

Quantifying the Environment

Field Measurement Methods in Soil Science

Stefan Wessel-Bothe • Lutz Weihermüller (Eds.)



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**Field Measurement Methods
in Soil Science**

S. Wessel-Bothe and L. Weihermüller (Eds.)

Field Measurement Methods in Soil Science

edited by
S. Wessel-Bothe and L. Weihermüller

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Preface

Soils are progressively recognized as critical environmental compartment due to the multitude of functions they provide as habitat, as medium for the production of food, fibre and bio-energy, as regulators of the cycling of energy, water and elements such as carbon and nitrogen in ecosystems, as filters and buffers for pollutants, and their role as archives of human and landscape history. Consequently, an increasingly broad spectrum of practitioners and scientists addresses soil issues and works with soils in the context of their specific field of interest and profession. The rising interest in soils drives a mounting demand for soil information, which frequently has to be generated using field measurements. When planning these field measurements, many questions arise: What is the particular question that has to be answered? Which specific parameters do I have to measure for answering this question? Which method and which equipment is best suited to record these parameters at which precision and cost? Which preconditions have to be met for using a certain method or equipment in a meaningful way? How is the equipment installed and used? How many replicates are required? Which model cases exist for the application of certain methods? Which pitfalls lurk when using a certain method? How are the generated data interpreted and quality checked?

Much know-how to answer these questions exists distributed for example in research institutes and extension services. However, the number of people in these institutions and their available time for supporting the planning of soil-related field measurements is increasingly limited. Therefore, the book at hand fills a critical gap by providing hands-on support for the design and operation of field measurements in soil science. The book is useful not only for soil science-“beginners” searching for an introductory overview of available techniques, but also for more experienced colleagues by providing “best practice” guidelines for comparable installation and operation of field instruments. Most likely, the book cannot substitute personal discussions and consultation, but it can make these discussions much more efficient and productive.

I thank all readers for their commitment to our precious soil resource. May this book contribute to the successful generation of soil information needed for the preservation of intact and functional soils for future generations.

Giessen, July 2019

Prof. Dr. Jan Siemens

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1. General Introduction

Lutz Weihermüller and Stefan Wessel-Bothe

Knowledge of the soil states (e.g., soil water content, soil pH, redox potential, matric potential) is imperative to reliably describe water and solute transport processes, changes in the soil compartment by e.g. human activities or climate change, to implement soil conservation measures, facilitate crop production, or for modeling purposes. Over the last decades, various new sensor types and measurement techniques were developed and sensor development is still an emerging field, resulting in improved or even new sensor techniques and types. Because of this, the user is more and more dependent on guidelines which sensor/technique is appropriate for the study planned.

As outlined in the documentation of the single sampling devices, sensors, and measurement techniques, the right choice of the measurement sensor/technique/sampling device is not an easy task. First of all, most sensors/techniques/sampling devices differ greatly with regard to the type of information they collect, their resolution in space and time, their cost and maintenance, as well as in the requirement of expert knowledge. Even if the individual chapters of this book try to point out advantages and disadvantages of each system/sensor, this should not be regarded as the *only recommendation* for later decisions. Moreover, this book should be conceived as a guideline for decision making taking all advantages/disadvantages, costs etc. into account, without losing the focus of the experiment planned.

1.1. Measurement location

In general, the scientist must ensure that the location of the soil monitoring station is well chosen, irrelevant if only one or several stations are to be distributed over an area or catena. To ensure that the selected location is representative for the study site, soil information should be gathered, which may be used for estimating the heterogeneity at the location. This information can be obtained from, for example, aerial views, topographical and fine scale soil maps, or information deduced from own mapping studies (e.g., Pürckhauer augering). Avoid previously disturbed areas, vicinity to buildings, and the influence of close by vegetation or surface waters which may have impact on the soil's hydrology. Influence factors such as these – if they are not part of the study – would interfere with your results in a misleading way.

1.2. Number of stations

In many cases, one is only able to operate one single monitoring station on one single site due to budget constraints. In these cases, it must be understood that i) the experimental design must be planned as meticulously as possible, and ii) that the results from one single site may only be representative of a limited area. The extent of transferability then depends on the landscape's particular features such as topography and the spatial heterogeneity of the soil.

