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Capacity Building for Efficient Utilization of Biomass for Bioenergy & Food Security in the GMS [TA7833-REG]

Output 4: Knowledge Product Series

2*:* Soils and Biomass Amendments

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CONTENTS

ABBREVIATIONS & ACRONYMS

ADE	Anthropogenic dark earths
C	Carbon
C/N	carbon-to-nitrogen ratio
Ca	Calcium
CH_4	Methane
CO_2	Carbon dioxide
DNA	Deoxyribo-Nucleic Acid
Fe	Iron
GHG	Greenhouse Gases
GMS	Greater Mekong Subregion
H	Hydrogen
H_2O	Water (vapor)
ha	Hectares
K	Potassium
Mg	Magnesium
mm	Millimeters
N	Nitrogen
NPK	Nitrogen, phosphorus and potassium
O_2	Oxygen
P	Phosphorus
PAN	Plant-available nitrogen
pH	Scientific measure of acidity
S	Sulfur
SOC	Soil organic carbon
SOM	Soil organic matter
SRI	System of Rice Intensification

EXECUTIVE SUMMARY

Soils consist of ***minerals***, organic matter and small spaces, or ***pores***, which hold gases and liquids. Soils also contain hundreds of thousands of types of ***micro-organisms*** - bacteria, viruses and fungi – and thousands of types of small animals, such as insects and worms.

Soils are classified according to the relative amounts of different particles - sand, silt and clay - they contain. Clay soils have good water-holding capacity and are efficient at retaining nutrients required by plants. They are, however, dense and readily become compact, preventing the movement of water and roots through them. Sandy soils are much less dense, but are unable to retain water or nutrients very well, hence exposing plants to water stress in dry conditions.

Soils form distinctive layers, or ***vertical horizons,*** consisting of organic matter (litter), top-soil and sub-soil. A ***healthy soil*** is one which, over the long-term, generally has:

- High soil organic matter (>5%) and high soil organic carbon (SOC) content;
- High humus content;
- A wide range of particle sizes - including 'aggregates' which combine minerals and organic matter and which help to stabilize the soil and prevent water and air erosion;
- A range of pores within the soil, since differently sized pores have different functions;
- Higher total nutrients, in a form and location which makes them available to plants;
- High quantity and diversity of beneficial micro- and macro-organisms (e.g. earthworms);
- Suitable balance of acid/alkali; pH 5-7 is appropriate for most crops;
- Ability to cope with extreme events such as intensive rainfall.

Soil organic matter (SOM) has an important effect upon the structure and behavior of soils. By reducing soil density, SOM tends to make it easier to plough and turn the soil, whilst the additional pores created increase the quantity of gases and liquids within the soil. In turn, this encourages the development of biological activity and improves the ability of the soil to retain water and nutrients. SOM contains both water and macro- and micro-nutrients itself, but before these can be made available to plants, the matter has to be broken-down by micro-organisms.

The most important ***macro-nutrients*** are nitrogen (N), phosphorus (P) and potassium (K), followed by sulfur (S), calcium (Ca) and magnesium (Mg). These nutrients are always required for plant growth and reproduction. Most plants also require very small amounts of ***micro-nutrients*** such as: boron (B), chlorine (Cl), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo) and nickel (Ni). The required amounts of macro-nutrients are well known for mainstream agricultural crops and are often added to soils as fertilizers, either in the form of synthetic chemicals or via organic soil amendments.

Plant roots take-up macro-nutrients as ions and mineral forms dissolved in water, including ammonium, nitrate, phosphate, potassium and calcium. Synthetic chemical fertilizers are designed to decompose to readily-available ions which are quickly taken-up by the plant roots and utilized. Organic matter contains these nutrients in an organic form, not in a plant-available, mineral form. However, micro-organisms are able to decompose the organic matter, with their populations expanding rapidly as they utilize the energy and nutrients released. When these bacteria and fungi die, they in turn decompose, releasing the nutrients in a mineral form which plants roots can take-up. The ***microbial decomposition*** of SOM takes some time to happen so the nutrients are usually only plant-available after a few months' time has passed.

Approximately half of SOM is carbon. Most SOM added to soils is broken-down relatively quickly into smaller molecules such as sugars and amino acids that can be rapidly utilized by a wide range of micro-organisms for energy and nutrients, in the process releasing carbon dioxide (CO_2) back to the atmosphere through the process of respiration. Soil respiration occurs more rapidly in hotter temperatures (e.g. tropical climates), so agricultural residues such as straw, husks, hulls, shells and stover added to soils break-down completely over a few months to a few years. Most of the carbon in SOM is therefore released to the atmosphere as CO_2 with only a very small amount of the added carbon (approximately 1%) remaining in the soil for a long time as a material called ***humus***.

Additions of organic matter to soil therefore have to be repeated regularly to sustain an increased level of ***soil organic carbon (SOC)***, but higher additions will tend to result in higher rates of respiration hence of SOC loss. If the intention is to increase SOC, a better (or complimentary) strategy is to add biochar, as found in abundance in the famous ***Anthropogenic Dark Earths (ADE)***[1] of Brazil (also known as '*Terra Preta*'). The ADEs are highly fertile soils, rich in nitrogen and phosphates, and alkaline, with a high capacity for retaining nutrients and water. They are more fertile than adjacent soils which have not received charcoal, pottery and other wastes from human-settlements.

Organic soil amendments can be classified according to the ratio of ***carbon-to-nitrogen (C/N)*** that they contain.

'Hot biomass' includes chicken manure, feathers, blood and fish waste which decomposes rapidly in the soil (within days or weeks), releasing N which is available to the crop. There is a relatively low C/N ratio in hot biomass. Hot biomass additions are useful for rapidly adding nutrients to soil.

'Cold biomass' like woody mulches and bark chips decompose very slowly (months to years) and have a relatively high C/N ratio. Micro-organisms breakdown cold biomass added to the soil, using the released energy and carbon to reproduce. However, there is insufficient N in cold biomass to fully support microbial expansion. The bacteria and fungi therefore extract nitrogen from any other sources available to them, notably the soil. As mineral N is taken-up by micro-organisms, it ceases to be available to plants. For this reason, adding cold biomass to soils will reduce N supplies to plants over the space of weeks and months. In the short-term, other additions of N are required to prevent deficiency for plant growth. In the long-term, cold biomass additions build-up the overall soil quality and structure by increasing SOM, therefore improving soil health – especially its ability to effectively retain and use nutrients.

In between hot and cold biomass are types of ***composted*** biomass. These do not generally release much plant available nitrogen (PAN) when first added to the soil, but will make N available after the material has been in the soil for several weeks. Whilst composted biomass releases less total N per unit of biomass added than 'hot biomass', it plays an equally important role in building-up SOM and carbon, which, in the long-term, improves general soil structure and overall health.

This approach to biomass utilization in soils improves net returns for producers while mitigating negative impacts on the environment and future soil productivity (***Climate-Friendly Agriculture***).

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[1] *See KP#4 for more detailed discussions of biochar and ADE*

1. INTRODUCTION

This paper provides a brief introduction into what soils are and their crucial role in supporting food production as well as fulfilling a range of important ecosystem service functions.

