Agriculture, Ecosystems and Environment 364 (2024) 108907

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Soil bulk density assessment in Europe

Panos Panagos [a,*], Daniele De Rosa [a], Leonidas Liakos [b], Maeva Labouyrie [a,c], Pasquale Borrelli [d,e], Cristiano Ballabio [a]

[a] *European Commission, Joint Research Centre (JRC), Ispra, Italy*
[b] *UNISYSTEMS, Bertrange, Luxembourg*
[c] *Department of Plant and Microbial Biology, University of Zurich, Zürich, Switzerland*
[d] *Department of Science, Roma Tre University, Rome, Italy*
[e] *Department of Environmental Sciences, Environmental Geosciences, University of Basel, Basel, Switzerland*

ARTICLE INFO

Keywords:
Packing density
Soil physics
Texture
Soil health
LUCAS
Soil compaction

ABSTRACT

The topsoil Land Use and Cover Area frame Statistical survey (LUCAS) aims at collecting harmonised data about the state of soil health over the extent of European Union (EU). In the LUCAS 2018 survey, bulk density has been analysed for three depths, i.e., 0–10 cm = 6140 sites; 10–20 cm = 5684 sites and 20–30 cm =139 sites. The laboratory analysis and the assessment of the results conclude that the bulk density at 10–20 cm is 5–10% higher compared to 0–10 cm for all land uses except woodlands (20%). In the 0–20 cm depth, croplands have 1.5 times higher bulk density (mean: 1.26 g cm^{-3}) compared to woodlands (mean: 0.83 g cm^{-3}). The main driver for bulk density variation is the land use which implies that many existing pedotransfer rules have to be developed based on land use. This study applied a methodological framework using an advanced Cubist rule-based regression model to optimize the spatial prediction of bulk density in Europe. We spatialised the circa 6000 LUCAS samples and developed the high-resolution map (100 m) of bulk density for the 0–20 cm depth and the maps at 0–10 and 10–20 cm depth. The modelling results showed a very good prediction (R^2: 0.66) of bulk density for the 0–20 cm depth which outperforms previous assessments. The bulk density maps can be used to estimate packing density which is a proxy to estimate soil compaction. Therefore, this work contributes to monitoring soil health and refine estimates on carbon and nutrients stocks in the EU topsoil.

1. Introduction

Bulk density is an important parameter for understanding the physical, chemical and biological soil properties (Al-Shammary et al., 2018). Dry bulk density and total porosity are the most frequently used indicators to characterize the state of compactness of a topsoil (Håkansson and Lipiec, 2000).

Accurate bulk density data is important for the determination of soil porosity and soil moisture (Robinson et al., 2022; Vereecken et al., 1989). Bulk density is inversely related to soil porosity which shows the space left in the soil for air and water movement (McNabb et al., 2001). Bulk density is used as a proxy indicator to determine the soil compaction stress in topsoils (Defossez et al., 2003; Stolf et al., 2011). In addition, the bulk density can be determinant for the penetration stress and therefore influence the availability of fertilizers to plants and their efficiency (Celik et al., 2010).

Accurately measuring bulk density is crucial for refining estimates of soil organic carbon stocks and their changes in time and space (Lee et al., 2009). The precise determination of soil bulk density holds particular significance in carbon crediting schemes, where farmers receive credits based on the absolute amount of carbon sequestered. However, it is important to acknowledge that measurements of soil bulk density are prone to random errors, which can reach up to 40% (Zhou et al., 2019). Moreover, in soils with high rock fragment content (> 30 vol%), this error is further exacerbated, reaching up to 100% if gravel content is not taken into account (Poeplau et al., 2017). Bulk density is calculated as the ratio of dried soil mass to its volume(Blake, 1965; Hillel, 1980):

$$\rho_b = M_s / V_s \tag{1}$$

ρ_b is estimated as Mg m^{-3} while Ms is the weight (Mg) and Vs the volume of the sampled dry soil (in m^3). In many other cases bulk density is reported as g cm^{-3}.

Since collecting samples for bulk density and analysing them in a

---

* Corresponding author.
E-mail address: panos.panagos@ec.europa.eu (P. Panagos).

https://doi.org/10.1016/j.agee.2024.108907
Received 25 October 2023; Received in revised form 21 December 2023; Accepted 22 January 2024

laboratory is costly (Keller and Håkansson, 2010), scientists have developed pedotransfer rules based on physical properties. Scientific groups have developed various functions to derive the bulk density (Dobarco et al., 2019; Montzka et al., 2017; Wösten et al., 1999). As an example, the bulk density can be obtained from a pedotransfer rule which includes packing density and clay content (Jones et al., 2003). In a more recent work, pedotransfer rules have been developed for cultivated soils and other mineral horizons taking into account organic carbon, sand and clay (Hollis et al., 2012). In a recent review, authors have evaluated 56 pedotransfer rules to derive bulk density using as

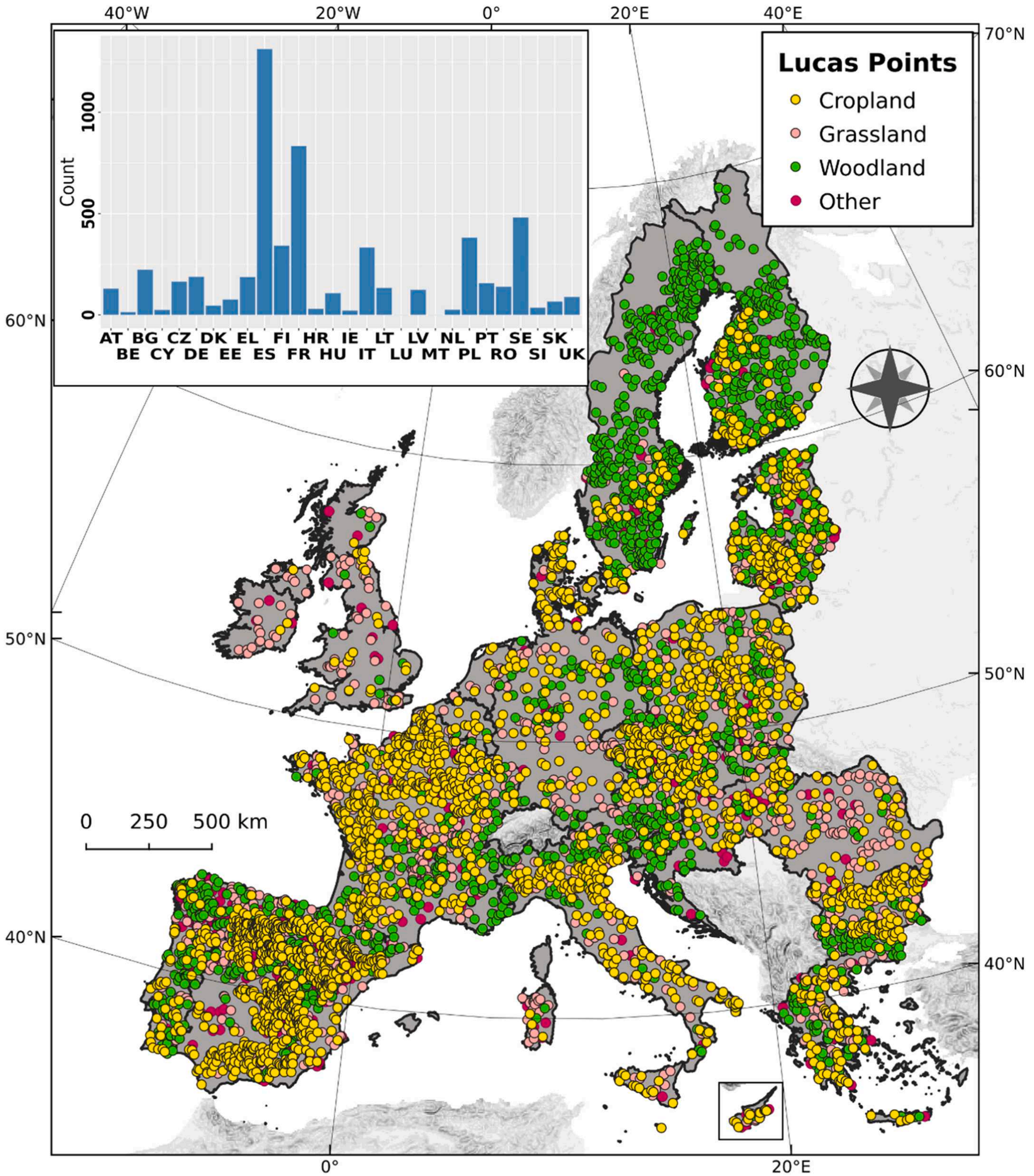

Fig. 1. Distribution of LUCAS 2018 points surveyed for bulk density. Colours are applied to show their distribution per land cover type (cropland, grassland, woodland and other). Vertical bars represent the number of points per country.

inputs organic matter/carbon, sand, clay and depth in various land uses (Sevastas et al., 2018).

Using such a pedotransfer rule based on soil texture (Jones et al., 2003), Ballabio et al. (2016) included as input ~20,000 soil samples of the Land Use and Cover Area frame Statistical survey (LUCAS) to develop the first high resolution pan-European map of bulk density. However, such assessments were accompanied by significant uncertainties, given that the applied pedotransfer rules might not be universally applicable to all different type of soils, climate and land uses in the European Union (EU). Nevertheless, the derived European bulk density map has been instrumental to estimate soil organic carbon stocks (Lugato et al., 2021), sediments distribution (Borrelli et al., 2018), mercury stocks in topsoils (Ballabio et al., 2021) and nutrients stocks (Panagos et al., 2022a). Therefore, there is an immediate and pressing need to produce a more accurate and detailed soil bulk density map. This becomes pivotal for improving the precision of current evaluations related to soil health indicators such as soil organic carbon stocks.

The primary objective of this study is to develop a bulk density dataset based on the ~6000 samples collected across the EU by using advanced machine learning methods. This study also aims to: a) investigate the impact of land cover (and crop systems) and soil depth in influencing bulk density; b) compare the results with the bulk density derived by pedotransfer rules and other studies which mapped BD and c) assess the packing density which is a proxy for susceptibility to soil compaction in EU agricultural soils. Finally, we make some considerations on how the findings will be further used in future modelling assessments combining them with management practices.

2. Methods and data inputs

2.1. Study area

The study area includes all land uses across the European Union (EU) and the United Kingdom (UK). The survey of bulk density took place in 28 countries and the presented datasets/maps refer to this area. The distribution of the surveyed points and the distribution per country and land cover is shown in Fig. 1.

2.2. LUCAS 2018 Topsoil database and bulk density survey

The LUCAS topsoil survey includes ~20,000 points in the EU with measured physical, chemical, and biological properties (Orgiazzi et al., 2018a). The LUCAS 2018 was the 3rd topsoil sampling campaign following the 2009 and 2015. The LUCAS 2018 soil introduced new modules for analysis in a limited number of samples due to budget restrictions. Those new modules include the assessment of soil biodiversity, pesticides residues, assessment of soil erosion features and bulk density.

