Soil sampling (disturbed and undisturbed), handling and storage for soil chemical, biological and physical properties

SOP ID: 003
Version: 1
Crop: All crops
Relevant KPIs: Soil health — soil carbon; Resource use efficiency — nutrient use efficiency
R&D stage (example of activities):

- Discovery stage (yield gap decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trials)

Required equipment

- Soil auger
- Scoop to recover soil from auger
- Soil sampling cylinders with lids (bulk density rings or soil cores)
- Spatula (narrow)
- Spatula or knife (wide)
- Containers or suitcases
- Containers, such as buckets or bowls
- Mallet or nylon hammer
- Pulling device
- Sample bags for disturbed samples
- Sealable sample containers for disturbed samples for water content determination
- Masking tape and marker
- Measurement tape or ruler (at least 30 cm).

Background

To describe soil quality, soil health or soil fertility, soil properties such as carbon content, pH, texture (sand, silt and clay content) and others, including biological variables, are required. Changes in soil properties need to be monitored as they may indicate changes in the soil's ability to support crop growth and the provision of environmental services. Soil is a heterogeneous medium, which is exposed to natural processes (rainfall, wind, flooding, drying) and human interference through agronomic management. Some soil properties may change rapidly in response to tillage, fertilizer application, irrigation and other practices, while others are relatively resilient and change slowly, depending on the type of intervention. In turn, these properties affect crops' responses to any agronomic management (e.g. fertilizer application, tillage, irrigation, planting density and weed control) and crops' responses to natural phenomena such as rainfall, storm, drought and extreme temperatures. Thus, correct sampling of soil is a key requirement for monitoring changes in soil properties, enabling assessment of the impact of agronomic practices on the environment, on crop responses and on the soil quality and health.

The soil sampling approach and methodology, the sample handling and the following analyses depend on the objectives of the research.

Module 1: Determining the type of soil sample to be taken

There are two major types of soil samples: disturbed and undisturbed. Certain analyses, such as bulk density (BD), aggregate stability and moisture retention at specified water tensions (pF characteristics), require undisturbed samples. Undisturbed soil samples are usually taken with sampling cylinders or metal rings. These can be of different diameters and lengths to obtain the required soil volume and the required soil layer depth. For example, standard bulk density rings are 5 cm in diameter and 5 cm long with a volume of 100 cm^3. Such samples are usually transported in special suitcases so the natural layering and soil particle arrangement are not altered before the sample reaches the laboratory.

Disturbed samples are all those that are taken by an auger and scooped from the auger. Due to the forces working on the soil while hammering the auger into the soil and when scooping the soil from the auger we cannot assume the soil remains in its natural arrangement. Samples taken with augers are suitable for determining chemical properties and some physical properties, such as particle size distribution (texture) or physical separation of organic matter (OM) fractions. They may also be suitable to determine certain biological properties, mainly the microbial biomass or composition or potential microbial activities (e.g. potential carbon [C] and nitrogen [N] mineralization rates).

Module 2: Choosing the appropriate time to sample soil

The determination of nutrient and C stocks is based on the simple calculation of concentration multiplied by the bulk density and the depth of the sampled soil layer. It is important to consider the best time to sample the soil to avoid artificial and erroneous results due to changes in the bulk density of the soil caused by tillage or compaction. See Module 10: Considerations when comparing soil properties over time.

Depending on the objectives of the trial, especially in long-term experiments in which the soil properties are to be monitored over time, it is important to define the best time to take the samples. In long-term trials, especially when different tillage options are being compared or carbon stocks in tilled soil are being compared over time, it is best to sample the soil shortly *before* the tillage operations, because tillage will temporarily reduce the bulk density and increase the heterogeneity of the bulk density, especially in clay-rich soils, and this has a strong impact on the soil mass sampled for a specific depth.

If the short-term effects of tillage operations on specific soil physical properties are an objective then pre- and post-tillage sampling are required. Soil sampling after ridging or mounding operations will produce highly unreliable data as the origin of the soil in the sample is no longer related to the natural layering of the soil. In ridged or mounded soil, there is no position that would reflect the previous soil layering.

An exception (but not recommended) is sampling soil on regularly plowed and harrowed soils on which the topsoil has been ‘homogenized’. In such situations, soil sampling post-tillage can be accepted, as long as the data are not used to compare soil properties over time. Results of the chemical analysis would only be reliable for the concentrations of carbon and nutrients; however, due to changes in the bulk density, even the calculation of nutrient and carbon stocks will be prone to error (see Module 10).

Module 3: Choosing the appropriate equipment to sample soil

Soil can be sampled with a wide range of tools, yet to ensure that the sample taken relates correctly to the natural layering and depth of the soil segment that the sample must represent, it is recommended to use professional equipment such as soil augers and soil core samplers.

Although recommended for large-scale sampling exercises, we do not recommend using spades or shovels to sample soil because with these tools it is difficult, if not impossible, to recover equivalent soil masses throughout the intended sampling depth.

For disturbed samples (mainly for soil chemistry) it is recommended to use straight soil augers of the Pürckhauer type (Fig. 1).

Figure 1. Left: Different types of Pürckhauer soil augers:
Large-diameter auger with fixed head (left); auger with detachable head (middle); small-diameter auger (right)
Note the cross bar is removed when hammering the auger into the soil.

Below: Typical tips of Pürckhauer soil augers.

To sample soil from shallow layers (to about 50 cm depth), simple small-diameter augers can be used. They are usually single-piece steel pipes with either exchangeable closed tips or fixed closed or open tips. These usually have a fixed handlebar (Fig. 2). They are not suitable for hammering into the soil (with a mallet or hammer), but should be pushed into the soil by the weight of the person sampling. There are two types of tips: one is open from the tip to the upper end of the auger; the other is closed at the tip but opens a few centimeters above it. Augers with a closed tip may have exchangeable tips, and thus are recommended for use in abrasive soils, where tips will wear and need to be replaced.

Figure 2. Left: Soil auger with an open tip. Right: Soil auger with closed tip. Both with a fixed handlebar to push the auger manually into the soil

In soils with a high clay content and with gravel layers or a high stone content or to sample to layers to 90 cm depth, the standard 20 mm inner diameter Pürckhauer soil auger should be used. This auger has a sampling opening of up to 90 cm length and an auger head of a greater diameter with a perpendicular hole to insert a handlebar. This auger needs to be hammered into the soil with a mallet or nylon hammer (Fig. 3). Avoid using metal hammers as these will deform the auger head and potentially deform the hole for the handlebar (making it difficult or impossible to recover the auger from the soil).

Figure 3. Nylon hammer with detachable nylon insets

Note: The cross bar handle inserted through the head of the auger should be removed while hammering the auger into the soil. Accidentally hitting the cross bar would cause damage to auger and handle.

This type of auger is available with different diameters of the sampling tool: some are relatively wide open (close to 50% of the circumference) others are more closed (Fig. 4).