If the budget allows setting up more than one site with the same instrumentation, the results so obtained will potentially be more representative of the area under investigation. Nevertheless, it is not always the best solution to have as many measuring points as possible within a study area. On the other hand, distributing only few sensors at various spots within the study area might cause a lack of information on the short term variability at each single location. Additionally, the reliability of sensor readings for each spot cannot be tested, unless replicate measurement data are available. A compromise would be to install fewer plots with a higher (vertical and horizontal) sensor density instead of installing too many plots within one single field with only sparse instrumentation. In some cases, the use of inexpensive but less sophisticated (less accurate) sensors may be an appropriate alternative. However, to obtain reliable results using low-cost sensors, it is always worth to consider the concessions concerning the quality of data from the sensors. In conclusion, lower quality readings are only acceptable when their statistic evaluation and the scientific goal will not be affected.

1.3. Experiment design

In a first step, the experimentalist should exactly define the study target and design the experiment appropriately *before* selecting any sampler or sensor. Based on the design and scientific questions, some sensor types or systems may be already identified. In the next step, different sensors providing the same information (e.g., water content information) should be reviewed and based on cost, maintenance, and existing expert knowledge an appropriate sensor/system should be chosen. In this context, maintenance denotes the sum of expenditure on human labor and service inspections, whereas the cost is the total of the maintenance, cost of acquisition, and installation of the sensors.

In conclusion, the decision on the appropriate sensor/system will be defined by i) the experimental target and ii) potential limitations in terms of installation effort, maintenance, financial background, and existing expert knowledge. In any case, the suitability of the sensor/sampling system must be carefully deliberated.

1.3.1. Spatial heterogeneity

Because most sensors/techniques determine the soil state of interest (e.g., water content) in a relative small (measurement) volume, but most applications of soil research address the field scale, a mismatch of measurement scale and scale of interest poses a serious problem, because it is generally questionable whether point measurements are representative of the larger scale. From a scientific point of view, soil can be understood as a porous medium variable in space and time, whereby its state variables (e.g., soil water content, soil pH, redox potential, matric potential) are extensive quantities. When measuring such extensive quantities, one must acknowledge that the quantity depends on the measurement scale. To account for the scale effect Bear (1972) introduced the concept of the representative elementary volume (REV), which states that a volume is representative to a certain extent as long as the state does not fluctuate within this volume. Unfortunately, the complexity of this simple definition increases whenever it is applied to a real world problem. Firstly, the actual size of the REV depends on the system under investigation (this means that specific REV volumes may be applicable for each, simultaneously measured parameter), and secondly, the actual size of the REV depends on the areal size of the sampled region. As Durner and Flüher (2005) have stated, enlarging the averaging volume will lead to the inclusion of new, larger size structural elements. The dependency of a soil state (e.g., soil water content) on the characteristic length of the averaging volume is shown schematically in Fig. 1.1.

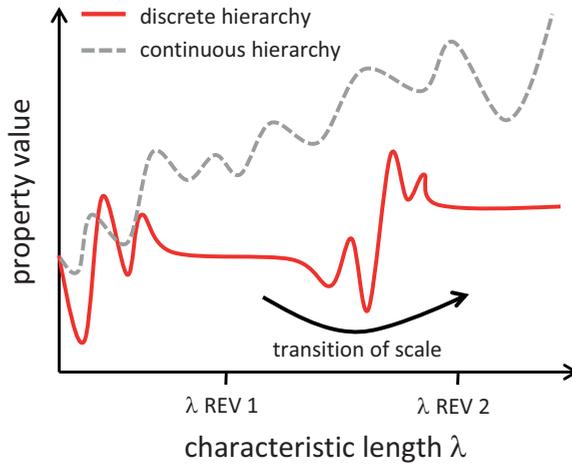


Fig. 1.1. Concept of the representative elementary volume (REV) assuming two different concepts of spatial heterogeneity (adopted from Zurmühl 1994). As can be seen, two different REVs are detectable (REV 1 and REV 2) for the discrete hierarchy at given characteristic length λ with two different property values. Moving from REV 1 to REV 2 changes the property value. On the other hand, a continuous hierarchy does not allow to delineate REVs.