For the 2018 LUCAS campaign, bulk density was measured on approximately 6000 locations across EU+UK. Even if the total LUCAS topsoil surveyed samples are almost 20,000, the bulk density analysis was limited to the 6000 points due to budget constraints. Bulk density was determined at various depth levels: 0–10 cm (6246 points), 10–20 cm (5786 points), and 20–30 cm (140 points, only for Portugal). Moreover, for locations where measurements were available for both 0–10 cm and 10–20 cm depths, the bulk density (BD) at the 0–20 cm stratum was computed by averaging the measurements from the 0–10 cm and 10–20 cm depths across 5659 points (Table 2).

The sampling strategy for bulk density points is similar to the one used to select the LUCAS 2018 points which includes criteria such as land use/cover, soil properties and topography. The highest number of points have been surveyed in Spain, France, Sweden, Poland, Finland and Italy (Fig. 1). The average density in the whole study area is 1 point every ~750 km^2 with smaller countries having higher density and Romania, Germany, Belgium, UK and Ireland having density around 1 point every 1700–3000 km^2. The low density of points in those countries is related to non-accessibility to planned surveyed points.

Table 1
Spatially continuous covariates used for modelling Bulk density at European scale.

Environmental feature	Covariate	Source	Covariate type
Land cover	CORINE land cover type	CORINE	Categorical
Soil	Soil chemical and physical parameters	LUCAS	Numerical
Topography	DEM derived topographic features	SRTM/EU DEM	Numerical
Vegetation	EVI, MODIS reflectance	MODIS/ Sentinel 2	Numerical

Table 2
Aggregated data per different depths. The filtered samples refer to the ones passing the quality checks and having valid coordinates and land cover information.

Depth	No of samples	No of filtered samples (complete info)	Mean (g cm^{-3})	Median (g cm^{-3})
0–10	6246	6140	1.04	1.09
10–20	5786	5684	1.13	1.18
0–20	5659	5659	1.09	1.14
20–30	140	139	1.21	1.24

At each chosen LUCAS location, before collecting the soil cores, stones larger than 6 cm, vegetation residues, grass, and litter were removed from the soil surface. The surveyors were advised to select the locations without stones and sample the fine soil in the ring. Upon cleaning the site, five soil cores were extracted using a 100 cm^3 metallic ring. The first soil core was collected directly from the georeferenced location (Fig. S1), while the other four cores were gathered from a distance of 2 m away, following the cardinal directions: North, East, South, and West. This process was repeated for the 0–10 cm and 10–20 cm depth intervals. For the 20–30 cm depth in Portugal, the number of soil cores collected were limited to three. Any excess soil around the ring was carefully scraped off with a knife. Each soil sample obtained from the metallic ring for each depth was then placed in a plastic bag and weighed.

These bulk samples (0–10 cm, 10–20 cm, and 20–30 cm depths) were subsequently left to air-dry, and their weights were recorded once more (Fig. S1). The plastic bags were securely sealed for transportation to the laboratory. Upon reaching the laboratory, to determine the soil mass fraction of the sample, a subsample of the bulk soil was transferred to a pre-dried and pre-weighed container (Fig. S1). This subsample (3–5 g of soil) was then oven-dried at 105 °C until it reached a constant weight. The final bulk density for each location was then calculated following the adapted ISO 11272:2017(Fernandez-Ugalde et al., 2022; ISO, 2017).

Of the initial 6246 samples for the depth 0–10 cm, 99 samples were omitted because of missing geographical coordinates (and land use information), 7 samples were sparse in wetlands and water areas and 31 samples had unrealistic BD (values <0.1 g cm^{-3} or >2.8 g cm^{-3}). As a rule, rocks and gravels have bulk densities higher than the 2.8 g cm^{-3} (Ramcharan et al., 2017; Rossi et al., 2008). Therefore, the filtered database (with complete information) included 6140 samples for the depth 0–10 cm. For the 10–20 cm strata, from the initial 5786 samples, 95 were excluded because of missing geographical information and 7 samples were located in wetlands/water; therefore, the filtered database included 5684 samples (Table 2). The common quality checked samples for both depths (0-10 cm, 10-20 cm) are 5689.

2.3. Model description for spatial interpolation of bulk density

The spatial interpolation of soil bulk density was performed using the Cubist regression trees (Fernández-Delgado et al., 2019). Based on the M5 model tree (Alckmin et al., 2022), in the Cubist regression model, decision trees contain a linear regression model in each terminal node. An M5 model tree (Alckmin et al., 2022) is a binary decision tree having linear regression functions at the terminal (leaf) nodes, which can predict continuous numerical attributes(Pal and Deswal, 2009). The decision tree is based on a series of "if then" rules branching the tree; each set of rules has an associated multivariate linear model used to calculate the predicted value. In addition, Cubist uses multiple training committees and neighbouring so as to make the weights more balanced. Neighbouring is used to modify the rule-based forecasts by adding more observations of the target variable. The neighbours belong to a closer set of observations in feature space, which are then averaged in order to reduce the influence of outliers. The use of committees means that a series of trees (with slightly different weights) are created for the same task and their outcome is then pooled into a single prediction akin to statistical boosting.

The Cubist approach was selected among other interpolation methods for its prediction performance and computational efficiency. Cubist resulted as the best (or on par) model for the given task after optimising the models to search for the best set of tuning parameters and predictive features. Moreover, given the number of pixels to be predicted, the computational efficiency of Cubist allows to produce maps in a shorter time with less computational burden. For these reasons, Cubist was selected over similarly performing models like Gaussian Process Regression (GPR) and Random Forests (RF). While both GPR and RF achieved similar performance metrics, their performance was less consistent under different cross validation runs. Moreover, RF resulted in a more biased prediction and widely varying outcomes when extrapolating from the observed range of target values. While GPR w produces unbiased estimates of the target variable, it is computationally extremely expensive as it relies on matrix inversion, resulting in (n^3) time complexity and (n^2) memory complexity (where n is the number of samples).

The computation of the bulk density maps was performed in R V4.2.3 (R Core Team, 2022) using he Cubist package (Kuhn et al., 2023) and the Terra package (Hijmans et al., 2022) for handling the input rasters.

2.4. Ancillary data - covariates

A set of candidate covariates were considered as proxies of bulk density owning to their link to soil properties (Table 1). Given the relation of soil bulk density with soil texture and soil organic matter content, such physical and chemical covariates were included (Ballabio et al., 2019, 2016). Soil texture and soil organic carbon are also analysed and made available through the LUCAS topsoil databases (Orgiazzi et al., 2018a). In addition, the surveyors record the land cover where the sample is taken.

In past spatial interpolation studies (Ballabio et al., 2019, 2016), we have used MODIS products. Given the finer spatial scale used in the current study, MODIS products (NDVI, radiance) were replaced by analogous Sentinel 2 (Copernicus Sentinel data, 2022) products. Terrain parameters were derived at a finer resolution using the 30 m version of the NASADEM (Abrams et al., 2020; Crippen et al., 2016).

In addition to the data sources previously used, the Synthetic Aperture Radar (SAR) data from the Sentinel-1 satellite (Copernicus Sentinel data, 2022) (Son et al., 2021) was included in the analysis. In particular, the value of the reflectance at different polarisations and their ratio at different times of the year was used as a proxy to describe (among other covariates) the soil water content and in turn the textural and organic matter content.

2.5. Packing density estimation

The Packing Density (PD) is a measure of compactness of the soil and can be a useful parameter for the spatial interpretation of the degree of soil compaction. The PD equation (Eq. 2) was initially developed to estimate soil compaction for the German soil mapping (Renger, 1970). Then PD has been proposed as a proxy indicator for soil compaction and the Eq. 2 has been applied in past studies (Jones et al., 2003; Micheli et al., 2008; Shamal et al., 2016):

$$PD = BD + 0.009 \text{ x } C \tag{2}$$

Where BD is the bulk density as g cm^{-3} (Section 3) and C is the clay content (%) (Ballabio et al., 2016). The estimated PD map will refer to 0–20 cm and is measured as g cm^{-3} (or Mg m^{-3}).

3. Results

3.1. Analysis per depth

Bulk density is a dynamic property that varies according to the profile depth due to changes in organic matter content, porosity and compaction (Chaudhari et al., 2013). According to estimated means and medians in different depths, bulk density is around 10% higher in the layer 10–20 cm compared to topsoil layer of 0–10 cm (Table 2).

A joint database for which bulk density information and land cover exist for both 0–10 cm and 10–20 cm includes 5659 records. The median bulk density for the 0–10 cm is 1.1 g cm^{-3} (mean: 1.04 g cm^{-3}) with the 25th percentile at 0.85 g cm^{-3} and the 75th percentile at 1.29 g cm^{-3} (Fig. 2). The median bulk density for the 10–20 cm is 1.18 g cm^{-3} (mean: 1.13 g cm^{-3}) which is 7% higher compared to the 0–10 cm. This layer has the 25th percentile at 0.95 g cm^{-3} and the 75th percentile at 1.36 g cm^{-3} (Fig. 2).

For few points, located in Portugal, we have performed the analysis for three depths (0–10, 10–20 and 20–30 cm). The results show that bulk density is increasing with depth, similar to the literature findings (Abu-Hamdeh, 2003). Subsurface layers ($>$ 20 cm depth) have less organic matter and root penetration is reduced compared to surface layers; this means less porosity and higher bulk density for the subsurface layers. The gradient of change in bulk density for the three depths is confirmed for all land cover types (cropland, grassland, woodland) (Fig. 3).

3.2. Analysis per land cover and crop types

Bulk density varies in different land cover types (Fig. 4). The higher values of bulk density are measured in croplands (for both depths: 0–10 and 10–20 cm) followed by bare lands and artificial lands. The shrublands and grasslands have similar median values while the lowest values have been found in the woodlands (Fig. 4). The highest mean and median BD value in cropland is explained due to the lower organic matter, soil compaction and management practices (e.g. tillage) (Biro et al., 2013).

The mean bulk density for more than 2330 samples in croplands is 1.24 g cm^{-3} for the top 0–10 cm and 1.29 g cm^{-3} for the 10–20 cm. The bare land is the second land cover category with median values at 1.2 and 1.27 g cm^{-3}. Even with a limited number of 26 samples in artificial land, this land use has the third highest bulk density. Grasslands and shrublands have similar mean values for bulk density. The mean bulk density in woodlands is very low for the 0–10 cm (0.73 g cm^{-3}) and relatively low for the 10–20 cm (0.93 g cm^{-3}). In most cases, forest soils have much lower values in their upper layer (0–10 cm) due to its richness in organic matter and biotic activity, which promotes formation of well-developed crumb structure and high porosity (Cambi et al., 2015; Corti et al., 2002). The mean bulk density in the 6 samples located in wetlands was very low at 0.2 g cm^{-3}.

