Australian Government

Australian Centre for International Agricultural Research

SMALLHOLDER COFFEE PRODUCTION IN PAPUA NEW GUINEA – FARMER TRAINING GUIDE

UNIT 2: MANAGING YOUR COFFEE GARDEN

MODULE 4:
DRAINAGE

Curry G, Tilden G, and Aroga L (2025) *Smallholder coffee production in Papua New Guinea: A training package for extension officers and farmers*, ACIAR Monograph No. 220, Australian Centre for International Agricultural Research, Canberra.

ACIAR Monograph Series No. 220 (MN220)

Cover: Drains in coffee gardens

Sources of photos:
Top: Bob Kora
RHS: Pennuel Togonave
LHS: Rauke Buimeng

Australian Government
Australian Centre for
International Agricultural Research

SMALLHOLDER COFFEE PRODUCTION IN
PAPUA NEW GUINEA – FARMER TRAINING GUIDE

UNIT 2: MANAGING YOUR COFFEE GARDEN

MODULE 4:
DRAINAGE

The Smallholder Coffee Production in Papua New Guinea Training Program

The training program contains modules prepared in partnership with the Australian Centre for International Agricultural Research (ACIAR) and by CARE-International. The structures of the Extension Officer Training Program and the Farmer Training Program are shown in the table below. Some modules also contain references to additional training that learners are encouraged to complete as part of their training.

Extension Officer Training Program

Title	Module reference
Introduction to smallholder coffee production in Papua New Guinea	ACIAR smallholder coffee production in Papua New Guinea Training Package
Extension Principles	
Introduction to the Coffee Extension Officer and Farmer Training Guides	ACIAR Extension Officer Guide Unit 1 Module 1
The extension officer - roles and effectiveness	ACIAR Extension Officer Guide Unit 1 Module 2
Knowing Your Farmers	
Getting to know our coffee smallholders	ACIAR Extension Officer Guide Unit 2 Module 1
What factors affect smallholder coffee production?	ACIAR Extension Officer Guide Unit 2 Module 2
Strongim grup: course facilitator guide	CARE Organisational Strengthening Training

ACIAR Resource

Monograph MN220 Smallholder Coffee Production in Papua New Guinea: a training package for extension officers and farmers. This package contains the modules for both the extension officer training guide and the farmer training guide.

The ACIAR monograph is available online from **www.aciar.gov.au/publication/MN220-PNG-coffee-manual-1**

Hard copies of the ACIAR training package may be available by contacting ACIAR or the Coffee Industry Corporation (CIC).

CARE Resources

Organisational Strengthening Training
CARE Family Money Management Training

The CARE modules are available online from **https://pngcdwstandard.com/resources-for-use-by-cdws-working-with-wards-communities-groups-and-smes**

Hard copies of the CARE modules may be available by contacting the CIC or CARE-International.

Farmer Training Program

Title	Module reference
Becoming a Coffee Farmer	
Knowing your coffee tree	ACIAR Farmer Training Guide Unit 1 Module 1
Coffee nursery development	ACIAR Farmer Training Guide Unit 1 Module 2
Establishing a new coffee garden	ACIAR Farmer Training Guide Unit 1 Module 3
Managing Your Coffee Garden	
Weed Control	ACIAR Farmer Training Guide Unit 2 Module 1
Maintenance pruning and rehabilitation	ACIAR Farmer Training Guide Unit 2 Module 2
Shade management	ACIAR Farmer Training Guide Unit 2 Module 3
Drainage	ACIAR Farmer Training Guide Unit 2 Module 4
Pest and disease management	ACIAR Farmer Training Guide Unit 2 Module 5
Coffee berry borer management	ACIAR Farmer Training Guide Unit 2 Module 6
Soil fertility and nutrient maintenance	ACIAR Farmer Training Guide Unit 2 Module 7
Intercropping in your coffee garden	ACIAR Farmer Training Guide Unit 2 Module 8
Harvesting and Processing Coffee	
Coffee harvesting and processing	ACIAR Farmer Training Guide Unit 3 Module 1
Coffee grading systems and pricing	ACIAR Farmer Training Guide Unit 3 Module 2
Establishing a mini wet factory	ACIAR Farmer Training Guide Unit 3 Module 3
Coffee Marketing	
Understanding the domestic coffee market	ACIAR Farmer Training Guide Unit 4 Module 1
Kamapim ol praioriti	CARE Organisational Strengthening Training
Kamapim ol eksen plen	CARE Organisational Strengthening Training
Setim gutpela kastom bilong ronim grup	CARE Organisational Strengthening Training
Wok bilong meneja na memba na lida	CARE Organisational Strengthening Training
Coffee certification	ACIAR Farmer Training Guide Unit 4 Module 2
Fair trade certification	ACIAR Farmer Training Guide Unit 4 Module 3
Family money management	CARE Family Money Management Training

CONTENTS

MODULE TOPICS

CONTRIBUTING AUTHORS

Leo Aroga, George Curry, Geraldine Tilden, Michael Kaugam,
Rauke Buimeng and Mark Thomas

ACKNOWLEDGEMENTS

This module is part of a series of modules developed specifically as a resource for extension officers for training smallholder farmer groups and the training of cadet extension officers. Most of the information provided in this module is from *The Papua New Guinea Coffee Handbook* (2nd edition), Coffee Industry Corporation Ltd.

The knowledge of the following contributors has been invaluable in the development and writing of this module:

Coffee Industry Corporation Ltd
Samson Jack, Rati Irikati and Bob Kora (illustrations)

Curtin University
Gina Koczberski

Australian Centre for International Agricultural Research
The development of this module was supported by the following ACIAR-funded projects:

- Improving livelihoods of smallholder families through increased productivity of coffee-based farming systems in the highlands of Papua New Guinea (ASEM/2008/036)
- Improving livelihoods of smallholder coffee communities in Papua New Guinea (ASEM/2016/100)

INTRODUCTION

Aim of Module:

The aim of this module is to improve farmers' awareness of the significance of a good drainage system in a coffee garden and to understand the steps involved in its construction and maintenance to ensure its long-term effectiveness.

One of the most important elements that impacts the health and productivity of the trees in a coffee garden is drainage. A good drainage system keeps coffee trees healthy and productive by enabling them to anchor securely to the soil and effectively absorb sufficient moisture and nutrients. It also prevents the loss of soil and valuable nutrients caused by erosion. For long-term effectiveness, the drainage system should be carefully planned, constructed and maintained.

LEARNING OUTCOMES

By the end of this module you will:

- Understand how a drainage system affects the health and productivity of coffee trees
- The importance of avoiding waterlogging and erosion
- Understand how to plan and construct a suitable drainage system
- Understand what is involved in the maintenance of a drainage system

LESSON PLAN

This module has three parts:

Sections 4.1 and 4.2	Types of drainage systems and their importance
Section 4.3	Planning a drainage system
Sections 4.4 and 4.5	Construction and maintenance of a drainage system

TIME REQUIRED TO COMPLETE THIS MODULE: 3–5 DAYS

LIST OF SYMBOLS:

Farmer notes, brochures & factsheets

For the Extension Officer

TEACHING AIDS

- Butchers' paper and coloured marker pens (or white board, coloured white board marker pens and white board eraser)
- The coffee calendar and stickers
- Farmer notes (one copy for each participant plus extra copies)
- A healthy young coffee tree removed from the ground, including its roots

PRE-TRAINING ACTIVITIES

- Confirm number of training participants
- Draw a large diagram of a root system
- Source a young coffee tree that can be removed on the day or the day before the training to demonstrate how a healthy root system should appear
- Arrange access to a coffee garden with drainage problems
- Arrange access to a coffee garden with a good drainage system
- Arrange a demonstration plot or access to a coffee garden in the early stages of development, where participants can mark out and dig a drain
- Arrange access to a coffee garden with a relatively good drainage system that requires some maintenance

EQUIPMENT REQUIRED BY FARMER GROUP DURING TRAINING

- Pegs and string line
- Measuring stick or tape measure (for accurate spacing)
- Bush knife (for clearing)
- Shovels and/or spades
- Pick axe, mattock and crowbar (for hard structured soils)
- Axe (for when roots interfere with drains)

PRELIMINARY ACTIVITIES

The farmers will complete two exercises prior to undertaking the module topics. These include the coffee calendar and the quiz. The purpose of these exercises is for the extension officer to assess the level of knowledge of farmers in the group prior to completing the module.

The coffee calendar

The coffee calendar lists the main events and activities occurring during an annual cycle of coffee production. The first item on the calendar is coffee berry development. All other activities are linked to the stage of development of coffee berries from flowering through to overripe cherry.

Annual coffee production events and activities (stickers)

1. Flowering and berry development
2. Harvesting coffee
3. Pulping and drying coffee
4. Maintenance – weeding, pruning, mulching, shade management, digging and maintaining drains, and maintaining fencing
5. CBB control measures

Using the stickers for each of the annual coffee activities listed above, work with the farmer group to attach them to the appropriate rows of the coffee calendar.

