Managing soil fertility in the tropics

Building common knowledge: Participatory learning and action research

Chapter 3: Sources and flows of nutrients in farming

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Chapter 3

Sources and flows of nutrients in farming

This chapter examines the dynamics of soil fertility and their underlying processes, which can best be illustrated by looking at resource flows between different parts of the farming system. Our analysis will be restricted to the plant nutrients nitrogen, phosphorus and potassium, and will not cover aspects of organic matter and energy dynamics.

When we study resource and nutrient flows we need to define the unit or system we are looking at. This chapter looks at how to choose the appropriate unit of analysis, the boundaries of each system, and how resources and their nutrients are transported between different parts of the system.

Some of the key questions in nutrient flow analysis are:

- **what makes up the system we are considering ; what is the defined unit of analysis?**
- **Where does the system begin, where does it end, and what are its boundaries?**
- **Which key elements of the system are relevant to nutrient analysis?**
- **What processes are involved in the transfer, transport and transformation of nutrients?**
- **What are the system's major nutrient sources and sinks, and where do we find them?**

3.1 Defining the unit of analysis

We have taken **the farm** as the main unit of analysis, as this is where the farmer and other household members decide on soil fertility strategies and activities.[1] The Guide outlines a series of tools to help farming families find out what is happening in terms of resource and nutrient flows on their farm, and how to manage them more effectively. This chapter provides a framework for analysing farming systems, which should be done in collaboration with the farmers.

When we look at the farm as the unit of analysis we can see an *arrangement of elements* that *interact* within a boundary; and we call this unit a **farm system**. It comprises resources such as fields, crops, animals, feeds and manure, etc., which are managed and transformed through human activity. Other elements of the farming system include the farming family, housing facilities and food stores, etc. As this kind of system has many elements and activities it can become quite complex and difficult to analyse.

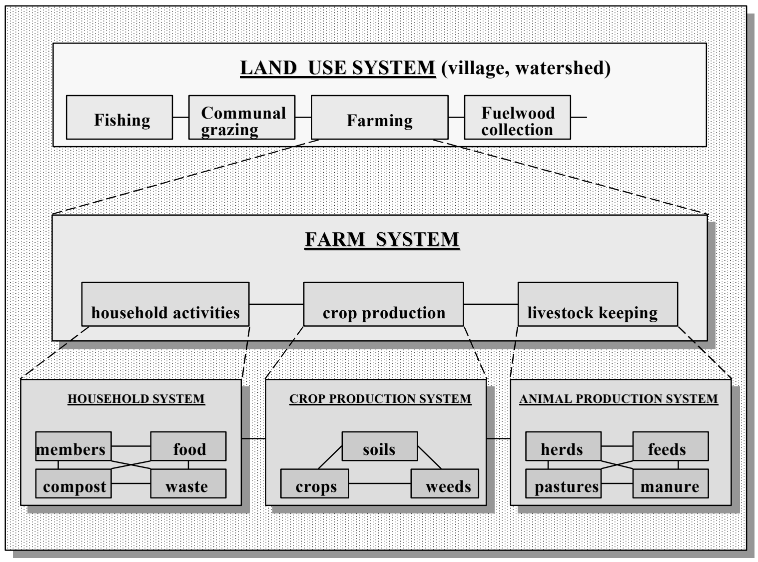
Although the idea of the farm as a unit suggests a clear-cut entity, the conditions in Africa can make it hard to define. In West Africa a farm is often made up of large family units which cultivate several family fields under the overall authority of the family head. The women and younger men of this family (both married and single) may also cultivate their own private fields, so they are a separate decision making unit and thus a separate farm. Taking account of the larger farm unit and all the links with sub-units can be a very complex process, so for the sake of clarity we have limited the analysis to the fields and farm elements that are directly under the authority of the head of the farm, whether this is the decision maker in the larger family unit, the women managing her private fields, or the younger married men directing a smaller farm unit. However, the fact that we focus on the smaller unit within a larger family unit does not mean that we neglect the functional links between the different units.

As farm systems are made up of various types of interacting elements it is useful to consider smaller units of analysis within the farm system. We can group interacting elements into various "*lower-level systems*" or "*sub-systems*". As a sub-system is also an arrangement of elements that interact within a boundary and thus constitutes a system in itself. The term *sub-system* indicates that it is linked to a *system at a higher level.*

In Figure 3.1 there are 3 distinguishable sub-systems within the farm system:

- the **crop production system,**
- the **animal production system**
- the **household system**.

Figure 3.1 also shows how farms fit into a higher system relating to **land use**, which is at the village or watershed level. The village land-use system is made up of farms and communal resources such as woodland, pastures and rivers. We can therefore talk about *a hierarchical classification of systems in which the farm system and its three sub-systems are part of the village land-use system.*



(Adapted from Fresco, 1986)

Figure 3.1 The farm system and its sub-systems, as part of the land-use system

When we analyse resource flows we need to determine which system to examine, and how it is linked to other systems on other levels. More precisely we have to determine:

- which system elements are relevant to soil fertility management;
- the presence and nature of system boundaries;
- the major resource flows involving the transfer, transport and transformation of nutrients.

We will now take a more detailed look at the farm and its sub-systems to find out which elements are the most important, what are the various sources of nutrients, and which resource flows are involved.

The crop production system

Soils constitute the bulk of plant nutrients in the crop production system**,** and are the primary source of fertility for crops. This fertility store can be seen as the farm's capital, which may be increased or depleted.

Crops are the outputs of farming which transform nutrients, water, light, labour and other inputs during their growth. A crop production system usually includes different **crop species** and **weeds** that are all competing for the same stock of nutrients, which may include additions of mineral and/or organic fertiliser.

Crop products such as food, feed or fibre are a source of nutrients that can be used by household members, fed to animals, sold or exchanged. **Crop residues** are another source of nutrients that can be put to various uses, such as fodder for livestock, roof straw for houses, or bedding in kraals, etc.

The important characteristics of a particular crop production system are the prevalent types of soils, crop species, associations and varieties, and crop management practices within the system's different fields.

The animal production system

Herds of animals transform plant biomass into **animal products** (meat, milk, eggs, hides, etc.) and **excrement** (faeces and urine**).** They may spend some time in a pen or kraal, where they generate an important source of **manure**.

A significant amount of the nutrients obtained by grazing remain temporarily immobilised in the animal's body, where they represent a stock of nutrients. **Animal products** are a source of nutrients that may be consumed by the household or sold on the market.

Manure is made up of decomposed faeces and urine that may have litter added to it (see paragraph 3.3.2). It generally constitutes an important source of nutrients for crops, but can also be used as fuel.

Pastures that are owned by the farming family fall within the boundary of their system. **Communal pastures**, on the other hand, are part of the greater land use system, and may be an important source of nutrients for the animal production system (see paragraph 3.2 and Chapter 4).

Supplementary feed stores are an intrinsic element of the animal production system, even if they are situated close to the compound.

Animal production systems vary greatly, depending on the species in question and the way they are managed.

The household system

Household members are a group of people who live together and who are usually related through kinship and marriage. The household is the centre where many decisions are made about the allocation of labour, capital and land, and about farm management.

Food: in terms of resource and nutrient flow analysis, food constitutes a significant source of nutrients which is either purchased or produced on-farm. An considerable amount of the nutrients consumed remains in the human body.

Waste: in rural Africa cereals are pounded in the compound, producing bran. This is either used as animal feed or becomes part of the household's waste, which is generally collected in a heap and taken out to the fields. Another important ingredient of waste is ash from cooking fires.

Attention should also be given to the disposal of faeces and urine, since a good deal of the nutrients generated within the farm find their way into the stomachs of the compound's inhabitants. If human faeces end up at the bottom of a pit latrine a significant share of the nutrients derived from the farm is stored untapped and unavailable for recycling.

Compost made from plant material can be another important source of plant nutrients.

There are interacting elements in both the crop and animal production systems, which means that we can identify distinct sub-systems within them. For example, the same farm may contain irrigated crops on fields that will never carry a dryland crop, and dryland crops in fields that will never be irrigated. The example from Sukumaland shown in Table 2.3 shows a wet-rice-based system on the clay soils at the lower end of the catena and a maize-millet-based system on the loamy-sand soils higher up the catena. The same farm system may even contain two further distinct crop production systems, such as perennial crop cultivation and gardening.

Similarly, different animal production systems are often found within the same farm system. A farmer may keep oxen in a stable and feed them on bought-in feed concentrates and fodder crops from the farm, while most of the cattle herd get the bulk of their food from grazing on communal pastures.

