

# Review on Nutrient Management, Cycles, Flows and Balances in Different Farming Systems

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## Summary

Soil fertility management is continuously modified and adapted as conditions change in time and integrated plant nutrient management is a holistic approach to optimizing plant nutrient supply for the objective of adequately nourish the crop as efficiently as possible, while minimizing potentially adverse impacts to the environment. Existence of life depends on continuous cycling of nutrients from the nutrient pool (in the abiotic component of environment) to the living beings and then back to the nutrient pool. These complex series of invisible, delicately balanced, and interrelated biochemical reactions fuel life on earth. Nutrients cycles have been substantially altered by human activities mainly agriculture with large positive and negative consequences for a range of ecosystem services and for human well-being and The presence of animals into the agricultural production system can modify the rates and flows of nutrient dynamics between the compartments of the system and Integrated crop-livestock systems can positively change the biophysical and socio-economic dynamics of farming systems, reestablishing sustainable rural development and promoting higher overall farm profitability. Soil nutrient balances reflect the net change in soil fertility and indicate trends in time, but do not necessarily determine the current state of soil fertility and can differ considerably between different crops, farming systems and agro-ecological zones

**Keywords:** Nutrients, nutrient cycle, nutrient balance

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## Introduction

Soil fertility management is continuously modified and adapted as conditions change in time and intensification of soil fertility depletion increases, when population pressure increases and suitable land becomes scarce (Boesen and Hansen, 2001). Eighty percent of arable land in Africa has low soil fertility and suffers from physical soil degradation as a result of massive nutrient loss caused by unsustainable soil management practices (Hengl T. *et al.*, 2015).

In Ethiopia, low-input agricultural production systems and poor agronomic management practices, limited awareness of communities and absence of proper land-use policies have aggravated soil fertility degradation (Getachew and Tilahun, 2017). This has also encouraged the expansion of farming to marginal, non-cultivable lands, including steep landscapes and range lands (Getachew and Taye, 2005).

Existence of life depends on continuous cycling of nutrients from the nutrient pool (in the abiotic component of environment) to the living beings and then back to the nutrient pool. These complex series of invisible, delicately balanced, and interrelated biochemical reactions fuel life on earth. These nutrient cycles, driven directly or indirectly by incoming solar energy and gravity, include the carbon, oxygen, nitrogen, phosphorous, sulfur and hydrologic (water) cycles and biogeochemical (nutrient) cycles connect past, present and future forms of life (J.N. Galloway *et al.*, 2004).

Nutrients cycles have been substantially altered by human activities mainly agriculture over the past two centuries (Vitousek *et al.* 1997, Bouwman *et al.* 2009), with large positive and negative consequences for a range of ecosystem services and for human well-being (MEA 2005a).

The integration of organic fertilizers, such as verm compost and conventional compost with inorganic fertilizers may improve and sustain crop yields without degrading soil fertility status. Integration of organic and inorganic fertilizers improved the crop yield compared to application of inorganic NP fertilizers alone (Getachew and Taye, 2005; Getachew *et al.*, 2014). Integrated soil fertility management plays important role in restoring soil fertility and availability of plant nutrients, enhancing crop growth and productivity (Geteet *et al.*, 2010; Vanlauwe *et al.*, 2010; Getachew and Tilahun, 2017).

Combined application of organic and inorganic fertilizers decreased soil bulk density, increased soil moisture, soil fertility, and improved maize grain quality (Ronget *et al.*, 2001). Technologies that combine mineral fertilizers with organic nutrient sources can be considered as better options in increasing fertilizer use efficiency, and providing a more balanced supply of nutrients (Donovan and Casey, 1998).

Integrated crop-livestock systems can positively change the biophysical and socio-economic dynamics of farming systems (Keulen and Schiere 2004), reestablishing sustainable rural development (Lemaire *et al.* 2003) and promoting higher overall farm profitability (Entzet *et al.* 2005).

Soil tests are designed to help farmers predict the available nutrient status of their soils. Once the existing

nutrient levels are established, producers can use the data to best manage what nutrients are applied, decide the application rate and make decisions concerning the profitability of their operations (Girma, 2016).

Sustainable crop production aims at maintaining high crop yield without adversely affecting ecosystems to meet the need of current as well as future generations. Since phosphorus in agriculture is the second most growth limiting macronutrient after nitrogen, its proper management in soil contributes significantly to sustainable crop production (Tilman *et al.*, 2002). To review nutrient management, cycles, flows and balances in different farming systems

### **Nutrient management in different farming systems**

Many farming systems still rely on natural release of nutrients from the soil through mineralization and approximately 60–80 % of the farm income was obtained at the expense of soil nutrient depletion, i.e. through un replenished nutrient uptake in marketable crops. Soil nutrient mining cannot be visualized easily and, therefore, indicators are often used to facilitate discussions on soil fertility management. Soil nutrient balances are a commonly used indicator (de Jager *et al.*, 2001)

Producing food for the world population, but with limited impact on world ecosystems, will be a major global challenge with no single solution by managing nutrients cycles in agriculture (crop and livestock systems) can certainly contribute to the goal and Conserving and using nutrients efficiently may help to increase crop yields and limit environmental impact (Griffon, 2006).

Few full-scale studies of farm systems exist that permit the comparison of NUEs. However, conventional, integrated and organic farming systems for their effects on soils and plant nutrition, pests and diseases, animal husbandry, economics, biodiversity and environment, and food quality and health. The main conclusion with regard to nutrient management was the risk in organic systems of depleting soil nutrient reserves, especially of K, owing to a lack of sources approved for use in organic systems (Tinker, 2000).

The fundamental doctrine of N management is to optimize efficiency of both introduced and native soil N by increasing the temporal and spatial coincidence between availability and root uptake of mineral N. Important management measures to improve N efficiency on farms include improved feeding efficiency of animals, reducing NH<sub>3</sub> losses and improving N retention in the crop–soil system as well as timing, rate, source/material and method of supply. The latter implies crop sequences that incorporate cover (or catch) crops, judicious use of soil tillage, improved timing and use of animal manures, crop residues and mineral fertilizers and a suitable balance between the plant production potential and animal stocking density (Christensen, 2004 ; Crews and Peoples, 2005 ).

The main challenge for N management in farming systems is tightening the cycle, in particular those of livestock production systems (Oenema *et al.* , 2007 ).

The total amount of N and P excreted in manure in 2011 was ~120 and 23 Tg respectively. These quantities are similar to or larger than synthetic fertilizer N and P use worldwide. However, manure N and P are not effectively used in crop production due to: (1) the very uneven distribution of faeces and urine by grazing animals; (2) the often incomplete collection and inappropriate storage of faeces and urine from housed animals, with large volatilization and leaching losses; (3) the poor timing and method of manure application; (4) the slow release of organically bound nutrients in the manures; and (5) the relatively low prices of chemical fertilizers (Sutton *et al.* 2013; Stroka *et al.* 2016; Houet *et al.* 2017).