- Begin by attaching the progressive stages of coffee berry development from flowering through to bright red cherry ready for harvest, and to overripe cherry
- Complete the remaining sections linking each activity with the different stages of berry development
- For this module, integrate the activities relating to soil conservation and erosion control listed below

Drainage activities

In a new coffee garden

1. Plan the drainage system
2. Mark out and dig the main drains
3. Mark the locations of the coffee trees
4. Mark out and dig the field drains
5. Plant the coffee seedlings
6. Modify drains

In an established coffee garden

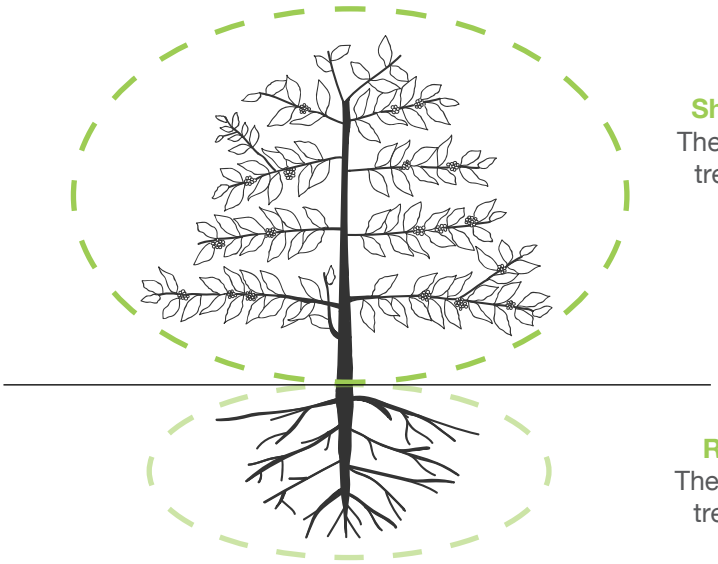
1. Maintain drains during the dry season
2. Maintain drains at intervals during the wet season, particularly after rain events

Quiz

- Before beginning the module topics, ask the farmers to complete the quiz at the end of this module
- Repeat the quiz on completion of the module topics

4.1 IMPORTANCE OF GOOD DRAINAGE

One of the most important requirements for growing strong and healthy coffee trees is good soil. Coffee trees grow best in soils that are fertile, have good structure and are well aerated, preferably to a depth of at least 50 cm. Approximately 80% of the roots of a coffee tree are located in the top 30 cm of soil, so it is important that the roots are able to access appropriate amounts of air, water and nutrients from this zone.

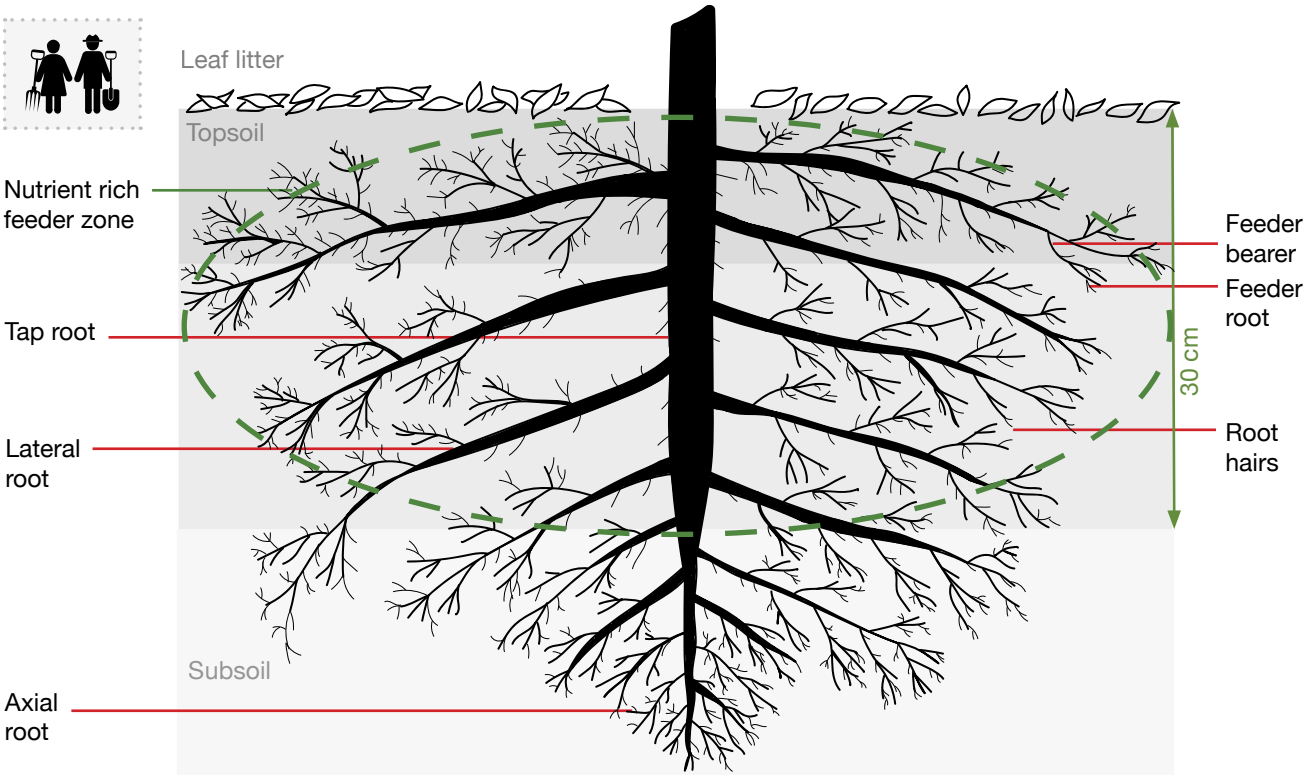


Coffee tree with a healthy shoot and root system

Root system

A healthy root system is vital to establishing a healthy coffee tree. The root system has three main functions:

1. To hold the tree in place in the ground
2. To take up water and nutrients from the soil
3. To transport water and nutrients up to the shoot system



Coffee tree root system

Activity 1: Coffee tree root system

Show a young coffee tree with a healthy root system. Point out:

- Tap root
- Lateral roots
- Axial roots
- Feeder bearers
- Feeder roots
- Root hairs

Maintaining a healthy root environment

If the soil in which the coffee trees are planted is not well cared for, the coffee trees may suffer, reducing cherry production and income.

- Coffee trees do not grow well in soils that have poor structure or are poorly drained
- While moisture in the soil is required for plant growth, too much moisture can have negative impacts on the coffee trees
- Maintaining good soil structure and nutrient reserves by way of the use of mulch and leaf litter from shade trees will not benefit the coffee trees unless they can access the moisture and nutrients
- Soil volume and valuable nutrients will be lost if the soil is subject to erosion

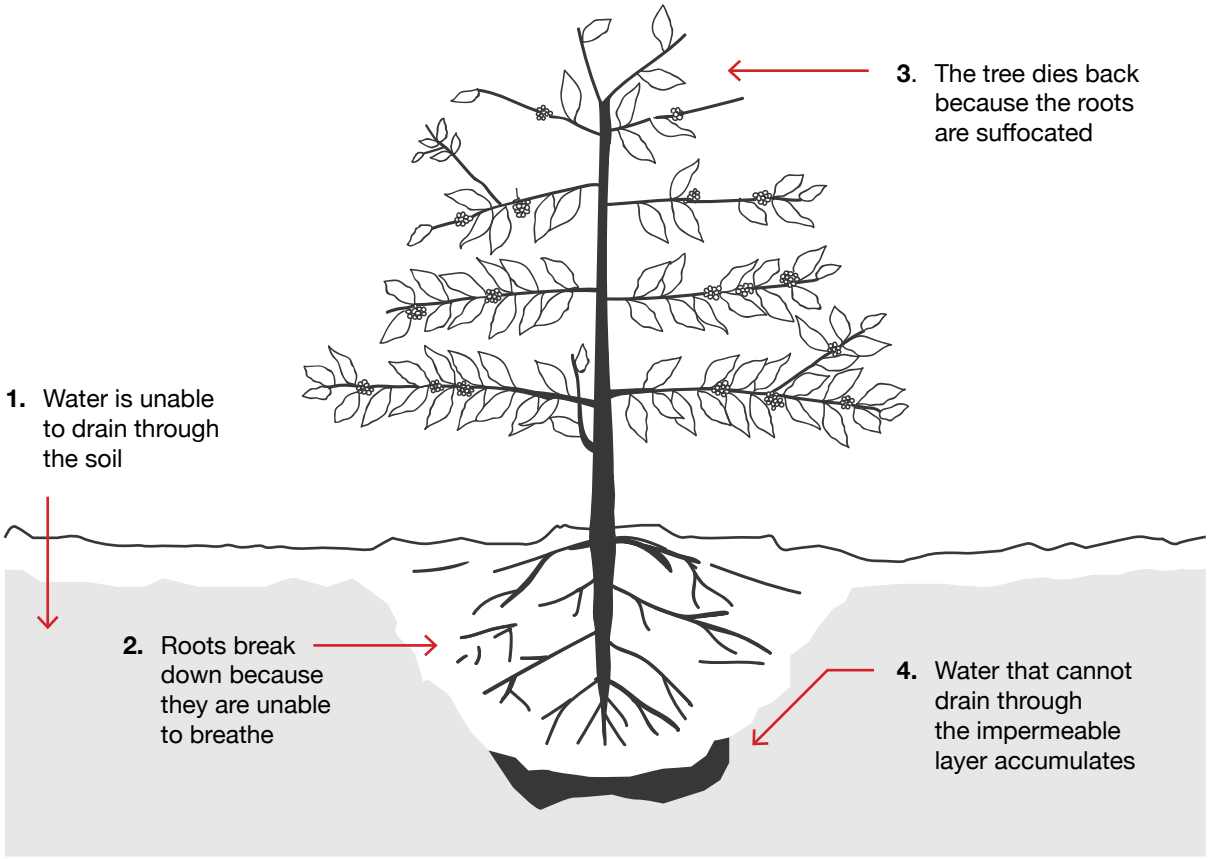
Waterlogging

What is waterlogging?