In order to identify which resource flows are leaving or entering the system it is important to be able to precisely define the unit of analysis and its **boundaries**. When material passes from one system to another it crosses a boundary, at which point the first system registers a loss and the second a gain.

We often take the field as our unit of analysis for crop production systems, so that flows leaving the system (crops harvested and transported) cross the physical border at the edge of the field plot. When the grain from a cereal crop is taken to the granary it enters the household system, which gains the material lost by the crop production system.

However, system boundaries are not always physical borders. In Africa farms are often composed of several fields scattered inside the village territory, which means that the elements of the farm system are not grouped together in a single plot and there is no clearly visible boundary for the farm as a whole. Nevertheless, if we consider the farm as a system, we can imagine a boundary. For example, when a farmer sells crops at the market a flow leaves the farm, crosses the boundary of the farm system and enters the broader market economy, which is a separate unit or system. Similarly, when livestock graze on communal pastures for part of the day but pass the night in a kraal on the farmer's field they cross the boundary of the farm system, bringing a flow of nutrients from the grazing land onto the farm when they deposit dung and urine in the kraal.

3.2 Resource and nutrient flows

We have shown that a system is a set of interacting elements and processes that occur within a boundary. Table 3.1 lists the input and output **processes** involving resource and nutrient flows at **farm level**. Processes with the same number share a common factor; for example *OUT 1* represents flows from the farm system in the form of products sold on the market, while *IN 1* represents an addition to the farm's nutrient stocks when mineral fertilisers are bought from the market. Similarly, the common factor in sedimentation (*IN 5*) and erosion (*OUT 5*) is soil transported by water or wind. Each set with the same number contains processes that **mirror** each other, such as biological N fixation (*IN 4*) where nitrogen changes from gas into liquid, and denitrification (*OUT 4),* when it changes from a liquid state back to a gas.

***Table 3.1 Resource and nutrient flows in the farm system*[2]**

N 1	**Application of mineral fertilisers bought at market**
N 2	**Organic inputs: organic waste or manure obtained outside the farm, feed for livestock obtained outside the farm (off-farm grazing, fodder and concentrates), food for family obtained outside the farm**
N 3	Wet and dry atmospheric deposition (dust, ash in rainwater)
N 4	Biological nitrogen fixation (e.g. through leguminous plants)
N 5	Sedimentation of material that has been eroded elsewhere[a]
N 6	Sub-soil exploitation by trees and other perennial crops
UT 1	**Harvested crops and livestock products (milk, meat, eggs, etc.) taken off the farm and sold at market**
UT 2	**Crop residues and manure that leave the farm (for example, when livestock graze on farm stubble but excrete outside the farm)**
UT 3	Leaching of nutrients below the root zone
UT 4	Volatilisation (losses into the air; denitrification, burning, nutrients in airborne ash)
UT 5	Water erosion (nutrients leaving the system via runoff, rivers, or semi-permanently in swamps[a]
UT 6	Human faeces deposited in deep latrines

a: Erosion and sedimentation of materials can only partly be considered as nutrient output or input, as some of the minerals are inert reserves in the soil and are therefore not available to plants.

(Adapted after Smaling, 1993; Smaling and Braun, 1996)

It is hard to observe some of the processes in Table 3.1, such as nutrient inflows from atmospheric deposition; and the fact that nitrogen can be found as a gas, a solid and a liquid further complicates matters. Other plant nutrients may not come in gaseous form, but can be carried in soot or airborne ash, as the products of fire. The complexity of the processes involved and their lack of visibility can make it very difficult to analyse these kinds of nutrient flows.

We will focus on the processes that are **comprehensible** to anyone working the land (literate or not), and which relate to farm management. Our analysis is generally based on the flows printed in bold in Table 3.1: mineral fertilisers *(IN 1),* organic inputs *(IN 2***),** crop products ***(OUT 1)*** and organic outputs *(OUT 2),* which relate to important elements of farm management and decision-making. Since the farm system is the unit of analysis *IN 2* also includes biomass eaten by farm animals while grazing on common pastures - nutrients leave the (higher level) village land-use system and enter the farm system. Similarly, organic outputs *(OUT 2)* include animal faeces excreted outside the farm while herds graze on common pastures or are penned in a kraal off the farm.

The Guide will not consider the other processes shown in Table 3.1 in such detail, since they are more difficult for farmers to quantify and apprehend. This does not mean that they should be systematically excluded from the analysis, but Guide users will need to judge whether it is appropriate to invest the time and effort in their analysis.

Rough estimates may be made for some of the processes, such as biological nitrogen fixation (*IN 4*), which should be taken into account where legume growing is an important activity as it is likely to be a significant flow. Denitrification from irrigated soils (*OUT 4*) may account for significant nitrogen losses from the system, and could be important in irrigated rice systems where high doses of nitrogen are applied. Nitrogen loss through volatisation (*OUT 4*) may also become important when organic fertiliser is left exposed to sunlight. Where water erosion is significant the analysis should take account of flows of nutrients leaving the system through runoff (*OUT 5*); and sedimentation (*IN 5)* may be important in flood plains. Pit latrines *(OUT 6)* generally represent a significant withdrawal of nutrients from the farm system; and high rainfall in areas of sandy soil is likely to lead to considerable losses of nitrogen and potassium through leaching *(OUT3*), which will increase as more fertiliser is applied.[3] Where agro-forestry is important *(IN 6)* should not be neglected.

The picture becomes slightly more complicated when we consider the sub-systems within the farm system. Some of the processes shown in bold type in Table 3.1 relate to the crop production system, while others relate to the household and animal production systems. Table 3.2 takes a closer look at some of the ways resources and nutrients are transferred in the **crop production system**, which is part of the farm system. This table only covers processes *IN 1, IN 2, OUT 1* and *OUT 2,* and for the sake of uniformity they are numbered in the same way as those in the farm system. Most of the processes have been sub-divided according to the **source or direction of the flows**.

Table 3.2 Resource and nutrient flows in the crop production system

IN 1	mineral fertiliser **applied** to fields
IN 2	organic fertiliser **applied** to fields
* *IN 21*	organic fertiliser **obtained outside** the farm
* *IN 22*	organic fertiliser **produced on the farm**; includes
- *IN 221*	manure produced **in the animal production system**
- *IN 222*	waste or compost **produced in the household system**
OUT 1	crop products **removed from fields**
* *OUT 11*	products that **leave the farm** (e.g. sold on market)
* *OUT 12*	products that **stay on the farm**
- *OUT 121*	products **going into the animal production system** (feed)
- *OUT 122*	products **going into the household system** (food)
OUT 2	crop residues **removed from fields**
* *OUT 21*	crop residues **taken from the farm** (sold; eaten by non-farm animals, or burned[a])
* *OUT 22*	crop residues that **stay on the farm**
- *OUT 221*	crop residues that **enter the animal production system** (e.g. crop residues eaten by farm animals, fodder transported to feed stores, litter in kraals)
- *OUT 222*	crop residues that **enter the household system** (e.g. straw for roofs, residues for composting)

[a] When crop residues are burned organic carbon and nitrogen are lost, while other minerals become directly usable