The paper covers the relationships between soil, carbon and nutrients such as nitrogen, phosphorus and potassium and outlines the concept of 'soil health' as a holistic indicator of its multiple functions and properties. Biomass soil amendments have multiple effects upon soil properties and functions and we evaluate which types of amendments are most useful in addressing agricultural soil constraints.

Agricultural plants derive most of their nutrient and water requirements from the soil. The nutrient requirements of rice and vegetable crops in the Greater Mekong Subregion (GMS) are briefly described.

Natural biomass-based soil amendments, alongside addition of organic and biofertilizers (biological fertilizers), is a traditional and sustainable approach to supplying nutrients to soils while enhancing their structure and long-term health as a living entity. The role of biomass-based fertilizers is discussed, along with their key characteristics compared with those of conventional synthetic fertilizers.

Anthropogenic Dark Earths (ADE) of Brazil are introduced and briefly described in contrast to weathered tropical soils. These unique soils provide important clues for creating sustainable, fertile soils that do not depend upon repeated additions of synthetic chemicals.

Key issues surrounding release of nutrients from organic soil amendments are described, in particular the problem of locking-up plant-available nitrogen (PAN) through excessive expansion of the community of soil micro-organisms when the carbon-to-nitrogen (C/N) ratio of the biomass is too high. We therefore aim to build understanding of the different effects of biomass soil amendment options and how judicious selection and combination of amendments can help to deliver the nutrient requirements of agricultural crops.

The decomposition of biomass to produce compost and use of anaerobic digestion to produce bioslurry is discussed as an alternative to incorporating fresh biomass directly into soil.

The purpose of the paper is to provide an overview of key knowledge regarding healthy soils and best practice for improving soil quality via efficient use of biomass for sustainable crop production in the GMS. Further detail on some of these subjects is presented in associated papers and compiled into a single compendium of best practice.

The content is tailored towards government officials at the national, provincial and district levels in the GMS countries, in addition to members of civil society engaged in relevant activities - especially small- and medium-sized agribusinesses, farming cooperatives and other non-governmental organizations working in rural / farming communities.

The paper includes references and direct links to source material for more detailed, subject-specific reading. Furthermore, the Glossary in ***APPENDIX 2:*** provides a ready reference and resource for some of the key concepts discussed in the paper.

2. OVERVIEW OF SOILS

2.1. WHAT ARE SOILS?

Soils are the skin of the earth. They consist of a mix of solid ***minerals***[i] and organic matter next to small spaces (***pores***[ii]) in between the solid particles. These pores hold gases and water (H_2O) containing many different chemicals.

Soils are biologically-active containing hundreds of thousands of types of ***micro-organisms***[iii] (bacteria, viruses and fungi), as well as thousands of macro-organisms such as insects and worms. ***Figure 1*** shows the main physical[2], liquid, gas and micro-organism components which together form soil.

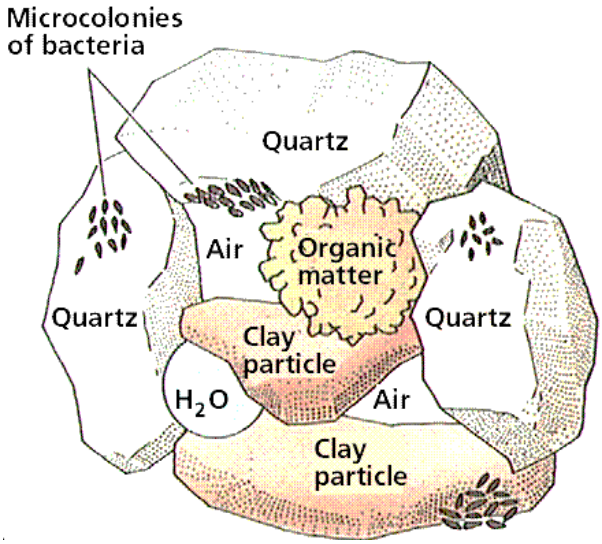


Figure 1: Main components of soil

2.2. HOW ARE SOILS FORMED?

Soils initially form as a result of the very slow but steady breakdown of surrounding rocks. This process occurs by:

- Physical means (e.g. freeze-and-thaw cycles caused by cold/hot temperatures);
- Chemical means (e.g. effects of acids on rocks), and;
- Biological means (e.g. impacts of lichens which grow on rocks).

Where and when flooding occurs, large amounts of sediment (small particles that are carried in the water) are deposited onto the land. These are called ***alluvial deposits***[iv] and are a very important source of nutrients and alkalis in soils. It is for this reason that the soils in the flood plains of the Mekong, Tonle Sap and Red rivers are more fertile and less acidic than adjacent soils which are not within these rivers' flood plains and deltas.

As plants grow, leaves, branches and whole trees die and fall to the ground. In addition, when plants die, their roots release organic chemicals into the soil. In this way, living organic matter is returned to the soil to become ***Soil Organic Matter (SOM)***[v]. For example, in a tropical rainforest, about nine tons per hectare (ha) of dead plant matter (leaves, twigs, branches, flowers, fruits) falls to the ground and becomes SOM every year.

As shown in ***Figure 2***, soils form into distinct layers of varying depths depending on the soil type and other factors. These layers are known as ***Soil Horizons***[vi] and include the: ***Surface Litter***[vii] (O) - living and dead plant matter, insects, etc.; ***Top-Soil***[viii] (A) - comprises humus, SOM, roots and organisms occupying the top few centimeters down to approximately 20cm; ***Sub-Soil***[ix] (B) - fine particles, leached materials and deeper roots present down to around 80-100cm, and; ***Parent Material***[x] - the rockier material from which the above soil is created.

2.3. WHAT DO SOILS DO?

Soils serve as the growing medium for much of the world's vegetation, including the majority of food crops, grasses and bushes that are grazed by animals that produce meat, dairy and other products for human use.

