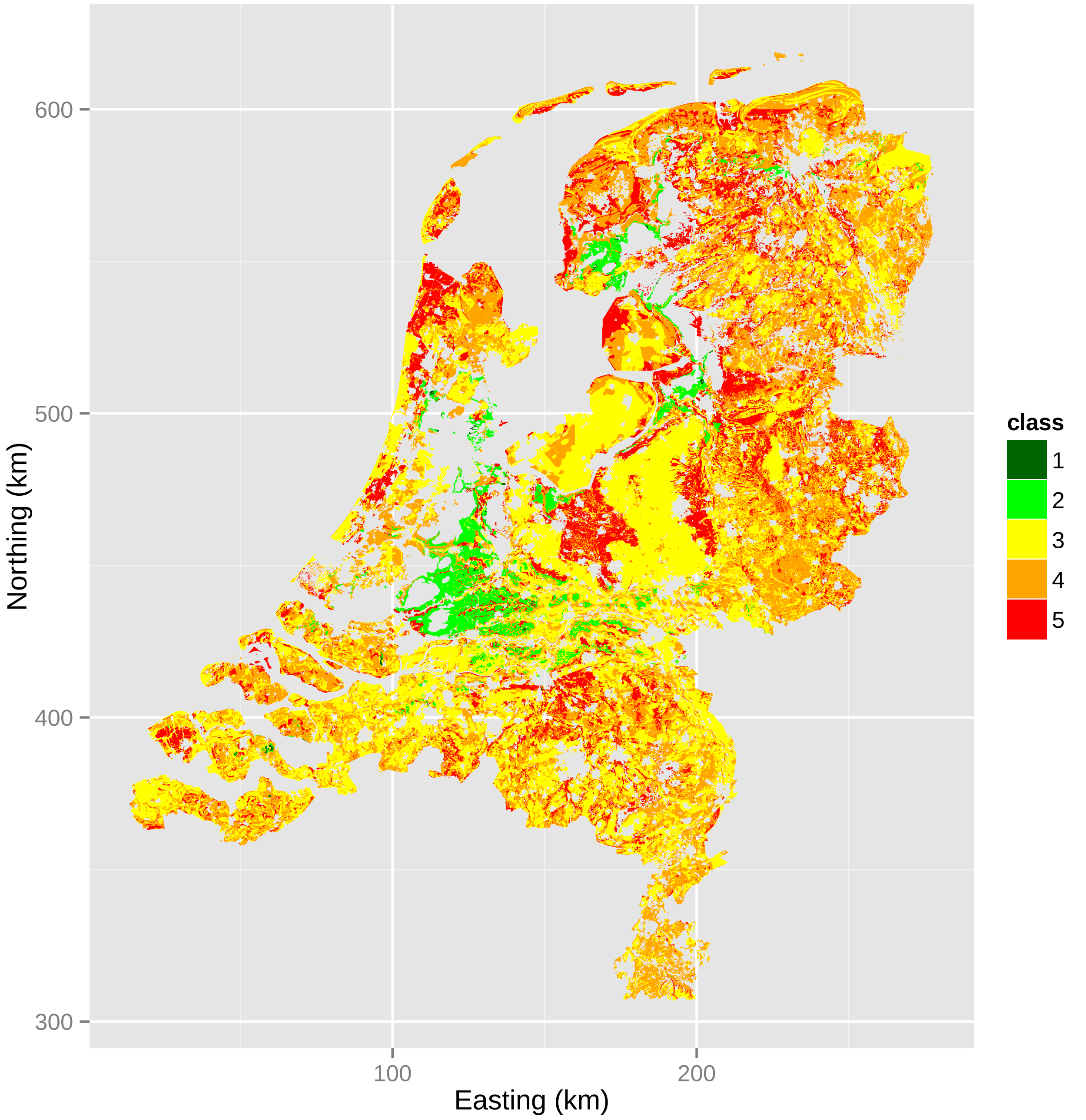

Figure 1. Map of risk for ~~soil~~ subsoil compaction (van den Akker et al., 2013)