Nitrogen is obtained by biological fixation by legumes, P from unrefined rock phosphate and K from seaweed and various K-containing minerals. Recycling of animal manures and composted wastes is central to organic management systems; deep-rooting plants are used to recycle nutrients from subsoil to topsoil (Goulding *et al.* 2000)

N losses are strongly linked to the presence of livestock activities in the cycle. Eighty five percent (85%) of total agricultural N losses, 72% of NH<sub>3</sub> and 74% of N<sub>2</sub>O losses, are related to manure management. estimated global NH<sub>3</sub> losses from agriculture to be: from housing and storage in mixed and pastoral systems 12-28%, from grazing 6% to 17%, from manure spreading in cropland and grassland 11-30, and from N fertilizer use in cropland 10-18%, and in grasslands 4-8%. (Beusen *et al.*, 2008)

At a cropping system level, management strategies available to improve overall P-use efficiency of cropping systems include the use of diverse crop rotations, the presence of cover or catch crops, and crop breeding for higher internal P-use efficiency, which will enhance crop P acquisition strategies. However, plant and microbial strategies need to be further improved, particularly the uptake of residual soil P (from applied fertilizers and manures) and subsoil P uptake (Richardson *et al.* 2011).

Phosphorus should be applied at the time of sowing of annual crops in bands in low-P soils. This reduces the fixation of the fertilizer P to a minimum as it allows the crop the best opportunity to compete with the soil P utilization (Menge *et al.*, 2001). If soil P content is higher or in the adequate range for crop growth, band and broadcast applications will be equally effective. The use of an adequate level of P for maximum economic yield is possible if P soil test calibration data are available for a given crop and soil type (Fageria *et al.*, 1997a). In

order to achieve better soil P availability indices for any given soil type and crop species, detailed field calibrations are needed in relation to the P extracted by any particular extracting and the economic crop yield response to various soil P fertilization levels (Fageria *et al.*, 1997a).

Integration of organic amendments of P with inorganic source is significantly better than the use of mineral P fertilizers alone. Effectiveness of inorganic P fertilizers was increased and P recovery was improved with the addition of organic manure (Whalen and Chang, 2001). Furthermore, most crop plants utilize organic P sources efficiently by increasing production of phosphatases, increasing fungal and bacterial growth (Tarafdar and Claassen, 1988).

Repeated applications of chemical P fertilizers is expensive and can lead to the loss of soil fertility by disturbing microbial diversity and reducing crops yield (Gyaneshwari *et al.*, 2002). The use of environment-friendly alternative to applications of P fertilizers is gaining increasing attention (Barea *et al.*, 1997). In regions where inorganic P fertilizers application is expensive, use of phosphate rocks in combination of phosphate-solubilizing microorganisms (PSM) is seen as a viable alternative.

Three major issues are correlated with the excessive fertilization of agricultural areas. The first issue that has to be addressed is the eutrophication affecting aquatic ecosystems. Another issue is the uneven terrestrial phosphate rock distribution, revealing a dipole of areas facing phosphorus over-accumulation and areas with restrictions in productivity due to major phosphorus deficiencies. Lately, an emerging issue is the assessment of the remaining global phosphorus reserves. The nutrient was characterized as a non-renewable resource, which should be efficiently exploited, taking into consideration the rules of sustainability (Cordell *et al.*, 2009). The combination of organic inputs with fertilizers could play a substantial role in increasing the agronomic use efficiency of P fertilizer (Vanlauwe *et al.*, 2010).

Globally, several efforts have been made targeting the improvement of phosphorus usage efficiency in crop fields and pastures (Schröder *et al.* 2011; Paganiet *al.* 2013). Among these is the 4R approach (Right product, Right rate, Right time, and Right place) by IFA (2009) and IPNI (2012),

Diversity and integration are often associated with sustainable and resource use efficient systems, in crop-livestock mixed systems, intensification may occur through the introduction of animal traction, use of animal manure, fodder production, stall feeding and replacement of animals. Intensification creates opportunities for increasing integration due to increased production of crop residues that may be fed to livestock, and manure that may be used for cropping (Dalsgaard and Oficial, 1997).

Integrated crop-livestock systems are organized to maximize synergies and minimize trade-offs between crops and livestock sub-systems through the production of crops and livestock on the same area, concurrently or sequentially in rotation or succession (Moraes *et al.*, 2014).

The result of an integrated system is that the whole is greater than the sum of its parts and resulting in having emergent properties (Anghinoniet *al.*, 2013). These integrated crop-livestock systems are produce with minimal supply of inputs and technologies (Moraes *et al.*, 2014). Crop-livestock integration is an effective means by which plant nutrients can be rapidly recycled within and between farms (Thornton and Herrero, 2001).

Integrated plant nutrient management is a holistic approach to optimizing plant nutrient supply. It includes: (1) assessing residual soil nutrient supplies, as well as acidity and salinity; (2) determining soil productivity potential for various crops through assessment of soil physical properties with specific attention to available water holding capacity and rooting depth; (3) calculating crop nutrient requirements for the specific site and yield objective; (4) quantifying nutrient value of on-farm resources such as manures and crop residues; (5) calculating supplemental nutrient needs (total nutrient requirement minus on-farm available nutrients) that must be met with “off - farm” nutrient sources; (6) developing a programme to optimize nutrient utilization through selection of appropriate nutrient sources, application timings and placement and the overall objective of IPNM is to adequately nourish the crop as efficiently as possible, while minimizing potentially adverse impacts to the environment (Roy *et al.*, 2006).

### **Nutrient cycle and flow in different farming systems**

The cycle of a nutrient in the soil-plant system can be defined as addition, transformation, and uptake by plants, loss from the soil-plant system, and immobilization (Fageria and Baligar, 2005a). The knowledge of nutrient cycling is important for the efficient use of soil nutrients, residues and fertilizers in the integrated crop-livestock system, because losses and additions of carbon and nutrients modify soil dynamics (Hentzet *al.*, 2014).

Nutrient stocks flow and budgets are increasingly being used as tools for estimating nutrient build-up and decline so as to provide an understanding of the potential and suitability of land for agricultural production (Van den Bosch H, and Jager AD, Vlaming J (1998)).

The conservation of O.M is crucial for the chemical, biological and physical properties of the soil in temperate and tropical environments (Batista *et al.*, 2014), and being an important constituent of nutrient reserve, whose availability can be rapid and intense, or slow and gradual, depending on the quantity, type of material and climatic conditions (Rosolem *et al.*, 2007).

Integrated crop-livestock systems can increase biodiversity via the attributes of organic matter provided by pastures resulting flora and fauna diversity, as well as microbial and faunal soil communities, change the soil and its physio-chemical properties (Lemaire *et al.* 2003). The heights of pasture management determines the total amount of dry matter produced by the aerial part and root system, the magnitude of the impact of the animal trampling and the amount of dry matter recycled in the system (Aguinaga *et al.*, 2008).