To sample beyond 90 cm depth, it is necessary to use augers with detachable heads and threaded bolts connecting the auger with an extension rod. This approach is risky in soils with stone layers and hard pans because the auger may get stuck or break. An additional problem is the risk of contaminating the sample with soil from upper layers when pulling the auger to the surface. It is advisable to create a wider hole from the surface to the start of the deeper layer with an Edelmann or bucket auger (Fig. 5) and to insert the Pürckhauer type auger through this larger hole to, for example, 90 cm depth and then take a sample from 90 cm to a maximum of 180 cm by inserting an extension rod.

Figure 4. Examples of detachable augers with different diameters and openings

If professional augers are not available, augers can be fabricated from steel pipes. However, the insertion depth will be limited due to the material not being strong enough to withstand the hammering to deeper layers and twisting to remove the auger. Nevertheless, to sample shallow layers to about 50 cm depth (depending on the soil's hardness and obstacles such as stone layers or hard pans), it is often less time consuming and less cost intensive to fabricate augers locally from available steel pipes.

If none of the straight Pürckhauer or self-made pipe-type augers is available, the Edelmann auger type can be used (Fig. 5). Note, however, that the tip displaces material when entering the soil and that the auger is limited in sampling depth to the straight length of the borer (length of the red arrow in Fig. 5). If you prefer to sample the entire required soil depth with one insertion, the Pürckhauer type is best suited.

Figure 5. Detachable tip of an Edelmann auger

The effective sampling depth is the distance between the end of the merged tip and the beginning of the semicircle top (red arrow).

Only if no soil augers are available is the use of a spade permitted.

To collect undisturbed soil samples, you need either soil sampling cylinders (soil cores or rings; Fig. 6) or special, usually large-diameter, augers with internal linings. Undisturbed soil samples are usually kept in the sampling tool such as the cylinders and they are carried in special suitcases (Fig. 6) to the laboratory, so they are not disturbed during transport. However, for certain parameters the soil can be removed into other containers, depending on the type of analysis to be conducted.

Figure 6. Left: Steel soil core samplers of different dimensions with a sharpened edge to cut into the soil. Right: padded suitcase to transport soil cores, blue lids for the cores and a sampling tool (front) into which cores are inserted and pushed into the soil

Module 4: Determining an appropriate number and distribution of samples

Soil samples being analyzed for any property are usually composed of a number of samples from the same unit and depth layer and mixed to reflect the unit from where the sample is originating. Thus, a sample consists of 'subsamples' from different spots in the sampled unit. These spots will be called sampling spots or insertion points (the place where an auger is inserted to take a subsample). Generally, soil samples submitted for analysis should not

be from a single insertion but should be composite samples obtained by carefully mixing multiple subsamples or insertions (Table 1). This is to ensure representativeness of the sample to cover spatial variation within a plot. However, there may be exceptions where small-scale high-resolution data are required, and single insertion samples are appropriate. The number of separate subsamples to be taken in a plot, a replicate (block) or across an entire field, thus depends on the type of research and the objectives of the trial. Although it is impossible to exclude an impact of the soil properties on crop responses, some research objectives might not require high-resolution data on the soil properties. In such cases it is sufficient to sample the entire trial area and combine all individual samples into one composite sample for analysis. However, this should be regarded as an exception and still requires taking several subsamples (insertions) across the field. It is recommended to at least sample soil by block or by repetition. This would enable relating differences in crop responses between blocks to soil properties. For trials dealing with nutrient supply, such as fertilizer application, mulching, addition of manure, compost or biochar, or when any other form of amendment is applied that should or could alter nutrient supply or nutrient use efficiency, then it is advisable to take several subsamples and combine them by treatment plot.

Table 1. Side length of square-shaped plots, according to surface areas and minimum number of soil subsamples (insertions) to be taken in plots, blocks or fields of different surface areas

Side length of a square-shaped plot or field (m)	Surface area of the plot or field (m^2)	No. insertions per unit area
2–2.5	4–6.25	2–3
> 2.5–7	> 6.25–49	4
> 7–12	> 49–144	5
> 12–21	> 144–441	6–9
> 21–100	> 441–10,000	10–16

The number of subsamples (insertions with the auger) to be taken, whether it is per field, per block or per plot, depends on the area of these units and on any available information on soil spatial heterogeneity. Plots should of course be placed such that soil spatial heterogeneity is negligible, for example by appropriate blocking. If heterogeneity is observed within replicates, then the sampling unit should be the plot. Ideally, blocks or replicates should be placed such that soil spatial heterogeneity is small. If it is not possible to avoid a gradient of soil properties within the sampling unit, then we propose to sample the areas of different properties separately and label the samples accordingly, yet to use a subsample distribution that does not bias toward any of the areas. An example is in Figure 9: the upper line of samples should be labeled to distinguish them from the samples of the two lines in the middle, and the lower-line samples should be labeled to distinguish them from all others. If soil properties are deemed important then the soil may need to be analyzed according to the gradient in the field, i.e. the samples from the upper versus the samples from the two middle lines and the samples from the lower line.

We recommend that the minimum number of subsamples (insertions) to be taken for one composite sample be determined by the plot, block or field size as shown in Table 1. However, these numbers can be increased according to the objectives of the sampling and when it is known there is high spatial variability in soil properties that could affect the reliability of the results of any analyses.

The distribution of the sampling spots or the insertion points of the augers follows the approach of the Soils4Africa project. For small plots, Huising *et al.* (2021) recommend distributing the insertion points in the centres of four sub-squares of half the side length of the entire plot (Fig. 7C). In smaller plots of up to 6.25 m^2 (Table 1) only two or three insertions are required. If two insertions are taken, they are in the centre of the diagonally opposite sub-squares of

the plot (Fig. 7A). If three insertions are considered required (Fig. 7B), it is proposed to create a circle that has a radius which is about 75% of half the length of the side length of the square or:

$$r = a \times 0.5 \times 0.75 \quad (1)$$

where r is the radius and a the side length of the square.

The sampling spots would then form an equilateral triangle. In plots of 6.25 to 49 m^2, or side length of 2.5 to 7 m, if square-shaped, soil is collected at four insertion points. The four soil samples are taken in the centre of the four sub-squares (Fig. 7C). In other words, the sampling points are configured like the four eyes on a die. For plots with a surface area of 49 to 144 m^2, requiring five insertions, it is proposed to add one insertion in the centre of the plot (Fig. 7D). In plots with side length of > 12 m or surface areas > 144 m^2, six to nine insertions should be made, and these are distributed by creating the appropriate number of sub-squares and sampling in the centre of each sub-square (Fig. 7E).