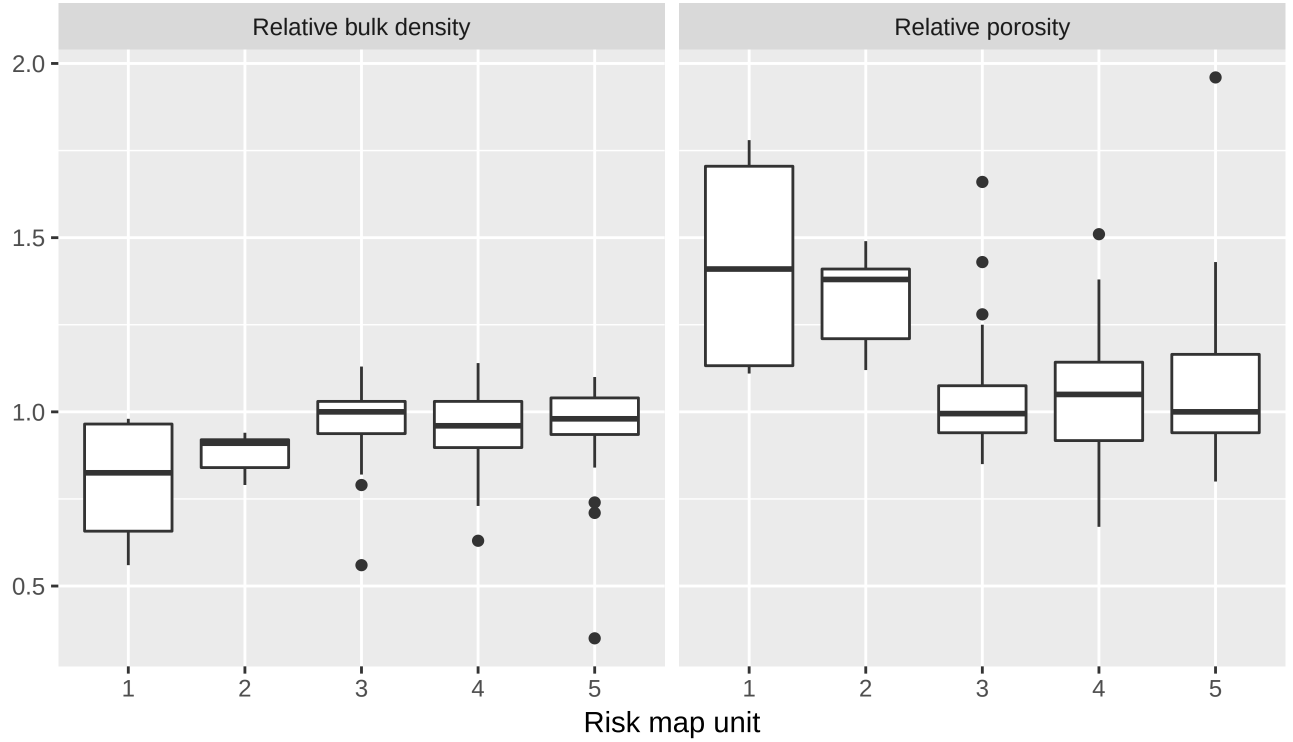

Figure 2. Boxplots of relative bulk density and relative porosity per risk map unit (1: low risk; 5: high risk)