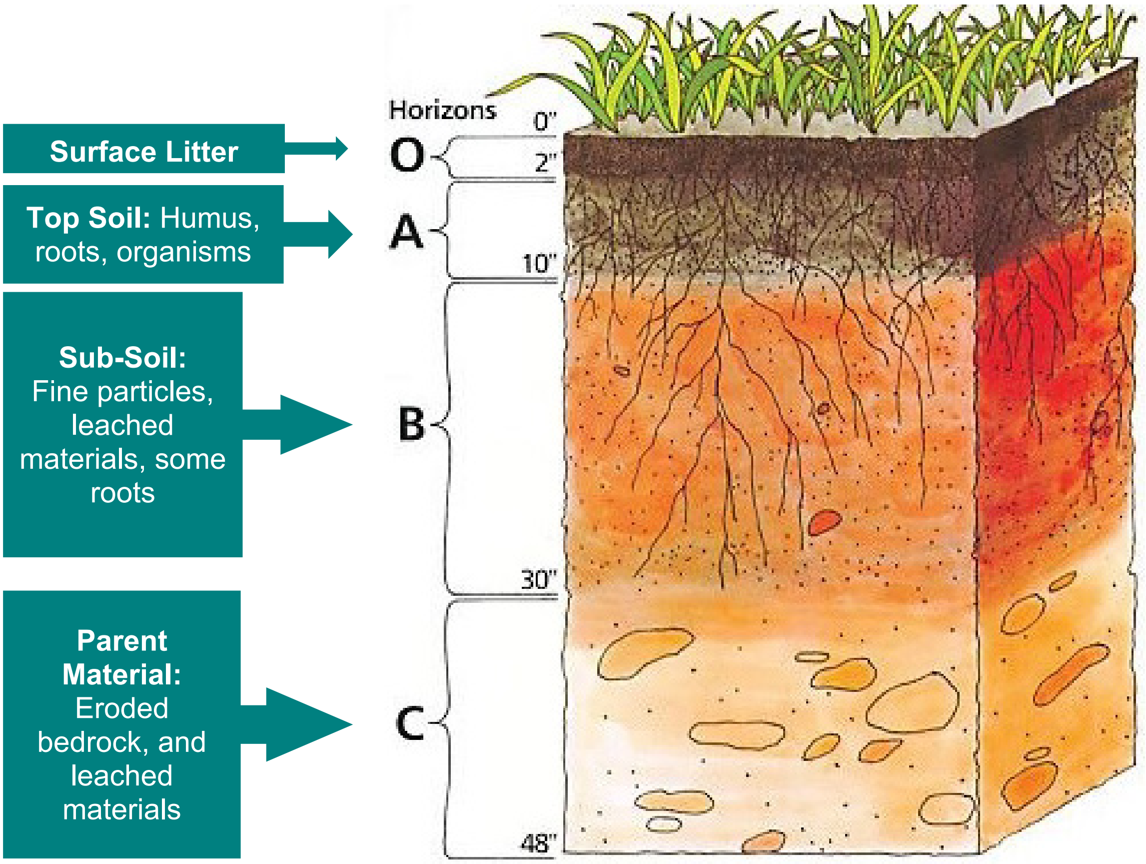
[2] *Quartz is a hard rock mineral*

Soils also serve as an important medium for water storage and purification. Soils interact with the atmosphere through exchange of gases, some of which are released back into the atmosphere as ***Greenhouse Gases***[xi] (such as methane, carbon dioxide, carbon monoxide and nitrous oxide).

Soils are also a major repository of the earth's biodiversity and contain many unique communities of micro-organisms, insects, worms and other macro-organisms, as well as some mammals.

Figure 2: Soil structure: Approximate guide to horizons and common composition of soils

(" = inches, where 1" ~2.54cm)



3. COMPOSITION AND CHARACTERISTICS OF SOILS

3.1. TYPES OF SOILS

Soil particles are distinguished by their particle size:

- Stones and gravel are anything larger than about 2 millimeters (mm);
- Sand particles range from 2 mm to 1/15th of a mm;
- Silt particles go down to 1/200th of a mm;
- The smallest particles in soil are clay, which go down to around 1/1000th of a millimeter.

Soil scientists measure the quantities of sand, silt and clay particles and use the different proportions of each in defining different soil types in standard soil classifications.

Annual plants (that live for no more than one year), including cereal crops, most vegetables and legumes (beans), tend to have most of their roots in the top soil layer. The SOM is higher in the top soil because this is where most of the dead plant material accumulates, supporting large communities of micro-organisms.

Perennial plants such as trees and bushes require more support and access to more water and nutrients than annuals and tend to have larger, deeper and more extensive root networks extending into the soil. Worms and other macro-organisms are important in moving organic matter down the soil profile and in mixing air into the soil pores, making the soil less compact.

Soil texture (how it looks and feels) and structure are important in that they influence the movement of water, air, micro-organisms and macro-organisms through the soil, and also how the soil responds to external disturbance. Clay soils, for example, are very compact (high bulk density) because the mineral particles from which they are composed are very small, limiting the space between such particles. They tend to be good at retaining water and nutrients in the small pore spaces but plant roots may struggle to grow into dense clays and access water and soluble nutrients. In parts of the GMS, clay forms an underlying 'cap' above sandy soils into which water cannot easily move.

Sandy soils are bulky (low density) because they are composed of large particles that consequently have a lot of spaces between them. As a result, water flows easily and rapidly through sandy soils, hence they dry out quickly ('water stress'). Loss of crop yield in dry sandy soils is not due only to lack of water however. As soils dry out, air penetrates into the soil causing iron to convert into more oxidized forms which then react with the vital nutrient phosphorus (P), reducing the availability of the P to plants.

3.2. SOIL COMPOSITION

3.2.1. Soil Organic Matter (SOM)

When soil is rich in SOM, the overall structure has an increased number of pores and therefore the amount of gases or liquids which can be held within the soil is also increased. This increases its overall volume per unit mass (lower bulk density). This helps to aerate the soil, encourages development of biological activity and improves the ability of the soil to hold on to water and nutrients. SOM also adds plant-essential nutrients such as organic forms of ***nitrogen (N)***, ***phosphorus (P)*** and ***potassium (K)*** along with variable amounts of secondary and micro-nutrients.

Typically a small portion (<1%) of the organic matter introduced to soils turns into a substance called ***humus***[xii], which will remain in the soil for decades and often binds with mineral particles such as clays to form a stable 'aggregate'. Humus is important in creating healthier soils, including improving soil structure and enhancing the soils capacity to retain nutrients and water.

Approximately 50% of SOM consists of ***carbon (C)***. The 'workability' of the soil (e.g. ease of ploughing, reducing the energy required for land preparation for crops) is enhanced by the presence of SOM.

3.2.2. Carbon

Carbon (C) is one of the building blocks of life. However, since plants cannot take up carbon via their roots, they absorb carbon dioxide (CO_2) via their leaves or stems through ***photosynthesis***[xiii]***.*** The carbon is then used in building plant matter whilst the oxygen (O_2) is released into the atmosphere. Plants also release CO_2 through respiration during the night time. Most of the plant carbon ends up in the stem, leaves and roots, grain, fruits, flowers, etc. In an undisturbed forest, when trees and other plants die, carbon is returned to the soil and the atmosphere.

Bacteria and fungi in the soil will quite rapidly break down the biomass in order to extract energy, carbon and other nutrients which they use to grow and reproduce. After several decades, ***equilibrium*** is reached whereby the amount of CO_2 taken-up by the forest from the atmosphere during photosynthesis is equal to the amount of CO_2 released back to the atmosphere through respiration. When forests are cleared, the soil is disturbed and oxygen from the air is used by micro-organisms to attack the organic matter releasing large amounts of carbon as CO_2.

Agriculture removes a large proportion of the carbon fixed by photosynthesis as food and agri-residues (e.g. rice husks, rice straw, corn stovers, etc.) removed with the harvested crop. Because of this net loss of carbon, the amount of ***Soil Organic Carbon (SOC)*** in agricultural soils is much smaller than the amount of SOC in forests.

Typically carbon constitutes 50% of SOM (by weight). Because of decomposition, SOC levels will only be sustained if SOM is continually added to the soil. If the inputs of organic matter stop, the SOC declines to very low levels. The rate of ***decomposition*** of organic matter in soils is highly temperature dependent. In the tropics, decomposition takes place much more rapidly because soil micro-organisms grow and multiply more rapidly at higher temperature (high soil 'respiration'). SOC in many tropical and sub-tropical agricultural soils is very low (<1%) because of these high soil temperatures and the net removal of carbon in the harvested product and residues. In colder climates, higher SOC levels are typical due to slower rates of SOM decomposition (low soil 'respiration').