Apparently, there is a clear disparity of hierarchical levels (scales), where repeated measurements (e.g., replicates in sensors) yield consistent values. In the transition zone of two hierarchical levels the measured value becomes unstable, which is indicated by increased variation of measured values (replicates).

1.3.2. Number of replicates

Because the natural variability of the soil states (often termed heterogeneity) is unknown, the experimentalist relies on a number of replicate measurements (sensors) per depth level. Unfortunately, the number of replications (n) is often falsely assumed to be sufficient if $n = 3$. As Weihermüller et al. (2005) nicely showed for suction cups sampling, n has to be far greater than 3 to estimate a mean solute breakthrough curve, even in a fairly homogeneous soil system. Therefore, the question arises how many replicates have to be installed? Logically, the required number can only be determined after analyzing ∞ replicates, which is neither feasible nor constructive. To get at least a hint of the number of replicates required, the literature should be screened for comparable setups and indications of heterogeneity. Because some parameters have a different distribution in soil than others (e.g., soil temperature has a generally lower vertical heterogeneity as soil water content), it is necessary to clarify the required number of replicates particular to the state of interest. It may be sufficient to install only one soil temperature sensor, while on the same site at least three sensors for water content are necessary. In most chapters of this book, general hints or a secret recommended number of replicates of instruments are presented for individual soil states of interest.

1.3.3. Precision, trueness and accuracy

The technical terms *precision*, *trueness*, and *accuracy* are often mixed up. In fact, the accuracy of a reading is a combination of its trueness and its precision. To clarify this, the definitions and differences of these terms are given below.

A) Precision

Precision or internal reproducibility is the degree of agreement between independent measurement results under given static conditions (e.g., constant soil water content or temperature). If the sensor output shows low variability in these conditions, the measurement method/sensor has high precision. On the other hand, it is important to note that a high precision does not mean that the measured values are correct. You could be precisely wrong (see Fig. 1.2).

B) Trueness

The trueness or external reproducibility denotes the degree agreement of the mean value from a large set of measured sensor data and the accepted reference value measured by a reference method. In other words, if the mean value of a large number of measurements is in good agreement with the reference value, the trueness is high. However, this procedure does not give any information about the scatter of the individual readings (see Fig. 1.2).

B) Accuracy

Accuracy is the degree of the correspondence between the (single) measurement result and the true value of the measured variable. A high accuracy can therefore only be achieved if both, the precision and the trueness, are high.

This relationship between precision, trueness, and accuracy can be visualized very well by a simple sketch of target symbols as shown in Fig. 1.2.

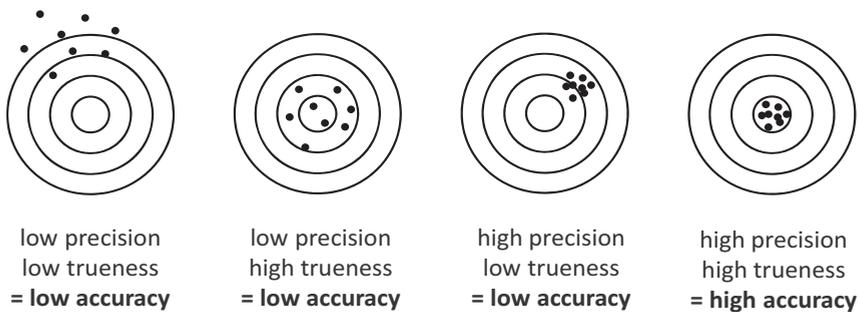


Fig. 1.2. Sensor/measurement accuracy as a function of precision and trueness. Note, that the center of the rings defines the real value.

Any measurement can only be accurate if it is precise *and* true. Looking at the given accuracy of a sensor/measuring system on one hand and the required accuracy for the study, the decision for high accuracy with high costs and low accuracy with low cost must be balanced carefully. In extreme cases, the instrumentation is unable to provide the information required and the success of the whole study might be affected by poor sensor instrumentation.

1.4. Sensor installation

Most of the chapters describing the sensors/devices/samplers provide links and procedures for the correct installation of the respective sensors. Nevertheless, some generally applicable remarks for the installation will be provided here.