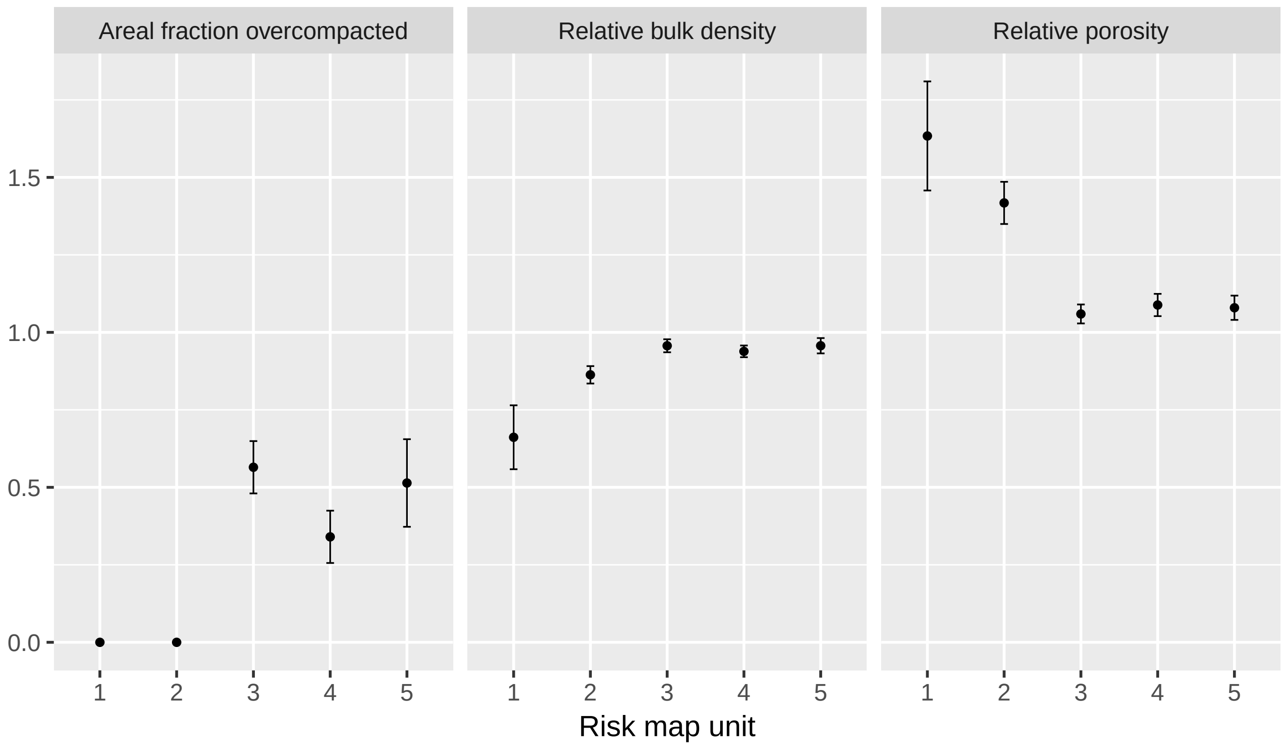

Figure 3. Estimated means of ~~soil~~ subsoil compaction parameters and areal fractions overcompacted subsoils for the five risk map units. The error bars indicate the standard error of the estimated means or areal fraction