Use of livestock for nutrient cycling and transfer to agricultural land presents another option of enhancing N recycling in the semi-arid conditions. It has been shown that livestock can recycle up to 48% of N intake as manure, which amounts to yearly average use on the cropped land of 1.2 kg ha<sup>-1</sup> N (Stoorvogel JJ, and Smaling EMA, 1990)).

The pastoral environment is particularly important to the colonization/extinction metapopulation processes of many organisms (eg. insects, mollusks) and is a forage resource for many birds and mammals, frequently being their reproduction site and pastures can be essential for biodiversity maintenance at the landscape level, being the habitat of invertebrates that are important to carbon and nitrogen cycles (Lemaire *et al.* 2003).

### **Role of organic matter in nutrient cycling**

Organic matter (that is, C-based compounds of biological origin) plays several pivotal roles in determining nutrient availability to plants and largest labile stock of nutrients in soils, sediments, and waters is typically contained in organic compounds. Since uptake by plants is almost exclusively in the inorganic form, the biologically mediated process of organic matter decomposition is crucial to nutrient availability (Parton *et al.*, 1988).

Organic matter provides energy for all microbial and faunal activities and thus allows them to build the micro aggregate structures that control soil hydraulic properties and serve to further conserve organic matter and deposition of straw on the soil surface of degraded soils attracts termites that feed on this resource and significantly improve water infiltration and storage in the galleries and porous constructions (Mando *et al.*, 1997).

The amorphous polymers act as reserves of nutrients, which are sequestered in their chemical structures for periods of centuries to millennia. Since its surface bears a significant electrical charge, organic matter (along with clay) is the main location on which the cationic and anionic forms of plant nutrients are retained prior to uptake, without being leached out of the soil (Lavelle and Spain 2001). O.M releases nutrients in a plant-available form upon decomposition. In order to maintain this nutrient cycling system, the rate of organic matter addition from crop residues, manure and any other sources must equal the rate of decomposition, and take into account the rate of uptake by plants and losses by leaching and erosion (FAO, 2005)

By breaking down carbon structures and rebuilding new ones or storing the C into their own biomass, soil biota plays the most important role in nutrient cycling processes and, thus, in the ability of a soil to provide the crop with sufficient nutrients to harvest a healthy product. The organic matter content, especially the more stable humus, increases the capacity to store water and store (sequester) C from the atmosphere (FAO, 2005).

Cycling of nutrients relies on the quality of agricultural soils, either directly through their capacity to receive nutrients and to convert them into or keep them in forms that are available to crops, or indirectly by governing the productivity and harvest ability of crops and thereby the effective capture of nutrients from soils (Keesstra *et al.*, 2016).

The capacity of soil to cycle nutrients is a series of consecutive steps. These steps are (i) the capacity of a soil to receive and retain nutrients, the 'accommodation value' (AV), (ii) the capacity of a soil to make and to keep nutrients available for crop uptake, that is to ascertain the FV of the applied residue, (iii) the capacity of a soil to facilitate the recovery of plant-available nutrients, the RV and finally, (iv) the capacity of a soil to support the successful collection and export of produce containing apportion, defined by the Nutrient HI, of the nutrients acquired by the crop to a subsequent processor or consumer (Keesstra *et al.*, 2016).

Organic inputs (crop residues and animal manures) are also an important source of nutrients, but their N, P, Mg and Ca content is only released following decomposition. By contrast, K is released rapidly from animal manures and crop residues because it is contained in the cell sap. Further, the amount of nutrients contained in organic resources is usually insufficient to sustain required levels of crop productivity and realize the full economic potential of a farmer's land and labor resources. Organic resources have multiple functions in soil, ranging from their influence on nutrient availability to modification of the soil environment in which plants grow and provide an energy source for soil microorganisms which drive the various soil biological processes that enhance nutrient transformation and other quality parameters of soil. (Fairhurst, T., 2012)

The response to fertilizer is greater when fertilizer is applied with added organic resources (e.g. animal manure) (line A, figure-1) and the response is even greater at higher rates of fertilizer input (line B figure-1). The impact of animal manure on response to fertilizer depends on the amount of manure added. A much larger amount of fertilizer is required to reach yield at line C, figure-1 when no organic matter is used (line A) compared with the use of mineral fertilizer in combination with organic matter (line B). (Fairhurst, T., 2012)

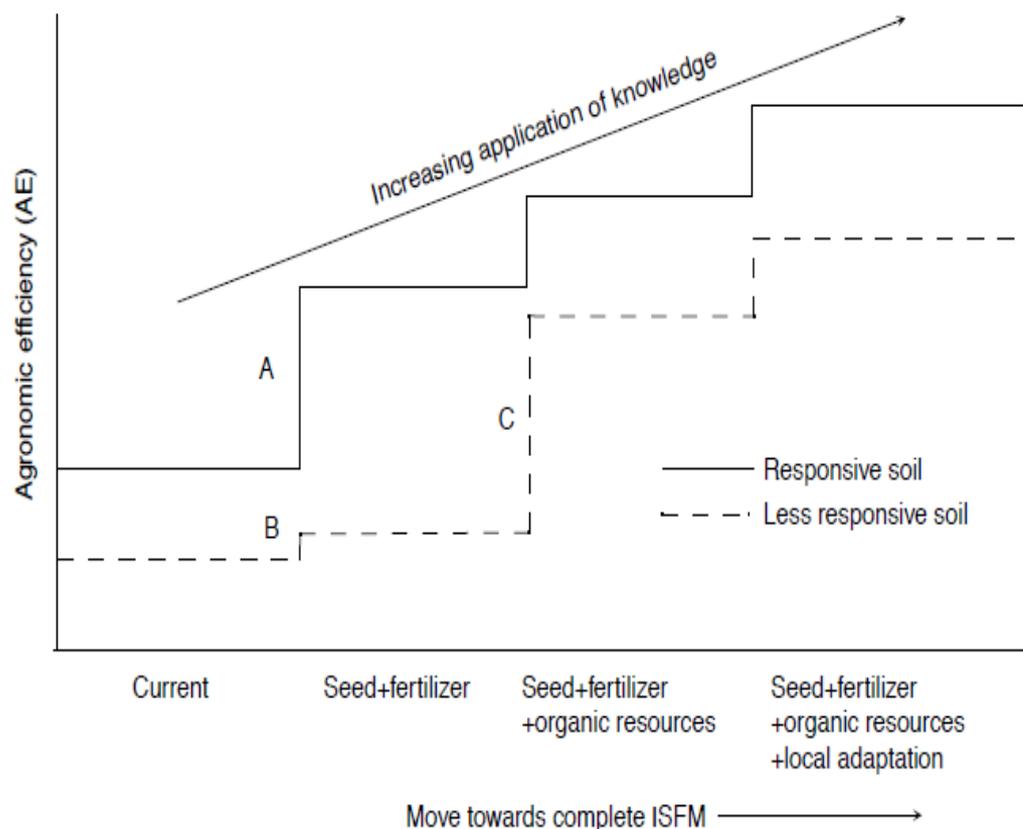


Figure-1: Relationship between the agronomic efficiency (AE) of fertilizers and organic resource and the implementation of various components of ISFM.

Source: (Fairhurst, T., 2012)

**Nitrogen (N)** is one of the most yield-limiting nutrients for crop production in the world. It is also the nutrient element applied in the largest quantity for most annual crops (Huber and Thompson, 2007). Nitrogen cycle in the soil–plant system is very dynamic and complex due to involvement of climatic, soil, and plant factors. Knowledge of the nutrient cycle in the soil–plant system is an important aspect of understanding the availability of N to plants and adopting management practices to maximize its uptake and use efficiency (Fageria and Baligar, 2005a).

The nitrogen cycle is the shift between different chemical forms of nitrogen through biologic, physical, and geologic processes on Earth. Nitrogen is an essential element for all living things. It is a building block of biologic molecules such as proteins and nucleic acids. The majority of nitrogen on the planet is in the form of molecular nitrogen in the air. Only certain bacteria can convert nitrogen into biologic molecules that occur mainly inside living cells. Humans are interfering with the nitrogen cycle by making nitrogen fertilizers and by oxidizing atmospheric molecular nitrogen through the extensive burning of fossil fuels. (Sergei A. Markov, 2015).

Legume-derived N from biological N<sub>2</sub> fixation (BNF) is critical to the sustainability of organic crop (annual and perennial) production systems on commercial farms (Woodley *et al.*, 2014), and contributes substantially to sustainability with respect to reduced energy use on organic farms (Lynch *et al.*, 2011). However, productivity and nutrient (N and P) loading and risk of losses, and nutrient use efficiency from organic production systems can vary with specific management practices and overall farm intensity of production; furthermore seasonal variation affects soil N mineralization and potential synchrony of soil available N supply with cash crop demand (Lynch *et al.*, 2012a,b).

The consequences of human intervention in the nitrogen cycle include the obvious benefits for food security with approximately half of the global human population dependent on the increased yields of agricultural crops owing to fertilizer nitrogen usage, and substantially enhanced carbon sequestration resulting from N deposition to forests and other semi-natural terrestrial ecosystems (de Vries W *et al.* 2009).

The nitrogen applied in agriculture is derived from atmospheric sources, but unlike the natural process of N fixation, most agricultural N is fixed industrially by the Haber–Bosch process (Smil V. 2001), the remainder by nitrogen-fixing crops (Sprent IJ. 1987).

For instance, estimated N losses from arable land to be 31, 68, 112 and 27 kg ha<sup>-1</sup> yr<sup>-1</sup> in Zimbabwe, Malawi,

Kisii, Kenya, and Tanzania, respectively (Stoorvoegelet al. 1993) similar results have been found in Mali. In Niger, N losses of up to 91 kg ha<sup>-1</sup> have been attributed to leaching (Brouwer J, Powell JM., 1998)).

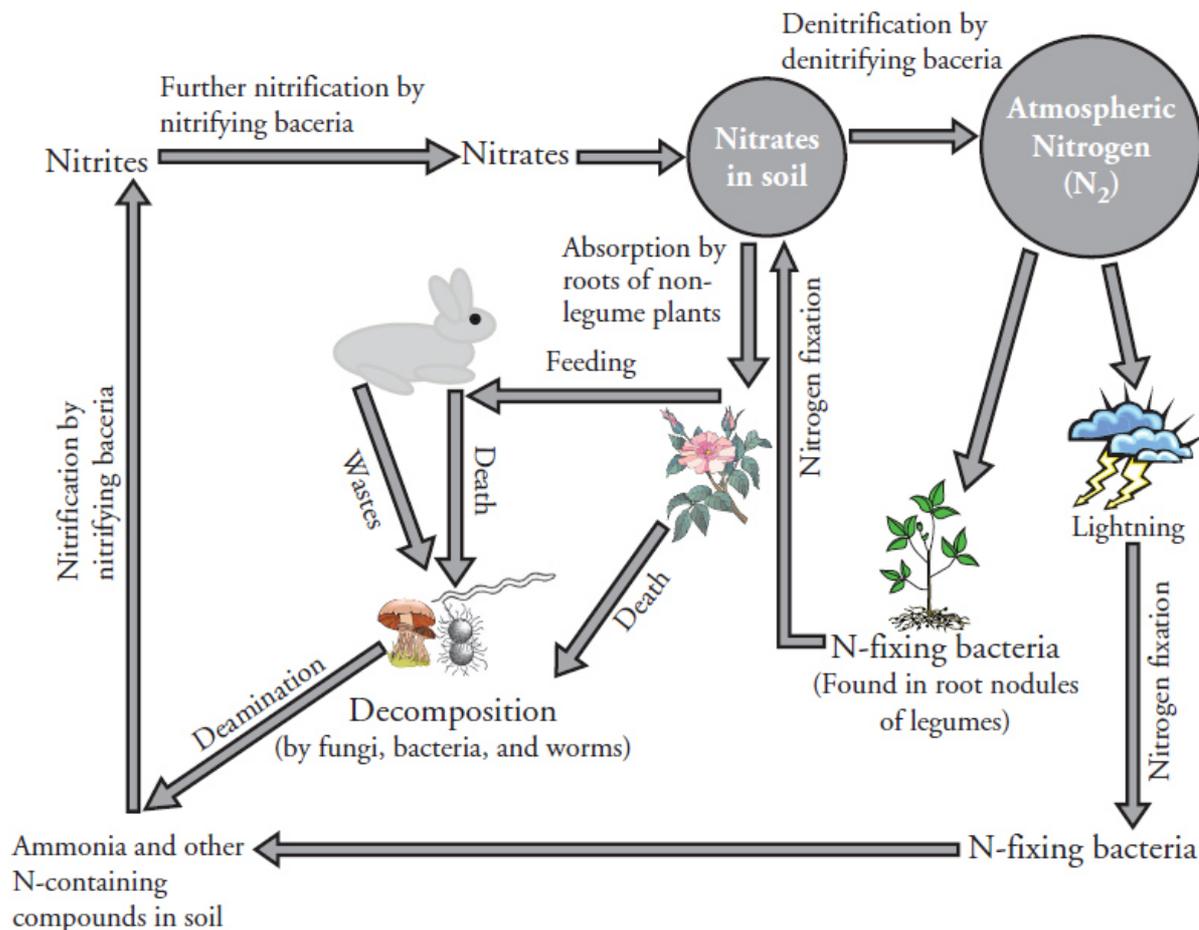


Figure 2: nitrogen cycle

Phosphorus (P) is a naturally occurring element that can be found in the earth's crust, water, and all living organisms. Primarily phosphorus is available in a few minerals, the main of which is apatite. Weathering of the apatite parent rocks releases P, this can be partially incorporated into the plant tissue and be transformed into an organic form (Filippelli, 2008)

Phosphorus (P) is a limiting nutrient for terrestrial biological productivity, and thus it commonly plays a key role in net carbon uptake in terrestrial ecosystems. Unlike nitrogen (another limiting nutrient but one with an abundant atmospheric pool), the availability of "new" P in ecosystems is restricted by its rate of release during soil weathering. The release of P places a limit on ecosystem productivity which in turn is critical to terrestrial carbon balances (Schlesinger, 1997).

Unlike nitrogen, which can be returned to the soil by fixation from the air, phosphorus cannot be replenished except from external sources once it leaves the soil in agricultural products or by erosion. Improving the efficiency and sustainability of P in the food system is currently based upon incremental adaptations to system management. An adapted food system can be considered as one where management has been altered to be more P efficient at the farm scale. Recycling is optimized as much as possible through integrated farming practices (Wezel, A, et al 2014), and P losses are managed by implementation of best management practices (Schoumans, O et al 2014).

Mixed crop-livestock farming, wider crop diversification and manure trading are examples of farm-scale adaptations which would stimulate P minimization through P recycling. Such recycling of bio-resources is a key 3R P stewardship strategy that benefits overall soil quality (Bhogal, A. et al2011), landscape biodiversity (Derner, J et al. 2009), and the resilience of farming systems, for example, to pest and disease attack or to commodity price fluctuations (Ryschawy, J et al2012).

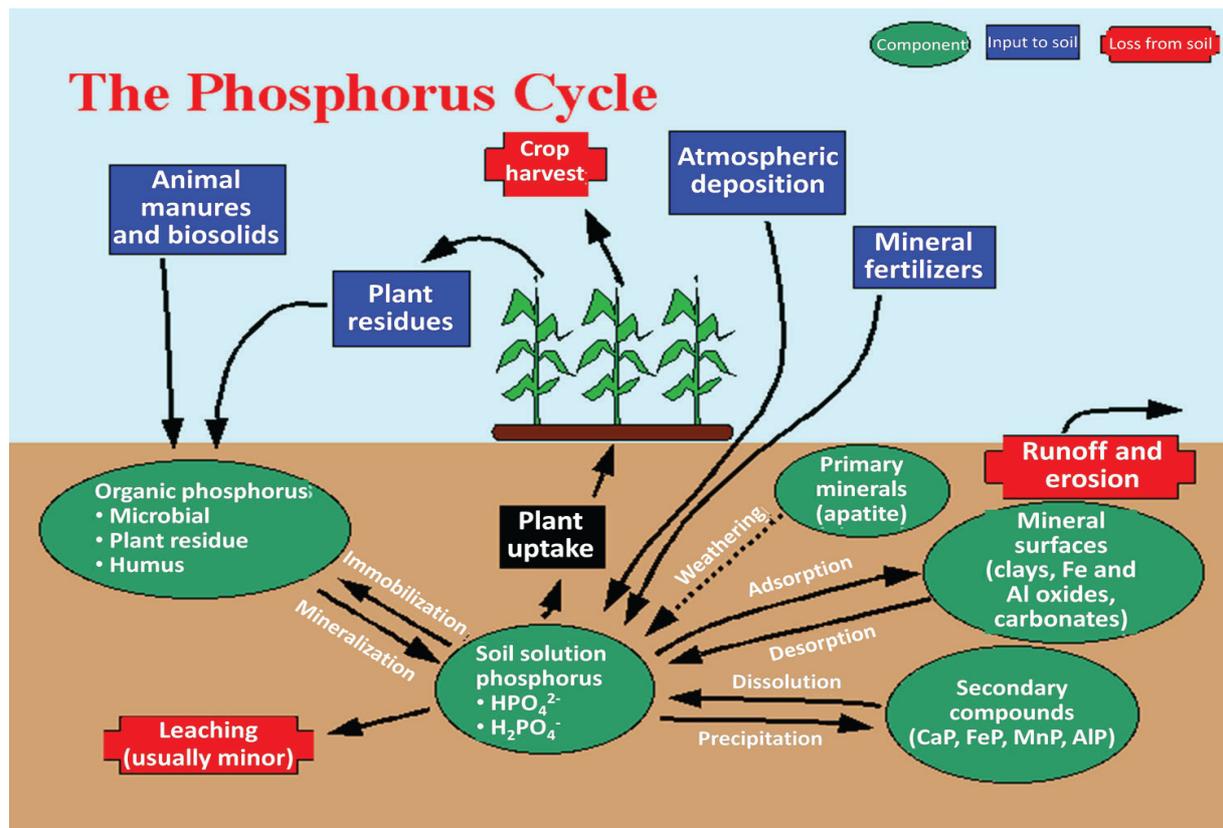


Figure 3: Phosphorus cycle

**Potassium:** As much K as N is taken up by many crops, so its supply is critical. Often, the ability of many soils to supply adequate amounts of K for many years leads to its under-application, and there are concerns that the UK and other countries are applying too little K (and P) owing to the need to save costs (Johnston *et al.* 2001). The supply of acceptable forms of K to organic systems is a particular problem (Watson *et al.* 2004).

Sulfur cycle is defined as the sequence of transformations undergone by sulfur wherein it is used by living organisms, transformed upon death and decomposition of the organisms, and ultimately converted to its original oxidation state (Soil Science Society of America 1997). Sulfur (S) has long been recognized as an essential element for plant growth and development and is classified as a macronutrient. Crop responses to applied sulfur have been reported in a wide range of soils in many parts of the world (Brady and Weil, 2002). Sulfur, an essential element for microorganisms and plants, is continuously being cycled between inorganic and organic forms (Castellano and Dick, 1990).

Table 1: Summary of Reactions for Nitrogen (N), Phosphorus (P), and Sulfur (S) Cycling

Process/reaction	Reactant(s)	Product(s)	Mediator
Assimilation	$\text{NO}_3^-$ (nitrate), $\text{NH}_4^+$ (ammonium) $\text{PO}_4^{3-}$ (phosphate), $\text{SO}_4^{2-}$ (sulfate)	Organic N, P, S	Plants, fungi, bacteria
Mineralization	Organic N, P, S	$\text{NH}_3$ (ammonia), $\text{NH}_4^+$ , $\text{PO}_4^{3-}$ , $\text{S}^{2-}$ (sulfide)	Bacteria, fungi
Nitrification	$\text{NH}_3$	$\text{NO}_2^-$ (nitrite), $\text{NO}_3^-$	Bacteria
Denitrification	$\text{NO}_3^-$	$\text{N}_2$ , $\text{N}_2\text{O}$ (nitrous oxide), $\text{NO}$ (nitrogen oxide)	Bacteria
Sulfate reduction	$\text{SO}_4^{2-}$	$\text{H}_2\text{S}$ (hydrogen sulfide)	Bacteria
Sulfide oxidation	$\text{S}^{2-}$	$\text{SO}_4^{2-}$	Bacteria
Adsorption	$\text{NH}_3$ , $\text{PO}_4^{3-}$ Organic N, P, S	Sorbed forms	Abiotic
Coprecipitation	$\text{PO}_4^{3-}$ , $\text{S}^{2-}$	Amorphous Fe (iron) and Al (aluminum) oxides, $\text{FeS}$ (iron sulfide)	Abiotic

Source, Michael E McClain, 2014

Magnesium ( $\text{Mg}^{2+}$ ) is an essential macronutrient for all plant growth and development. Its adequate level in

the soil is important for producing maximum economic yields. Like deficiency of calcium ( $\text{Ca}^{2+}$ ), deficiency of magnesium in crop production is more common on highly weathered acid soils (Fageria and Souza, 1991).

The cycle of  $\text{Mg}^{2+}$  in soil–plant systems involves its addition to soils and depletion by several processes. The main sources of  $\text{Mg}^{2+}$  addition are liming,  $\text{Mg}^{2+}$  fertilizers, crop residues, farmyard or green manures, and liberation by weathering of parent materials. Its removal or depletion from the soil–plant system is mainly through uptake by crops, soil erosion, and leaching. In addition, some part of  $\text{Mg}^{2+}$  is also fixed in the soil–plant system by soil colloids and microorganisms. Significant amounts of  $\text{Mg}^{2+}$  fixation in Oxisols and Ultisols when limed to pH above 7.0. Most of the  $\text{Mg}^{2+}$  is present in the soil as primary minerals, and very little exists in organic forms or in the form of organic complexes (Sumner *et al.* 1978; Grove *et al.* 1981).

Carbon cycle: Carbon (C) storage is an important ecosystem function of soils that has gained increasing attention in recent years. Changes in soil C impacts on, and feedbacks to, the Earth’s climate system through emissions of  $\text{CO}_2$  and  $\text{CH}_4$  as well as storage of carbon removed from the atmosphere during photosynthesis and S.O.M itself also confers multiple benefits for human society by enhancing water purification and water holding capacity, protecting against erosion risk, and enhancing food and fiber provision through improved soil fertility (Pan *et al.*, 2014).

Global C cycle is currently out of balance principally as a result of the burning of fossil fuels, but also due to the conversion of high C-density natural ecosystems, such as forests and grasslands, to lower C-density agro-ecosystems. It should be noted that the C cycle has been perturbed by about 13% relative to its preindustrial state, compared with figures of 100% or more for the N, P, and S cycles (Falkowskiet *al.* 2000).

An increase in organic C is often accompanied by increased N resource use efficiency in croplands (Pan *et al.*, 2009), especially when SOC is increased with biochar (Huang *et al.*, 2013).

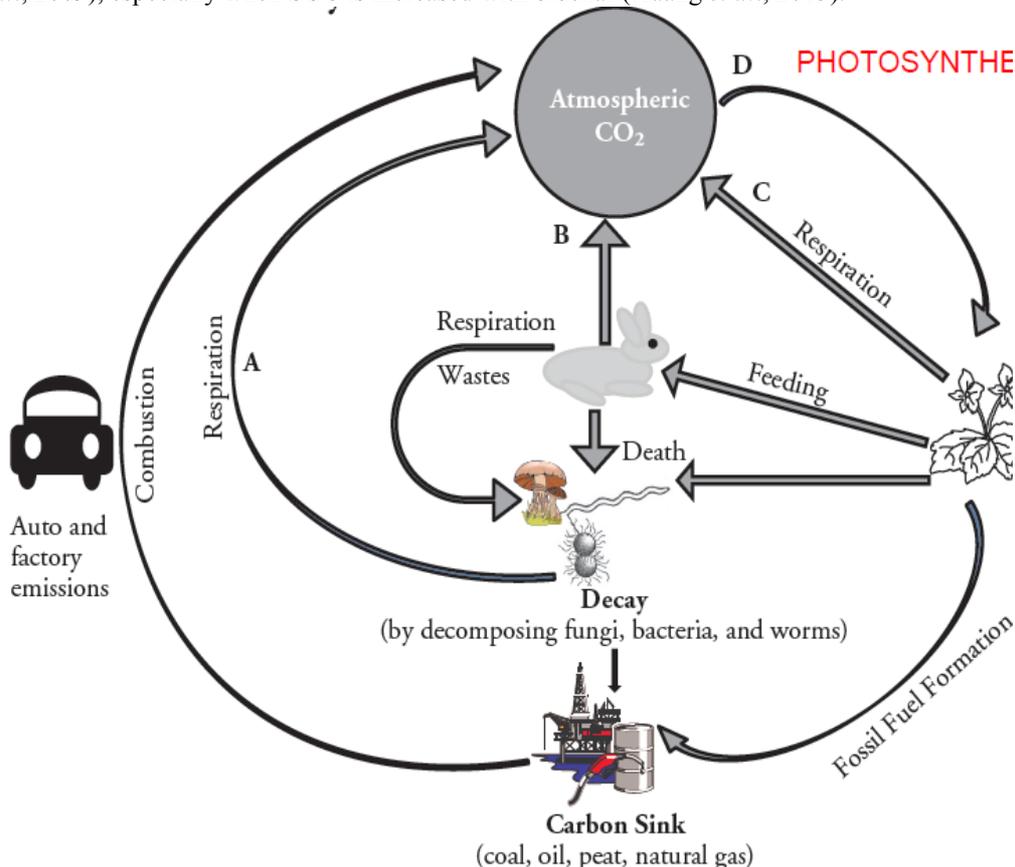


Figure 4 carbon cycle

The availability of both macro- and micronutrients is influenced by soil chemical and physical properties. The soil nutrient content may not be always enough to fulfill crop requirement. Similarly, most of the micronutrients, for example Fe and Mn are readily fixed in soils having alkaline pH as carbonates and/or bicarbonate compounds. Plant roots are unable to absorb these nutrients adequately from dry topsoil (Graham *et al.*, 1992; Foth and Ellis, 1997). Similarly, some nutrient elements, such as Ca, Mg and Mn are not easily translocated to leaves within the plant system (Foth and Ellis, 1997).

Insufficient soil micronutrients are affecting both crop yield and reduce quality, and it is partly responsible for decreasing efficiency of N, P and K fertilizers. In rain fed areas, in spite of subsistence agriculture over a long period, soils are depleted not only major nutrients but also micro-and secondary nutrients (FAO, 2006).

### Nutrient flows

Soil nutrient flow is the amount of plants nutrients that flow in and out of a system. The difference between nutrient inflow (sum of nutrient inputs) and outflow (sum of nutrient outputs) is the nutrient balance (Nkonya *et al.*, 2004).

The presence of animals into the agricultural production system can modify the rates and flows, that is, the nutrient dynamics between the compartments of the system (Anghinoni *et al.*, 2013). The net flow of N from the land into the oceans and the atmosphere is unsurprising given the mobility of N in soil water and transfer to the oceans by rivers and the advection of the atmospheric N by wind over coastlines (Billen G *et al.* 2013).

There are increasing concerns about soil fertility and the risks of nutrient deficiencies in the crop production in extensive agricultural production systems, including a major proportion of organic farming systems. The limited scope for importing nutrients to organic farms can make balancing inflows against outflows difficult, which may result in nutrient imbalances and deficiencies (Watson *et al.*, 2002).

Nutrient stocks flow and budgets are increasingly being used as tools for estimating nutrient build-up and decline so as to provide an understanding of the potential and suitability of land for agricultural production. Partial balance approach has a shortcoming in that it excludes flows (e.g., N fixation, erosion) which could have high relative importance, especially in low external input agriculture (Janssen BH, 1999).

Nutrient flows and balances are currently and increasingly being used as powerful tools for estimating nutrient depletion or accumulation. The relevance of soil nutrient balances to agricultural potential of land has been emphasized by many scientists (Stoorvoege *et al.*, 1993;

Smaling, 1993; Van den Bosch *et al.*, 1998)

Nutrient output flows comprise removal of economic crop products and crop residues, leaching, gaseous losses, runoff and erosion. A situation where inputs exceed outputs is termed as surplus nutrient accumulation; when outputs exceed inputs, this is nutrient depletion. The concept of nutrient depletion is derived from quantifying nutrient flows resulting in nutrient balances and/or stocks (Vlaming *et al.*, 2001).

N internal flows within a system include household waste feeds, crop residues, grazing of vegetation, and animal manure and farm products to a household. The potential supply of mineral-N by soil is determined by factors such as the mineralization-immobilization and N-loss mechanisms operating during the cropping season (Mtambanengwe F, Mapfumo P, 2006)

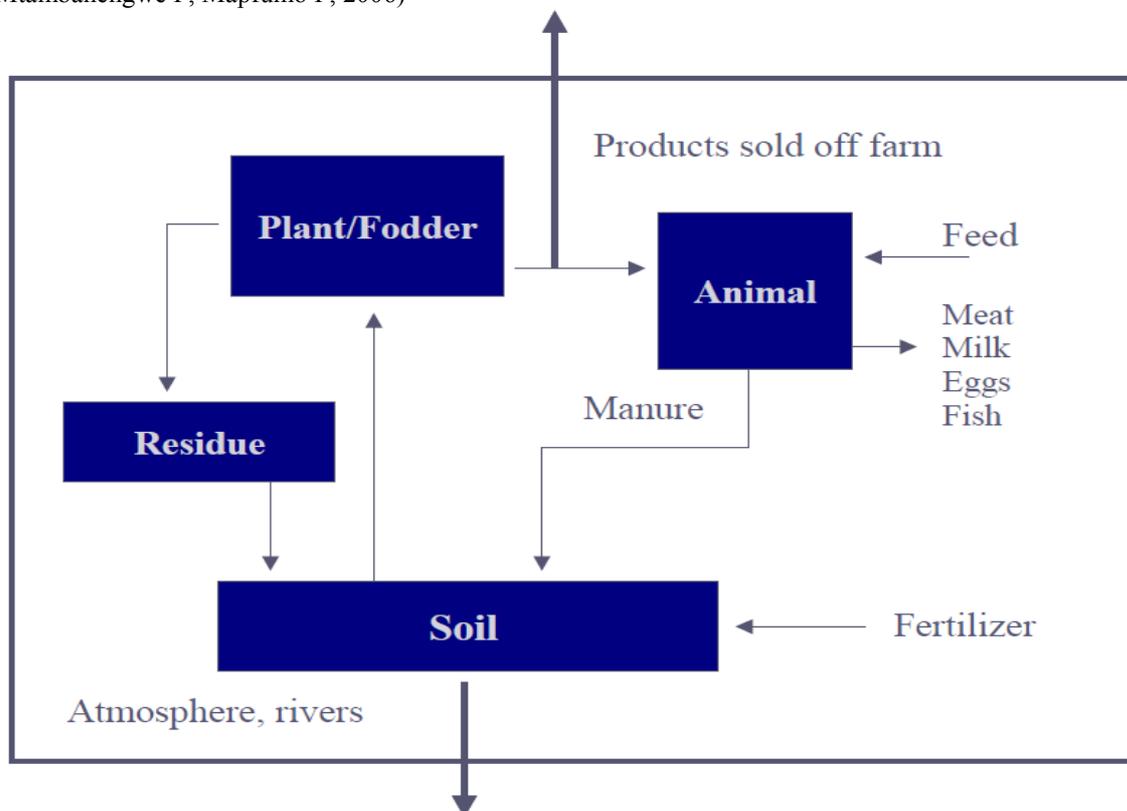


Figure 5: Nutrient Flows at the local Scale  
Source, Ulrike Grote *et al.*, 2014

### **Nutrient balance in different farming systems (NPK)**

Soil nutrient balances are a commonly used indicator and are defined as the difference between the sum of nutrient input flows and the sum of nutrient output flows within a specific system (field, farm, nation) over a certain period (season or year). Soil nutrient balances reflect the net change in soil fertility and indicate trends in time, but do not necessarily determine the current state of soil fertility. To determine the severity of the depletion rate, nutrient balances can be related to the soil nutrient stocks, where typically a depletion rate of more than 2 % per year of the soil nutrient stock is considered unsustainable (Elias 2002).

Negative nutrient balances indicate that a system is losing nutrients; on the contrary, excess nutrient accumulation may lead to extended losses as a result of toxicities. The net difference between inputs and outputs of nutrients expressed in kg nutrients integrated over a certain area and time gives the net soil nutrient budget (Stoorvogel and Smaling, 1990). Balanced or equilibrium nutrient levels occur when inputs equals outputs. Hence, a summary of nutrient inputs and outputs from a defined system over a defined period of time is the nutrient budget for that spatio-temporal unit (Oenema *et al.*, 2003).

Nutrient budgets are important indicators of potential land degradation, for optimizing nutrient use, and designing policy to support improved soil fertility management by smallholder farmers and have been used extensively for improving natural resource management and/or for policy recommendations over the last decades (Grote *et al.*, 2005).

Today there is an increasing need for a balanced fertilization strategy, minimizing the use of mineral fertilizers to enhance both crop production and quality and nutrient uptake under low input conditions (Murillo - Amador *et al* 2015). Mineral fertilizers can be replaced by organic fertilizers (Szparaga, A. and Kocira S. 2018), plant bio stimulants (Alori, E *et al* 2018), and beneficial microbial inoculants (Fiorentino, N *et al*, 2018).

Regional and national estimates of N balances are negative in most of sub-Saharan Africa region. Numerous studies focusing on N balance, have consistently reported negative national averages which can be ascribed to the several N losses channels especially through harvest, soil erosion and low or non-use of external soil inputs (Milka N., 2019). For Africa as a whole, low level of inputs relative to outputs results in a consistently negative balance (Stoorvoegelet *al.*, 1993).

Element balance calculations at farm/field level can be a tool for evaluation of different farming systems from an environmental perspective (risks for emissions from agriculture) and a sustainable nutrient management perspective (Öbornet *al.*, 2003). Balances of both nutrients and trace metals for different types of agricultural systems can be used to gain insights into the long-term development of soil quality and sustainability of the system. The balance calculation tool has become widely used by policy-makers, extension workers (advisors), certification organizations and farmers as an instrument for planning and control of on-farm nutrient management directed towards more sustainable agricultural production (Goodlassset *al.*, 2003).