- Water runs down through ('infiltrates') the soil when it rains
- When the soil is saturated with water, we say it is 'waterlogged'
- When waterlogging occurs, there is a shortage of air present in the soil
- The ability of soil to absorb and filter water, as well as the speed at which this process occurs, is determined by soil type

How does waterlogging affect coffee trees?

- The coffee tree roots cannot access the oxygen they require for respiration – it is similar to being unable to breath
- It may cause nutrient deficiencies, toxicities and a decline in soil structure
- It reduces the plant's ability to absorb nutrients from the soil
- The roots die and rot, stalling growth and development of the tree
- Soil microbes that are beneficial to the health of the coffee trees cannot survive
- If the coffee tree is unhealthy and weak, it becomes more susceptible to pests and diseases
- Some plant diseases can survive well in waterlogged soil and have a negative impact on the health of the already stressed coffee trees
- If waterlogging only lasts for a short time, the plant will resume taking up oxygen as soil aeration improves, with little or no effect on the health of the tree
- If periods of intermittent waterlogging continue to occur, the tree roots will continue to break down. The result will be poor productivity and the tree may eventually die
- If a single waterlogging event persists for an extended length of time, the tree will die
- It reduces the ability of nitrogen-fixing shade trees to carry out this function



Effect of waterlogging on a coffee tree

How is waterlogging identified?

Waterlogging is often not identified until water appears on the soil surface. By this time the coffee tree roots may already be damaged and productivity may have declined.

Waterlogging can be identified by:

- The presence of water on the soil surface, usually seen glistening in small depressions – this is the most obvious indicator of waterlogging
- Dark, wet or slimy topsoil, usually with algae on the surface
- Boggy soil
- Soil that is yellow or grey, or in extreme cases, almost blue
- Yellowing and premature fall of leaves
- The presence of weeds that typically grow in wet areas, such as sedges (nut grass), rushes and mosses

Waterlogged soil (*Source: Mike Webb*)

If you suspect a site is waterlogged, but cannot see water on the soil surface, dig one or two holes to a depth of about 30 cm and see if water flows into them.

Typical weeds that may be present in waterlogged soil:
(left) nutgrass (*Cyperus sp.*) (Source: Pacific Pests, Pathogens and Weeds);
(right) bulrush (*Typha sp.*), also known as cumbungi and cattail.

Soil erosion

What is soil erosion

- Soil erosion is the wearing away of soil by wind or water

How does soil erosion occur?

- In coffee growing areas in PNG, soil erosion is almost always caused by water
- Much of the rainfall in coffee growing areas is of high intensity, and this can cause the soil to dislodge and erode
- Many coffee gardens are located on slopes, and these sites are the most susceptible to soil erosion
- Soil loss increases with land slope, water velocity (speed of runoff) and the amount of rainfall

What impact does soil erosion have on coffee trees?

Most of the roots of a coffee tree are concentrated in the top 30 cm of soil. If the topsoil is subject to continual erosion:

- Mulch and soil particles are washed away
- The depth of useful soil declines
- The volume of soil that can be used by the coffee tree roots declines
- The water and nutrients available to the coffee trees are reduced

Soil erosion in a coffee plantation has washed away valuable nutrients and exposed the roots of some trees. (*Source: CIRAD website*)

While the impacts of waterlogging and soil erosion can be quite obvious, in some situations these processes are slow and may go unnoticed. In situations where waterlogging and soil erosion occur over a long period of time, the soil gradually becomes degraded. This reduces the long-term productivity of the coffee trees.

How does soil erosion impact the environment?

Soil erosion can have negative impacts on the downslope environment, including:

- Siltation of streams, reduced water storage capacity in ponds and flash flooding
- Reduction in water quality downstream

Objective:

To observe a coffee garden with drainage problems and identify why the garden is not draining effectively

You will need:

Access to an established coffee garden with poor drainage

EXERCISE 1

Observing an ineffective drainage system

Discussion

1. Identify and discuss why the drainage system is not functioning effectively
2. Consider soil type, landscape, planting arrangement, catchment area, slope, location, depth and spacing of drains

4.2 DRAINAGE SYSTEMS

Functions of drainage systems

A drainage system may be developed for one of two reasons:

- **To drain waterlogged land to bring the land into production**
  Land that is too wet to grow coffee may have to be drained prior to establishing a coffee garden
- **To safely remove excessive water flows**
  Most coffee gardens established on slopes require drainage systems to adequately remove water during storms or periods of high rainfall and control surface erosion. It is important that any excess water is drained away from the coffee trees in a controlled manner

Selecting a site for a new coffee garden

Important drainage considerations

Selecting a suitable site is one of the most important decisions to be made when establishing a new coffee garden. It is best to locate the garden on soil that is fertile and well drained. However, if the only option available is waterlogged soil, or soil that is poorly drained, it may be necessary to construct a drainage system to make the land suitable for planting coffee.

- Drainage and the effective depth of the soil are the most important attributes affecting the suitability of a site for growing coffee trees. These factors influence the extent to which roots can develop in the soil. The shallower a root system, the less effectively it will:
  - Absorb moisture or nutrients from the soil
  - Securely anchor the coffee tree to the ground
- At some sites, the depth of free-draining soil maybe insufficient to grow coffee. In many of these situations, this can be improved by establishing field drains
- Whether or not a site is suitable will depend on the ease and practicality of draining the site
- It is important to consider the existence of suitable outlets for discharging the excess water, such as a stream, natural drainage channel or lower land
- If the depth of free-draining soil cannot be increased because of the presence of rock, gravel or other impenetrable layers, the site is not suitable for growing coffee
- It is recommended that smallholders do not grow coffee on sites requiring high inputs of labour to establish and maintain drains

Drainage and site suitability ratings

- Sites rated R1 or R2 are suitable for smallholders to establish a coffee garden on
- Sites rated R3 contain inadequate depths of free-draining soil, but with appropriate drainage inputs can be made suitable
- Sites rated higher than R3 are not recommended

Drainage and effective soil depth			
Suitability rating	**Depth of free-draining soil**	**Site drainability**	**Effective soil depth**
R1	> 1.2 m	No drainage necessary	> 1.2 m
R2	0.5–1.2 m	Only shallow surface drains are necessary	≥ 0.50 m
R3	0.2–0.5 m	Frequent drains are necessary to a depth of 1 m and suitable outlets exist	>0.5 m after draining
R4	0.2–0.5 m	Frequent drains are necessary to a depth of 1 m but no suitable outlets exist	–
R5	<0.5 m over rock	Effective soil depth is inadequate	–
	<0.2 m	Too wet to drain	–

Notes: Values for depth of free-draining soil refer to the soil condition at the end of the wettest time of year. Shallow surface drains are typically 0.3–0.5 m deep. Frequent drains are typically 5–10 m apart.

Excessive water flows

PNG has more rain and water than coffee trees require. It is essential to dig drains to remove excess water in the coffee garden. If there is a lot of water in the soil, the coffee trees will not grow well. It is also important that the excess water is drained in such a way that it will not erode or wash away the soil. Optimum moisture levels for the coffee trees and soil conservation are key factors influencing the design of a drainage system.

Traditional drainage systems

Traditionally, drainage has been aligned downslope to drain water rapidly away from the garden. However, this reduces infiltration of water into the soil and increases soil erosion. **This system is no longer recommended.**

In the past, traditional drainage systems were appropriate for low-pressure agricultural systems. Now, with higher population densities, greatly reduced vegetation cover and permanent cropping, like coffee, traditional drainage systems are no longer sustainable.