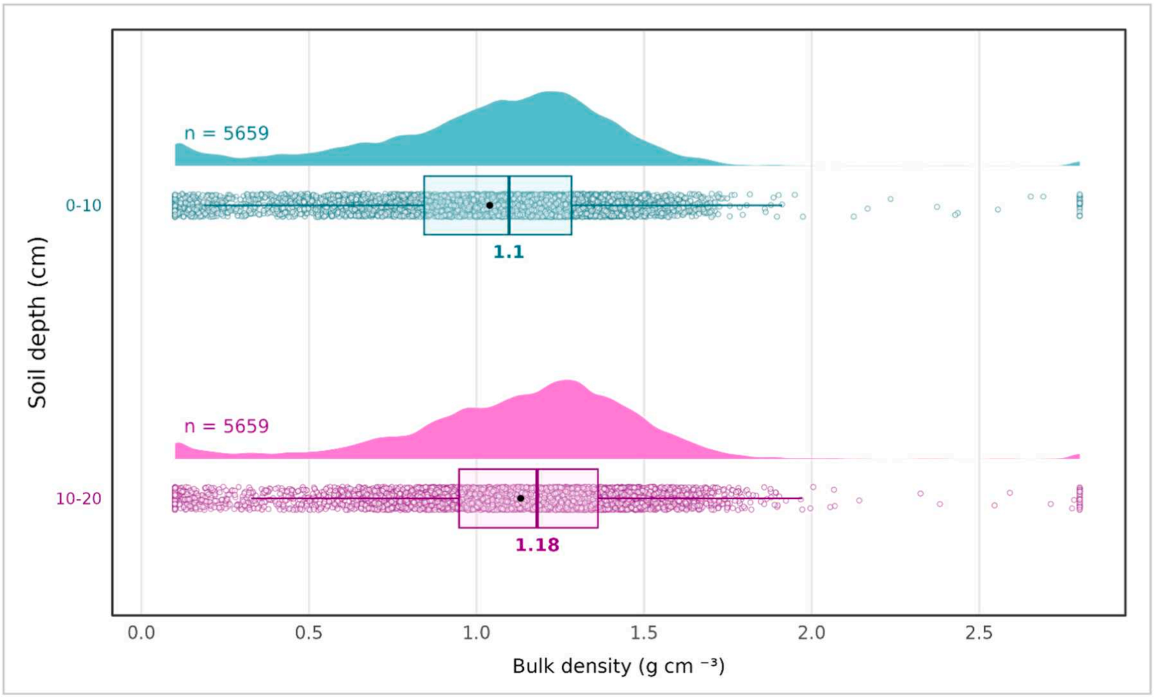

Fig. 2. Bulk density distribution per soil depth for the common points. Vertical line represents the median and dot represents the mean.

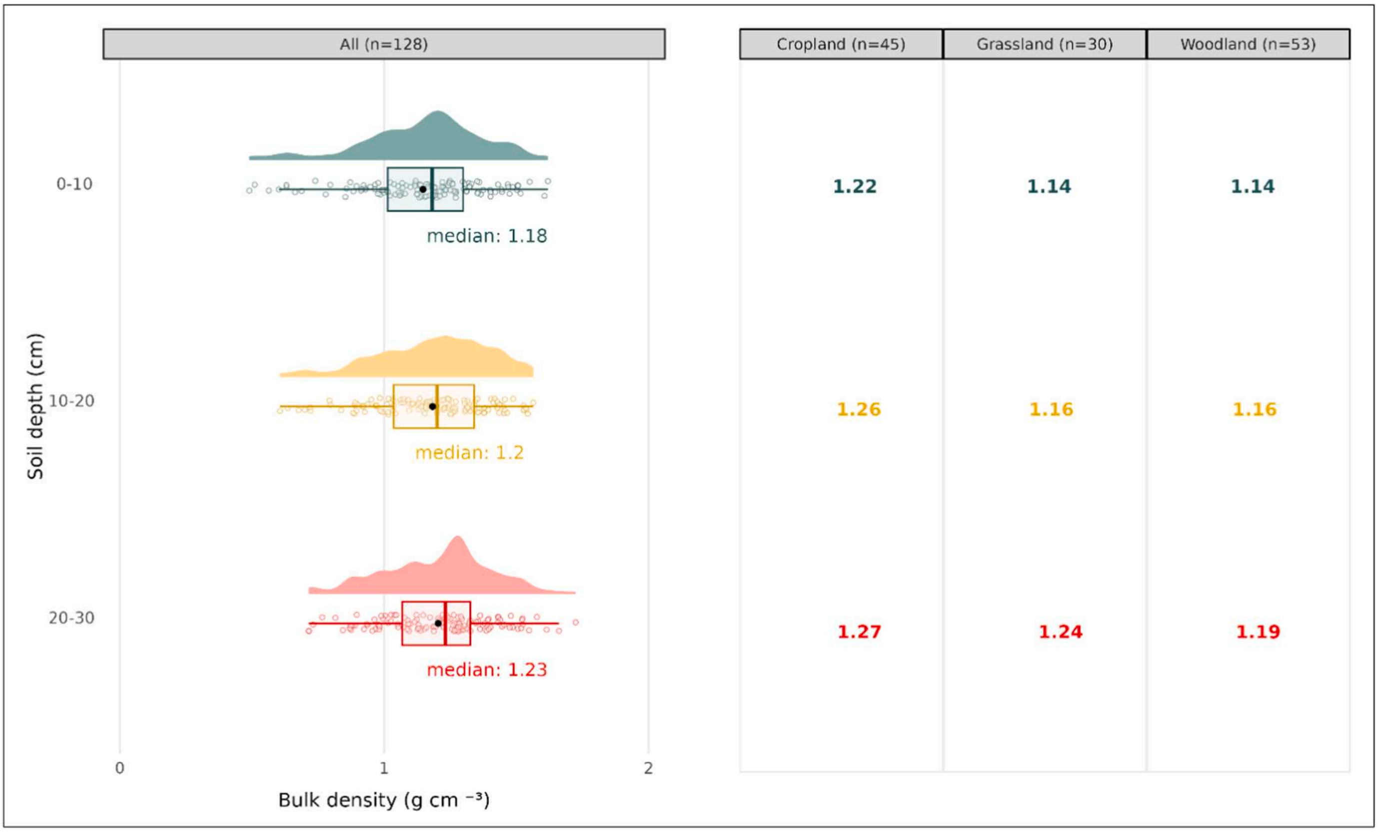

Fig. 3. Soil bulk density in three depths (0–10, 10–20, 20–30 cm) for a limited number of samples in Portugal.

For croplands and artifical lands, the median in the 10–20 cm depth is 4–5% higher than the one in the 0–10 cm depth. For grasslands and shrublands, the median in the 10–20 cm depth is 8–10% higher compared to the top 10 cm. In woodlands, the median bulk density of the 10–20 cm is 28% higher compared to 0–10 cm.

Combining both depth and land cover type, we notice a relatively higher change of bulk density due to change of depth in woodlands and grasslands compared to croplands (Fig. 4). In woodlands, the mean bulk

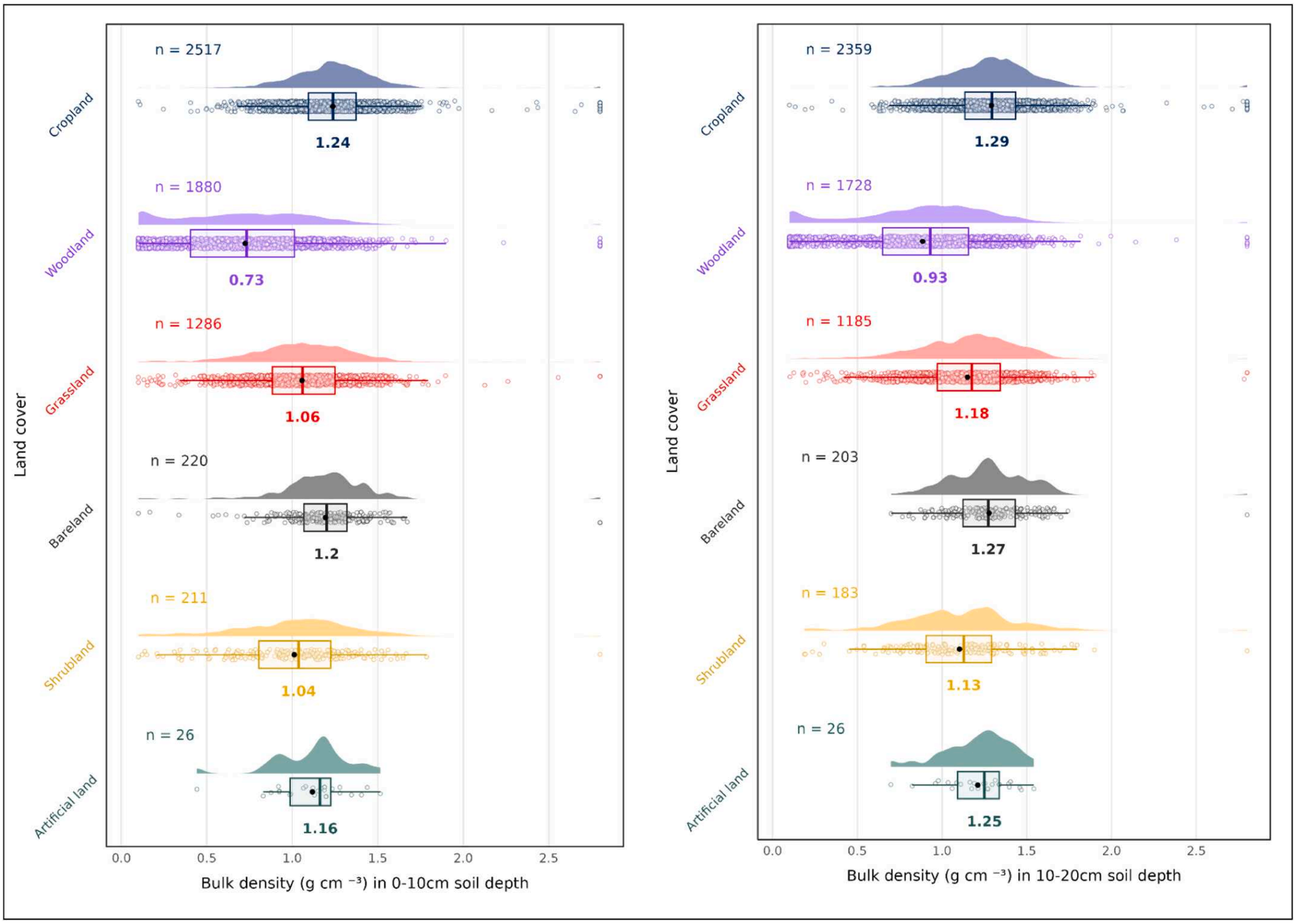

Fig. 4. Bulk density per land cover type and depth (0–10 cm, 10–20 cm). The "n" on the top left represents the number of samples per land cover category, the line in the boxplot is the median value and the dot is the mean value.

density in 10–20 cm is 28% higher compared to the 0–10 cm while this increase is 11% in grasslands and 4% in croplands (Fig. 4).