Soil respiration requires the presence of oxygen, so where very low oxygen conditions occur (***anaerobic***), such as in a flooded rice field, the decomposition of organic matter is much slower and part of the carbon (approximately 10% in a flooded rice field) is converted into methane (CH_4). When the rice fields are drained, however, the remaining organic matter will be subject to rapid soil respiration and converted to CO_2.

One experiment using rice husks showed that in oxygen-rich tropical soils (aerobic conditions), 80-100% of the carbon in the husks was decomposed into CO_2 within three years. This compares to cooler climates where approximately 20% of organic matter added to soils was still there ten years later.

3.2.3. Nitrogen

Nitrogen (N) is a key constituent of proteins as well as of ***DNA*** - the genetic code of all living organisms. Unlike C, plants need to take up N via their roots in a mineral or soluble form (i.e. in water), also known as ***'plant-available nitrogen (PAN)'***. In general, PAN comes in the form of ammonium or nitrate ions. N in living plant matter is in an organic, not mineral, form but soil bacteria and fungi are able to use the non-mineral forms of N through use of specialized chemicals. The bacteria and fungi tend to have short life times and, as they die and decay, they release N in a mineral form accessible to the plant.

3.2.4. Other nutrients

Phosphorus (P), potassium (K) and other nutrients are also ‘mineralized’ and made available for uptake by plant roots through the decomposition of plant and animal organic matter by bacteria and fungi.

3.3. SOIL HEALTH

The concept of soil health brings together all the different features above.

Soil can be considered healthy, when it sustains long-term biological productivity (including for agriculture), maintains environmental quality and sustains the health of surrounding plants, animals and micro-organisms.

A healthy soil generally has:

- High SOM (>5%) and high SOC content;
- High humus content (the carbon in humus is much more resistant to decay than that in fresh SOM);
- A wide range of particle sizes - including ‘aggregates’ which combine minerals and organic matter and which help to stabilize the soil and prevent soil loss from water and air erosion;
- A range of pore sizes within the soil, since differently sized pores will have different roles to play;
- Higher total nutrients and PAN;
- Greater amounts and diversity of micro-organisms and macro-organisms (including earthworms).
- Suitable pH. 5-7 is appropriate for most crops;
- Ability to cope with extreme events such as intensive rainfall.

When tropical and sub-tropical forests are first cleared, the soils are highly fertile for the first year or two, but fertility rapidly declines as rainfall and flooding leaches all the nutrients away, at the same time increasing soil acidity. The soil just doesn’t have the right structure, physical and chemical properties to hold nutrients and to maintain soil moisture. As these soils dry, air penetrates deeper into the soil, causing iron to oxidize and bind the P,

‘Terra Preta’ is an example of a famously healthy soil from Brazil. Also known as anthropogenic (*human-made*) dark earths (ADEs), they are partly human-created through addition of charcoal, animal and human wastes, pottery and other kitchen wastes mixed together over long time periods. These patches of ADE extend downwards from the surface for 2-4 meters and are much darker in color than the lighter, highly weathered soils next to them.

This can be seen below where a soil profile of a highly weathered soil on the left is compared with an area of ADE in the same area. Even though such soils were produced in settlements that were abandoned 500 years ago and reclaimed by the forest, they have sustained their fertility. ADEs:

- have high levels of SOM, NPK, calcium (Ca) and other nutrients essential to plant growth;
- are effective at retaining nutrients;
- have a higher pH (less acidic; more alkaline);
- have a high water holding capacity;
- are more productive than non-ADE soils from the same agro-ecological zones.

Photos courtesy of: www.biochar-international.org/biochar/soils limiting the plant availability of this vital nutrient. High acidity also increases the exposure of plant roots to aluminum and manganese which may then become toxic and inhibits plant root growth.

As soils dry out and become more exposed to air at high tropical temperatures, SOM rapidly decomposes to produce CO_2 – a process known as '***mineralization'***. As the SOM disappears, soil structure is further weakened and the risk of soil erosion increases, potentially removing tons of soil per hectare along with any Nitrogen, Phosphorus and Potassium (NPK) held by this soil. Hundreds of tons of soil may be lost per hectare per year when forest is cleared, with associated loss of NPK per year. Very rapidly, soil health falls to very low levels, as seen in many areas of cleared tropical and sub-tropical rainforest in the GMS today. These very poor soils are often referred to as 'highly weathered' soils.

4. SOILS AND AGRICULTURE

4.1. WHAT SOIL CONDITIONS DO AGRICULTURAL CROPS REQUIRE?

It is not possible to change the type of parent bedrock underlying a soil so the farmer has to make the best use of what is available. Even the poorest quality soils can be improved through appropriate management, for example, by steadily building-up the SOM content. The luckiest farmers are those who farm on ***loamy*** soils – combining the best properties of clay soils (holding on to water and nutrients) and sandy particles (good drainage and sufficient aeration of the soil). However, naturally occurring high quality soils are rare and their quality will frequently deteriorate over time. For example, drained peaty soils are very high quality as a growing media but are prone to oxidation and will disappear fairly rapidly.

Like all living organisms, agricultural crops require the building blocks of life – in particular the non-mineral essential elements: C, O_2 and hydrogen (H). These are critical for constructing hydro-carbons of which all life forms are formed. C, O_2 and H are converted into these hydro-carbons during the process of photosynthesis, with C and O_2 being sourced from CO_2 in the atmosphere and H and O_2 coming from water taken-up by the plants roots.

The three primary mineral 'macro-nutrients': Nitrogen (N) - a key component of proteins and DNA; phosphorus (P) - essential for photosynthesis, production of proteins and cell division, and; potassium (K) - required for producing proteins, regulating growth and for controlling exchange of air with the plant. These are commonly and collectively known as ***NPK***.

The secondary macro-nutrients required by plants are: calcium (Ca) - required for cell wall development and growth and for enzyme activity and cell growth; magnesium (Mg) - a key component of chlorophyll, the chemical responsible for photosynthesis, and; sulfur (S) - a constituent of proteins.

Macro-nutrients are required in tens of kilograms per hectare for most crops. However, they have to be in a plant-available form, which usually requires the prior decomposition of SOM by micro-organisms and the subsequent release of minerals when bacteria and fungi die and decompose. The 'mineralized' macro-nutrients enter into solution in water and are taken-up by the plant roots.

There are a large number of 'micro-nutrients' which are also vital for healthy plant growth, but are required in much smaller amounts. These include elements such as: Zinc, Boron, Molybdenum, Copper, Iron, Chloride, and Manganese.

In general agricultural crops respond well to the addition of synthetic (inorganic) NPK fertilizers since they are composed of primary macro-nutrients in a plant-available form: N as ammonium nitrate (urea); P in fertilizers such as rock phosphate, superphosphate, mono- and di-ammonium phosphate, and; K in potash, potassium chloride, etc. Therefore, when fertilizers are applied to the soil, they rapidly dissolve into the soil water and are taken-up in solution via plants' roots.

