IECAG 2021

Proceedings

Considering cloddiness when estimating rooting capacity and soil fertility†

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† Presented at the 1st International Electronic Conference on Agronomy, 3–17 May 2021; Available online: https://sciforum.net/conference/IECAG2021

Abstract: The estimate of soil fertility, namely, water and nutrient availability, and biological activity, is usually made considering soil as being uniform in the reference layer. The potential fertility is thus estimated for homogeneous soil volumes. However, both the soil profile and its horizons are often not homogeneous for many characteristics and properties. The soil rooting volume, in particular, can be limited by the presence of obstacles, such as bedrock, cemented layers, and stones, but also by soil masses, or clods, that are so dense that cannot be penetrated by roots. Clods can not only occur at the soil surface, but also throughout the soil profile and within a horizon. The presence of clods is usually only considered for the soil surface, and always overlooked in the estimation of soil fertility. In this work, an innovative method, which considers the presence of clods in the soil volume for estimating the potential soil rooting capacity, is explained, and used to estimate the available water holding capacity according to soil rootability. Correcting the values of water holding capacity according to the potential soil rooting volume increases its correlation with plant phenology and the agronomic result. The method could be also applied for a better estimate of the stock of available nutrients and considered in precision farming.

Keywords: soil fertility; soil structure; clods; rooting; precision farming; viticulture; available water capacity.

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Proceedings* **2021**, *68*, x. https://doi.org/10.3390/xxxxx

Published: date

1. Introduction

Soil fertility is the ability to sustain plant growth, mainly by providing water and nutrients through the root system. Then the soil fertility concept embraces the soil physical, chemical, and biological characteristics allowing the roots to grow.

The estimate of soil fertility can be carried out following different methodologies. Many of them are based on the laboratory analysis of soil samples to check a set of physical, chemical, and biological characteristics, functional to plant development (a.o. [1]). The assessment of available water holding capacity and nutrient content receives particular attention under agricultural land uses, since they are used to steer agricultural practices such as irrigation and fertilization. The values of the analytical parameters are expressed in relation to the unit of soil mass, or volume, and form the first elements for the evaluation of soil fertility. According to the comparison with reference levels, the value of the analysed parameter may be classed, for instance, as very low, low, medium, high, and very high (a. o. [2]).

Another approach considers the stock of nutrients present in soil, pondering the values according to the reference volume and soil bulk density (a. o. [3]). The estimates can be referred to the topsoil only or extended to different depths (a. o. [4]). Other methods make use of models, which evaluate soil fertility through the simulated response of plant growth, constrained by different water and nutrient availability [5-6].

In most cases, the studied soil is considered uniform and without limiting factors, but in some methods the presence of rock fragments, underlying bedrock, or limiting layers for rooting, are taken into account [7]. The presence of clods within the soil, that is, soil masses that are compacted and impenetrable by roots, is usually neglected. However, soil compaction is an increasing threat to soil, exacerbated by drivers such as intensive agriculture and the use of heavy machinery, as well as the side effects of other soil degradation processes, like soil erosion, organic matter depletion, and soil salinisation.

In this paper, an innovative method for estimating the actual soil rooting capacity, or rootability, introduced in [8], is better explained and used to show how the correction of the estimates for available water holding capacity according to soil rootability may explain plant phenology and the agronomic result.

2. Cloddiness and soil rooting capacity

The term "cloddiness", or "clodiness", is usually used to indicate the presence of clods at the soil surface, that is, lumps, clumps, or chunks of soil masses that form artificial structural units at or near the surface, which are created by improper cultivation, often of fine textured soils [9]. When not hard, clods may be destroyed with the cultivation which follows the mouldboard ploughing. Clods are usually firm when moist and hard when dry, but they may also be very or extremely firm and hard, depending on the soil type and condition of formation. Poorly structured soils, with low organic matter, or with ferric properties (reach in iron), tend to form very compacted and difficult to break clods after ploughing. Clods are distinguished from soil peds, produced by pedogenetic processes such as those related to macro, meso and microbiological activity, shrinking and swelling of clays, wetting and drying, freezing and thawing [10]. Clods limit the volume of soil that can be explored by roots. This feature is poorly considered or neglected in most soil evaluations, in spite of the fact that the soil mass can only be crossed from the roots in the parts where the macroporosity allows it, while the more compact masses remain practically rootless.

The term cloddiness can be extended to the entire soil, including the compacted masses that not only occur at the soil surface, but also throughout the soil profile. Their presence in depth can be due to natural causes, as in the case of soil with a fragipan or with semi-consolidated sediments at shallow depth, but more frequently is due to man-made activities, like soil deep ploughing of soils subjected to hard-setting, physical breaking of compacted or cemented horizons through rippers or chisels, stripping of compacted soil layers or coherent sediments from the lower part of the soil and their redistribution throughout the soil mass.

