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Integrated Soil Fertility Management Practices for Coffee in Tanzania: A Review

Godsteven Maro*, Suzana Mbwambo, Deusdedit Kilambo, Leonard Kiwelu

Tanzania Coffee Research Institute, P.O. Box 3004, Postcode 25301, Moshi, TANZANIA
*Corresponding author: marogp2011@gmail.com

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Abstract Soil fertility decline in coffee growing areas of Tanzania has been noted as one important limitation to coffee production, thus calling for appropriate remedial measures. This paper reviews soil fertility and its management, with a focus on integrated soil fertility management for coffee in the country. As a general rule, ISFM takes proper germplasm material as one of its tiers. With coffee in Tanzania however, this tier is removed from the sequence following the release and promotion of the 19 improved Arabica coffee varieties and 4 of Robusta, which are considered perfect. A 7-tier sequence is suggested. The first three tiers (terrain management, choice of shade trees and intercropping patterns) are concerned with field establishment and are more or less permanent, while the other four (green manuring, application of manures/composts, strategic application of reduced doses of inorganic fertilizers and soil amelioration) are related to routine management, and can swap between seasons depending on the farmer's resource endowment. The whole idea is to always have accumulation of organic matter in the soil, which mineralizes slowly to release nutrients for plant use. Tanzania Coffee Research Institute (TaCRI) will continue research on ISFM and its promotion to its stakeholders through community-based organizations such as AMCOS. Formal and indigenous knowledge systems must become better integrated to allow farmer associations to recognize, adapt, and implement ISFM practices.

Keywords: *Coffee, ISFM, Plant nutrition, soil fertility, Tanzania*

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1. Introduction

Soil degradation and nutrient depletion pose a serious threat to rural wellbeing in Africa [1]. For instance, over the next 40 years the population of Sub-Saharan Africa is predicted to increase by 700 million inhabitants. This translates into a massive increase in the need for food, feed, fibre and fuel, in a region where many countries are already net food importers. As such, it is likely that there will continue to be pressure for expansion in the area cultivated, a pressure further complicated by increased rural urbanization and restrictions of wildlife habitats. With the population increasing against dwindling physical land resources, there is little option other than to devise systems that will increase agricultural production through sustainable intensification of production on land already under cultivation.

Soil fertility decline in coffee growing areas of Tanzania has been noted as one important limitation to coffee production [2,3]. This has been reported by many authors, including [4,5,6,7] among others. As remedial measures, use of industrial fertilizers has been promoted since the Green Revolution, but indiscriminate usage causes soil loss of microbes, increasing acidity and formation of less stable aggregates, exacerbating the problem [8]. The need for renewable, locally available and cheaper options for supplying nutrient to crops is increasingly becoming important because of the need for sustainable agriculture and the escalating price of the fertilizers. Maintenance of soil fertility at the economically optimum levels with appropriate combinations of nutrient sources is essential for sustainable crop production [9]. In response to that, TaCRI is actively promoting integrated soil fertility management (ISFM) among its stakeholders.

Appropriate ISFM sequence varies with, and is supposed to be tailored to, crop types, farming systems, terrain structures and resource endowments. Many of the researches documented thereon are based on annual staple food crops such as maize [9,10,11], rice [12], sorghum [13], etc., much less so with coffee, and especially in Tanzania. This paper reviews soil fertility and its management, with a focus on integrated soil fertility management for coffee, whereby a 7-tier sequence is proposed.

1.1. Soil Fertility and Coffee Nutrition

1.1.1. Soil Fertility

Soil fertility is well described by [14,15] among others. It is the capacity of the soil to support healthy growth and sustainable crop production. It differs from place to place depending on the salient soil properties [16]. These are what we call indicators of soil fertility, categorized as physical (texture, structure, colour), chemical (pH, cation exchange capacity, organic matter content, availability and balance of various nutrients) and biological (presence and diversity of living organisms).

pH is very important because it determines the chemistry of the soil and availability of nutrients to plants [17]. Acidity causes deficiency of major cationic nutrients, P fixation, Fe & Al toxicity [18] and creates a friendly environment to fusarium bark disease in coffee. Alkalinity, which is not very popular in coffee areas, causes deficiency of micronutrients and is associated with salinity/sodicity effects. Acceptable pH for Arabica coffee is in the range 5.2 - 6.5; whereas for Robusta it is 4.5-7.0 [19]. Reference [7] suggested the most optimal pH of 5.8 (red vertical dashed line in Figure 1).