While NPK addition can be very beneficial to plant growth, there are some key concerns from agricultural, scientific and environmental experts:

- Production of synthetic fertilizers is very energy intensive and leaves a large carbon footprint, contributing to ***climate change***;
- Nitrogenous fertilizers tend to be inefficient since some of the nitrogen added is converted into the gas nitrous oxide (N_2O) – a very powerful greenhouse gas - while some is lost from the field as nitrate run-off - which can then cause pollution in waterways.
- Rock phosphate contains the heavy metals uranium and cadmium and there are concerns about the long-term impacts of incorporating large amounts of rock phosphate fertilizer into soils.

NPK addition also changes the way that plants grow. If there is less readily available NPK, the plant has to work harder to seek out available sources. This may be achieved by forming close associations between the plant roots and fungi and bacteria which can supply mineralized forms of NPK. Legumes (beans and peas) form close associations with specialized soil bacteria in root nodules which are capable of fixing nitrogen directly from the air in the soil and which then supply the plant with some of the N in a mineralized form, but the majority of agricultural crops cannot do this.

Nevertheless, all plants form associations with micro-organisms and fungi to obtain needed nutrients and water but if these nutrients are readily available from chemical inputs, there is less requirement for the plant to cultivate such associations and, arguably, less use is made of what is already present or can be made available through microbial assistance.

Calcium (as lime), sulfur and magnesium additions to soil are also common. In ‘high precision’ farming, soil analysis is undertaken yearly and any deficiency in micro-nutrients identified and corrected. Precision-farming is more expensive and requires more data and technical capabilities, though the costs are reducing through technical innovation. Certain crops are known to be prone to micro-nutrient deficiency, e.g. rice and maize plants suffer from deficiency in zinc and boron.

Trees and plants growing naturally do not need synthetic fertilizers to grow perfectly efficiently and healthily. This is because perennial plants develop extensive root networks and close associations with fungi and bacteria which, over time, supply the plant with enough nutrients. There is also a continual return of organic matter and nutrients back to the soil as leaves and branches are shed. However, most agricultural crops are grown for only one season and plant breeding has selected those crops which respond effectively to synthetic NPK (and in some cases, addition of pesticides, herbicides and fungicides, etc.).

4.2. NUTRIENT REQUIREMENTS OF RICE

Conventional practice is to add N to rice nurseries and then, after transplanting, to add N at 14 days and then again at 21 days. This helps the ***tillers*** to grow strongly.

The flowering head at the end of the tiller is called the ***panicle*** which turns into the grain, taking between 45 and 90 days before being ready for harvesting. Many farmers add more N when the panicle starts to develop. Recommended practice for rice is to add 100-150kg N per hectare, though this may be too expensive for many farmers, while in situations where fertilizers are subsidized, higher applications of over 200kg N/ha are common. The appropriate amount of NPK to add is heavy dependent upon the soil type and current conditions because some soils already contain NPK and/or respond better to NPK additions than others. In Cambodia, for example, recommended levels for rice vary from 30-120kg N/ha, 4-15kg P/ha and 0-30kg K/ha across the nine main soil types nationwide. According to recommended practice, approximately half of the N is added during the 'active tillering’ stage. Adding excessive NPK is inefficient and expensive, while frequently contributing to environmental pollution.

Rice agriculture is rapidly changing in areas such as the Mekong Delta, where increasing land consolidation, land levelling, mechanization of land preparation, direct seeding and harvesting, use of the ***System of Rice Intensification (SRI)*** and loss of rural labor force due to urban migration are common. Labor costs have risen rapidly. All these changes are modifying how and when farmers use fertilizers. If they can make fewer separate operations they reduce the need for labor.

Pelletization of NPK in both Viet Nam and Cambodia has been successful because it is a one-time operation during the last land cultivation prior to sowing or transplanting, cutting down the need for one or two additional NPK additions during the crop growing period. The NPK pellet is incorporated into the soil close to the plant root zone and slowly breaks down, releasing the nutrients within easy access of the roots (i.e. a slow release fertilizer). By contrast, 'broadcasting' of NPK by hand or machinery ends up positioning some of the nutrients away from the roots. Furthermore, a lot of the NPK is dissolved into water when the rice fields are flooded; some NPK leaches away from the plant roots into nearby rivers or groundwater and ends up not being available to (hence used by) the crop.

4.3. NUTRIENT REQUIREMENTS OF VEGETABLES

Most vegetables grow for a short period (20-50 days) and grow continuously, meaning they have a constant demand for nutrients. As a very rough and average estimate, and assuming irrigation is available, the nutrient requirements of vegetables are: 20-200kg N/ha, 5-50 kg P/ha, 10-70kg K/ha, 100-600kg CaO/ha and 20-60kg MgO/ha. Due to the short growing season, most nutrients are added to the soil at the last soil cultivation as a one-time application.

Vegetables can be grouped into low, medium and high nitrogen demanding crops. Those requiring less N (2-4kg N per ton of produce (approximately 100kg N/ha) include: carrots, cucumbers, lettuce, onions, parsley, peppers, tomatoes, melons and watermelons. Those taking up more than 4kg N per ton produce (approximately 220kg N/ha) include: asparagus, aubergines (eggplants), cabbage (and other brassicas), cauliflower, celery, garlic, radish, spinach and turnips.

Vegetables also take up different amounts of P, with 1-2kg P per ton of produce for aubergines, carrot, cauliflower, cucumber, garlic, lettuce, onion, peppers, parsley, spinach, tomatoes, melon and watermelon. Asparagus, cabbage, celery, radish and turnip take up more than 2kg P per ton of produce. Few crops, on the other hand, take up less than 4kg K per ton produce.

Vegetables which have a lower ***harvest index*** - less harvestable produce as a proportion of the overall weight of the above ground plant biomass - tend to use more nutrients to produce one ton of produce. Also cultivars which have been bred and selected to have higher yields also tend to have higher nutrient demand per ton produce.

As for any crop, the nutrient demands depend upon the quality of the soil in which they are grown. Three to four times more P and K needs to be added for vegetable growth in a very poor quality soil compared with a high quality soil. In terms of SOM, the ideal for vegetable cultivation is 2.5-3% for sandy soils and 6-8% for clay soils.

5. BIOMASS AMENDMENTS AND SOILS

5.1. OVERVIEW

The so-called *'Green Revolution'* led to an increase in crop yields enabling population increases due to expanded food availability to households as well as contributing overall wealth to the economies of many agriculturally-dependent countries. However, this rapid and wide scale expansion in production has left an environmental legacy.[3]

Whilst farming using inputs of synthetic NPK and pesticides, herbicides and insecticide is currently economically viable on many soil types, the environmental sustainability of such high-energy and carbon-intensive farming is increasingly questioned. Some experts and members of the public are concerned about the long-term health impacts arising from farming which relies upon high levels of synthetic inputs, especially when over-application occurs.

One response to these issues has been a renewed interest in ***organic*** forms of agriculture - where no synthetic NPK, pesticides, herbicides and/or unnatural additions or genetic modifications to plant or animal strains are permitted.

Climate-Friendly Agriculture (CFA) covers management practices that improve net returns for producers, whilst generating bioenergy, mitigating negative impacts on the environment and boosting future soil productivity.