1.4.1. Spatial resolution

1.4.1.1. Installation at a specific depth

Sensor or system installation at different depths often follows a classical scheme, where the sensors are equally distributed over a depth range (e.g., 30, 60, 90, 120 cm). Generally, most soil states unfortunately do not vary linearly with time and depth and most of variation in the soil states are often observed close to dynamic boundaries. These boundaries are the atmosphere with dynamic changes between precipitation and evapotranspiration but can also be dynamic water table fluctuations at greater depths. A sketch of the dynamic behavior with time is provided in Fig. 1.3 where soil state dynamics are depicted as a system response to atmospheric forcing (here atmospheric temperature changes).

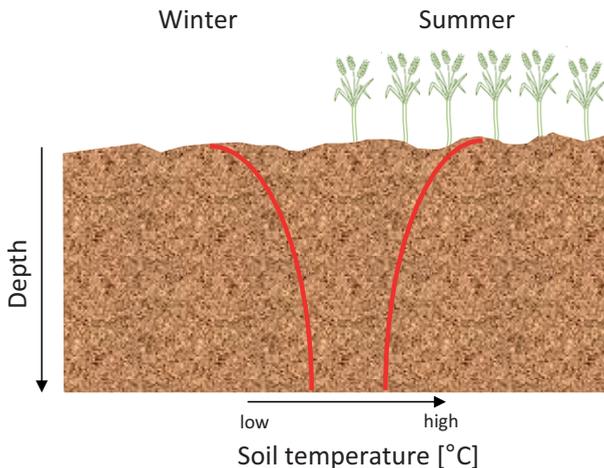


Fig. 1.3. Typical distribution of state values and dynamics over depth for two different situations. Here, soil temperature profile in winter and summer. The strongest gradients are observed at the soil/atmosphere interface and decrease with soil depth.

As can be exemplarily seen from the sketch in Fig. 1.3, the soil temperature distribution over depth varies extremely close to the surface between seasons and shows less difference at greater depth. Due to the direct control exerted on soil temperature by the atmosphere, other states behave similarly, e.g. soil water content/soil matric potential in a dry period and after a long rainfall period. Consequently, the top soil layer responds more dynamically and directly than do deeper zones and also shows the largest range of readings under such conditions. To monitor this general behavior properly, the sensor spacing should be denser close to the soil surface and at greater distances in deeper zones. Therefore, good experiences were made with non-uniform

installation depths (e.g., 5, 10, 20, 40, and 80 cm or 15, 30, 60, and 120 cm. In these cases, the installation depth of the topmost sensor (e.g., 5 cm) is always multiplied by 2: $a(n) = 5 \text{ cm} * 2^{(n - 1)}$, where a = installation depth (cm) and n = number of steps. It has to be noted, that these depths are only a generalized suggestion and actual installation depths *should be always adapted to local site conditions and the experimental question*. For some sensors (e.g., soil water content sensors) the presence of soil horizons within the soil profile has to be also taken into account because sensor installation at the interfaces between soil horizons will influence measured data and later cause serious problems interpreting the data so collected.

1.4.1.2. Installation of sensors in space

1.4.1.2.1. Arrangement of replicates

As Ghodrati & Jury (1990) pointed out, diverse arrangements of instruments may lead to very different interpretations of the state distribution, and thus affect the interpretation of the processes. Hence, some attention must be devoted to the spatial arrangement of the sensors in the experimental setup. If, for example, three instruments of the same type are going to be installed at a given depth as replicates, it should be avoided that all devices for one depth are clustered and the cluster at the next depth level is at close distance (see Fig. 1.4).