Focusing just on croplands, an analysis per category of crops showed that the bulk density is much higher in annual crops (1.28 g cm^{-3}) compared to permanent crops (1.2 g cm^{-3}) (Fig. 5). This implies that the soil disturbance is limited in the permanent crops compared to the annual crops. In the annual crops category, the root crops (e.g. sugar beets, potatoes) have the highest bulk density (1.32 g cm^{-3}) due to intensive tillage operations, heavy machinery trafficking and more disturbance.

3.3. *Mapping bulk density in the EU*

Using the advanced interpolated methods such as Cubist (Zhou et al., 2019) (described in Section 2), we have developed the maps of bulk density at 100 m (Fig. 6; Fig. S2). The analysis below is derived from the raster map of bulk density.

The mean bulk density for the 0–10 cm map in the EU is 0.97 g cm^{-3} with the 25th percentile at 0.76 g cm^{-3}, 50th percentile at 1.02 and the 75th percentile at 1.2 g cm^{-3}. The 10–20 cm bulk density map has a mean of 1.08 g cm^{-3} with the 25th percentile at 0.83 g cm^{-3}, 50th percentile at 1.11 and the 75th percentile at 1.23 g cm^{-3}. The corresponding values for the aggregated map at 0–20 cm are the averages of the two depths (Fig. 6). The mean bulk density in EU and UK for the 0–20 cm is 1.03 g cm^{-3} with 50th percentile at 1.06 g cm^{-3}.

Arable lands have the highest mean bulk density ranging from 1.22 g cm^{-3} in 0–10 cm to 1.29 g cm^{-3} in 10–20 cm. Permanent crops have slightly lower bulk density while heterogeneous agricultural areas (mixed cropland with pastures) range between 1.1 and 1.17 g cm^{-3}. Therefore, agricultural management (tillage, trafficking, induced disturbance) is influencing the bulk density and the soil compaction. The difference of bulk density between croplands and pastures is around 0.17 g cm^{-3} as also found in regional studies (Schneider and Don, 2019).

The disturbed soils (arable, permanent crops) have bulk densities in the range of 1.2–1.3 g cm^{-3} while the woodlands have bulk densities in the range of 0.75–0.9 g cm^{-3} (Fig. 7). The bulk density at 10–20 cm is 5–10% higher compared to topsoil part of 0–10 cm (for all land cover categories) with the exception of woodlands where the difference is at 20% (Fig. 7). Such a difference is also noticed when presenting the ratio of BD of the 10–20 cm compared to the upper layer (Fig. S3) as the areas dominated by woodlands have even 25% higher BD in 10–20 cm compared to the top layer.

3.4. *Performance of the spatial interpolation model*

The Cubist model was trained on 80% of the data, leaving 20% of the samples for cross-validation. The fitting was performed using an adaptive resampling strategy to explore the better combination of Cubist tuneable parameters. The metrics used to select the best model were calculated through repeated (10 repeats) k-fold (6 folds) cross-validation. The best model was found to use 95 committees and 3 neighbours with a k-fold R^2 of 0.66 and RMSE of 0.20. Once fitted, the Cubist model is highly efficient in predicting bulk density values from

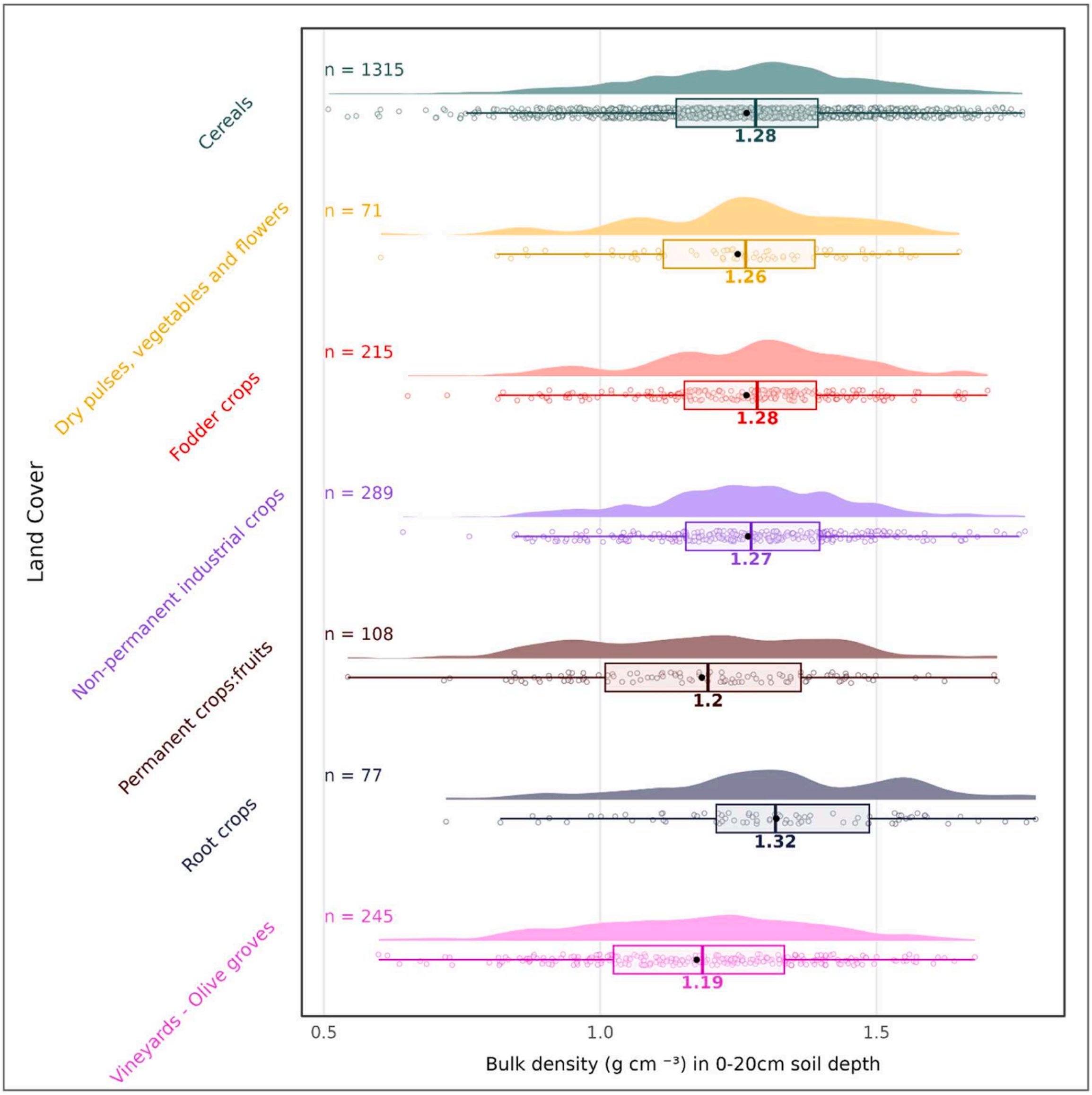

Fig. 5. Mean bulk density (0–20 cm) per major crop categories. The “n” on the top left represents the number of samples per land cover category, the line in the boxplot is the median value and the dot is the mean value.

ancillary data with an R^2 of 0.96 for the training set and 0.64 for the validation set (Fig. 8).

4. Discussion

In this paper, we focus on a core method to extract bulk density involving extraction of soil samples, followed by sample mass determination (weighting) and volume estimation. There are alternatives to the core method such as the three-dimensional scanning, the pedotransfer functions and gamma radiation (Throop et al., 2012). The advantage of the core method is the use of simple equipment which allows a massive elaboration for large number of cores (Throop and Archer, 2008). As a major drawback for this method, we refer to the small volumes collected (which may not be spatially representative of the location) and to the importance of coarse fragments (Vincent and Chadwick, 1994).

4.1. *Other factors related to bulk density*

Bulk density is also influenced by other factors such as tillage practices, crop residues, livestock density, grazing, and rainfall (moisture). In intensively-managed pasture systems, severe animal treading (especially in animal traffic and camp areas) increases soil compaction (De Rosa et al., 2020; Pulido et al., 2018). Soil compaction in pastures affects the soil bulk density, hydraulic conductivity, soil aeration, macropore volume, and penetration resistance of the soil (Hamza and Anderson, 2005).

In croplands, the tillage practices contribute to bulk density as conservation tillage improves soil structure and has a reduced bulk density compared to conventional tillage in the topsoil layer. Those conclusions are derived from long-term experimental sites both in Romania (Topa et al., 2021) and in China (Gao et al., 2019) which also consider the positive effect of crop residues in reducing bulk density. Comparing “No tillage” and conventional tillage, the former had mixed effects on soil bulk density in a review of 62 studies (Blanco-Canqui and Ruis, 2018). Machinery trafficking has an important impact in soil structure and soil compaction in poorly drained soils (Bondi et al., 2021).

As those information (tillage practices, crop residues, livestock density, grazing, and humus) are not available for the LUCAS sampling points, it is fairly difficult to correlate those factors with bulk density values in the present study. However, further research can address this