- If rainwater is drained away too rapidly, less water will enter the soil for use by the coffee trees. While it is important that the trees do not sit in waterlogged soil for any length of time, they still need moisture for healthy growth
- The fast-moving water in the downhill aligned drainage system erodes the soil. Erosion reduces the amount of soil available to the roots of the coffee trees to physically hold the trees in place, and decreases the availability of valuable soil nutrients
- Shade trees are difficult to establish in sites with poor drainage
- Water travelling downhill quickly in channels in high volumes can cause local flooding when it reaches the bottom of the slope

Modern drainage systems

A suitable drainage system is required in the coffee garden that will minimise both the impacts of waterlogging and soil erosion. A good drainage system should:

- Drain away excess water and discharge it in a **controlled** manner
- Avoid overflowing of water onto low-lying areas
- Control runoff from steep sites
- Avoid large obstacles that may prevent the smooth flow of water

Modern drains in a coffee garden

Prevent waterlogging

- An effective drainage system will minimise waterlogging in low-lying areas of the coffee garden

Control erosion

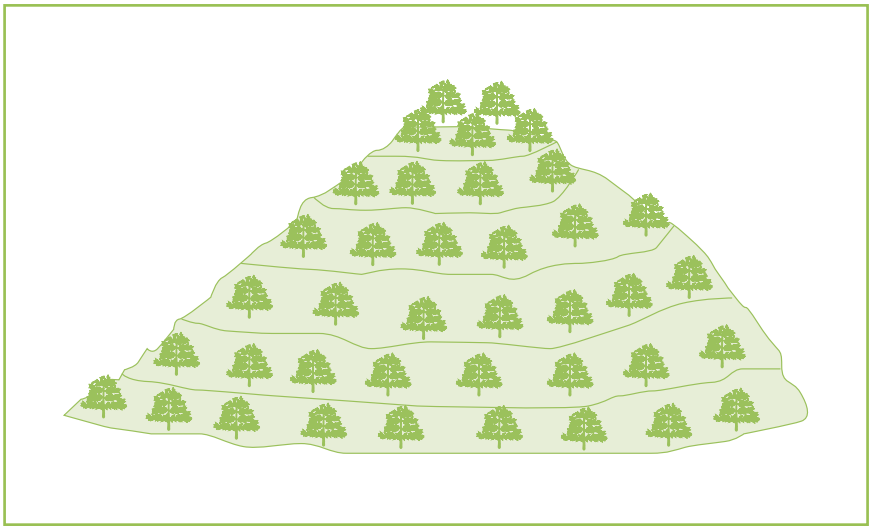
- The speed of flow of rainfall runoff determines the rate of erosion. It is important to minimise soil erosion by **reducing water runoff and flow rates**
- Reducing the rate of runoff also improves infiltration of water into the soil and therefore the rate of replenishment of the soil water reservoir
- A good drainage system is the best way to control soil erosion from high volumes of fast flowing water

Other soil conservation practices

Alongside a good drainage system, other techniques should be used to supplement the drainage network to reduce erosion and waterlogging, and maintain soil structure and nutrient availability to the coffee trees.

Planting arrangement

- If the coffee garden is on a steep slope, the coffee trees should be planted in one of two ways:
  - In rows that run across the slope, at right angles to the direction of the slope
  - In a triangular pattern to slow downhill runoff



Coffee trees planted across the slope.

- Other anti-erosion measures such as ridges (or bunds), ditches and vegetative measures (such as hedges) for erosion control should also run along the contour between the coffee rows. These will help disrupt the downward flow of water runoff and direct the runoff to waterways

Shade trees

- Shade trees can reduce runoff and erosion by intercepting rainfall before it reaches the soil surface (however, some shade trees promote erosion because they concentrate rainfall energy through dripping)
- Leaf litter from suitable shade trees, such as yar (*Casuarina oligodon*) and marmar (*Albizia* sp.), reduces soil erosion as it provides a protective barrier decreasing the energy of the rainfall and subsequent splash
- Leaf litter also impedes runoff by reducing its ability to dislodge soil
- As leaf litter decomposes, it improves soil structure and stability and increases resistance to erosion, as well as providing the soil with additional nutrients

Leaf litter from yar trees protects the soil from erosion.

Cover crops and intercrops

- Cover crops, intercrops and crop residues reduce soil erodibility, impede runoff and improve resistance to erosion
- Crop residues add nutrients to the soil as they decompose

Intercrops in a newly planted coffee garden help reduce erosion on a slope. (*Source: Emma Kiup*)

Hedgerows

- A hedgerow is a row of closely planted shrubs acting as a contour barrier to slow water flow, increase water infiltration, and trap and stabilise the soil. Examples of plants used in hedgerows include tanget (*Cordyline* spp.), sisal (*Agave sisalana*) or vetiver grass (*Chrysopogon zizanioides*)
- They are a cost-effective and efficient system for soil conservation, particularly on steep slopes
- They are usually planted along the contour of the slope, at right angles to the flow of water

Hedgerow of sisal (left) and tanget (right)

Mulch

- Mulches absorb the impact of rain drops and control dislodgement of surface soil particles
- They can be used to improve the structure and drainage capacity of soils
- They should be used with caution during very wet periods, as they slow evaporation and drying of the soil

Other

- Trunks or pruned branches of yar, or other tree species, can be laid across the slope to create a contour barrier
- Small brush fences made from branches of small shrubs or trees can be built in parallel lines 5–10 m apart, each fence rising 20–30 cm above the soil surface. The benefit of a brush fence rarely lasts for more than a year – live fences (hedgerows) are more enduring
- If some areas of the coffee garden are subject to waterlogging, the coffee trees can be grown on raised beds, on top of the soil excavated during the digging of new drains

4.3 PLANNING A DRAINAGE SYSTEM

If a farmer is not sure how to choose a site for a coffee garden, or how to develop a drainage system, they should seek advice from CIC or someone with good knowledge of drainage.

Drainage is one of the most important elements of a coffee garden and a lot of labour is required in establishing a drainage system, It is important that it is planned and prepared correctly. Making modifications to the drainage system later could be costly.

Factors affecting the layout of a drainage system

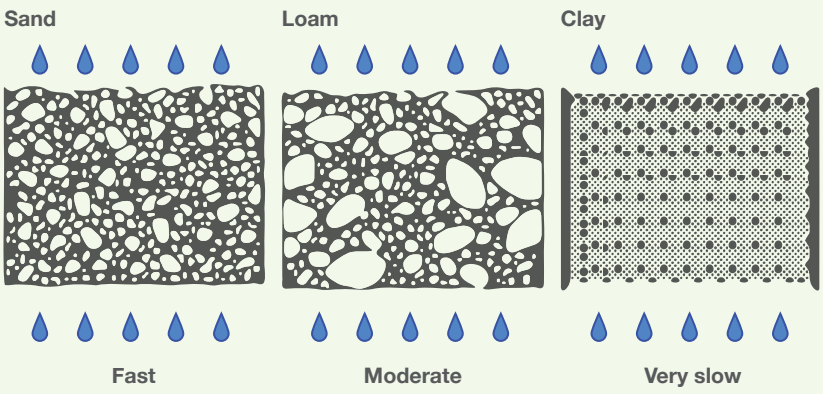
It is difficult to generalise about the drainage requirements for coffee gardens, as each site will differ. There may also be differences within a site. The drainage requirements of each garden will depend on:

- The soil characteristics
- The size of the catchment area of the garden, which will affect the amount of water entering the coffee garden
- The topography or the physical features of the landscape, such as hills, creeks and valleys

Soil characteristics

- Soils differ in their capacity to drain water. How water drains through the soil is determined by the:
  - Soil type (e.g. sand, loam or clay)
  - Soil texture – proportions of sand, silt and clay
  - Soil structure – extent to which soil particles arrange into larger aggregates
  - Organic matter content
- Soil permeability is the rate of water movement through soil and depends on the soil texture:
  - Sandy soils have relatively large particles and water can pass through these soils quickly
  - Clay soils have very fine particles and water passes through them more slowly by comparison
- There may be different soil types within a coffee garden, each requiring different drainage solutions

Soil permeability



Soil permeability depends on the soil texture

Note: Refer to Farmer Training Guide Unit 2, Module 7 'Soil fertility and nutrient maintenance' for further information.