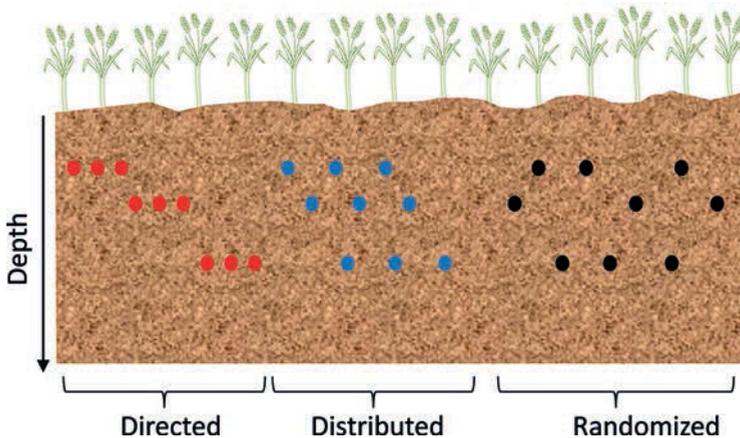


Fig. 1.4. Possible arrangements of 9 sensors with 3 replicates in 3 installation depths.

In soils where soil properties change greatly at short horizontal distances (e.g., changes in horizon depths, surface structures such as tractor tracks) the directed sensor pattern may result in different mean values for each sampling depth compared to values obtained by using a distributed or the randomized installation pattern (Fig. 1.4). In extreme cases, the directed pattern may lead to false conclusions. Additionally, soil heterogeneity, mutual influence, and other factors must be considered in order to avoid systematic errors caused by sensors and by the installation procedure of the sampling devices in the field. A randomly distributed sensor- or sampling system was described e.g. by Wessel-Bothe (2002) who used such experimental design to study the migration of solutes through the soil.

Generally, if sensors are to be installed at different depths, sensors or sampling systems should never be installed below each other to rule out shading effects. Additionally, the use of some

sampling systems (e.g., soil water extraction systems) will invariably influence the natural water and solute flow locally. For this reason, sensors should always be placed at a certain distance from each other in order to avoid artifacts by neighboring instruments.

1.4.1.2.2. Installation from the surface or from a profile wall?

After a decision has been made with respect to distribution of sensors or sampling devices with depth and in space for a particular site, it must be decided *how* the devices will be installed in the field. In general, there are two different options: i) installation from the soil surface or ii) installation from a pit or trench. Irrespective of the installation method of choice (from the surface or from a pit/trench), any hydrological shortcuts have to be avoided. As mentioned, different ways of sensor/sampling device installation procedures are feasible.

A) Diagonal sensor installation from the surface

The instrument is installed from the soil surface at a given angle, e.g. 45°, to avoid direct flow of precipitation along the shaft to the measuring- or sampling tip of the device. It has to be noted, that surface installation is always prone to the risk of hydraulic shortcuts in dry soils (with a potential to shrink) or if the diameter of the borehole for sensor installation is larger than the sensor shaft itself. To install the sensor, the borehole is deepened at a constant angle, whereby the desired length of the installation borehole must be calculated trigonometrically and depends on the angle and the desired installation depth: $L = D/\sin \alpha$, where L = length of the installation borehole, D = desired depth of installation and α is the angle of the installation tool relative to the soil surface. For example, if the desired installation depth is 50 cm below surface and the installation angle is 45°, the borehole must have a length of ~71 cm.

B) Installation from a soil pit or trench

Many scientists prefer the installation of sensors/devices from a profile pit or trench to avoid the risk of hydraulic shortcuts by vertical installation. Another advantage of the horizontal installation from a pit/trench is that the sensors/sampling systems do only provide measurements from one horizontal depth. This holds especially for water content sensors, which classically integrate their measurement over a specific sensor length (see chapter 4).

Whenever horizontal installation of sensors is carried out, the influence on the state variables in the undisturbed soil profile from the soil pit/trench must be considered, even if the pit/trench is backfilled after installation. The reason for this is that the native soil structure of the excavated soil material is destroyed by the excavation process, homogenizing the excavated material. This invariably causes differences in soil physicochemical properties and water, solute, air, as well as thermal fluxes. These modifications will not only change the soil state parameters within the backfilled soil but also in the adjacent natural soil to which it is connected lateral by (e.g., hydraulic) exchange and other processes. Consequently, sensors/sampling systems installed from a pit/trench should be installed in the native soil at a certain distance (classically 30 cm are recommended) from the pit/trench wall in order to minimize their influence on the measurements.