In general, CFA practices:

- Reduce Greenhouse Gas emissions through carbon capture and soil storage;
- Improve fertilizer management to reduce wastage and pollution;
- Minimize water use;
- Harness agricultural residue biomass to produce bioenergy;
- Utilize biomass by-products to build, restore and sustain soil structure and productivity.

Figure 3: Climate Friendly Agriculture

Another approach in the GMS and elsewhere is the promotion of low carbon or ***Climate-Friendly Agriculture***[xiv] (***Figure 3***) management practices. These aim to reduce local ecosystem degradation whilst mitigating the impact of farming as a driving force of climate change.

In many cases, additional SOM and/or ***biofertilizers***[xv] are used to ensure an adequate supply of macro- and micro-nutrients to sustain or enhance long-term productivity with the absence / lack of synthetic NPK.

5.2. DECOMPOSITION OF BIOMASS

Composting of biomass is a biological process of decomposition which takes from 15 days to three months, depending on the type of biomass, management approach and the climatic conditions. Micro-organisms and macro-organisms are responsible for the progressive breakdown of more complex, larger molecules into simpler ones that can be readily digested and thereby provide a source of energy and nutrients for further growth and reproduction.

Composting is a largely aerobic process, meaning that frequent turning of the compost heaps is required. In most types of biomass there is a variable proportion which is much harder to break-down to simpler chemicals. This is known as ***'recalcitrant biomass'*** and would contribute to the humus fraction of the soil. When fresh biomass is added to the soil, it undergoes biological

[3] *See TA7833 KP#1:Climate Change, Agriculture & Food Security (https://drive.google.com/file/d/0B1wKP1C0cX-jdEZMVkh3d2xzV28)*

decomposition, but usually at a slower pace than in a compost pile due to the dispersion / dilution of both the biomass and micro-organisms within the soil compared to the compost pile.

5.3. IMPACT ON SOIL HEALTH OF BIOMASS AMENDMENTS

The addition of SOM to soils as a ***soil amendment*** increases the humus in the soil, which many experts consider to have numerous positive impacts.

Studies of rice straw incorporation into soils, compared to open burning in fields, have identified significant benefits, including:

- Reduction in fuel consumption for crop cultivation operations by 20-30%;
- Time taken for cultivation operations is reduced by 10%;
- The largest benefit occurs where land is already water logged and soils compacted.

Adding biomass to soils is generally a beneficial intervention but the right biomass has to be used for the right soil, whilst taking into account the crop to be cultivated and the growing season. Different soil functions are addressed by adding different kinds of biomass.

'Hot biomass' such as chicken manure, feathers, blood and fish waste decompose rapidly in the soil (within days or weeks), releasing N which is available to the crop. ***'Cold biomass'*** like woody mulches and bark chips decompose very slowly (months to years) and will reduce PAN. In between is composted biomass, which tends to neither increase or decrease supplies of PAN but are a good way of building-up SOM and carbon, which, in the long-term, improves soil structure and health.

The available ***carbon-to-nitrogen (C/N) ratio*** is a key indicator of the properties of biomass soil amendments and of soil health.

There is always more C than N in biomass, but the ratio can change greatly between different feedstocks. Woody materials like sawdust, bark and wood chips have a very high C/N ratio of at least 60 and as high as 600, as shown in ***Figure 4***.

Biofertilizers (biological fertilizers) are biomass-based formulations containing plant-available nutrients in which the biomass has undergone decomposition such that its biological activity is largely stabilized.

Biofertilizers are commonly defined as:
"…substances which contain living microorganisms which, when applied to seed, plant surfaces or soil, colonize the rhizosphere (root zone) or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant".

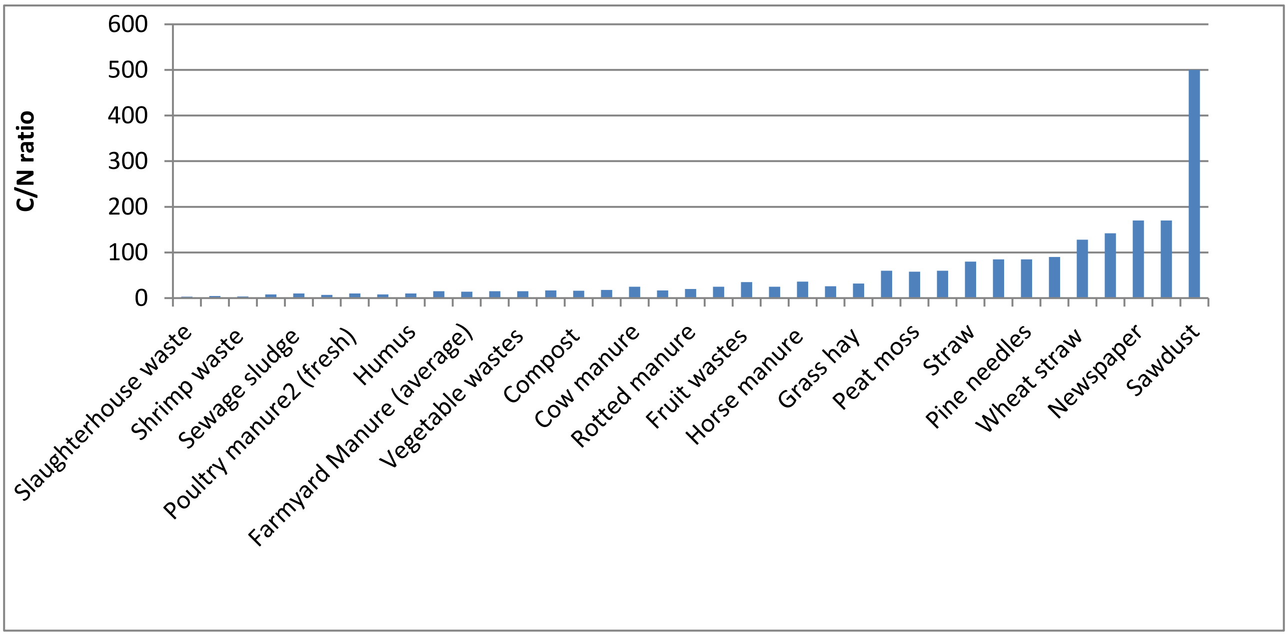
The constituents of biofertilizers tend to be composted manure (e.g. chicken, pig, cow and buffalo dung), compost-like outputs, leaf litter, bioslurry, digestates and a whole range of other potential biomass residues and wastes. During production, the biomass may be chopped, sieved, fermented, ground, etc.

Biofertilizers can be considered organic fertilizers provided there is no contamination with synthetic chemicals. To be strictly organic, the plant material should also come from fields or animal communities that do not use synthetic chemicals or drugs. The key properties and contaminant thresholds of organic biofertilizers have been set out in legally-binding documents in countries such as Thailand, Malaysia and Cambodia. Different terms might be applied to biofertilizers such as *green* manure or compost.

Vessey, J.K. 2003. Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255, 571-586)
Biofertilizer Manual, FNCA, Japan Atomic Industrial Forum, 2006.