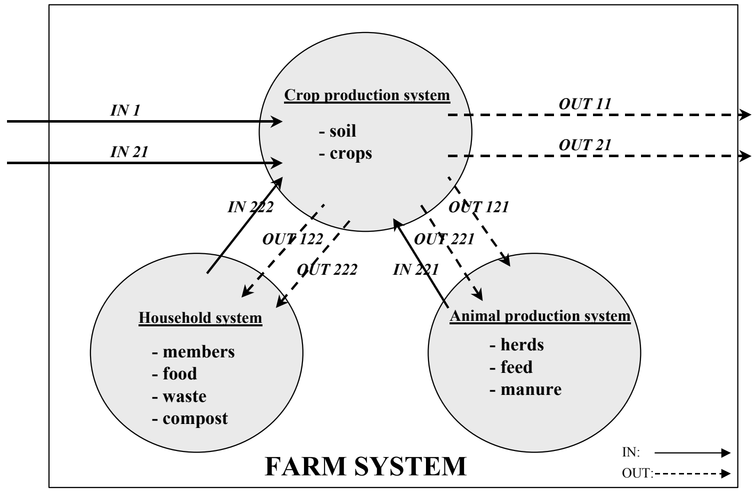


Figure 3.2 Resource flows involving nutrients in the crop production system

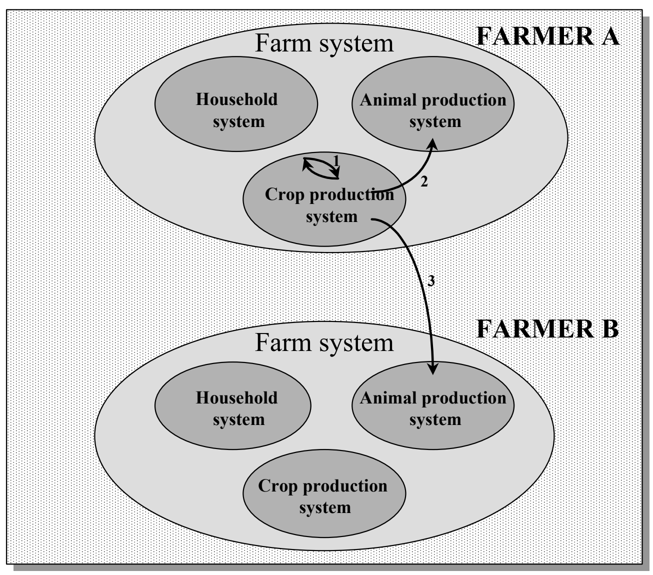
Figure 3.2 shows the same nutrient flows in the crop production system, and their movement to and from the household and animal production systems. Each flow has been subdivided according to whether it is inside or outside the farm system. Organic fertiliser *(IN 2)* can be obtained outside the farm (*IN 21*) or produced inside it (*IN 22*), and a further distinction can be made between what is produced by livestock (*IN 22)* and what is produced by the household and its members in the form of household waste and compost (*IN 222*).

Output processes can be similarly subdivided. We can distinguish between crop produce sold on the market (*OUT 11*) and crop produce that remains on the farm (*OUT 12*) and is consumed by the farm's livestock (*OUT 121*) or by household members (*OUT 122*).

If a farmer leaves crop residues (*OUT 2*) in the field there is no flow from the field. Part of the crop residues left there will be eaten by termites and the rest will be incorporated into the soil when the land is prepared for the next season. However, when crop residues are burned some nutrients do leave the field and the farm in soot and ash *(OUT 21*). Crop residues also leave the farm when they are sold as fodder or when animals from a neighbouring farm come and graze them but defecate elsewhere. The crop residues that are used as outputs on the farm (*OUT 22*) can be divided into those which go into the animal production system as fodder or bedding in the kraal *(OUT 221)*; and those used in the household system for composting or for roofs *(OUT 222).*

Note that these subdivisions may be made more or less detailed according to each situation. As we said at the beginning of this chapter, it is important to clearly specify the unit of analysis under consideration, which means clearly defining the system and its boundaries, as shown in Figure 3.3.

For example, crop residues left and eaten by termites in farmer A's field represent nutrients recycled within the crop production system (see flow 1; Figure 3.3). When the same crop residues are eaten by farmer A's animals (see flow 2; Figure 3.3) the material leaves his crop production system *(OUT 221)* and enters his animal production system. If farmer A's crop residues are eaten by farmer B's animals (see flow 3; Figure 3.3) the materials leave farmer A's crop production system and his farm system *(OUT 21)* and enriches farmer B's animal production and farm systems. These examples show how important it is to define the unit of analysis and to understand the flows between different units in order to determine whether a system is being enriched or is subject to gradual impoverishment.



(1) Resource recycling

(2) Resource transfer from crop production system to animal production system **within** the farm system

(3) Resource transfer **between** farm systems

Figure 3.3 Resource flows within and between farm systems and sub-systems

3.3 Sources of nutrients

So far we have defined systems by the **elements** interacting within their **boundaries** and by **flows** of resources and nutrients. Systems also contain reservoirs or **stocks** that store energy, matter, nutrients or information. These stocks are increased when matter is added and depleted when matter is removed from them to provide a **source for another system**.

The rest of this chapter deals with some of the major sources of nutrients in the farm system: nitrogen (N), phosphorus (P) and potassium (K). These are generally considered the most important nutrients for crop production, and are often called **macro-nutrients**. Chapter 4 describes how to draw up a nutrient balance to show which nutrient limits crop production the most. **Micro-nutrients** (such as calcium, magnesium, etc.) may also limit crop production, but they will not be dealt with by this Guide.

Within the farm system and sub-systems we can distinguish between nutrient sources that are from **within** the farm system and those which are brought in from **outside** the farm system.

Soil is the major element of the crop production system and constitutes the primary source of plant nutrients**.**

Crops produced on the farm provide nutrients in feed for livestock and food for the people living on the farm.

Crop residues and **grass** from pastures are also sources of nutrients for livestock.

Manure produced by the farm's livestock, and **waste** and **compost** produced by the household are other sources of plant nutrients.

Mineral fertilisers are important sources of purchased plant nutrients. Organic fertilisers, food and feed can also be bought off the farm.

3.3.1 The soil as a source of nutrients4

Soil covers a thin layer of the earth's surface. It is made up of solid particles derived from weathered rocks and decaying organic matter, with liquid and gases in the spaces between the particles. We will mainly look at the soil as a source of plant nutrients, although organic matter is also very important for the soil's structure and stability.

The mineral reserves in soil are not seen as plant nutrients. Elements of these reserves slowly become available as plant nutrients, as soil minerals alter and dissolve. Mineral elements may also become unavailable to plants, for example when phosphorus or potassium is irreversibly fixed.[5]

A soil's fertility is determined by the type of rock from which it is derived, but very old soils will have had many of their original chemical elements removed by leaching, and water and wind erosion. This guide deals with a widespread group of soil types that are characterised by a relatively **sandy topsoil**, a **clay content that increases with depth** and a generally **weak soil structure**.[6] Sometimes the clay content changes very suddenly, and when this happens it can hinder root growth. Heavy tilling can weaken the structure of the soil, and when it does not contain much organic matter it may form a surface crust. When these types of soils are intensively cultivated it becomes increasingly difficult for rainwater to penetrate their surface, and there is an increased risk of runoff and soil erosion. Although soils under forest or bush cover contain relatively high levels of organic matter, this rapidly decreases to very low levels in the first few years after clearing. Generally speaking, the less organic matter a soil contains, the weaker its structure and the greater the risk of serious erosion. As a preventive measure soil should contain at least 0.6% of organic matter.

Table 3.3 Status of some important soil parameters

	Status of factor in the soil		
Factor	**Good**	**Deficient**	**Poor**
pH-water	5.5-7.0	-	-
Organic matter (%)	> 1.7	0.9-1.7	< 0.9
Total nitrogen (%)	> 0.1	0.05-0.10	<0.05
Available phosphorus (P- Bray; mg/kg)	> 6	3-6	< 3
Cation Exchange Capacity (CEC; $cmol_{(+)}$/kg)	> 10	5-10	< 5
Available potassium (meq/100g; $cmol_{(+)}$/kg)	> 0.25	0.10-0.25	< 0.10

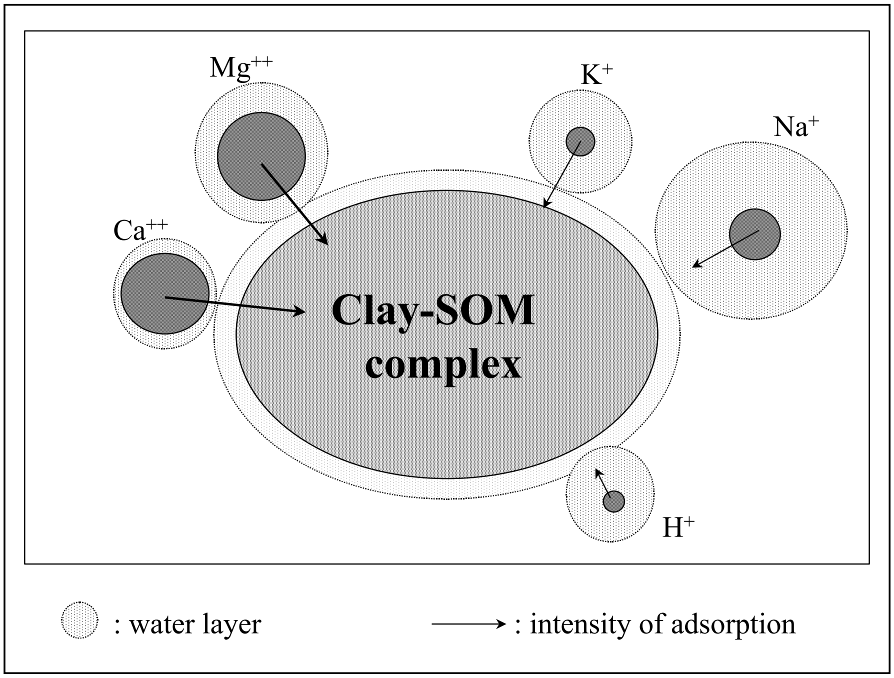
Soils whose underlying rock material is **evenly coloured** normally have poor fertility status. If the underlying rock material is **dark and multi-coloured** the soils above tend to be relatively fertile, and provide an environment with relatively luxurious natural vegetation. However, if the soil material was formed a long time ago the soils may have become leached and infertile.