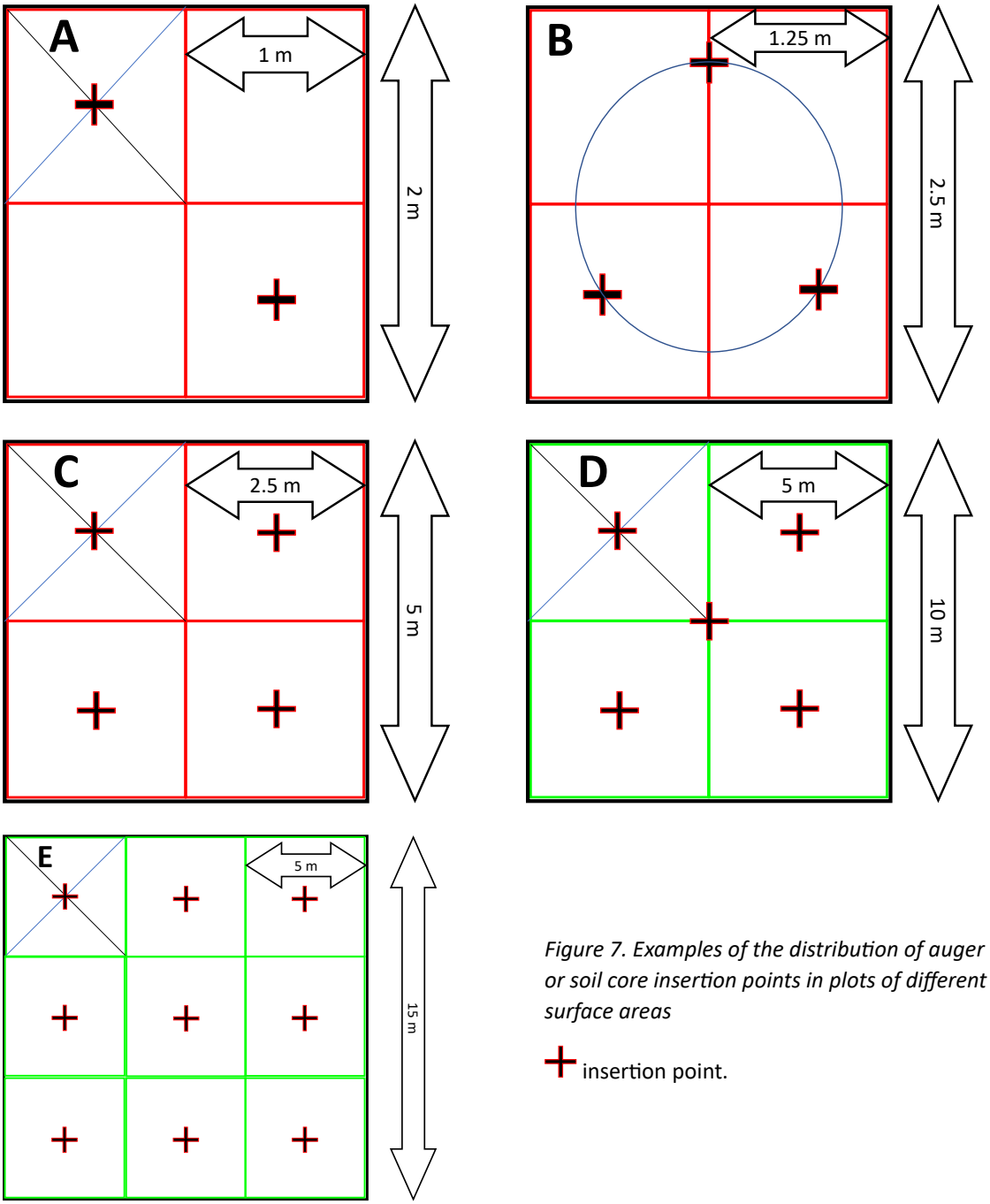

Figure 7. Examples of the distribution of auger or soil core insertion points in plots of different surface areas

+ insertion point.

This sampling spot distribution system shows the principal rule for the minimum number of insertion points. If the research objectives require a greater number of subsamples to be taken, then the resolution is simply increased by creating more sub-squares. If, for example, a 1 ha field is to be sampled, this can be done with 4, 9, 16, 25, 36, 49, etc. sub-squares.

In plots, blocks or fields that are rectangular, the same principle can be applied by dividing each side length by the same divisor to create sub-rectangles (Fig. 8A). However, this approach should only be used up to a side length ratio of 3:2 to avoid heterogeneous insertion point distribution. If the side length ratio is wider than 3:2 and plots are narrow and long, it is advisable to use sub-squares to retain a uniform distribution of sampling spots (Fig. 8B). Note that the example in Fig. 8B is a plot of 144 m^2, and thus should have between six and nine sampling spots. Here the sub-square approach produced 16 sub-squares. Therefore, the sampling spot number was reduced by sampling every other sub-square in each row with a one-position offset distribution, i.e. a zigzag pattern.

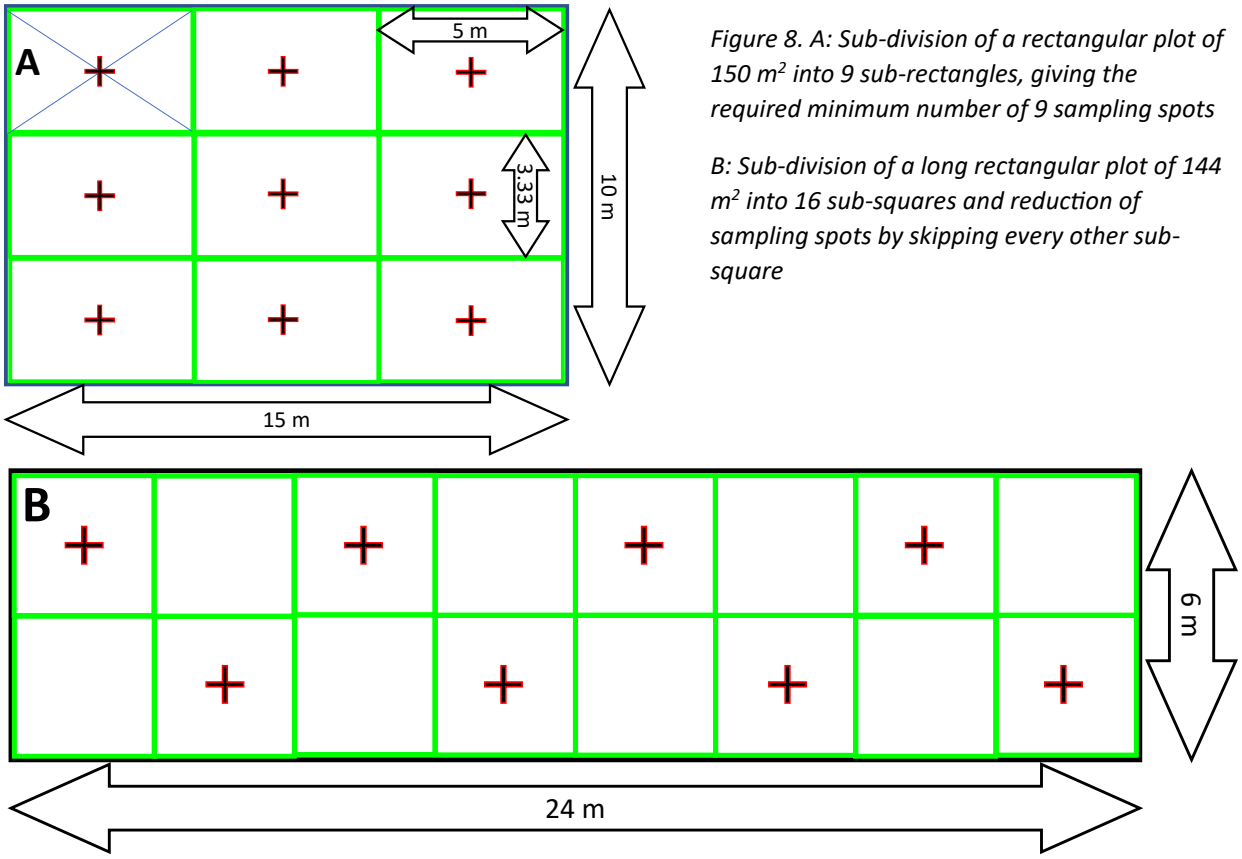

Figure 8. A: Sub-division of a rectangular plot of 150 m^2 into 9 sub-rectangles, giving the required minimum number of 9 sampling spots