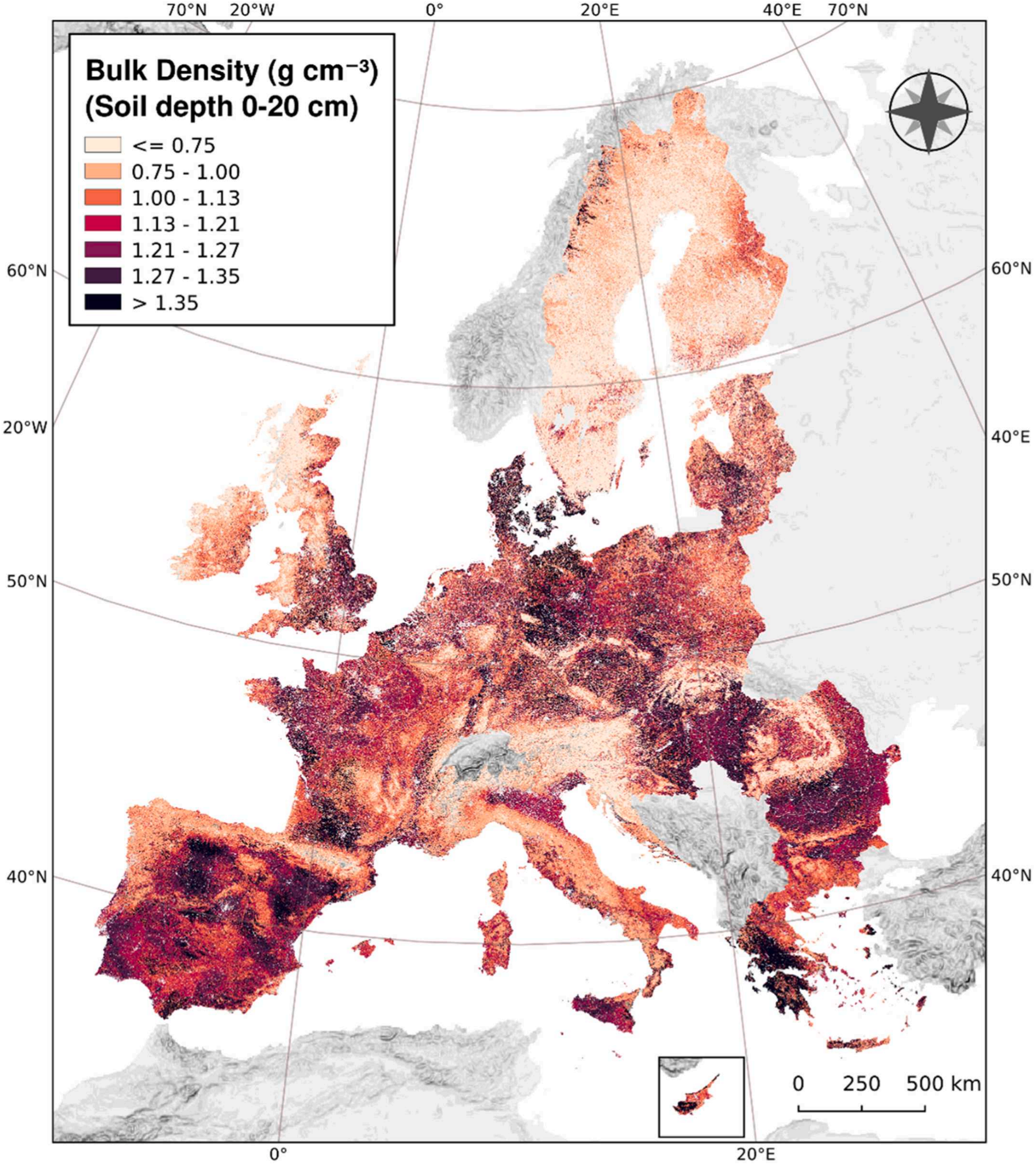

Fig. 6. Bulk density map (100 m resolution) in the EU and UK (0–20 cm depth).

topic based on available local/regional data.

4.2. Packing density as a proxy for soil compaction

Bulk density is mainly driven by land cover type with croplands having the highest BD and woodlands the lowest in all depths. As the soil BD is the mass of dry soil per unit volume, then the relationship between soil compaction and its capacity to store and transport water or air is obvious (Hamza and Anderson, 2005). As the vertical stress in soils is part of modelled soil compaction, the bulk density can estimate this vertical stress to topsoil (Van den Akker, 2004).

Soil compaction is a major threat to soils particularly in intensively agricultural systems. Soil compaction is known to reduce agricultural productivity, decrease crop yields, decrease water infiltration and

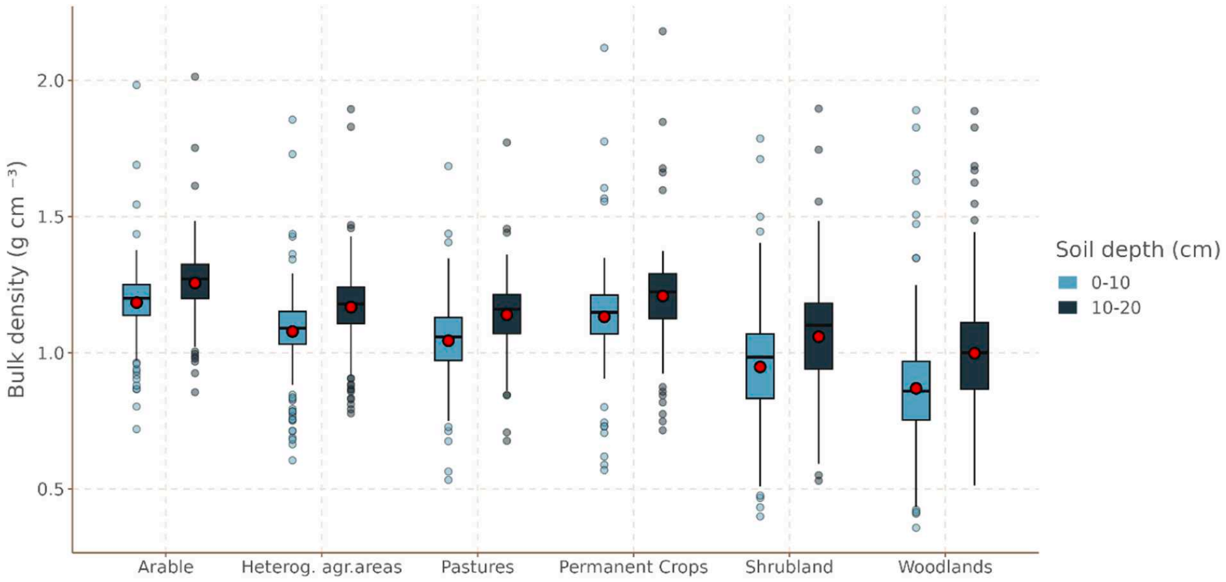

Fig. 7. Median (bars) and mean (dots) bulk densities per land cover type and soil depth. Data have been aggregated at regional level. The boxplot is the interquartile range (IQR) expressed as the difference between the 25th (Q1) and 75th percentiles (Q3); the bottom line is the result of the operation: Q1 - 1.5 * IQR and top line is the result of the operation: the Q3 + 1.5 * IQR.

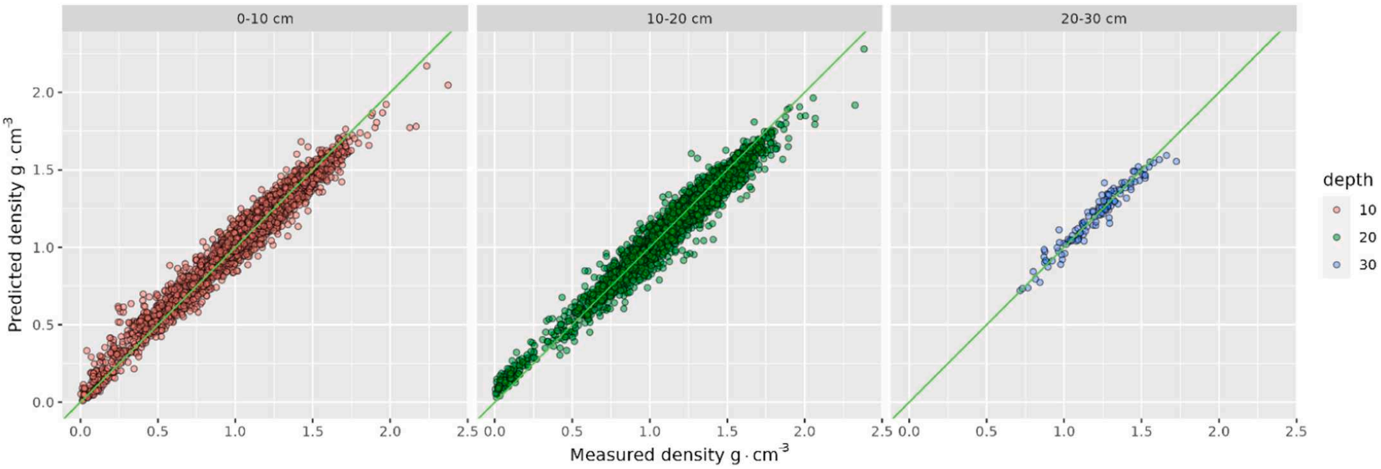

Fig. 8. Predicted vs observed bulk density plots for the different LUCAS sampling depths (0–10 cm, 10–20 cm and 20–30 cm) for the training set.

accelerate run-off and risk of soil erosion (Troldborg et al., 2013). Tractors with their wheel load, tyre type and inflation pressure increase soil bulk density (Horn et al., 2003) and play an important role in increasing soil compaction. Soil compaction alters soil structure by crushing aggregates and increasing bulk density and decreasing the coarser pores (Delgado et al., 2007). This leads to reduced permeability to water and increased runoff and erosion. In addition, compacted soils affected by wheel tracks would provoke the water to flow downslope, accelerating further land degradation (Ledermann et al., 2010). This would decrease crop growth and yield as nutrients are lost with runoff and roots cannot grow properly (Batey, 2009). Even soil compaction is a major threat in agricultural soils, there can be woodlands where animal trampling or vehicular traffic may increase soil compaction.

We estimated the packing density (PD) using the Eq. 2 and as inputs the bulk density map (Fig. 6) and the clay content (Ballabio et al., 2016). Soils with high PD (>1.75 g cm^{-3}) are compacted and not susceptible to further compaction (Jones et al., 2003; Păltineanu et al., 2015). The medium compacted soils are found in the range of 1.40 g cm^{-3} < PD < 1.75 g cm^{-3} while the low compacted soils being vulnerable to loads are the ones with PD < 1.40 g cm^{-3} (Jones et al., 2003; Păltineanu et al., 2015). The major part of all lands (71.8%) are low compacted, the 2.2% is compacted and the rest 26% has a medium compaction (Fig. 9). In the arable lands, the dominant class is the medium compacted soils (58.7%) while the compacted ones are at 3.2% (Fig. 9; Fig. S4).

Therefore, packing density can be used as a proxy for soil compaction identifying hotspots where soils are highly compacted. This correlation is also confirmed by experimental results as compacted soils had higher bulk soil tensile strength, higher bulk density and poorer fragmentation (Abdollahi et al., 2014).

4.3. *Comparison with pedo-transfer functions derived bulk density*

In the past, bulk density was estimated using an equation (pedo-transfer function) which included the packing density and clay content (Jones et al., 2003). Based on this equation, the bulk density was estimated for circa 20,000 points in the EU collected with the LUCAS 2009 campaign. In a subsequent step, the estimated bulk density points were interpolated using the Multivariate Adaptive Regression Splines (MARS) in order to produce the bulk density map (Ballabio et al., 2016) (Fig. S5).