A combination of well decomposed soil organic matter (SOM) and available clay particles forms a **clay-SOM complex**. This is a chemically active complex which absorbs cations (K^+, Ca^{++}, Na^+, Mg^{++}, NH_4^+, Al^{+++}, H^+, etc.) and anions (NO_3^-, SO_4^{--}, HPO_4^{--}, etc.). The absorbed ions are in equilibrium with the soil solution, and together they make up the exchangeable form of soil nutrients available for plants. When an ion from the soil solution is absorbed by a plant it is liberated by the clay-SOM complex, and the solution remains in equilibrium (see Figure 3.4). Conversely, when fertiliser is applied to the soil, part of it will be absorbed by the complex. [7]

The chemical elements in the soil solution that are in equilibrium with those absorbed in the clay-SOM complex are called **immediately (or readily) available** nutrients. There are two other forms of minerals in the soil:

- the **dynamic reserve** which is made up of elements present in the SOM;
- the **inert reserve,** which consists of mineral reserves in the soil.

A soil's fertility is determined by the interface between the plant nutrients available in soluble form in the SOM, and in the clay-SOM complex. Elements from the SOM become available as plant nutrients through mineralisation. The soil's inert reserve is not considered to be a source of plant nutrients.



Note: The intensity of ion absorption depends on the valence of the ions and thickness of the water layer

Figure 3.4 Absorption of ions by the clay-SOM complex

Soils with a good capacity to store nutrients in the clay-SOM complex will be rich in nutrients available to plants. This capacity is referred to as the **Cation Exchange Capacity**, or the **CEC**. The CEC is the sum of exchangeable cations absorbed per unit weight of soil. Clay and SOM both add to the CEC; and in soils where there is little clay, organic matter automatically becomes more important for storing nutrients. When organic matter is lost through intensive cultivation the soil also loses its capacity to store nutrients, and it is not easy to make good this loss. In general, soils which are poor in clay are particularly vulnerable to such losses.

One of the consequences of a poor CEC (lower than 5 $cmol_{(+)}$ /kg; see Table 3.3) is that added nutrients are easily lost through leaching. In the lowland tropics soils, with a low CEC generally have only limited potential. Farmers wanting to increase the production potential of such soils would either have to move large quantities of clay to the field or add an enormous amount of organic matter, which would eventually turn into SOM and thereby contribute to the CEC. While this strategy could work in the cooler conditions[8] of the highlands, the temperatures in the tropical lowlands cause organic material to decompose too rapidly to make any significant contribution to the SOM in the short-run.

Sandy soils are generally at risk of **acidification**, especially if they are under continuous cultivation, and if nitrogen fertilisers are regularly applied. A soil's acidity depends on the concentration of hydrogen ions (H^+), and is measured by the **pH** scale, which runs from 0 (pure acid) to 14 (pure alkaline). A pH level of 7 is called "neutral", and soils with pH 5 or less are called acid soils. Soil acidity diminishes the CEC, as large quantities of H^+ in the clay-SOM complex make it impossible for other ions to be absorbed. As the unabsorbed ions remain in the soil solution they are easily leached away, so soil acidification can cause the same sort of effects as soil nutrient impoverishment. Moreover, acid soils are often characterised by toxic concentrations of aluminium and manganese.

We have already noted that the Guide only covers the major characteristics of the three most important plant nutrients: Nitrogen (N), Phosphorus (P) and Potassium (K). We have put the nutrients into two broad categories for calculating nutrient reserves in the soil:

- nutrients which are readily available for crops (mainly the soluble form in the soil solution and the exchangeable form absorbed by the clay-SOM complex); and
- nutrients which are part of the more or less stable nutrient reserve in the soil (the insoluble form).

Nitrogen

Nitrogen is vital for plant growth, and is an important component of plant proteins. It is a very mobile nutrient and can move relatively quickly by infiltrating rainwater or by changing from a soluble form in soil solution to gaseous forms that eventually escape into the air. Because it is so mobile nitrogen moves rapidly to the growing part of the plant, and often produces a green 'flush' at the start of the wet season. After a dry period soil life regains momentum, and rapidly decomposing organic material generates a sudden increase in available N. If there are no roots to capture the flush, significant quantities may be leached and eventually lost. Plants lacking in nitrogen turn a light green/yellow, especially the older leaves.

Nitrogen is unstable, and when it is applied in mineral fertilisers it can easily be lost through leaching and N-carrying gases. Such losses can be reduced by applying nitrogen fertilisers at several intervals during the wet season, particularly after rain or during rainy periods, when there is less risk of it burning the crop. Sources of organic matter which increase nitrogen levels in the soil include animal manure, compost and green manure.

For nitrogen, the fertility status of a soil can be estimated by observing its surface colour, texture and structure. A dark, clayey and well-structured soil with plenty of active soil fauna (especially worms) indicates good levels of nitrogen.

Table 3.4 Estimated nitrogen reserves in the soil's rooting zone

	% Soil nitrogen	Available for crop growth (kg/ha)	Dynamic reserve (kg/ha)	Inert reserve (kg/ha)
Good level	> 0.1	15-90	> 1,500	1,500
Low level	0.05-0.1	20-45	750-1,500	750-1500
Very low level	< 0.05	8-20	< 750	< 750

Note: 'rooting zone' refers to the layer of the soil where most of the roots of a seasonal crop are found, usually approximately 0-20 cm[9]

Box 3.1 How to estimate soil's nitrogen reserves

For light, sandy soils one can assume that 1 litre of soil weighs 1.5 kg. Soils with a higher clay content tend to be heavier, weighing about 1.7 kg/l.

If we take the top 20cm of soil the volume of one hectare will be:

10,000 m^2 x 0.2 m depth = 2,000 m^3 of soil; or

2,000 x 1,000 litres = 2,000,000 litres.

This equals 2,000,000 x 1.5 kg of soil = 3,000,000 kg.

A soil with a good supply of nitrogen contains about 0.1% nitrogen (see Table 3.4), so one hectare will contain 3,000,000 kg x 0.1/100 = 3,000 kg of nitrogen. Of this, 1500 kg (50%) represents the 'dynamic reserve'. Only about 1-4% of this is directly available for crop production, and is subject to losses of between 15-90 kg.

This estimate of available N shows the relative importance of nutrient recycling during crop production. The ratio of nitrogen exported (through removing crops) : the dynamic reserve indicates how long a farmer can afford to continue extracting N without replacing it. If, for example, the dynamic reserve is less than 750 kg/ha and a crop annually exports 75 kg/ha, crop yields will soon drop.

Table 3.4 gives an idea of the quantities of nitrogen in different kinds of soil. The total reserve of nitrogen in the soil can be estimated by measuring the percentage of soil nitrogen. About half of this reserve will always be available as it is stored in the relatively active form of organic matter. This part is called the **dynamic reserve,** and it will give an indication of the length of time that crop production is potentially possible. As reserves diminish it becomes increasingly difficult for a crop's roots to find the nitrogen they need, and consequently yields decline. The other half of the total nitrogen reserve, a fraction of organic matter that does not easily release its nutrients is called the **inert reserve**. It should be noted that only about 1-4% of the dynamic reserve is directly available for crop production, and this is subject to losses (see Table 3.4, column **available for crop production)**. Box 3.1 shows how to calculate the different amount of nitrogen reserves in the soil.

Phosphorus

Phosphorus is a basic nutrient which, like nitrogen, contributes to essential proteins in the plant. As it is not a mobile nutrient and cannot easily be lost through leaching, applying P-fertiliser can be a good investment that will bring returns over many years. However, when organic matter is added to the soil phosphorus may become more mobile[10], and erosion can also cause substantial losses when it removes the more fertile topsoil.

Plants that suffer from phosphorus deficiency tend to be stunted [11] and often have dark green leaves and reddish-purple leaf tips.

Phosphorus can be applied in less soluble forms such as rock phosphate (which is especially recommended for acid soils), and is also present in organic fertilisers such as animal manure. Farmers using phosphorus fertiliser need to take account of the soil's nitrogen status, as it is only economical to apply large quantities of phosphorus when there is enough N in the soil. Red soils tend to contain significant amounts of iron, and when phosphorous is added to such soils it may become fixed to the iron compounds. This means that the farmer will have to use large quantities of phosphorus fertiliser to ensure some phosphorous remains available for the plants.

In general there is not much phosphorus available in soils unless they are regularly fertilised. The P-reserve is mainly found in organic matter, and is fixed in barely soluble aluminum- and iron-compounds in the soil. In areas where the soil is aluminum-saturated, large amounts of phosphorus may slowly become available, keeping the P-reserve well supplied. In other areas, such as the Sahel, P reserves are more reliant on the SOM content, as is the case with nitrogen.

There are several ways of extracting phosphorus. The Bray method is used for more acid soils, while the Olsen method is more generally applicable.

P-Bray gives an estimate of the phosphorus that is **immediately available** for crop growth. As a rule of the thumb, 6 or more mg/kg P-Bray shows that there is enough phosphorous for the coming cropping season; less than 6 mg/kg indicates a possible deficiency (see Table 3.5).

P-Olsen gives an indication of the **total P reserve**. A concentration of less than 200 mg/kg P-Olson shows a poor phosphorus reserve, while more than 800 mg/kg indicates a good P reserve. Sandy soils usually contain less phosphorus than soils with a high clay content, and a pH of less than 5.0 (acid soils) often means that very limited amounts of P are available.

The **dynamic reserve** of phosphorous is roughly 80% of the total reserve, of which 50% is found in the SOM. So a soil with a total P reserve of 2,500 kg/ha will contain a dynamic phosphorus reserve of about 2,000 kg/ha, of which 1,000 kg/ha is found in the SOM. Box 3.2 shows how to calculate the different amounts of phosphorus reserves in the soil on the basis of soil analytical data.

Table 3.5 Estimated phosphorus reserves in the soil's rooting zone

	P-Bray		**P-Olsen**	
	Soil analytical data (mg/kg)	**Immediately available (kg/ha)**	**Soil analytical data (mg/kg)**	**Total reserve (kg/ha)**
Good level	> 25	> 75	> 800	> 2,500
Average level	6-25	18-75	200-800	600-2,500
Low level	3-6	9-18	100-200	300-600
Very low level	< 3	< 9	< 100	< 300

Note: 'rooting zone' refers to the layer of the soil where most of the roots of a seasonal crop are found, usually approximately 0-20 cm

Box 3.2 How to estimate soil's phosphorus reserves

This estimate assumes that we are looking at a soil whose top layer weighs 3,000,000 kg per hectare (see Box 3.1). In that weight of soil we could expect to find about 6 ppm (parts per million or mg/kg) P-Bray, which amounts to 18,000,000 mg or 18 kg of available P per hectare (see Table 3.5).

To gauge the significance of P extraction we compare the amount of available P per hectare with the amount of P exported in crops and residues removed from the field. A cotton crop yielding 2,000kg of fibre and 3,000kg of straw exports about 11 kg of P (see Table 3.13), which means that more than half of the immediately available P in the soil is removed with the crop.

Potassium

Potassium is essential to plants for the formation and transfer of carbohydrates in photosynthesis, and also for protein synthesis. It is particularly important for fruits, leaves and stems, and is needed to strengthen the plant's structure. Potassium deficiency in plants can be quite difficult to detect, but indicators are yellowing leaf tips and margins, and increased lodging.

Potassium promotes high crop yields, particularly in root and tuber crops. Farmers aiming to maintain maize yields of over 2 tons per hectare will need to apply extra potassium, as well as large amounts of nitrogen and phosphorus. Crop residues often contain considerable quantities of this nutrient, so it is important to recycle them to maintain the soil's potassium levels. Mineral fertilisers do not always contain potassium, so that mining can take place.

Potassium reserves are largely dependent on the type of soil minerals present. Soil potassium may be classified according to its availability to plants, and falls into three categories: (1) the inert reserve or slowly available K; (2) the dynamic reserve and (3) the readily available reserve.

The **inert reserve** or **slowly available potassium** constitutes about 95% of the soil reserve, and is mainly contained in primary minerals and clays such as *vermiculite* or *illite*. These minerals release K very slowly, and the amount released over a single growing season is negligible.

The **readily available potassium** is measured by the exchangeable K (expressed as $cmol_{(+)}/kg$) absorbed in the clay-SOM complex and found in the soil solution. Normal (kaolinitic) soils contain about twice as much K in their **dynamic reserve** as in their readily available reserve.

When plants take up potassium the equilibrium between the dynamic and readily available reserves is temporarily disrupted. Some of the exchangeable K must then be immediately released into the soil solution to re-establish this equilibrium. Clayey soils contain more potassium than sandy soils, so that a soil containing about 40 % clay has four times more exchangeable K available than a soil with only 10 % clay.[12] Table 3.6 shows the levels of exchangeable K in soils of different quality, with columns 4 and 5 indicating the levels of the inert potassium reserve.

Box 3.3 shows how to calculate exchangeable K in the soil.

Table 3.6 Estimated potassium reserves in the soil's rooting zone

	Exchangeable K		**Slowly available K**	
	Soil analytical data ($cmol_{(+)}/kg$)	**Readily available (kg/ha)**	**Uniform parent rock (kg/ha)**	**Variable parent rock (kg/ha)**
Good level	> 0.25	> 300	> 1, 800	> 9,000
Average level	0.10-0.25	120-300	700-1,800	3,500-9,000
Low level	0.05-0.10	60-120	350-700	1,800-3,500
Very low level	< 0.05	< 60	< 350	< 1,800

Note: 'rooting zone' refers to the layer of the soil where most of the roots of a seasonal crop are found, approximately 0-20 cm

Box 3.3 How to estimate the availability of potassium

This estimate assumes that we are looking at a soil whose top layer weighs 3,000,000 kg/ha, as in Boxes 3.1 and 3.2.

Exchangeable potassium is expressed in $cmol_{(+)}$/kg, which originates from the atomic weight of the element, 39. One $cmol_{(+)}$ corresponds to 39 ÷ 100= 0.39g. This weight is always expressed per kg soil.

So, if a soil contains 0.10 $cmol_{(+)}$/kg soil of exchangeable K, the total amount of readily available potassium for the given soil layer will be:

3,000,000 kg x 0.1 x 0.39/1,000 = 117 kg/ha.

The ratio of potassium exported through crop removal : exchangeable K indicates how long a farmer can afford to continue extract K without adding fertiliser (compare to Box 3.1).

3.3.2 Fertilisers

There are two main types of plant fertilisers:

- **mineral fertilisers** that are normally industrially produced;
- **organic fertilisers** that have a biological origin. In Africa these are generally produced on the farm.

Both types of fertiliser have a high nutrient content compared to the nutrient concentrations found in the soil, so it is worth transporting and applying them to enrich the soil.

Mineral fertilisers

In contrast to organic fertilisers, mineral fertilisers generally have a high, fixed nutrient content, which is normally printed on the bags they come in. They may contain one or more of the essential nutrients, and those that contain only one nutrient are called **single** or **simple** fertilisers, while those that contain two or more of the major elements are called **mixed** or **compound** fertilisers. Table 3.7 lists the fertilisers that are regularly used in Africa.

Table 3.7 Mineral values of the mineral fertilisers most used in Africa

Fertiliser	% N	% P	% K
Single fertilisers			
• Ammonium sulphate	21		
• Ammonium nitrate	33		
• Calcium nitrate	15.5		
• Calcium-ammonium nitrate	25		
• Urea	46		
• Single super phosphate		9	
• Triple super phosphate		20	
• Rock phosphate[a]		8-12	
• Potassium sulphate			42
• Potassium chloride			33-50
Compound fertilisers			
• Di-ammonium phosphate	18	21	
• Potassium nitrate	14		37
• 15-15-15[b]	15	6.5	10.7

[a] There are several types of rock phosphate; the one here comes from 'Tilemsi', a place in Mali where rock phosphate is mined

[b] 15-15-15 is a compound fertiliser containing the 3 major nutrients: N, P, K; 15% N, 15% P_2O_5 and 15% K_20; converted into N, K, P this comes to 15, 6.5, 10.7%

Applying single element fertilisers is a short term and potentially damaging strategy that will eventually exhaust the soil's other principal nutrient reserves, which are also needed for crop growth. A sound strategy for achieving more sustainable land use in nutrient-poor agro-ecosystems is to apply a combination of fertilisers. Box 3.4 shows how applying single fertilisers can exhaust the soil.

Box 3.4 Example of enhanced nutrient extraction in a rice-based crop production system[13]

Kg/ha	N	P	K
Resources leaving the field			
- in additional grain yield (900 kg)[a]	- 10.4	- 1.8	- 3.5
- in additional straw yield (1030 kg)[a]	- 6.4	- 1.1	- 19.5
Nutrients added to the field			
- urea (65 kg)	+ 30		
Balance	+ 13.2	- 2.9	- 23.0

The figures above show that applying 30 kg/ha of N in the form of urea can increase the grain yield by 900 kg per ha, and the straw yield by 1,030 kg per ha. They also show that applying a single fertiliser (urea) drains the other plant nutrients, especially potassium.

Farmers want to increase their straw yield because it is needed locally for a variety of essential purposes - for thatching, as supplementary feed for animals during the dry season, and as bedding in kraals. Any straw left over after threshing is often burned outside the boundaries of the field, so that at the field level all the nutrients once contained in the above-ground parts of the rice crop are often lost.

[a] values of N, P, K are calculated using conversion figures presented in Table 3.13

Animal manure

Animal manure (called manure here) is an organic fertiliser consisting of a partly decomposed mixture of dung and urine, and possibly litter. Organic fertilisers from other sources are discussed in the following section.

Manure is recognised as a key resource in sustaining soil fertility in Africa, supplying the soil with a range of macro- and micro- nutrients and organic matter. However, the management of this resource raises several questions:

- what is the nutrient content of manure?
- how much manure is produced by cattle?
- what are the losses during storage and how can they be reduced?

We will consider these questions by following manure production from the livestock consuming feed and transforming and storing it in their bodies, to the handling and storage of manure. We will focus on cattle and small ruminants (sheep and goats), which are the most important dung producers.

Feeds and their digestion by livestock

The daily amount of fodder (dry weight) consumed by a ruminant can be expressed as a percentage of its live weight. For cattle this averages out at 2.5% (1.8-3.2%), while for small livestock the average is 3.2 % (2.4-4.0%). A standard animal with a live weight of 250 kg, is called a Tropical Livestock Unit (TLU). On average a TLU consumes 250 x 0.025 = 6.25 kg of dry matter per day. A sheep with an average weight of 25 kg consumes about 25 x 0.032 = 0.8 kg of dry matter per day.

The amount an animal eats is affected by the demands made on it and the quality of available feed. In the early rainy season a lactating cow can consume up to 3% of its live weight; while in the second half of the dry season there is little left to graze, and a cow's feed intake may drop to 2% (or less) of its live weight.

Natural grassland vegetation constitutes the main feed resource for most animal production systems in Africa. Cattle and sheep are grazers that mainly eat grasses and forbs, whereas goats are browsers that prefer herbs and the leaves and pods of shrubs and trees. When the feed quality of grass is very poor cattle and sheep will compensate by eating the leaves of tree and shrub species as well as grass. In many savannah areas dry grass is burned in the second half of the dry season to stimulate the regrowth of perennial grass species, and provide cattle and sheep with better quality feed.

Livestock often have access to crop residues left in the fields after harvesting, which provide relatively good and abundant forage but are usually quickly finished. In many areas farmers store the better quality residues such as groundnut and cowpea straw, and some of the maize, sorghum or millet straw, which they use in the dry season to supplement animal feed. Fodder crops are not widely cultivated in most parts of Africa, and they are usually grown in association with a cereal crop. An example of this type of combination is maize-dolichos (*Dolichos lablab*), which is grown in Southern Mali.

Box 3.5 shows how much grass and crop residue ruminants consume on a typical farm.[14]

Box 3.5 Ruminants' consumption of grass and crop residues on a typical farm

Consider a farm with 5 TLUs and 2.5 hectares of maize. The maize produces 3 tons of grain and 10 tons of straw which is all left in the field, where about 30% (3 tons) of it is consumed by the farmer's livestock.

The 5 TLUs consume 250 x 5 x 0.025 = 31.25 kg of residue per day, which means that the crop residues left in the field will last the animals for 96 days (10,000 x 0.3/31.25 = 96). Over the dry season the animals spend 3 months on communal village pastures, where they consume 2,812 kg of grass (250 x 5 x 0.025 x 90 = 2,812). In the last month of the dry season the animals only spend 4 hours a day on common pastures, so they only ingest half of their dietary requirements there, and will need 470 kg of residues to supplement their diet (250 x 5 x 30 x 0.025/2 = 470). Assuming that 50% of the pen-fed residues are eaten, a total of approximately 940 kg of residues is required.

Feed varies in digestibility, from 40% for poor quality roughage (straw) to 65% for young, green grass, and 85% for concentrates (see Table 3.8). This means that between 35-60% of the ingested forage (the undigested part) leaves the animal in the form of faeces.

Table 3.8 Mineral content and digestibility of animal feeds in %

Animal feed	N	P	K	Digestibility
Feed from pastures				
- young grass	1.6 - 2.6	0.1 - 0.3	1.1 - 2.4	50 - 60
- mature, dry grass	0.4 - 1.2	0.1 - 0.2	0.6 - 2.3	40 - 50
- forbs	1.3 - 2.8	0.1 - 0.3	0.9 - 2.4	50 - 70
- tree leaves	1.3 - 3.2	0.1 - 0.3	0.8 - 1.6	30 - 70
Crop residues				
- sorghum leaves	0.7 - 1.3	0.1 - 0.2	1.2 - 1.5	50
- sorghum stalks	0.2 - 0.5	0.08 - 0.16	1.3 - 2.4	30
- cowpea straw	2.2 - 3.4	0.26 - 0.35	1.1 - 3.2	50 - 60
Feed concentrates				
- cotton seed cake	6.1 - 8.0	1.1 - 1.4	1.07 - 1.44	70 – 85

Source: Rivière (1991); Renard (1997)

Ruminants use most of the digested feed to maintain their body and gain weight, to produce offspring and milk, or to work. Most of the digested feed (85-100% of the organic matter) is used as energy for body maintenance, and finally leaves the animal in the form of heat and CO_2. Only a relatively small amount of minerals ends up in animal products (see Table 3.9).

Table 3.9 Mineral contents of milk and meat in %

	N	P	K
Milk (cows)[a]	0.55	0.065	0.079
Meat[b]			
Cattle	3.0	0.83	0.36
Sheep	3.3-3.6	0.115-0.19	
Goats			

[a] For milk the percentage is in kg per 100 litre

[b] For meat the percentage is in kg per 100 kg dry weight

Source: Rivière (1991); Renard (1997)

Quantity and composition of faeces

The organic part of the feed consumed by ruminants is decomposed by microbes living in the animal's stomach. As organic matter decomposes more quickly in the animal's body than it does through mineralisation in the soil, ruminants help speed up the recycling of minerals.

The annual amount of faeces produced by livestock can be calculated on the basis of two estimated parameter values:

- feed consumption
- digestibility

(see example in Box 3.6).

As a rough estimate we can say that one Tropical Livestock Unit (TLU) produces 1 ton of dry faeces per year.

Box 3.6 Calculating manure production

One TLU consumes 250 x 365 x 0.025 = 2,280 kg dry matter per year. The average digestibility of dry matter for cattle is estimated at 55%, so one TLU will produce (100-55) x 2,280 = 1,026 kg dry faeces per year.

One small ruminant weighing 25 kg consumes 25 x 365 x 0.032 = 292 kg dry matter per year. The average digestibility of dry matter for small ruminants is estimated at 60%, so one small 25 kg ruminant will produce approximately (100÷60) x 292 = 117 kg dry faeces per year.

Quantities of faeces are calculated as dry matter.

The importance of manure in soil fertility management depends on a number of factors, one of which is livestock management.

Ruminants that pass all their time on communal grassland defecate on that grassland, and consequently have little direct impact in transferring nutrients for crop production. However, ruminants grazing crop residues left in the field will drop some of their faeces and urine on that field. At night animals are sometimes left in temporary enclosures on cultivated land, so deposits of faeces and urine are concentrated in part of that field. Faeces and urine can be spread over the whole field by moving the enclosure.

Livestock also pass the night in kraals close to the homestead to which resources and nutrients from pastures and field are transferred. The deposits of faeces and urine concentrated in the kraal are called manure. Since animals defecate at fairly regular intervals through the day and night, the proportions of faeces and urine left in fields, pastures and kraal can be calculated according to the time spent in each location.

Faeces and urine contain minerals, most notably N, P and K[15 16]. P is mainly excreted in faeces, K mainly in urine and N in both. Some 40-50% of the total N excreted is found in urine, and animals eating protein rich diets (e.g. young grass) will produce urine with a higher N content. Table 3.11 shows that the mineral content of faeces varies considerably, depending on the quality of the feed consumed.

Storing and handling manure

The nutrient content and amount of manure obtained from kraals, pens or stables can be estimated on the basis several factors:

- the quality and quantity of faeces and urine;
- the number of animals kept;
- the time spent in the enclosure;
- the amount and quality of litter added to the manure.

The quantity of manure produced can be considerably increased by:

(1) extending the number of hours per day that the animals are enclosed and/or the period of the year that the animals are enclosed;

(2) putting litter in the kraal.