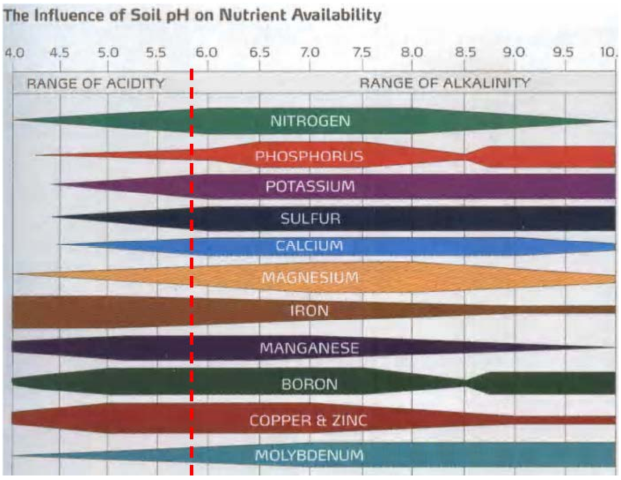

Figure 1. Influence of soil pH on the availability of different nutrients (after [7])

CEC is the ability of soil particles to adsorb, and then exchange, cationic nutrients with plant roots. It is measured by the number of negatively charged exchange sites present at the walls of each colloidal particle, usually clay and/or humus [20]. It is a very important soil property influencing structural stability, nutrient availability, and the soil's reaction to fertilizers and other ameliorants [21], with implication on soil management regimes such as frequency of irrigation, amount and frequency of liming and fertilization [22].

Organic carbon (OC) is a measure of organic matter content in the soil. Organic matter is one important pillar of ISFM. There are numerous benefits to having a relatively high stable organic matter level in an agricultural soil. According to [23], physical benefits include enhancement of aggregate stability, water infiltration, water holding capacity and soil aeration; and reduction of stickiness and surface crusting in clay soil. Chemical benefits include increase of CEC, improvement of the soil's buffering capacity and supply of nutrients upon decomposition. Biological benefits include food provision for soil-inhabiting organisms, enhancement of microbial diversity and activity which can suppress diseases and pests, and enhancement of pore space which helps to increase water infiltration, discouraging runoff.

1.1.2. Plant Nutrition

Plant nutrition is the availability, uptake and utilization of essential nutrients for plant growth [14]. There are 14 nutrients, in addition to C and O from the air, and H from water. Nutrients from soil are of three categories: Primary macronutrients: nitrogen (N), phosphorus (P), potassium (K); secondary macronutrients: calcium (Ca), magnesium (Mg), sulphur (S); and micronutrients: boron (B), chlorine (Cl), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo) and nickel (Ni). The functions of each element in coffee are well described by [24,25] among others.

1.2. Soil Fertility Deterioration in Tanzanian Coffee Areas

The smallholder coffee productivity per tree in Tanzania ranges between 250 and 300 g of parchment which is very low compared to the potential yield of over 1 kg per tree [26]. Of the constraints pointed out as the cause of this low productivity, soil fertility decline is one of the most limiting factors [27]. This has been verified by [4]. According to [28,29,30], the following are possible explanations for the trend: (a) The soil conditions in the coffee growing areas, related to the type and age of the parent material and factors of soil formation; (b) climate and terrain features which influence the nature and direction of nutrient flows (e.g. washing away of cationic nutrients by rain in upper slopes, which lowers soil pH); (c) the life span of a coffee tree which is perennial, therefore having to be in place for over 30 years and continuously mining specific nutrients from the soil (Table 1), and (d) improper soil fertility management by the coffee growers (inability/reluctance to invest in soil fertility replenishment, improper farming practices that encourage leaching and erosion).

Table 1. Quantities of major nutrients mined from the soil by coffee plant parts per ton green coffee per year [29]

Part of harvested cherry	N (kg)	P_2O_5 (kg)	K_2O (kg)
Green beans	31.0	5.2	25.8
Parchment	1.5	0.2	1.3
Pulp	10.4	2.5	18.7
Total	43.0	8.0	45.7

2. Soil Fertility Management

Soil fertility management includes all human efforts, through application of inputs and other related practices, with the aim to attain and sustain the adequacy in available nutrient in the soil and optimum uptake by plants. According to [31], it is highly complex given the myriad of interacting factors that dictate the extent to which farmers invest in the fertility of their soils [32]. It is slightly (but significantly) different from nutrient management. While the latter dwells more on the chemistry and the availability of nutrients, the former is conceptually deeper, including also the subsidiary conditions that support uptake of those nutrients and utilization by plants. For instance, the amount of water a soil can hold (which is determined mainly by soil texture) has direct impact on the amounts of nutrients taken up by plants regardless of the amount available in the soil because plants take up nutrients in solution. Thus, soil fertility management encompasses nutrient management/supplementation, soil amelioration, soil water management and erosion control, and compaction management [16]. When these components are used together to complement one another for the sake of economic profitability and environmental sustainability, the phenomenon is called integrated soil fertility management (ISFM).