That an insufficiently compacted pit/trench will begin to settle and compact naturally over time due to the overburden and changes in water content is obvious and must be another concern. Compaction has the effect that a constant, natural bulk density and soil structure is only reached after several months to even years. Because the installed instruments are installed within the static natural soil (the trench wall) and cable and tubes are run through the backfilled soil material, compaction of the refill may cause stress (pull) on the cables/tubes. In the worst case, this stress may propagate to the sensor/sampling device and may cause the loss of contact of the sensor/sampling device and the native soil surrounding it and cause instrument malfunction or failure.

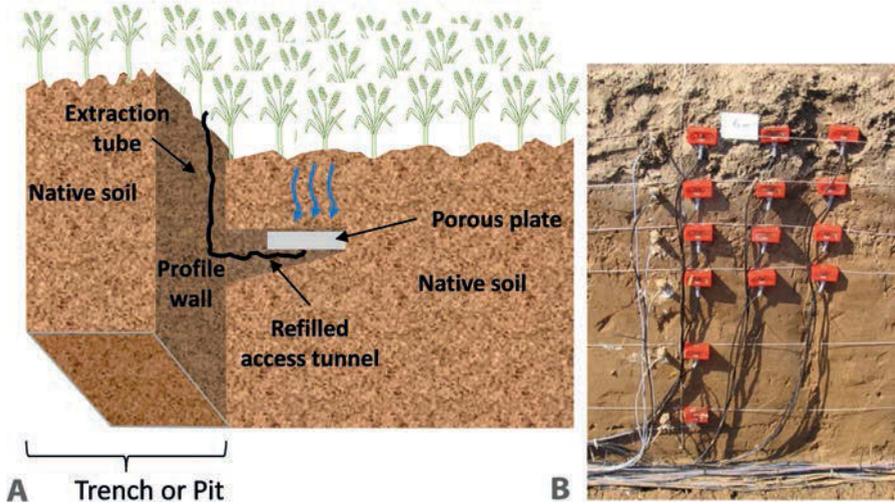


Fig. 1.5. Installation of instruments from a profile pit. A) schematic sketch of the installation of a porous suction plate and b) photo of installed suction cups, tensiometers, and TDR-sensors (photo: Lutz Weihermüller).

To reduce the buildup of such stresses, such pits/trenches should be backfilled layer by layer (with a layer thicknesses of 10–15 cm each) and each layer should be compacted manually or by appropriate machines. Ideally, the soils from different horizons should be separated while the pit/trench is being dug and refilled according to its natural stratigraphy. During refilling, care must be taken not to disturb exposed cables and tubes. To this end, it may be very useful to fix cables and tubes to the profile wall with e.g., tent pegs.

C) Installation of sensors without shaft from the surface and refilling the borehole

Some devices have no extensions or shafts, so only power supply and data transfer cables or vacuum and extraction tubes must be run from the instrument to the surface. In these cases, the borehole above the sensor should be filled with slurry made of the parent material dug out for installation. The risk of causing hydrological shortcuts may be avoided by thoroughly filling the borehole partly or completely with bentonite pellets or a mixture of bentonite and soil slurry. In the latter case, it has to be made sure that the bentonite does not affect local water contents to such an extent that the bentonite influences the measurements (e.g., water content).

As bentonite will shrink under very dry conditions, this is however only working under the condition that the soil water content remains above a minimum which prevents the formation of cracks and thus hydraulic short cuts. As Wessel-Bothe (2002) showed, the breakthrough of solutes over a period of 22 months was not significantly affected by the vertical installation of shaftless suction cups even if the boreholes were completely filled with parent soil material and without bentonite.

1.5. Arrangement of enclosures, cabinets, housings etc.

All sensors require dedicated data loggers and power supplies and to operate water extraction systems, sampling bottles and vacuum pumps must be installed also. In most cases, these peripheral devices are located in enclosures, housings, or cabinets to protect sensible electrical

parts and sampling bottles from precipitation, light, and/or temperature. The enclosures, cabinets, or housings will shadow the rain in direct vicinity, on the one hand, and cause local preferential infiltration paths where the water runs off the enclosure, housing, or cabinet. Therefore, these above-ground components should be set up as far away as possible from the buried sensors. On the other hand, the distance between the sensors/devices and the loggers, power supply, pumps, or sampling bottles should be kept as short as possible in order to reduce the risk of damage (e.g., by animals, machines) and dead volume (for water extraction devices). In some cases, long cables may unduly attenuate the measurement signal, especially weak analog signals.

