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Stone and gravel contents of arable soils influence estimates of C and N stocks

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ABSTRACT

Studies concerning the stoniness of arable soils are scarce since those soils are commonly regarded as composed mainly of fine earth. However, even the influence of lesser volumes of stones and gravel on estimates of nutrient stocks may be significant. Nutrient analyses are performed on the fine earth fraction. It is therefore necessary to determine the bulk density and the relative soil volume that is occupied by fine earth when expressing nutrient stocks per unit area and to a certain depth. In this study, relative volumes of stones and gravel were investigated in the top soils, i.e. down to 30 cm depth, of five Swedish arable sites. Bulk density and gravel volume were determined by soil coring and stone volume using the rod penetration method. A function for estimation of relative stone volume from mean penetration depth was developed. The function is suitable for soils with low stoniness, i.e. less than 10%. The results showed that although the relative volumes of stones and gravel were small, at most 8%, neglecting the volume occupied by rock fragments led to an overestimation of C and N stocks by 8–9%. The moderate volumes of stones and gravel also significantly affected comparisons between sites. It was concluded that the inclusion of stone and gravel volume of arable soils may be important if nutrient stocks of different sites are compared, or the effects of land use changes are scaled up to regional or global levels.

1. Introduction

Coarse inorganic fractions such as gravel, stones and boulders often form a substantial part of the soil volume. Different degrees of weathering of the parent material results in a wide range of particle shapes and sizes, and various systems for classification of soils based on particle size have been developed. Hydrological, chemical and biological processes in the soil are highly dependent on soil particle composition. It is now generally established to divide soil particles into two main fractions, i.e. fine earth with particles less than 2 mm in diameter, and rock fragments with sizes from 2 mm and larger (e.g. Novák et al., 2011). Rock fragments influence a number of soil properties, for example, hydrology (Cousin et al., 2003; Flint and Childs, 1984; Novák et al., 2011; Tetegan et al., 2011; van Wesemael et al., 2000), soil temperature (Casals et al., 2000; Childs and Flint, 1990; Mehuys et al., 1975), bulk density of the fine earth (Poesen and Lavee, 1994; van Wesemael et al., 2000) and the amount of available nutrients (Lyford, 1964; Poesen and Lavee, 1994). A negative correlation between the volume of rock fragments in the soil and the bulk density of the fine earth has been shown (Poesen and Lavee, 1994; Tamminen and Starr, 1994; van Wesemael et al., 2000). This may be caused by higher biological and chemical activity in the fine earth in the presence of rock fragments (e.g. Childs and Flint, 1990).

Apart from microclimatic changes associated with the physical structure of the soil, a large volume of rock fragments reduces the space that is otherwise occupied by fine earth, air and moisture. Lyford (1964) has described this as a dilution of the soil. Results from analyses of soil elements are commonly expressed as mass concentrations of the fine earth fraction, e.g. mg g^{-1} dry soil. However, there is often a need to express the amount of nutrients per unit area and to a certain depth, i.e. in a known soil volume. To convert concentrations into amounts per soil volume, two parameters must be known: (i) the bulk density of the fine earth, and (ii) the relative soil volume that is represented by the fine earth fraction. It has been regarded as a paradox in soil science that the use of advanced laboratory equipment improves the last decimals of the results of analyses, whilst the relative volume of the analysed fine earth fraction often is unknown (e.g. Eriksson and Holmgren, 1996).

Global estimations of the size of carbon (C) and nitrogen (N) stocks in soils are complicated by a number of factors, amongst which spatial variations in stoniness and bulk density are crucial (e.g. Batjes, 1996). These physical soil properties are also important parameters when modelling soil organic carbon (SOC) dynamics. It has been stressed that the greatest uncertainty in the estimates of SOC in the soil includes determination of stoniness (IPCC, 2003). Land-use changes, for example afforestation of former agricultural land, are expected to alter the C and N stocks, both in the vegetation and in the soil. Afforestation of arable land has become an important land-use change in Sweden as

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well as in the rest of Europe and it may be regarded as one of the major potential carbon sinks in Europe (Powlson et al., 1998). A model study predicted that fast-growing tree species, planted on 400,000 ha of abandoned arable land, would capture C to the extent of nearly one tenth of the annual anthropogenic emissions of CO_2 in Sweden today (Rytter, 2012). To verify such effects of land use changes, accurate estimates of soil nutrient stocks are needed which includes volumetric estimates of rock fragments.

Estimates (soil particle classification according to Atterberg, 1905) of fine earth bulk density (particle size < 2 mm) and relative gravel volume (2–20 mm) are commonly obtained by core sampling. Coarser fragments, i.e. stones (0.02–0.2 m) and boulders (>0.2 m) will not be sampled due to the restricted diameter of the core sampler. However, the stone and boulder content of soils may be substantial. For example, the relative volume of stones and boulders was estimated to be 42% on average in Finnish forest soils (Viro, 1958). The corresponding values for forest soils in Sweden were 43–50% (Eriksson and Holmgren, 1996; Stendahl et al., 2009). More than half of the volume of some Gloucester forest soils was occupied by coarse fragments (Lyford, 1964). In contrast to forest soils, arable soils are most often regarded as composed mainly of fine earth since stones have been removed during decades or even centuries; therefore, little attention has been paid to the stone content of arable soils to date.

