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Field-scale estimation of the volume percentage of rock fragments in stony soils by electrical resistivity

M. Tetegan [a,b], C. Pasquier [a], A. Besson [a,c], B. Nicoullaud [a], A. Bouthier [b], H. Bourennane [a], C. Desbourdes [d], D. King [a], I. Cousin [a,*]

[a] Institut National de la Recherche Agronomique, UR 0272 Science du Sol, Centre de recherche d'Orléans, 2163 Avenue de la Pomme de Pin, CS 40001 Ardon 45075 Orléans Cedex 2, France
[b] ARVALIS – Institut du Végétal, Domaine expérimental du Magneraud 17700 Saint Pierre d'Amilly, France
[c] Institut National de la Recherche Agronomique, UMR LISAH, 2 place Pierre Viala, 34060 Montpellier cedex 1, France
[d] ARVALIS – Institut du Végétal, 45 voie Romaine, 41240 Ouzouer le Marché, France

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ABSTRACT

Analysing the properties and functional characteristics of heterogeneous soils containing several phases requires a correct estimation of the volume proportion of each phase. In the case of stony soils, the volume percentage of the content of rock fragments remains difficult to estimate in situ. This paper presents a method that uses field spatial electrical resistivity measurements to determine the volume proportion of rock fragments. Based on the hypothesis that the electrical resistivity signal noise increases as the proportion of rock fragments increases, a model was developed that uses the standard deviation of the apparent electrical resistivity measurements over a small area as an indicator of rock fragment contents. The model was tested on three study areas of several hectares containing soil units with varying quantities of rock fragments. The estimation of the rock fragment content was accurate, and the error estimation of about 6% was the same order of magnitude as the Bussian model (1983). The developed model strongly depends on the water content in the soil and the rock type and must be calibrated in each context. Nevertheless, estimations of the rock fragment content in stony soils can be performed efficiently in the surface horizon as well as all along the soil profile.

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1. Introduction

Currently, it remains difficult to provide estimates of the hydraulic properties of stony soils at the regional scale. To avoid bias, the hydraulic properties of stony soils must account for the presence of both rock fragments and fine earth, i.e., the characteristic individual hydraulic properties, and their volume content (Cousin et al., 2003; Tetegan et al., 2011; Ugolini et al., 1998). The estimation of the volume content of rock fragments is challenging although several methods have been used for a long time. For instance, estimates of rock fragment content can be measured from the soil surface reflectance by remote sensing; this method distinguishes among soil types and soil surface conditions, such as soil micro topography and vegetation cover (Girard and Girard, 1989). Other studies have demonstrated that a relationship exists between the percentage of rock fragments and the brightness index (Bhattacharya and Chandrakar, 1999; Mathieu et al., 2007; Post et al., 1999). However, this method strongly depends on the colours of the rock fragments and the soil conditions. Indeed, directly following a rain, the presence of the cleaned rock fragments is easier to detect. In contrast, after ploughing, the fine earth embedding the rock fragments can introduce a bias into the estimation of the volume content of rock fragments.

The rock fragment content of the deepest soil layers can be estimated by invasive methods, such as soil sampling. Soil sampling requires digging a pit, and large volumes of soil, i.e., large enough to be representative of the soil particle size distribution, must be sampled in each soil horizon and sieved. A visual estimation can also be performed with a chart, but this method strongly depends on the operator (Folk, 1951; Jeffrey, 1985; Terry and Chilingar, 1955). Thus, a real challenge still exists in terms of estimating the rock fragment content along a soil pit without disturbing the soil.

Geoelectrical methods, such as electrical resistivity profiling, are non-invasive methods that are useful for characterising the spatial variability in soils (Samouëlian et al., 2005; Sudduth et al., 2001). Variations in electrical resistivity result from differences in soil textures, soil structure and some other physical soil properties including for instance the salt content, the water content and the bulk density of the soil (Besson et al., 2004; Rhoades, 1993; Seger et al., 2009). However, the electrical resistivity method requires good contact between the soil and electrodes to facilitate the injection of a direct electrical current into the soil. Faulty electrodes can introduce noise into a dataset, i.e., unexpected zero values or very high values. In particular, this

* Corresponding author. Fax: +33 2 38 417869.
E-mail addresses: Marion.Tetegan@orleans.inra.fr (M. Tetegan), Isabelle.Cousin@orleans.inra.fr (I. Cousin).

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noise arises from i) measurement errors due to the measuring device, ii) sporadic errors due to external effects (Tabbagh, 1988) and iii) poor electrode contact that can occur frequently in dry and stony soils.

The presence of rock fragments can strongly affect the electrical signal. Rock fragments located at the soil surface are responsible for noise in the measurement dataset due to interference with electrode/soil contact. In addition, the resistivity of rock fragments is generally higher than the resistivity of fine earth by several orders of magnitude (Schon, 1996; Telford et al., 1982). Several laboratory experimental studies have been conducted to study the electrical properties of rocks (Guichet, 2002; Marescot, 2006; Olhoeft, 1981; Parkhomenko, 1967; Schon, 1996; Telford et al., 1982). Experimental measurements by Rey et al. (2006) on two-phase heterogeneous media consisting of resistive inclusions embedded in a conductive matrix demonstrated the validity of the model of Bussian (1983) for estimating the volume proportion of rock fragments in the soil. Following these promising experiments, we propose using electrical resistivity data to estimate the volume percentage of rock fragments at the field scale.

