FIELD GUIDE FOR SAMPLING AND DESCRIBING SOILS IN THE PAPUA NEW GUINEA NATIONAL FOREST INVENTORY

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CONTENTS

ABBREVIATIONS

EU	European Union
BD	Bulk density
FAO	Food and Agriculture Organization of the United Nations
LULUCF	Land Use, Land Use Change And Forestry
NFI	National Forest Inventory
PNG	Papua New Guinea
PNGFA	Papua New Guinea Forest Authority
PNGRIS	Papua New Guinea Resource Information System
REDD	Reducing Emissions from Deforestation and Forest Degradation
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture

1. RATIONALE FOR A SOIL CARBON INVENTORY IN PAPUA NEW GUINEA FORESTS

Deforestation is the second largest anthropogenic source of atmospheric carbon dioxide, after fossil fuel combustion (van der Werf et al. 2009); the total amount of carbon emitted due to tropical deforestation is estimated to be 1.5 Gt y^{-1} (or 20% of global anthropogenic emissions (Gullison et al. 2007)). As Papua New Guinea (PNG) has one of the most significant areas of largely-intact tropical forest in the world, the Papua New Guinea Forest Authority (PNGFA), with the support of the FAO and the EU, is currently preparing the first National Forest Inventory (NFI) for PNG. The NFI will be a basis for planning sustainable forest management in relation to ecosystem carbon stocks and fluxes. The NFI will also be a key element of the National Forest Monitoring System that PNG is required to establish in order to participate in the expected United Nations Framework Convention on Climate Change (UNFCCC) mechanism on REDD+ and will be a major source of data for the PNG national greenhouse gas (GHG) inventory.

Soil carbon is one of the five forest carbon pools which need to be reported under UNFCCC. The NFI includes soil carbon assessment so that total ecosystem carbon in PNG forests can be systematically estimated. Estimating carbon stored in the soil is important when assessing PNG forest carbon stocks as initial results indicate that up to 50–75% of PNG forest carbon is held in the soil and at some sites a significant proportion of soil carbon may be held below the topsoil layer (Nimiago et al. 2014, summarising results of Edwards and Grubb 1977, Matsuura 1997, Abe 2007, and Nimiago 2011). The first phase of NFI assessment, based on remote sensing, was completed in March 2014: land use and vegetation type were assessed at more than 25,000 1-ha plots. From these 1000 NFI sites were chosen for biodiversity assessment.

A subset of 100 plots will be selected and their soil carbon content measured. But before designing a soil carbon survey several issues must be resolved:

(1) At any particular site, how many replicates are required to take into account the soil variation present, especially on hilly and steep land?

(2) Should the survey sites be selected randomly or selected using a process of stratification (i.e. should sampling take into account known vegetational, climatic or geological patterns)?

(3) Is the survey intended to measure only the soil carbon most sensitive to land use change, or is it intended to measure total soil carbon stocks?

(4) Is the survey only concerned with soil carbon measurement or should it address the other issues identified in the REDD+ programme?

These important questions are not specifically addressed in high-level protocol agreements concerned with estimating effects of land use, land use change and forestry (LULUCF). For example, concerning **Question (1)** above, the UN Report on Kyoto Revised Supplementary Methods (Hiraishi et al. 2013) suggests that “Tier 3 models” (the most detailed and field-oriented methods considered) should be calibrated against soil carbon measurements at benchmark sites, but the report does not specify how the benchmark sites should be set up or sampled. Stolbovoy et al. (2005) recognised that general norms provided by Kyoto Protocol documents were insufficient to guide monitoring of soil carbon at the LULUCF plot level. Although Stolbovoy et al. (2005) accordingly provided a statistical guide to sampling procedure for surveys in European forests, actual procedures to follow at monitoring plots themselves were only sketched. However, in their review of soil carbon assessment written for the FAO prior to a survey of soil carbon in Tanzania Mäkipää et al. (2012) addressed field sampling issues in more detail. They concluded that stratification of sampling could lead to significant time and cost savings relative to random sampling if within-stratum variability is lower than the variability within the entire population being sampled. They restricted sampling to the 0–30 cm soil layer as they assumed that land management effects are most pronounced in this layer. Although they recognised that in boreal forests 10–20 samples per plot or more are required in order to reasonably estimate actual soil carbon on an area basis (Mäkipää et al. 2013; Muukkonen et al. 2009), they recommended only four samples per plot in their design for soil carbon assessment in Tanzania. This small number of replicates is likely to be insufficient to allow detection of changes by repeat sampling (Mäkipää et al. 2012, figure 3) and could potentially undermine the usefulness of soil carbon surveys. In a study not designed to address the specific issue of within-site soil carbon variation, McIntosh et al. (1997) found that 10 topsoil samples per plot, separately analysed, were sufficient to demonstrate significant ($P<0.05$) differences in soil carbon concentrations (C%) between different vegetation types, soil types and land use.

Although further detailed studies addressing Question 1 would be useful, it appears that 10 samples per plot is the minimum required to provide a reliable mean value for accumulated soil carbon at a site. Given the amount of work required to obtain and process soil samples, the ideal number of 20 or more per plot (Mäkipää et al. 2013; Muukkonen et al. 2009) will be achievable only in scientific research projects and not in national inventories.

In regard to **Question (2)** above, the importance of stratification when selecting sites for detailed study in the PNG NFI has been accepted by UN-REDD+ researchers and coordinators in PNG (Dr Hitofumi Abe, PNGFA, personal communication). The stratification criteria adopted include geological substrate as well as vegetation type (broadly corresponding to climate). Geological substrate has been chosen as a surrogate for soil type, as there has been no national soil survey in PNG and regional surveys undertaken by the Australian CSIRO in the 1960s and 1970s (summarised by Bleeker 1983), often at the level of the soil association rather than soil type, do not provide sufficient coverage for soil information to be extrapolated nationally. The digital resource inventory (PNGRIS) for PNG (Bryan and Shearman 2008) includes a modelled soil layer using the USDA classification but the accuracy of the predicted soil pattern has been found to be low in an area east of Port Moresby (R. Doyle, unpublished information). The accuracy of the soil layer has not been tested nationally.

Questions (3) and (4) above raise important questions about why soil carbon is being measured in national forest inventories. Is the objective of soil carbon measurement to provide a baseline against which effects of future land use (most probably negative) can be measured; or should it be used to guide land use policy so that negative effects can be avoided?

We suggest that both objectives should apply to soil carbon inventory in PNG. The purpose of REDD+ is “to reduce emissions from deforestation and forest degradation, and to promote the conservation, management and enhancement of forest stocks”, i.e. REDD+ is intended to have an immediate practical impact as well as a long-term monitoring function.

At least half of PNG’s soil carbon stocks are found in the soil, and PNG soils vary in their susceptibility to soil carbon losses by land-use change. These losses can occur through the processes of cultivation, run-off, stream erosion and mass movement, among others (Bleeker 1983, table 12.3; Rijkse and Trangmar 1995; Trangmar et al. 1995; McIntosh 2013, p. 47–61). Stream erosion and mass movement in particular involve more than surface horizon changes. Therefore in any national effort to conserve carbon in forest soils it is essential to understand the nature of the whole soil in its landscape context if risks to soil carbon loss by land use change are to be avoided.

For the reasons discussed above, 100 sites in the NFI survey will be selected for soil survey by stratifying sites by geological units as well as by vegetation and climate (Appendix 1). Geological units will be grouped by their estimated ability to complex soil carbon (McIntosh 2014), which is broadly related to the amount of short-range order clays (especially Al and Fe oxides and hydroxides) in soils (Brydon and Sowden 1959; Gu et al. 1995; Egashira et al. 1997; Chevallier et al. 2010; Miyazawa et al. 2013). Within the NFI plots topsoil samples will be taken at three depths (0–10 cm; 10–20 cm and 20–30 cm) at ten replicate sites, with one of these sites being the soil profile site; a soil profile dug to 1 m depth will also be sampled for soil carbon and other chemical properties and described in sufficient detail for it to be classified by the FAO (IUSS Working Group 2014) and USDA (Soil Survey Staff 2014) systems.

It is recognised that describing soil profiles and taking samples from layers other than the top 30 cm of soil will result in more time being needed at NFI plots, and increased soil analysis costs, but the extra time and additional expenditure required will be small in relation to the total costs of the NFI survey and will be more than compensated for by the greatly enhanced site data that this extra work will generate for the NFI in PNG, and its educational value for reducing potential land degradation and its scientific value as a database for the future. Not only will the susceptibility of land to soil carbon loss and soil erosion be much easier to predict in different landscapes if detailed site and profile data are available, but the total soil carbon stored in PNG’s forests will be able to be more accurately calculated and extrapolated because the soil information will be able to be linked to mapped geological units as well as to vegetation types.

At the 1000 NFI clusters to be studied in detail for biodiversity values (“Bio” clusters) topsoils will be sampled at 0–10 cm, 10–20 cm and 20–30 cm depths, but profile samples will not normally be taken. The procedures for topsoil sampling and sample processing are identical to those detailed for profile sites in this guide, but actual sampling sites will be accurately positioned with respect to cluster margins, so that the sites have the potential to serve as reference or baseline sites and can be revisited in the future to detect changes. A defined number of replicate topsoil samples (assumed to be ten in this guide) will be taken around the perimeter of a plot, normally the central plot of an NFI cluster.