After the instruments are installed, avoid any artificial disturbance of the measurement plot e.g. by treading on it or vehicular traffic.

1.6. Post-processing of acquired data

After the measurements were performed, appropriate data post-processing must follow. For detailed information about appropriate statistical analysis we refer to the respective literature (e.g., Sokal and Rohlf 2012) and here, we only restrict our recommendation to two major often observed problems.

1.6.1. Calculating mean concentrations from multiple, measured concentrations

All solute extraction devices (see chapter 6) produce two types of data, namely the volume of extracted soil pore water and the concentration of the target substance in it. If more than one sampler in one location (e.g., at different depths) was installed, a mean concentration is often calculated from the samplers as the first step of data post-processing. Due to differences in the amount of soil pore water extracted by each individual sampler device, the mean of all samples cannot directly be calculated from the different measured concentrations. Instead, the solute masses and water amounts of each single measurement should be summed up, and from those sums the bulk or mean concentration should be calculated. Alternatively, the replicate samples of a given depth level may all be lumped together and the concentration of this sample will provide the mean concentration. This procedure of course precludes the determination of a standard deviation at this given depth level from the corresponding device data and is unable to supply information on the variation of concentrations at that depth level.

1.6.2. Calculating mean pF and pH-values from replicate measurements

Because matric potential and proton (H^+) concentrations are classically expressed in logarithmic form (pF and pH-value), the calculation of mean values is not straight forward. Calculating the mean value of measured pF and pH values might cause wrong mean values. Therefore, the data have to be converted to absolute (e.g., H^+ -)concentrations, from which a mean can then be computed. Finally, the mean pF and the mean pH values may be calculated from the mean of the absolute values.

1.7. Concluding remarks

The authors did not intend to be complete in listing and describing all existing sensor types and measurement techniques. Moreover, the most accepted sensors/measurement techniques will be described and discussed. Also some novel sensors/measurement systems are associated to brand names and sensors of similar type are also often available and can be used instead.

1.8. References

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Soil physicochemical parameters

2. Soil redox potential

T. Mansfeldt

2.1. Introduction

2.1.1. Objectives of redox potential measurements in soils

During oxidation and reduction reactions, electrons are transferred from one chemical element (in its elemental form, as ion or molecule) to another element. Because free electrons do not exist in chemical reactions, oxidation, i.e. the loss (donation) of an electron, and reduction, i.e. the gain (acceptance) of an electron, are always coupled. By the transfer of electrons, energy is additionally transferred which is the energy of life. Hence, reduction–oxidation (redox) reactions support the life on Earth, even in soils.

The most important source of electrons in soils is reduced carbon (C) occurring in the soil organic matter (SOM) pool. By photosynthesis, tetravalent oxidized C in carbon dioxide (in CO₂, C has an oxidation state of +IV) is reduced to organic C species (with an oxidation state of 0) and plant biomass is formed (Eq. 2.1):



The SOM pool is continuously replenished by inputs of dead plant and animal residues and can be considered a large electron reservoir (electron donor). Metabolizing plant roots and microorganisms are able to oxidize the reduced C forms enzymatically. Electrons released during the oxidation of C are transferred to elemental oxygen (which occurs as oxygen gas O₂) which, in turn, is reduced to water (H₂O). Hence, O₂ is the terminal electron acceptor. Soil redox conditions under which O₂ is stable and hence available are called *oxidizing*, and characterized by low electron availability. The O₂ pool of soils is continuously replenished by O₂ diffusion through soil pores, as long as they are filled with air. When filled with water (caused by high ground water levels, perched water table, natural or artificial flooding), O₂ diffusion is extremely slow and depending on metabolic activity, the soil O₂ pool is more or less rapidly exhausted. Soil redox conditions under which O₂ partial pressure is low or O₂ is absent are called *reducing*, and are characterized by high electron availability. Under reducing soil conditions, elements other than O are the terminal electron acceptors. These include pentavalent nitrogen (N^V) in nitrate (NO₃⁻), tri- and tetravalent manganese (Mn^{III, IV}) in Mn oxides (e.g., birnessite, δ-MnO₂), trivalent iron (Fe^{III}) in Fe oxides (e.g., goethite, α-FeOOH), hexavalent sulfur (S^{VI}) in sulfate (SO₄²⁻) and tetravalent C in CO₂. Although, some overlap may occur, the use of the different electron acceptors is a stepwise one and known as the sequential reduction sequence (Ottow 2011, Ponnamperuma 1972).