The aim of this study was to test the efficiency of the electrical resistivity method for estimating the rock fragment content of soil at the field scale. This analysis was based on two methods. The first method is an application of the model of Bussian (1983) that was previously used by Rey et al. (2006). The second method focuses on noise data extracted from spatial unfiltered electrical resistivities of soil. These geophysical methods were compared to those usually used in the field, visual descriptions from a cartographic survey and measurements of the volume content of rock fragments after soil sampling.

2. Materials and methods

2.1. Study area

The study area was located in the Beauce region (Villamblain, France) about 110 km southwest of Paris. It extended over an area of 115 hectares and was generally cropped with maize and wheat (Nicoullaud et al., 2004). The climate is temperate continental with an oceanic influence and was characterised by an average temperature of 10.5 °C, a modal rainfall of about 623–630 mm and an evapotranspiration of about 767–783 mm (Besson et al., 2010; Michot et al., 2003). These mean values were calculated over a period of 32 years (1967 to 1996), and the evapotranspiration was calculated using the Penman-Monteith formula. In 1995, i.e., prior to geophysical surveys, 290 auger holes were dug to develop a description of the soils in the study area. The information obtained from the auger holes was used to establish a soil database for the study area. The soils consisted of a loamy-clay layer (about 60% loam and 30% clay) developed over lacustrine limestone deposits, which were locally cryoturbed. The thickness of this loamy-clay layer varied between 0.2 and 0.9 m. According to i) the spatial variability of the soil characteristics, ii) the depth and type of limestone where soil horizons were developed and iii) the thickness of the loamy-clay layer, the study area was classified into eight main soil units (Besson et al., 2010; Nicoullaud et al., 2004). These units were mainly haplic calcisols and calcaric cambisols (IUSS Working Group WRB, 2006) containing various quantities of rock fragments with different sizes, from gravels to blocks. As described by King et al. (1999) and Bourennane et al. (1998), the soil units formed on cryoturbed limestone deposits or on soft limestone deposits had the deepest loamy-clay layer (up to 0.8 m deep), whereas the shallowest soils (about 0.3 m deep) developed directly on hard calcareous bedrock.

In this study area, three plots with surface areas ranging from 1 to 10 ha were worked. The three plots were denoted A, B and C (Fig. 1). These three plots encompassed stony soil horizons with i) various proportions of rock fragments, ranging from 0% to more than 30% (volume percentage) and ii) various lithologies, including soft limestone, hard limestone and cryoturbed limestone.

2.2. Electrical resistivity data

2.2.1. Electrical resistivity measurements

Field-scale geophysical surveys were accomplished using a Multi-Continuous Electrical Profiling device (MuCEP device) that allows measurements of spatial field electrical resistivity with a high spatial resolution. The device was composed of a Doppler radar, which triggered a measurement every 0.1 m along an electrical transect, a global positioning system and four pairs of electrodes that generated three

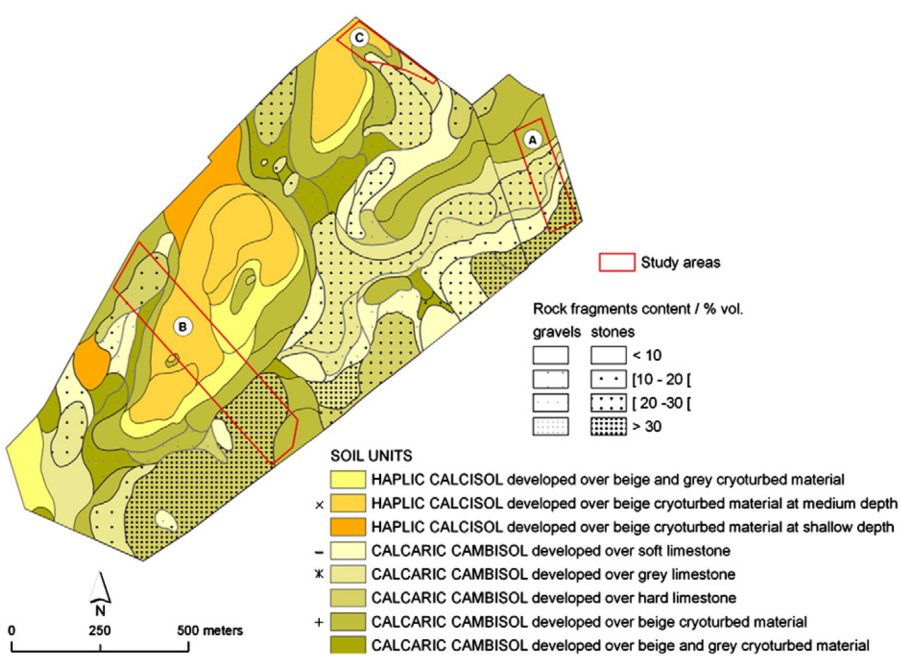

Fig. 1. Soil map of the study areas at 1/5000 established in 1995. The soil units were described using the IUSS Working Group WRB (2006) classification. The symbols (×, −, ∗ and +) correspond to those used in Fig. 8.

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