When conducting a soil survey and sampling for soil carbon it is important to standardise procedures, so that inter-site comparisons can be made. However, many foresters have no formal training in soils and geology, and others have different levels of expertise, so to ensure consistency during the NFI sampling the UN-REDD+ organisation in PNG and The Crawford Fund (Australia) funded a soils training course for potential supervisors of soil sampling and soil description, which is described by McIntosh et al. (2015). In this course various methods of sampling soils outlined in a draft field guide distributed to participants were trialled. Subsequently the first edition of this guide was published in December 2015.

Experiences during a soil survey under difficult (wet) conditions in Madang province in March 2016 led to recommendations for further changes (McIntosh 2016) and a second edition of the guide. The revised guide included procedures for sampling topsoils (0–30 cm soils) at NFI “Bio” sites, as discussed in email correspondence between Dr H. Abe and the senior author on 19 April 2016. Further surveys in Central and Morobe Provinces in March 2017 highlighted the need for further clarification of sampling and laboratory procedures in the guide. This third edition of the *Field Guide* addresses these issues.

2. SURVEY TECHNIQUES NOT COVERED BY THIS PUBLICATION

This publication does not cover methods of sampling peats, swamps or coastal soils with mangrove forests, which require specialist equipment and techniques (e.g. de Vleeschouwer et al. 2010) which, at the time of writing this report, have not been trialled for the purpose of soil carbon inventory in PNG.

3. SELECTING NFI SITES FOR THE SOIL PROFILE SURVEY

All 1000 NFI clusters will be sampled for topsoil (0–30 cm) characteristics. In this guide these are called **Bio** sites. Only 10% (100) of the NFI sites (clusters) will be sampled for soil profile characteristics. In this guide these are called **Profile** sites.

Profile sites should be selected so that, at a national scale, they cover a representative range of altitudes (broadly represented by forest types) and soil parent materials (broadly represented by rock types). Ideally soil variation at the local scale (e.g. variation related to slopes, erosion and land use) should also be measured, but with funding for detailed soil characterisation at only 100 sites not all factors likely to affect carbon content of soils can be taken into account in the NFI. Appendix 1 in this report proposes a practical sampling strategy. But in practice even this strategy may need to be modified because of access and logistical issues, and funding limitations. For example, during team surveys the most efficient way of conducting a survey is to sample at NFI clusters which are close geographically, so that up to 6 profile sites can be sampled in a week to ten days.

4. ORGANISING THE SOIL PROFILE SURVEY

It is envisaged that, as proposed by McIntosh (2016), a *scientific coordinator* will work with a *survey supervisor* to plan the actual survey. Before fieldwork begins the following questions need to be addressed:

- Do the sites (clusters) for soil survey vary in their geology? Has the geology of each of the sites been checked on geological maps?
- Are all sites accessible by road or boat, i.e. within about 2 km of a drivable track or boat landing?
- Does any extra equipment need to be purchased?
- Has the *survey supervisor* checked with landowners and gained permission for access? Does the consulted landowner represent all landowners affected?

4.1 Information needed

Once the NFI clusters for soil survey have been chosen the *survey supervisor* will need to collect all relevant geological, soils and land information for the site:

- **Geological maps.** The Mineral Resources Authority of PNG publishes a large range of geological maps at 1:250 000, 1:100 000 and 1:50 000 scales. Paper maps (hard copies) are more useful than digital maps which may only provide a map unit label and a short descriptor. Geological maps are available from the Mineral Resources Authority http://www.mra.gov.pg/shop/tabid/227/categoryid/8/language/en-us/default.aspx and provide more information than is available on PNGRIS. The NFI has purchased paper 1:250 000 geological maps for the following areas:

Buna	*Wabag*	*Talasea-Gasmata*
Port Moresby-Kalo-Aroa	*Kutubu*	*Gazelle Peninsula*
Tufi-Cape Nelson	*Ramu*	*Pomio*
Abau	*Karimiu*	

- **CSIRO soil surveys**. In the 1970s the Australian CSIRO published a series of regional soil and land use maps for PNG. These were republished in 2010. For a list of titles and areas covered visit http://www.publish.csiro.au/index.cfm . Note that the soil classification system used for the surveys is an early version of USDA Soil Taxonomy and will need updating if used in the present survey.

- **PNG Resource Information System (PNGRIS).** The third edition of PNGRIS contains map layers representing: climate, elevation, topographic position, slope, aspect, landform, geology and soil. However the soil layer is predictive but not ground-truthed. The PNGRIS manual (Bryan and Shearman 2008) is available at www.pngsdf.com/research.htm .

- **Other information.** Includes research papers, forestry company reports and maps, and gas pipeline technical reports.

4.2 Equipment needed

Each survey team will need to pack the following equipment:

Implements

- One split-tube Eijkelkamp soil sampler 48 mm internal diameter (Figure 1), designed to take topsoil samples 30 cm deep, with mallet.
- One "Rowfit" soil sampler[1] (Figure 2) and aluminium liners, designed to take an undisturbed sample 10 cm deep.
- Two spare sharpened aluminium liners and a block of wood
- One long-handled shovel
- Two strong spades with sharpened blades
- One crowbar
- A 2 m tape measure with millimetre scale
- Flexible soil profile scale marked at 10 cm intervals
- Two builders' trowels with sharpened edges
- Two square-ended paint scrapers or putty knives
- Bush knife
- Two serrated kitchen knives
- One rubber mallet with a ~1 kg head
- One coarse file

Instruments

- Camera
- Clinometer

[1] Manufactured by Rowfit International, PO Box 383, Huonville, Tasmania, Australia http://www.rowfit.com/

- GPS
- Spare batteries for GPS and camera

Books and field sheets

- This field guide
- Laminated copies of the profile description and soil classification pages of this guide (pages 13–27).
- Munsell soil colour book
- 10 copies of *Brief Soil Description Card*, printed on waterproof paper
- Clipboard

Figure 1. The Eijkelkamp sampler (A). This sampler is designed for topsoil sampling in stone-free soils. It is hammered into the soil to about 37 cm depth. The corer is then rotated to break the soil column and pulled out of the soil. One half of the cylinder is removed to reveal the 30+ cm core (B). This is cut into 10 cm lengths (measured from the top) for bagging as 0–10 cm, 10–20 cm and 20–30 cm samples (C). Cut and remove cores on a board or plastic sheet so that spilled soil can be retrieved.

Figure 2. The Rowfit sampler is designed to take an undisturbed core 10 cm deep from stone-free or slightly stony soils. It consists of a stainless steel outer cylinder which encloses a removable aluminium liner. *From top left*: gently hammering the sampler into the soil using a rubber mallet; extracting the sampler; unscrewing the top; cutting excess sample from the base of the extracted internal liner of the sampler before bagging the sample.

The Rowfit sampler is robust and should be carried for subsoil sampling and as an "insurance" corer for topsoils in case the Eijkelkamp corer is damaged during soil survey. In clayey sticky soils the sampler can be used without the aluminium liner (see text).

Other essential items

- 100 small plastic bags c. 20 x 30 cm (for profile samples)
- 50 medium plastic bags c. 30 x 40 cm (will contain ten 10-cm Eijkelkamp samples)
- 10 large plastic bags about 40 x 80 cm
- Plastic or cloth "duct tape" for mending punctured plastic bags
- String
- Plenty of indelible felt pens and pencils and ballpoints
- Plastic crates, rice sacks and backpacks for carrying equipment and soil samples
- Rags for cleaning soil samplers
- Light oil for screw thread lubrication
- Nails for horizon markers
- Vinyl or plastic-coated paper triangles to mark horizons
- Umbrella

5. THE PROFILE SURVEY

5.1 Choosing the profile pit site

The pit for the soil profile should ideally be located within the NFI cluster, but not within any of the four 25-m radius plots used for biodiversity assessment. The soil pit will usually be placed just outside the central plot. The *survey supervisor* should choose a profile site on the dominant landform of the cluster, e.g. if the cluster plots are on steep terrain, choose a pit site on steep terrain and not on a ridge. The pit should be at least 5 m from large trees.

5.2 Aims

At each site the soil team needs to achieve the following:

- Describe the soil profile to 1 m depth, or to a rock contact, and classify it.
- Sample ten replicate topsoil samples at 0–10 cm, 10–20 cm and 20–30 cm depth. These are the **replicate** samples. In the laboratory they will be subsampled for bulk density (BD) and soil chemistry.
- Sample the subsoil below 30 cm depth for bulk density, at two depths. These are the **profile BD** samples.
- Sample the entire profile for soil chemistry at 0–10 cm, 10–20 cm, 20–30 cm, 30–60 cm and 60–100 cm depths. These are the **profile chem** samples.

The **replicate** samples will be analysed for organic carbon and nitrogen to provide information for organic matter accounting in PNG's forest estate. BD will also be calculated for these samples so that results can be expressed on a t/ha basis.

The **profile chem** samples, along with the profile description and soil classification, will provide information for PNG's national soils database and guide appropriate land-use. The **profile BD** samples from subsoils will allow calculation of organic carbon and nitrogen on a t/ha basis for the whole profile to 1 m depth.

5.3 Digging the pit

- The pit should be approximately 1 m wide x 1.2 m long. It should be 1 m deep, or shallower if rock is encountered. On sloping ground align the long axis of the pit up and down slope.
- Keep one face (the "sampling" face) neat and keep spoil off the ground surface behind it. This face will be photographed, described and sampled. It is useful to mark this with flagging tape. Throw spoil to one side of the pit. Cut a couple of steps into the pit for easy access, digging and sampling. Snip off protruding roots. Use a trowel to clean up spade marks on the sampling face.
- While the pit is being dug the *survey supervisor* will decide which method to use for soil sampling:
    - use the Eijkelkamp sampler for topsoil sampling in stone-free soils.
    - use the Rowfit sampler for sampling in slightly stony soils, and for subsoil sampling
    - use a sharpened Rowfit liner banged directly into the soil if the soil is very clayey and sticky
    - use the rectangular box method for stony soils.

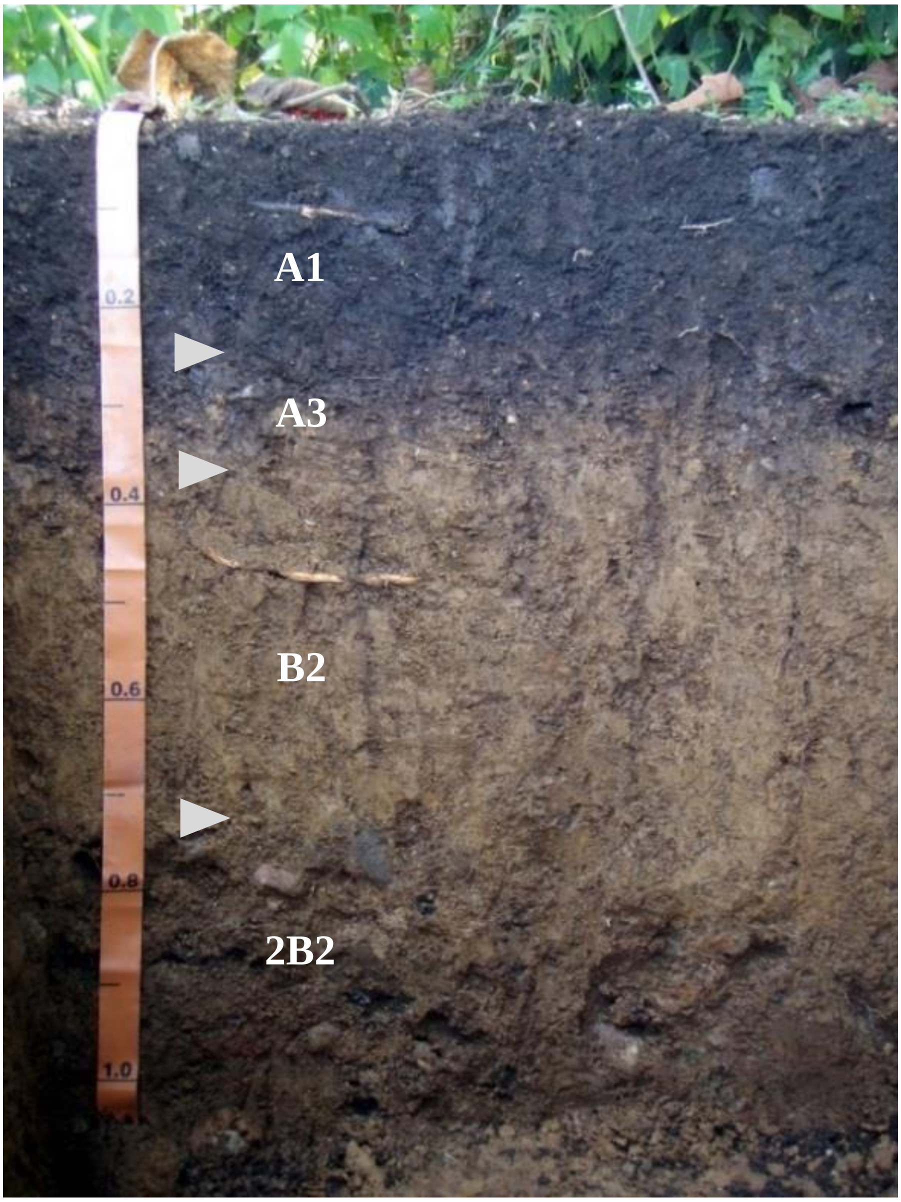
5.4 The profile description

(The layout on the following pages is designed to allow for easy photocopying.)

Profile photograph

The photograph is a very important part of the soil survey and should be taken with future publication in mind.

- Make sure there are no spade marks on the photographed face.
- Hang a tape marked at 10 cm intervals on the left hand side of the sampling face. Make sure the tape is vertical.
- Mark horizon boundaries with triangular tabs neatly placed adjacent to the tape.
- Try to take photos with natural light rather than a flash. Steady the camera if necessary.



Site characteristics

Record the site characteristics, as listed on the *Brief Soil Description Card*.

BRIEF SOIL DESCRIPTION CARD	
NFI Site ID:	Described by:
Profile No:	Landform:
Date:	Average slope of dominant landform (°):
General location:	Aspect: N NE E SE S SW W NW
GPS coordinates:	Rock type as mapped:
Altitude:	Rock type as observed:
Site Supervisor:	Soil parent material:
Vegetation type (general) (e.g. cutover rainforest):	
Species – trees and understorey (continue on back of this sheet):	
Disturbance:	

	1	2	3	4	5
Horizon symbol					
depth (cm)					
Matrix colour (moist)					
Mottle (1) colour					
abundance %					
size (mm)					
Mottle (2) colour					
abundance %					
size (mm)					
Consistence (strength)					
Peds (structure) type					
development					
size (mm)					
Texture					
Estim. clay %					
Gravel abundance %					
size					
shape					
rock type					
Roots (1) size					
abundance					
Roots (2) size					
abundance					
Notes					

Circle the method used for topsoil replicates (the same method <u>must</u> be used for all ten replicates)	A (Eijkelkamp)	B (Rowfit)	C (rectangular box)
Method used for subsoil BD Size of rectangle used if greater than 10 cm:		B (Rowfit)	C (rectangular box)

Provisional FAO Soil Classification:
Provisional USDA Soil Classification:

Landform and slope

The following landscape units are common in PNG. The list is not exhaustive. A more detailed list is given in the "Landform" chapter in the Australian Soil and Land Survey Field Handbook (National Committee on Soil and Terrain 2009).

LANDFORM	COMMON PARENT MATERIAL[1]
On flat land:	
Marine (coastal) terrace	Alluvium: marine silt, sand and gravel
Tidal flat	Alluvium: marine silt and sand
Raised reef	In-situ limestone
Floodplain	Alluvium: silt, sand and gravel (rounded)
Alluvial terrace	Alluvium: silt, sand and gravel (rounded)
Swamp	Peat and clay alluvium
On undulating to rolling land:	
Alluvial fan	Alluvium: gravelly sand and silt; gravels are angular
Dissected terrace	Alluvium: weathered sand, silt and gravel
Volcanic ash terrain	Recent or weathered volcanic ash
Dunes	Aeolian sand
On hilly or steep land:	
Ridge	In-situ rock
Upper slope	In-situ rock and colluvium
Midslope	Colluvium
Toeslope	Deep colluvium
Landslide scar	Thin colluvium on rock or weathered rock
Landslide debris	Deep colluvium

[1]On old and weathered landforms the original parent material may have been modified (e.g. weathered to clays) and may have different properties and size grades to those listed in this table.

Horizons

Soil horizons are often distinguished by colour, but can also be distinguished by stoniness, structure (natural aggregates or peds) or texture (proportion of sand, silt and clay). Normally 3 to 5 horizons can be distinguished. Horizons are designated as follows.

Horizon designation	Characteristics
O1	Undecomposed organic debris
O2	Decomposed organic debris; original form cannot be recognised
P1	Undecomposed organic debris (peat) that has accumulated in wet conditions
P2	Decomposed organic debris (peat) that has accumulated in wet conditions
A1	Mineral horizon with some accumulation of organic matter
A2	Mineral horizon with less organic matter, less accumulation of Fe and Al oxides and less clay than immediately adjacent horizons; usually pale in colour
A3	Transitional horizon between A and B, *dominated by A horizon characteristics*
B1	Transitional horizon between A and B, *dominated by B horizon characteristics*
B2	Horizon with maximum pedological change, e.g. iron accumulation or clay formation or clay accumulation
B3	Transitional horizon between B and C, *dominated by B horizon characteristics*
C	Partially weathered material little affected by pedogenic processes; can be dug with hand tools
D	Horizon unlike the C horizon or overlying horizons
R	Rock; cannot be dug with hand tools; may have cracks down which roots penetrate

If necessary add a suffix to provide more detail about horizons. For example, Ab indicates a buried A horizon. The following suffixes are commonly used. For a complete list refer to the Australian Soil and Land Survey Field Handbook.

b	Buried horizon
c	Concretions of Fe, Al or Mn oxides.
e	Bleached horizon (commonly A2e)
g	Strong gleying
m	Strongly cemented
r	Weathered rock that can be cut with a spade
s	Accumulation of metal oxide-organic matter complexes dominated by Fe
t	Accumulation of clay
w	Development of colour or structure in the B horizon
x	Fragipan or earthy pan, seemingly cemented when dry but weaker when moist
?	Horizon designation uncertain

Colour

Matrix Colour

Estimate colour of natural aggregates (moist) using the Munsell Soil Color Charts. Record hue, value and chroma in this order, e.g. 10YR4/2.