3. Integrated Soil Fertility Management

Integrated soil fertility management is defined as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity [1,33]. ISFM is a response to the recognition that soil degradation and nutrient depletion pose a serious threat to rural wellbeing. Smallholder farming practice in Sub-Saharan Africa is too often abusive, mining the soil of its nutrients and leading to degraded, non-productive farms [34]. Such mining can take the form of removal of crops and crop residues, the latter used as animal feed. To reverse the trend, we need a system that will ensure sustainable soil replenishment of the mined nutrients. Combining fertilizer addition with locally available organic inputs while retaining or enriching crop residues improves nutrient use efficiency and protects soil quality. ISFM is particularly appropriate when employed in conjunction with less-than-optimal rates of fertilizer addition through its improvement of AE and supplementation by organic resources [35]. ISFM is not characterized by unique field practices, but is rather a fresh approach to combining available technologies in a manner that preserves soil quality while promoting its productivity. ISFM practice assists in overcoming a wide range of crop constraints, including those not directly related to nutrient supply. For example, the use of crop residues as surface mulch not only releases mineralized nutrients over time but also reduces soil moisture loss and resists erosion. That is where ISFM matches another paradigm SALM (Sustainable Agricultural Land Management) [36], more inclined towards soil conservation and climate change response.

ISFM for coffee appears to be a compromise paradigm between strictly organic and conventional farming systems. Discussing strictly organic farming, Reference [37] noted that smallholder farms with no access to external inputs often produce less than 300 kg ha^{-1} year^{-1} green coffee beans, while intensively managed plantations of arabica coffee at conventional spacing may yield 2 mt ha^{-1} year^{-1} averaged over several years and Robusta coffee plantations up to 3.5 mt ha^{-1}. Nitrogen is regarded as one of the key factors limiting productivity. Organic farming systems have the potential to supply large amounts of N but there is poor synchronization of N availability versus crop demand. Composting of manures and plant residues causes a significant reduction in available N, due to volatilization and transformation into stable organic forms [38]. There is also no evidence that the fundamental nutrient cycling processes in organically managed soils differ significantly from those in conventionally managed soils [39]. Generally, in agronomic terms, organic farming has no significant advantage over conventional farming; it reduces yields and the premium prices offered cannot offset the (opportunity) cost of organic certification and practices. This was also noted by [40] who saw organic certification as a poverty trap. As regards the TaCRI improved varieties, they are bred to be high yielding, therefore needing larger amounts of nutrients than can be provided by any organic fertilizer, applied alone.

On the other hand, total dependence on inorganic fertilizers and indiscriminate application thereof may be detrimental to crops, soils and the environment. One typical example is eutrophication of downstream water bodies due to indiscriminate fertilizer application upstream [17]. With smallholders however, such heavy applications are uncommon with the escalating global fertilizer prices. Reacting to the common claim by Kagera elite farmers that inorganic fertilizers damage the soil, [41] noted that it is possible if the “four Rs” of nutrient stewardship suggested by [24] and [42] are not adhered to. This is: applying the Right fertilizer type to the Right soil, in the Right dosages and at the Right time. They suggested to start with the soil by exploration of its fertility through soil and plant analysis, and make informed decisions thereon. If, for example, an uninformed farmer decides to apply an acidifying fertilizer like SA in already acidic soils, the fertilizer will render the soil too strongly acidic to grow crops for a considerable time period.

4. ISFM Implementation in Coffee

Coffee ISFM is a process of system change, whereby a field should pass preliminary stages before actual investment starts. The aim is to enable the soil to regenerate its own fertility by stocking high amounts of organic matter that mineralizes gradually to release nutrients. According to [43], the first entry point of ISFM is focusing on the agronomy of crops and inorganic fertilizers. Interventions on germplasm involve the selection of varieties, spacing and planting date. Interventions on fertilizer use target the formulation, placement, rate and timing of inorganic nutrient inputs. The second entry point targets interventions on organic resource management, including the return of crop residues, manure, compost and other types of organic wastes, rotation or intercropping with legumes and use of plant growth promoting micro-organisms. The third and last entry point deals with any other amendments that may be needed to lift limitations to productivity such as soil acidity, micronutrient deficiency, erosion, soil compaction or pests and diseases. While the recommended sequence in this paper is based on the above, some rearrangement was necessary with coffee, first as a perennial cash crop (as opposed to annual and semi-perennial food crops focused by many ISFM researchers) and secondly, as a crop whose suitable varieties are known.

TaCRI has released 19 improved varieties of Arabica and 4 of Robusta, that are renowned for their resistance to the stubborn diseases (CBD and CLR for Arabica and CWD for Robusta), in addition to other lucrative attributes of high yields, large bean sizes and internationally accepted cup quality [44-45]. As such, germplasm has been detached from the proposed sequence, while inorganic fertilizers are brought further down as a more mature tier. The result is a seven-tier sequence as shown in Appendix 1. The first three tiers are more to do with field establishment, and are rather permanent and mandatory – they cannot be pursued correctly in already existing coffee farm without risking damage. The rest (tier 4-7) are more flexible in time and space, meaning that you can switch from one tier to another across seasons, depending on available resources. A brief elaboration for each of them is given below.

4.1. Adapted Soil Conservation Measures for the Terrain Structure

Tier-1 is about soil conservation; broadly described by [46,47] among others. More specifically in the context of Tanzanian coffee, we are talking about erosion control, particularly water erosion. This is because coffee, especially Arabica species, is known to thrive in highlands where sloppy terrains are not uncommon. Cultural measures include contour farming, minimum/zero tillage, ridging, mulching and use of manures, while biological measures include crop rotation, intercropping, strip cropping, grass strips and trash lines. Physical measures are terraces, cut-off drains and artificial waterways. Most of these are also outlined in the climate smart GAPs toolkit [48].

It is recommended that, during the establishment of a new coffee farm, a thorough study be made on its terrain structure and appropriate soil conservation measures planned (Figure 2). Reference [49] does not encourage coffee establishment in too steep terrain (>20% slope) and, where it is absolutely necessary due to land scarcity, permanent terraces should be constructed. At a slope between 10% and 20%, temporary terraces and/or grass strips are recommended, whereas mulching can be practiced at <10% slope. Similar suggestions were given by [50] for large scale coffee farms in Kiambu District, Kenya.

Figure 2. Soil conservation measures: Contour cultivation (left), bench terracing (right)

4.2. Choice of the Right Shade Trees

Tier-2 involves proper selection and planting of shade trees. Most smallholder coffee farmers in Tanzania practise shaded culture, while a good number of coffee estates prefer unshaded culture. This trend is however changing gradually as some estates are going for certification schemes that require shade trees (such as Rainforest Alliance – [51,52,53]. Whereas [19] admits higher and faster yields in unshaded culture, there are many advantages of shaded culture as noted in many literatures like [54]. Shade reduces sunlight and moderates extremes of temperature; thus attenuating the phenomenon of biennial bearing [55,56]. It also reduces the rate of evaporation from the soil and transpiration; and protects the soil from raindrop impact and wind [19]. Shade also depresses noxious weed growth, especially of grass type like Couch grass [57].

The most significant advantage, as regards ISFM, is that shade provides some nutrients through leaf fall and decomposition. According to [58], shade trees are known to sustain higher soil fertility than conventional monoculture systems. Deep rooted shade trees can access deep soil layers and recycle water and nutrients otherwise inaccessible to coffee plants. Litter input from shade trees contributes to soil nutrient and organic matter. Shade tree droppings like those of Albizzia are easily decomposable, having relatively low C:N ratio. Most legumes have nodulated roots and live in symbiosis with micro-organisms such as bacteria (rhizobium) and arbuscular mycorrhizal fungi which fix atmospheric nitrogen and make it available to plants [59,60,61].

A good shade tree should be as long-lived as the coffee. Its wood must not be brittle, and leaves should be feathery to allow partial insolation. It should respond to training into a clear straight trunk for 8-10m, and have a fairly rapid growth with deep roots. It should keep leaves during the hottest time of the year. It should not affect coffee trees nearby or act as alternate host to coffee pests or diseases [19]. The ideal permanent shade tree for coffee is *Albizzia maranguensis* [49] whose ideal spacing is 20m x 20m. Other less favoured trees are *Albizzia chinensis*, *Acrocarpus fraxinifolius*, *Cordia holstii* and *Maesopsis eminii*. Temporary shade can be afforded by *Leucaena glauca*, *Sesbania sesbani* or *Cassia didymobotria*. Smallholder coffee culture is sometimes associated with fruit trees such as *Mangifera indica*, *Persea americana*, etc. A common exotic species *Grevillea robusta*, mistakenly used as shade trees, is more suited for windbreaks. The shade culture augurs well with single stem system, in which case damage can be minimized in case of tree or branch fall. It needs careful regulation by training for an appropriate clearance and pruning to discourage overshading. When shade trees are removed, thinned, pruned or broken by the wind, some damage to coffee underneath is inevitable.

4.3. Appropriate Intercropping System for Organic Matter Enrichment

Tier-3 involves deciding which crops to intercrop with coffee, whose residues will add organic matter to the soil (Figure 3). Coffee banana cropping system is common in smallholder's farms in Kilimanjaro Region and other regions such as Mbeya, Kagera and Arusha. The role of both crops (banana and coffee) as source of cash for smallholders is very well known. Research done by [62] suggested 3 rows of coffee between 2 rows of bananas as the best pattern in terms of yield and benefit-cost ratio. Some guidelines thereon have been outlined by [42]. As it regards ISFM, you will only harvest the banana bunch, while the residue, which consists of leaves, sheaths and pseudo-stems, are chopped and spread in the farm to rot, thereby adding organic matter to the soil. This may not be too practical in places like Arusha and Kilimanjaro where sheaths and leaves are useful as fodder for zero-grazed livestock.

Another type of intercropping is with annual leguminous crops like beans [63]. It is pactised by both estates and smallholder farms. Beans are intensively sown between coffee rows (especially in the first two years when the coffee is still young) so as to cover the surface and discourage weeds. Rather than competing with coffee for N, they fix the atmospheric N and make it available to coffee. During harvesting, ISFM suggest to harvest only the pods, and leave everything else there in situ to rot and add organic matter to the soil. This is however not very suitable in termite-endemic areas.

Figure 3. Intercropping coffee with bananas (left) and beans (right)

4.4. Green Manuring

Tier-4 includes green manuring, which is the process of raising a cover crop (intercropped with coffee or raised ex-situ) for purposes of ploughing under at tender age (Figure 4). It has become one of the most important strategies in ISFM. Reference [64], in their on-farm assessment of six leguminous plant species incorporated into maize plots found that velvet bean (*Mucuna pruriens*) and jackbean (*Canavalia ensiformis*) gave highest grain yields of 3.5 and 3.4 tons per ha respectively. In another study by [35], green manures (the two species above with two others Lupine (*Lupinus albus*) and Sunhemp (*Crotalaria ochroleuca*) showed about ten times higher nutrient release potential as compared to cattle manure.

Figure 4. Green manure plants raised in situ (left) and ex situ (right)

Alternatively, you can opt to make liquid fertilizers from them (Figure 5). Liquid organic fertilizers are the so-called "teas", distinguished as compost teas [65, 66], fresh plant teas (also known as weed teas – [67]) and manure teas. With regard to weed teas, common plants used are nettle [68] and comfrey [69]. To make weed fertilizer tea, weeds are picked just before flowering, from an area not previously treated with any chemical, chopped as necessary, placed in a 25-litre bucket and covered in rain water. In anywhere from 3 days to 3 weeks the water is separated from the weeds and used to fertilize plants. If used after 3 days, no need for dilution; but if used from 1-3 weeks, you need to dilute it, one part tea and nine parts water. Rather than just weeds, green manure plants, being legumes, are preferred since they are nutrient-rich.

Figure 5. The making of fertilizer "tea" from green manure plants

4.5. Application of Manures/Composts

Tier-5 involves application of organic fertilizers (manures or composts), which has been a traditional soil fertility intervention pathway for ages, especially with smallholder farmers, who practise integrated agriculture with livestock keeping. Farmyard manure differs in nutrient content, depending on the kind of animals producing it and the feeds they consumed [16]; but the content is in all cases much lower than in mineral fertilizers (Table 2). Again, the way the manure is handled before application has a bearing on the amount of nutrients, especially N, which is actually applied to the field. Proper handling of FYM from the kraal increases its nutrient value significantly [70]. Most farmers lump it in open air where many nutrients get lost by volatilization. Even the manure from open kraals is of very low quality.

Table 2. Average nutrient content comparison of manure from different species of livestock (modified from [71])

Type of animal	N	P	K	Ca	Mg
	Percentage in air-dried samples				
Cow	0.5	0.2	0.5	1.1	0.2
Goat	0.4	0.2	0.7	0.9	0.1
Sheep	1.3	0.4	1.0	2.5	0.8
Chicken	1.3	0.8	0.3	1.7	0.3
Pig	0.4	0.3	0.3	0.5	0.2

To increase the quality of FYM immediately removed from an indoor kraal: heap the manure in a shallow pit 15-20 cm deep. Cover with a layer of plant litter. Cover with a polythene sheet and leave. If you have few animals, and therefore need to clean the kraal several times before making a sizeable heap, keep the heap covered between pilings. At least twice a month, open the heap, mix the contents and cover again. Continue like this for 3-4 months (depending on weather), and the manure is ready for application.

Composting is recycling organic wastes and transforming them into a stable humus form for application to the soil. It can be done under controlled conditions in compost heaps and pits, where sequential layers of coarse branches, fresh materials like kitchen waste (here you can use manure or fresh coffee pulp – [72]), dry materials like straw, an additive like rock phosphate and soil are arranged, with a vertical pole in the middle, which will later be removed to create an air vent. Some water is added (20 l m-2). When the heap is considered large enough (say, 1-1.5m high for heap), it is covered with polyethylene material, leaving that vent open. Mixing and re-moistening are done once a month, and the material is considered ripe in 3-4 months depending on weather. Successful composting depends upon the sufficient availability of organic materials, water and “cheap” labour [73]. Where these inputs are guaranteed, composting can be an important method of sustainable and productive agriculture. It has ameliorative effects on soil fertility and physical, chemical and biological soil properties. Well-made compost contains all the nutrients needed by plants. It can be used to maintain and improve soil fertility as well as to regenerate degraded soil. As part of coffee ISFM, apply at least one tin (20 litre capacity) of either manure or compost per tree at the onset of season, as substitute to the first dose of NPK fertilizer.

4.6. Strategic Application of a Reduced Dose of Inorganic Fertilizer

Tier-6 involves the strategic application of mineral fertilizers. A thorough insight of mineral fertilizers is given by [24] [74,75], whereby they are grouped into two major types, namely straight fertilizer and compound fertilizers. The straight fertilizers are subdivided according to the nutrients they provide. Nitrogenous fertilizers common in coffee are calcium ammonium nitrate (CAN) 26%N, suitable for application in acid soils of high-sloping terrain that receive high rainfall; ammonium sulphate nitrate (ASN) 26%N and ammonium sulphate (SA) 21%N, both suitable for alkaline soils (which are not very common with coffee), and urea 46%N, preferred for normal soils, medium slope terrain and moderate rainfall [49]. In ISFM, straight N fertilizers are used at fruit setting, in half the normal dose for areas applying two rounds per season (those of bimodal rainfall pattern), and one third of the normal dose for areas applying three rounds (those of unimodal rainfall pattern).

Compound fertilizers contain more than one primary macronutrient namely nitrogen, phosphorus and potassium, mechanically mixed in specific percentage ratios [75]. Sometimes they can have some filler materials containing other nutrients like calcium, magnesium or micronutrients. The most used ratio is NPK 20:10:10 (or 20:10:20 for areas with significantly low K), though others exist like 17:17:17, 15:15:15, etc. Of late, as promoted by [7], compound fertilizers NPKS are available at ratios 15:9:19+3S, 22:6:12+3S and 20:10:15+2S for application in areas where sulphur is a limiting factor. Ideally, these are applied to coffee at the onset of season (half dose for bimodal rainfall areas and one third for unimodal rainfall areas). The logic is that the trees are fresh from the previous crop and are bracing up for the next, thus requiring a balanced cocktail with as many nutrients as possible. Under ISFM however, it has been proved that you can substitute this first dose with a tin of organic manure/compost per tree without a significant change in yield [35]. In areas where three rounds are applied, one third dose of compound fertilizers constitute the last round. Other forms of compound fertilizers are the foliar feeds such as Polyfeed, Polycoffee, Booster, etc. These are sprayed to the leaves of heavily bearing trees in dry season (in which case it is difficult for plants to extract nutrients from the soil) to offset an imminent problem of overbearing dieback, by supplying nutrients in a balanced form, which are utilized much faster.

4.7. Soil Amelioration by expert advice

Tier-7 involves amelioration of problem soils, and the most salient problem in coffee is acidity (low pH), usually corrected by liming [18]. Common liming materials are the oxides, hydroxides, carbonates, and silicates of Ca or CaMg mixtures; the commercial ones being calcitic and dolomitic lime respectively. Liming is a rather sensitive operation that calls for expert advice, particularly in establishing the Lime requirement (LR), which is the amount of liming material that must be applied to a soil to raise its pH from an initial acid condition to a level selected for near-optimum plant growth. Over seven different methods are available globally for the determination of LR, including titration, incubation and buffer methods. For the coffee soils of Tanzania, TaCRI has adopted the Barium chloride – Triethanolamine titration method [76].

Liming is usually aimed at attaining a known optimum pH level for an intended crop which, for coffee, is 5.2 (Conventional approach, aimed at raising pH – [25]) or 5.5 (Albrecht approach, aiming at raising both pH and Ca levels – [7]). On the other hand, overuse of lime is not uncommon and can be dangerous creating a lot of problems in the soil. The most common effects of overliming include a disruption of cationic nutrient balance (whereby uptake of some is inhibited) and a fixation of some vital micronutrients.

Lime, both calcitic and dolomitic, is typically an ameliorant with very little if any, value as a fertilizer; so it should be applied in addition to, and not in place of, routine fertilizers. On the other hand, some materials have both ameliorant and fertilizer properties, such as CAN (10% Ca) and Minjingu Rock Phosphate (33% Ca), and therefore they can be slotted into the routine fertilizer programme.

5. Status and Prospects of Coffee ISFM in Tanzania

Despite the proven significant benefits of ISFM for food security, household income and environmental protection, the adoption of practices by farmers is usually low and incomplete. Of the list given by [43] detailing the most important factors curtailing adoption, low awareness and common disbeliefs about the benefits of soil fertility management [77], cost and availability of labour [78], lack of information about soil fertility and rainfall forecasts [4], and scarcity of organic residues and competition for residues with livestock [79], are considered to be key issues.

As seen earlier, TaCRI has been actively promoting ISFM, as a compromise paradigm between the strictly organic and conventional coffee farming. Considerable research has been done on the nutrient supply potential of organic materials within the smallholder farming system, such as coffee pulp, husks, Albizzia droppings and some green manure plants [35]; and other plant species valuable as hedgerows or temporary shade [80]. Research is going on about how best to include these in the coffee ISFM programme, and their appropriate modality of application in the field. There is a need to further strengthen research and develop high-resolution information on soil fertility to customize practices and maximize the benefits of ISFM, as well as decision-support tools that consider resource endowments and production objectives of farm households. One such tool is the SAFERNAC model [81] which is currently at the stage of validation.

All the tiers being proposed here have been part of the TaCRI training packages for years now, and they are even included in the TaCRI GAPs Handbooks for Arabica and Robusta coffees [44,45]; only that they were hitherto not considered as a single package. Now that they are, they need to be promoted as a single ISFM package. Extension staff must be retrained for effective delivery of ISFM technologies at the farm level. Community-based organizations such as AMCOS should be mobilized to promote ISFM; and maybe facilitated to turn their farms into ISFM farmer field schools and have their coffee certified as 4C (the certification scheme best suited to ISFM). Some pilot efforts have been initiated under the EU-funded AgriConnect Programme in the Southern Highlands, to train coffee farmers on SALM, of which ISFM is part and parcel. Formal and indigenous knowledge systems must become better integrated to allow farmer associations to recognize, adapt, and implement ISFM practices.

6. Conclusion

This paper has reviewed soil fertility and its indicators, together with nutrients required by a coffee crop. Appreciating that soil fertility in the Tanzanian coffee growing areas is on a declining trend and may soon be unsustainable, we looked critically into the root causes that are four-fold: lithology, climate and terrain structure, the perennial life of a coffee tree and land mismanagement. Only the fourth reason touches the farmer directly and, if properly addressed, the rest are moderated and the declining trend is reversed. That's where ISFM comes in, as a way to manage soil fertility properly using organic and mineral nutrient sources, and optimization of conditions for their uptake and utilization by plants.