B: Sub-division of a long rectangular plot of 144 m^2 into 16 sub-squares and reduction of sampling spots by skipping every other sub-square

When sampling soil in oddly shaped fields (Fig. 9), of which the approximate size and the rough dimensions in two directions are known, it is advised to create a set of parallel lines across the field that would dissect the field into slices of about same 'thickness'. The length of each line would be measured as indicated in Fig. 9 and the total length of the lines calculated: here 110 + 120 + 110 + 80 = 420 m. The total length of all lines is divided by the number of samples you need to take, here 16. The resulting figure here is 26.25 and is used to divide each of the line lengths. This will give 110/26.25 = 4.19; 120/26.25 = 4.57 and 80/26.25 = 3.05. These results are rounded to the nearest full number giving the number of insertion points along each line, i.e. 110 m = 4; 120 m = 5; 80 m = 3. The position of the insertion points along each line should be such that there is the same distance between points within the line and the first insertion from the edge of the field is at about half the distance between points.

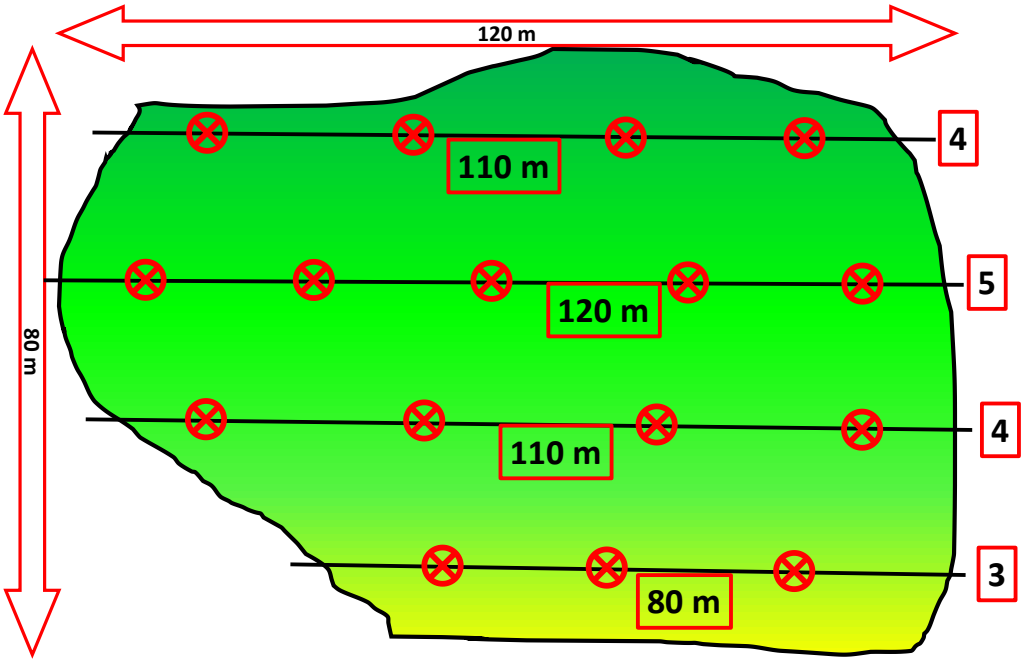

Figure 9. Distribution of 16 soil sampling spots in a field of close to 1 ha using parallel lines and equal distances between sampling spots along the lines

See detailed explanation of the procedure in the text.

For instance, along the 110 m line there are four insertions; thus, 110 / 4 = 27.5 m and half the distance is 13.75 m. The first sample along the 110 m line is taken at 13.75 m (or 14 m) from the edge of the field, the second at 41.5 m, the third at 69 m and the fourth at 96.5 m. Small deviations (< 2 m) from the calculated distances between insertion points are permissible. If an insertion point falls in an area with unusual features not regularly found in the field (e.g. termite mound, old tree root stock, ash or charcoal patch from earlier burning of biomass), the insertion should be shifted away from such areas. However, if such features are frequent in a field then they should be sampled if a sampling spot falls within their area.

Module 5: Soil sample collection — Disturbed samples

All samples are to be labeled with the depth from which they originate. Soil depth is measured from the soil surface, which is defined as the surface of the mineral soil. The litter layer, and any vegetation and vegetation residues are not included, and should be carefully removed before soil samples are taken. In case a crop or natural vegetation is present, the sampling spot should be cleared by cutting the plants at the soil surface without disturbing the soil — do not uproot plants as this will disturb the soil by mixing upper- and lower-layer material and removing soil attached to roots.

This section describes the sampling procedure with three different tools. The sampled depth layers are not specified and should be chosen as required for the trial being sampled.

Soil sample collection using a Pürckhauer type soil auger (Fig. 1 to 4)

1. Clear the soil surface insertion point of litter and vegetation.
2. If the auger has no depth markings, mark out your required depth layers or use the standard 20 cm and 50 cm marks on the outside of the auger.
3. Insert the auger straight into the soil to the required depth by first pressing the auger manually into the soil. Keep the auger vertically straight while pushing to ensure the opening of the auger is filled with soil.

4. Should the soil be too hard to reach the required depth, use a mallet or nylon hammer to reach the required depth. Note: if the auger does not at all penetrate deeper into the soil when hammering it, remove the auger and choose another spot to insert it. Large stones or tree roots will prevent the auger from reaching the required depths and using more force may break or bend the auger.
5. Pass the handlebar through the auger head and turn the auger once around (360 degrees).
6. Pull the auger from the soil — try not to touch the walls of the hole to prevent contamination of lower-layer soil with upper-layer soil.
7. Place the auger on a horizontal or slanted surface. Do not let the tip touch the ground!
8. Remove any excess soil along the length of the auger from the open side of the auger and discard (as this is likely contaminated with soil from different layers).
9. Mark on the soil in the auger the depth layers into which the sample is to be separated.
10. Scoop the soil at the tip of the auger into a container (e.g. bucket or bowl) labeled with the respective depth.
11. Scoop the next layer into a container labeled with the respective depth and continue until the auger is empty.
12. Clean the auger and proceed to the next insertion.

Once all insertions are done and all soil is in the containers for the respective depth layers, the soil in each container is crumbled and thoroughly mixed to be able to take a representative subsample, and a portion of the soil is transferred into a properly labeled sample bag. Ensure the labels cannot be rubbed or wiped off (use masking tape or other porous material to write on). Keep the sample bags in a closed container where they are not exposed to sunlight or heat. The best choice is a simple cooler (cool bag or cool box). It is important to collect enough soil for all analyses to be carried out and remember that a large part of the mass of the sample is water, therefore if the lab requests 500 grams of soil it is safe to carry 800 grams of moist soil.