N balances in most wealthy farms were positive while those for medium and poor farms were close to zero or negative. Apart from the assumption that fields near the homesteads are zones of nutrient accumulation and distant fields are zones of depletion, N balances also depend on the value of the crop grown as perceived by the farmers and the intensity of soil management practices (Giller KE, *et al* 2006, Tittonell PA, 2007). At crop level higher inflows of both inorganic and organic fertilizers for maize compared with groundnut, as farmers invariably applied more fertilizers to maize crops with little or nothing to the groundnuts. As a consequence, N balances were mostly positive for maize and negative for groundnuts (Zingore *et al.*, 2000).

In assessing nutrient depletion through use of nutrient balances at any given time, a number of inputs and outputs are considered. Nutrient input processes are: application of mineral fertilizer and organic manure, atmospheric deposition, Biological N<sub>2</sub> fixation and sedimentation by irrigation and flooding. Even though a number of nutrient flows can easily be quantified and valued in monetary terms based on the input and output processes (partial balance), other flows are hard to quantify hence often estimated on the basis of transfer functions, for instance those developed for sub-Saharan Africa by (Stoorvoegelet *al.*, 1993), adopted and critically reviewed by others Scoones and Toulmin, 1998; FAO, 2003). A partial nutrient balance considers direct nutrient inflows from mineral fertilizers and organic materials and outflows resulting from harvested products and crop residues (Harris, 1998).

Table 2: Average Nutrient Balances for Selected Sub-Saharan African Countries

Country	N		P		K	
	1982-84	2000	1982-84	2000	1982-84	2000
	kg/ha/year					
Benin	-14	-16	-1	-2	-9	-11
Botswana	0	-2	1	0	0	-2
Cameroon	-20	-21	-2	-2	-12	-13
Ethiopia	-41	-47	-6	-7	-26	-32
Ghana	-30	-35	-3	-4	-17	-20
Kenya	-42	-46	-3	-1	-29	-36
Malawi	-68	-67	-10	-10	-44	-48
Mali	-8	-11	-1	-2	-7	-10
Nigeria	-34	-37	-4	-4	-24	-31
Rwanda	-54	-60	-9	-11	-47	-61
Senegal	-12	-16	-2	-2	-10	-14
Tanzania	-27	-32	-4	-5	-18	-21
Zimbabwe	-31	-27	-2	2	-22	-26

Source: Roy *et al.*, 2003

Ethiopia is considered as one of the most vulnerable countries in sub-Sahara Africa (SSA) with regard to soil fertility depletion because of its mountainous topography and intensive farming systems based on small cereals. Indeed, national averages of nutrient balances were estimated at -41 kg N, -6 kg P and -26 kg K per ha per year, which is among the highest nutrient depletion rates for sub-Saharan Africa (Stoorvogel and Smaling 1993). Yet, soil nutrient balances can differ considerably between different crops, farming systems and agro-ecological zones (Sommeret *al.* 2014).

The nutrient input flows and output flows were monitored over a period of 3 years (2012–2014) using the monitoring for quality improvement toolbox. Average nitrogen (N), phosphorus (P) and potassium (K) balances were  $-23 \pm 73$ ,  $9 \pm 29$  and  $-7 \pm 64$  kg ha<sup>-1</sup>, respectively. (C. L. van Beeket *al.* 2016).

Table 3: Nutrient balances of CASCAPE and previously reported values for Ethiopia (kg ha<sup>-1</sup>)

	References	Farming system	N	P	K
1	C. L. van Beeket <i>al.</i> 2016	Mixed, smallholder	-24	9	-7
2	Stoorvogel and Smaling (1993)	National level	-47	-7	-32
3	Elias (1998); Atichoet <i>al.</i> (2011)	Enset—coffee (Wolaita)	?3	+5	n.d.
4	Hailelassieet <i>al.</i> (2006)	Cereal (Central Ethiopia)	-50	-4	-64
5	Hailelassieet <i>al.</i> (2006)	Enset (Guraghe highlands)	+68	+7	-23
6	Hailelassieet <i>al.</i> (2006)	Cereal (western Ethiopia)	-46	?3	-75
7	Asefaet <i>al.</i> (2003)	Low potential Tigray (Atsbi)	-65	-6	-34
8	Elias (2002)	National average	-92	?5	-49

n.d.= no data

Source: NutrCyclAgroecosyst (2016)

### Summery and conclusion

Soil fertility management is continuously modified and adapted as conditions change in time and integrated plant nutrient management is a holistic approach to optimizing plant nutrient supply for the objective of adequately nourish the crop as efficiently as possible, while minimizing potentially adverse impacts to the environment. Nutrients cycles have been substantially altered by human activities mainly agriculture over the past two centuries with large positive and negative consequences for a range of ecosystem services and for human well-being. Ecosystems regulate the flows and concentrations of nutrients through a number of complex processes including a diversity of species.

Integrated crop-livestock systems can positively change the biophysical and socio-economic dynamics of

farming systems, reestablishing sustainable rural development and promoting higher overall farm profitability to maximize production of crops and livestock on the same area, concurrently or sequentially in rotation or succession

Organic matter plays several pivotal roles in determining nutrient availability to plants. Since uptake by plants is almost exclusively in the inorganic form, the biologically mediated process of organic matter decomposition is crucial to nutrient availability

Many farming systems still rely on natural release of nutrients from the soil through mineralization and approximately 60–80 % of the farm income was obtained at the expense of soil nutrient depletion. Soil tests are designed to help farmers predict the available nutrient status of their soils. Once the existing nutrient levels are established, producers can use the data to best manage what nutrients are applied, decide the application rate and make decisions concerning the profitability of their operations

In Ethiopia, low-input agricultural production systems and poor agronomic management practices, limited awareness of communities and absence of proper land-use policies have aggravated soil fertility degradation. This has also encouraged the expansion of farming to marginal, non-cultivable lands, including steep landscapes and range lands. Soil nutrient balances can differ considerably between different crops, farming systems and agro-ecological zones. For example, +68 and -46 for nitrogen, +7 and +3 for P, -23 and -75 for K on Enset and on cereal respectively

### Prospects

- ✓ Limited use of nutrient inputs among smallholder farmers exacerbates soil nutrient deficiency.
- ✓ African fertilizer use was never high, averaging about 9 kg per hectare
- ✓ The estimated losses, due to erosion, leaching, and crop harvests are sometimes staggering, at over 60 – 100 kg of N, P, and K per hectare each year in Western and Eastern Africa
- ✓ SSA's depleted soils; production cannot be increased without bringing to the farm nutrients from outside either through livestock manure or mineral fertilizer

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### Abbreviation

AV	accommodation value
BNF	biological N <sub>2</sub> fixation
FV	fertilizer value
IPNM	Integrated plant nutrient management
NUE	Nitrogen use efficiency
OM	organic matter
PSM	phosphate-solubilizing microorganisms
RV	recovery value
SOC	soil organic carbon
SOM	soil organic matter

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