As a general rule, ISFM takes proper germplasm material as one of its tiers (together with organic fertilizers, mineral fertilizers and ameliorants). With coffee in Tanzania, this tier is removed from the sequence because of the 19 improved Arabica coffee varieties and 4 of Robusta, that TaCRI has released and expect all farmers to have adopted those improved varieties by 100% by 2025. A 7-tier sequence is advocated. The first three tiers are to do with field establishment (terrain management, choice of shade trees and intercropping patterns) and are more or less permanent, while the other four are related to routine management, and can swap between seasons depending on the farmer's resource endowment. The whole idea is to always have accumulation of organic matter in the soil, which mineralizes slowly to release nutrients for plant use. Each tier has been sufficiently covered.

The key components to supporting ISFM development and adoption involve actions by different actors. Tanzanian scientists must be encouraged to adopt ISFM philosophies, design innovative soil fertility management practices, and develop strategies for their dissemination. Extension staff must be retrained for effective delivery of ISFM technologies at the farm level. Community-based organizations such as AMCOS must be mobilized to promote ISFM; and maybe facilitated to turn their farms into ISFM farmer field schools and have their coffee certified as 4C (the certification scheme best suited to ISFM). Formal and indigenous knowledge systems must become better integrated to allow farmer associations to recognize, adapt, and implement ISFM practices. There is a need to strengthen research on and dissemination of practices at local level. At the same time there is great need for high-resolution information on soil fertility to customize practices and maximize the benefits of ISFM, as well as decision-support tools that consider resource endowments and production objectives of farm households.

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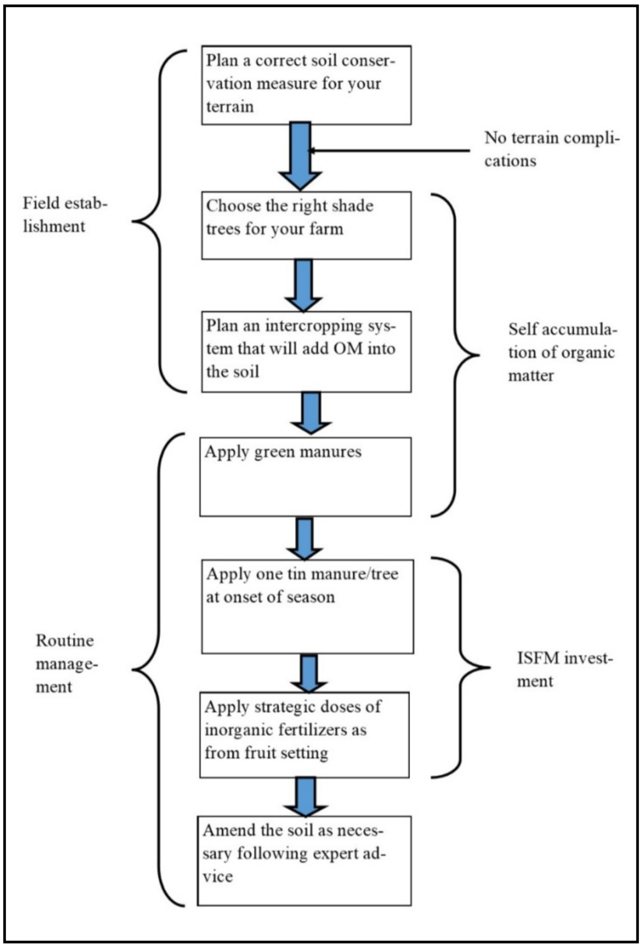
Conflict of interest

The authors declare that there are no conflicting interests in publishing this paper.

Abbreviations

AE: Agronomic efficiency (of fertilizer use)**; AMCOS:** Agricultural marketing cooperatives; **ASN**: Ammonium sulphate nitrate; **CAN**: Calcium ammonium nitrate fertilizer; **CBD:** Coffee berry disease; **CEC**: Cation exchange capacity of a soil; **CLR**: Coffee leaf rust; **CWD:** Coffee wilt disease; **FAO:** Food and Agriculture Organization of the United Nations; **FYM:** Farmyard manure; **GAPs**: Good agricultural practices; **ISFM**: Integrated soil fertility management; **LR**: Lime requirement; **NPK**: Compound fertilizer containing nitrogen, phosphorus, and potassium; **OC**: Organic carbon (a measure of organic matter); **SA**: Sulphate of ammonia; **SAFERNAC**: Soil analysis for fertility evaluation and recommendation on nutrient application to coffee (a crop model); **SALM:** Sustainable agricultural land management; **TaCRI**: Tanzania Coffee Research Institute; **TCB**: Tanzania Coffee Board; **4C:** Common code for coffee communities (a certification scheme).

Appendix 1: Diagrammatic representation of the proposed ISFM sequence



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