If the soil is very hard and the auger needs to be hammered even into the upper layers, it is least risky and most labor efficient to sample each depth layer separately by first inserting the auger to the top layer's depth and removing the sample. Then re-insert the auger into the same hole and hammer it to the depth of the next layer, remove and empty the auger. Continue until all layers are sampled. In this situation, soil from the upper layers will fall into the hole and form the top of the sample of the next layer. You need to control the sample from the subtending layer, i.e. the sample from the next lower soil layer, for such contamination and remove soil that has fallen into the hole from the preceding sample. This should be easy if the topsoil has a different color from the deeper layers. To minimize the risk of sample contamination, it is recommended to take the sample across all layers in a single insertion, if the hardness of the soil allows.

Sample collection using an Edelmann type bucket auger (Fig. 5)

1. Clear the soil surface of litter and vegetation at the insertion point.
2. Put the auger straight down and auger vertically downward by turning the handlebar; prevent the auger from slanting sideways as this will scoop more soil into the inner portion of the auger than it should hold.
3. When the auger has reached the depth that fills it to the top where the semicircle iron starts, remove the auger from the soil and empty the soil into the container labeled with the appropriate soil depth.
4. Re-insert the auger into the same hole and auger the next soil layer.
5. Remove the auger from the hole and empty the soil into the appropriately labeled container.
6. Repeat the procedure until all soil depths have been sampled.

Note: When inserting the Edelmann auger for the second layer and thereafter, it is highly likely that soil from the top will fall into the hole and be on top of the next sampled layer. **Before removing the soil sample from the auger, remove any soil from the surface (topsoil) that fell into the auger hole. This is usually possible if the topsoil has a different color from soil from deeper layers. Alternatively, remove the upper one third part of the soil in the auger and discard it**. This procedure is required for every layer below the topsoil.

The usual sampling depth of an Edelmann type auger is 10 cm; thus you need to insert and auger in 10 cm steps: 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm and so on.

Once all insertions are done and all soil is in the containers for the respective depth layers, the soil in each container is crumbled, thoroughly mixed and poured into a properly labeled sample bag. Keep the samples away from sunlight and heat.

Clean the soil auger before moving to the next sampling location.

Soil sample collection using a spade

To sample soil with a spade, you need to use a spade that has a straight cutting edge and is relatively flat (Fig. 10A). Spades with a curved edge and strongly bent are not suitable for sampling (Fig. 10B).

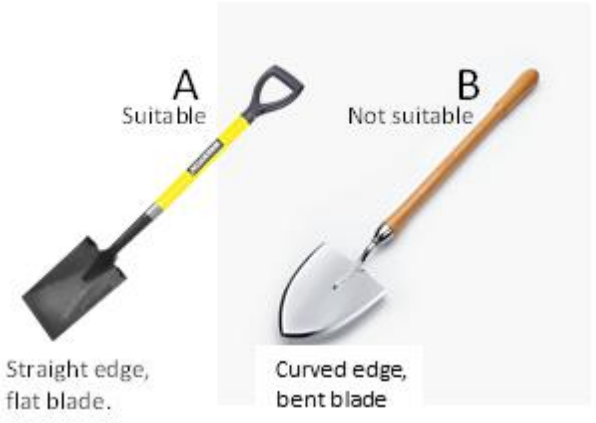

Figure 10. (A) A suitably shaped spade with a straight edge and a flat blade

(B) A spade unsuitable for soil sampling due to the edge being curved and the blade being bent. It is not possible to recover a soil slice of the same thickness and width to the required sampling depth

1. Clear the soil surface of litter and vegetation at the insertion area. Remove all vegetation by cutting it at the soil surface, best done with a sharp knife or cutlass. However, do not ram the cutlass into the soil as this may disturb the surface and lead to soil loss.
2. Dig a V-shaped hole with the spade to the required first sampling depth (Fig. 11A).
3. Remove any soil that fell into the V-shaped hole.
4. Cut a 3 cm thick slice of soil from one side of the V-shaped hole by inserting the spade parallel to the side of the hole (Fig. 11B).
5. Lift the slice of soil from the hole and keep it on the spade.
6. Cut the sides of this slice on the left and the right side of the spade retaining a strip of soil of about 5 cm width in the middle of the spade (Fig. 11C).
7. Check that the thickness of this slice of soil is constant from the top to the bottom of the slice.
8. If the thickness is constant drop the soil into the container with the respective soil depth label.
9. Clean the spade and repeat the procedure in the next sampling spot in the same plot.

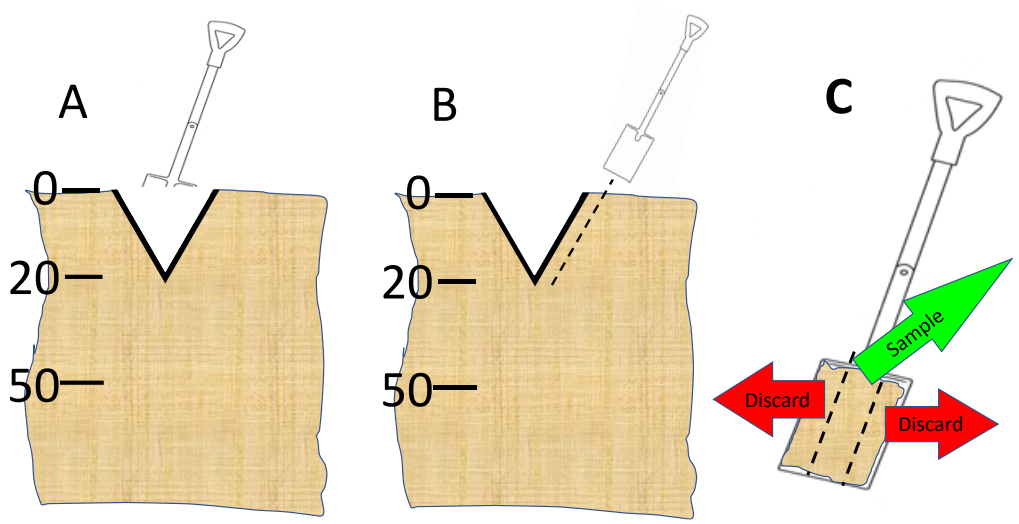

Figure 11. (A) Cutting a V-shaped hole into the soil to 20 cm depth, (B) slicing off a 3 cm thick layer of soil along the wall of the V-shaped hole, (C) cutting off the left and right side of the slice of soil (discard) and the retained portion of the sample (green)

To sample depth layers beyond the length of the spade blade you need to remove the soil from an area large enough to make a V-shaped hole with the spade into the next depth layer. The procedure for the next layer is as above. However, sampling to 50 cm depth is difficult, labor intensive and rather destructive to the plot.