Several methods have been practiced for estimating the relative volume of stones in the soil, i.e., the stoniness. For example, the stoniness of soils may be estimated by digging pits of known volume, sieving the soil, and weighing the different particle fractions (Alexander, 1981). This is a labour intensive method that requires numerous pits (Buchter et al., 1994). It is also a destructive method which may not be suitable for all studies. For instance, non-destructive methods are desirable in ecosystem studies where soil fauna and vegetation otherwise might be disturbed. One non-destructive method is the rod penetration method where a thin metal rod is driven through the soil until it is stopped by a stone or a boulder (Viro, 1952). The average penetration depth is noted, and a reference function is developed by digging pits for determination of the relative stone volume. Reference functions are available for forest soils (Eriksson and Holmgren, 1996; Stendahl et al., 2009; Tamminen and Starr, 1994; Viro, 1952). Those functions were developed for soils with high stoniness, i.e. they have a steep slope and might also have a lower limit of about 10% which make them less suitable for soils with low stoniness. Stendahl et al. (2009) forced a function through 0% but it has not been validated for soils with low stone content. Thus, there is a need to develop a reference function for soils with a relative stone volume less than ca 10%, for example, arable soils. Another non-destructive technique is the ground-penetrating radar which has been shown to improve the accuracy of depth estimations compared to auger measurements (Daniels, 2005; Jol, 1995; Sucre et al., 2011).

The present study was performed on five arable sites in Sweden which were planned for future afforestation with fast-growing tree species and included in a tree species trial with emphasis on biomass production (Rytter and Lundmark, 2010) and the influence of different tree species on soil chemistry and C and N sequestration (Rytter and Högbom, 2010). The sites were selected in order to be representative of arable land of the specific region, i.e. with an average fertility of the region, and they were also spread in a north–south direction over the country. Thus, regional variations in soil types occurred.

The objectives of the present study were: (i) to investigate the stoniness of arable sites, by using the rod penetration technique, and develop a function for soils with low stoniness; and (ii) to determine the influence of relative stone- and gravel volume on the estimates of nutrient contents in the top soil volume, i.e. per ha and down to 30 cm depth. It was hypothesized that the stoniness of arable sites was considerably lower compared to forest sites in Sweden, but neglecting the volume of stones and gravel would significantly overestimate nutrient content in the investigated soil volume.

2. Material and methods

2.1. Site description

In Sweden, loose deposits have been formed by several glaciations during the last two million years. Thus, the current soil morphology is strongly influenced by the last glacial period, Weichsel, which ended about 10,000 years ago (Lundquist, 1994). The dominant soil is till, formed under glacial ice and covering 75% of the land area. The till is mainly composed of granite and gneiss in the eastern parts of the country, whilst Jotnian sandstone and porphyry are dominant in the western parts (SGU, 2011). Postglacial sediments, formed by the postglacial land uplift, are found in central Sweden and along the northern coast, with the western boundary following the highest coastline after glaciation. The present study included five arable sites, located from north to south in Sweden, at latitudes 56°–64° and longitudes 13°–21° (Fig. 1a). The spread of the sites over the country implies a variation in soil characteristics from moraine clay and loam in the southern parts to postglacial silt in the north (SGU, 2011, Table 1). A comprehensive study of Swedish agricultural soils classified 55% of the investigated soils as clay soils, according to the Swedish nomenclature (Eriksson et al., 1999). Converted to the international classification system (FAO, 1990) loams are dominating (64%). It should be noted that the conversion between the classification systems is approximate unless complete texture analysis data are available (Eriksson et al., 1999). All the investigated soils in the present study are mineral soils which have been cultivated with annual crops during the last decades. Most of the agricultural soils in Sweden are mineral soils. Organic soils have been estimated to cover only about 10% of the total arable land area (Berglund, 1996). Arable soils are characterized by a top soil layer rich in humus and a compacted plough pan below, at around 30 cm depth. The top soil layer is characterized as a special form of mull (e.g. White, 2006). The mull contains more mineral than organic material in general. Over the years larger stones have been removed from arable soils on moraines and repeated ploughing and harrowing have created a homogenous distribution of the remaining stones in the topsoil.

2.2. Stoniness

All sites were predesigned for the establishment of experimental plantations with the aim to evaluate the production capacity of six tree species (Rytter and Lundmark, 2010) and their influence on carbon sequestration and soil chemistry (Rytter and Högbom, 2010). On each site, a total of 24 square plots (40 × 40 m) were arranged in four repetitions, i.e. blocks (Fig. 1b). Within each block, stoniness was estimated from four circular plots. Each plot had a diameter of 20 m and was covering an area of 314 m^2. The plots were randomly positioned within a block (Fig. 1c). There were 16 circular plots on each experimental site and 80 circular plots in total. Rod penetration depths (see method description below) were measured at 52 systematically distributed points over each circular plot area. A reference pit, 30 × 30 × 30 cm, with a volume of 0.027 m^3, was dug at the centre of each plot. In total 80 reference pits were dug. The soil from a pit was sieved through a tray with the mesh size of 0.02 × 0.02 m and all stones (≥20 mm) were cleaned and weighed. On some occasions a stone was only partially included within the volume of the reference pit. The part of the stone belonging to the pit was marked with a felt pen and the stone volume was estimated by water replacement. Before digging the reference pit, the rod penetration depth was measured at 16 systematically distributed points from the pit surface, i.e., within 30 × 30 cm.

The rod penetration method was described by Viro (1952). A thin metal rod is driven down through the soil, to a predetermined maximum depth, by a small sledgehammer, until it is stopped by a stone. It was assumed that a stone would stop the rod from further penetration of the soil, and that smaller particles would not. However, the method requires