Integrated Plant Nutrient Management in Major Agricultural Soils of Sri Lanka: A Review of the Current Status and the Way Forward

W. S. Dandeniya and R. S. Dharmakeerthi

1 Introduction

Being exposed to the tropical hot and humid climate, majority of the soils in Sri Lanka is highly weathered. Soil erosion, high rates of organic matter decomposition, leaching of basic cations, and removal of nutrient at a high rate through biomass produced under moist environmental conditions are common natural processes in such climatic regions resulting in low inherent soil fertility. Thus, supplying inputs externally to replenish soil nutrient pools is crucial to maintain or enhance crop productivity on these soils. Low productivity in agricultural lands usually leads to less agricultural inputs by farmers, which in turn aggravated the soil fertility depletion. To minimize land degradation through nutrient impoverishment and increase the productivity, fertilizers are applied since 1940s, under numerous subsidy schemes, as many farmers are not in a financially sound position to afford the cost of fertilizers. The mineral fertilizers, such as rock phosphates and dolomite, and chemical fertilizers, such as urea, muriate of potash, and triple superphosphate, which are collectively referred to as synthetic fertilizers hereinafter, are the most popular external nutrient inputs used for cropping in Sri Lanka. Fertilizer recommendations in the country have evolved, integrating synthetic and organic fertilizers in nutrient management programs over the years (Nagarajah 1986; Palm and Sandell 1989). Yet, overapplication of fertilizers polluting the environment and underapplication causing nutrient mining are often observed in farmers' fields (Kendaragama 2006). Although self-sufficiency in some crop sectors has been achieved in Sri Lanka due to the introduction of improved varieties periodically, subsidized fertilizers, and related technological advances in the agriculture sector, sustenance of the achieved productivity levels is becoming increasingly challenging.

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It is estimated that more than 50% of the arable land in the country are subjected to soil fertility deterioration due to poor nutrient management (Nayakekorale 1998). Decrease in area for food crop production with changes in land use, population increase, and rapid urbanization creating sinks for agricultural produce are continuing, forcing the agriculture sector in Sri Lanka to increase productivity of land while being conscious on environmental quality. At present, the per capita arable land extent in Sri Lanka is only 0.16 ha, and it is one of the lowest in Asia (FAO 2017). To bring marginal lands back to successful crop production, it is vital to address soil fertility issues hindering crop productivity. In this chapter, the history of soil fertility management in Sri Lanka is examined along with currently adopted management practices, lessons learned, and the way forward for environmentally sustainable soil fertility and plant nutrition management.

2 Management of Soil Fertility and Plant Nutrients: Paradigm Shift

Low productivity of agricultural lands is a major contributing factor to inadequate food production and poor nutritive value of food resulting in undernourishment and malnutrition among the people in developing countries, whom accounts to nearly two-third of the world's population. Soil fertility decline is one of the key reasons for reducing the productivity of arable lands in many countries including Sri Lanka (Sanchez 1997; Nayakekorale 1998). Traditionally, soil fertility is viewed as the ability of a soil to support plant growth. This concept has a long history as proven by the writings dating back to 2500 B.C. of ancient Mesopotamians. Historical evidences indicate Chinese, Greek, Indian, and Egyptian civilizations, among others, practiced manure application to increase productivity of agricultural lands. Some of them used green manure crops, wood ash-like materials, and closely available mineral salts. However, the precise role of nutrients on productivity of land was not established until Justus Von Liebig (1803–1873), the father of modern fertilizer industry, has scientifically proven the value of mineral elements found in soils for plant growth.

With the dawn of fertilizer industry, nutrient availability in soil was identified as the major factor deciding plant growth, which may have led to overlook the other fertility parameters. It was expected that a fertile soil should be able to provide all essential mineral nutrients for plants in available forms, in quantities, and in a suitable balance. Hence, soil fertility management mainly focused on management of plant nutrient supply from the soils. Different types of fertilizers started being manufactured and applied in Europe since late 1800s, and manufacturing processes improved commencing from early 1900s. A number of fertilizers were available for the research work that initiated for "green revolution" by the 1930s. Thus, after World War II, in postwar period (1950s) with "green revolution," the application of external inputs, supplying nutrients mainly via synthetic fertilizers, emerged as the first soil fertility management paradigm in the modern history (Sanchez 1994). Synthetic fertilizers together with improved germplasm during "green revolution" increased the crop production in the world as never seen before. By the 1970s, synthetic fertilizer usage has become popular in many parts of the world. The significant impact of the fertilizers had on crop production made it the silver bullet people seek for soil fertility improvement for any crop for a few decades to come. However, failure of this concept in improving yields under resource poor settings such as in sub-Saharan Africa and increased notion toward sustainable agriculture and conscience on environmental health urged a paradigm shift in soil fertility management (Sanchez 1997; Bationo 2009).

With advancements in knowledge on soil nutrient dynamics and the interactive role of soil physical, chemical, and biological properties on plant performances, the scope of soil fertility has expanded resulting in a second paradigm shift in soil fertility management in the late 1980s (Sanchez 1997). Accordingly, an integrated soil fertility management (ISFM) approach that encourages the use of both synthetic and organic fertilizers/amendments was introduced to minimize the total reliance on synthetic fertilizers. In addition, social, cultural, and economic challenges like availability of inputs, cost, technical feasibilities, etc. in adopting soil fertility management under different settings were also considered in ISFM (Sanchez 1997; Bationo 2009). Although still an external input paradigm, the second paradigm is viewed as more appropriate due to numerous benefits the approach had on physical, chemical, and biological aspects of soil fertility and socioeconomic feasibility. In parallel to ISFM, site-specific soil fertility management addressing the spatial and temporal heterogeneity in soil fertility status also started to evolve.

At present, the soil fertility management research is at the verge of a third paradigm shift, in which enhancing the nutrient-supplying power of soil with renewable soil fertility replenishment strategies is being looked into (Sanchez 1997; Ajayi et al. 2007). These approaches include relying more on biological processes (adapting germplasm to adverse soil conditions, enhancing soil biological activity, optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use, crop rotations with legume crops, etc.) and improving soil organic carbon pool through C sequestration with deep-rooted crops, use of carbonaceous compost, biochar application, etc. to improve overall soil fertility. The paradigm shift in soil fertility management is illustrated in Fig. 1. Considering these developments, conceptualizing soil fertility as the capacity of a soil to receive, store, and transmit energy to sustain plant growth as indicated by Food and Agriculture Organization of the United Nations (FAO) is more meaningful.

2.1 A Historical Account on Plant Nutrient Management Approaches in Sri Lanka

The present land use pattern in Sri Lanka is a legacy of land policy of the colonial past where export-based commercial plantation agriculture was superimposed on a traditional subsistence farming system (Mapa 2003). Before being colonized by the British in late seventeenth century, Sri Lankan farmers used organic inputs, crop rotations, shifting cultivation, and crop diversification like practices and biodynamic farming techniques for maintaining or improving crop productivity. Such organic

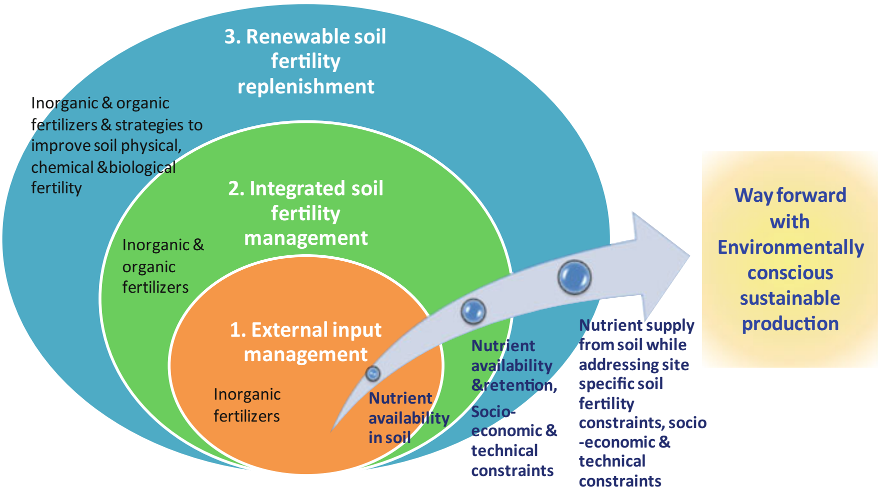

Fig. 1 Paradigm shift in the approaches of soil fertility and plant nutrient management highlighting the main factors considered and inputs used at different stages

and biodynamic means of farming were continued until the 1940s for all the crops except for large-scale tea and rubber plantations established under the British governance. With the postwar recession in economy in the 1950s, food shortage in the world limiting importations, and increase in population, there was a clear need to increase crop yields, thus making synthetic fertilizers a popular choice for soil fertility management. During the 1940s to 1960s, the traditional crop breeds/varieties that performed well under biodynamic means of farming at subsistence scale were replaced with nutrient-responsive high-yielding varieties cultivated at commercial scale in many parts of the country, demanding a change in the means of plant nutrients management. This change came as countrywide adoption of synthetic fertilizer application for nutrient management, and under this context, Sri Lanka reaped the benefits of green revolution on one hand (Nagarajah 1986; Palm and Sandell 1989). On the other hand, some farmers used integrated approach in nutrient management by combining biodynamic methods and organic farming techniques they have used for generations with synthetic fertilizer application.

Government institutions in Sri Lanka such as Department of Agriculture and Plantation Crop Research Institutes and universities are conducting research related to soil fertility and plant nutrition in parallel to other parts of the tropics since long. However, changes in fertilizer recommendations to reflect the paradigm shift in soil fertility and plant nutrient management happened at a very slow pace in Sri Lanka due to various socioeconomic challenges. The integrated soil fertility management (ISFM) approach appeared in nutrient management recommendations in late 1990s, nearly a decade later from its introduction in other parts of the world. The nutrient recommendations being practiced for many crops, including rice, tea, rubber, and coconut, are still based on yield targets defined by agroclimatic conditions or

Table 1 A historical account on soil fertility and plant nutrient management approaches in Sri Lanka

Soil fertility management approach	Introduction	Remarks
Natural means for replenish soil fertility	Precolonial era	Natural methods were used to replenish soil fertility Used organic inputs, crop rotations, shifting cultivation, and crop diversification like practices and biodynamic farming methods
External input paradigm	1940s	Bone meal, a natural fertilizer, first introduced as an external nutrient input for rice, tea, and rubber
	1950s	Synthetic fertilizers were introduced for rice farming and plantation crops as blanket recommendations Countrywide adoption of synthetic fertilizers for nutrient management in annual crops
	1970s	Blanket fertilizer recommendations changed into more specific recommendations; Rice: Based on soil types, climatic regions, agroclimatic regions and yield targets Plantation crops: Soil types/region Other crops: Blanket recommendations
Integrated soil fertility management (ISFM)	1990s	Site-specific fertilizer recommendations containing both synthetic and organic sources were introduced; Rice: Agroclimatic region/water management method/yield target and soil test based Plantation crops: Soil series level and field level using soil and foliar analysis (rubber) and later for coconut and tea
	2018	Other crops: Blanket recommendations with organic and synthetic fertilizers as sources of nutrients Site-specific nutrient requirements decided based on soil test kits are under investigation
Renewable soil fertility replenishment	2010	Related technologies are mostly at research level and still not appearing as recommendations

Sources of information: Amarasiri (1986), Nagarajah (1986), Yogaratnam and Silva (1987), TRI (2000), Bandara et al. (2003), CRI (2008), DOA (2013), Sirisena et al. (2015), Sirisena and Suriyagoda (2018)

irrigation management than site-specific soil fertility constraints. Table 1 summarizes the evolution of soil fertility and plant nutrient management approaches in Sri Lanka. Details of the recommendations for nutrient management are discussed later in this chapter.

3 Fertility Status of Soils of Sri Lanka

Agricultural landscapes are often very diverse in terms of cropping patterns, geo-physical environments, input usage, resource availabilities, etc. Plate 1 depicts a specific situation related to the hill country where cropping systems and their management vary within a very small area. Further, soil resource also shows high

Plate 1 Diversity of an agricultural landscape under intensive cultivation in hilly Nuwara Eliya District, Sri Lanka, showing high spatial heterogeneity. (Photo credit: Dr. R.S. Dharmakeerthi)

spatial heterogeneity. Thus, soil fertility constraints are spatially variable, and the ISFM programs should acknowledge and address this heterogeneity by identifying site-specific constraints in order to be successful. As in other parts of the tropics, Sri Lanka has problem soils such as acid sulfate and saline soils, which are not suitable for cropping under their natural state. Problem soils present a unique set of soil fertility constraints, hence requiring special management approaches. The focus of this chapter is limited to soil fertility constraints in agricultural lands that do not encompass problem soils.

Many tropical soils are impoverished in mineral nutrients (Tiessen et al. 1994), and agricultural soils of Sri Lanka are no exception. Analysis of soil from different parts of Sri Lanka under different crops revealed deficient status of macro-, secondary, and micronutrients (Indraratne and Thilakarathne 2009; Kumaragamage and Indraratne 2011). In a study conducted using soil samples from 52 locations of Sri Lanka, Indraratne and Thilakarathne (2009) reported that most of the tested soils are deficient in available N, P, K, Ca, Mg, Cu, Zn, S, Mn, and B for plant growth. Low availability of N is largely due to poor organic matter content, and high losses of N due to leaching, volatilization, and denitrification (Kumaragamage 2010). High fixation reduces the availability of P in soil (Withana and Kumaragamage 1995). Alfisols, the dominant agricultural soils in the dry and intermediate zones, may display deficiencies of sulfur and cationic micronutrients such as copper (Cu) and zinc (Zn) (Kumaragamage 2010), whereas Ultisols, the main agricultural soils in the wet zone, generally have low cation exchange capacity and base saturation, are acidic in nature, and often exhibit deficiency of potassium (K) and magnesium (Mg) (Kumaragamage et al. 1999) and Al toxicity. The use of high inputs in intensive cultivation of soils having high infiltration rates such as sandy regosols in Kalpitiya and red latosols in Jaffna Peninsula, and soils with shallow depth to groundwater, leads to pollution of water with nutrients that leach through soil, which has serious implications on human and environmental health (Kuruppuarachchi 2010; Young et al. 2010; Jayasingha et al. 2011). Studies conducted in coastal sand aquifers under intensively cultivated vegetable cropping systems have revealed that the buildup of nitrate is quite dramatic and indicated that intensive vegetable cultivation is a major source of nitrate to groundwater (Kuruppuarachchi 2010; Jayasingha et al. 2011). According to a study conducted over a 2-year period using 58 sampling locations, Jayasingha et al. (2011) reported that nitrate-N in well water in Kalpitiya ranged from 0.60 to 212.40 mg/L in the dry seasons and 0.20 to 148.50 mg/L in rainy seasons with 50% of the samples in each season exceeding WHO standards for nitrate-N in drinking water (10 mg/L).

In tropical soils, the cation exchange capacity (CEC) is very low due to many reasons, which includes, but not limited to, the dominance of iron and aluminum oxides and kaolinite minerals (Indraratne 2006), low soil organic matter (OM) contents, and low pH values. Because of the low CEC, applied nutrients are rapidly leached below the root zone of annual crops. To increase nutrient use efficiency in annual crop production, techniques must be developed to retain applied nutrients in the root zone of the crop. Restoring and maintaining soil OM content in the long term is essential to enhance soil physical, chemical, and biological fertility aspects and thereby improve nutrient-supplying power.

Intensive cultivation without adopting any soil fertility restoration mechanisms exploits soil resource resulting in decline in soil fertility and depletion of the nutrient-supplying power of soil (Kendaragama et al. 2001). Continuous cropping and removal of harvest deplete soil nutrient pool, and this is more of a concern for annual crops than perennials, since most annual crops produce high amount of biomass within a short period of time, thus removing large quantities of plant nutrients from the soil. For instance, the removal of P from soil with the harvest of some popular crops such as capsicum, cabbage, tomato, carrot, and potato cultivated in the wet zone of the country is recorded as 5, 18, 18, 24, and 27 kg/ha, respectively (Wijesundara 1990). Nearly 20 kg of P per season is estimated to be removed with the harvest of lowland rice at an average yield of 6 t/ha (Suriyagoda et al. 2014). The soils are not always replenished with nutrients via fertilizer application since the decision on nature and amount of fertilizer applied with the next cropping is affected by number of factors like availability of material, willingness of the farmer to pay, market value of the crop, risks taken, etc. (Wjewardana and Amarasiri 1990; Sirisena and Suriyagoda 2018). When applied at recommended dosages, the nutrient input to soil via fertilizers for vegetable crops is higher than the nutrient removal with the harvest of these crops since the recommendations allow a compensation for the nutrient unavailable for plant uptake due to fixation in soil and losses due to runoff and leaching. For example, P input with synthetic fertilizer recommendation for vegetable crops ranges from 50 to 70 kg/ha (Wijewardena 2005), whereas removal of P with the harvest is only 5 to 30 kg/ha (Sirisena and Suriyagoda 2018). In one hand, many commercial-scale vegetable producers in up-country wet zone are known to apply synthetic fertilizers, foliar fertilizers, and animal manures, at or above the recommended dosages, when they cultivate high-value crops, sometimes leading to building up of nutrients such as P (Kendaragama et al. 2001; Sirisena and Suriyagoda 2018) and heavy metals like Cd, Cu, Zn, Ni, and Pb in soils (Premarathna et al. 2005). Wijesundara (1990) reported 68% of the intensively vegetable-cultivated fields had soils with available P (Olsen P) contents greater than 100 mg/kg, whereas in general, the optimum value of Olsen P ranges from 10 to 24 mg/kg depending on the crop. On the other hand, most of the low-value vegetable crops (pumpkin, radish, lettuce, etc.) and other field crops (maize, millets, sorghum, etc.) receive only partial amount of the recommended fertilizer dosage (Wjewardana and Amarasiri 1990; Nayakekorale 1998) leading to nutrient mining from soil. Depletion of nutrients negatively affects biological activity in soils, which in turn lowers physical fertility aspects such as aggregate stability, moisture holding capacity, etc., thus deteriorating overall soil fertility.

4 Inputs for Plant Nutrient Management: Use of Synthetic Fertilizers

The use of synthetic fertilizers has become an essential crop management practice in present-day agriculture. Synthetic fertilizers are applied with the sole objective of increasing plant available nutrient levels in soil. Even though 14 elements are identified as essential plant nutrients supplied by soil (N, P, K, Ca, Mg, S, Fe, Mn, Zn, Mo, Cu, B, Cl, and Ni), the major plant nutrients that are being supplied as chemical fertilizers in Sri Lanka are N, P, K, and Mg, while Zn, Cu, and B are also supplied under specific conditions for tea (TRI 2000), paddy (DOA 2013), or fruits and other annual crops (Wijewardena 2005).

Marking the history of introduction of fertilizers for crop nutrient management, the government of Sri Lanka freely issued bone meal, an organic fertilizer containing 3% N and 22% P_2O_5, to rice growers in the 1940s (Nagarajah 1986). Since then, synthetic fertilizers as straight fertilizers (a source targeting to supply one macronutrient) and different fertilizer mixtures (a source targeting to supply more than one nutrient at a time) have been used in the country depending on the evolution of fertilizer recommendations. For example, the fertilizer recommendation for rice changed 11 times from 1950 to 2013, fertilizer mixtures were recommended in three instances (1950, 1971, and 1980), and straight fertilizers were recommended in other eight events (Nagarajah 1986; Sirisena and Suriyagoda 2018). An account on evolution of fertilizer recommendations and the types of synthetic fertilizers used for plantation crops, rice, and other annual crops until 1985 is presented in Volume 4 of Soil Science Society of Sri Lanka Journal published in 1986 and discussed later in this chapter.

4.1 Sources of Phosphorous (P)

Prior to 1970, use of “low-analysis fertilizer” such as rock phosphate (RP) and bone meal, which in general has less than 30% of the total available primary nutrient, was a common feature not only in perennial crop sectors but also for annual crops such as paddy (Wijewardena 2005). Bone meal was recommended for rice farming in 1940 as the P source. Fertilizer recommendations for rice in 1950, 1956, 1967, and 1971 included rock phosphate and triple superphosphate as P sources, and the recommendations in 1959 and 1964 included only rock phosphate as the P source. With the increased adoption of new improved varieties, which are highly responsive to fertilizers, superphosphates and fused phosphates became the sole source of P since 1980. At present, the most popular P source in annual cropping systems is TSP. In the plantation crop sector and other perennial cropping systems, P is supplied as phosphate rock powder. The imported rock phosphates (IRP) were replaced gradually by locally produced Eppawala rock phosphate (ERP) since the discovery of this ore at Eppawala (8.1456° N, 80.4048° E), Sri Lanka, in 1971. Being an igneous and/or metaigneous rock, apatite in this ore shows low solubility in water and in citric acid (Zoysa et al. 2001). Much research has been conducted over the last few decades to increase the P availability of ERP for annual crops. Selectively mined and powdered Eppawala apatite crystals are marketed as high-grade ERP (HERP) which has about 35–42% P_2O_5 content (Dahanayake et al. 1995). Mixing ERP or HERP with peat (Dahanayake et al. 1991; Rathnayake et al. 1993), composts (Mawalagedera et al. 2012), P-solubilizing microorganisms (Tennakoon et al. 2016; Hettiarachchi et al. 2017), organic wastes, or acid-forming N fertilizers (Zoysa et al. 2001) to increase P availability has been tested and gained varying degrees of success at laboratory or greenhouse studies. However, the effectiveness of such technologies under field conditions with different ecophysiological situations needs confirmation through further research. Single superphosphate had been produced by acidulating ERP (ESP) by using nitric acid (Tennakone and Weragama 1992) or using sulfuric acid by the Lanka Phosphate (Pvt) Ltd. Field evaluations have been carried out on this product during 2010/2011 by the Department of Agriculture and have confirmed that ESP can be used as an effective P fertilizer for paddy-growing soils in Sri Lanka (D.N. Sirisena, Personal Communications). However, it has still not been produced at commercial scale.

4.2 Sources of Nitrogen (N)

In the early 1960s, ammonium sulfate was used as the N fertilizer; however, during the period of 1967–1978, urea became the major source of N, because of its low cost per unit of N and also due to severe soil acidification observed under application of ammonium sulfate in wet zone soils (Wickremasinghe et al. 1981; Dharmakeerthi and Thenabadu 1996). Since the 1980s, the fertilizer research in Sri Lanka focused more on improving fertilizer use efficiency and reducing groundwater and surface water pollution. In order to increase the efficiency of urea in paddy-growing soils, prilled urea was introduced in 2013. Slow-releasing N fertilizers like sulfur-coated urea and IBDU are available in international market but have not been introduced to Sri Lanka yet. At present, research is being conducted on producing slow-released fertilizers using nanotechnology to improve the N fertilizer use efficiency in agricultural systems (Kottegoda et al. 2011, 2016).

4.3 Sources of Potassium (K), Magnesium (Mg), and Calcium (Ca)

Muriate of potash (MOP) is the most commonly used K source in the country since the late 1960s. In nursery formulations in the plantation crop sector, and for some Cl-sensitive crops such as tobacco, sulfate of potash (SOP) is being used. Dolomite is another fertilizer that is locally produced and used as both Mg supplement and ameliorant of soil acidity. Dolomite also supplies Ca. This is mostly used as a liming material in tea plantations and vegetable production systems in the up-country of Sri Lanka and also known to provide benefits in upland cropping systems in low country dry zone of Sri Lanka (Eeswaran et al. 2016). The use of kieserite and Epsom salt as Mg supplement can be observed under nursery conditions or to correct Mg deficiency in plants.

4.4 Fertilizer Formulations

Both urea and ammonium sulfate (SA) readily release N, increasing plant available N contents in soil, and since most of the arable lands have N-deficient situations for crop growth, plants respond quickly when N fertilizers are added. This sometimes led to mismanagement of fertilizers by farmers (Nagarajah 1986). Overapplication of N fertilizers beyond recommended dosage and disregard of application of P and K sources due to lack of visible response from the crop for these two nutrients resulted in introduction of fertilizer mixtures (formulations) as recommendations for most crops (Amarasiri 1986; Nagarajah 1986). However, when fertilizer formulations are used, it is difficult to address site-specific issues related to nutrient imbalances, and that results in risk of overloading or underapplying a nutrient to soil environment and difficulty in matching nutrient supply with crop growth requirement. Thus, fertilizer formulations could lead to poor fertilizer use efficiency (Nagarajah 1986). The formulations were removed since the 1990s from fertilizer recommendations of annual crops.

In the plantation crop sector, fertilizer mixtures have been formulated predominantly using urea and/or SA, ERP, and MOP. Even when the nutrient requirement for a specific field is identified through soil and foliar analysis, a fertilizer mixture for that NPK ratio is often formulated in plantation crop sector to minimize application cost, and it ensures correct proportions and quantities of NPK that is required for the optimum growth of the plant in that field. Fertilizer formulations are also popular in floriculture and home gardening, which operate at comparatively less diverse agro-ecological conditions compared to annual cropping systems. The formulations

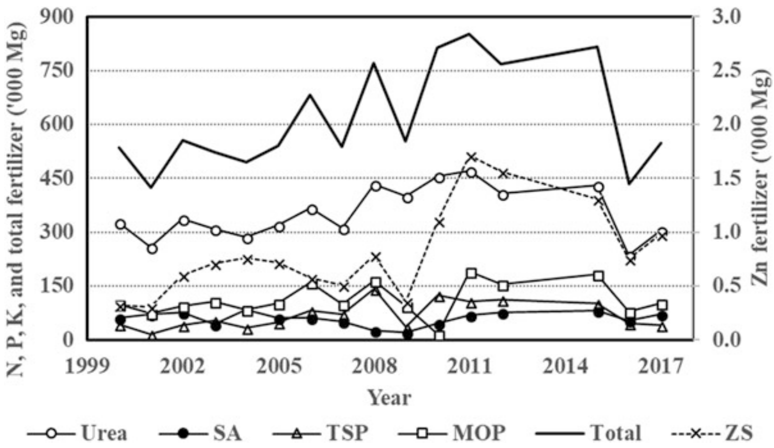

Fig. 2 Imported quantities of NPK fertilizers [urea, ammonium sulfate (SA), triple superphosphate (TSP), muriate of potash (MOP)] and Zn sulfate (ZS) during 2000 to 2017. (Source: National Fertilizer Secretariat, Sri Lanka 2017)

prepared at present for floriculture and home gardening purposes contain number of nutrients in addition to N, P, and K, and the composition depends on the targeted growth stage of the crop and mode of application (to soil or foliar).

4.5 Present Situation of Synthetic Fertilizer Usage in Sri Lanka

Although a number of plant nutrients are deficient in Sri Lankan soils (Kumaragamage and Indraratne 2011), most commonly used chemical fertilizers are urea, SA, TSP, ERP, MOP, and dolomite, supplying only N, P, K, Ca and Mg. The use of chemical fertilizers containing micronutrients is often less than the recommended levels. Quantities of major fertilizers imported into the country during the last two decades are given in Fig. 2. The quantities imported have a direct influence from changing government policies on fertilizer subsidy scheme (Weerahewa et al. 2010; Wijetunga and Saito 2017). In 2015, Sri Lanka had imported nearly 816,000 tons of synthetic fertilizer which dropped by about 33% in 2017 (Fig. 4.1) mainly due to a policy change from a material subsidy to a cash subsidy. From the imported synthetic fertilizers, 54% was urea and about 20% was MOP. The proportion of TSP importation dropped continuously from 14% in 2012 to about 7% by 2017.

From the total chemical fertilizer usage in the country in 2017 (0.6 million tons), 30% was consumed by rice cultivation (0.8 million ha) and 24% by the tea plantations (0.2 million ha) followed by 12% by vegetable crops (0.1 million ha) (Table 2). Similar proportions could be observed in other years as well. Hence, fertilizer usage in Sri Lanka vary between 80 and 700 kg/ha depending on the crop sector, with a national average of about 270 kg/ha.

Table 2 Distribution of some important chemical fertilizers in different crop sectors in Sri Lanka in 2017

Crop	Urea	SA	TSP	ERP	MOP	DOL	ZS	Other	Total
	------------------------------'000 Mg -----------------------------------								
Paddy	142.9	2.6	14.1	<0.1	18.8	<0.1	0.03	2.27	180.7
Tea	73.5	27.1	0.4	21.6	32.1	3.0	0.40	10.7	168.8
Rubber	4.4	0.9	<0.1	3.0	2.3	0.3	0.00	0.8	11.7
Coconut	17.4	3.3	2.4	7.8	15.1	2.8	<0.01	1.2	50.0
OFC	2.3	2.4	2	<0.1	2.2	0.3	<0.01	1.5	10.7
Vegetable	17.6	22.7	10.5	1.4	13.9	2.8	0.11	8.29	77.3
Other	46.2	12.3	11.1	5.4	16.8	3.0	0.44	5.16	100.4
Total	304.3	71.3	40.5	39.2	101.2	12.2	0.98	29.92	599.6

SA ammonium sulfate, *TSP* triple superphosphate, *ERP* Eppawala rock phosphate, *MOP* muriate of potash, *DOL* dolomite, *ZS* zinc sulfate, *OFC* other field crops
Source: National Fertilizer Secretariat, Sri Lanka. Sector-wise Fertilizer Distribution Report (2017)

4.6 Regulation of Synthetic Fertilizer Usage in Sri Lanka

Out of many synthetic fertilizers required to improve crop growth and yield in Sri Lankan soils, only rock phosphates and dolomite are locally produced, which account for only 9% of the total fertilizer usage (Table 2). All others are imported to the country by state-owned and private companies under the strict regulation set by the government. Fertilizer formulations are prepared locally from the imported raw materials by private sector and state-owned companies. The importation, formulation, and distribution of chemical fertilizers in the country are regulated by the Regulation of Fertilizer Act No. 68 of 1988. The Fertilizer Advisory Committee, which comes under the purview of the National Fertilizer Secretariat according to this law, has the sole authority to recommend the fertilizers to be imported to Sri Lanka. Currently, the importation of bio- and organic fertilizers is not allowed except for research purposes, and this move aims to protect the biodiversity in the country. Any chemical fertilizer imported to Sri Lanka should abide by quality standards set forth by the Sri Lanka Standards Institute (SLSI), and this is implemented by the National Fertilizer Secretariat. A comparison of quality standards for potentially toxic trace elements adopted by some countries is given in Table 3.

5 Inputs for Plant Nutrient Management: Use of Organic Fertilizers

Organic materials have an important place in soil fertility management due to their short-term effect on nutrient supply and long-term contribution to soil organic matter replenishment (Lal 2004). Increase of soil organic carbon pool in degraded soils increases crop yields through beneficial effects on nutrient supply, biological activities, water holding capacity, and soil structure (Chathurika et al. 2015; Mariaselvam et al. 2016; Chathurika et al. 2016). According to Lal (2004), an increase of 1 ton of soil carbon pool of degraded cropland soils may increase

Table 3 Maximum permissible levels (total content mg/kg) of the five potentially toxic trace elements for synthetic fertilizer in some countries

Country	Cd	As	Pb	Cr	Hg	References
Brazil (For simple mineral fertilizers and compound fertilizers containing macro and micro nutrients)	4–57	2–500	20–1000	40–500	0.05–10	Goncalves Jr. et al. (2014) DOI: https://doi.org/10.5772/57268
USA (Texas) (Any type of fertilizer)	39	41	300	17	NA	Goncalves Jr. et al. (2014) DOI: https://doi.org/10.5772/57268
EU countries (Phosphate fertilizers)	50–275	NA	NA	NA	NA	
New Zealand (Phosphate fertilizers)	280	NA	NA	NA	NA	
Canada (Any type of fertilizers)	20	75	500	NA	NA	
Australia (Any type of fertilizers)	10–300	NA	100	NA	5	National Code of Practice for Fertilizer Description and Labelling – Australia (2011)
Japan (Phosphate fertilizer)	343	50	100	5	NA	Goncalves Jr. et al. (2014) DOI: https://doi.org/10.5772/57268; Journal of Scientific Research and Reports (2014): Vol 3(4): 610–620, JSRR.2014.007
China (Any type of fertilizers)	8	50	100	500	5	
Sri Lanka (Any type of fertilizers)	0.2–3.0	0.3–25	0.2–30	3–50	0.1–1.0	Sri Lanka Standards Institute, 2014 (SLS 644, 748, 812, 1104)

NA not available, a range of values indicate different standard limits for different types/categories of fertilizers

maize yield by 10–20 kg/ha. An increase in soil organic C (SOC) stock leads to increased crop yield even in high-input agriculture (Bauer and Black 1994) but especially in SOC-depleted soils (Johnston 1986).

5.1 Conventional Organic Fertilizers

Animal manures and green manures are conventional organic inputs utilized by farmers. These amendments, generally of high quality, contain low amounts of lignin- and phenol-like compounds, release nutrients quickly, and are known to improve soil fertility and crop yield. The decomposition rates of animal and crop residues are high in soil and, thus, should be added repeatedly and in high quantities to achieve significant improvement in soil fertility and carbon sequestration (Sommerfeldt et al. 1988; Sukartono et al. 2011). *Crotalaria juncea*, *Tithonia diversifolia*, *Calliandra calothyrsus, Gliricidia sepium, and Vigna radiata* are examples of commonly used green manure crops in Sri Lanka (Palm and Sandell 1989). In addition, in the plantation crop sector of Sri Lanka, particularly in rubber-, coconut-, and oil palm-grown soils, the cultivation of leguminous cover crop species such as *Pueraria phaseoloides*, *Desmodium ovalifolium*, and *Mucuna bracteata* is a common practice to conserve soil from erosion. An additional advantage of this practice is the addition of organic matter by cover-crops into soils.

Cattle manure is popular among Sri Lankan farmers even before the introduction of synthetic fertilizers. Poultry farming is more organized and happens at a large scale in the country under intensive management practices compared to cattle farming. Therefore, poultry manure (i.e., litter mixed with feces and urine of chickens) is more available and cheaper than cattle manure; thus, poultry manure is the most commonly used animal manure in the country. Application of untreated poultry manure could lead to spread of antibiotic resistance in the environment, which is an emerging threat to human health management (Martinez 2009; Herath et al. 2016). High rates of manure application can cause water pollution due to nutrients and greenhouse gas emissions.

Compost is another popular organic fertilizer in Sri Lanka. With the government interventions in the late 1990s to recycle solid waste at municipal council level, several composting stations were established in the country. As quality control measures, standards for compost produced from municipal solid waste and agricultural waste were introduced in 2003 by Sri Lanka Standards Institution (SLSI 1246:2003). A few companies are producing compost at large scale in the country, and several small-scale producers are also contributing to the market. Compost is a popular organic fertilizer applied in floriculture industry, nursery management, and home gardening but not widely used in commercial-scale cultivation of annual and perennial crops.

5.2 Carbon-Rich Organic Soil Amendments

Carbonaceous organic soil amendments having high C/N ratio contain high level of recalcitrant C, release C to the soil slowly over time, and retain in the soil for a long time. Such materials are added with the objective of increasing overall soil fertility than as sources of nutrients; hence, it is better to refer to as organic soil amendments. Further, these materials give the best results when incorporated in IPNM along with synthetic fertilizers (Mariaselvam et al. 2014).

Common high C/N ratio amendments such as rice straw, sawdust, and rice husks can be used as soil amendments to retain C for a long period. However, due to low N content in these high C/N amendments, N immobilization may occur soon after the application to soils. Rao and Mikkelsen (1976) found that when soil and rice straw were not incubated prior to planting rice seedlings, applied N was immobilized, causing inhibition of plant growth and low N content in plants. Mariaselvam et al. (2014) studied different C-rich mixtures prepared using cattle manure, rice straw, wood shavings, and sawdust in fresh and incubated forms on nutrient release from an alluvial soil (Entisol) and a red-yellow podzolic soil (Ultisol) to identify their suitability as soil amendments. They found that some organic materials mineralize faster (rice straw-based materials) than the others (wood-based materials). Further, the contribution of wood-based materials to long-lasting C pools in soil is higher than rice straw-based materials. Therefore, all organic materials are not equally suitable as organic soil amendments to improve soil carbon sequestration. The results further indicate that the organic materials affect nutrient cycling in soil, and the effect of the material on short-term nutrient cycling should be considered when selecting a material as an amendment. Otherwise, crop growth may impede due to temporary nutrient immobilization in soil when C-rich material is added.

Recently, application of biochar is being promoted to arrest fertility degradation, and even to revert degraded agricultural soils in the tropics, because of number of positive characteristics in biochar (Lehmann 2007; Dharmakeerthi et al. 2015). High in porosity, specific surface area, charge density, and pH as well as being a source of plant nutrients together with high recalcitrant organic C content are the main features of biochar that enhance soil physical, chemical, and biological fertility in many soils (Enders et al. 2012; Vasujini et al. 2014). But the quality of biochar varies with the pyrolysis conditions and feedstock used (Enders et al. 2012; Vasujini et al. 2014). Slow-release fertilizers are being developed using biochar and N fertilizers to increase the fertilizer use efficiency in Sri Lankan agricultural soils (Gamage et al. 2013; Kottegoda et al. 2011, 2016). However, lack of effective technologies to produce good-quality biochar in large scale has delayed the adaptation of this technology in Sri Lankan agriculture.

It has been suggested that amending soils with biochar could arrest, or sometimes even revert, degradation of tropical agricultural lands (Kimetu et al. 2008). Different application rates of biochar tested in alluvial (Entisol), reddish brown earth (Alfisol), and reddish brown latosolic (Alfisol) soils from Sri Lanka indicated that soil fertility status could be improved by adding biochar at the rate of 1 Mg/ha. Cattle manure and sawdust mixed and incubated for 2 months (CSi) and applied at 2 Mg/ha rate has given comparable results to biochar at 1 Mg/ha with respect to soil fertility and productivity (Chathurika et al. 2015). In nursery rubber plants, Dharmakeerthi et al. (2012) observed a significant growth improvement (26–61%) when an acidic Ultisol is amended with 1% (w/w) rubber wood biochar in combination with N and Mg fertilizers.

A major constraint for commonly used or presently recommended organic soil amendments like compost, green manure, and animal manure is their unavailability to apply at the recommended rate (10 Mg/ha) in each season. Further, the availability of materials shows high variability in regional scale. Thus, requirement of material at a lower rate (nearly ten times) with long-lasting effects on soil are positive traits related to biochar and CSi. Moreover, sawdust, which is the base material in both organic soil amendments, is a waste product in timber mills with little economic value. Use of sawdust to produce these organic amendments will be a solution to manage waste of one industry. The concern on contaminants, pests, and diseases that could be introduced through these two organic amendments is minimal in comparison to other alternatives like compost.

5.3 Biofertilizers

Another important group of organic fertilizers that is being researched in Sri Lanka is biofertilizers (Palm and Sandell 1989; Seneviratne et al. 2011). Nitrogen-fixing inoculants were introduced in the late 1980s but did not become popular due to restrictions of supply of the material to farmers and need of repeated application, among other reasons (Granhall et al. 1987; Palm and Sandell 1989; Catroux et al. 2001). Further, the inoculant did not show significant advantage over the use of synthetic fertilizers, and the effects on crop performance were inconsistent over field and with time (Granhall et al. 1987). The nature of indigenous microbial population of soil, the inoculation rate, the adaptability of the inoculants to environmental stresses, the purity of the inoculants, and the shelf life of the formulations affect the significance of the impact of using biofertilizers in agriculture (Catroux et al. 2001; Herrmann and Lesueur 2013). Thus, the features of biofertilizers such as successful inoculation and maintenance of quality in processing and storage have to be improved in order to promote adoption of biofertilizers for nutrient management (Catroux et al. 2001; Herrmann and Lesueur 2013). A number of success stories exist from different countries on the use of plant growth-promoting bacteria inoculants and mycorrhizal fungi as biofertilizers to improve crop productivity, soil fertility, and plant tolerance for stresses in sustainable agriculture (Adesemoye et al. 2009; Mahdi et al. 2010; Bhardwaj et al. 2014; Gracia-Fraile et al. 2015). In a study conducted in Auburn, USA, supplementing 75% of the recommended fertilizer rate with inoculants to a tomato crop resulted in yield and nutrient uptake statistically equivalent to the full fertilizer rate without inoculants (Adesemoye et al. 2009). Ability to reduce synthetic fertilizer usage when applied with biofertilizers without sacrificing crop productivity under tropical conditions has been observed in many other studies as summarized in reviews by Bhardwaj et al. (2014) and Garcia-Fraile et al. (2015).

In Sri Lanka, since 2003, several products to increase decomposition of straw, solubilize ERP, and fix P forms in soil, and N_2 fixation, were researched and tested at different scales for annual crops (Seneviratne et al. 2009; Kumari et al. 2010; Rajapaksha 2010; Rajapaksha et al. 2011; Katulanda and Rajapaksha 2012) and plantation crops (Seneviratne et al. 2011; Hettiarachchi et al. 2014, 2017; Tennakoon et al. 2016) with the participation of Department of Agriculture and various research institutes. Based on greenhouse-scale and field-scale experiments with rice cultivation, Rajapaksha et al. (2011) reported that 50% of TSP could be substituted with ERP along with seed inoculants formulated with *Enterobacter gergoviae*, *Bacillus mycoides,* and *Bacillus pumilus*. These products, if successful, are along the line of third paradigm of soil fertility and plant nutrient management. Improvement of soil fertility under the application of biofertilizers has been observed (Rajapaksha 2010; Seneviratne et al. 2011). The diversity with respect to soil conditions creating diverse ecological conditions for microbial communities and the diversity in farming systems (input usage, agronomic practices, crop rotations, etc.) stand as challenges in developing effective biofertilizers because the microorganisms used show niche specificity (Granhall et al. 1987; Catroux et al. 2001; Rajapaksha 2010; Herrmann and Lesueur 2013). A few government-funded projects to formulate biofertilizers for annual crops (rice, vegetables) and plantation crops (tea and rubber) are in progress at present.

6 Fertilizer Recommendations in Sri Lanka

Fertilizer application for different crops was initially based on experiences of the growers on ad hoc fertilizer applications. Therefore, initial fertilizer recommendations were based solely on crop demand and yield goals. Systematic fertilizer trials conducted later for different crop-soil systems revealed variable responses of plant growth and yields to added fertilizers (e.g., Constable and Hodnett 1953 for rubber). Although initial fertilizer recommendations comprised of synthetic fertilizers, only with the adoption of ISFM approach organic fertilizer inputs were introduced to fertilizer recommendations of most crops (Yogaratnam and Silva 1987; Bandara et al. 2003). The rates of organic fertilizers to be applied in integrated nutrient management approach vary across crops, and this is discussed under the section on integrated plant nutrient management in this chapter.

Even though fertilizer recommendations for different crop sectors initially started as blanket application irrespective of soil variability, most of the synthetic fertilizer recommendations developed at present encourage soil test-based nutrient management (Bandara et al. 2003; Weerasinghe 2017). However, detailed information generated through soil survey and classification efforts (Moorman and Panabokke 1961; Mapa 2005; Mapa et al. 1999, 2009) have not been effectively utilized in fertilizer recommendations for any crop in Sri Lanka.

6.1 Plantation Crops

From the plantation crops, rubber was the first to incorporate soil series-based fertilizer recommendations. By the late 1970s, the Rubber Research Institute of Sri Lanka introduced a site-specific fertilizer recommendation based on soil and foliar analysis for mature rubber plants (Yogaratnam and Silva 1977). For example, fertilizer recommendation for rubber (*Hevea brasiliensis* L.) varies according to the K status of the soil (Yogaratnam et al. 1984). Similarly, tea and coconut research institutes in Sri Lanka later introduced soil- and foliar-based fertilizer recommendations for mature plantations (CRI 2008; TRI 2000).

The second highest chemical fertilizer consumer in Sri Lanka is tea plantations, consuming about 24% of the imported fertilizer. Fertilizer usage in rubber plantations is low, with about 240–675 kg of NPK fertilizer/ha/year depending on the soil type and the age (Samarappuli 2001), while fertilizer use in tea plantations is the highest among traditional plantation crops, with 350–1750 kg of NPK fertilizer/ha/year depending on the age and yield target (TRI 2000). The very high rates of N fertilizer use, initially as sulfate of ammonia and currently as urea, have contributed to soil acidification in tea-growing areas. Hence, these soil require special management practices such as the application of 1–2 Mg of dolomite/ha once in every 3 years. Fertilizer requirement in coconut plantations in Sri Lanka varies from 230 to 600 kg of NPK fertilizers /ha/year depending on the age of the palm, soil type, and cycle of replanting. Low productivity in coconut lands of the acidic wet zone soils of Sri Lanka has been due to Mg deficiency, and as a prophylactic measure, application of 240–320 kg of ground dolomite is usually recommended for wet zone soils (CRI 2008). However, the application of chemical fertilizers by coconut growers in Sri Lanka is very low. Compared to tea, rubber, and coconut, the extent under oil palm is low and only 8000 ha in Sri Lanka, but because of the labor scarcity and very high profit margin, there is a tremendous pressure on converting rubber plantations in the wet zone of Sri Lanka to oil palm cultivation. The government aims to increase the total extent under oil palm up to 20,000 ha by year 2020. The fertilizer requirement of oil palm is very high due to high nutrient removal from the fields (Goh 2004). Even though there is no fertilizer recommendation as such for oil palm in Sri Lanka, commercial planters apply between 420 and 2100 kg of NPK fertilizers per ha per year (Prof. A Nugawela, personal communications). Residual effects and environmental impacts when high doses of chemical fertilizers are applied to oil palm plantations need to be assessed critically.

6.2 Paddy

Paddy consumes a large proportion of the imported fertilizer, i.e., 45–55% of urea, 35–55% of TSP, and 15–35% of MOP, and the recommended rate is around 225 to 340 kg of NPK fertilizers per hectare per season (Weerasinghe 2017). In comparison to fertilizer usage in other countries, this is a moderate amount. However, fertilizer for paddy cultivation in Sri Lanka is provided free or at a very high subsidy since the 1940s (Nagarajah 1986; Weerahewa et al. 2010); thus, actual chemical fertilizer usage in some farmer fields could be much higher than the recommended rates. Kendaragama (2006) observed that in rice-based cropping systems, the actual fertilizer usage has ranged from 50 to 300% of the recommended rates. The low rates were observed in rice-rice cropping systems in the coastal areas and in some up-country rice-vegetable cropping systems.

Fertilizer recommendation for rice cultivation has been revised from time to time since its first tentative recommendation in 1950 (Nagarajah 1986), considering research findings, farmer experience, and/or government policies. Because of very low yield response to added P fertilizers, application of TSP has now been recommended once in two seasons. This could be partly due to P buildup in soil due to continuous application of P fertilizers (phosphate rocks until the 1990s and concentrated superphosphate thereafter). However, measurement of available P may not be helpful to explain the low responses to added P in soils with very low Olsen P levels and/or positive response in soils with high Olsen P. Sirisena and Suriyagoda (2018) speculated that the degree of P saturation may be a better indicator to predict crop response to added P. Moreover, the basal application of N fertilizer has now been shifted to 2 weeks after transplanting in order to increase the fertilizer use efficiency (DOA 2013). Since the burning of rice straw in paddy fields is discouraged, the amount of K fertilizer requirement could be decreased up to 50% (Sirisena et al. 2015) without affecting the crop yield. Zn is deficient in most rice-growing soils, and therefore application of 5 kg of $ZnSO_4$ has been recommended to all soils as a precaution, but only a few farmers have adopted this recommendation.

6.3 Other Annual Crops

Considering the nutrient requirement of different crops, various fertilizer mixtures have been introduced in the first fertilizer recommendations released for cereals, vegetables, and fruit crops in 1980 (Nagarajah 1986). Basal application from the relevant NPK mixture varied depending on the crop species from 125 kg/ha (soybean) to 625 kg/ha (vegetables) to 1500 kg/ha (up-country potato). Generally, vegetables and potato, which consume the highest amount of chemical fertilizers in this category of crops, are cultivated in steeply dissected hilly landscapes in the up-country wet zone of Sri Lanka and/or sandy soils in the dry zone that has a shallow ground water table with quick recharge. Vegetable and potato cultivation is a year-round practice in these areas, and cropping at least three times a year has become a common practice. In order to minimize the rate of soil fertility degradation due to intensive cultivation of high nutrient-demanding crops without adopting proper soil conservation practices, farmers in these areas apply large quantities of organic manures in addition to the recommended doses of chemical fertilizers. Application of around 10 Mg of poultry manure/ha/season that is rich in P and readily available N or composts made using such manure or solid wastes is popular among these farmers. For example, Kendaragama et al. (2001) observed that chemical fertilizer usage in vegetable cropping systems in these areas is about six to nine times higher than the recommended rates. High levels of available P (Mehlich-3 extractable P ranging from 17 to 298 mg/kg with 95% of analyzed soils having values greater than 45 mg/kg) and P sorption capacity (as indicated by single-point adsorption capacity, P_{150}, of soils ranging from 185 to 1167 mg/kg with a mean value of 665 mg/kg) are reported for up-country intensively cultivated vegetable fields (Amarawansha and Indraratne 2010). High levels of NO_3-N (300 ppm) in the ground waters of the vegetable-cultivated areas with sandy soils (Kuruppuarachchi 2010) have been observed. For food crop sector, a soil test-based fertilizer recommendation was first introduced in 1993 in order to minimize the excessive building up of nutrients and increased productivity (Weerasinghe 2017).

7 Integrated Plant Nutrient Management

Effective and efficient management of plant nutrients can be achieved only when the nutrient management plan addresses the physical, chemical, and biological fertility aspects of soils simultaneously (Chathurika et al. 2015; Mariaselvam et al. 2016). Identification of soil fertility constraints and selection of soil amendments and/or corrective measures to improve soil fertility should be essential in a nutrient management plan (Chathurika et al. 2015; Mariaselvam et al. 2016). Improving soil organic matter pool is essential in most of the degraded tropical soils. Lal (2015) suggested that restoration of soil organic C to threshold levels of at least 11 to 15 g kg^{-1} (1.1–1.5% by weight) within the root zone is critical to reducing soil and environmental degradation risks.

Understanding the importance of soil organic matter pool on sustainability of Sri Lankan agriculture, application of organic amendments is highly encouraged for all cropping systems. From plantation crops, rubber and coconut adopt the establishment of leguminous cover throughout its life span, in addition to recommending the application of composts and organic residues as mulches around tree (Samarappuli 2001; Tennakoon and Bandara 2003). Cover crops minimize the erosion of organic matter containing top soil while helping to provide organic matter through its litter. In tea cultivations, rehabilitation of tea lands by growing Mana or Guatemala grasses for 2 years prior to replanting, burying of prunings, and application of compost at replanting has been recommended in addition to the synthetic fertilizer application (TRI 2000, 2016). For rice fields, returning paddy straw back into the field and application of 6 Mg of compost/ha/year have been recommended on top of the synthetic fertilizer inputs. Recently, the application of 0.6 Mg of partially burnt paddy husk/ha/year has been encouraged among paddy farmers. In most of the annual cropping systems managed with synthetic fertilizer inputs, application of 10 Mg of organic manure has been recommended (Wijewardena 2005). Most of these recommendations rather help to arrest further degradation of soil organic matter reserves than increasing the reserves up to the sustainable limit suggested by Lal (2015) for developing countries in the tropics.

Biochar is being considered as an organic soil amendment that can be effectively used in ISFM approach. Under Sri Lankan conditions, application of synthetic fertilizers along with biochar has decreased soil acidity, increased nutrient availability (Dharmakeerthi et al. 2012), improved soil physical properties (Gamage et al. 2016), and enhanced soil carbon pool and crop yields (Mariaselvem et al. 2014; Chathurika et al. 2016). In addition to organic and synthetic fertilizers, the use of rock powder as soil amendment to improve soil fertility status has been reported in the tropics (Silva et al. 2013; Chathurika et al. 2015). Improvement in maize yield with the inclusion of rock powder in ISFM was observed by Chathurika et al. (2015).

8 Way Forward in Soil Fertility Management

More than 75 years have passed since the introduction of synthetic fertilizers for plant nutrient management. Yet the use efficiency of the synthetic fertilizers remains around 10–50% under farm field condition. Strategies to improve N fertilizer use efficiency up to 40% was introduced by the Rice Research and Development Institute (DOA 2013), but it is not being practiced by majority of rice farmers yet due to number of environmental, social, political, and technical reasons. Therefore, soil fertility and plant nutrition management plans should be researched and developed to maximize the resource use efficiency in agricultural systems, which will provide additional benefits such as reducing the indirect costs on recovering from environmental and health issues created due to agricultural pollutants.

Cultivation of same crop(s) in a plot of land and application of synthetic fertilizers over several decades have changed the soil fertility in most agricultural lands. Therefore, man-made spatial heterogeneity is becoming more prominent among farmer fields than the inherent heterogeneity. Soil test-based fertilizer recommendation is effective under these conditions. However, lack of effective soil testing mechanism for farmers, together with very high fertilizer subsidy, hinders the adoptability of this site-specific technology and harnessing the positive impacts on soil and the environment. Soil fertility evaluations and land suitability for cropping are conducted by only a few large-scale agro-industries. Research should be carried out to develop a farmer-friendly soil test kit and quick and easy way to obtain the fertilizer recommendations by a farmer to his field. The Department of Agriculture is developing a farmer-friendly fertilizer management protocol using soil test kits and plant sap test kits to determine nutrient status of plants and available nutrients in soils (mainly N, P, and K) based on colorimetric assays. This research program was initiated in 2017, and now the protocol is being tested at pilot scale.

The soil testing is currently carried out by the Department of Agriculture, or respective crop research institutes with the mandate, or by some private sector companies that are still limiting their analysis for available nutrients, pH, and electrical conductivity and occasionally for soil texture. These analyses would reveal only the potentially available level of nutrients to support plant growth in the short run. Therefore, a package of soil analyses that warrant the understanding of overall soil fertility (chemical, biological, and physical fertility) at an affordable price to the farmers should be developed, and farmers should be encouraged to keep records on soil health for crop production. This is being effectively practiced in some European countries and in North America, which encourages the farmers to be accountable and environmentally conscious.

Development of soil fertility management apps aiming for e-agriculture could be more effective in the present-day farming. Moreover, further research is required to improve the currently adopted algorithms and/or to develop new algorithms where required, to determine the optimum fertilizer rates for a given soil-crop system based on the soil test values. A better understanding on soil fertility constraints and their spatiotemporal variability is required to support the development of effective site-specific nutrient management strategies.

Applying fertilizer inputs to a degraded soil or to a soil having restrictions for crop growth such as compaction, poor drainage, poor biological activity, and nutrient toxicities is not cost-effective. Soil physical and biological fertility are relatively new concepts to the stakeholders involve in management of soil fertility and plant nutrition in Sri Lanka. Thus, a consorted effort should be taken to educate farmers, agricultural officers, and other stakeholders about the environmental consequences related to improper soil fertility management and to encourage conscious adoption of best management practices to enhance productivity in the long run with environmental consciousness.

Incorporation of organic fertilizers or organic soil amendments is beneficial in soil fertility and plant nutrition management (Sirisena et al. 2015). Development of soil-crop system-specific technologies to increase soil organic matter pool above a critical level in Sri Lankan agricultural lands should be encouraged. Moreover, technologies to produce organic soil amendments in required quantities by recycling agricultural and urban wastes need to be developed or made available to the farmers. Effective N-fixing, P-solubilizing, and/or plant growth-promoting soil microorganisms have been already isolated from various soil-crop systems; however, their commercialization needs to be promoted. Regulations with respect to quality of external inputs should be developed to safeguard the environment and enhance the food safety, especially when animal manures and compost from municipal solid wastes are being used. These regulations should not be limited to nutritive composition but extend to assessing the contamination levels by potentially toxic trace elements (Cd, Pb, Co, As, Hg, etc.) and antibiotics and biocides. Moreover, policies on fertilizer usage in the country should be focused not only to increase the productivity of the land but also to safeguard the environment. Therefore, the material fertilizer subsidy given to farmers needs to be critically evaluated, and a better environmental-friendly policy should be adopted.

References

Adesemoye AO, Torbert HA, Kloepper JW (2009) Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microb Ecol 58(4):921–929

Ajayi OC, Akinnifesi FK, Sileshi G, Chakeredza S (2007) Adoption of renewable soil fertility replenishment technologies in the southern African region: lessons learnt and the way forward. Nat Res Forum 31(4):306–317. https://doi.org/10.1111/j.1477-8947.2007.00163

Amarasiri SL (1986) Some considerations in arriving at fertilizer recommendations for annual crops. J Soil Sci Soc Sri Lanka 4:30–34

Amarawansha EAGS, Indraratne SP (2010) Degree of phosphorous saturation in intensively cultivated soils in Sri Lanka. Trop Agric Res 22(1):113–119

Bandara WMJ, Wickramasinghe WMADB, Sirisena DN (2003) Potassium fertilization of paddy in Sri Lanka. In: Importance of potash fertilizers for sustainable production of plantation and food crops in Sri Lanka, pp 143.11

Bationo A (2009) Soil fertility-paradigm shift through collective action. CTA, Wageningen, The Netherlands. http://knowledge.cta.int/en/Dossiers/Demanding-Innovation/Soil-health/Articles/Soil-FertilityParadigm-shift-through-collective-action. Accessed 14 May 2018

Bauer A, Black AL (1994) Quantification of the effect of soil organic matter content on soil productivity. Soil Sci Soc Am J 58(1):185–193

Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N (2014) Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microb Cell Factories 13(1):66–76

Catroux G, Hartmann A, Revellin C (2001) Trends in rhizobial inoculant production and use. Plant Soil 230:21–30

Chathurika JAS, Indraratne SP, Dandeniya WS, Kumaragamage D (2015) Beneficial management practices on growth and yield parameters of maize (*Zea mays*) and soil fertility improvement. Trop Agric Res 27(1):59–74

Chathurika JAS, Kumaragamage D, Zvomuya F, Akinremi OO, Flaten DN, Indraratne SP, Dandeniya WS (2016) Woodchip biochar effects on selected soil fertility parameters in two Chernozemic soils. Can J Soil Sci 96:472–484

Constable DH, Hodnett GE (1953) The manuring of *Hevea brasiliensis* at Dartonfield. Ceylon Empire J Exp Agric 21:131–136

CRI (2008) Use of fertilizer for coconut and land suitability (in Sinhala). Advisory circular no. 01. Coconut Research Institute, Sri Lanka
Dahanayake K, Senaratne A, Subasinghe SM, Liyanaarachchi A (1991) Potential use of naturally occurring sulphuric acid to beneficiate poorly soluble phosphate from Eppawala, Sri Lanka. Fertil Res 29(2):197–201
Dahanayake K, Ratnayake MP, Sunil PA (1995) Potential of Eppawala apatite as a directly applied low-cost fertilizer for rice production in Sri Lanka. Fertil Res 41(2):145–150
DOA (2013) Department of Agriculture Fertilizer Recommendation for Rice, Sri Lanka: Department of Agriculture
Dharmakeerthi RS, Thenabadu MW (1996) Urease activity in soils: a review. J Natl Sci Found Sri 24(3):159–195
Dharmakeerthi RS, Chandrasiri JA, Edirimanne VU (2012) Effect of rubber-wood biochar on nutrition and growth of nursery plants of *Hevea brasiliensis* established in an Ultisol. Springer Plus 1:84
Dharmakeerthi RS, Hanley K, Whitman T, Woolf D, Lehmann J (2015) Organic carbon dynamics in soils with pyrogenic organic matter that received plant residue additions over seven years. Soil Biol Biochem 88:268–274
Eeswaran R, De Costa WAJM, De Costa DM, Dandeniya WS, Sivakumar S, Suriyagoda LDB (2016) Evaluation of a climate change-adaptive, eco-friendly agronomic package for potato (*Solanum tuberosum* L.) cultivation in the farmer fields of the Jaffna district of Sri Lanka. Trop Agric Res 27(2):190–202
Enders A, Hanley K, Whitman T, Joseph S, Lehmann J (2012) Characterization of biochar to evaluate recalcitrance and agronomic performance. Bio Resour Technol 114:664–653
FAO (2017) Special report FAO/WFP crop and food security assessment mission to Sri Lanka. 22 June 2017, Food and Agriculture Organization of the United Nations
Gamage DV, Mapa RB, Dharmakeerthi RS, Biswas A (2016) Effect of rice-husk biochar on selected soil properties in tropical Alfisols. Soil Res 54(3):302–310
Gamage A, Basnayake B, Costa J, Vidanagamage K (2013) Evaluation of total N, P, K and organic matter contents of soil amended with paddy husk charcoal coated urea and comparison of the yield of paddy. http://dl.lib.mrt.ac.lk/handle/123/8892. Accessed 23 June 2018
Garcia-Fraile P, Menendez E, Rivas R (2015) Role of bacterial biofertilizers in agriculture and forestry. Bioengineering 2(3):183–205. https://doi.org/10.3934/bioeng.2015.3.183
Goh KJ (2004) Fertilizer recommendation systems for oil palm: estimating the fertilizer rates. In: Soon CP, Pau TY (eds) Proceedings of MOSTA best practices workshops: agronomy and crop management. Malaysian Oil Scientists and Technologies Association, Kuala Lumpur, pp 235–268
Granhall U, Kulassoriya SA, Hirimburegama WK, De Silva RSY, Lindberg T (1987) Nitrogen fixation in some rice soils in Sri Lanka. MIRCEN J Appl Microbiol Biotechnol 3(4):367–388
Herath EM, Palansooriya AGKN, Dandeniya WS, Jinadasa RN (2016) An assessment of antibiotic resistant bacteria in poultry litter and agricultural soils in Kandy District, Sri Lanka. Trop Agric Res 27(4):389–398
Herrmann L, Lesueur D (2013) Challenges of formulation and quality of biofertilizers for successful inoculation. Appl Microbiol Biotechnol 97(20):8859–8873
Hettiarachchi RP, Dharmakeerthi RS, Jayakody AN, Seneviratne G, De Silva E, Gunathilake T, Thewarapperuma A (2014) Effectiveness of fungal bacterial interactions as biofilmed biofertilizers on enhancement of root growth of *Hevea* seedlings. J Environ Prof Sri Lanka 3(2)
Hettiarachchi RP, Dharmakeerthi RS, Seneviratne G, Jayakody AN, De Silva E, Gunathilake T, Thewarapperuma A, Maheepala CK (2017) Availability and leaching of nutrients after biofilm biofertilizer applications into a red yellow Podsolic soil. J Rubber Res Inst Sri Lanka 94:43–53
Indraratne SP (2006) Occurrence of organo-mineral complexes in relation to clay mineralogy of some Sri Lankan soils. J Natl Sci Found Sri 34(1):29–35. https://doi.org/10.4038/jnsfsr.v34i1.2073

Indraratne SP, Thilakarathne JKDAK (2009) Sorption capacity and deficiency of nutrients in some soils of Sri Lanka. J Soil Sci Soc Sri Lanka 29:17–26

Jayasingha P, Pitawala A, Dharmagunawardhane HA (2011) Vulnerability of coastal aquifers due to nutrient pollution from agriculture: Kalpitiya, Sri Lanka. Water Air Soil Pollut 219 (1–4):563–577. https://doi.org/10.1007/s11270-010-0728-y

Johnston AE (1986) Soil organic matter, effects on soils and crops. Soil Use Manag 2(3):97–105

Katulanda P, Rajapaksha CP (2012) Response of maize grown in an alfisol of Sri Lanka to inoculants of plant growth promoting rhizobacteria. J Plant Nutr 35(13):1984–1996

Kendaragama KMA (2006) Fertilizer use efficiency in farming systems in Sri Lanka. J Soil Sci Soc Sri Lanka 8:1–18

Kendaragama KMA, Lathiff MA, Chandrapala AG (2001) Impact of vegetable cultivation on fertility status of soils in the Nuwara Eliya area. Ann Sri Lanka Dep Agric 3:95–100

Kimetu JM, Lehmann J, Ngoze SO, Mugendi DN, Kinyangi JM, Riha S, Verchot L, Recha JW, Pell AN (2008) Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems 11(5):726–739

Kottegoda N, Munaweera I, Madusanka N, Karunaratne V (2011) A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. Curr Sci 10:73–78

Kottegoda N, Madusanka N, Sandaruwan C (2016) Two new plant nutrient nanocomposites based on urea coated hydroxyapatite: efficacy and plant uptake. Indian J Agric Sci 86(4):494–499

Kumaragamage D (2010) Site specific nutrient management in soils of Sri Lanka: a review of recent work using a systematic approach to formulate fertilizer recommendations for annual crops. J Soil Sci Soc Sri Lanka 22:1–16

Kumaragamage D, Indraratne SP (2011) Systematic approach to diagnosing fertility problems in soils of Sri Lanka. Commun Soil Plant Anal 42:2699–2715

Kumaragamage D, Nayakekorala HB, VidhanaArachchi LP (1999) Risks and limitations of wet zone soils. In: Mapa RB, Somasiri S, Nagarajah S (eds) Soils of the wet zone of Sri Lanka. Soil Science Society of Sri Lanka/Survodaya Publishers, Peradeniya, pp 139–159

Kumari PDSU, Nanayakkara CM, Bandara JMAU (2010) Development of a fungal inoculum for efficient phosphate utilization in agriculture. In: Proceedings of the 15th international forestry and environment symposium, 26–27 November 2010, Nugegoda, Sri Lanka

Kuruppuarachchi DSP (2010) A review on the leaching of nitrate from agricultural soils and pollution of ground water in Sri Lanka. J Soil Sci Soc Sri Lanka 22:37–49

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustainability 7(5):5875–5895. https://doi.org/10.3390/su7055875

Lehmann J (2007) Bio-energy in the black. Front Ecol Environ 5:381–387

Mahdi SS, Hassan GI, Samoon SA, Rather HA, Dar SA, Zehra B (2010) Bio-fertilizers in organic agriculture. J Phytol 2(10):42–54

Mapa RB (2003) Sustainable soil management in the 21st century. Trop Agric Res Ext 6:44–48

Mapa RB (ed) (2005) Soils of the intermediate zone of Sri Lanka. Soil Science Society of Sri Lanka/ Survodaya Publishers, Peradeniya

Mapa RB, Somasiri S, Nagarajah S (eds) (1999) Soils of the wet zone of Sri Lanka. Soil Science Society of Sri Lanka/Survodaya Publishers, Peradeniya

Mapa RB, Somasiri S, Dassanayake AR (eds) (2009) Soils of the dry zone of Sri Lanka. Soil Science Society of Sri Lanka/Survodaya Publishers, Peradeniya

Mariaselvam AA, Dandeniya WS, Indraratne SP, Dharmakeerthi RS (2014) High C/N materials mixed with cattle manure as organic amendments to improve soil productivity and nutrient availability. Trop Agric Res 25(2):201–213

Mariaselvam AA, Dandeniya WS, Indraratne SP, Dharmakeerthi RS (2016) Beneficial nutrient management practice for improving maize (*Zea mays*) yield in a tropical Entisol. Trop Agric Res 27(2):147–158

Martinez JL (2009) Environmental pollution by antibiotics and by antibiotic resistance determinants. Environ Pollut 157(11):2893–2902
Mawalagedera SM, Weerakkody WA, Premaratne KP (2012) Circulation culture of tomato for efficient nutrient uptake and high yield in tropical greenhouses. Trop Agric Res 23(3):204–217
Moorman FR, Panabokke CR (1961) Soils of Ceylon. Trop Agric 117:5–69
Nagarajah S (1986) Fertilizer recommendations for rice in Sri Lanka: a historical review. J Soil Sci Soc Sri Lanka 4:4–14
Nayakekorale HB (1998) Human induced soil degradation status in Sri Lanka. J Soil Sci Soc Sri Lanka 10:1–35
Palm O, Sandell K (1989) Sustainable agriculture and nitrogen supply in Sri Lanka: farmers' and scientists' perspective. Ambio 18:442–448
Premarathna HMPL, Hettiarachchi GM, Indraratne SP (2005) Accumulation of cadmium in intensive growing soils in the up country. Trop Agric Res 17:93–103
Rajapaksha RMCP (2010) Exploring unseen: a review on the diversity and functions of soil microorganisms of selective ecosystems in Sri Lanka. J Soil Sci Soc Sri Lanka 22:51–70
Rajapaksha RMCP, Herath D, Senanayake AP, Senevirathne MGTL (2011) Mobilization of rock phosphate phosphorus through bacterial inoculants to enhance growth and yield of wetland rice. Commun Soil Sci Plant Anal 42(3):301–314
Rao DN, Mikkelsen DS (1976) Effect of rice straw incorporation on rice plant growth and nutrition. Agron J 68:752–756
Rathnayake MP, Kumaragamage D, Dahanayake K (1993) A comparison of citric acid solubilities of commercially available Eppawala rock phosphate and selectively mined primary apatite crystals after mixing with peat. Trop Agric Res 5:69–76
Samarappuli L (2001) Nutrition. In: LMK T, Nugawela A (eds) Handbook of rubber, vol 1: Agronomy. Rubber Research Institute of Sri Lanka, Agalawatta, pp 156–175
Sanchez PA (1994) Tropical soil fertility research: towards the second paradigm. In: Transactions of the 15th world congress of soil science, vol 1. Mexican Society of Soil Science, Chapingo, pp 65–88
Sanchez PA (1997) Changing tropical soil fertility paradigms: from Brazil to Africa and back. In: Moniz AC et al (eds) Plant-soil interactions at low pH. Brazilian Society of Soil Science, Piracicaba, pp 19–28
Seneviratne G, Thilakaratne RMMS, Jayasekara APDA, Seneviratne KACN, Padmathilake KRE, De Silva MSDL (2009) Developing beneficial microbial biofilms on roots of non legumes: a novel biofertilizing technique. In: Microbial strategies for crop improvement. Springer, Berlin/Heidelberg, pp 51–62
Seneviratne G, Jayasekara APDA, De Silva MSDL, Abeysekera UP (2011) Developed microbial biofilms can restore deteriorated conventional agricultural soils. Soil Biol Biochem 43 (5):1059–1062
Silva B, Paradelo R, Vazquez N, Garcia-Rodeja E, Barral MT (2013) Effect of the addition of granitic powder to an acidic soil from Galicia (NW Spain) in comparison with lime. Environ Earth Sci 68:429–437
Sirisena D, Suriyagoda LD (2018) Toward sustainable phosphorus management in Sri Lankan rice and vegetable-based cropping systems: a review. Agric Nat Resour 52:9–15
Sirisena D, Wanninayake W, De Silva AGS (2015) Potassium dynamics in irrigated low land paddy soils and its relation to plant K and grain yield of rice. Trop Agric 163:89–99
Sommerfeldt TG, Chang C, Entz T (1988) Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. Soil Sci Soc Am J 52 (6):1668–1616
Sukartono WH, Utomo KZ, Nugroho WH (2011) Soil fertility status, nutrient uptake, and maize (*Zea mays* L.) yield following biochar and cattle manure application on sandy soils of Lombok, Indonesia. J Trop Agric 49:47–52

Suriyagoda L, De Costa WAJM, Lambers H (2014) Growth and phosphorus nutrition of rice when inorganic fertilizer application is partly replaced by straw under varying moisture availability in sandy and clay soils. Plant Soil 384(1–2):53–68

Tennakone K, Weragama UT (1992) Nitric acid treated phosphate fertilizer from Eppawala apatite in Sri Lanka. Fertil Res 32(1):115–119

Tennakoon NA, Bandara SH (2003) Nutrient content of some locally available organic materials and their potential as alternative sources of nutrients for coconut. Cocos 15:23–30

Tennakoon PL, Rajapaksha RM, Hettiarachchi LS (2016) Potentials of plant growth promoting Rhizobacteria based bio-fertilizers for tea. In: Proceedings of the 232nd meeting of the experiments and extension forum. The Tea Research Institute, Sri Lanka, pp 26–39

Tiessen H, Cuevas E, Chacon P (1994) The role of soil organic matter in sustaining soil fertility. Nature 371:783–785

TRI Advisory Circular (2000) Fertilizer recommendations for mature tea. Circular no. SP3, serial no. 00/3. Tea Research Institute, Sri Lanka

TRI Advisory Circular (2016) Fertilizer recommendations for mature tea in small holdings. Interim circular no. SP10, serial no. 01/16. Tea Research Institute, Sri Lanka

Vasujini P, Dandeniya WS, Dharmakeerthi RS (2014) Assessing the quality of biochar produced from coconut husk waste. J Soil Sci Soc Sri Lanka 24:21–28

Weerahewa J, Kodithuwakku SS, Ariyawardana A (2010) The fertilizer subsidy program in Sri Lanka. In: Pinstrup-Andersen P, Cheng F (eds) Food policy for developing countries: case studies. Cornell University, Ithaca

Weerasinghe P (2017) Best practices of integrated plant nutrition system in Sri Lanka. Best practices of integrated plant nutrition system in SAARC Countries, 135

Wickremasinghe KN, Sivasubramaniam S, Nalliah P (1981) Urea hydrolysis in some tea soils. Plant Soil 62(3):473–477

Wijesundara SM (1990) Removal of nutrients by vegetable crops cultivated in the mid-and upcountry wet zone. Trop Agric 146:79–85

Wijetunga CS, Saito K (2017) Evaluating the fertilizer subsidy reforms in the rice production sector in Sri Lanka: a simulation analysis. Adv Manag Appl Econ 7(1):31

Wijewardena JDH (2005) Improvement of plant nutrient management for better farmer livelihood, food security and environment in Sri Lanka. In: Improving plant nutrient management for better farmer livelihoods. Food Security and Environmental Sustainability, Beijing, pp 73–93

Withana AK, Kumaragamage D (1995) Evaluation of phosphorous extraction methods for assessing phosphorous availability of some Sri Lankan soils. Trop Agric Res 7:143–151

Wjewardana JDH, Amarasiri SL (1990) Comparison of phosphate on growth of vegetable crops on acid soil. Trop Agric 6:57–68

Yogaratnam N, Silva P (1977) Use of leaf analysis as a guide to manuring of rubber. Bull Rubber Res Inst Sri Lanka 12:46–50

Yogaratnam N, Silva FPW (1987) Use of organic materials as fertilizers. Bull Rubber Res Inst Sri Lanka 24:17–20

Yogaratnam N, Silva FPW, Weerasuriya SM (1984) Recent developments in the nutrition of Hevea in Sri Lanka. In: Proceedings of the international rubber conference, vol 1, Part (1) September 17–19. Rubber Research Institute of Sri Lanka, Colombo, Sri Lanka, pp 207–247

Young SM, Pitawala A, Gunatilake J (2010) Fate of phosphate and nitrate in waters of an intensive agricultural area in the dry zone of Sri Lanka. Paddy Water Environ 8(1):71–79

Zoysa AK, Loganathan P, Hedley MJ (2001) Comparison of the agronomic effectiveness of a phosphate rock and triple superphosphate as phosphate fertilisers for tea (*Camellia sinensis* L.) on a strongly acidic Ultisol. Nutr Cycl Agro ecosyst 59(2):95–105