Module 6. Soil sample collection — Undisturbed samples

Undisturbed soil samples are taken with soil cylinders (Fig. 6). The cylinders need to be inserted exactly vertically into the soil if taken from the soil surface. To ensure vertical movement it is recommended that you place a short piece of wood across the top of the cylinder and carefully hammer the cylinder into the soil. To avoid compacting the soil by hammering the cylinder too deep into the soil, the wooden piece should be placed with the narrow side on the cylinder so the depth to which the cylinder is hammered into the soil is visible. Alternatively, a gadget holding the cylinder can be used (Fig. 12, upper right). Such a gadget enables vertical control of insertion due to the long handle and it prevents compaction. However, it is less exact in controlling the insertion depth as the upper edge of the cylinder is not visible. As with the Pürckhauer type augers, it is advised to use a mallet (Fig. 12, lower left). Once the cylinder is flush with the soil surface (be careful not to compact the soil in the ring by hammering more than needed), a hole needs to be dug next to the cylinder, which is best done in a semi-circle around the cylinder to a few centimeters deeper than the insertion depth of the cylinder. To cut the cylinder from the subtending soil push a broad spatula or knife under the cylinder and lift the cylinder from the soil. Cover the top of the cylinder with a lid and turn it over to cut all excess soil exactly along the edge of the cylinder (Fig. 12, lower right) — it may be necessary to cut roots with scissors (do not pull them out!) — then cover with a lid and place it in the transport suitcase (Fig. 6).

Figure 12. Upper left: Soil cylinder being hammered into the soil from the surface with a mallet and a piece of wood to cushion the mallet strikes. Upper right: Soil cylinder set in a gadget with a long handle to insert vertically into the soil. Lower left: Soil cylinder set in a gadget with a short handle and cross bar, hammered into the soil. Lower right: Soil cylinder recovered from the soil and the excess soil being cut off with a knife along the lower edge of the cylinder

If soil cylinder samples are taken for bulk density or for volumetric water content determination, you may choose to take several subsamples and merge them into one larger sample. In this case, the sample may be disturbed but needs to be volumetrically exact. In case the variability of bulk density or water content are the objective of your research, you will need to keep all cylinder samples separately and determine the required variable for each cylinder. If the number of soil cylinders is limited, you can take the soil cylinder sample and remove the soil into a paper bag for drying to determine bulk density. Similarly, soil samples taken for the volumetric water content can be moved from the cylinder into an airtight container that prevents moisture loss until the sample is weighed and placed in the oven.

To sample soil cylinders from layers below the length of the cylinder you need to dig out the soil of the top layer until you have created a plane surface from which you can insert the cylinder to the next layer. This approach usually works for the first 15–20 cm, but destroys a large surface area of the plot. If you need to take cylinder samples of deeper layers (beyond 20 cm depth), it is advised that you first dig a hole to the depth you want to sample and smooth one wall vertically. Insert the cylinders vertically at the required depths (Fig. 13 A to D).

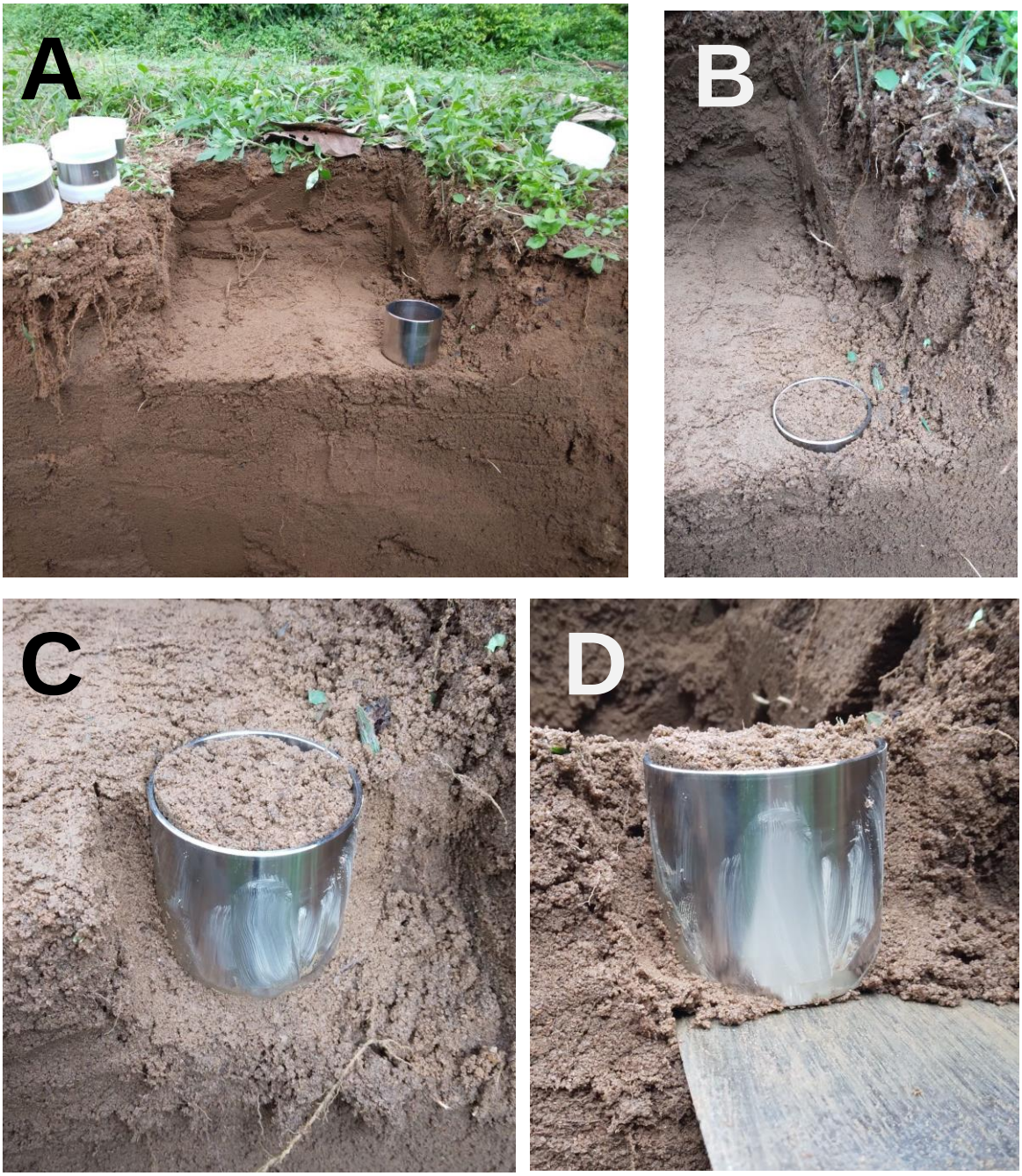

Figure 13. (A) After the top layers are sampled a horizontal surface is established from which the next deeper layer is sampled. (B) The cylinder is pushed into the soil to be flush with the surface of the layer. (C) The cylinder is liberated from surrounding soil and (D) is levered from the soil by pushing a spatula just under the lower end of the cylinder

To recover the cylinders, remove the soil surrounding them on the upper side and then cut with a wide spatula along the end of the cylinder vertically down to detach it from the soil. Repeat this procedure throughout the layers you want to sample (Fig. 14 A and B).