Measuring soil texture

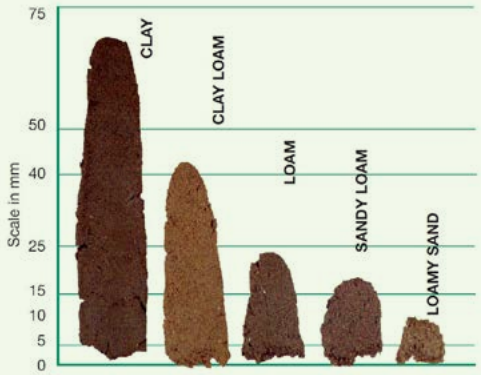
1. Take a small handful of soil

2. Add enough water to make a ball

3. Knead the ball and add more water until it stops sticking to your fingers
   - If you can't make a ball, the soil is very sandy
   - If it feels silky it contains silt
   - If it feels sticky it contains a lot of clay

4. Gently press the soil between your thumb and index finger to form a ribbon about 2–3 mm thick

5. Gently push the ribbon until it is hanging from your fingers – the more clay there is in the soil, the longer your ribbon will be before it breaks off



Adapted from Department of Primary Industries and Regional Development (2021), 'Estimating soil texture by hand', Government of Western Australia, available at agric.wa.gov.au/n/2786

Catchment area

- The catchment area is the area over the natural landscape that collects and delivers water into the coffee garden following rain, including the coffee garden itself
- All the water collected in the catchment area runs downhill and eventually flows into drains and water courses, such as creeks and rivers
- The size of the catchment area will influence the volume of water that is flowing through the coffee garden

Natural features of the land (topography)

- The natural features of the land surface, such as slopes, natural drainage lines and boundaries, determine the flow path of water
- The positions of hills and ridges will affect the layout of drains
- Existing natural watercourses in the coffee garden should be taken into account when planning the drainage system

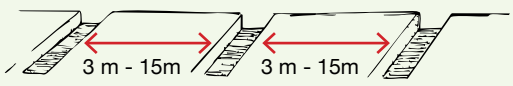
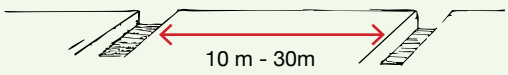
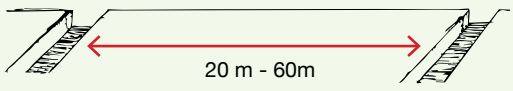
Drain spacing, depth and width

The spacing, depth and width of the drains are directly related. Any change in one will affect the other.

Spacing

- The greater the soil's infiltration capacity (the amount of water able to enter the soil), the further apart the drains can be:
  - Sandy soils: As water can flow through sandy soils very quickly, the drains can be widely spaced
  - Clay soils: Water passes through clay much more slowly, so the drains must be close together
- On highland soils, drains are typically 15–20 m apart

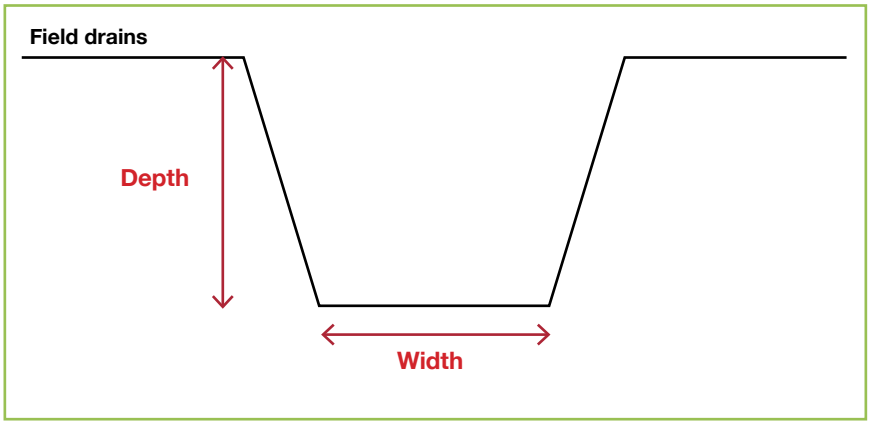
Drain spacing in different soil types

Closely spaced drains in clay soils: Water movement through clay is very slow. Clay soils are often saturated with water during wet weather. Closely spaced drains are recommended.	**Clay** 
Medium spaced drains in loam soils: Loam soils are composed of sand, silt and clay. Water movement through loam soils will vary. It will move faster in these soils than in clay soils, so drains can be spaced further apart.	**Loam** 
Widely spaced drains in sandy soils: Water moves through sandy soils rapidly. Wider spacing between drains is recommended.	**Sandy** 

(*Credit: Leo Aroga & Bob Kora*)

Depth and width

- The amount of water that needs to be carried away will determine the required depth and width of the drains, and this relates to the infiltration rate of the soil
- The frequency of rainfall, the catchment area and the length of the drain will also influence the volume of water that has to be drained from the coffee garden
- In general, the greater the water volume, the wider and deeper the drains need to be
- The depth and width of the drains also depends on how far apart they are
- Depending on the soil type, the drain depth should range from 50–100 cm; in clay soils, the depth may need to be 150 cm deep
- Drains should be a depth that can be easily dug and maintained
- Drains that are too deep can have areas of accumulation of silt and will be more difficult to maintain
- The width will depend on the depth of the drain and water volume



The greater the volume of water, the deeper and wider the drain must be

Drain slope (gradient)

The slope, or gradient, of the drain plays a very important role in determining the flow and speed of water.

- The soil characteristics (soil type, texture, structure and organic matter content) will determine the gradient of the drains
- If the gradient is too steep, scouring (rubbing) and erosion of the soil inside the drain channel may occur, as the water will travel down the drain too quickly
- If the gradient is too flat (not steep enough), water will travel too slowly along the drain and may cause flooding. Silt may also accumulate in the drain and contribute to flooding
- In many smallholder gardens where drains are relatively short, the slope may be quite steep, up to 1:4 (for every horizontal distance of 4 m, elevation will increase by 1 m)

Sediment traps

- Sediment in the water flow can usually be controlled by vegetation, or by digging a simple box or trap in the bed of the drain. If this is not done, the sediment will flow down the drain and eventually be lost into waterways
- A sediment trap slows the flow of water sufficiently to allow sedimentation (settling of particles from runoff). The trap creates a pool, and if the water flow is reduced sufficiently the fine sediment in the water drops to the bottom of the trap
- A sediment trap directs mobile sediment to accumulate where it can be easily recovered and reused within the coffee garden

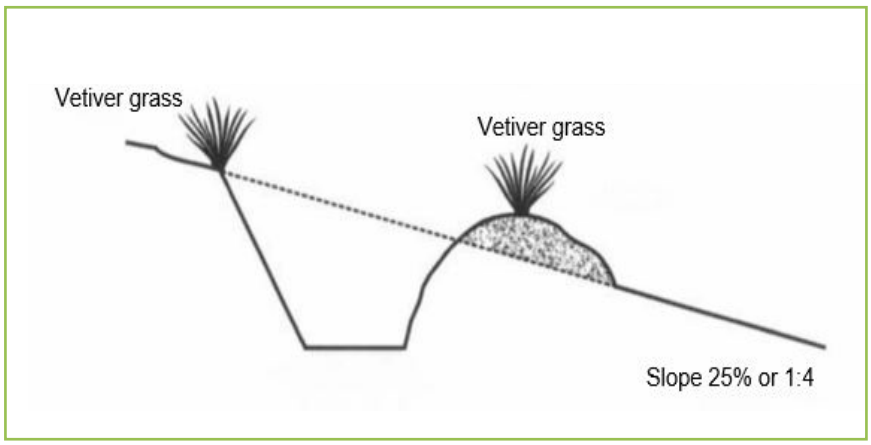
Other considerations

Existing drainage system

- In an existing coffee garden, there may already be a drainage system present
- Some upgrading and/or modifications of an existing drainage system may be required to provide effective drainage for the new coffee garden

Steep slope

- If the coffee garden is on a steep slope, water running down the slope and through the rows of coffee trees may need to be intercepted
- The water can be directed into large drains or natural water courses by digging inter-row (between row) ditches at right angles to the slope
- Alternatively, inter-row ridges or hedgerows may be used to retain runoff and allow seepage into the soil, with excess water being diverted to the main drains or natural water courses
- Inter-row ridges should be stabilised with vegetation, such as vetiver grass



Inter-row ridge stabilised with vetiver grass
(*Adapted from Descroix and Wintgens, 2004*)

Coffee tree spacing

- The distance between the rows of coffee trees will affect where the drains are located

Permanent shade trees

- Existing permanent shade trees should be accounted for when planning a drainage system
- It is best to route drains at least 15 m from permanent shade trees to reduce the risk of tree roots blocking the drains during prolonged wet periods

Location of fences

- Existing fences, and any that are going to be constructed, should be accounted for when planning a drainage system

Neighbours

- Ensure water is not being discharged onto neighbouring coffee or food gardens

Objective:

To observe an effective drainage system in an existing coffee garden and identify positive and negative aspects of its design

You will need:

Access to an established coffee garden with a good drainage system

EXERCISE 2

Observing an effective drainage system

Discussion

Discuss why the drainage system is a good design. Identify and consider:

- Soil type
- Features of the landscape
- Spacing of coffee trees and shade trees
- Garden catchment area
- Slope
- Presence of natural waterways and low points
- Location of main drains
- Location of field drains
- Drain spacing, depth and width
- Drain maintenance

4.4 DRAINAGE SYSTEM CONSTRUCTION

Drainage construction

Construction of a drainage system involves a sequence of operations. It is important that the sequence is followed correctly:

1. Mark and dig the main drains
2. Mark the positions of coffee trees and permanent shade trees
3. Mark and dig the field drains
4. Dig the planting holes and plant the coffee seedlings
5. Modify the drains if necessary

Note: Refer to Farmer Training Guide Unit 2, Module 3 'Shade management' for further information

Once the drainage system has been carefully planned, construction can begin. Digging drains is hard work and requires quite a lot of skill. It is important to get it right – mistakes could be costly and time-consuming to fix.