If biomass with such a high C/N ratio is added to soils, the micro-organisms within the soils will respond by breaking down the hydrocarbons as a source of both energy and carbon. However, because the biomass is in a complex form with long and large molecules (e.g. ligno-celluloses), it takes specialized microbes to break it down into smaller, simpler molecules such as sugars which are further broken-down by a large number of common microbes. Once such decomposition is underway, the bacterial and fungal populations will increase very rapidly and, because N is an essential nutrient for cell division and reproduction, the demand for N will also grow quickly. Supplies of N in the introduced biomass are rapidly depleted. In order to sustain their high levels of

Figure 4: C/N ratio for a range of biomass materials



growth the micro-organisms will extract N from other sources in the soil, effectively 'sucking-up' all available supplies. The means that the N is no longer available to plants.

This process is called ***'nitrogen immobilization'***. If a farmer adds a high C/N biomass to soil prior to cultivation, there is a real risk of N immobilization. The seedlings will struggle to access the N that they require in order to grow well unless sufficient additional PAN (such as synthetic fertilizer) is added to the soil.

When all available stocks of N are used up, the continued growth of microbes is constrained and soon slows down or even stops. For this reason, decomposition of organic matter in a compost heap is slower when the C/N ratio is higher, as shown in ***Figure 5***.

The temperature of the compost heap is a good indicator of the rate of decomposition. With a C/N ratio of 60, the process is medium-temperature at around 40^{o}C compared to the high-temperature composting (70^{o}C) when the biomass C/N ratio is 30.

Thermophilic decomposition is preferable as it produces quality compost in a shorter period of time and is more likely to kill-off pathogens and the seeds of weed species. Adding biomass with a lower C/N ratio to soil likewise results in higher rates of decomposition, releasing plant-available nutrients more quickly. This occurs because microbial growth is less constrained by N availability, allowing more rapid and extensive microbial growth – these microbes then die and decompose releasing plant-available mineral forms of N and P.

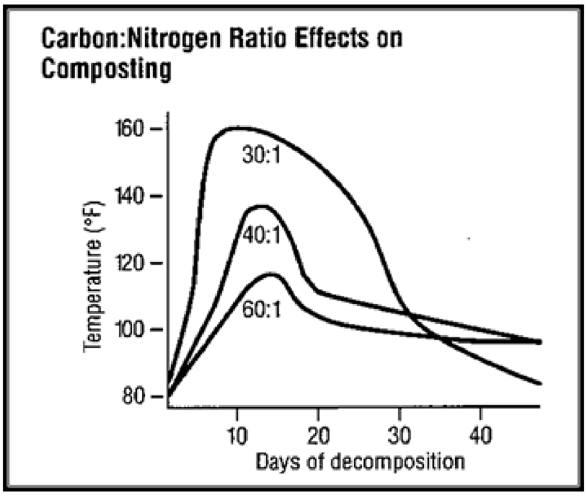


Figure 5: Biomass with a higher C/N ratio decomposes more slowly and the conversion temperature is lower

If a high C/N biomass is added to soil in a fallow-period, then N immobilization will occur initially but the microbial decomposition cycle will then release the N back into the soil as PAN. Straw (C/N ratio of approximately 80) incorporation into soil at harvesting will immobilize N for several months, with the actual length of time depending on other factors such as soil temperature, etc. Straw incorporation will work in terms of then re-releasing

N while increasing SOC and returning other nutrients from the straw back to the soil where there is a sufficiently long fallow period between crops (e.g. one main crop per year). However, where there is a rapid turn-around from one crop to the next, straw incorporation is likely to run into the problem of N immobilization, requiring addition of PAN such as synthetic fertilizer. Mechanical harvesting of rice paddy leaves more straw in the field than with hand harvesting, exacerbating the problem of N immobilization if it is incorporated into the soil.

The C/N ratio affects not only the availability of N but also of P and other nutrients. Just as microbes suck-up available sources of N in soil, so they will draw upon supplies of P, reducing their availability for crops. Because P is not required by living organisms in such high amounts as N, the C/P ratios that result in immobilization are much higher than for C/N. Where organic amendments have a high C/P ratio (≥ 300), P immobilization occurs. But soil amendments with a C/P ratio of ≤200 result in net P mineralization.

By contrast with these 'cold' types of biomass, the 'hot' biomass is that which is readily broken down by microbes, such as cover crops, some hays and many unprocessed animal wastes including from slaughterhouses, fish meal and wastes, some food, vegetable and fruit wastes, human excrement, sewage sludge and chicken manure. These materials have a very low C/N ratio (e.g. 2-10) and contain a lot of sugars, proteins and other high N-containing molecules which are readily broken down by commonly found soil micro-organisms. The nitrogen is released as ammonium, which other microbes break down to nitrates, both of which are easily taken-up by plant roots. The initial break-down of the 'hot' biomass is very rapid, releasing most of the PAN. Decomposition and further release of PAN then slows down as only the more fibrous (higher ***lignin*** content) substances remain.

'Hotter' biomass have 6-12% N, chicken manure has about 4% N, while composts typically have 0.5-1.5% N. ***Table 1*** provides some examples showing that 'hotter' biomass with a lower C/N ratio usually has a higher N content and releases more of that N in a plant available form during the crop growing period. For instance, there is no release of PAN during the growing season from the solid manure with bedding which has a high C/N ratio and low N content. On the other hand 75% of the N in blood, fish and feather biomass (very low C/N ratio and high N content) is released in a plant-available form over the growing season.

Composts, well-rotted down manures and bedding materials (from cow, pigs, horses, etc.) have already gone through a decomposition process, so the fast break-down and initial release of N has largely already taken place. For this reason, adding these materials to soils is for the purpose of building-up the long-term quality and structure of the soil by increasing SOM and, in the long-term, this will improve soil health, including its ability to effectively retain and use nutrients, including N.

Table 1: Plant-available nitrogen (PAN) contents of different biomass types

Nitrogen content (%)	Biomass	C/N ratio	PAN (after 28 day of crop cultivation (% of total N)	PAN (over whole growing season) (% of total N)
1	Solid manure with bedding	35	<0	0
2	Dairy solids (lactose, proteins and minerals removed from milk)	18	0	15
4	Chicken manure	9	30	45
6+	Blood, feathers, fish meal, etc.	< 6	60	75

Such soil amendments decompose at much slower and steadier rates than 'hot' biomass and they do not have much of an effect upon the availability of nitrogen to plants. There is a cut-off in the range of a C/N ratio from 15-20; a lower C/N than this results in a steady increase in PAN whilst above this, there will either be no significant change in PAN or else N will become immobilized.

The C/N ratio can vary widely for the same biomass type due to variation in production and management conditions. Mixtures of biomass with low C/N and high C/N can be undertaken so as to get the ratio of the mixed material to an appropriate C/N ratio.

In measuring C/N, care needs to be taken to ensure that the quoted C/N ratios represent available carbon. If the carbon is very stable, such as in lignin, humus and (even more so) ***biochar***, then the C/N ratio can be a bit misleading as it is usually based upon total, not available C. The C/N ratio of biochar, for instance, can vary from 50-500, but 80-95% of that carbon is very stable and not available to micro-organisms, so the available C/N ratio is much lower.

5.4. NUTRIENT CONTENTS OF BIOMASS AMENDMENTS

Because cereal crops and vegetables require considerable amounts of primary (NPK) and secondary (Ca, Mg, Fe) macro-nutrients, if the source of these nutrients is going to be solely, or partly, from biomass amendments, it is important to know about the nutrient levels and their availability. In this way, field application rates and other additions can be adjusted appropriately.