The amount of faeces and urine deposited in a kraal increases in proportion to length of time the animals spend there. However, manure production can be further increased by adding litter to the waste. Litter is organic material deposited in the kraal either as the uneaten component of the animals' forage, or as larger quantities of low quality material (e.g. sorghum and cotton stalks) added to increase manure production. Adding litter to the pen improves the conservation of minerals as it absorbs urine; and smaller litter particles (which have been well chopped or trampled) will absorb more than large ones. The amount of litter added per animal depends on the availability of material, the amount of rainfall, and the length of the rainy season. Table 3.10 shows how the amount of litter added to pens affects the amount of manure produced in them. It is based on data obtained from various sources in Mali.

Table 3.10 Amount of litter added to kraals and its effect on manure production

Litter added	**Cattle enclosed during the day**[a]	**Manure production (kg dry matter/year/TLU)**	
		Zone 600 mm rain/year	**Zone 1200 mm Rain/year**
No	No	130	190
Yes[b]	No	400	960
Yes[c]	During dry season	925	1295

[a] All animals were penned at night (14 hours). Dry season of 4 months

[b] Litter added during rainy season: 300kg dry matter in the 600mm zone, and 1000kg dry matter in the 1200 mm zone.

[c] Litter was added in the dry season (120kg dry matter in the 600mm zone and 210 kg dry matter in the 1200 mm zone) as well as the rainy season.

The data suggests that manure production can amount to twice the volume of dung excreted; and records of the most dry manure produced by one TLU per year vary between 1000kg and 2500 kg. Box 3.7 shows how to calculate the manure production and requirements for a typical farm.

Box 3.7 Calculating manure requirements for a typical farm

Consider a farm in a relatively wet area with 5 TLUs and 2.5 hectares of cotton (See Table 3.10: 1,200 mm of rain per year). To maintain the level of organic matter in the soil the farmer needs to add 2.5 tons of manure per hectare each year, so the annual manure requirement is 6.25 tons. If the farmer puts litter in the cattle pen s/he will need 5 x 1,000=5,000 kg of crop residue to produce 4,800 kg of dry manure. This will be enough to fertilise 1.85 hectares (about 75% of the cultivated area) at the recommended rate.

A substantial increase in manure production may not only require drastic changes in livestock management, but also major investments in equipment (carts), animal enclosures (improved kraals, stables) and labour. Farmers are often unable to intensify manure production because they cannot afford to buy or hire carts, or find the added labour to cart large amounts of forage to the animal enclosure, and manure to the fields. Box 3.8 shows the time and effort involved in manuring crop fields at different distances from the kraal.

Box 3.8 Calculating the time it takes to transport forage and manure

A farmer has 2 one hectare fields, the first 250 m away from the kraal and the second 1 km away. Every year each field requires 2.5 tons of dry manure. To produce 1 ton of manure the farmer has to transport approximately 1 ton of forage as bedding. A donkey cart can carry between 60 and 120 kg of crop residues, and 150 to 200 kg of manure.

It takes 15 minutes to make one trip to and from the nearest field, and 60 minutes for the furthest field; so it will take 5.2-10.5 hours to transport bedding to produce manure for all of the nearby field, and 20.8-41.6 hours for the furthest one.

Transporting manure (with a 75% dry matter content) to the nearest field takes 4.2-5.5 hours, and it will take 16.7-22.2 hours to take it to the furthest field.

This means that the total time required to produce and transport manure for one hectare of land ranges from 9-16 hours for a nearby field, and 37-64 hours for one that is 1 km away. It may in fact take even longer, as we have not taken account of the fact that carts are often operated by more than one person, or the time required to collect the bedding material and empty the pen.

The dry matter content of manure can vary considerably (see Table 3.11). Adding litter can produce manure with a dry matter content of between 30-50%, but these percentages may increase in the dry season without additional litter. The nutrient content of manure is also highly variable and we often found it difficult to make useful comparisons with the data available to us. The ranges presented in

Table 3.11 should therefore only be taken as a rough guide. The data is based on dry matter content, as organic matter percentages were not available for all data.

Table 3.11 Mineral and dry matter content of manure (in %)

	N	P	K	Dry matter
Cattle manure				
• Fresh manure	1.4-2.8	0.5 - 1.01	0.5-0.6	15-25
• Kraal manure[a]	0.5-2.3	0.22-0.81	0.77-5.44	40-60
• Kraal manure[b]	1.5-2.5	0.2-0.6	1.5-2.0	30-50
Goat and sheep				
• Fresh manure	2.2-3.7	0.25-1.87	0.88-1.25	50-70

[a] Without litter[17]

[b] With litter

The N content of manure is affected by the way it decomposes. In aerobic conditions (which are prevalent in most cattle pens) N loss may be high, and ammonia volatilisation from aerated manure can remove up 60% of its total N content. These losses increase with prolonged storage and greater moisture content. In anaerobic conditions N may be lost through denitrification. Substantial amounts of mineral and organic material can also be lost through surface water run-off and leaching, which increases with higher rainfall and prolonged storage.

Other organic fertilisers18

There are many other sources of organic fertiliser apart from animal manure, and these are particularly important for farmers who have a limited number of livestock. The three main types of organic fertiliser covered in the Guide are:

- green manure;
- compost;
- household waste.

Crops used for green manure are usually fast-growing annual legumes or grasses. They are generally grown in rotation with cereals and incorporated into the soil when they are still green and succulent. The advantage of green manure is that it increases the content of organic matter, improves the structure of the soil, and makes phosphorus more available to plants. Moreover, in the case of legumes, nitrogen is added to the soil through biological nitrogen fixation. Velvet bean (*Mucuna pruriens*) is a rapidly growing legume that can fix up to 60 kg N/ha/year and produces large amounts of organic matter. It can grow in most soils and suppresses weed growth, but requires an annual rainfall of more than 1,000 mm. *Sesbania rostrata, Sesbania sesban, Tephrosia vogelii* and *Crotalaria* sp. are other legumes which are mainly promoted as green manure crops, and which have a nitrogen fixing capacity of 10 to 50 kg N/ha.

Legumes are often inter-cropped, as well as being sown as a sole crop in rotation with cereals. Cultivating cereals with legumes can improve both the stability and level of yields. For example, by inter-cropping maize and cowpeas or *Dolichos lablab* the farmer can replace up to 30% of the nitrogen taken up by maize.[19] However, it seems that most of the N fixed by legumes only becomes available for subsequent crops.[20] Legumes contribute to soil fertility not only through nitrogen fixation, but also as a supply of green manure and fodder.

Compost is a mixture of partially decomposed plant material, such as grass, crop residues and weeds. Composting is usually done in a pit about 60 cm deep, which is filled with alternating layers of different types of plant material. These layers are about 15cm thick and should preferably include some animal dung, ash, lime or small quantities of mineral fertiliser (such as rock phosphate), which will increase the speed of decomposition and improve the quality of the compost. While it is decomposing the material needs to be kept moist and must be turned frequently to keep it aerated. The nutrient content of compost will vary considerably depending on the source of the plant material and other materials added[21]. Composting demands a significant amount of labour for digging and filling the pits, turning the material, and watering the contents to keep it damp.

Household waste is a mixture of ashes and various organic materials collected in and around the household compound. Organic materials include food leftovers and bran from pounded cereal, as well as small amounts of chicken dung, etc. This is all usually put on a heap near the compound, along with household sweepings, dust and ashes, and left to partially decompose. The mineral content of household waste varies considerably, depending on the contents and origin of organic material and the conditions in which the waste has decomposed. Making household waste does not require much labour, and in Africa it is usually part of the daily round of sweeping and housekeeping.

Table 3.12 Mineral composition of other organic fertilisers (in %)

Origin	N	P	K
Fresh green manure[a]	2.0-4.3	0.1-0.3	1.0-3.4
Compost	0.3-0.9	0.07-0.17	0.14-1.3
Household waste	0.2-0.9	0.05-0.5	0.1-2.1
Ash from cooking	0.2-0.6	0.1-0.6	1.1-2.7

[a] In legumes, biological N-fixation ranges from 10 to 60 kg N/ha

3.3.3 Crop products

The crops grown in farmers' fields play an essential part in several stages of the nutrient cycle:

- nutrients from the soil and added fertilisers enable crops to grow;
- crops are the main source of nutrients for humans (e.g. cereals, tubers, root crops, etc.);
- crop residues are fed to domestic animals, which then produce organic fertiliser that is returned to the soil.