Drainage construction should begin during the dry season, well before the onset of the wet season, as construction may take quite some time. Drain construction should be completed in time for planting the coffee seedlings at the beginning of the wet season.

Mark and dig the main drains

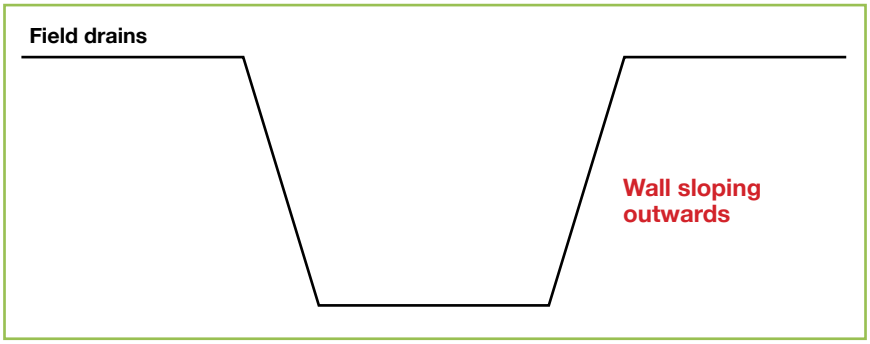
- Runoff from higher ground should be diverted to the main drains passing through the coffee garden
- Mark the path of the main drains using pegs or sticks at intervals, and a string line that is pulled tight. This will ensure that the drains are dug straight and at a uniform width
- Mark one side of the drain, then measure the other side to the required width
- Begin digging the drains at the outlet end, so that if any water accumulates during construction, it will drain away
- Check the progress of the drain at intervals to ensure it is being dug correctly, especially if you have others helping
- Dig holes, or sediment traps, in the drains to collect soil that washes down the drains. The depth of sediment traps and the intervals between them will depend on the soil type, slope and amount of runoff

Mark the positions of coffee trees and permanent shade trees

- Mark out the location of the coffee trees using sticks
- Use the recommended spacing for smallholders (2.5 m x 1.5 m), unless it is not appropriate for the site
- The spacing of shade trees will depend on the type of tree being planted

Mark and dig the field drains

- Mark out the field drains between the rows of coffee tree markers using pegs and a string line
- Dig the field drains, ensuring they are not too close to the coffee tree markers
- Dig the walls of the drains so that they slope slightly outwards towards the top of the drain to reduce the risk of collapse

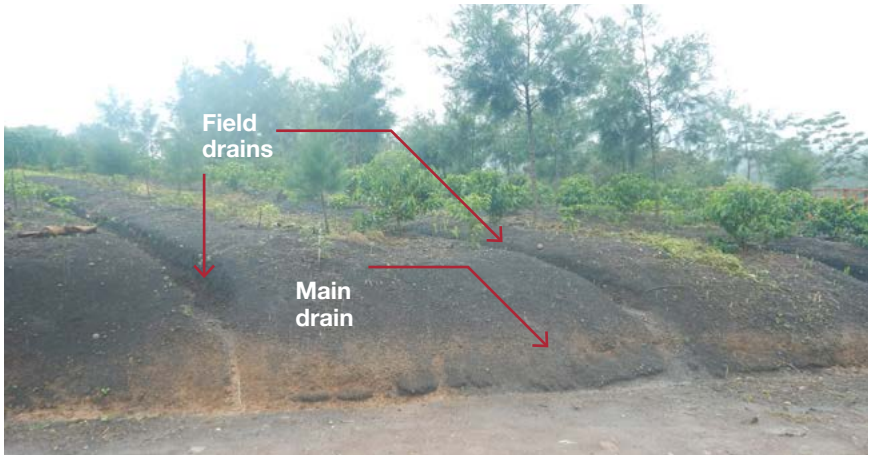


Note: Refer to Farmer Training Guide Unit 1, Module 3 'Establishing a new coffee garden'

Dig the planting holes and plant the coffee seedlings

- Dig the planting holes and plant the coffee seedlings

Field drains in a new coffee garden
(*Source: Michael Kaugam*)

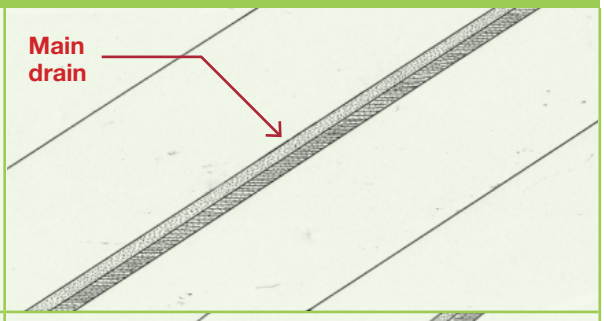
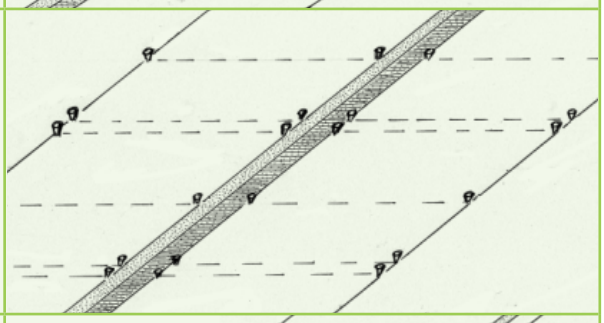
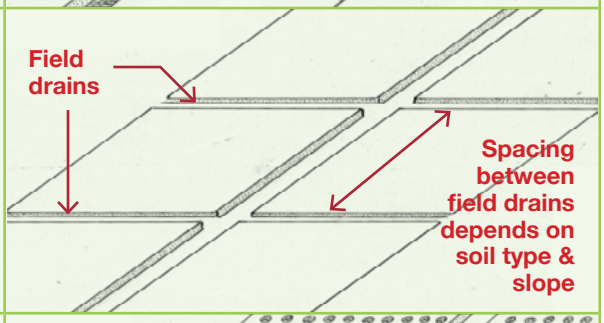
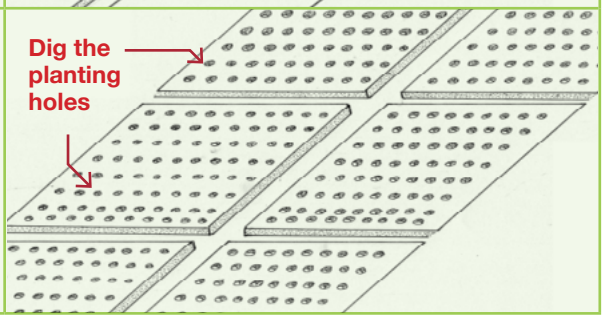


Field drains running into a main drain in a new coffee garden
(*Source: Michael Kaugam*)

Modify the drains if necessary

- After the coffee seedlings have been planted, it may be necessary to modify some of the drains
- When the wet season begins, drains may require some modification to improve their ability to discharge excess water from the site
- Extra drainage may also be needed in waterlogged areas

Drain construction

Step 1: Mark out and dig the main drains. Spacing and depth are important factors here.	
Step 2: Using sticks or other markers, mark out the coffee planting area, including the position of permanent shade trees, and field drains	
Step 3: Dig the field drains.	
Step 4: The seedlings can now be planted.	

(*Credit: Leo Aroga & Bob Kora*)

Digging a main drain in a low-clay soil (*Source: Rauke Buimeng*)

A deep drain in soil with a high clay content (*Source: Bob Kora*)

Objective:

To learn how to identify the drainage requirements in a field to be planted with coffee seedlings

You will need:

A field site that is going to be (or could be) planted to coffee

EXERCISE 3

Planning a drainage system

Practical activity

Carry out the soil texture test described on page 21 and identify the soil type

Discussion

Identify and discuss:

- Soil type
- Features of the landscape
- Slope
- Presence of natural waterways and low points
- Location of main drains
- Recommended drain spacing for the soil type (use the table below as a guide)
- Required drain depth and width for the soil type and slope
- Presence of other elements that may affect the design of the drainage system such as existing drains or permanent shade trees

Soil type	Drain spacing
Clay	3–15 m
Loam	10–30 m
Sand	20–60 m

Objective:

To understand how to construct a drainage system

You will need:

- **A field site that is going to be (or could be) planted to coffee**
- **Butchers' paper and marker pens to draw a drainage system**
- **Equipment for digging a field drain (pegs and string/ rope, measuring stick, shovels/spades, crowbar, pick axe and mattock)**

EXERCISE 4

Constructing a drainage system

Discussion

1. List and discuss the sequence of tasks involved in construction of a drainage system
2. List and discuss the equipment required for construction of the drains (pegs and string line, measuring stick, spade/shovel, and crowbar)

Practical activity

3. Draw a plan for a drainage system for this block on butchers' paper
4. On a small section of the block:
   - Using pegs, mark out the location of some of the coffee trees using the recommended spacing for smallholders of 2.5 m x 1.5 m
   - Using pegs and string line, mark out some of the field drains using the recommended spacing for the relevant soil type
5. Construct one of the field drains using the appropriate slope

Discussion

6. What modifications may be required once the drainage system has been constructed?

4.5 DRAIN MAINTENANCE

For a drainage system to remain effective for the long-term, it is important that it is well maintained. This is one of the key aspects in keeping your coffee trees healthy and productive.