Mottle colour

Mottles are produced by alternating oxidising and reducing conditions in the soil. Mottles are associated with imperfect to poor drainage and commonly occur as orange-brown patches in a bluish-grey or greenish-grey matrix. Record the percentage of the mottles and their size. If there are two sets of mottles with different colours, record the colour, size and percentage of both.

Mottles formed by earthworm mixing or other processes should also be recorded and a note should be made on their origin (e.g. "10YR4/2 mottles are introduced by earthworms" or "7.5YR5/6 mottles are weathered sandstone stones").

Consistence (soil strength)

Assess how much force is required to make a 20 mm diameter cube of soil disintegrate:

Loose	No force required (e.g. loose sands)
Very weak	Very small force
Weak	Small but significant force exerted between thumb and forefinger
Firm	Moderate or firm force exerted between thumb and forefinger
Very firm	Strong force, but within that exerted between thumb and forefinger
Strong	Cannot be crushed between thumb and forefinger; crushes underfoot with small force
Very strong	Crushes underfoot with full body weight applied slowly
Rigid	Cannot be crushed underfoot with full body weight applied slowly

Peds

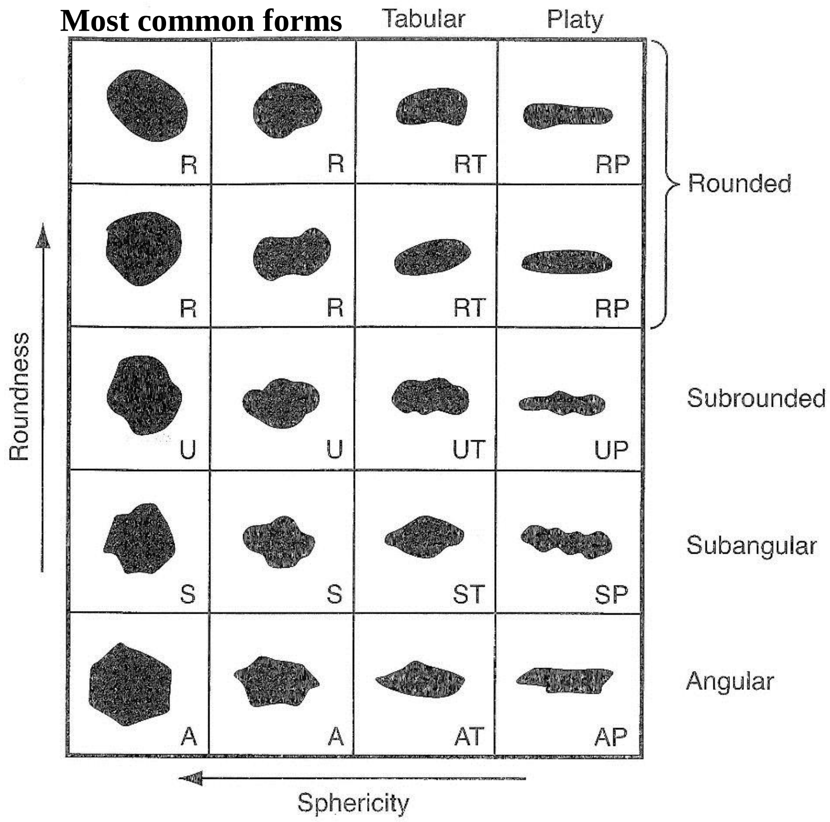
Peds are natural aggregates in the soil. Record ped type, ped development and ped size.

Ped types

Ped types are defined by ped shape. The definitions below are slightly simplified from those in the Australian Soil and Land Survey Field Handbook

Columnar	Vertical columns with flat surfaces on adjoining columns
Angular blocky	Aggregates with flat surfaces and sharp angles; peds fit with each other
Subangular blocky	Aggregates with flat to rounded surfaces and rounded angles between faces; peds fit with each other
Polyhedral	Subrounded aggregates with rounded angles between faces; most peds fit with each other
Granular	Almost spherical (rounded) peds; peds don't fit with each other

Most common forms



Ped development (also known as soil structure)

- Record whether ped development is **weak**, **moderate** or **strong**.
- If there are no peds and the soil breaks into individual grains (usually sands) write **single grain**
- If there are no peds and the soil particles stick together, write **massive**

Ped size

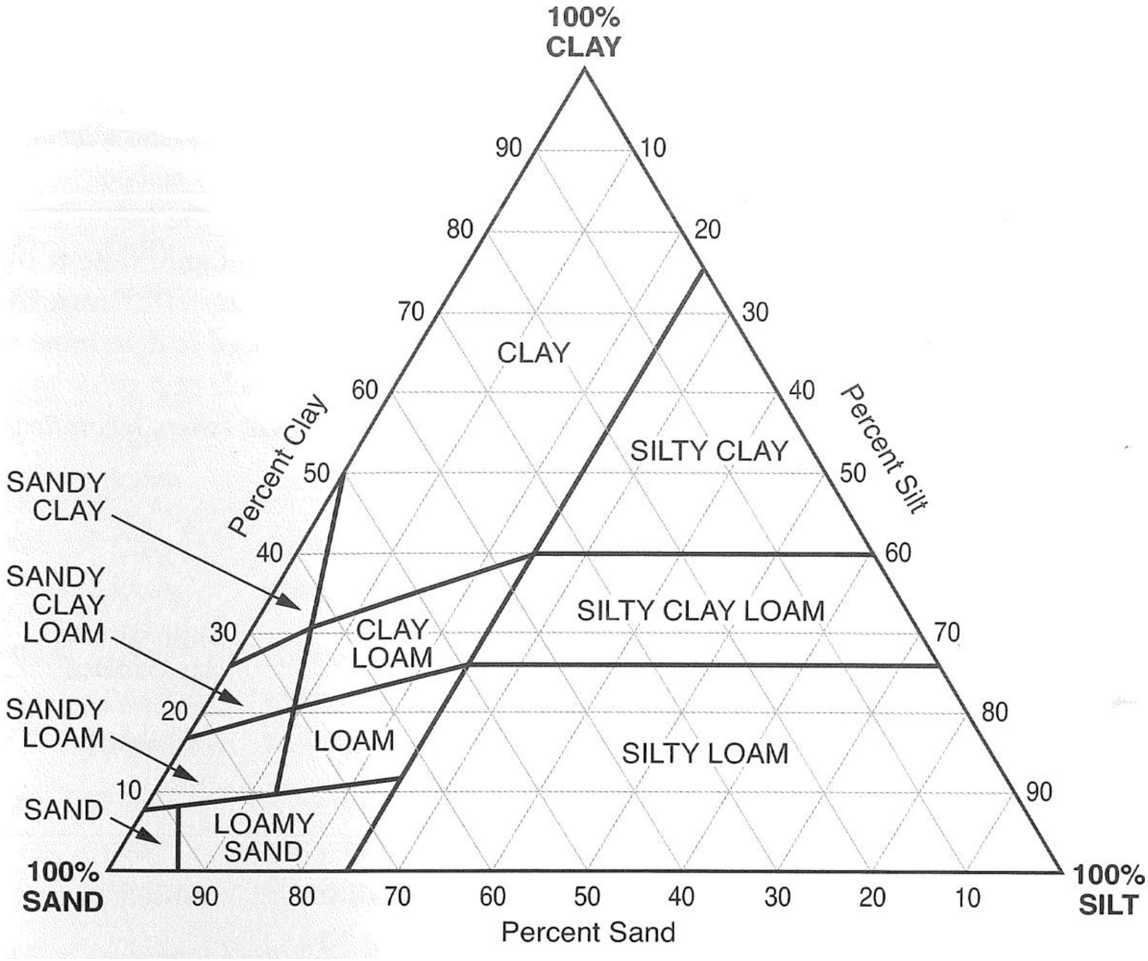
Record ped diameter in millimeters

Texture

Texture is the proportion of sand silt and clay in a soil, excluding stones (particles greater than 2 mm diameter). It is assessed in the field by testing the properties of moist soil between the thumb and forefinger. See p.163–164 of the Australian Soil and Land Survey Field Handbook (National Committee on Soil and Terrain 2009). Use the following abbreviations:

Sand	**S**	Sandy clay	**SC**
Loamy sand	**LS**	Silty loam	**ZL**
Sandy loam	**SL**	Silty clay loam	**ZCL**
Loam	**L**	Silty clay	**ZC**
Sandy clay loam	**SCL**	Clay	**C**
Clay loam	**CL**		

A texture diagram is used to determine texture class.



Stones

Stones are rock fragments >2 mm diameter. Record

- abundance (% by volume)
- shape (**rounded**, **subrounded**, **subangular** or **angular**)
- maximum diameter
- rock type – there may be a mixture of rock types

Roots

Record the abundance of roots in a 10 x 10 cm square on an exposed vertical face.

For the NFI project classify roots into the two predominant size classes present, using the following table:

Root size	**Diameter**
Very fine	<1 mm
Fine	1–2 mm
Medium	2–5 mm
Coarse	>5 mm

Different abundance classes are applied, depending on root size:

	Number of roots in a 10 x10 cm square	
	VERY FINE and **FINE**	**MEDIUM** and **COARSE**
No roots	0	0
Few	1–10	1–2
Common	10–25	2–5
Many	25–200	>5
Abundant	>200	>5

Classifying the profile

Once the soil profile has been described, provisionally classify the soil using the FAO and USDA (Soil Taxonomy) systems (Tables 1 and 2).

Table 1. A simplified guide to the FAO soil classification system for PNG forest soils

This key is based on pages 79–10 of the FAO World Resources Report 106 (IUSS Working Grope 2014) and the short key prepared by Kuzyakov (2012)[2]. Reference Soil Groups most likely to occur in Papua New Guinea forests are shown in bold underlined capitals. Use this key for provisional classification to FAO level. Final classification should be made using the complete key in the FAO World Resources Report (IUSS Working Group 2014).

HISTOSOLS (peaty soils)
Having organic soil material, *either*
1. 10 cm or more thick starting at the soil surface and immediately overlying continuous rock, or fragmental materials, the interstices of which are filled with organic soil material; *or*
2. cumulatively within 100 cm of the soil surface, either 60 cm or more thick if 75% (by volume); *or* more of the material consists of moss fibres; *or* 40 cm or more thick in other materials and starting within 40 cm of the soil surface.

ANTHROSOLS (man-made soils used for agriculture)
1. having *either* a hortic, irragric, plaggic or terric horizon 50 cm or more thick; *or*
2. an anthraquic horizon and an underlying hydragric horizon with a combined thickness of 50 cm or more; *or*
3. a pretic horizon.

TECHNOSOLS (other man-made soils)
1. having 20% (by volume, by weighted average) or more artefacts in the upper 100 cm from the soil surface or to continuous rock or a cemented or indurated layer, whichever is shallower; *or*
2. a continuous, very slowly permeable to impermeable, constructed geomembrane of any thickness starting within 100 cm of the soil surface; *or*
3. technic hard rock starting within 5 cm of the soil surface and covering 95% or more of the horizontal extent of the soil.

CRYOSOLS (soils with permafrost)
1. having a cryic horizon starting within 100 cm of the soil surface; *or*
2. a cryic horizon starting within 200 cm of the soil surface and evidence of cryoturbation in some layer within 100 cm of the soil.

LEPTOSOLS (soils on rock)
1. having one of the following:
a. limitation of depth by continuous rock within 25 cm of the soil surface; *or*
b. less than 20% (by volume) fine earth averaged over a depth of 75 cm from the soil surface or to continuous rock, whichever is shallower; *and*
2. no calcic, chernic, duric, gypsic, petrocalcic, petroduric, petrogypsic, petroplinthic or spodic horizon.

[2] http://wwwuser.gwdg.de/~kuzyakov/soils/WRB-2006_Keys.htm

SOLONETZ (soils with high exchangeable sodium)
Other soils having a natric horizon beginning within 100 cm from the soil surface.

VERTISOLS (clay-rich soils with cracks)
1. having a vertic horizon starting within 100 cm of the soil surface; *and*
2. after the upper 20 cm have been mixed, 30 percent or more clay between the soil surface and the vertic horizon throughout; *and*
3. cracks which open and close periodically.

SOLONCHAKS (salty soils)
1. having a salic horizon starting within 50 cm of the soil surface; *and*
2. no thionic horizon starting within 50 cm of the soil surface.

GLEYSOLS (mottled soils, periodically water saturated)
1. having within 40 cm of the mineral soil surface, in some parts, reducing conditions and in half or more of the soil volume AND a gleyic colour pattern; *or*
2. a mollic or umbric horizon with reducing conditions.

ANDOSOLS (soils in volcanic ash)
1. having one or more layer with andic or vitric properties with a combined thickness of *either*
a. 30 cm or more within 100 cm of the soil surface and starting within 25 cm of the soil surface; *or*
b. 60% or more of the entire thickness of the soil when continuous rock or a cemented or indurated layer is starting between 25 and 50 cm from the soil surface; *and*
2. no argic, ferralic, petroplinthic, pisoplinthic, plinthic or spodic horizon (unless buried deeper than 50 cm).

PODZOLS (soils with subsoil accumulations of humus and/or Fe and Al oxides)
Having a spodic horizon starting within 200 cm of the mineral soil surface.

PLINTHOSOLS (soils with pans)
Having *either*
1. a plinthic, petroplinthic or pisoplinthic horizon starting within 50 cm of the soil surface; *or*
2. a plinthic horizon starting within 100 cm of the soil surface and, directly above, a layer 10 cm or more thick, that has in some parts reducing conditions for some time during the year and in half or more of the soil volume, singly or in combination
a. a stagnic colour pattern; *or*
b. reducing conditions.

NITISOLS (red clay-rich soils with high Fe; good structure)
1. having a nitic horizon starting within 100 cm of the soil surface; *and*
2. no ferric, petroplinthic, pisoplinthic, plinthic or vertic horizon starting within 100 cm of the soil surface; *and*
4. no layers with reducing conditions above or within the nitic horizon.

FERRALSOLS (red clay-rich soils with high Fe and kaolinite; good microstructure)
1. having a ferralic horizon starting within 150 cm of the soil surface; *and*
2. no argic horizon that has, in the upper 30 cm, 10% or more water-dispersible clay unless the upper 30 cm of the argic horizon has one or more of the following:
a. geric properties; *or*
b. 1.4% or more organic carbon; *or*
c. <10% water-dispersible clay

PLANOSOLS (soils with a prominent pan restricting drainage)
Having an abrupt textural change within 100 cm of the soil surface and, directly above or below, a layer 5 cm or more thick, that has in some parts, reducing conditions for some time during the year and in half or more of the soil volume, singly or in combination with a stagnic colour pattern.

STAGNOSOLS (waterlogged soils)
1. having within 50 cm of the mineral soil surface, in some parts, reducing conditions (from perched water tables) for some time during the year and in half or more of the soil volume, singly or in combination *and* a stagnic colour pattern.

CHERNOZEMS (thick black topsoil; pedogenic carbonate)
1. having a mollic horizon with a moist chroma of 2 or less to a depth of 20 cm or more, or having this chroma directly below any plough layer that is 20 cm or more deep; *and*
2. a calcic horizon, or concentrations of secondary carbonates starting within 50 cm below the lower limit of the mollic horizon and, if present, above a cemented or indurated layer; *and*
3. a base saturation (by 1 M NH4OAc) of 50% or more from the soil surface to the calcic horizon or to concentrations of secondary carbonates.

KASTANOZEMS (dark topsoil; pedogenic carbonate)
1. having a mollic horizon; *and*
2. a calcic horizon, or concentrations of secondary carbonates starting within 50 cm below the lower limit of the mollic horizon and, if present, above a cemented or indurated layer; *and*
3. a base saturation (by 1 M NH4OAc) of 50% or more from the soil surface to the calcic horizon or to concentrations of secondary carbonates.

PHAEOZEMS (dark topsoil; no pedogenic carbonate unless very deep)
1. having a mollic* horizon; *and*
2. a base saturation (by 1 M NH4OAc) of 50 percent or more throughout to a depth of 100 cm or more from the soil surface or to continuous rock or a cemented or indurated layer, whichever is shallower.

UMBRISOLS (soils with thick dark topsoils, low base status)
Having an umbric* or mollic* horizon

DURISOLS (soils with a silica pan)
Having a petroduric or duric horizon starting within 100 cm of the soil surface.

GYPSISOLS (soils with pedogenic gypsum)
1. having a petrogypsic horizon starting within 100 cm of the soil surface; *or*
2. a gypsic horizon starting within 100 cm of the soil surface and no argic horizon unless the argic horizon is permeated with gypsum or calcium carbonate.

CALCISOLS (soils with secondary carbonate)
1. having a petrocalcic horizon starting within 100 cm of the surface; *or*
2. a calcic horizon starting within 100 cm of the soil surface; *and*
a. a calcareous matrix between 50 cm from the soil surface and the calcic horizon throughout if the calcic horizon starts below 50 cm; *and*
b. no argic horizon unless the argic horizon is permeated with calcium carbonate.

RETISOLS (soils with clay-enriched subsoils)
Having an argic horizon within 100 cm of the soil surface and retic properties (interfingering pale coarse material) at its upper boundary.

ACRISOLS (soils with subsoil clay accumulation, low activity clays, acid)
1. having an argic horizon, which has a cation exchange capacity (by 1 M NH4OAc) of less than 24 cmol kg^{-1} clay in some part to a maximum depth of 50 cm below its upper limit, either starting within 100 cm of the soil surface, or within 200 cm of the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout, *and*
2. a base saturation (by 1 M NH4OAc, and including KCl extractable Al) of less than 50% in the major part between 50 and 100 cm.

LIXISOLS (soils with subsoil clay accumulation, low activity clays, not acid)
Having an argic horizon, either starting within 100 cm of the soil surface and a cation exchange capacity (by 1 M NH4OAc) of 24 cmol kg^{-1} clay or less throughout or to a depth of 50 cm below its upper limit (i.e. in its upper part) and a high base saturation at 50–100 cm depth.

ALISOLS (soils with subsoil clay accumulation, high activity clays, acid)
1. having an argic horizon and a base saturation (by 1 M NH4OAc, and including KCl extractable Al) of less than 50% in the major part between 50 and 100 cm.

LUVISOLS (soils with subsoil clay accumulation, high activity clays, not acid)
Other soils having an argic horizon within 100 cm of the soil surface.

CAMBISOLS (young soils with weathered and structured B horizons
1. having a cambic* horizon starting within 50 cm of the soil surface and having its base 25 cm or more below the soil surface or 15 cm or more below any plough layer; *or*
2. an anthraquic, hortic, hydragric, irragric, plaggic or terric horizon; *or*
3. a fragic, petroplinthic, pisoplinthic, plinthic, salic or vertic horizon starting within 100 cm of the soil surface; *or*
4. one or more layers with andic or vitric properties with a combined thickness of 15 cm or more within 100 cm of the soil surface.

ARENOSOLS (sandy soils)
1. having a weighted average texture of loamy sand or coarser, if cumulative layers of finer texture are less than 15 cm thick, either to a depth of 100 cm from the soil surface or to a petroplinthic, pisoplinthic, plinthic or salic horizon starting between 50 and 100 cm from the soil surface; *and*
2. less than 40% (by volume) of gravels or coarser fragments in all layers within 100 cm of the soil surface or to a petroplinthic, pisoplinthic, plinthic or salic horizon starting between 50 and 100 cm from the soil surface.

FLUVISOLS (layered alluvial soils)
Having fluvic material greater than 25 cm thick starting within 25 cm of the soil surface.

REGOSOLS (poorly developed soils)
Other soils

A **mollic A1 horizon is generally identified by its dark colour and thickness (20 cm or more), caused by the accumulation of organic matter, well-developed structure (usually a granular or fine subangular blocky structure), high base saturation (>50% and pH_{H2O} > 6).*
*An **umbric** horizon has similar properties but has lower base saturation. For further details see FAO (2014).*

Table 2. A simplified guide to the USDA soil classification system (Soil Taxonomy) for PNG forest soils

Note: this key is based on The Illustrated Guide to Soil Taxonomy (Soil Survey Staff 2014). Orders most likely to occur in Papua New Guinea forests are shown in bold underlined capitals. Use this key for provisional USDA soil classification to Order level. Final classification to Order level, and to lower levels (Suborders and Great Groups) should be made using the complete key in The Illustrated Guide.

1. Permafrost – Gelisols

2. Peaty – **HISTOSOLS**
Must have histic epipedon; usually aquic soil moisture regime; no diagnostic subsurface horizons; rapid decomposition when aerated; peat or bog; >20% organic matter; organic soil materials extending down to an impermeable layer or with an organic layer that is more than 40 cm thick and without andic properties; common in wetlands (swamps, marshes, etc.).

3. Spodic horizon more than 10 cm thick – Spodosols

4. Andic soil properties (i.e. recent volcanic ash) in >60% of profile – A**NDOSOLS**
Form from volcanic ejecta, dominated by allophane or Al-humic complexes; must have andic soil properties: high in poorly crystalline Fe and Al minerals, high in phosphorous, low bulk density, and high proportions of glass and amorphous colloidal materials, such as allophane, imogolite and ferrihydrite; high organic matter content, sometimes melanic epipedon.

5. An Oxic horizon – **OXISOLS**
Most soil profile development of all soils; must have oxic horizon within 150 cm of soil surface; low nutrient availability; no argillic horizon; highly weathered; dominated by end-member clays, Al and Fe oxides; commonly in old landscapes in tropics.

6. >30% clay and cracks that open and close – **VERTISOLS**
Usually mollic epipedon; high in shrinking and swelling clays; >30% clay to a depth of 50 cm; deep cracks (gilgai) form when soil dries; form from parent material high in clay (e.g., shales, basins, exposed Bt horizons of old soils).

7. Arid climate? – Aridisols

8. An argillic or kandic horizon and <35% base saturation – **ULTISOLS**
Must have argillic or kandic horizon; low base saturation of <35% at 2 m depth or 75 cm below a fragipan; common in subtropical regions; often known as red clay soils.

9. A mollic epipedon and base saturation >50% in all horizons – **MOLLISOLS**
Must have mollic epipedon; high base saturation of >50%; dark soils; some with argillic or natric horizons; common in grasslands.

10. Other soils that have an argillic or kandic horizon – **ALFISOLS**
Must have argillic, natric, or kandic horizon; high-to-medium base saturation; moderately weathered; commonly form under boreal or broadleaf forests; rich in iron and aluminum; commonly in humid areas, semi-tropics, and Mediterranean climates.

11. Other soils with a cambic horizon or placic horizon – **INCEPTISOLS**
A B horizon is evident; no other diagnostic subsurface horizons; on landscapes continuously eroded or young deposits; cambic, sulfuric, calcic, gypsic, petrocalcic, or petrogypsic horizon, or with a mollic, umbric, or histic epipedon, or with an exchangeable sodium percentage of >15% or a fragipan.

12. Other soils with little or no horizon development – **ENTISOLS**
Little or no development of soil horizons, other than a slightly darkened ochric (typically thin and/or light-coloured) epipedon as a surface layer; found in coarse rocky material as well as in recent fluvial sediments and permanently submerged sediments.

Diagnostic horizons, properties, and temperature and moisture regimes
Soil Taxonomy uses the concepts of diagnostic horizons and properties, and temperature and moisture regimes. Abbreviated definitions of the more useful terms for classifying PNG forest soils are given below. For complete definitions see Soil Survey Staff (2014).

Surface horizons (epipedons)
- **Anthropic** – a thick horizon formed in human-altered or human-transported material
- **Folistic** – a more or less freely drained horizon formed in organic material
- **Histic** – a saturated horizon formed in organic material
- **Melanic** – a thick, dark-coloured humus-rich horizon in which organic carbon is associated with poorly crystalline short-range-order minerals or aluminium-humus complexes
- **Mollic** – a dark well-structured topsoil with base saturation >50%
- **Ochric** – a more or less minimally developed surface horizon, typically thin or light coloured, that does not meet the criteria for any other epipedon
- **Plaggen** – a human-developed surface layer resulting from long term manuring and cultivation
- **Umbric** – a thick dark coloured humus-rich horizon with low base status

Subsurface horizons

- **Argillic horizon** – a horizon resulting from clay accumulation down the profile, combined with evidence of clay movement (clay skins)
- **Cambic horizon** – a well-drained horizon, not water saturated within 50 cm of the soil surface, that has more colour and structure than the horizon below
- **Kandic horizon** – a horizon resulting from clay accumulation with a CEC of 16 cmol(+)/kg or less (kaolinite dominates)
- **Oxic horizon** – less than 10% weatherable minerals, <5% stones, CEC of 16 cmol(+)/kg or less, only a small clay increase with depth
- **Placic horizon** – a thin Fe, Mn or organic pan
- **Spodic horizon** – accumulation of subsoil Al, organic matter and Fe

5.5 SAMPLING THE SOIL PROFILE

The profile needs to be sampled for soil chemistry and for subsoil bulk density (BD), so that chemical data can be expressed on an area basis (t/ha) to 1 m depth.

Soil chemistry sampling

- For soil chemical analysis sample in a continuous column down the profile face, to avoid bias. This is called “channel” sampling.
- For each depth (0–10 cm, 10–20 cm, 20–30 cm, 30–60 cm and 60–100 cm) transfer about 2 kg of moist soil to labelled plastic bags using a spade and trowel.
- Put an extra waterproof paper label in each bag.

Subsoil bulk density sampling

For non-stony sandy or loamy soils or soils containing less than 10% stones

1. Use the Rowfit sampler to sample at 40–50 cm depth using a bench cut at 40 cm depth. In coherent soils the Rowfit sampler can be inserted horizontally, with its centre at 45 cm.
2. Remove the sampler and the liner. Discard samples that do not fill the sampler. Cut off excess soil from the lower end of the liner and transfer contents to a labelled plastic bag.
3. Repeat at 75-85 cm depth (80 cm if inserting the sampler horizontally).

For stony soils

1. Cut a bench at 40 cm depth. Outline a square 10 x 10 cm on the exposed surface[3]. Carefully dig out a mini-pit 10 x 10 x 10 cm and transfer the contents into the plastic bag labelled **Profile BD 40–50 cm depth**. Larger stones can be discarded.
2. Cut a bench at 75 cm depth and repeat the sampling, transferring the contents of the mini-pit into the plastic bag labelled **Profile BD 75–85 cm depth**.

Record the method used

Record the method used for BD determination in subsoils on the profile sheet.

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[3] If stones are large use bigger squares. Record the size of the squares used on the profile sheet.

6. TOPSOIL REPLICATE SAMPLING

The aim of topsoil replicate sampling is to cover the variation in soil properties at the profile site, because soil properties in topsoils are variable and measurements at a single site may not give a typical result. Take samples with the Eijkelkamp split-tube sampler or the Rowfit sampler or the rectangular box method as appropriate. Use a sharpened Rowfit liner on its own in sticky clayey soils.

- Ensure all replicate ten sites are on the same landform as the profile.
- One of the ten replicates should be taken at the profile site.
- Avoid disturbing the NFI clusters – take replicate samples from outside the 25 m radius plots used for biodiversity assessment.
- Always **sample at right angles to the soil surface.**
- Replicate sampling sites should be at least 5 m from large trees and about 10 m apart.
- **Use the same method for all topsoil samples**. Record the method used on the profile sheet.
- Label three large plastic bags with the site name or number, e.g. **reps 0–10 cm**, **reps 10–20 cm**, and **reps 20–30 cm**.
- Keep count of samples taken by marking off samples taken on the sides of the bags with a felt pen.

6.1 Notes on different sampling methods

- It is a good idea to insert the Eijkelkamp sampler about 37 cm into the soil and then cut up the soil into 10 cm lengths while still in the half-tube. Lay the sampler on a board so that any spilled soil can be collected and added to the relevant soil bag.
- When sampling at 10-20 cm and 20-30 cm depth with the Rowfit sampler, a fresh bench (parallel to the ground surface) will need to be cut at 10 cm and 20 cm depth.
- Use a rag to clean the samplers between sample sites.

7. TOPSOIL SAMPLING DURING BIODIVERSITY ASSESSMENT

Topsoil (0–10, 10–20 and 20–30 cm) samples will be taken at every NFI cluster during biodiversity assessments. These samples should be labelled **Bio BD**. Use either the Eijkelkamp or Rowfit sampler on non-stony soils, or the rectangular box method on stony soils.

The *scientific coordinator* needs to be able to match these topsoil samples to a corresponding profile, so that total soil carbon (to 1 m depth) can be correctly predicted at NFI sites having similar geology and landforms. To facilitate this correlation a member of the biodiversity team must record the following site characteristics at the centre plot of the NFI cluster:

- **Site slope** (use a clinometer)
- **Landform** (see p. 15)
- **Parent material** (see p. 15)
- **Geology** as shown on **geological maps** (original geological maps, not PNGRIS)
- **Geology** as determined in the **field** (e.g. in nearby road cuttings or streams)

Topsoils should be sampled in a circle just outside the centre plot of the cluster. Sample in a circle of about 26 m radius, at ten points roughly 15 m apart. If more samples are taken record the number. Follow the instructions on page 28. The three sample bags for each cluster should be labelled clearly with the NFI cluster number, sample depth, and the words **Bio BD**, to clearly distinguish the samples from any Profile BD replicate samples.

8. IN THE LABORATORY

8.1 Topsoil replicate samples

The preparation of the bulked topsoil replicates is identical for Profile sites and Bio sites. The aim of the laboratory work is to:

- Calculate the bulk density of 0–10 cm, 10–20 cm and 20–30 cm topsoil layers.
- Obtain a subsample of each layer for chemical analysis. The laboratory requires a minimum of 50 g of <2 mm air-dry soil for each of the three layers (3 samples in total).

8.2 Profile samples

The aim of the laboratory work is to:

- Calculate the bulk density of samples taken in the 30–60 cm and 60–100 cm depth intervals.
- Prepare "profile chem" samples for laboratory analysis. The laboratory requires a minimum of 50 g of <2 mm air-dry soil for each sample (5 samples in total).

8.3 Sample preparation

Topsoil replicate samples

Use Table 3 to record laboratory data and calculate bulk density.

Calculating bulk density

1. Weigh the three bulked replicate samples for 0–10 cm, 10–20 cm and 20–30 cm depths. (First tare the scales with a plastic bag and label.)
2. Record the weight of 3 labelled aluminium trays.
3. Mix the moist soil in each bag, take a sample of about 1 kg and weigh it in a tray.
4. Dry this sample overnight at 110^{o}C and weigh it. Re-weigh the sample after further drying for 1 hour to check that all moisture has been driven off.
5. Sieve the dried soil through a 2 mm sieve. Calculate the weight of the <2mm fraction either by weighing the stones (>2 mm) or weighing the fine earth fraction (<2 mm). Discard the stones.
6. Calculate the total weight of dry soil <2 mm in the total sample for each depth.
7. Calculate BD (in t/m^3) for the <2 mm soil fraction in the bulked replicates for the relevant depth.

8. Calculate the weight of <2 mm soil in t/ha for the sampling depth. (For a 10 cm sampling depth the weight of <2mm soil = 10^3 x BD t/ha.)

Subsamples for topsoil chemistry (three samples)

1. From each of the three bags of mixed moist soil, take a separate 500 g subsample.
2. Air dry each sample at 30°C overnight. Sieve through a 2 mm sieve. Discard the >2mm fraction (stones). Put the <2 mm fraction into a labelled plastic bag for chemical analysis. Label the bags **Profile chem** or **Bio chem** as appropriate. (The laboratory requires a minimum of 50 g of air-dry soil.)

Subsoil BD samples (two samples)

1. Weigh the samples for 40–60 cm and 75–85 cm depth.
2. Dry each sample overnight at 110°C. Re-weigh the sample after further drying for 1 hour to check that all moisture has been driven off.
3. Sieve each dried soil through a 2 mm sieve. Calculate the weight of the <2mm fraction either by weighing the stones (>2 mm) or weighing the fine earth fraction (<2 mm). Discard the stones.
4. Calculate the total weight of dry soil <2 mm in the total sample for that depth.
5. Calculate the BD of the <2 mm soil for each depth.

Profile chemistry and replicate chemistry samples (eight samples)

1. Air dry each sample at approximately 30°C.
2. Sieve through a 2 mm sieve. Discard the >2mm fraction (stones). Put the <2 mm fraction into a labelled plastic bag for chemical analysis. (The laboratory requires a minimum of 50 g of air-dry soil.)

8.4 Sending samples for analysis

For each profile site eight samples will be sent to the laboratory for carbon and chemical analysis – three from the bulked 0–10 cm, 10–20 cm and 20–30 cm samples, and five from the profile. For each biodiversity site there will be 3 topsoil samples, normally for carbon and nitrogen analysis only.

9. CALCULATING SOIL CARBON PER HECTARE

Carbon analyses received from the laboratory will be expressed as % carbon in the <2mm soil. Calculate t/ha values using Table 4. Note that topsoil carbon values must be corrected for slope by dividing by the cosine of the slope angle (Appendix 2). Subsoil carbon values do not require slope correction.

Table 3. Record sheet for bulk density calculation.

Site name: **Date:** **Measurements by:**

Depth (cm)	**Sampling method (E, R or RB)**	**Number* of cores or samples**	**Total weight of sample (tared) (g)**	**Weight of tray (g)**	**Weight of field-moist subsample with tray (g)**	**Weight of field-moist subsample without tray (g)**	**Weight of oven-dry subsample with tray (g)**	**Weight of oven-dry subsample without tray (g)**	**Calculated dry weight of total sample (g)**	**Total volume sampled** (m^3)**	**BD (t/m^3)**
0-10		10									
10-20		10									
20-30		10									
30-60		1									
60-100		1									

*Adjust number of cores as required.

***the volume of ten 10 cm columns of soil sampled by Method E (the Eijkelkamp sampler) is 0.001810 m^3;*
the volume of ten 10 cm columns of soil sampled by Method R (the Rowfit sampler) is 0.004537 m^3;
the volume of ten 10 x 10 x 10 cm samples sampled by Method RB (the rectangular box method) is 0.01 m^3.

Table 4. Calculating soil carbon content to 1 m depth.

Column:	**a**		**b**	**c**		**d**		**e**
Sampling depth	BD (t/m3)	Formula to determine **b**	<2 mm soil (t/ha)	C (%)	Slope angle (deg)	Cosine slope angle	Formula to determine **e**	C (t/ha)
0–10 cm		a x 10^3					(b×c)/(100×d)	
10–20 cm		a x 10^3					(b×c)/(100×d)	
20–30 cm		a x 10^3					(b×c)/100×d	
30–60 cm		3a x 10^3					(b×c)/100	
60–100 cm		4a x 10^3					(b×c)/100	
TOTAL CARBON TO 1 m DEPTH								

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APPENDIX 1. A SAMPLING STRATEGY FOR SELECTING CLUSTERS FOR SOIL SURVEY IN THE NFI

BACKGROUND

Papua New Guinea Forest Authority (PNGFA) with the support of UN-REDD and EU, is currently preparing the first National Forest Inventory (NFI). This NFI will provide a basis for planning activities in the forestry sector and in particular for those related to sustainable forest management. The NFI will also be a key element of the National Forest Monitoring System that PNG is required to establish in order to participate at the expected UNFCCC mechanism on REDD+ and will be one of the main data sources for the PNG national greenhouse gas (GHG) inventory. Phase 1 (remote sensing based) of the NFI assessment was completed in March 2014. A total of 25,279 1-ha plots systematically distributed on 0.04x0.04 degree grid over the country were assessed to identify the land use and vegetation type. One thousand plots will be visited and surveyed on the ground for detailed information including biodiversity. One hundred of these will be selected for detailed soil study including carbon determination to 1 m depth. Soil carbon is one of the five forest carbon pools, which need to be reported under UNFCCC. The NFI includes soil carbon assessment, so that total ecosystem carbon in PNG forests can be systematically estimated.

Maintaining healthy levels of soil organic matter in soils has traditionally been linked with the maintenance of soil fertility and structure, but recently the storage of carbon in the soil has become a matter of importance in its own right, because of its potential as a carbon sink for mitigating the effects of carbon accumulation in the global atmosphere.

The carbon in forest biomass in PNG has been measured in several studies. Fox et al. (2010), working in permanent sample plots throughout PNG, estimated total above-ground biomass carbon to be 80–90 t/ha in secondary forests (120 sites) and 121–168 t/ha in primary forests (13 sites). Bryan et al. (2010), using transect methods at 12 sites in lowland forest of Western Province, estimated the above-ground biomass to be 193–253 t/ha in unlogged forests, which translates to biomass carbon of 87–127 t/ha. Edwards and Grubb (1977), studying a montane site (2500 m altitude) on the flanks of Mt Kerigomma in the Bismarck Range, found that total above- and below-ground biomass carbon was c. 175 t/ha, with about 20 t/ha of this being contributed by roots.

Soil carbon has been measured in many early PNG soil surveys published in the CSIRO Land Research Series reports, summarised by Bleeker (1983), but these results cannot be expressed accurately on an area (t/ha) basis because soil bulk density was not systematically measured. Later surveys (Table 1) have addressed this issue. Matsuura (1997) found that forested soils at five sites in schist and sedimentary rocks contained between 86 and 132 t/ha of carbon to 1 m depth. There was no clear relationship of soil carbon to rock type or slope position. Nimiago (2011) measured soil carbon values on an area basis to 30 cm depth at five sites in PNG forests and showed that montane forest soils contained more carbon than lowland forests, but whether the differences observed were due entirely to altitude was unclear: values were probably affected by disturbance, soil parent material and rainfall. Abe (2007) measured soil carbon to 1 m depth in soils derived from limestone in the Mongi-Busiga forest developed on soils in uplifted coral limestone and found that organic carbon (analysed separately from total carbon, partly derived from carbonates) was in the range 101–157 t/ha.

Table 1. Soil carbon in PNG forests and selected Tasmanian and New Zealand examples.

Site	Brief description	Depth (cm)	Total carbon (t/ha)	Reference
Papua New Guinea				
Oomsis-1	Lowland, schist, upper slope	0–100	86	Matsuura 1997
Oomsis-2	Lowland, schist, lower slope	0–100	132	Matsuura 1997
Buang	1400 m, schist* upper slope,	0–100	97	Matsuura 1997
Madang-Kumil	Lowland, sedimentary, upper slope	0–100	123	Matsuura 1997
Madang-Kumil	Lowland, sedimentary, lower slope	0–100	95	Matsuura 1997
Kui	Logged pre-1990, lowland, stony	0–30	45	Nimiago 2011
Danar 1	Cultivated plot, lowland, degraded	0–30	56	Nimiago 2011
Danar 3	Logged 2006, lowland, degraded	0–30	31	Nimiago 2011
Watut 3	Logged 1995, montane	0–30	113	Nimiago 2011
Watut 7	Primary forest, montane	0–30	103	Nimiago 2011
Mt Kerigomma	Primary forest, montane	0–25	164	Edwards and Grubb 1977
Mt Kerigomma	Primary forest, montane	25–100	435	Edwards and Grubb 1977
Mongi-Busiga 9720	Primary forest, 150 m, 34° slope, slight erosion	0–100	157	Abe 2007
Mongi-Busiga 9721	Primary forest, 130 m, 17° slope, no erosion	0–100	101	Abe 2007
Mongi-Busiga 9722	Primary forest, 130 m, 17° slope, slight erosion	0–100	112	Abe 2007
Mongi-Busiga 9720	Primary forest, 160 m, 13° slope, slight erosion	0–100	134	Abe 2007
Tasmania				
Stronach	Wet eucalypt forest on granite	0–25	103	Grant et al. 1995
Warra	Wet eucalypt forest on fan alluvium	0–25	65**	McIntosh 2012
New Zealand				
Edendale	Wet broadleaf podocarp forest on loess	0–25	139	McIntosh 1995
South Island	Wet forest and ex-forest sites on loess	0–20	88–104	McIntosh et al. 1997

*Described as 'sedimentary' by Matsuura (1997) but the Markham geological map shows schist.
**Value may have been reduced by a fire c. 120 years ago.

Nimiago's (2011) topsoil carbon values obtained for PNG montane sites (103–113 t/ha) and the values obtained by Abe (2007) for topsoils (67–127 t/ha) are comparable to those obtained by McIntosh (1995) and McIntosh et al. (1997) for topsoils in lowland forest and ex-forest (native grassland) sites in New Zealand's South Island (88–139 t/ha) and to the 103 t/ha figure for a wet eucalypt forest site on granite in Tasmania (Grant et al. 1995), but higher than the result obtained (65 t/ha) for a lowland wet eucalypt forest site at Warra in Tasmania (McIntosh 2012) which may have been affected by historic fires. Three profiles in siltstones in Madang Province, sampled using methods developed for the NFI survey (see this report) produced carbon values in the range 87–135 t/ha (Nimiago et al. 2016a, b, c).

The very high total soil carbon content (599 t/ha) of the PNG soil (0–100 cm) studied by Edwards and Grubb (1977) is probably not typical of PNG soils in general: at the study site the soil is formed in gabbroic alluvium and volcanic ash, and contained high amounts of amorphous clay (hydrated iron oxides) which are known to form stable complexes with organic matter (Gu et al. 1994). Excluding the result of Edwards and Grubb (1977) and the stony and degraded soils reported by Nimiago (2011), PNG studies show that total carbon to 1 m depth in many forest soils is likely to be in the range 85–160 t/ha, and above-ground biomass carbon is likely to be in the range 80–170 t/ha, i.e. topsoil carbon is likely to contribute to up to 50% of total ecosystem carbon.

Thus soil carbon is not an insignificant contributor to total ecosystem carbon in PNG forests, and should be measured if an accurate estimate of ecosystem carbon is to be calculated. This appendix, which is developed from initial ideas proposed by Nimiago et al. (2014), outlines a strategy for measuring soil carbon at representative sites in PNG, so that (among other objectives) the total carbon content of PNG forest ecosystems can be estimated.

METHODS

Sampling strategy

The main factors influencing carbon levels in well drained soils are likely to be geology (Edwards and Grubb 1977) and altitude (Nimiago 2011), which can be broadly related to forest type (NFI, Phase 1, unpublished); aspect-related differences of soil carbon are likely to be small relative to effects in temperate low-latitude countries like New Zealand (McIntosh et al. 2000). We therefore suggest that within the structure of the NFI survey, a subset of clusters should be sampled following a factorial design covering the main altitude-related forest types, as determined in Phase 1 of this study, as well as the most extensive soil-forming rock types in PNG (D'Addario et al. 1975; Davies 2012). A factorial design should allow altitude-related and geology-related effects to be determined and therefore facilitate extrapolation of results with some confidence over the wider area of PNG forests. However, it is impossible to take into account important local factors affecting soil carbon content like slope, land use history and landslides (Rijkse and Trangmar 1995; Trangmar et al. 1995) in a "broad brush" factorial design of only 100 sites. These important local factors may over-ride the effects of geology – essentially the factorial design is simply a means of obtaining a representative subsample from the 1000 clusters available for soil survey, rather than a design for later statistical analysis.

If (a) the influence of altitude and vegetation can be reasonably considered as being affected by three vegetation types; and a (2) factorial soil sampling strategy is accepted; and (3) the ten "Fundamental Groups" (other than Swamps and Marine/estuarine silts and clays) listed by McIntosh (2014) are selected as requiring equal emphasis in the survey; and (4) funds allow for detailed soil survey at 100 sites, then a possible factorial sampling strategy is:

3 Forest types x 10 Geological substrates x 3 replicates (90 clusters in total)

Table 2. Forest types

Forest types (from Phase 1)
Low altitude forest on uplands
Low altitude forest on plains and fans
Lower montane forest

Table 2. Geological substrates

Geological substrates (defined by McIntosh 2014)
Basic and Ultrabasic rocks including basic schist
Limestone, dolomite, calcarenite etc
Silica rich volcanics - pumice and rhyolite and dacite
Intermediate volcanics - andesites and tuffaceous sediments
Sandy and gravelly sedimentary rocks
Siltstones, mudstones and shales, including calcareous sediments
Coarse alluvium - terrace and fan gravels
Fine alluvium - silty and clayey
Quartz-mica schist
Granite and granodiorite

Swamp forests and Marine estuarine silts and clays will require separate sampling because they require different sampling methods, which have not yet been trialled. Because the distribution of these soils is determined by drainage rather than geology, and poor drainage favours organic matter accumulation, forests on these parent materials are likely to contribute to PNG soil carbon stocks out of proportion to their area. Once appropriate methods for sampling have been determined, Swamp forests and Marine estuarine silts and clays can be sampled at a total of ten sites. A possible sampling strategy is:

3 clusters located on marine/estuarine silts and clays
1 cluster in low altitude Swamp forests
1 cluster in upland Swamp forests
1 cluster in montane Swamp forests.

This leaves funds for soil sampling at 4 clusters to obtain data for minor forest types defined in Phase 1 (e.g. Dry Seasonal Forest, Woodland), each covering <4% of PNG's forested area.

APPENDIX 2. COSINE TABLE

Slope in degrees	Cosine
0	1.0000
1	.9998
2	.9994
3	.9986
4	.9976
5	.9962
6	.9945
7	.9925
8	.9903
9	.9877
10	.9848
11	.9816
12	.9781
13	.9744
14	.9703
15	.9659
16	.9613
17	.9563
18	.9511
19	.9455
20	.9397
21	.9336
22	.9272

Slope in degrees	Cosine
23	.9205
24	.9135
25	.9063
26	.8988
27	.8910
28	.8829
29	.8746
30	.8660
31	.8572
32	.8480
33	.8387
34	.8290
35	.8192
36	.8090
37	.7986
38	.7880
39	.7771
40	.7660
41	.7547
42	.7431
43	.7314
44	.7193
45	.7071