Horizontal insertion of the cylinders (Fig. 15 A to C) should only be done if bulk density or water content are to be determined. For the determination of hydraulic properties, the cylinders need to be inserted vertically to not upset the normal movement of water in the soil.

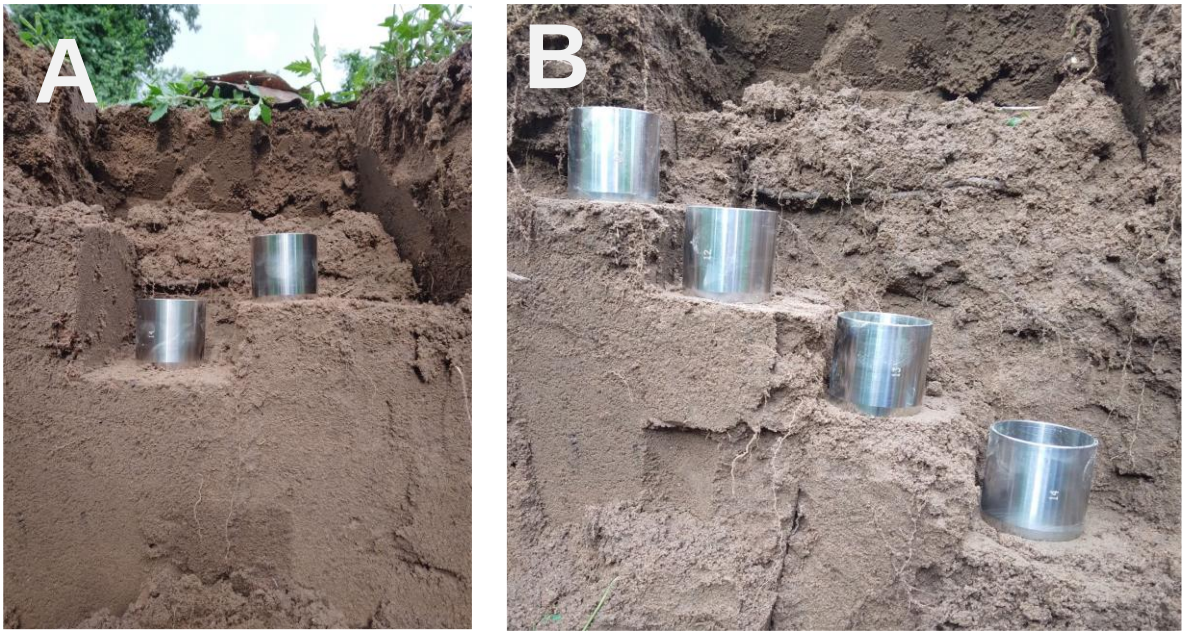

Figure 14. (A) Cylinders set to sample two consecutive layers; (B) cylinders set to sample four consecutive layers. This procedure can be repeated for as many layers as fit into the soil pit

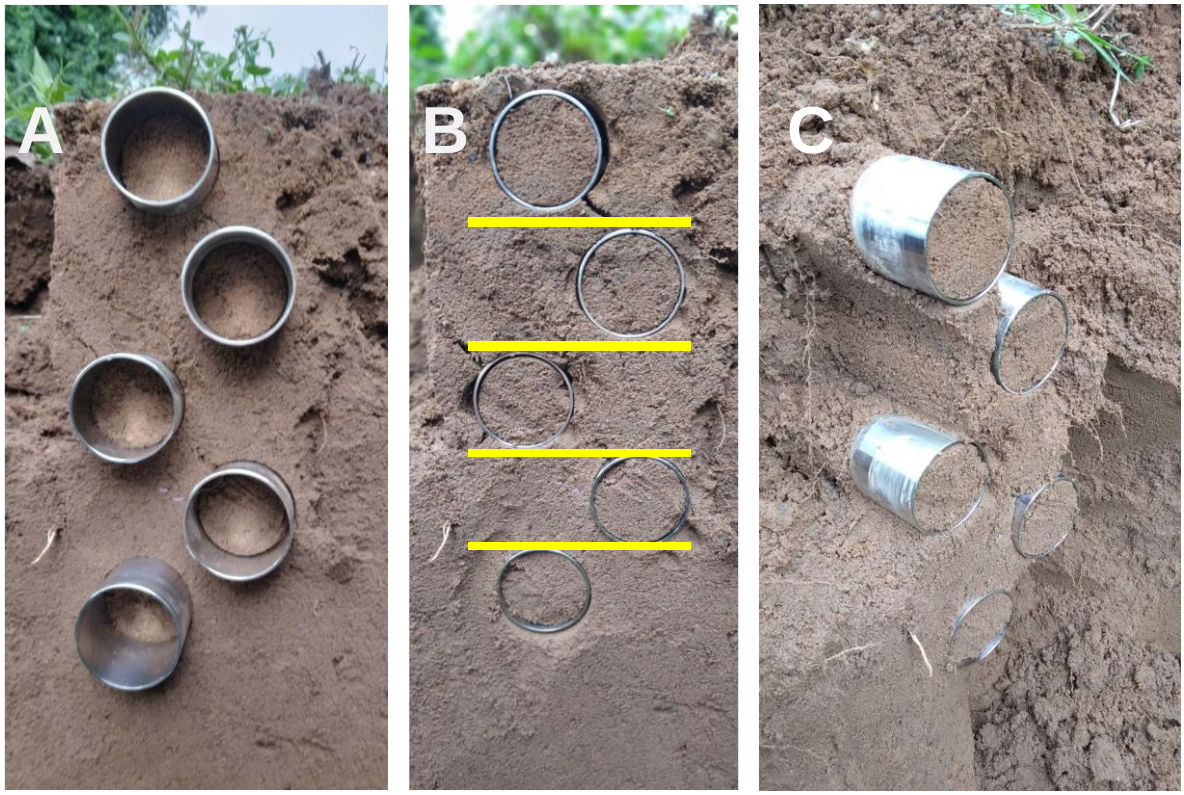

Figure 15. (A) Soil cores inserted horizontally into the wall of a soil pit with about the cylinder diameter depth increment. (B) cylinders fully inserted. It is advisable to mark the depth layers in which the cylinders are to be inserted (yellow lines). (C) To recover the cylinders, liberate the cylinders from the surrounding soil, start from the top to avoid cylinders becoming lose and falling

In soils with a high proportion of stones and especially if the stones are large, such as in excess of the sampling cylinder's diameter, larger cylinders need to be used. A sample taken with a cylinder in which a stone was displaced by being moved or broken by the cylinder edge is no longer an undisturbed sample. To decide whether sampling with

cylinders is appropriate, the stone content and the size of the stones needs to be determined prior to sampling. In soils with highly heterogeneous stone sizes, using cylinders may be inappropriate and another method to recover undisturbed soil may need to be used such as breaking larger fragments from the soil and bedding them in wax or resin to measure hydraulic properties. This SOP does not present the detail of such highly specific sampling procedures.

Module 7: Sample handling

Disturbed soil samples can be placed in a plastic container (bucket, flat bowl) until all subsamples that are to be merged into a composite sample are collected. When all subsamples are in the container, any larger lumps should be crushed to get a more homogeneous mix of the subsamples. Crude materials such as roots, biomass pieces from the soil surface and (accidentally) included meso- and macrofauna (insects, mites, earthworms) or parts thereof need to be removed from the sample. Soil samples should not be kept in plastic bags if they need to be dried and they should not be exposed to sunlight and heat as this may cause rapid changes in some chemical forms of some elements.

For samples that need to be dried without determining soil moisture content, we recommend use of paper bags for the collection and transport to the drying facility. The samples may remain in the paper bags for air- and oven-drying.

Soil samples taken with an auger to determine soil moisture content need to be transferred immediately after collection into an airtight container (ziplock bags or moisture cans with tight lids). They must not be kept in the open while collecting further subsamples. Any airtight containers of metal, glass and specific heat-resistant plastic containers can be used if they can be closed with tight lids. The advantage of collecting into such containers is that they can be weighed fresh, dried and the empty container weighed to get the tare after the drying process is concluded, without the need to transfer the sample. It is, however, important to avoid moisture losses during the field sampling, i.e. the containers need to be shaded and closed, most appropriately in a cool box.

Undisturbed samples taken with soil cores need to be handled with great care. The upper and lower ends of the core need to be covered as soon as the sample is taken from the soil and the excess soil has been removed from the upper and lower openings. Most cores are delivered with lids for both ends (Fig. 6) and these should be used after sampling. If lids are not available, the openings can be covered with aluminum or plastic foil. However, foil will not prevent particles or aggregates moving or detaching from the sample and thus is not suitable if the samples are used for pF characteristics or any soil water dynamics–related determinations. Placing several layers of tape over the plastic foil will reduce the displacement of particles.

Module 8: Sample storage

Ideally, soil samples should not be stored for any longer than necessary. This is especially important for samples collected to determine biological properties. This recommendation also applies to undisturbed samples for the determination of soil physical properties. Remember that the conditions for microbes will change as soon as a cylinder or sample is removed from the soil. Such changes may affect the composition of the microbial community and any related physical properties such as aggregate stability and even the pF characteristics.

Samples taken to determine the volumetric or gravimetric water content should be weighed and dried to constant mass at an appropriate temperature: up to 65°C if chemical analysis is to follow and up to 105°C if only the water content is required. Soil samples to be analyzed for chemical properties should be dried to constant mass at temperatures no higher than 65°C and then stored in airtight containers until processing for analysis. The best option is storage in vacuum containers or bags to minimize the risk of chemical alterations (e.g. oxidation). Generally, soil samples should be kept at low temperature, low humidity and in darkness. It is further advised to store samples in containers that prevent access of insects and rodents.

Module 9: Sample preparation before analysis

The preparation of soil samples for analysis of biological and physical properties depends strongly on the type of analysis to be performed. Sample preparation should follow specific protocols for the required analyses — for example, Anderson and Ingram (1993). Sample preparation for individual analyses cannot be treated here.

Dry soil samples for chemical analysis should be inspected for organic materials such as living roots, charcoal and dead soil fauna (earthworms, insects). These materials should be removed before passing the sample through a 2 mm sieve. Because such materials are rich in carbon, cations and/or nitrogen compared with the mineral soil and because they can break easily and (at least partially) pass through the sieve, their presence in the < 2 mm sample would result in strong bias of the analysis. The remaining soil is gently passed through a 2 mm mesh sieve. Aggregates must be crushed, yet without breaking small stones > 2 mm to pass through the sieve. We therefore do not recommended grinding the soil sample in a mortar with a pestle or using a mechanical grinder. Depending on the objectives of the trial, the mass of material retained on the sieve and the < 2 mm fine soil may be weighed to obtain the stone content (i.e. particles > 2 mm).

The proportion of > 2 mm material may be important as these materials usually do not allow root penetration and are not part of the fine soil from which water and nutrients are absorbed. The higher the proportion of > 2 mm material in soils the stronger the effect on the actual water and nutrient availability. Chemical analysis of the fine soil (< 2 mm) should always be corrected for the stone content (> 2 mm) when calculating C or nutrient stocks in a soil layer. The stone content is calculated as

$$\text{Stone content} = \frac{(\text{Mass of material} > 2\ \text{mm})}{[(\text{Mass of material} < 2\ \text{mm}) + (\text{Mass of material} > 2\ \text{mm})]} \quad (2)$$

Module 10: Considerations when comparing soil properties over time

The usual method to calculate nutrient and carbon stocks in soils is the multiplication of the nutrient or carbon concentration by the bulk density and the sampling depth of the analyzed layer. The resulting data are thus volume based because the bulk density is mass per unit volume. For a single measurement, this is acceptable and valid. However, if the same site is sampled over time, it is necessary to consider changes in bulk density over time and the fact that the sampling depth may not be the same at a later sampling date as at the initial sampling. As an example: imagine a soil to be sampled to 30 cm depth with a homogeneous bulk density of 1.25 g/cm^3 throughout the 30 cm layer. This soil layer has a volume of 3000 m^3 and a mass of 3750 tonnes. If this soil is now tilled in the upper 20 cm with a consequent reduction in bulk density to 1.00 g/cm^3 in the top 20 cm and 1.25 in the sub-layer at 20–30 cm, the volume of the soil will have increased. The pre-tillage upper 20 cm now has a thickness of 25 cm because the bulk density decreased and the mass of the pre-tillage 2500 tonnes of the 20 cm layer now fills a volume of 2500 m^3. If a new sample was to be taken from 0–30 cm depth, the samples would be recovered from a layer that does not reach the same depth as the initial sample but rather 5 cm short of the previous soil depth. Although the concentrations of the nutrients and carbon have not changed, the new calculation would result in lower nutrient and carbon stocks in the 0–30 cm layer simply because the bulk density was reduced. Following through with this example over a cropping season, during which the soil may be compacted by rain impact and operations on the field, the bulk density may have increased to 1.40 g/cm^3 throughout the 0–30 cm layer. At this bulk density, the 30 cm soil layer has a mass of 4200 tonnes. The initial soil mass of 3750 tonnes at a bulk density of 1.25 g/cm^3, with a volume of 3000 m^3 now has a bulk density of 1.4 g/cm^3 and a volume of 2678.6 m^3. This means the auger going to 30 cm depth will sample the previously sampled 26.8 cm and an additional 3.2 cm from the subtending layer. Consequently, additional soil is in the sample that was not part of the sample analyzed initially and the calculation with a higher bulk density will result in higher nutrient and carbon stocks at this later stage although this was only caused by the higher bulk density and not by actual gains.

For the above reasons, comparisons of soil nutrients and carbon stocks over time cannot be based on the soil volume but need to be based on soil mass. Details of the approach to compare nutrient and carbon stocks over time are presented in Wendt and Hauser (2013).

Contributors

Stefan Hauser (International Institute of Tropical Agriculture [IITA]), Kazuki Saito (Africa Rice Center [AfricaRice]), Mirjam Pulleman (The Alliance of Bioversity International and the International Center for Tropical Agriculture [Alliance Bioversity & CIAT])

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