Soil horizons with difficult or only partial penetrability are particularly common in degraded soils due to improper management. Impeding parts can be created temporary, as when clayey and silty soils are cultivated wet, especially with the mouldboard plough or with rotative tools, or are compacted by the passage of heavy machinery. In these cases, many farmers try to increase soil macroporosity using rippers or other cultivators, which however can break the soil mass of the firm horizons until the working depth, but not in between the cutters. Therefore, clods throughout the soil profile tend to be a permanent feature, especially when created during deep earthworks.

During land surface levelling and preparation for new agricultural fields, in particular for tree crops plantation, the soil is frequently subjected to partial or total loss of structure and horizons mixing [11-12]. Land reshaping can remove partially or totally the structured part of the soil profile and let outcrop masses of the underlying poorly structured or massive parent material [13].

3. Estimating soil rooting capacity.

An accurate estimation of the soil volume that can be explored by roots is based on multiple factors. First of all, on the rooting depth, that is, the distance between the soil surface and a horizon or layer preventing root penetration, for instance, a consolidated substrate, a cemented pedogenetic horizon, a layer very rich in salts, a water table [10].

Then there is the need to consider the quantity of skeleton, or coarse fragments (and its alteration state) present in the soil horizons, by subtracting the quantity of volume occupied by unaltered rock fragments, and finally cloddiness, the fraction of the volume of soil which cannot be explored by roots.

Then the potential rooting volume can be estimated through the sum of the values resulting from the following equation:

$$Rc = Rd \times (1 - St) \times (1 - Cl) \quad (1)$$

Where: *Rc* (rooting capacity) is the volume of potential rooting until the reference depth, *Rd* (rooting depth) is the thickness of the soil horizon or depth of rooting up to an impeding horizon or layer, *St* (stoniness) is the volume of the soil occupied by unaltered stones and *Cl* (cloddiness) is the fraction of the volume of soil mass that cannot be penetrated by the roots, because compacted and massive.

In numerical values, *Rc* is expressed in unit volume (mm), *Rd* is the depth in mm, *St* and *Cl* are the equivalent in mm of the percentage volume of the mass occupied by the stones and by the non-rootable soil mass, respectively. If the soil profile shows heterogeneous horizons, *Rc* is the sum of the results of (1) for each horizon.

For the calculation of *Rc*, the most difficult parameter to evaluate is certainly *Cl*, even though in the literature there are some references that can be followed for this purpose. The Soil Service of the USA has developed an empirical report indicating the bulk density values that limit plant growth, depending on both soil texture and structure [14]. The U.S. Natural Resources Conservation Service has also produced a model and related software for estimating the main hydrological soil parameters, including AWC, which considers texture, amount of skeleton, average compactness, salinity, and organic matter content, but not cloddiness and rootability [15]. Then it should be used separately for clods and soil peds.

A different approach is proposed by Dexter [16], which uses the S index, called the "Soil physical quality index", derived from the slope of the water tension—volume curve and has a corresponding bulk density value for each soil textural class. The threshold value of S sets the limit of soil masses that can be penetrated or not by the roots. The S index may be calculated from the analysis of different parts of the same horizon to estimate cloddiness.

Pagliai and Vignozzi used the micromorphometric approach to quantify the macroporosity and characterize the quality of the soil [17]. Below 10% macroporosity, soils were classified as compact and difficult to be penetrated from the roots. An image analysis of soil thin sections could help identifying the presence of micro-clods in the studied soil horizon.

Finally, Ball et al. [18] proposed a field classification of the structural quality of each soil horizon. Classes are assigned with comparison to reference tables, reporting different proportions of unaggregated or compacted soil masses and kinds and dimensions of soil aggregates. With a visual inspection and a certain approximation, it is possible to assign percentage values of soil rootability to each class of structural quality.

4. Potential soil rootability and available water capacity.

Soil availability water capacity (AWC) is the major constraint to crop productivity, especially in semiarid or sub-humid climatic conditions. To show the relevance of the estimation of the potential soil rooting capacity, an example is reported of the calculation of the potential AWC for a viticultural soil of Italy (profile MPULC 01, Figure 1). The soil evolved from silty clayey sediments of the marine Pliocene but was profoundly influenced by the earthworks made for the preparation of the plantation surface [19]. These involved levelling the original surface with the almost complete removal of the pre-existing soil by bulldozer and subsequent ploughing up to a depth of about 600 mm. The resulting soil has a silty clay texture along the entire profile, is very poor in organic matter, strongly calcareous, without skeleton, and show two main horizons. The first, which derives from the deep ploughing (Ap), is about 600 mm deep, compact, with a poorly developed angular and prismatic polyhedral structure, of coarse size, very firm consistency, and a bulk density of 1.45 g cm^3. The Ap overlays the Cg horizon, poorly pedogenized, hydromorphic, unstructured, and extremely firm, but with fissures and cracks that cross the horizon, and a bulk density of 1.75 g cm^3. The average quantity of roots is low throughout the whole profile, but in the first horizon the roots of the vines develop mainly in a sub-horizontal way and are in quantity less than 10 every 100 cm^2, in the Cg they are only occasional and follow the cracks vertically up to about 1500 mm in depth.