Because they are such a vital part of the nutrient cycle it is important to have estimates of the nutrient composition of the major crops. Table 3.13 shows the minimum, maximum and average values for some of the major crops grown in Africa, giving figures for the nutrient content of crop produce and residues as well as grain to straw conversion factors. The table shows considerable variations in the nutrient content of different crops. Box 3.9 illustrates how to estimate the quantity of different nutrients in grain and straw.

Table 3.13 Mineral composition of crop products and residues (in %), and grain to straw conversion factors

	N	P	K	Grain to straw conversion factor
Pearl millet				3.5
• grain	1.0-2.9 (1.85)	0.17-0.44 (0.31)	0.28-0.67 (0.48)	
• straw	0.24-1.1 (0.70)	0.03-0.18 (0.09)	0.73-3.41 (2.09)	
Sorghum				4.0
• grain	1.09-3.14 (1.69)	0.13-0.38 (0.26)	0.25-0.50 (0.34)	
• straw	0.25-1.18 (0.65)	0.02-0.21 (0.08)	0.31-2.07 (1.09)	
Maize				1.4
• grain	0.88-2.67 (1.55)	0.16-0.44 (0.29)	0.25-0.57 (0.35)	
• straw	0.45-1.24 (0.66)	0.02-0.14 (0.08)	0.80-1.64 (1.16)	
Rice				1.2
• grain	0.82-1.58 (1.16)	0.13-0.45 (0.20)	0.20-0.97 (0.39)	
• straw	0.35-1.59 (0.62)	0.02-0.26 (0.11)	0.27-3.05 (1.89)	
Cotton				4.0
• fibre + grain	0.15-4.05	0.29-0.65	0.82-1.31	
• straw	0.60-1.78	0.09-0.27	0.07-2.68	
Groundnut				1.9
• grains	3.91-5.76	0.22-0.78	0.60-0.81	
• podshells	0.75-1.34	0.04-0.07	0.40-0.90	
• straw	1.19-2.74	0.05-0.26	0.34-2.63	
Bambara nut				5.3
• grains	2.56-3.36	0.30-0.55	1.20-1.57	
• podshells	1.10	0.07	0.80	
• straw	1.19-1.30	0.09-0.11	0.68-1.10	
Cowpea				2.3
• grains	1.43-5.50	0.15-0.63	1.18-2.1	
• pods	1.07-2.46	0.09-0.30	1.08-1.24	
• straw	0.54-4.04	0.09-0.45	0.09-0.45	

Note: Figures show minimum - maximum values, with the average in brackets[22]

If you want to estimate the quantity of straw, multiply the grains harvested by the conversion factor. Weights are based on air-dried material. For pulse crops, the harvested fruits are the basis for conversion. Fruits = unshelled pulses[23]

Box 3.9: How to estimate the quantity of nutrients in grain and straw

Let us assume that a field of rice produces 1,000 kg of grain per hectare.

The nutrient contents for rice grain are 1.16 %(N), 0.20 %(P) and 0.38 %(K) , or 11.6 kg, 2 kg and 3.8 kg respectively for this level of rice yield.

The grain to straw conversion factor is 1.2, so the estimated quantity of straw is 1.2 x 1,000 = 1,200 kg. The straw contains 7.4 kg N, 1.3 kg P and 22.7 kg K.

If all the crop (grain + straw) is taken away, the farmer will remove an estimated total of 19 kg N, 3.3 kg P and 26.5 kg K. This shows that a considerable amount of K is lost when rice straw is removed from the field, rather than being recycled.

Notes to Chapter Three

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[1] It is not easy to characterise farming systems because of the complexity and heterogeneity of the elements involved. There is a huge amount of literature on farming systems, their characterisation and hierarchical classifications. **Duckman AN, Masefield GB** have grouped systems into 4 broad classes which reflect their fundamental structural differences, and **Grigg DB** (1974) classified systems according to geographical units. The best known classification was devised by **Ruthenberg H** (1980), but as he does not deal with the farm as a unit he also omits the crop production system, animal production system and household systems as important, interactive sub-systems of the farm systems. He also makes little distinction between the levels of analysis. However, **Fresco LO** (1986) pays specific attention to the farm as a system, composed of 3 sub-systems: the crop production system, the animal production system and the household system. The farm level is particularly important for our consideration of resource and nutrient flow analysis as it is at this level that decisions are made by the farmer (and his household members, the basic elements of the household system) about allocating resources within the crop and animal production systems. For more information on the systems theory see **Bauden RJ** (1995) ; **Checkland** (1981); **Jones J** (1990);

[2] Originally proposed by **Smaling EMA** (1993) and **Smaling EMA, Braun AR** (1996). This table has been slightly adapted.

[3] We are conscious of simplifying reality by focusing on flows IN1&2 and OUT1&2. The difference caused by the other flows will sometimes be very high, but in some cases, especially P and K, they will be rather low: see Table below (**Pol F**, personal communication).

Estimated nutrient flow under cotton in southern Mali

	Nitrogen (Kg/ha/yr)	**Phosphorus (Kg/ha/yr)**
IN 1:	32	11
IN 2:	14	3
Other inputs	*10*	*2*
OUT 1	255	4.5
OUT 2	12	2
Other losses	*41*	*2*
Partial balance	+9	+7.5
Total balance	*-12*	*+7.5*

[4] There is some excellent writing on tropical soils and their properties; for example see **Sanchez PA** (1976).

[5] The erosion and sedimentation of materials is therefore only partly considered as nutrient output or input. For example, when some potassium is occluded in clay particles it is no longer available to plants. For more details on the difference between nutrients and minerals in the soil see: **Frissel MJ** (1978), **Pieri C** (1989) and **Pol F** (1992).

[6] There is a great variety of soil types in Africa. In the context of this Resource Guide it is not possible to treat them all. W e will not discuss minority soil types, such as the very heavy cracking clays ('vertisols') that are found in large plains in the Sudan, and in the Ethiopian highlands, the red clayey soils, with relatively higher production capacity for mechanized farming, and the shallow and gravely soils on hill slopes or on plateaux. For more detail on these see relevant hand books such as; **Landon JR** (1991).

[7] The distribution of ions among these 3 forms differs according to the intensity with which they are absorbed. Ions generally exchange quite easily between the soil solution and the complex. However, in some cases potassium (K^+) may be strongly fixed to the clay and is therefore effectively unavailable to plants. The same holds for HPO_4^{--} which is easily absorbed by the complex and not easily liberated.

[8] In the past in The Netherlands and elsewhere in Western Europe poor sandy soils were made productive by adding organic matter (manure and material) from moors and heathland. Farmers developed arable land in a process that took decades (and in some cases hundreds of years) of hard labour on the land. Such man-made soils can occasionally be found in the tropics at higher altitudes. See for example **Milne GG** (1938).

[9] For the example we have taken a rooting zone of 20cm, knowing that roots of cereals can be found much deeper (see **Noordwijk M**, 1989). Taking a rooting zone up to 20 cm allows to make the comparisons with estimated nutrient reserves presented in the tables.

[10] See **Brouwer J, Powell JM** (1993).

[11] More information on the effect of low P on plant growth can be found in **Foth HD** (1990).

[12] The sandy granitic soils in Zimbabwe seem to supply adequate K for productive crops.

[13] See **Kajiru GJ, Kileo RO, Stroud A, Budelman A** (1998).

[14] Animals eat more when the fodder is more easily digestible, although this does not seem to have any clear effect on the production of faeces. However, cattle and sheep may not produce much manure in the dry season if there is not enough forage available. Goats often eat well in the dry season as they prefer to browse leaves and seeds of shrubs and trees.

[15] Minerals in dung are found in two forms: those directly soluble in water and those which are part of the organic material and will be freed after mineralisation.

[16] Kraal manure contains more sand than faeces because livestock trample faeces and litter into the soil, particularly in muddy cattle pens. This can result in an exceptionally high sand content of over 50%.

[17] For more details see **Renard C** (Ed.) (1997) and **Rivière R** (1991).

[18] More information on alternative techniques for producing organic manure can be found in **Pretty J** (1994).

[19] The FSR team in southern Mali has done extensive research on maize - *Dolichos lablab* intercropping; a technical note is available in French: **ESPGRN** (1994).

[20] For more information on the effect of biological nitrogen fixation by legumes see: **Giller, Cadisch** (1995).

[21] In the Philippines a method of rapid composting using fungi has been developed; see **Cuevas VC, Samulde SN, Pajaro PG** (1988) and **Cuevas VC** (1997).

[22] Data for this Table was collected in Mali by **Duivenbooden N van** (1992); **Stoorvogel JJ, Smaling EMA** (1990); **Renard C** (1997) ; **Rivière R** (1991).

[23] For data see **NAS** (1996) and **Linnemann AR** (1994).