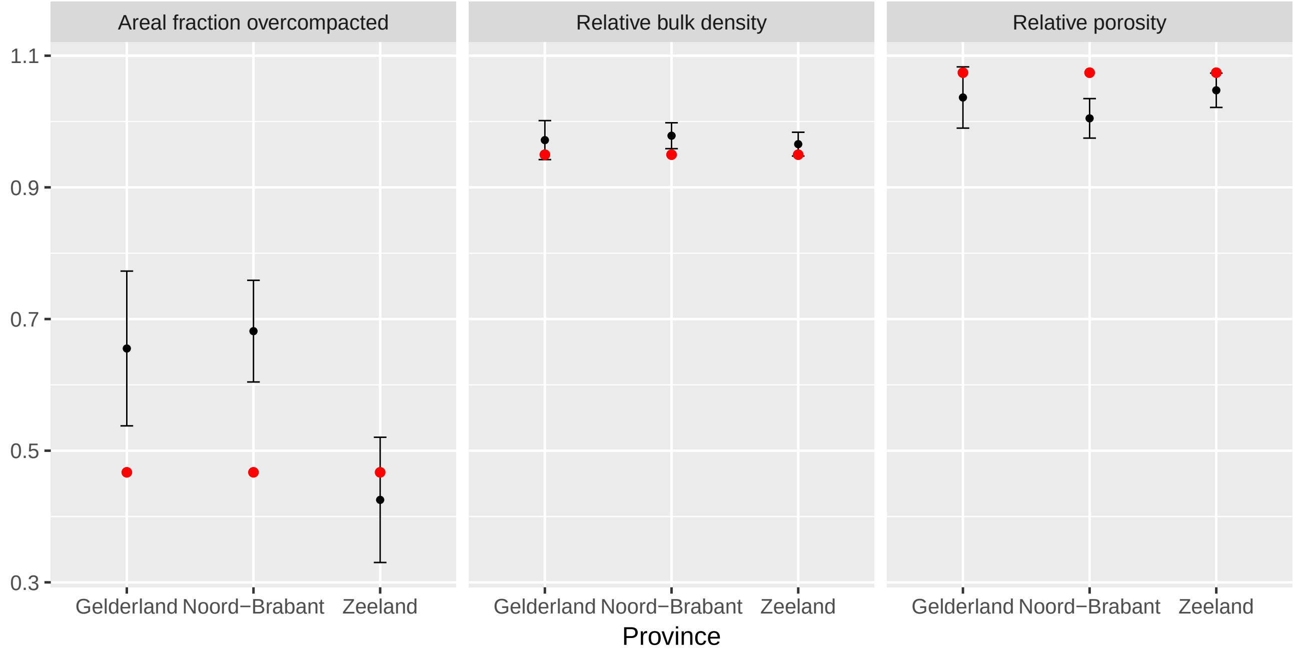

Figure 4. Estimated means of ~~soil~~ subsoil compaction parameters and areal fractions overcompacted subsoils for 'high risk' group of map units (units 3, 4 and 5) inside the three provinces. The error bars indicate the standard error of the estimated means or areal fraction. The ~~horizontal line is~~ red dots are the estimated ~~global mean~~ means or areal fraction for the Netherlands.

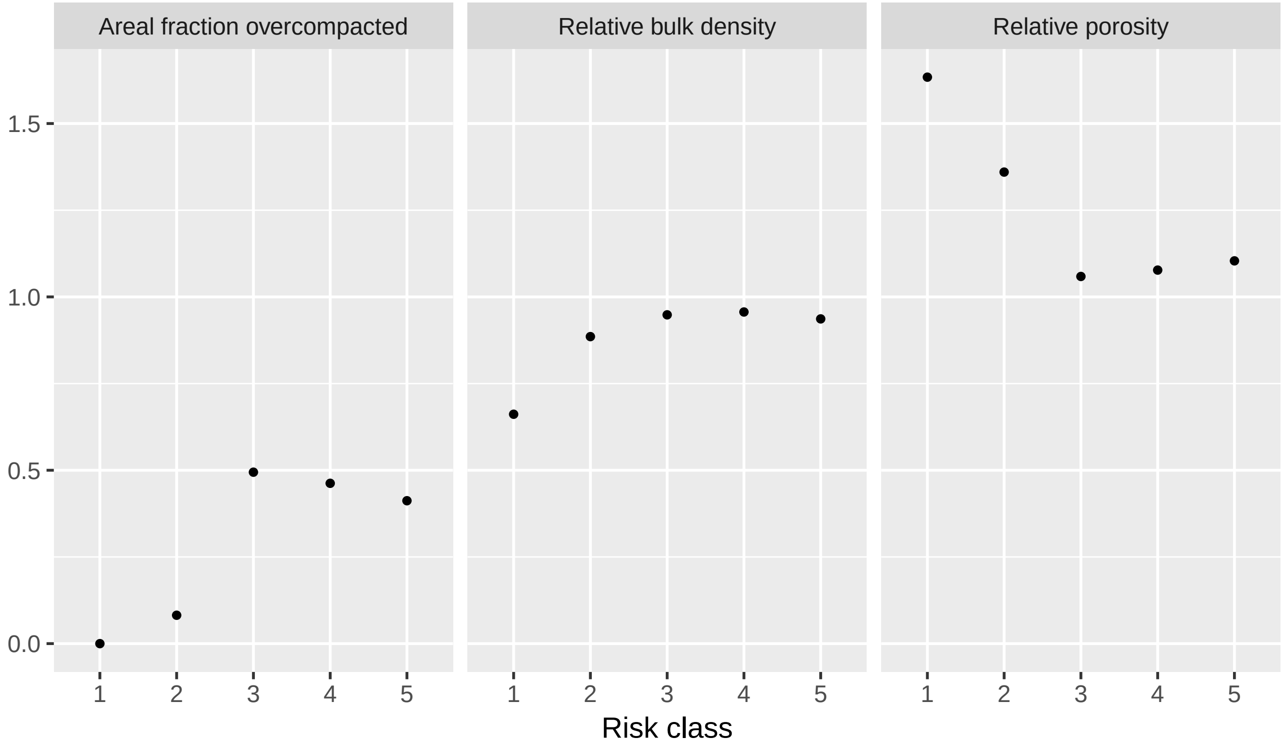

Figure 5. Estimated means of subsoil compaction parameters and estimated areal fraction overcompacted subsoils for the risk classes in the field.