The AWC of the soil corresponding to this texture, density, compactness, salinity and organic substance is, according to [15], 0.13 mm mm^{-1}. Considering the standard depth of one meter, the overall AWC correspond to 130 mm. However, if we take into account the rooting capacity of the horizons and the observed rooting depth, the estimate changes as follows:

- Ap horizon:
- thickness: Rd = 600 mm
- stoniness: St = 0
- cloddiness: Cl[1] = 0.5
- rooting capacity: Rc = Rd x (1-Cl) = 300 mm
- AWC = 300 mm x 0.13 mm mm^{-1} = 39 mm

- Cg horizon:
- thickness: Rd = 900 mm
- stoniness: St = 0
- cloddiness: Cl[1] = 0.95
- rooting capacity: Rc = Rd x (1-Cl) = 45 mm
- AWC = 45 mm x 0.13 mm mm^{-1} = 5.85 mm

The total available water capacity of the soil profile until the maximum observed rooting depth corresponds to only 44.85 mm, a value that is very different from the 130 mm estimated with the method suggested by the NRCS.

Figure 1. Profile of a soil in a vineyard of Montepulciano (central Italy), resulting from the operations of deep ploughing and surface leveling. Rootability is limited by clods in the Ap horizon (first 60 cm). The overlaid poorly pedogenized parent material (Cg horizon) shows deep fissures and cracks, where the roots of the vines occasionally penetrate (photo Costantini E.A.C.).

4.1. Agronomic relevance of a corrected estimate of AWC

[1] Estimated following the field visual assessment method [18], and bulk density of the soil textural class [14].

Following the proposed methodology, the estimate of the potential AWC is much more accurate and more corresponding to the vegetative-productive behaviour of the vines, which appears to be greatly reduced. According to the common risk assessment schemes of water deficit, depending on the AWC values of the soil, the estimate with the NRCS methodology falls into the "moderate" risk class, but "very strong" with the proposed method [20]. In a four-year test carried out on the soils of Montepulciano, the monitoring of the water content indicated the presence in this type of soils of a long summer period of water deficit, which corresponded to a multiannual average grape production significantly lower than that obtained from soils on the same lithology, but with AWC values ranging between 100 and 150 mm or between 150 and 200 mm. The oenological result was on average good, but very dependent on the climate of the year, with musts obtained in the driest years that were too rich in sugar, too low in acidity, and unbalanced in the phenolic and aromatic composition [19].

In the study case, the methodology adopted to design the new vineyard produced a poorly resilient soil, with a low AWC, letting vines very sensitive to the risk of water deficit. In choosing the type of earthworks, the approximate knowledge of the nature of local soil and geology weighed heavily. The clayey silty sediment on which the work was done is locally called "mattaione gentile" (soft clay), which is differentiated from the so-called real "mattaione" (clay). In the second case, they mean clayey and very compact sediments, corresponding to the geological formation of “marine blue clays", while the soft clay, or “mattaione gentile”, is silty clay or silty clay loam and more easily workable, often included in the geological maps within the formation of “marine sands”. The agronomic result of the earthworks of land levelling and deep ploughing had relied on the presumed ability of roots to penetrate the soft clay and of deep ploughing to create a favourable environment for the growth of the vines, but actually they did not consider the real nature of soils and sediments and their consequences on the resulting soil profile.

5. Conclusions

Soil cloddiness is becoming more and more frequent, because of increasing intense mechanization and worsening of soil structure. Hard clods can be not only found at the soil surface but also throughout the soil mass, deeply affecting soil rootability.

The proposed methodology considers cloddiness in the estimation of the actual rootability of the soil mass. Although there are still some uncertainties in the choice of the standard method for the quantification of the soil structural units that are so dense that cannot be penetrated by roots, the fact that this estimate can be done in the field through a visual assessment seems encouraging its adoption in routine soil surveys. In fact, other characteristics that are foreseen in the current soil survey manuals show a similar degree of approximation, like, for instance, the presence of impenetrable layers, the porosity, the consistency [10]. In spite of their guesstimate, these characteristics are routinary surveyed and provide important clues to understand soil genesis and functioning.

The case study presented in this paper demonstrates that a dramatic change in the evaluation of soil AWC may occur, but similar results could have been found in the estimation of the potential quantity of nutrients. Therefore, it is strongly advisable to consider cloddiness also in the modelling of soil processes and plant growth, as well as in the adopting of precision farming approaches. In this sense, future field investigations, and further availably of portable devices and software applications, such as image analysis techniques, could facilitate a better quantification of cloddiness.

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