Cropping systems and soil fertility management in the humid and subhumid tropics with special reference to West Africa

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Introduction

Traditional cropping systems vary and have developed in response to prevailing soil and climatic conditions and socioeconomic and ethnological preferences. In the humid zone, traditional agriculture is dominated by tree components including plantain and bananas. These are the most stable production systems for the humid tropics.

Multiple cropping is a widely practiced arable cropping system. Although a large number of species may be encountered in intercropping systems, on the basis of the dominant crop(s), seven major crop-based systems can be distinguished in West Africa. These cropping systems strongly reflect the influence of climate and soils. The cassava-, plantain-, and rice-based systems are prevalent in the humid region with acid and low-base-status soils, whereas the maize-, yam-, sorghum- and millet-based systems are more common in the high-base-status soil.

Large areas of humid and subhumid tropical Africa are dominated by low-activity clay (LAC) soils consisting mainly of Alfisols and Ultisols. These soils have major constraints for intensive and continuous arable crop production. Traditional farmers rely on the fallow period for restoring the soil fertility which is exhausted during the short cropping cycle. Although information on fertilization practices for multiple cropping is scarce, there are some general concepts that can assist in more efficient fertilizer use. Reduced tillage systems combined with use of crop residue and in situ mulches from planted fallow play an important role in maintaining the level of soil organic matter and soil fertility. With judicious fertilizer use and liming, sustained crop yields can be attained on Alfisols and Ultisols. Integration of food and tree crop production as in alley cropping can be used as a low-input (nitrogen) soil fertility maintenance system for continuous food crop production in the tropics.

A. U. Mokwunye et al. (eds.), *Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa*

'Cropping system' refers to the kinds or combinations of sequences of arrangements in time and space in addition to practices and technologies used in production of crop(s) in a specified area [41]. Consequently, cropping systems differ depending on climatic and soil conditions and on socioeconomic, technological, and managerial factors of the agricultural production process. The farmer thus manages his crop(s) in such a way as to obtain maximization of outputs with the most efficient utilization of inputs.

The traditional cropping system, which has been the mainstay of agricultural production in tropical Africa, is undergoing rapid changes in response to increasing population and land use pressures and changes in socioeconomic conditions. The system, which relies on restoration of soil fertility by means of a long fallow period, is not well suited to these rapid changes. Shortening the fallow period because of land scarcity and prolonging the cropping cycle with no inputs have thus resulted in a rapid decline in soil fertility and crop yields as already observed in many areas in tropical Africa dominated by highly weathered and LAC soils.

Despite the considerable efforts made by various research institutions during the last two decades to describe, improve, and develop alternative methods to the traditional production systems, progress attained is still limited. Similarly, only some progress has been made in developing soil fertility management practices for sustained and viable crop production on the LAC upland soils [24]. Some of these developments will be discussed in this paper.

Crop production systems

Tree-based cropping systems

Traditional cropping systems are varied and flexible and are well adapted to the local environment, socioeconomic factors, and farmers' needs. In a recent survey on prevailing farming and cropping systems in the humid zone of southern Nigeria [16] it was observed that the traditional agriculture is predominantly upland and that it consists mainly of the following subsystems:

1. Bush fallow 'slash-and-burn' food crop production and land rotation system.
2. Permanent tree crop farming.
3. Taungya system.
4. Multistory cropping in compund farming.

The above systems are dominated by a tree component. Tree crops including plantain and bananas account for 67% of the land under cultivation, while arable crops account for only 25%.

The Taungya system is practiced in areas where the forestry department is establishing tree plantations. Food crop production is practiced only during the period between land clearing and the tree establishment phase [30]. The Taungya system is not attractive to farmers, and it persists only where there is population pressure.

Multistory cropping in compound farming is an intensive management system. Both trees and arable crops are found, usually in mixtures. Plantains and bananas are of special significance in this system. The high organic matter produced by the bananas and plantains serves as mulching materials and combines with the house refuse usually dumped on the soils to maintain the soil fertility and increase the productive life of the land.

Although trees and shrubs play an important role in nutrient recycling during the fallow period in the humid zone, their roles decrease in the subhumid and semiarid regions.

In the traditional agriculture, multiple cropping is the widely practiced system for arable cropping. Multiple cropping is defined as the growing of two or more crops on the same field in a year [6]. This may include intercropping (growing of two or more crops simultaneously on the same field per year) and sequential cropping (growing of two or more crops in sequence on the same field per year). Despite its popularity, it is only during the last two decades that serious research efforts have been made to better evaluate the merits of multiple cropping. Many of the studies have shown numerous advantages of intercropping systems including higher combined yields, higher yield stability from season to season, better spread of production over the growth period, improved quality of products reduced adverse effects of pests, higher returns, and better soil protection against erosion [5,9,39,41,49]. There are also several disadvantages related to intercropping, especially those difficulties related to the use of mechanized equipment, the use of fertilizer and pesticides, more serious drought stress, and the complexity of interactions.