According to this mapping exercise which used the Jones (2003)

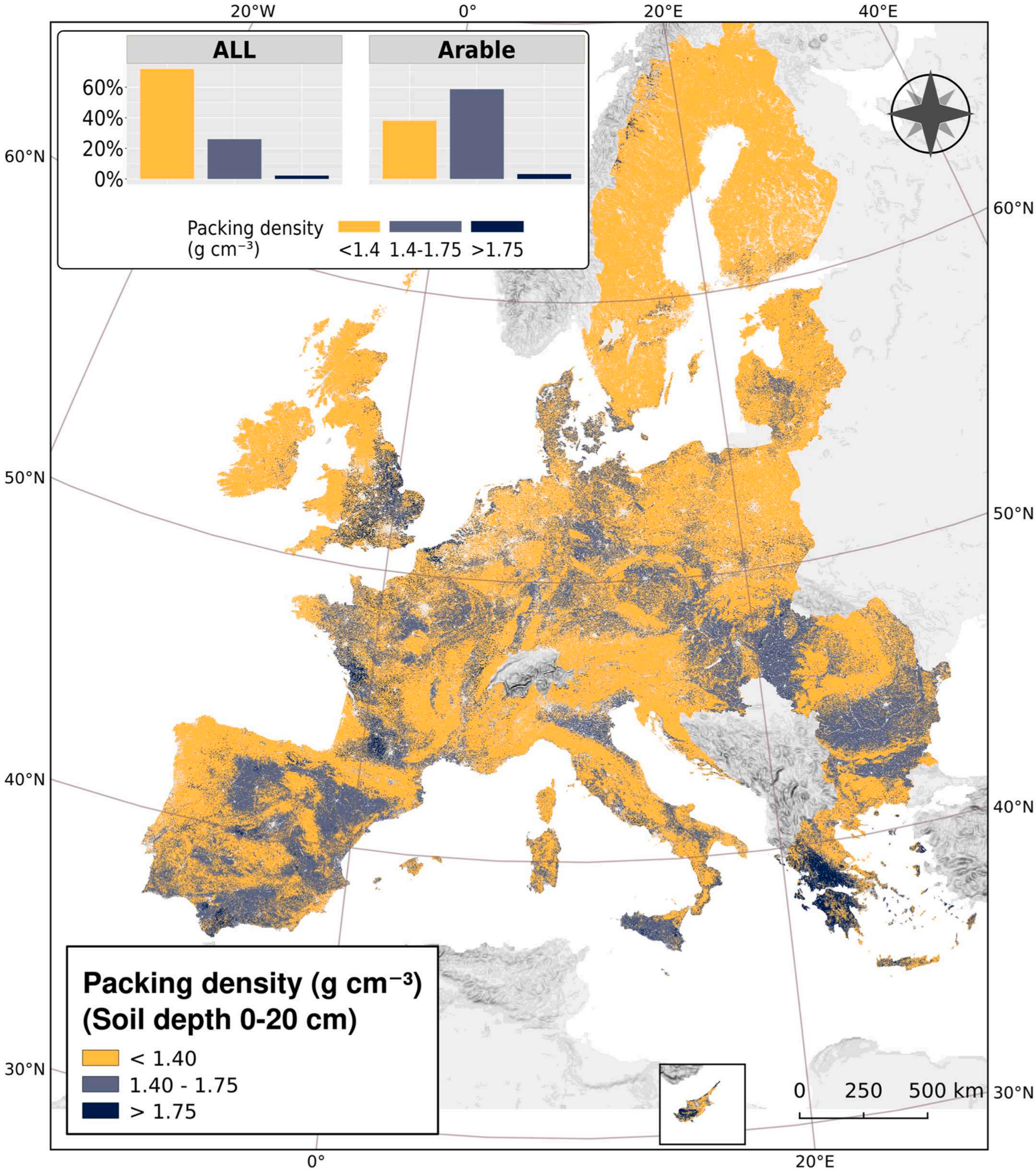

Fig. 9. Packing density based on equation of Jones et al. (2003) and aggregated statistics.

pedotransfer function, the mean bulk density is 1.21 g cm^{-3} with 25th percentile at 1.08 g cm^{-3} and the 75th percentile at 1.34 g cm^{-3}. Comparing the mean values per land cover type, the pedotransfer function derived bulk density map has similar averages to our new bulk density map (Fig. 6; Fig. 7) for arable lands, permanent crops, and heterogeneous agricultural areas (difference at 2–5%). However, the pedotransfer function derived map overestimates the bulk density on average at 40% for woodlands (Figs. S5) and 10% for pastures compared to the dataset which was derived based on measured LUCAS bulk density (Fig. 6). Therefore, countries with large proportion of woodlands (Sweden, Finland, Austria and Baltic States) have quite high biases in the bulk density estimates (Fig. S5). Also, the variability (expressed as standard deviation) was lower in the pedotransfer function derived map.

We also compared the measured bulk density of agricultural soils with the estimated one based on pedotransfer functions (PTF) using as inputs texture and soil organic carbon (Hollis et al., 2012) (Fig. 10). Even if there was a large variability within the measured soil bulk density of LUCAS 2018 surveyed agricultural soils, the values predicted by the PTF aligned strongly with those measured in the LUCAS soil survey (Fig. 10a). On average the bulk density in arable lands is estimated 8% higher with the PTF (Hollis et al., 2012) compared to the measured BD (1.37 cm g^{-3} vs. 1.26 cm g^{-3}). For woodlands, it is evident that the PTF overestimates the BD as most of the points are on the upper right part (Fig. 10b). The mean BD in woodlands estimated by the PTF is 24% higher compared to the measured one (1.02 cm g^{-3} vs. 0.83 cm g^{-3}). The main reason for this systematic error is that the PTF considers organic carbon, clay and sand content which has as a consequence this overestimation in woodlands (Fig. 10b).

To provide a comparison of the performances of the current assessment with past ones (Ballabio et al., 2016; Hengl et al., 2017; Poggio et al., 2021), four linear regression models were fitted using the LUCAS and World Soil Information Service (WoSIS) (Batjes et al., 2020) measured soil bulk density values as an independent variable. The comparison between measured and modelled BD (Fig. 11) graphically highlights how our new BD estimate outperforms (R-Squared) the other regional (Ballabio et al., 2016) and global (Hengl et al., 2017; Poggio et al., 2021) models.

4.4. Uncertainties - Limitations

The pan European assessment of bulk density does not challenge any local or regional assessment which have developed with higher density of analysed samples. We acknowledge that the LUCAS topsoil database of 6000 samples is limited for a pan European study but this is the most comprehensive EU survey till now. Some issues with non-accessibility of points did not allow to have a much higher number of samples for the analysis. Both the derived maps (bulk density in different depths and packing density) and the point data will become available in the European Soil Data Centre for inter-comparison and further assessments.

The sampling time is also an important factor which may add uncertainties to the bulk density values. The management practices of a farmer (tillage, harvesting) may influence the composition of the sample and the derived BD values. Also, in grasslands, the livestock density and grazing are important missing information for better interpreting bulk density in LUCAS. The size of the coring cylinder (rings) used, the operator experience, and in-situ soil moisture content significantly affect BD accuracy.

4.5. Importance of bulk density for soil-related policies

The new developments in the EU Green Deal have put soil protection in a high position in the EU policy agenda (Montanarella and Panagos, 2021) and healthy soils are important to achieve climate neutrality, zero pollution, sustainable food provision and a resilient environment. Soil bulk density is of crucial importance to estimate carbon and nutrient stocks at local, regional, national and continental scale (Sequeira et al., 2014). In addition, soil bulk density affects other soil properties such as porosity, soil moisture, water availability and hydraulic conductivity (Dam et al., 2005).

Accurate monitoring of soil bulk density affects the amount of Soil Organic Carbon (SOC) that can be stored in soils and the potential SOC stock changes (Don et al., 2011). Bulk density is also an indicator of the soil structure as high bulk density could reduce water infiltration and limit plant growth (Topa et al., 2021). As the carbon-related policies in the EU (Fit for 55, Monitoring Reporting Verification for Carbon Removal Certification, LULUCF regulation, Soil Monitoring Law) aim to mitigate erosion and preserve soil health and carbon stocks, there is a need for better monitoring bulk density. It is also important to address future analysis of bulk density in horizons deeper than 30 cm depth as this can contribute to subsoil compaction and estimation of carbon sequestration in deeper soil horizons (Lorenz and Lal, 2005).

As bulk density is a measured indicator which can contribute to the assessment of soil packing density and further of soil compaction, it is important to introduce management practices which reduce bulk density in croplands. Therefore, cover crops and crop residues have a positive effect in reducing bulk density in croplands (Chalise et al., 2019; Franzluebbers and Stuedemann, 2008). Other important management practices which can contribute to improvement of compacted soils are: minimal soil disturbance when soils are wet, reduce the number of trips across the field and use of low pressure tractor tyre (Bazzoffi et al., 1998).

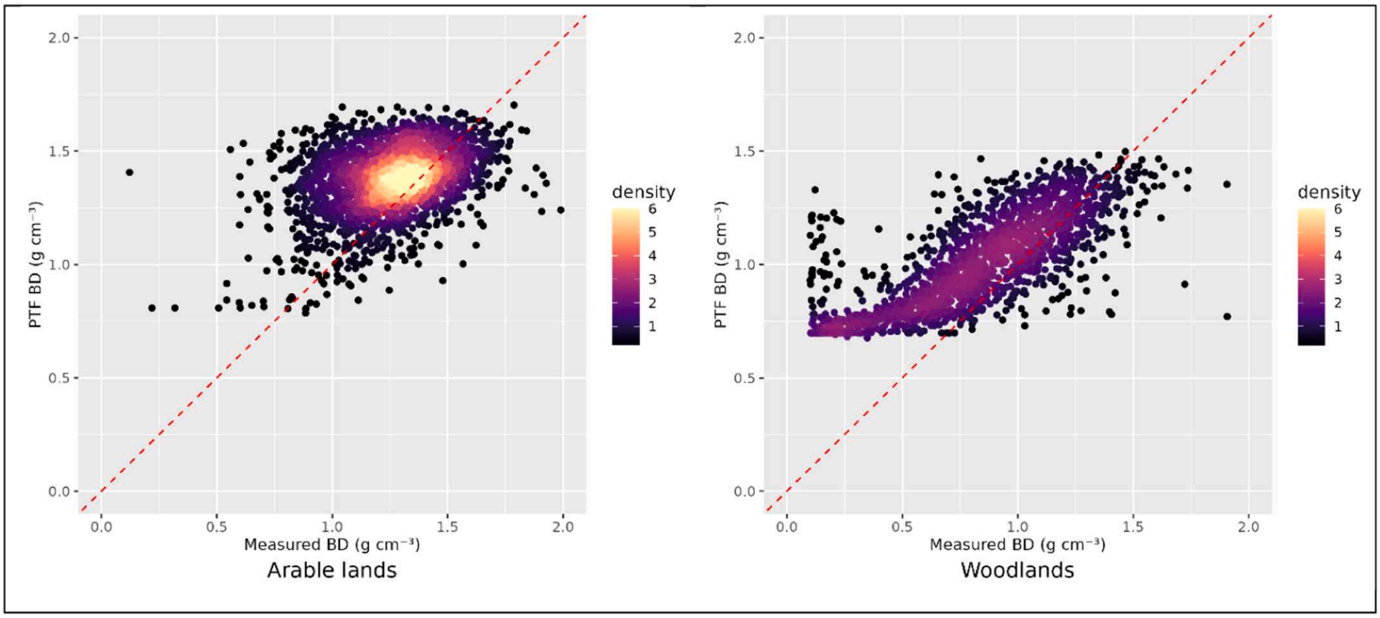

Fig. 10. Comparison of LUCAS measured bulk density and the estimated one based on Pedotransfer functions (PTF) (Hollis et al., 2012) for arable lands (left) and woodlands (right).

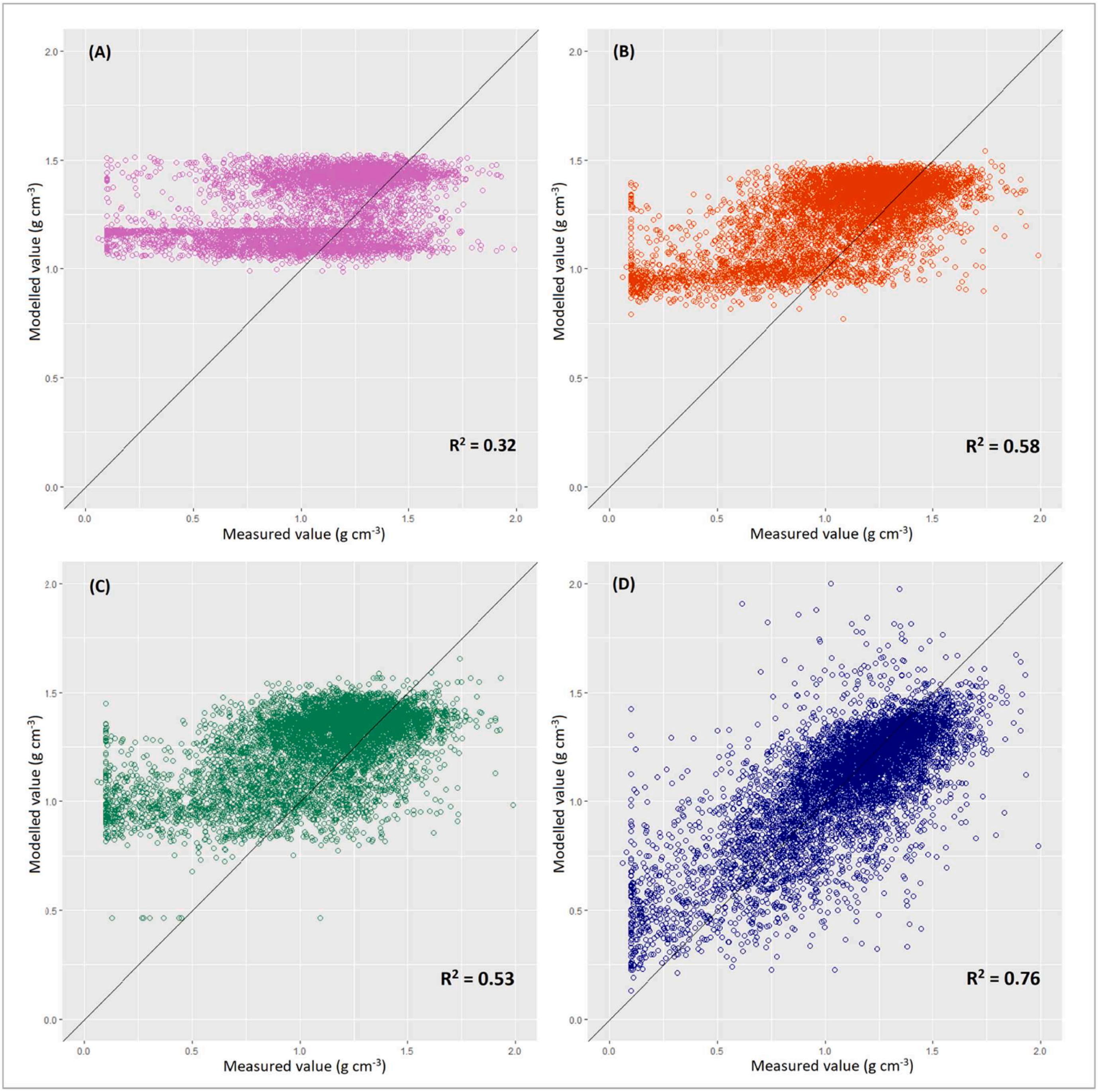

Fig. 11. Comparison of predicted vs measured bulk density (g cm^{-3}) for the three previous (A - Ballabio et al. 2016; B - Hengl et al. 2017; C - Poggio et al. (2022)) and the (D) presented assessment.

4.6. Data availability

The data and maps of bulk density for different depths (0–10 cm, 10–20 cm and 0–20 cm) and the packing density map will be available in the European Soil Data Centre (ESDAC) (Panagos et al., 2022b). The bulk density point data have been released with the LUCAS 2018 data in summer 2022.

5. Conclusions

This is the first ever high resolution continental estimate of bulk density in two depths (0–10, 10–20 cm) using more than 6000 measured samples of LUCAS 2018 survey. Based on those measured data, the high resolution map at 100 m of bulk density in 0–10 cm, 10–20 cm and 0–20 cm has been developed. The mapping results were very well compared with the point data.

The bulk density dataset can be used as input to estimate the packing density which is a proxy of soil compaction. The bulk density map can be also a baseline to which future assessments can be also compared in order to estimate the vertical stress to soils. The main driver for bulk density variation is the land cover type and in cases of agricultural areas, the crop type. The mean soil bulk density for the depth 0–20 is 1.01 g cm^{-3} for all lands with high variability between different land uses. Arable lands have the highest mean BD at 1.26 g cm^{-3}, followed by permanent crops (BD= 1.23 g cm^{-3}), heterogeneous agricultural areas (BD= 1.14 g cm^{-3}), pastures (BD= 1.08 g cm^{-3}), shrublands (BD=

1.01 g cm^{-3}) and woodlands (BD= 0.84 g cm^{-3}). Trafficking, land use and management practices have such an important impact in bulk density as arable lands have almost 1.5 times higher BD compared to woodlands (mainly undisturbed soils).

Compared to past estimates of bulk density which were based on pedotransfer rules, we found an overestimation of bulk density in woodlands (~25%) compared to the measured bulk density in LUCAS 2018 survey. This could have an important implication in estimating and reporting the carbon and nutrient stocks in forests.

CRediT authorship contribution statement

Ballabio Cristiano: Data curation, Formal analysis, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Borrelli Pasquale:** Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Labouyrie Maeva:** Conceptualization, Formal analysis, Methodology, Writing – original draft. **Liakos Leonidas:** Data curation, Resources, Software, Visualization. **De Rosa Daniele:** Conceptualization, Data curation, Methodology, Validation, Writing – original draft. **PANAGOS PANOS:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Panos Panagos reports was provided by European Commission Joint Research Centre Ispra. Panos Panagos reports a relationship with European Commission Joint Research Centre Ispra that includes: employment. none.

Data Availability

The data will be available in the European Soil Data Centre (ESDAC).

Acknowledgements

Administrative Arrangement on Land Use/Land Cover Area Frame Survey (LUCAS) between JRC and DG ENV. Administrative Arrangment on Soil Mission Monitoring (SoMiMo) between JRC and DG AGRI/RTD. M.L contributed to this work under the Collaborative Doctoral Partnership Agreement No. 35594 with the University of Zurich. P.B was funded by the Horizon Europe project AI4SoilHealth (Grant No. 101086179).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.108907.

References

Abdollahi, L., Schjønning, P., Elmholt, S., Munkholm, L.J., 2014. The effects of organic matter application and intensive tillage and traffic on soil structure formation and stability. Soil Tillage Res 136, 28–37.

Abrams, M., Crippen, R., Fujisada, H., 2020. ASTER global digital elevation model (GDEM) and ASTER global water body dataset (ASTWBD). Remote Sens 12, 1156.

Abu-Hamdeh, N.H., 2003. Compaction and subsoiling effects on corn growth and soil bulk density. Soil Sci. Soc. Am. J. 67, 1213–1219.

Alckmin, G.T., Lucieer, A., Rawnsley, R., Kooistra, L., 2022. Perennial ryegrass biomass retrieval through multispectral UAV data. Comput. Electron. Agric. 193, 106574.

Al-Shammary, A.A.G., Kouzani, A.Z., Kaynak, A., Khoo, S.Y., Norton, M., Gates, W., 2018. Soil bulk density estimation methods: a review. Pedosphere 28, 581–596.

Ballabio, C., Jiskra, M., Osterwalder, S., Borrelli, P., Montanarella, L., Panagos, P., 2021. A spatial assessment of mercury content in the European Union topsoil. Sci. Total Environ. 769, 144755.

Ballabio, C., Lugato, E., Fernández-Ugalde, O., Orgiazzi, A., Jones, A., Borrelli, P., Montanarella, L., Panagos, P., 2019. Mapping LUCAS topsoil chemical properties at European scale using Gaussian process regression. Geoderma 355, 113912.

Ballabio, C., Panagos, P., Monatanarella, L., 2016. Mapping topsoil physical properties at European scale using the LUCAS database. Geoderma 261, 110–123.

Batey, T., 2009. Soil compaction and soil management–a review. Soil Use Manag 25, 335–345.

Batjes, N.H., Ribeiro, E., Van Oostrum, A., 2020. Standardised soil profile data to support global mapping and modelling (WoSIS snapshot 2019). Earth Syst. Sci. Data 12, 299–320.

Bazzoffi, P., Pellegrini, S., Rocchini, A., Morandi, M., Grasselli, O., 1998. The effect of urban refuse compost and different tractors tyres on soil physical properties, soil erosion and maize yield. Soil Tillage Res 48, 275–286.

Biro, K., Pradhan, B., Buchroithner, M., Makeschin, F., 2013. Land use/land cover change analysis and its impact on soil properties in the northern part of Gadarif region, Sudan. Land Degrad. Dev. 24, 90–102.

Blake, G.R., 1965. Bulk density. Methods Soil Anal. Part 1 Phys. Mineral. Prop. Stat. Meas. Sampl. 9, 374–390.

Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma 326, 164–200.

Bondi, G., O 'Sullivan, L., Fenton, O., Creamer, R., Marongiu, I., Wall, D.P., 2021. Trafficking intensity index for soil compaction management in grasslands. Soil Use Manag 37, 504–518.

Borrelli, P., Van Oost, K., Meusburger, K., Alewell, C., Lugato, E., Panagos, P., 2018. A step towards a holistic assessment of soil degradation in Europe: Coupling on-site erosion with sediment transfer and carbon fluxes. Environ. Res. 161, 291–298.

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015. The impact of heavy traffic on forest soils: A review. . Ecol. Manag. 338, 124–138.

Celik, I., Gunal, H., Budak, M., Akpinar, C., 2010. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. Geoderma 160, 236–243.

Chalise, K.S., Singh, S., Wegner, B.R., Kumar, S., Pérez-Gutiérrez, J.D., Osborne, S.L., Nleya, T., Guzman, J., Rohila, J.S., 2019. Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. Agron. J. 111, 99–108.

Chaudhari, P.R., Ahire, D.V., Ahire, V.D., Chkravarty, M., Maity, S., 2013. Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. Int. J. Sci. Res. Publ. 3, 1–8.