Inspection and maintenance

- The best times to inspect drains and undertake drainage maintenance are during the dry season and at intervals during the growing season, particularly after rainfall events
- Check for signs of erosion of the drains
- Inspect the main drains and field drains a couple of days after a heavy rainfall event, looking for ponding or very wet spots, which may indicate that a drain is blocked
- Annually check that the coffee crop appears to be growing uniformly. Changes in uniformity may be an indicator of a poor drainage system
- Annually check that roots from large shade trees are not restricting water flow in drains
- Check the outflow of drains

Potential problems with drains

Problems that can occur with drains if they are not regularly maintained include:

- Slumping or collapsing of the sides or walls of the drain (more common in clay soils)
- Erosion of drains, particularly in the first few years after construction
- Accumulation of silt and debris in the bed of the drain
- Dense vegetation clogging the drain and preventing free flow of water
- Animals, such as pigs, entering the coffee garden and damaging drains

Vegetation blocking drain flow

Prevention of problems

- Plant grasses or shrubs along the edge of the drain to hold the soil together
- Slash, but do not remove, vegetation growing along the edges of the drain
- Constantly remove silt and debris (including grass cuttings) from the bed of the drain to prevent water overflowing from the drain. There may be quite a bit of sediment discharging in the first year
- Slash any vegetation growing in the bed of the drain to maintain the original slope and depth, then remove the cut debris
- Fence and preserve drain outlets to maintain flow and prevent entry by animals
- Clean out sediment traps
- If a drain is vulnerable to slumping, the sides can be reinforced with bamboo or timber retaining walls
- Cut off roots of large trees that may be slowing water flow

Objective:

To understand the maintenance requirements of a drainage system to ensure its long-term effectiveness

You will need:

- **An existing coffee garden with a relatively good drainage system that requires some maintenance**
- **Equipment for drain maintenance (bush knife for slashing vegetation, shovels/ spades, crowbar, mattock and pick axe)**

FIELD EXERCISE 5

Drain maintenance

Discussion

1. List problems that can occur with drains
2. List things to look out for when inspecting drains (e.g. eroded or collapsed walls, blockages of the drains and outlets by vegetation, and silt accumulation)
3. List the tasks involved in general maintenance of drains (e.g. slashing grasses along the sides and beds of the drains, cutting off tree roots that may be blocking the drains, removing accumulated debris from the bed of the drains)
4. Identify any problems with the drains in this coffee garden

Practical activity

5. Carry out the required maintenance of an existing drain in the coffee garden

4.6 KEY MESSAGES

- For coffee trees to be healthy and productive, they must be able to access air, water and nutrients from the root zone
- Waterlogging and erosion reduce the ability of roots to provide a coffee tree with appropriate amounts of water and nutrients and could result in deterioration and even death of the trees
- The purpose of a drainage system is to keep the roots of coffee trees healthy by draining excess water away in a controlled manner
- Other practices that may be used in conjunction with a good drainage system for the purpose of soil conservation include planting:
  - shade trees that provide good amounts of leaf litter
  - cover crops and intercrops
  - hedgerows
- It is important that a drainage system is planned carefully and correctly as a lot of labour is required in its construction
- Drainage requirements will depend on the soil characteristics, the size of the coffee garden catchment and the physical features of the landscape
- The drainage capacity of the soil and the features of the land will determine the distance between drains
- Drains are spaced wider apart for sandy soils and closer together for clay soils
- Drain depth and width is dependent on the volume of water and the spacing of drains
- The gradient or slope of the drain will determine the flow rate of water and is also dependent on the soil characteristics
- Other factors that may affect the layout of a new drainage system include:
  - existing drains
  - the slope of the coffee garden
  - coffee tree spacing
  - the location of permanent shade trees, fences and neighbours
- The phases of construction of a new drainage system should be undertaken in the following sequence:
  - mark and dig the main drains
  - mark the positions of coffee trees and permanent shade trees
  - mark and dig the field drains
  - dig the planting holes and plant the coffee seedlings
  - modify the drains if necessary
- Drains should be regularly inspected and maintained so that they remain effective for the long term

4.7 QUIZ

Place a '✓' in the correct box.

1 Why is it important to have an effective drainage system in a coffee garden?

- A Because coffee trees do not grow well in waterlogged or eroded soils
- B To drain excess water away from the coffee trees in a controlled manner
- C To enable the roots of the coffee trees to provide the shoot system with enough air, water and nutrients for healthy growth
- D All the above

2 When does waterlogging occur?

- A When a dam forms at the top of a slope
- B When the soil is saturated with water and there is little air present in the soil
- C When logs block the flow of water down a slope
- D When soil is dislodged and lost in fast flowing water

3 How can soil erosion be overcome?

- A By reducing water runoff and rates of flow
- B By planting coffee trees at low densities
- C By removing groundcover from the coffee garden
- D By changing the soil type

4 What are the three main factors that affect the requirements of a drainage system?

- A Soil type, catchment area and coffee variety
- B Catchment area, soil texture and soil depth
- C Soil characteristics, catchment area and features of the landscape
- D Soil type, existing groundcover and catchment area

5 What is the catchment area of a coffee garden?

- A The area in the landscape which captures rainfall that eventually flows into the coffee garden
- B The area within the coffee garden where water flows
- C The area at the bottom of the coffee garden where water collects
- D The area at the top of the coffee garden where water collects before running down the slope

6 The size of the particles in the soil affect its drainage capacity. The greater the particle size:

A The faster the flow of water through the soil
B The slower the flow of water through the soil
C The better a soil is at holding water
D The greater the requirement for drains

7 Sandy soils contain large particles and are fast-draining whereas clay soils contain very small particles and are slow-draining. This means that drains in sandy soils:

A Are spaced closer together than those in clay soils
B Are spaced further apart than those in clay soils
C Must be deeper than those in clay soils
D Must be wider than those in clay soils

8 What determines the depth and width of drains?

A The width of the rows between the coffee trees
B The amount of labour available to build the drains
C The size of the outflow of the drains
D Drain spacing and the volume of water flowing through the drains

9 The slope of a drain determines the flow rate of water through it. If the slope is too steep:

A Runoff may not make it into the drain
B Silt may accumulate in the drain and cause a blockage
C The water flow may be too fast, causing the sides of the drain to erode
D The whole coffee garden may become waterlogged

10 When should main drains and field drains be constructed in a new coffee garden?

A Both should be constructed prior to planting the coffee trees but the location of the coffee trees should be marked out prior to marking out and digging the field drains
B Both should be constructed after planting the coffee trees because then it is easier to determine where the drains should be located
C Main drains before planting and field drains after planting
D They can be constructed either before or after planting the coffee trees

11 What are some things to look out for when inspecting drains?

A Health of the coffee trees
B Erosion of the walls
C Build-up of debris and silt in the bed of the drain
D All the above

12 Which of these practices will help to stabilise a drain and keep it clear?

A Completely removing all grasses and shrubs along the edge and bed of the drain
B Allowing silt and debris to accumulate in the drain
C Slashing vegetation growing along the edges and bed of the drain, and then removing the cut debris
D Allowing debris to accumulate at the outflow of the drain so that the outflow doesn't become eroded

13 What are the best times to inspect and undertake maintenance of drains?

A During the wet season and at intervals during the dry season
B After harvest and then after coffee processing is completed
C During the dry season and only when there are dry periods during the wet season
D During the dry season and at intervals during the wet season, particularly after rainfall events

14 What is the recommended drain spacing in loam soils?

A 3–15 m
B 10–30 m
C 20–60 m
D 40–70 m

True or false

Place a '✓' in the correct box.

	True	False
a. It is important to plan a new drainage system carefully, because once it is constructed it cannot be modified.	☐	☐
b. Shade trees, cover crops, intercrops and hedgerows can be used along with a drainage system to conserve soil.	☐	☐
c. The greater the water volume, the deeper and wider the drain must be.	☐	☐
d. The most effective way to prevent waterlogging in the long term is to apply mulch.	☐	☐
e. A drainage system is only required if the coffee garden is on a steep slope.	☐	☐
f. Consistent waterlogging over an area in a coffee garden will cause the coffee tree roots to rot, leading to poor productivity and possibly death of the trees.	☐	☐

Answers to quiz questions

Multiple choice

1. Why is it important to have an effective drainage system in a coffee garden?

   Answer = D. All the above (Because coffee trees do not grow well in waterlogged or eroded soils; To drain excess water away from the coffee trees in a controlled manner; To enable the roots of the coffee trees to provide the shoot system with enough air, water and nutrients for healthy growth)

   Section 4.1: Healthy productive coffee trees require a healthy root system and root environment with access to sufficient air, water and nutrients. A good drainage system will help keep the root environment healthy by draining excess water away in a controlled manner.