Major food crop-based systems

Specific intercropping systems have developed over centuries in the different regions in response to the prevailing soil and climatic conditions and socioeconomic and ethnological preferences. Though a large number of species may be encountered in intercropping, there are usually two or three major crops that are dominant components [3,39]. Seven major systems based on the dominant crop can be distinguished in West Africa [47].

Cassava-based cropping systems
– These are mainly found in the poor sandy soils of the coastal belt, where other food crops perform less satisfactorily except for coconuts or oil palm. Cassava is mainly associated with maize.

Plantain-based cropping system
– This system is predominant in the forest areas from the Ivory Coast to Cameroon. Major food crops are plantains, cocoyams, maize, and cassava. Plantains and cocoyams are planted after the land is cleared at the beginning of the season. Maize is planted after the onset of regular rains. Cassava closes the rotation and is planted only in the second and third year and grows into the fallow period. Other important secondary crops are yams and groundnuts.

Rice-based cropping systems
– Rice-based cropping systems are common in the forest areas from Western Ivory Coast to Sierra Leone. Here the field is opened for rice, planted at the first rain, and intercropped later with maize and cassava as well as vegetables and spices. Cassava is not harvested until the second and third year. Rice is planted either as pluvial (upland) rice or as hydromorphic rice in valley bottoms (bas-fonds).

Yam-based cropping systems
– In the forest and derived savanna transition zone and in the southern Guinea savanna, cropping systems are traditionally based on yams. Yams are normally planted in the first year after bush clearing. Usually early and late yams are planted in the same field, either intercropped or in separate plots. Yams are often intercropped with cowpea or maize, cassava, vegetables, plantains, and often groundnuts. In the second year maize and/or pluvial rice will be intercropped with different minor crops and the first-year cassava crop.

Maize-based cropping system
– A maize-based system is dominant in the forest and derived savanna transitional zone and in the southern Guinea savanna. It is usually intercropped with cassava, yam, and cowpea. The maize-cassava intercrop is a very productive combination and is widely practiced in the zone. Maize is also well adapted to the tropical highlands where it has the highest production potential. In the highlands of Cameroon it is associated with cocoyams, yams, beans, and groundnuts.

Sorghum-based cropping systems
– These cropping systems are typical of the northern Guinea and the Sudan savannas. Major crops in the systems are millet, maize (only in the Guinea savanna), groundnut and cowpea. Another secondary crop is bambara nut that is mainly planted on soils too poor for groundnuts.

In this region cropping patterns are also changing with the position in the toposequence. Millet is often planted as a sole crop on the shallow soils on the top of the hills, sorghum and millet are intercropped on the slopes, while sorghum may be monocropped on the deeper, more fertile soils in the valley bottoms.

Millet-based cropping system
– With decreasing rainfall (less than 600 mm/year) millet becomes the predominant food crop in the northern Sudan savanna zone. The choice of crops is rather limited because of uncertain rainfall distribution and the short growing season. Millet/groundnut and millet/cowpea are most important combinations.

The above crop-based systems greatly reflect the influence of climate and soils. The cassava-, plantain-, and rice-based systems are predominant in the humid region dominated by acid and low-base-status soils, whereas the maize-, yam-, sorghum-, and millet-based systems are dominant in the high-base-status soils.

Fertility management for crop production

Major soil constraints for crop production

Large areas of humid and subhumid tropical Africa are dominated by low-activity clay soils consisting mainly of Alfisols, Ultisols, and Oxisols [7]. These soils have a humber of major physical and chemical constraints for arable crop production [23,33,36]. The humid region, dominated by the low-base-status and acid Ultisols and Oxisols, is more suitable for tree crop production than for food crop production. Tree- and shrub-based production systems are proving to be most stable in this region, as shown by the existence of highly successful tree crop plantations of rubber and oil palm. Traditional farmers have also successfully used trees and shrubs to maintain soil fertility during the fallow period.

The major soils also have specific problems for use in food crop production. The Alfisols and associated soils are extremely susceptible to soil erosion and compaction; they also have low water retention capacities, and thus are subject to drought [26,32,33]. Deficiencies of nitrogen and phosphorus are common, while localized deficiencies of patassium, magnesium, iron. zinc, and sulfur occur under intensive cultivation [12,23]. The Ultisols and Oxisols have acidity and aluminum toxicity problems. Although phosphorus deficiency is widespread, the soils have only a moderate degree of phosphorus fixation [21]. Low nutrient reserves, nutrient imbalance, and multiple nutrient deficiencies of nitrogen, phosphorus, potassium, calcium, magnesium, and zinc are common problems [22,24]. Soil fertility management systems for intensive and continuous crop production on these soils have therefore to take into account these soil constraints. Failure to do so will lead in most cases to a rapid loss in soil fertility and result in soil degradation and decreasing yields.

Soil fertility maintenance in the traditional system

In the humid and subhumid zones, traditional farmers rely on the fallow period for restoring soil fertility, which is exhausted during the short cropping cycle. Deep-rooting trees and shrubs in the fallow play a very important role in pumping up plant nutrients from lower soil horizons and retaining most of them in the biomass. Though traditional burning of the biomass following land clearing is seldom complete, it assists in the release of the nutrients for the crop. The effect of burning on soil fertility is influenced by the type and age of fallow vegetation and soil properties. Results of observations in southern Nigeria showed that the effect of burning following a long fallow period is more pronounced on the acid and low-base-status Ultisols than on the high-base-status Alfisols [26]. The effect of burning on soil fertility, particularly on the acid Ultisols is only of short duration, i.e., for 1 to 2 seasons [42,48].

Although in the savanna zone, the grass fallow also plays an important role in improving soil fertility [46], it is less effective in nutrient recycling than are the deep-rooted trees and shrubs grown in the humid zone. Jaiyebo and Moore [20] showed that mixed bush in nutrient recycling was more effective than grass fallow (star grass) or annual leguminous cover crop (kudzu). Despite the effectiveness of the traditional fallow system in soil fertility regeneration, it has the disadvantage of requiring a long fallow period for soil fertility restoration. In some areas of humid West Africa a minimum fallow period of 5 or more years is required before crops can be successfully cultivated again [38]. The large requirement of land area for sustaining the system makes it unprofitable. Rapid population growth as observed in many parts of tropical Africa has also placed considerable pressure on the system, forcing a drastic shortening in the fallow period. The shortened fallow cycles usually do not allow sufficient soil fertility regeneration for sustained agricultural productivity and result in rapid soil degradation and reduction in crop yields [17]. This necessitates the development of alternative soil fertility management techniques that can increase and sustain crop production.

Fertilizer use and soil fertility management in multiple cropping systems

Besides its many advantages for increasing production, another reason for multiple cropping is to utilize more efficiently native and applied nutrients [40]. Although multiple cropping is widely practiced in the humid and subhumid tropics, information on fertilization practices for this system is scarce and is concerned mainly with nitrogen fertilization and, to a limited extent, with phosphate fertilization. However, certain basic information from sole cropping can also be applied to multiple cropping situations. Based on the soil and particularly on characteristics of the crops to be grown in combination, some basic concepts can be formulated to assist in determining the most efficient fertilizer use for a particular multiple cropping pattern [40,43,45].

An intercropping system may not require additional fertilizer if only one component needs fertilizer and there is little competition between the component crops for the nutrients concerned [43]. For example, in a sorghum-pigeon pea intercropping, nitrogen needs to be applied only to the sorghum crop, which shows good response to nitrogen. Similar principles also apply to phosphorus. For sequential cropping and intercropping of cereal and pigeon pea, phosphorus needs to be applied only to the more responsive cereal crop.

Where both component crops in a multiple cropping system require the same amount of nutrients, an increase in fertilizer requirements can be expected. For cereal-legume intercrop the phosphorus and sulfur requirements may be greater than under sole cropping. Similarly, in a cereal-cereal intercrop, the nitrogen requirement may be greater.

Inclusion of legumes in multiple cropping systems or in crop rotation offers considerable benefits because of their ability to fix nitrogen biologically. There are two main types of mechanism postulated for the beneficial effects of legumes in multiple cropping systems [43]: (1) through immediate transfer, in which nitrogen travels from the legume directly to the associated crop, and (2) through residual effects in which nitrogen fixed by the legume is available to an associated sequentially cropped non-legume after senescence of the legume and decomposition of its organic residue. Although several research workers [15,44] reported some direct transfer of nitrogen in a maize-cowpea intercrop, most studies indicate a residual effect from the leguminous crop [2,27,43].

Soil fertility management with continuous cropping

Significant changes in soil properties occur on the upland soils following land clearing and cropping. Investigations on Alfisols and Ultisols showed a sharp decline in the soil organic matter level during the first few years following land clearing and cropping [1,10,14]. Continuous cropping on the Alfisols also results in a sharp decline in soil pH. The pH decline is more pronounced when moderate to heavy rates of acidifying fertilizers are used [8,26]. The decline in soil organic matter level combined with soil acidification with cropping will reduce the soil effective cation exchange capacity and increase losses of exchangeable calcium and magnesium [26]. It thus appears that after several years of continuous cropping liming may be needed, even on the high-base-status Alfisols.

Soil organic matter plays an important role in managing the fertility of these fragile soils. Reduced tillage systems, combined with use of crop residue mulches and in situ mulches from cover crops (such as *Mucuna utilis*) or from live mulches, play a very important role in maintaining the soil organic matter level and soil productivity [4,33,34]. The presence of mulch cover besides a high nutrient status and high biological activity, also maintains favorable soil physical conditions [31]. On the generally highly erosive Alfisols, the no-tillage production systems with crop residue mulching on newly cleared forest land have shown distinct advantages [13,31]. Higher maize yields can be maintained for 24 consecutive crops with no-tillage than with plowing on an Alfisol [19].

With good soil management combined with judicious fertilizer use and improved varieties, high crop yields can be maintained on the Alfisols and associated soils. In a field trial conducted at the International Institute of Tropical Agriculture (IITA) site in Ibadan on a kaolinitic Alfisol derived from banded gneiss, with moderate annual fertilizer application (60-120 kg N, 60 kg P, and 80 kg K/ha), the main-season maize yields for 12 years of cropping were sustained at over 4.5 tonnes/ha. Yields of minor-season cowpea relay cropped on residual fertilizers (applied to preceding maize crops) was maintained at about 1.0 tonne/ha. Important components for successful continuous cropping included crop rotation, provision of the nutritional needs of the crop in relation to changes in soil properties, and retention of crop residue.

Various institutions working in the humid tropics in recent years have also developed soil management technologies that will permit continuous crop production soil management technologies that will permit continuous crop production on low-base-status and acid Ultisols [18,35,37]. High combined yields of maize, upland rice, rice-beans, and cassava were maintained on fragile Ultisols in south Sumatra, Indonesia for a 5-year period, with initial application per hectare of 80 kg N, 80-120 kg P, 50 kg K, 50 kg Mg, and 1,000 kg lime and annual applications per hectare of 125 kg N and 100 kg P [35]. On high-activity clay Ultisols in the upper Amazon of Peru, sustained and moderately high yields of upland rice, groundnuts, and soybeans (in rotation) of over 2.0 tonnes/ha were obtained for each of the crops with adequate fertilization and liming [37].

Recent investigations for managing the coarse-textured kaolinitic Ultisol (Typic Paleudult) for sustained crop production in the humid zone of southeastern Nigeria showed that sustained yields of maize and cowpea can be obtained over a period of 7 years on small farms with application of low rates of lime (200-400 kg/ha annually) in combination with an application of 120-50-30-5 kg/ha as N-P-K-Mg (plus S and Zn) applied to the first-season maize crop [19]. The cowpea crop planted in the second season received no fertilizer. At the low rate recommended, the lime can be regarded as a fertilizer rather than a major soil amendment.

With intensive and continuous cropping, crop yields can be sustained by the judicious use of fertilizers and small quantities of liming material on these soils. However, high prices for fertilizers and lime and their limited availability will curtail their use by farmers. In addition, as mentioned earlier soil acidification may also become a problem with continuous cropping and repeated use of acidifying fertilizers. There is therefore a need to develop an integrated approach to soil fertility management on these soils in order to better utilize native nutrient sources and biologically fixed nitrogen sources and thus reduce dependency on purchased inputs.

Low-input fertility management involving trees and shrubs

Integration of food crops with tree crops in agroforestry systems has received considerable attention in recent years as an alternative low-input soil fertility management possibility for the humid and subhumid tropics [11,28]. Integration of limited food production at the initial stage of forest regeneration, known as the Taungya system, has been successfully practiced with no inputs required [30].

The traditional cropping and bush fallow land rotation system relies on trees and shrubs for nutrient recycling and soil fertility regeneration. In an effort to improve this system and make it more productive, IITA has developed the alley cropping system [25], in which food crops are grown in the alleys formed by hedgerows of planted shrubs and trees. The hedgerows are periodically pruned during the cropping season to prevent shading and to provide mulch and green manure for the companion crop. Inclusion of leguminous trees and shrubs such as *Leucaena leucocephala* and *Gliricidia* *sepium* in the hedgerows can contribute fixed nitrogen to the system. Results of 7 years of observations in southern Nigeria indicated that this system can contribute between 40-60 kg N/ha to the companion maize crop and be used successfully as a low-input (nitrogen) soil fertility maintenance system for food crop production on high-base-status Alfisols and related soils [28,29].

Since fertilizer use in improved farming systems will result in larger removal of nutrients in the crops, a correspondingly increased return of cations will be required to correct acidity and maintain high levels of production on these fragile soils. In many parts of the humid tropics where lime is not readily available, inclusion or integration of trees and shrubs in the crop production system as practiced in alley cropping can serve as an important solution to part of the acidity problem in LAC soils. The trees and shrubs with their deep rooting are able to gather cations leached from the surface and return them to the topsoil through leaf litter or prunings.

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