Redox conditions of soils are classically assessed by measuring the redox potential, which is abbreviated either as Eh or E_H. The letter E denotes the electrode potential and h/H represents the

element hydrogen (H). As symbols of chemical elements are generally capitalized, the abbreviation E_H is used here. Sometimes the abbreviation ORP (Oxidation–Reduction Potential) is used.

According to the preferential electron acceptor, a more precise classification of the soil redox status (at pH 7) can be defined (Reddy and DeLaune 2008, Zhi-Guang 1985): *oxidizing* conditions prevail where the E_H is > 300 mV and O_2 is predominant; *weakly reducing* conditions occur where E_H ranges from 300 to 100 mV and NO_3^- and $Mn^{III,IV}$ are reduced; *moderately reducing* conditions are where E_H ranges from 100 to -100 mV and Fe^{III} is reduced; under *strongly reducing* conditions SO_4^{2-} and CO_2 are reduced and the corresponding E_H is < -100 mV. Figure 2.1 illustrates this sequential reduction sequence. It is worth noting that some redox species change aggregate state during the electron transfer, e.g., from an aqueous species (NO_3^-) to a gas (N_2).

Although, subject to some limitations, redox conditions may be assessed by measuring the soil redox potential with a platinum (Pt) electrode. The assessment of the soil redox potential is particularly useful to characterize the onset of reducing condition in soils caused by a lack of O_2

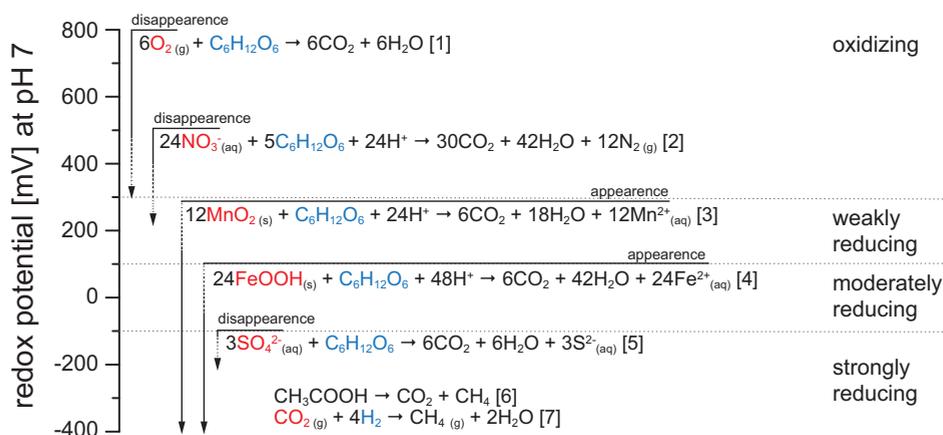


Fig. 2.1. The idealized sequential reduction sequence in waterlogged soils and a classification of redox zones. The primary electron donor (denoted in blue) is the soil organic matter, which is designated for simplicity by the glucose molecule. The different terminal electron acceptors are denoted in red. Note that there are no sharp boundaries for the redox processes but some overlaps. Aggregate states are aqueous (aq), gaseous (g), and solid (s).

and associated biogeochemical processes such as denitrification and redoximorphosis (creation of distinctive soil color pattern). Some detailed examples will be given in section 3.5.2 and important restrictions for the interpretation of measured redox potentials in section 3.5.3.

2.1.2. Fundamentals of redox reactions

In the following section, the theoretical background of the redox potential and the role of protons in redox reactions will be outlined. For a more in-depth discussion of these issues, the reader is referred to textbooks, e.g., Essington (2015) and Strawn et al. (2015).

The theory behind redox potential can be derived by considering the general redox half reaction (in this case the reducing reaction)