Corti, G., Ugolini, F.C., Agnelli, A., Certini, G., Cuniglio, R., Berna, F., Fernández Sanjurjo, M.J., 2002. The soil skeleton, a forgotten pool of carbon and nitrogen in soil. Eur. J. Soil Sci. 53, 283–298.

Crippen, R., Buckley, S., Agram, P., Belz, E., Gurrola, E., Hensley, S., Kobrick, M., Lavalle, M., Martin, J., Neumann, M., 2016. NASADEM global elevation model: Methods and progress. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 41, 125–128.

Dam, R.F., Mehdi, B.B., Burgess, M.S.E., Madramootoo, C.A., Mehuys, G.R., Callum, I.R., 2005. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil Tillage Res 84, 41–53.

De Rosa, D., Rowlings, D.W., Fulkerson, B., Scheer, C., Friedl, J., Labadz, M., Grace, P.R., 2020. Field-scale management and environmental drivers of N 2 O emissions from pasture-based dairy systems. Nutr. Cycl. Agroecosystems 117, 299–315.

Defossez, P., Richard, G., Boizard, H., O'Sullivan, M.F., 2003. Modeling change in soil compaction due to agricultural traffic as function of soil water content. Geoderma 116, 89–105.

Delgado, R., Sánchez-Marañón, M., Martín-García, J.M., Aranda, V., Serrano-Bernardo, F., Rosua, J.L., 2007. Impact of ski pistes on soil properties: a case study from a mountainous area in the Mediterranean region. Soil Use Manag 23, 269–277.

Dobarco, M.R., Cousin, I., Le Bas, C., Martin, M.P., 2019. Pedotransfer functions for predicting available water capacity in French soils, their applicability domain and associated uncertainty. Geoderma 336, 81–95.

Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks–a meta-analysis. Glob. Change Biol. 17, 1658–1670.

Fernández-Delgado, M., Sirsat, M.S., Cernadas, E., Alawadi, S., Barro, S., Febrero-Bande, M., 2019. An extensive experimental survey of regression methods. Neural Netw. 111, 11–34.

Fernandez-Ugalde, O., Jones, A., Scarpa, S., Orgiazzi, A., 2022. LUCAS 2018 Soil Module. Presentation of dataset and results. ISBN 978-92-76-54832-4 EUR 31144 EN. https://doi.org/10.2760/215013.

Franzluebbers, A.J., Stuedemann, J.A., 2008. Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. Soil Tillage Res 100, 141–153.

Gao, L., Wang, B., Li, S., Wu, H., Wu, X., Liang, G., Gong, D., Zhang, X., Cai, D., Degré, A., 2019. Soil wet aggregate distribution and pore size distribution under different tillage systems after 16 years in the Loess Plateau of China. Catena 173, 38–47.

Håkansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res 53, 71–85.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res 82, 121–145.

Hengl, T., Mendes de Jesus, J., Heuvelink, G.B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12, e0169748.

Hijmans, R.J., Bivand, R., Forner, K., Ooms, J., Pebesma, E., 2022. Terra.: Spat. data Anal. R. Package Version 1.

Hillel, D., 1980. Fundamentals of Soil Physics. Academic press, New York.

Hollis, Hannam, J., Bellamy, P.H., 2012. Empirically-derived pedotransfer functions for predicting bulk density in European soils. Eur. J. Soil Sci. 63, 96–109.

Horn, R., Way, T., Rostek, J., 2003. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. Soil Tillage Res 73, 101–106.

ISO, 2017. ISO 11272:2017. Soil Quality. Determination of dry bulk density.

Jones, R.J., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil Tillage Res 73, 131–143.

Keller, T., Håkansson, I., 2010. Estimation of reference bulk density from soil particle size distribution and soil organic matter content. Geoderma 154, 398–406.

Kuhn, M., Weston, S., Keefer, C., Kuhn, M.M., 2023. Package 'Cubist.' Rule- Instance-Based Regres. Model. R Package Version 04 1.

Ledermann, T., Herweg, K., Liniger, H.P., Schneider, F., Hurni, H., Prasuhn, V., 2010. Applying erosion damage mapping to assess and quantify off-site effects of soil erosion in Switzerland. Land Degrad. Dev. 21, 353–366.

Lee, J., Hopmans, J.W., Rolston, D.E., Baer, S.G., Six, J., 2009. Determining soil carbon stock changes: simple bulk density corrections fail. Agric. Ecosyst. Environ. 134, 251–256.

Lorenz, K., Lal, R., 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. Adv. Agron. 88, 35–66.

Lugato, E., Lavallee, J.M., Haddix, M.L., Panagos, P., Cotrufo, M.F., 2021. Different climate sensitivity of particulate and mineral-associated soil organic matter. Nat. Geosci. 14, 295–300.

McNabb, D.H., Startsev, A.D., Nguyen, H., 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Sci. Soc. Am. J. 65, 1238–1247.

Micheli, E., Bialousz, S., Bispo, A., Boixadera, J., Jones, A.R., Kibblewhite, M.G., Kolev, N., Kosmas, C., Lilja, H., Malucelli, F., 2008. Environmental assessment of soil for monitoring, volume IVa prototype evaluation. Off. Off. Publ. Eur. Communities, Luxemb. 96pp..

Montanarella, L., Panagos, P., 2021. The relevance of sustainable soil management within the European Green Deal. Land Use Policy 100, 104950.

Montzka, C., Herbst, M., Weihermüller, L., Verhoef, A., Vereecken, H., 2017. A global data set of soil hydraulic properties and sub-grid variability of soil water retention and hydraulic conductivity curves. Earth Syst. Sci. Data 9, 529–543.

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., Fernández-Ugalde, O., 2018a. LUCAS Soil, the largest expandable soil dataset for Europe: a review. Eur. J. Soil Sci. 69, 140–153.

Pal, M., Deswal, S., 2009. M5 model tree based modelling of reference evapotranspiration. Hydrol. Process. Int. J. 23, 1437–1443.

Păltineanu, C., Calciu, I., Vizitiu, O., 2015. CHARACTERIZING SOILS COMPACTION BY USING PACKING DENSITY AND COMPACTION DEGREE INDICES. Soil Sci. 49, 65–71.

Panagos, P., Köningner, J., Ballabio, C., Liakos, L., Muntwyler, A., Borrelli, P., Lugato, E., 2022a. Improving the phosphorus budget of European agricultural soils. Sci. Total Environ., 158706

Panagos, P., Van Liedekerke, M., Borrelli, P., Köninger, J., Ballabio, C., Orgiazzi, A., Lugato, E., Liakos, L., Hervas, J., Jones, A., 2022b. European Soil Data Centre 2.0: Soil data and knowledge in support of the EU policies. Eur. J. Soil Sci. 73, e13315.

Poeplau, C., Vos, C., Don, A., 2017. Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. Soil 3, 61–66.

Poggio, L., De Sousa, L.M., Batjes, N.H., Heuvelink, G., Kempen, B., Ribeiro, E., Rossiter, D., 2021. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. SOIL 7, 217–240.

Pulido, M., Schnabel, S., Lavado Contador, J.F., Lozano-Parra, J., Gonzalez, F., 2018. The impact of heavy grazing on soil quality and pasture production in rangelands of SW Spain. Land Degrad. Dev. 29, 219–230.

R Core Team, 2022. R: A language and environment for statistical computing [WWW Document]. R-Proj. URL ⟨https://www.R-project.org/⟩.

Ramcharan, A., Hengl, T., Beaudette, D., Wills, S., 2017. A soil bulk density pedotransfer function based on machine learning: A case study with the NCSS soil characterization database. Soil Sci. Soc. Am. J. 81, 1279–1287.

Renger, M., 1970. Uber den Einflus der Dränung auf das Gefüge und die Wasserdurchlässigkeit bindiger Böden. Mitt. Dtsch. Bodenkd. Ges. 11, 23–28.

Robinson, D.A., Thomas, A., Reinsch, S., Lebron, I., Feeney, C.J., Maskell, L.C., Wood, C. M., Seaton, F.M., Emmett, B.A., Cosby, B.J., 2022. Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. Sci. Rep. 12, 1–13.

Rossi, A.M., Hirmas, D.R., Graham, R.C., Sternberg, P.D., 2008. Bulk density determination by automated three-dimensional laser scanning. Soil Sci. Soc. Am. J. 72, 1591–1593.

Schneider, F., Don, A., 2019. Root-restricting layers in German agricultural soils. Part I: extent and cause. Plant Soil 442, 433–451.

Sequeira, C.H., Wills, S.A., Seybold, C.A., West, L.T., 2014. Predicting soil bulk density for incomplete databases. Geoderma 213, 64–73.

Sevastas, S., Gasparatos, D., Botsis, D., Siarkos, I., Diamantaras, K.I., Bilas, G., 2018. Predicting bulk density using pedotransfer functions for soils in the Upper Anthemountas basin, Greece. Geoderma Reg. 14, e00169.

Shamal, S.A.M., Alhwaimel, S.A., Mouazen, A.M., 2016. Application of an on-line sensor to map soil packing density for site specific cultivation. Soil Tillage Res 162, 78–86.

Son, N.-T., Chen, C.-F., Chen, C.-R., Toscano, P., Cheng, Y.-S., Guo, H.-Y., Syu, C.-H., 2021. A phenological object-based approach for rice crop classification using time-series Sentinel-1 Synthetic Aperture Radar (SAR) data in Taiwan. Int. J. Remote Sens. 42, 2722–2739.

Stolf, R., Thurler, Á. de M., Bacchi, O.O.S., Reichardt, K., 2011. Method to estimate soil macroporosity and microporosity based on sand content and bulk density. Rev. Bras. Ciênc. Solo 35, 447–459.

Throop, H.L., Archer, S.R., 2008. Shrub (Prosopis velutina) encroachment in a semidesert grassland: spatial–temporal changes in soil organic carbon and nitrogen pools. Glob. Change Biol. 14, 2420–2431.

Throop, H.L., Archer, S.R., Monger, H.C., Waltman, S., 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. J. Arid Environ. 77, 66–71.

Topa, D., Cara, I.G., Jităreanu, G., 2021. Long term impact of different tillage systems on carbon pools and stocks, soil bulk density, aggregation and nutrients: a field meta-analysis. Catena 199, 105102.

Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013. Application of Bayesian Belief Networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. Soil Tillage Res 132, 56–68.

Van den Akker, J.J.H., 2004. SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. Soil Tillage Res 79, 113–127.

Vereecken, H., Maes, J., Feyen, J., Darius, P., 1989. Estimating the soil moisture retention characteristic from texture, bulk density, and carbon content. Soil Sci. 148, 389–403.

Vincent, K.R., Chadwick, O.A., 1994. Synthesizing bulk density for soils with abundant rock fragments. Soil Sci. Soc. Am. J. 58, 455–464.

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185.

Zhou, J., Li, E., Wei, H., Li, C., Qiao, Q., Armaghani, D.J., 2019. Random forests and cubist algorithms for predicting shear strengths of rockfill materials. Appl. Sci. 9, 1621.