2. When does waterlogging occur?

   Answer = B. When the soil is saturated with water and there is little air present in the soil

   Section 4.1: Waterlogging occurs when the soil becomes saturated with water and the coffee tree roots cannot access oxygen which they require for respiration. If waterlogging occurs over an extended period, the roots and eventually the coffee tree may die.

3. How can soil erosion be overcome?

   Answer = A. By reducing water runoff and rates of flow

   Section 4.2: Reducing water runoff and rates of flow will reduce the risk of erosion. This can be attained by constructing an effective drainage system as well as implementing other measures such as growing cover crops, intercrops or a living contour barrier (hedgerow), and maintaining an appropriate stand of shade trees.

4. What are the three main factors that affect the requirements of a drainage system?

   Answer = C. Soil characteristics, catchment area and features of the landscape

   Section 4.3: Soils differ in their capacity to drain water. The size of the catchment area will influence the volume of water that is flowing through the coffee garden. The natural features on the land surface, such as slopes, natural drainage lines and boundaries, determine the flow path of water. All these factors will determine what drainage is required.

5. What is the catchment area of a coffee garden?

   Answer = A. The area in the landscape which captures rainfall that eventually flows into the coffee garden

   Section 4.3: The catchment is the area over the natural landscape of the coffee garden where water collects when it rains. All rain and runoff in the catchment runs downhill where it naturally collects in water courses such as creeks and rivers.

6. The size of the particles in the soil affect its drainage capacity. The greater the particle size:

   Answer = A. The faster the flow of water through the soil

   Section 4.3: Water can flow very quickly through soils with large particles, such as those containing a lot of sand. Water passes much more slowly through soils with very fine particles, such as clays.

7. Sandy soils contain large particles and are fast-draining whereas clay soils contain very small particles and are slow-draining. This means that drains in sandy soils:

   Answer = B. Are spaced further apart than those in clay soils

   Section 4.3: Because sandy soils can drain so quickly, fewer drains are required. Clay soils, on the other hand, drain very slowly, so require more drains spaced closer together.

8. What determines the depth and width of drains?

   Answer = D. Drain spacing and the volume of water flowing through the drains

   Section 4.3: The frequency of rainfall, catchment area and the drain length will influence water volume. In general, the greater the water volume, the wider and deeper are the drains. Water volume, as well as drain spacing, will determine the actual depth and width of the drains.

9. The slope of a drain determines the flow rate of water through it. If the slope is too steep:

   Answer = C. The water flow may be too fast, causing the sides of the drain to erode

   Section 4.3: If the gradient is too steep, scouring (rubbing) and erosion of the soil inside the drain channel may occur as the water will travel down the drain too quickly.

10. When should main drains and field drains be constructed in a new coffee garden?

    Answer = A. Both should be constructed prior to planting the coffee trees but the location of the coffee trees should be marked out prior to marking out and digging the field drains

    Section 4.4: First dig the field drains, then mark out where the coffee trees and permanent shade trees are to be planted. The field drains can then be marked out and dug.

11. What are some things to look out for when inspecting drains?

    Answer = D. All the above (Health of the coffee trees; Erosion of the walls; Build-up of debris and silt in the bed of the drain)

    Section 4.5: Check for erosion, blockages, slumping or collapsing of the drain walls, drain outflow, and the health and uniformity of growth of the coffee trees.

12. Which of these practices will help to stabilise a drain and keep it clear?

Answer = C. Slashing vegetation growing along the edges and bed of the drain, and then removing the cut debris

Section 4.5: Practices that assist in stabilising drains and keeping them clear include slashing but not removing vegetation growing along the edges of drains, removing silt and debris, slashing the bed of the drains and then removing the cut debris, clearing sediment traps, fencing and preserving drain outlets, and removing blockages such as roots of large trees.

13. What are the best times to inspect and undertake maintenance of drains?

Answer = D. During the dry season and at intervals during the wet season, particularly after rainfall events

Section 4.5: During the dry season, more time is available to spend on drain maintenance. During the wet season, especially after rainfall events, it is easier to identify where there may be a drainage problem.

14. What is the recommended drain spacing in loam soils?

Answer = B. 10–30 m

Section 4.3: Approximate spacing of drains in sandy soils is 20-60 m, loam soils 10–30 m and clay soils 3–15 m. In the majority of soils, drains are spaced 15–20 m apart.

True or false

a) It is important to plan a new drainage system carefully, because once it is constructed it cannot be modified.

Answer = FALSE

Section 4.3: The drainage system can be modified if need be, but at a cost. It is better if construction is correct to begin with, as a lot of labour is required to establish it.

b) Shade trees, cover crops, intercrops and hedgerows can be used along with a drainage system to conserve soil.

Answer = TRUE

Section 4.2: Along with drainage, there are many measures that can be used in soil conservation. These include shade trees, cover crops, living hedgerows and other hedge barriers.

c) The greater the water volume, the deeper and wider the drain must be.

Answer = TRUE

Section 4.3: Volume determines depth and width. The greater the volume of water, the greater the depth and width of the drain. Depth and width also depend on drain spacing.

d) The most effective way to prevent waterlogging in the long term is to apply mulch.

Answer = FALSE

Section 4.1: A good drainage system is the most effective method in preventing waterlogging in the long term.

e) A drainage system is only required if the coffee garden is on a steep slope.

Answer = FALSE

Section 4.1: A good drainage system in coffee gardens on steep slopes is important in preventing soil erosion and loss of valuable nutrients. However, even in a coffee garden with little slope, drainage can be a problem. Water can still accumulate in low points, causing waterlogging. It is important that an effective drainage system is constructed in all coffee gardens, regardless of slope.

f) Consistent waterlogging over an area in a coffee garden will cause the coffee tree roots to rot, leading to poor productivity and possibly death of the trees.

Answer = TRUE

Section 4.1: When the soil is waterlogged, coffee tree roots cannot access oxygen or nutrients from the soil and the roots begin to break down. If waterlogging occurs continually, the coffee trees may die.

4.8 SOURCES OF FURTHER INFORMATION

Aroga L (2007) *Coffee Rehabilitation and Management Notes*, Coffee Industry Corporation, Research and Grower Services Division, Aiyura, PNG.

Aroga L (2008) *Coffee Units – Lower and Upper Secondary – (Grades 9–12), Coffee Teaching Resource Book* (first edition), Coffee Industry Corporation, Coffee Research Institute.

Blanco Sepúlveda R and Aguilar Carrillo A (2015) 'Soil erosion and erosion thresholds in an agroforestry system of coffee (*Coffea arabica*) and mixed shade trees (*Inga* spp. and *Musa* spp.) in Northern Nicaragua', *Agriculture, Ecosystems and Environment* 210: 25–35.

Bourke, RM (2001) 'Intensification of agricultural systems in *Papua New Guinea', Asia Pacific Viewpoint* 42(2–3): 219–235.

Coffee Industry Corporation (2016) *The Papua New Guinea Coffee Handbook* (second edition). Available at www.cic.org.pg/wp-content/uploads/2021/08/52029_CIC-Handbook.pdf

Curry GN, Webb M, Koczberski G, Pakatul J, Inu SM, Kiup E, Hamago MR, Aroga L, Kenny M, Kukhang T, Tilden G and Ryan S (2017) *Improving livelihoods of smallholder families through increased productivity of coffee-based farming systems in the highlands of PNG*, final report FR2017-08 for ACIAR project ASEM/2008/036. Available at espace.curtin.edu.au/handle/20.500.11937/54174 or www.aciar.gov.au/publication/asem-2008-036-final-report

Department of Primary Industries and Regional Development (2021) *Estimating soil texture by hand*. Government of Western Australia. Available at www.agric.wa.gov.au/soil-constraints/soil-texture-estimating-hand

Descroix F and Wintgens JN (2004) 'Establishing a coffee plantation', in Wintgens JN (ed.) *Coffee: Growing, Processing, Sustainable Production: A Guidebook for Growers, Processors, Traders, and Researchers* (second edition), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Donjadee S and Tingsanchali T (2013) 'Reduction of runoff and soil loss over steep slopes by using vetiver hedgerow systems', *Paddy and Water Environment* 11: 573–581.

Wintgens JN (ed.) (2009) *Coffee: Growing, Processing, Sustainable Production: A Guidebook for Growers, Processors, Traders, and Researchers* (second edition), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Australian Centre
for International
Agricultural Research

Australian
Aid