Anaerobic digestion of biomass results in production of CH_4 as a gas and a liquid called ***bioslurry***. About 40% of the total organic matter added to an anaerobic digester is converted into CH_4 or CO_2.

The bioslurry is the product left after digestion in the absence of oxygen. An equal mixture of water and dung results in a bioslurry that has 93% water and 7% suspended solids. The bioslurry contains NPK at a ratio of about 3.6, 1.8 and 3.6% (when dried). Most of the N in bioslurry is organic and hence available to plants after mineralization. However, some (15-35%) of the organic N in bioslurry is turned into ammonia and disappears into the atmosphere as a gas. The bioslurry has to be covered, mixed with other biomass and kept out of the sun in order to reduce the loss of N as ammonia. The bioslurry is alkaline with a pH of approximately 8.

Bioslurry is an excellent soil conditioner and contains useful quantities of plant available nutrients. As a source of organic matter, bioslurry addition adds humus and improves the soil structure, water holding capacity and soil properties in the long-term. Bioslurry can be applied directly to land used for growing vegetables or fruit crops and added to irrigation channels for arable crops.

As an example, consider a compost product which has 1.5% N and a C/N ratio of 16%. This is a material which will improve soil health but not have much of an effect upon supplies of PAN in the first growing season. After several months have elapsed, however, more of the nutrients will become available. In subsequent growing seasons, an addition of 7-10 tons of compost per hectare should supply the NPK requirements for a rice crop.

Applying this much biomass per hectare is challenging, however, in terms of:

- How much biomass is available in reality, given the decline in livestock numbers in countries that are moving towards greater agricultural mechanization;
- The logistical challenges associated with preparing, storing and applying large quantities of biomass, and;
- The associated costs, which are likely to be more expensive than applying the equivalent nutrients through addition of synthetic NPK due to greater labor requirements.

6. SUMMARY & KEY CHALLENGES

This paper has introduced the non-expert to some key information and concepts in soil science, including what soils are, their main constituents, structure and properties, how they are made and what makes a good quality soil.

The key focus has been on soil organic matter and soil organic carbon and the impacts of adding biomass soil amendments. The role of soil in supplying plants with nutrients, water and a physical structure in which to develop is covered along with a comparison between the supply of nutrients via biomass soil amendments and synthetic chemicals.

Perhaps the most important concept presented is that of the role of micro-organisms in decomposing organic matter added to soil. Microbial breakdown of SOM helps to explain how and when the nutrients in biomass become plant-available as well as highlighting the fate of different types of biomass added to soil. At first glance it might be assumed that adding organic matter to soil would increase the net SOM. This assumption does not take into account the microbial decomposition of biomass, especially at higher soil temperatures. The more organic matter is added to soil, the more microbes break it down to carbon dioxide. The only way to increase SOM substantially is to keep adding biomass amendments on a regular basis. Alternatively, a more stable form of carbon can be added to the soil, such as biochar.

While SOM has many important benefits - including better soil structure, retention of water and nutrients, improved soil 'workability' and provision of nutrients - evidence that SOM is better than synthetic chemical addition of fertilizers is not straightforward. This depends on what is meant by 'better'. If the only indicator of ‘better’ is crop yield, then chemical fertilizers, applied correctly, work well by providing plant available nutrients (PAN) quickly. However, from a climate change and sustainable agriculture perspective, synthetic chemical fertilizers can have disadvantages in terms of causing lasting environmental pollution, releasing Greenhouse Gases, impacting human health, increasing costs of production and damaging the natural fertility of complex soil ecosystems.

The key challenge is how to create organic and / or biofertilizers which are able to deliver the nutrients and other requirements of agricultural crops. There is no single answer to this problem since it depends upon the soil, the crop cultivated, the agricultural management regime and the objectives of the farming system. Understanding these relationships and pathways is crucial for farmers and their partners to make informed decisions.

APPENDIX 1: REFERENCES AND FURTHER READING

i) Mark Ashman and Geeta Puri (2002), Essential Soil Science: A Clear and Concise Introduction to Soil Science, Blackwell, Oxford.

ii) C/N ratios. http://oregonbd.org/Class/CtoN.htm

iii) http://www.norganics.com/applications/cnratio.pdf

iv) Eric S. Gale, Dan M. Sullivan, Craig G. Cogger, Andy I. Bary, Delbert D. Hemphill, and Elizabeth A. Myhre (2006), 'Estimating Plant-Available Nitrogen Release from Manures, Composts, and Specialty Products', 35: 2321 - 2332

v) North Caroline Cooperative Extension Service, www.soil.ncsu.edu/publications/Soilfacts/AG-439-04

vi) Compiled from results undertaken for, and provided by, COMPED, Cambodia.

vii) Industry-sourced data.

APPENDIX 2: GLOSSARY OF TERMS

i **Minerals**	A solid naturally-occurring substance that is stable at room temperature, and has a known and ordered atomic structure.
ii **Pores**	Holes, spaces or gaps on the surface or within an otherwise solid material.
iii **Micro-organisms**	Organisms which are too small to be seen with the naked eye and require magnification to be observed. They may be singe-cell organisms (e.g. bacteria, viruses, some fungi) or multi-cellular (e.g. some fungi).
iv **Alluvial deposits**	Small silt or clay-like particles derived from less stable hilly ground, conveyed by river or lake waters moving over land and deposited onto land over which the river or lake flows.
v **Soil Organic Matter**	Organic matter contained within soil, i.e. any material recently derived from biomass.
vi **Soil Horizons**	The vertical profile of the soil layers.
vii **Surface Litter**	Plant- and animal-derived biomass which collects upon the surface of the soil.
viii **Top-Soil**	The top 10 to 20 cm of the soil, in which most agricultural plant roots develop and in which most nutrients are concentrated.
ix **Sub-Soil**	The layer of soil below the top-soil, from 10 to 20cm below the surface, extending down a variable depth to the underlying bed rock.
x **Parent Material**	The material from which some other substance is ultimately derived, e.g. sediment derived from erosion of rocks.
xi **Greenhouse Gases**	Gas constituents of the atmosphere, both natural and from human activity, which absorb radiation at specific wavelengths emitted by Earth's surface, the atmosphere and by clouds (H_2O). These gases can contribute to positive climate forcing of the atmosphere, adding to anthropogenic climate change.
xii **Humus**	The fraction of SOM that does not have a clearly defined form or cellular structure characteristic of plants, micro-organisms or animals. Humus significantly influences the bulk density of soil and contributes to moisture and nutrient retention.
xiii **Photosynthesis**	A process used by plants and other organisms to convert light energy, carbon dioxide and water into chemical energy to fuel the organisms' activities. A by-product of this process is oxygen. *http://en.wikipedia.org/wiki/File:Photosynthesis.gif*
xv **Climate-Friendly Agriculture (CFA)**	Supports management practices that aim to improve producer net returns while also reducing the impacts of their production on the environment and the future productivity of their soils.
xv **Biofertilisers**	A substance which contains living micro-organisms which, when applied to seed, plant surfaces, or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant