Methods for Rapid Testing of Plant and Soil Nutrients

Chapter · July 2017

DOI: 10.1007/978-3-319-58679-3_1

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Chapter 1
Methods for Rapid Testing of Plant and Soil Nutrients

Christian Dimkpa, Prem Bindraban, Joan E. McLean, Lydiah Gatere, Upendra Singh, and Deborah Hellums

Abstract Low nutrient levels in soil are a recognized limitation to crop production. Yet, farmers in certain agro-ecoregions either do not apply fertilizers, apply inadequate amounts, or apply the wrong fertilizers due to a mismatch with the nutrient needs of their soil. In many cases, lack of availability of wet chemistry capabilities contribute to farmers in less developed regions not routinely conducting soil tests prior to fertilizer application. Fortunately, novel technologies and commercial products have become available, providing on-farm, timely, and relatively inexpensive soil and plant nutrient analytical services.

Here, we identified rapid soil and plant nutrient testing technologies, currently in the market, based on a web search, and evaluated the basis for deploying them as alternative nutrient analytical systems. Thirty six of such applications were identified, out of which only 5 are dedicated solely to plant analysis. Collectively, the functioning mechanisms of most of the products were found to be based on colorimetry, spectroscopy or sensor technology. However, in comparison with traditional wet chemistry methods, the accuracy of the products is yet to be fully resolved, given the paucity of data in that regard. Subsequently, we reflected upon the effectiveness of the products in generating relevant information to guide rationale fertilizer recommendations, and in that context discussed the concept of balanced fertilizer regimes that consider soil levels of different nutrients; associated soil factors that determine nutrient bioavailability and actual uptake by crops; and

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E. Lichtfouse (ed.), *Sustainable Agriculture Reviews*, Sustainable Agriculture Reviews 25, DOI 10.1007/978-3-319-58679-3_1

complex farming systems that may undermine the precision and efficiency of fertilizer application.

Keywords Balanced fertilizer recommendation • Critical nutrient level • Nutrient bioavailability • Rapid nutrient testing method • Soil and crop-specific fertilizer regime • Wet chemistry

1.1 Introduction

30-50% of crop yield increases have been realized through use of chemical fertilizers (Stewart 2002), primarily nitrogen, phosphorus and potassium (NPK), combined with improved crop varieties, pesticides and mechanization, in relatively fertile agricultural soils. However, with the increasing human population and associated increase in food requirements in both quantitative and qualitative terms, there is heightened need to more effectively utilize less-fertile and/or degraded lands for agriculture, in order to minimize encroachment into high-value ecosystems. Given the importance of fertilizers in crop productivity, Bindraban et al. (2015) argued for a paradigm shift in re-designing fertilizer products by (i) taking plant biological and ecological processes as a starting point for innovative packaging and delivery of nutrients to plants and (ii) re-tuning agronomic fertilizer recommendations to make them more specific to crop, soil and agro-climatic conditions within the socio-economic context of varying farming practices. Such re-tuning implies that soil fertility and plant nutrition diagnostic tools would also have to be reassessed, with a view to making them more attuned to the realities of different categories of farmers worldwide. However, retuning fertilizer recommendations and re-designing fertilizers are not trivial exercises, due to the complex nature of the nexus of plant-soil-water-farming systems. Additionally, minimizing emissions, losses and attendant environmental side effects of chemical fertilizers that contribute to climate change and eutrophication warrants precision in fertilizer application (Attanandana et al. 2008).

Soil fertility issues are of particularly serious concern in Sub-Saharan Africa, due to inherently low nutrient levels caused by the weathered nature of soil parent materials. For instance, of five African countries recently studied for crop responses to nutrients in multiple locations, only one, Malawi, showed available P median level, averaging 33.6 mg/kg, that was above the critical level (15 mg/kg) needed for good maize productivity. The rest, including Nigeria, Tanzania, Kenya and Mali, had available P median values of between 3.6 mg/kg and 9.9 mg/kg (Kihara et al. 2016). For this reason and the inadequate, and often, outright non-amendment of agricultural soils with mineral fertilizers, African soils have been rendered less productive. This evidences the need to add specific nutrients (micro and macro) in fertilizers to boost yield responses (Vanlauwe et al. 2014). In addition, the use of high-yielding crop varieties and their associated high N needs have led to significant stripping of

the soil of micronutrients (Cakmak 2009; Jones et al. 2013; Shukla et al. 2015). Therefore, in the context of balanced fertilizers, the depletion of micronutrients in continuously cultivated soils warrants a reassessment of the composition of fertilizers, to sustain and increase yield, and to contribute in restoring the nutritional contents of food, fruit and vegetable crops that have been in steady decline over the past decades (Fan et al. 2008; Mayer 1997). Given these scenarios, fertilizers should be effective for crop production, and investment in them rewarding to farmers. The nutrients in fertilizers should be taken up by plants as instantaneously as possible, so as to prevent or minimize their contribution in degrading the ecosystem and soil health, such as by reducing soil microbial diversity (see for e.g., Geisseler and Scow 2014). Unfortunately, this is not the current situation, as most nutrients applied to the soil, about 90% in the case of P, do not end up in the intended target, but are lost to the environment (Baligar et al. 2001).

Ironically, it is in this same regions of the world with low soil fertility that farmers – especially smallholders – have the most limited access to standard soil analysis infrastructure and accompanying appropriate fertilizers. Also, there is a lack of facilities or capabilities for soil analysis, and where these exist, they are mostly substandard, yet expensive, and thus beyond the reach of most smallholder farmers. Fortunately, novel technologies and commercial products have become available, with claims of providing on-farm, timely, inexpensive, yet accurate evaluation of soil fertility and nutrient status of crops. In addition to measuring the nutrients themselves, these mobile soil testing products are also claimed to be able to determine soil physico-chemical properties such as texture, pH, organic matter content, cation exchange capacity, and soil moisture, among other factors that co-determine nutrient availability to plants. Upon these determinations, fertilizer recommendations may be made in accordance with the test results. Notably, the manufacturers of these mobile soil-plant nutrient testing systems claim good performance of their products, relative to reference standard wet chemistry methods. In this paper, we will collectively refer to these applications as rapid nutrient testing methods.

However, despite rapid soil-plant nutrient testing methods having been in existence for a couple of years now, only a few studies have attempted to evaluate their utility and efficiency as components of an integrated soil fertility management strategy. In fact, only a few of these products have had any sort of independent validation, as evidenced by the paucity of information in the scientific literature. The objectives of this review, therefore, are (i) to identify the suite of commercial soil and plant nutrient testing methods currently in the market, (ii) to evaluate the basis for deploying them as alternative soil and plant nutrient analytical systems, and (iii) to reflect on their effectiveness for generating relevant information for arriving at rationale fertilizer recommendations. It is anticipated that this work will provide helpful information in support of soil fertility and crop nutrition research and development activities in regions where standard wet lab capabilities are limited, expensive, or non-existent.

1.2 Relationship Between Soil Nutrients, Plants and Fertilizer Requirements

The optimal growth and yield of food crops require the presence in soil and availability to plants of multiple essential nutrients, namely N, P, K, calcium [Ca], magnesium [Mg], sulfur [S], copper [Cu], iron [Fe], manganese [Mn], molybdenum [Mo], nickel [Ni], zinc [Zn], boron [B] and chloride [Cl]. In addition, silicon [Si], selenium [Se] and cobalt [Co] are classified as "non-essential", but have been found to stimulate crop productivity. Given this multiplicity in the nutrient needs of crops, it is not surprising that fertilizer formulations containing specific combinations of nutrients could dramatically increase growth and yield, with responses of 10% to over 100% observed, dependent on the nutrient and crop (see a review of this topic in Dimkpa and Bindraban 2016). To be effective, however, these nutrients must be present in the soil at levels that are sufficiently bioavailable for plant uptake, and must actually be taken up into the plant tissue. The availability of nutrients to crops is, nevertheless, influenced by various soil physico-chemical properties such as pH, organic matter, cation exchange capacity, presence of anions that interact with specific cations, as well as soil moisture content (for more details about these topics, readers are directed to Marschner 2012). In addition to these abiotic factors, biotic factors such as rhizosphere microbes play a role, sometimes conflicting, in nutrient dynamics. For example, some microbes may compete with plants for specific nutrients, while others may avail plants of nutrients under conditions in which such nutrients would otherwise be unavailable to the plant (De-la-Peña and Loyola-Vargas 2014; Dimkpa et al. 2015; Dotaniya and Meena 2015; Koele et al. 2014; Kuzyakov and Xu 2013; Zhu et al. 2016). While these abiotic and biotic edaphic factors may not influence an ex-situ chemical extraction procedure to determine nutrient levels, they do determine the in-situ efficiency of crops in acquiring and using nutrients in the soil. Hence, a comprehensive soil testing system should consider not only the nutrients in soil, but also the presence of such abiotic, and possibly, biotic soil properties, since they are relevant in the subsequent derivatization or modeling of the potential bioavailability and actual uptake of nutrients by plants that lead to fertilizer recommendations.

Except for N, which mainly has to be fixed into the soil from the atmosphere, crop nutrients are naturally soil-occurring, and are present in different forms and amounts, from high and optimal, to low and very low, dependent on soil type, history of crop species, intensity of cropping, and weather conditions. Regardless, an optimum level of each nutrient is required to drive crop productivity, as proposed by Liebig's law of the minimum. For this reason, fertilizers are supplemented into the soil to either supply nutrients where they are inherently lacking, or to replenish soil nutrient stocks depleted due to crop growth. Figure 1.1 shows a schematic representation of the relationship among the level of nutrients in soil, crop responses to the presence of nutrients, and fertilizer recommendation rates based on soil nutrient levels. It shows a "critical" nutrient level, defined as the level of a specific nutrient in the soil below which crop performance (growth and yield) could be progressively

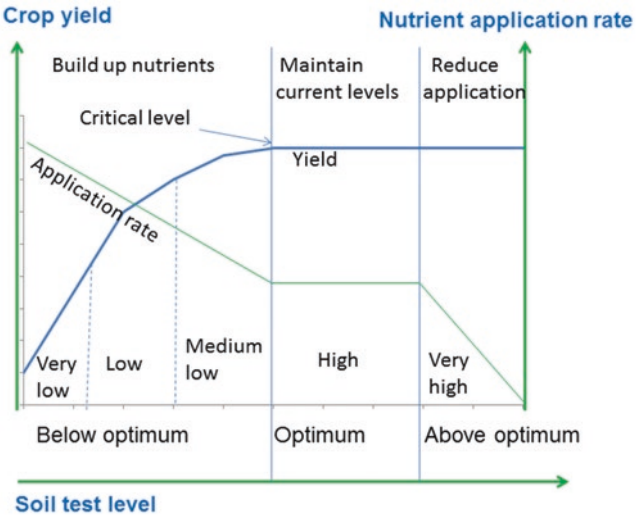

Fig. 1.1 Conceptual relationships among soil nutrient level, fertilizer recommendation and crop yield. The level of nutrients in soil based on soil test can be correlated with crop yield level, on the basis of which fertilizer recommendation is made, not only to increase yield, but also to ensure that only the appropriate rates of nutrients are applied, and when they are needed (Figure modified from Laboski's online resources at: http://www.soils.wisc.edu/extension/materials/Sampling_Fert_Recs_Econ.pdf)

negatively impacted. Thus, below the critical level, addition of that nutrient would trigger a positive response. However, the relevance of a critical soil nutrient value is dependent on a number of factors, including specific crop requirement for that nutrient; soil texture; the soil depth sampled; the relative ratio of nutrient concentrations in soil that drive antagonistic or synergistic outcomes (Voortman and Bindraban 2015), and the chemical extraction agent used for its determination. Thus, the critical level of a nutrient in the soil in relation to commensurate fertilizer recommendation must be considered in the context of crop-soil specificity and the effectiveness of the extraction procedure. Table 1.1 shows examples of ranges of values for critical levels of different nutrients that may be found in agricultural soils, based on data obtained from different soil-crop conditions and a specific extraction procedure (Alloway 2008; Anderson et al. 2013; Heckman 2006; Koenig 2002). Because nutrients in soil are in constant flux between soil particles they are bound to and soil solution phase, their bioavailable levels could vary even within the same soil and cropping conditions for the same nutrient, dependent on sampling time, and also on the extraction method employed (Pradhan et al. 2015; Sobral et al. 2013). In laboratory extraction procedures, relatively high concentrations of acids (e.g., acids in Mehlich-3; diethylenetriaminepentaacetic acid [DTPA]) are used for soil extraction. This is in contrast to the low levels of organic acids (e.g., malic, oxalic, succinic, dimugineic) typically present in plant root exudates used by plants for natural dissolution of nutrients (Keuskamp et al. 2015). Thus, compared to root exudate-based

Table 1.1 Critical levels of nutrients in soils

Element	Critical level (mg kg^{-1})
N	4 – 15[+]
P	11 – 31[a]
K	17–74[a]
Ca	308–504[a]
Mg	23–42[a]
S	8–10*
Zn	0.5–1.0[b]
B	0.25–0.5[c]
Mo	0.10–0.15[d]
Mn	50–100[b]
Cu	0.1–0.2[b]
Fe	2.5–4.5[b]

Extractant: [a]Mehlich-3; [b]DTPA; [c]hot water; [d]NH_4OAc
[+]Unspecified, but $CaSO_4$ or KCl commonly used. [*]KCl40-S

levels of bioavailable nutrients, artificially determining nutrient availability using chemical extractants may provide an overestimation of actual plant- available soil nutrient levels.

Accordingly, different nutrient levels can be distinguished: total (ultimate level in soil), extractible (fraction of total obtainable using a specific extraction method), bioavailable (fraction of total present for potential uptake by crops), in planta (fraction of bioavailable actually taken up from soil by plant). While an array of soil physico-chemical properties dictate what fraction of the total nutrient level would be plant-available, plant-dependent factors, on the other hand, may result in the bioavailability of soil nutrients not correlating with their actual uptake into the crop. Such factors may include (i) inherent differences in the metabolic characteristics of plants related to nutrient mobilization (e.g., quality, quantity, and rate of root exudation; Keuskamp et al. 2015); (ii) different abilities (e.g., enzymatic and/or root architectural differences) of crops to interact with different nutrients and to take them up efficiently (White et al. 2013); (iii) a specific crop's need for a specific nutrient that may be temporal in nature (Monreal et al. 2016); and (iv) plant growth rate determined by above ground conditions. Because of the many inter-related factors at play at the plant-soil-water-farming systems nexus, clear identification of real and potential variables and measurable parameters that should direct rational fertilizer regimes from the soil, plant and fertilizer perspectives is necessary (Table 1.2). This table adopts a systems approach whereby, on the basis of the measured physico-chemical parameters, the bioavailability and uptake of the nutrients by crops can be predicted, for instance, using modelling approaches (Duffner et al. 2014; Sattari et al. 2014).

From the foregoing, it is evident that addressing the complexities in soil fertility and crop nutrition dynamics would require that novel and innovative crop-nutrient strategies be devised and implemented. This would improve nutrient measurement

Table 1.2 Variables, parameters and corresponding rationales for soil and plant testing and fertilizer recommendations

Variable	Parameter	Rationale
Soil nutrient-related processes		
Total soil nutrient content	Total amount present in the soil for a given nutrient	Total amount of a nutrient in the soil can be higher, (10 -100 times higher) than needed by plant. These are not all readily available for plant uptake, but could potentially be released from the soil solid phase.
Extraction method	Which fraction of total nutrient in soil can be extracted and by which method	Chemical extractants, while they provide some indication of what fraction of total nutrients may be available for plant uptake, tend to lack specificity in distinguishing how nutrient elements are distributed and bound among different soil mineral phases.
Nutrient-soil processes	What soil factors are interacting with nutrients	In situ mid infrared (MIR) spectroscopy can be used to identify soil minerals and organic matter species, and nutrients interacting with them, but are unable to differentiate between total and extractible levels of such nutrients.
Soil abiotic characteristics that determine availability of nutrients	pH, organic matter, soil texture, CEC, water retention	Determination of these parameters will allow for tweaking of soil properties to permit nutrient availability. Eventually, soils of different textures, organic matter content, CEC and moisture levels would require different nutrient management strategies.
Soil biotic characteristics that determine nutrient availability	A variety of soil microbes, including bacteria, fungi and oomycetes	Soil microbial population and dynamics as well as the degree of their ability to influence nutrient cycles and other soil properties are important to delineate microbial effects on soil fertility.
Availability levels	Categories of soil availability (very low to excessively high) can be distinguished.	Determination of critical levels are important in order to decide if and when to supplement the soil with specific nutrients and what amounts to recommend.
Plant nutrient-related physiology and plant sampling strategies		
Root morphology	Root elongation and lateral root proliferation	The volume of rooting determines the reach by plants of soil nutrients located in and around the rhizosphere. Thus, both root elongation and lateral root proliferation have ramifications for crop nutrition.

(continued)

Table 1.2 (continued)

Variable	Parameter	Rationale
Root exudates	Root exudate classes and plants releasing them	Knowledge of root exudates and their efficiencies in availing plants of different nutrients may be useful in breeding or engineering plants with enhanced uptake capacities and in designing mixed cropping systems in which crops with low exudate capacity can benefit from those exuding nutrient mobilizing metabolites.
Destructive sampling	Tissue (shoot, seed, grain and root) preparation methods	Destructive sampling would permit the determination of nutrient compartmentalization in roots, leaves and seeds. However, results between sampling of same treatments may vary due to phenological effects over time and biomass accumulation and consequent dilution of nutrient levels. Phenological normalizations are required to address such differences.
Non-destructive measurement	Spectral analysis on in vivo plant tissues	In situ and real time elucidation of nutrient dynamics in planta obtained from sampling intact plants has the capability of informing on which nutrients may be limiting growth at specific times.
Critical levels of nutrients in different plant organs	Nutrient contents of leaf, grain/fruit/seed or xylem sap. Also root nutrient content excluding surface-adsorbed nutrient	Levels of nutrients in the plant are an indicator of their bioavailability in soil and the efficiency of their translocation into the plant.
Nutrient deficiency symptoms diagnostics	Timing and method of application	The uptake and internalization of nutrients are key factors in determining crop health, growth, yield, and produce nutritional quality. Timely and proper diagnosis of nutrient levels in crops tissues can lead to designing corrective strategies on time.
Nutrients in fertilizers		
Chemical composition of fertilizers	Specific nutrients and the quantities needed in a fertilizer formulation	Nutrient composition of fertilizers should be in agreement with plant physiology and soil conditions. This is important for soil and crop-specific fertilizer recommendations.
Ratio of nutrients in fertilizers	Ratio of one nutrient to another in a fertilizer	Ratios of the different nutrients in fertilizers is important to prevent antagonistic nutrient-nutrient interactions while promoting synergistic outcomes.

(continued)

Table 1.2 (continued)

Variable	Parameter	Rationale
Packaging of nutrients in fertilizer formulations	Form of nutrients (granular, tableted, salts, micro or nanoparticulate); enabled fertilizers (nutrients with nano or micro polymer surface modifications), shape of fertilizers (spherical, rod-like, triangular)	Form size, shape and surface properties of nutrients in fertilizer formulations may be important in the eventual state of the nutrients in the environment and how they influence crop performance and the environment (leaching, fixation, persistence, etc).
Quantity of fertilizer required	Amount of fertilizer to be applied per unit area	Amounts needed for a given expected crop yield should be applied. This will avoid both under -and over- application of nutrients, which respectively, results in poor crop response and nutrient losses or potential phytotoxicity
Method of application	Soil, foliar, seed coating	Crop response can vary among fertilizer application methods.
Timing of application	Timing of application, growth stage of plant	Synchronizing application timing and crop need for a nutrient is important to maximize fertilizer use.
Effects of fertilizers on soil	Fertilizers change the soil conditions – e.g. pH, soil microbiology.	Certain fertilizers may acidify or alkalinize the soil. Fertilizer application must consider these outcomes in relation to the natural soil pH. Dramatic changes in soil chemistry, flora and fauna caused by fertilizers can have serious implications for soil health.

practices, their availability under natural conditions, their supply to soil (fertilizer application), and their utilization by plants, leading to improved crop production and reduction in the negative effects of chemical fertilizers.

1.3 Rationale for Rapid Soil and Crop Nutrient Testing Strategies

1.3.1 Standard Wet Chemistry for Soil and Plant Analysis: An Overview

In this section, we will provide an overview of standard wet chemistry soil and plant analysis and the rationale for alternative nutrient testing pathways. Current soil nutrient testing methods are dependent on chemical extraction of nutrients from the soil, with the selected extractant based on soil properties, in particular pH. Following that, the concentration of the extracted nutrients is correlated with plant response.

Traditionally, soil nutrient levels are determined by collecting soil samples, keeping in mind that sampling should be representative of the field, and the importance of soil depth and timing of sampling in the accuracy of the test result. A variety of tools can be deployed for nutrient analysis. Total carbon, nitrogen and sulfur analysis can be made using a CNS analyzer. Atomic absorption spectrophotometer (AAS), inductively coupled plasma emission spectrometer (ICP-emission), or inductively coupled plasma mass spectrometer (ICP-MS) are used for K, Mg, Ca, Fe, Mn, Cu, Ni, Zn, and Mo (and P, B, and S, also by ICP instrumentation). Colorimetric methods are used for phosphate, ammonium-, nitrate- and nitrite-nitrogen, and B; and ion chromatography for Cl, sulfate, nitrate-nitrogen and nitrite-nitrogen. Different species of Fe (ferric vs ferrous) and Cu (cupric vs cuprous) can be distinguished by colorimetry using different color-reactive chemical chelators. Prior to analytical measurements, the processing steps involved in traditional wet lab methods differ among the nutrients, dependent on whether they are metallic or non-metallic, and the specific extraction chemicals involved. In all cases, though, the soil is sieved to a 2 mm diameter size. In comparison, the steps involved in wet lab processing for plant tissues are more uniform than those for soil methods because plant tissues involve total analysis of each nutrient, while soil analysis are partial extractions that vary dependent on the method used. In addition, plant tissues are typically subjected to the same processing steps (e.g., drying, grinding, one acid-type digestion), irrespective of the nutrient to be determined from the plant sample or tissue type.

Extraction methods vary dependent on soil type; and combined or separate extractants can be used. In the USA, for example, Land Grant Universities provide soil testing and fertilizer recommendations to the public. Table 1.3 lists the parameters included in “basic” or “routine” soil testing to determine these recommendations, the methods used, and costs. There is no single set of test recommended across these laboratories located in California, Utah, New York, Iowa, and Georgia, representing the Western, Northeastern, North Central and Southern States respectively, due to differences in soils types, major crops and anticipated soil deficiencies. A major determinant in selecting an extracting solution is soil pH. For example, the DTPA (diethylenetriaminepentaacetic acid) procedure buffered at pH 7.3 (with triethanolamine; TEA) was developed to determine micronutrient concentrations in neutral to calcareous soils. This procedure is, thus, not appropriate for acid soils, for which the Mehlich I extracting solution (0.05M hydrochloric acid and 0.0125M sulfuric acid) is used. Both of these methods have been modified to include the extraction and analysis of phosphate and potassium (DTPA with ammonium bicarbonate buffer at pH 7.6; Mehlich III method using 0.2M acetic acid, 0.25M ammonium nitrate, 0.015M ammonium fluoride, 0.013M nitric acid, and 0.001M ethylenediaminetetraacetic acid; EDTA). Methods for each region participating in the North American Proficiency Testing program are available via the following links: http://www.naptprogram.org/files/napt/western-states-method-manual-2005.pdf; http://pss.uvm.edu/vtcrops/articles/RecSoilTestProcNE.pdf; http://www.naptprogram.org/files/napt/north-central-states-methods-manual-2012.pdf; http://www.clemson.edu/agsrvlb/sera6/MethodsManualFinalSERA6.pdf

Table 1.3 Parameters, methods and costs for routine soil testing in the USA

Region	Producer/supplier	Analyte/method	Cost per sample[a]
Western California	Basic	NO_3-N (KCl)	$35.50
		P (Olsen or Bray)	
		K (exchangeable)	
(UC Davis: http://anlab.ucdavis.edu/forms-and-guides/files/feesched2013b.pdf)	Group 2	Above +	$84.90
		K, Na, Ca, Mg (exchangeable)	
		Cation Exchange Capacity	
		Organic matter (Loss on ignition)	
		pH	
	Micronutrients	Fe, Mn, Cu, Zn (DTPA-TEA)	$55.90
Western Utah	Routine	pH	$23
		Salinity (electrical conductivity)	
		Texture (by hand)	
		P (Olsen)	
		K (Olsen)	
Utah State University: http://www.usual.usu.edu/forms/soilform.pdf	Complete	Above +	$61
		NO_3-N ($Ca(OH)_2$)	
		Fe, Mn, Cu, Zn (DTPA-TEA)	
		Sulfate-S (Calcium phosphate)	
		Organic matter (Walkley Black)	

(continued)

Table 1.3 (continued)

Region	Producer/supplier	Analyte/method	Cost per sample[a]
Central Iowa	Standard	K (Mehlich III)	$18
Iowa State University: http://soiltesting.agron.iastate.edu/Soil%20%20form-Standard%20fertility.pdf		P (Mehlich III)	
		pH	
		Lime requirement	
		Organic matter	
		Zn (DTPA)	
Northeast New York	Basic	pH	$50
		Organic matter	
		P (Morgan)	
		K (Morgan)	
		Fe, Mn, Cu, Zn (Morgan)	
		Wet aggregate stability	
		Soil respiration	
Cornell University: http://soilhealth.cals.cornell.edu/testing-services/comprehensive-soil-health-assessment/	Standard	Above +	$95
		Texture	
		Citrate extractable protein test	
		Available water capacity	
South Georgia	Routine	pH	$6
University of Georgia http://aesl.ces.uga.edu/FeeSchedule/Complete.pdf		Lime requirement	
		P (Mehlich I)	
		K, Ca, Mg (Mehlich I)	
		Zn, Mn (Mehlich I)	

[a]Prices listed on web sites February 21, 2016

1.3.2 State of Standard Wet Chemistry Analysis of Soil and Plant Samples in Africa

In contrast to the USA, in Africa, farmers, most of them small-scale, do not typically evaluate the nutrient status of their soils. Hence, its ramifications for, or constraints to, their productivity levels are unclear. In most African countries, laboratories conducting soil tests and providing soil management services are few and far between, and the costs are beyond the reach of most farmers in the region. As indicated previously, without such soil information, it is impossible to provide soil-specific fertilizer and soil management recommendations for farmers. Furthermore, soil quality has been shown to vary with farmer wealth, where poorer farmers tend to own and cultivate land of lower soil quality (Marenya and Barrett 2009). Therefore, poorer farmers are likely more in need of explicit, site-specific information on their soils and resulting cost-effective recommendations.

In Table 1.4, a soil and plant analytical information adapted from CROPNUTS Laboratory Services Kenya is provided. CROPNUTS is a well-known laboratory that provides soil and plant analytical services for clients in Kenya, including the authors' institution, IFDC. The Table provides an indication of the state of wet chemistry-based soil and plant tissue analyses in Kenya, which has some of the most advanced soil-plant testing systems in Africa. It shows that in Kenya, wet chemistry methods for nutrient determination require prolonged (up to 10 days) waiting times between sample submission and results generation. Furthermore, at first glance, it would appear that in terms of cost per sample, these analyses are cheaper in Kenya than in the United States (Table 1.3 vs Table 1.4; 100.00 KSH = $1.00). However, compared to US farmers, each of these analyses would be considerably less affordable to Kenyan farmers, given their lower financial situations. We argue that these costs would be higher in other African countries with less advanced soil testing systems than Kenya.

For these reasons, alternative soil testing methods such as rapid nutrient testing methods, are being deployed in Africa to complement wet chemistry analysis. Generally, compared to wet chemistry methods that are performed in fixed laboratory facilities, rapid testing methods have the advantage of being portable, quicker turn-over time of results, relatively inexpensive, and in many cases require little training to perform. However, as with wet chemistry, there is no single rapid nutrient testing method that can determine or measure all the 14 or more crop nutrients in soil, in addition to all of the soil properties that influence nutrient dynamics. Indeed, both wet chemistry and rapid testing methods can provide only partial elucidation of these soil properties. Yet, data generated from a rapid testing method for a specific nutrient or edaphic factor should be comparable with that from the cognate wet chemistry method, to ensure an acceptable level of agreement. However, as important as it is to correlate wet chemistry and rapid testing results, it is also imperative to determine what soil testing method best correlates with crop responses.

Whereas the need for alternative or complementary soil and crop nutrient testing capabilities is crucial for certain agro-ecoregions such as Africa, whether wet

Table 1.4 Capabilities and costs of soil and plant analytical services in Kenya based on standard wet chemistry methods

Test matrix	Analysis type	Nutrient or soil property measured	Price/sample in Kenyan Shillings (KSH) (excl. 16% VAT)	Days to result
Soil (field crops)	Basic soil analysis	pH, %OM, %N, P,K, Mg, Ca, with Basic RX	2000	7
	Complete soil analysis	pH, EC, %OM, %N, P, Ca, Mg, Na, S, Fe, Mn, Cu, B, Zn, CEC, plus Ca:Mg ratio, %Ca, %Mg, %K, %Na, %OB, %H, with fertilizer recommendation (RX)	4500	7
	Available soil nitrogen	Available soil nitrogen kg/ha (top soil + sub soil)	3500	7
	Soil life test	Soil biota respiration test (indicator of soil health)	2800	7
	Exchangeable Acidity (Hp)	Hp	405	7
	Soil texture analysis	%Sand, %Silt, %Clay	2000	10
Soil (flowers and greenhouse crops)	Drip & 1:2 volume extract (soil analysis)	pH, EC, NO_3, NH_4, Cl, HCO_3, P, K, Ca, Mg, Na, S, Si, Cu, Fe, Zn, Mo, B with RX	3780	5
Leaf tissue	Complete leaf analysis	N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu, B, Na (with RX)	3500	7
Manure and compost	Complete manure/compost analysis	% DM, %C, %n, (C:N ratio), P, K, Ca, Mg, Na, S, Cu, Fe, Mn, Zn, B	5760	10
	Compost liquid extract analysis	pH, EC, NO_3, NH_4, Cl, HCO_3, P, K, Ca, Mg, Na, S, Si, Cu, Fe, Zn, Mn, Mo, B	4500	7
	Compost 1:1.5 water extract analysis	pH, EC, NO_3, NH_4, Cl, HCO_3, P, K, Ca, Mg, Na, S, Si, Cu, Fe, Zn, Mn, Mo, B	4500	7
Fertilizer and lime	Lime quality assessment	%Ca, %Mg, CCE, PSRE (Mesh size), ECCE (Eff. calcium carbonate equiv.)	7000	14

chemistry or rapid testing, reproducibility/consistency and correlatability with crop uptake/response of the system are among the critical factors to consider. Unfortunately, these factors are often under the influence of the large spatial and temporal variabilities in soil properties, complicating the precision and accuracy of any given testing method.

1.4 Commercially Available Rapid Soil Nutrient Testing Applications

In this study, an in-depth web search was conducted to identify the suite of rapid nutrient testing methods currently available in the market. The search was done using keywords/phrases including "quick soil testing kits," "quick soil analysis tools," "quick plant nutrient testing kits," "quick plant analysis kits," "portable nutrient testing kits" and "mobile nutrient testing kits." A list of products or methods identified from the search is presented in Table 1.5 (for soil kits) and in Table 1.9 (for plant kits). It is worth mentioning that this list of 36 products is not exhaustive, as new products may have been introduced into the market since the search was made, or the existence of some kits may not have been publicized through the popular internet. Notably, the tables show that most of the kits are designed for the detection of NPK and one or more other soil chemical properties; and for soil analysis, compared to plant tissue analysis. However, a number of kits were identified that are capable of detecting both macro and micro nutrients, in addition to other soil chemical parameters. The Tables also describe specific parameters that would assist with decision making regarding the use of any identified kit, including:

1. The nutrients that can be measured.
2. The detection mechanism involved.
3. How rapid (time lag between soil sampling and result generation) the application is.
4. The accuracy of measurement.
5. The level of training required to use the system.
6. Availability and nature of independent scientific scrutiny of the product to validate claims.
7. Cost of obtaining or applying the product.

Other pertinent information were also collected, such as the availability of refill or replacement product – an important parameter from the point of view of the sustainability of the system. In addition, information on the producer and country where produced were also included. Unfortunately, a complete set of answers to all the parameters could not be obtained for many of the products found. For such products, these information are simply not available on the manufacturers' websites, in addition to there not being any independent validation or scientific evaluation entity for those products that could serve as a source of information.

Table 1.5 Rapid soil test kits identified from web search

Product	Producer/supplier	Method	Nutrient detected	Soil physico-chemical properties determined
Garden Kit Model EL	LaMotte	Colorimetry	N, P, K	pH
LaMotte Soil Fertility Testing Kit	LaMotte	Colorimetry	Fe, Mn, Cl, N, P, K, Ca, Mg, S	pH, organic matter
LaMotte AST-5	LaMotte	Colorimetry	NO_3^--N, P, K, Ca, Mg and Cl, Cu	pH, humus
LaMotte Soil Micronutrients Kit	LaMotte	Colorimetry	NO_3^--N, Ca, Cl, Fe, Mg, Mn, NH_3, S	None indicated
Model SCL-12 (SMART 3) Electronic Soil Lab kit	LaMotte	Colorimetry	N,P,K, Ca, Mg, S, Cl, Fe, Mn, Cu, Zn	pH
Nutrient analyzer	CleanGrow	Electrode sensors for different nutrients	Ca, Mg, Cl, K, Na, NO_3^--N, NH_4^+-N	None
Hach	HATCH CO.	Colorimetry	NO_3^--N, P, K	pH, EC
Kasetsart (N-P-K)	Kasetsart University and Boon Din Thai Co.	Colorimetry	N,P,K	pH
Soil Test Strips	AccuGrow Hach Inc.	Colorimetry	NO_3^--N, P, K	pH
SoilDoc	Columbia Univ./ Univ. of Maryland	Electrode Sensor Meters for different nutrients, Colorimetry + Android App system	N (NO_3^-; NO_3^-N), phosphate-P,K, sulfate-S	pH, organic matter, EC, texture, compaction, Biologically active Carbon
Model SIW-1	HATCH	Colorimetry	N,P,K	pH, salinity, texture
Soil Testing Kit	Growers Suppliers	Colorimetry	N,P,K	pH
Rapitest Digital Soil Test Kit	CAROLINA Biological Supply Co.	Electronic Meter with LED test-result indicator	N,P,K	pH
Rapitest Soil Test Kit	CAROLINA Biological Supply Co.	Colorimetry	N,P,K	pH

(continued)

Table 1.5 (continued)

Product	Producer/supplier	Method	Nutrient detected	Soil physico-chemical properties determined
Eartheasy Soil Test Kit	EARTHEASY Co.	Colorimetry	N,P,K	pH
Luster Leaf 1605 Rapitest Digital Soil Testing Kit	Luster Leaf Products	Colorimetry with LED output.	N,P,K	pH
LusterLeaf 1601 Rapitest Soil Test	Luster Leaf Products	Colorimetry	N,P,K	pH
Luster Leaf 1880 Rapitest Electronic 4-Way Analyzer	Luster Leaf Products	Electronic Meter	N,P,K	pH
Botanico Soil Test Kit	Amazon UK	Colorimetry	N,P,K	pH
"Mobile Lab"	SoilCares	X-ray fluorescence and (mid) infrared spectroscopy.	N,P,K, Ca,Mg	pH, texture, organic matter, CEC
"Sensor"	SoilCares	X-ray fluorescence and/or (near) infrared spectroscopy.	Macro and micro nutrients	
Compact laboratory	SoilCares	Electromagnetic and fluorescence detection (installable "laboratory" in a farm or in the booth of a farmer's car)	Macro and micro nutrients	
TRANSCHEM Soil Test Kit	Transchem Agritech Ltd.	Colorimetry	NO_3^- -N, NH_4^+-N, P, K, Ca, Mg, S	pH, organic carbon
PRERANA Soil Testing Kit	PRERANA Laboratories	Colorimetry	N,P,K	pH, organic carbon
Soil Testing Kit	Innovative Instruments – India	Colorimetry	N,P,K	pH, organic carbon
Portable soil testing kit	Nagarjuna Agro Chemicals Pvt. Ltd.	Colorimetry	N, P, K, S $CaCO_3$, Zn, Fe, B	pH, EC, organic carbon
SKW 500 Complete soil Kit	PALINTEST – United Kingdom	Colorimetry and electrochemical sensor	NO_3^- -N, NH_4^+-N, P, K, Mg, Ca, Cl, Cu, Fe, Mn, S	pH, salinity conductivity

(continued)

Table 1.5 (continued)

Product	Producer/supplier	Method	Nutrient detected	Soil physico-chemical properties determined
SKW 400 professional soil management kit	PALINTEST – United Kingdom	Colorimetry and electrochemical sensor	N,P,K, Ca, Mg,	pH, conductivity
SKW 300 soil test kit	PALINTEST – United Kingdom	Colorimetry and sensor	N (NO_3^-),P,K, Ca, Mg,	pH
Synergy Soil Test Kit	Synergy Consulting, Australia		NO_3^-N, NH_4^+-N, P, K, S, Cu, Zn, Mn, Fe	pH, organic carbon, EC
Laqua Twin Nutrient Meters	Spectrum Technology	Meter with sensor	NO_3^--N, Ca, K, Na	pH

Product	Relative rapidity	Complexity	Nutrient fraction measured	Scrutiny/online reviews
Garden Kit	Min	Simple		No external reviews, no journal articles
Model EL				
LaMotte Soil Fertility Testing Kit	Min	Less simple due to multiple nutrients	Bioavailable fraction	No external reviews, no journal articles
LaMotte AST-5	Min	Simple	Bioavailable fraction	IFDC-tested, recommended
LaMotte Soil Micronutrients Kit	Min	Less simple	Bioavailable	
SMART 3 Electronic Soil Lab	Min	Simple	Bioavailable	
Nutrient analyzer	Sec-Min	Simple		No external reviews, no journal articles
Hach	Min	Requires some skill and training	Bioavailable fraction	IFDC-tested, recommended
Kasetsart (N-P-K)	Min	Simple	Bioavailable fraction	IFDC-tested, recommended
Soil Test Strips	Min	Simple	Bioavailable fraction	IFDC-tested, least recommended
Soil Doc	1-2 days	Requires skill and training	Bioavailable fraction	Being tested in Africa; widely acclaimed
Model SIW-1	Min	Simple		
Soil Testing Kit	Min	Simple		
Rapitest Digital Soil Test Kit	Min	Simple	Bioavailable fraction	

(continued)

Table 1.5 (continued)

Product	Relative rapidity	Complexity	Nutrient fraction measured	Scrutiny/online reviews
Rapitest Soil Test Kit	Min	Simple	Bioavailable fraction	
Eartheasy Soil Test Kit	Min	Simple	Bioavailable fraction	
Luster Leaf 1605 Rapitest Digital Soil Testing Kit	Min	Simple	Bioavailable fraction	Mixed customer review (Amazon)
LusterLeaf 1601 Rapitest Soil Test	Min	Simple	Bioavailable fraction	Good customer review (Amazon)
Luster Leaf 1880 Rapitest Electronic 4-Way Analyzer	Min	Simple	Bioavailable fraction	Mixed customer review (Amazon)
Botanico Soil Test Kit	Min	Simple	Bioavailable fraction	Mixed customer review (Amazon)
Mobile Lab	Hrs	Complex, requires training	Total and bioavailable	Published methodology
Sensor	Min	Simple		
Compact laboratory				
TRANSCHEM Soil Test Kit	Min	Simple, no special training required	Total and bioavailable	Claimed validation by the Indian soil science/ agric. institutes and universities
PRERANA Soil Testing Kit	Min	Simple, no special training required	Bioavailable	
Soil Testing Kit	Min	Simple, no special training required		Claimed validation by ICAR (India)
"Portable soil testing kit"	'On the spot' detection	Appears simple		No external reviews, no journal articles; self claim to work well in mildly acidic, saline, alkaline and calcareous soils.
SKW 500 Complete Soil Kit.	Several mins	Would require some training for calibration		No external reviews but appears to be an interesting product
SKW 400 professional soil management kit	Several mins	Would require some training for calibration		No external reviews but appears to be an interesting product

(continued)

Table 1.5 (continued)

Product	Relative rapidity	Complexity	Nutrient fraction measured	Scrutiny/online reviews
SKW 300 soil test kit	Several mins	Some level of training	Bioavailable	No external reviews
Synergy Soil Test Kit				
Laqua Twin Nutrient Meters	Sec-Min	Simple		None

Product	Country	Price/Kit ($)	Sustain ability (Refill)	Contact	Strength/ Weakness of results
Garden Kit Model EL	USA		Refill available	www.lamotte.com	Quantitative (range)
LaMotte Soil Fertility Testing Kit	USA	609	Refill available	www.lamotte.com	Quantitative, but requires calculations; unable to detect Zn, Cu and B
LaMotte AST-5	USA	309	Refill available	www.lamotte.com	Quantitative for Cu, Mg and Cl
LaMotte Soil Micronutrients Kit	USA	555.95	Refill available ($310.95)	www.lamotte.com	Semi-quantitative
SMART 3 Electronic Soil Lab	USA		Refill available	www.lamotte.com	Semi quantitative
Nutrient analyzer	USA; UK; Ireland			http://www.cleangrow.com/nutrient-analyzer/	Quantitative
Hach	USA	700	Refill available	http://www.hach.com	Quantitative
Kasetsart (N-P-K)	Thailand	1.5/ sample	Refill available		Quantitative
Soil Test Strips	USA	24	Refill available	http://www.accugrow.com	Quantitative
Soil Doc	USA	3/ analysis	Refill available	http://agriculture.columbia.edu/projects/agriculture/soildoc/	Quantitative

(continued)

Table 1.5 (continued)

Product	Country	Price/Kit ($)	Sustain ability (Refill)	Contact	Strength/ Weakness of results
Model SIW-1	USA	1513		http://www.hach.com/soil-and-irrigation-water-test-kit-model-siw-1/product?id=7640217314	
Soil Testing Kit	USA	31.95		https://www.growerssupply.com/farm/supplies/prod1;gs_lawn_and_garden-gs_soil_testing_meters;pg105068.html	
Rapitest Digital Soil Test Kit	USA	34.95		http://www.carolina.com/	Quantitative
Rapitest Soil Test Kit	USA	22.50		http://www.carolina.com/	Quantitative
Eartheasy Soil Test Kit	USA	12.95		http://eartheasy.com/soil-test-kit	
Luster Leaf 1605 Rapitest Digital Soil Testing Kit	USA	22.31		http://www.lusterleaf.com/nav/soil_test.html	Quantitative
LusterLeaf 1601 Rapitest Soil Test	USA	11.95		http://www.lusterleaf.com/nav/soil_test.html	Quantitative
Luster Leaf 1880 Rapitest Electronic 4-Way Analyzer	USA	24.09		http://www.lusterleaf.com/nav/soil_test.html	Quantitative; for solid soil testing only and will not function in liquid
Botanico Soil Test Kit	UK	27.33		http://www.amazon.co.uk/Nortene-Botanico-Soil-Test-Kit/dp/B0013A1IP2	

(continued)

Table 1.5 (continued)

Product	Country	Price/Kit ($)	Sustain ability (Refill)	Contact	Strength/ Weakness of results
Mobile Lab	Kenya/The Netherlands			http://www.soilcares.com/marketing@soilcares.com	Requires tedious sample preparation step.
Sensor	Kenya/The Netherlands			http://www.soilcares.com/	
Compact laboratory	Kenya/The Netherlands			http://www.soilcares.com/	
TRANSCHEM Soil Test Kit	India			http://www.transchem.in/soiltesting.htm	
PRERANA Soil Testing Kit	India		Refill available	http://www.preranalab.com/Soil-Testing-Kits.html	
Soil Testing Kit	India			http://innovativeinstruments.in/soil-testing-equipment.html	
Portable soil testing kit	India		No info	www.nagarjunaagrochemicals.com	Qualitative results only
SKW 500 Complete Soil Kit	UK/USA		Refill reagents available	http://www.palintest.com/products/skw-500-complete-soil-kit/	Quantitative, with range of detection for all nutrients
SKW 400 professional soil management kit	UK/USA		No info	http://www.palintestusa.com/products/skw-400-professional-soil-management-kit/	Quantitative
SKW 300 soil test kit	UK		Replace ment sensors/ refills available	http://www.palintestusa.com/products/soil-management-kit/	No fertilizer recommen dations
Synergy Soil Test Kit	Australia		No info	http://www.synergyco.com.au/index_sub2-1.html	Independent interpretation provided
Laqua Twin Nutrient Meters	USA	435-495	Replacement sensors available	www.specmeters.com;	Limited in what can be measured

While some of the identified rapid nutrient testing methods provide generalized or specific fertilizer recommendations tailored to the soil test results, others require post measurement calculations and derivatizations to arrive at fertilizer requirements appropriate for the results. Nevertheless, collectively, the level of information available, if well synthesized, could provide substantial basis to inform on the promise or otherwise of a specific rapid nutrient testing package.

1.5 Properties of Rapid Nutrient Testing Applications

As indicated in Table 1.5, most of the available rapid nutrient testing methods for soil are based on colorimetry principles. However a number of others are based on an integration of colorimetry with Android application systems, while others are based on spectroscopy (X-ray, infrared) and sensor meters. In this section some broad descriptions of the properties and methods of operation of the products are provided, according to these groupings.

1.5.1 Colorimetry-Based Systems for Rapid Soil Nutrient Testing

Central to colorimetry or photometry-based nutrient testing methods is the development of color or turbidity in soil samples, which intensities are directly correlated with the concentration of specific nutrients. Hence, in colorimetric testing methods, different nutrients are indicated by different color or turbidity reactions. Using the LaMotte AST-5 kit as an example, the soil is extracted with the Mehlich I solution for the analysis of NO_3-N, NO_2-N, phosphate, K, Ca, Mg, NH_4-N, Cu, Mn, and Fe. The procedures are based on standard laboratory protocols for the determination of these nutrients, as used in Soil Testing Laboratories before more sophisticated instrumentation was employed. Most of these analyses are based on the formation of a color with reactions between the test analyte and the prescribed reagent(s) included in the test kit. The color formed is matched to a plastic color wheel mounted on a viewer. NO_3-N is determined using the diazotize dye method after conversion to nitrite using cadmium. NH_4-N is determined using Nessler reagents; P by the stannous chloride method; Fe using bipyridal; Cu by diethyeldithiocarbamate; and Mn is oxidized by periodate to form permanganate. Other methods form precipitates including: K by precipitation with tetraphenylboron, S by precipitation with barium, and Cl by precipitation with silver. Ca and Mg are determined by EDTA titration.

On a general basis, colorimetry-based methods require sample preparation steps, including mixing the extraction solutions of specific nutrients with a specific quantity of soil; shaking and incubating the mixture for a specified time period (usu-

ally 1-5 min); collecting the clear upper liquid and adding to a nutrient indicator reagent or tablet (dissolved in water); mixing until well dissolved and then further incubation ($\leq$ 5 min). Color development occurs, followed by a color interpretation on a pre-made color chart. The color reading is then correlated to actual values (estimates), within a range, for each parameter. Subsequently, the estimates are used to inform fertilizer recommendations for each nutrient for the soil in question. These steps may be specific for the nutrient being determined; but many, however provide only information on whether the specific nutrient is ranked as low, medium, or high and provide fertilizer application rates that are not specific for a crop or soil type.

From this generic description, it is obvious that by having an extraction procedure in the colorimetric rapid nutrient methods, potentially bioavailable fractions of nutrients can be determined. On the flip side, however, colorimetric testing methods could be fraught with certain problems: the outcome may be subjective and lack procedural reproducibility, due to any number of human errors introduced in the steps. For example, mistiming (under or over) the incubation of the reaction mixtures may influence the extent of color development, as would incomplete dissolution of powder reagents or tablets. Also, field environmental factors such as ambient light and different light intensities may confound colorimetry readings (Moonrungsee et al. 2015).

Recent advancements in the digital technology realm have led to the possibility of integrating mobile colorimetric soil nutrient testing with digital application systems such as Android operating systems, using smart phones. With that, color development can be captured photographically, displayed, and stored digitally in real time. Moonrungsee et al. (2015) reported on the use of a colorimetric analyzer-Android mobile phone system to detect P in soil. The study investigated the effects of several factors such as reaction time, ambient light, light intensity, and camera focal length on the accuracy of the mobile camera analyzer. They found variation in the color intensities of the same P concentration under different lighting conditions (dim vs bright/outdoor), when illumination was controlled by switching lights on and off, without and with the analyzer box lid. However, results in the bright environment (lights on) agreed with that from outdoor measurements. Furthermore, using soil samples collected from fruit orchards to evaluate the effect of reaction time (intra and inter day), the authors concluded, as exemplified in Fig. 1.2, that the results from their mobile detection system correlated well with those from wet spectrophotometric measurement of soil P levels. In other studies, colorimetric analysis of water or sand samples for K and Cu using mobile phone application support have also been reported (García et al. 2011; Iqbal and Bjorklund 2011). In the case of K, the degree of agreement in the results from the phone system vs atomic absorption spectroscopy in different aqueous matrices was demonstrated, showing no significant difference between them (García et al. 2011).

Advanced colorimetric rapid nutrient testing methods such as the Palintest's SKW 400 and 500 soil test kits deploy Bluetooth-enabled photometers, multiparameter sensors and reagent chemicals to analyze multiple soil parameters: pH, macronutrients, salinity and conductivity. The Palintest SKW 400 and 500 soil test procedures involve soil extraction with specific reagents, incubation, measurements

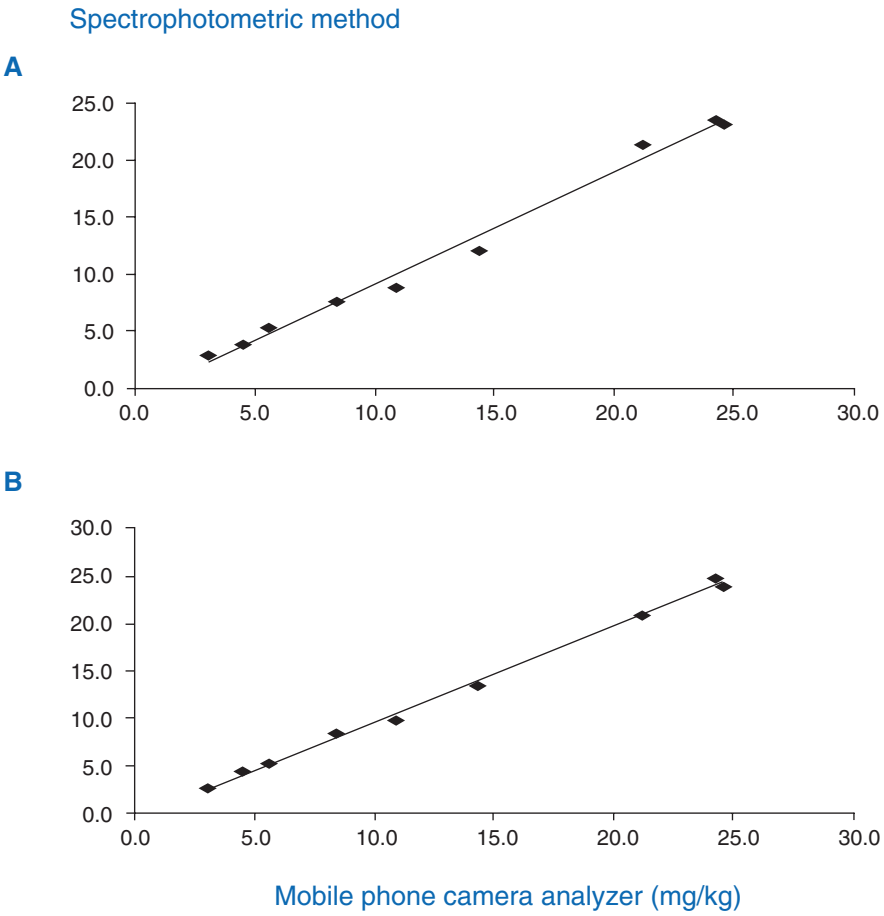

Fig. 1.2 Correlation graphs of phosphorus contents obtained from spectrophotometric method and mobile camera analyzer: (**a**) intra-day [y = 0.981–0.638; R^2 = 0.990]; and (**b**) inter-day [y = 1.005-0.382; R^2 = 0.996] measurements (Figure reproduced from Moonrungsee et al. 2015 with permission)

of color intensities using the Bluetooth-enabled photometer-sensor apparatus (referred to as "Soiltest 10 Bluetooth system"), and data comparison with stored calibration data. Upon selecting a specific test from the multiple test choices, the instrument automatically chooses the required parameters, including wavelength. Soil pH, conductivity and salinity are determined using electrochemical measurement techniques with the multiparameter pocket sensor. The sensor's dual LCD display indicates the pH and conductivity, as well as the sample's temperature. Ultimately, the Soiltest 10 Bluetooth enables wireless connectivity for digital transfer of test results.

1.5.2 Meter-Based Systems for Rapid Soil Nutrient Testing

Meter-based nutrient testing methods are miniaturized instruments operationally akin to their lab-scale counterparts employing battery-operated, nutrient-specific meters housing electrode sensors or field-portable spectrometers, as well as ion calibration solutions. These applications can perform different measurements such as electrical conductivity (EC) and pH, among others. In some cases, such as with the Nutrient Analyzer (CleanGrow) which measures EC, the meter head is digital and can be connected wirelessly to an iPod or iPad via Bluetooth, using a specific App. Among meter-based testing applications, the SoilDoc is hereafter discussed in more detail, due to its current widespread testing and deployment in field situations**.** SoilDoc is a mobile integrated package for soil fertility management developed collaboratively by the Agriculture and Food Security Center of Columbia University New York and the University of Maryland. It involves the use of reagents, battery-powered portable meter, Android Apps and Android phone or tablet, for assessing different soil parameters, including extractable macronutrients, nitrate-N, sulfate-S, phosphate-P, and potassium-K; pH; biologically active soil organic matter; EC; texture; compaction; aggregation stability, and soil moisture. In the package, a handheld penetrometer is used to determine soil compaction, and aggregation is determined using a custom-designed sieve. Electrode sensors are used to analyze pH, EC, N and K, while P, S and organic carbon are determined by colorimetry measured with a portable meter. In these cases, a soil extraction procedure is involved. The sensors are calibrated with each use; calibration standards are provided in the package. The determined variables are analyzed, interpreted through an in-built algorithm, and stored in the cloud. The information for each geo-referenced soil sample is transmitted via an android tablet or phone to a central operating system, and farmers receive quality recommendations communicated in real time. The SoilDoc system not only links soil tests with fertilizer recommendations, it also, as claimed, identifies fertilizer companies that may be present in the region to blend fertilizer types relevant for a geo-referenced agroecology.

SoilDoc has been widely promoted in Africa, and currently being deployed in several countries including Nigeria, Kenya, Tanzania, Ethiopia, Malawi, Zambia, Mozambique, Mali, Niger and Burkina Faso. In Nigeria, for example, it is being tested nationwide under the auspices of the Federal Ministry of Agriculture, alongside a number of colorimetry-based kits. Although SoilDoc may initially be cost-prohibitive, compared to the colorimetric kits being co-evaluated in the Nigerian study, a single unit of the SoilDoc system can analyze 1000 soil samples, a number far greater than the average colorimetric system that typically analyze <100 samples/kit. Noteworthy also, each sample analysis costs about $3 (Table 1.5). However, like many of the colorimetric systems, the current version of SoilDoc is unable to determine soil micronutrient status. Furthermore, being partly a reagent-based system, the SoilDoc, like the colorimetric methods may suffer from the potential problem of availability of refill chemicals in remote locations. However, the reagents are available in larger cities with improved laboratory supplies systems.

1.5.3 *Spectroscopy-Based Systems for Rapid Soil Nutrient Testing*

Non-liquid nutrient testing methods such as those based on spectroscopy are at the cutting edge of soil/plant analysis. They include applications based on X-ray fluorescence (XRF), mid-infrared (MIR) and near-infrared (NIR) spectroscopies. A powerful analytical tool, spectroscopy can be used to identify soil minerals and organic matter species. For example, prior studies used MIR diffuse reflectance (DRIFT) spectroscopy with a partial least square regression technique to successfully predict the major elemental composition, pH, organic carbon, N, cation exchange capacity (CEC), carbonate and clay concentrations, of a wide range of Australian soils (Janik and Skjemstad 1995; Janik et al. 1995, 1998). The procedure generally requires little, if any, sample preparation step; testing can be done in situ using unprocessed soil samples (Shepherd and Walsh 2007). Thus, compared to portable colorimetry-based methods, mobile spectroscopic methods for soil analysis are more advanced systems. Their high reproducibility, when compared to wet chemistry, may in part be related to the elimination of error-prone sample preparation steps by directly scanning soil samples. Each nutrient or soil parameter has unique spectral features to aid in identification and quantification (Terhoeven-Urselmans et al. 2010). Among the innovations in spectroscopy-based mobile soil testing that may be of special interest are those either being developed or already deployed by the International Center for Research in Agroforestry (ICRAF), SoilCares, CleanGrow and Spectrum Technology, among others (see Tables 1.5 and 1.9), all of which are capable of measuring pH, organic carbon, CEC, Ca, Mg, K, clay content, sand, total N, and the total contents of other macro and micro nutrients. SoilCares has its own calibration database containing many different soil samples (http://soilcaresresearch.com/project/soil-fertility-and-soil-quality). A proposed hand-held scanner being developed by SoilCares will measure NPK, pH, and soil organic matter. Data from the scans will be compared to information in the digital soil database that currently covers the East African countries of Kenya, Burundi, Rwanda, Uganda and Tanzania; and soon, elsewhere, like the Philippines, Russia, United States, Ukraine and Brazil. Scan results are returned to the farmer as fertilizer and lime recommendations.

Due to the non-involvement of chemical preparation steps, spectrometric-based testing methods have the advantage of excluding the problems associated with color or light interference, improper dissolution of extractant powders (where applicable), and temporal variability in color development that may significantly impair color interpretation. On the flip side, however, spectrometry-based testing methods are unable to determine fractions of nutrients in soil that are potentially bioavailable to the crop, unlike reagent based systems in which the extraction chemicals provide some indications of "bioavailable" elemental concentrations. Moreover, spectroscopic methods would be more expensive per initial investment. They, however, are likely to be more durable and reusable over a long time period compared to colorimetric methods; and just with a few buttons to press, training needs for users may not be dramatic (http://www.soilcaresscanner.com/).

To recap, this chapter has demonstrated that there are multiple rapid nutrient testing applications with different operational advantages and limitations, as well as costs. This gives farmers an array of choice and capability to rapidly assess soil/plant testing services on-farm, dependent on their need and affordability. Clearly, given the anticipated variabilities in the levels of accuracy and reproducibility of these systems, independent systematic evaluation and identification of the best commercially available rapid nutrient testing options will serve as a decision support tool for informed soil fertility and crop nutrition research and development efforts, especially in regions where standard wet chemistry capabilities are limited, expensive, or even non-existent.

1.6 Independent Scientific Assessment of Rapid Nutrient Testing Applications

Most claims regarding the accuracy and efficacy of the above-described rapid nutrient testing technologies have been made by the manufacturers based on their own in-house evaluation of the products. Only a limited number of independent studies have attempted to verify such claims by systematically evaluating specific test kits. Even at that, based on the original intention of the testing method, most such studies have been conducted for the purpose of detecting macronutrients (NPK) and a limited number of soil parameters. For example, Faber et al. (2007) examined the accuracy of measuring soil pH, nitrate-N, P and K of five commercially available rapid soil testing kits, compared to standard laboratory analysis. They showed that the accuracy (i.e., the degree to which the results are similar with a standard wet lab analysis) of the test results could vary significantly, dependent on the chemical composition of the extractants in the kit. The authors reported that the "La Motte Soil Test Kit" was more accurate than the "Rapitest", "Quick Soiltest", "Nitty-Gritty", and "Soil Kit" testing systems, in that order, for the measured soil parameters. Another study by Maggini et al. (2010) used quick color-reactive strips (Reflectoquant test kits), specific for NO_3^--N, $NH4^+$-N and P, coupled with reflectometry (RQFlex Plus portable reflectometer, Merck, Darmstadt, Germany) to determine the contents of these nutrients in a soil solution, compared to lab-based ion chromatographic results. They reported that the degree of accuracy was dependent on the constituents of specific kits that could interfere with the readings. The NO_3^--N kit showed the greatest relationship with the ion chromatography standards in terms of linearity, accuracy, precision and selectivity, followed by the P kit.

Another comparative study of colorimetric rapid soil testing kits, namely "Hach NPK-1", "LaMotte AST-5" (presumably the same product used in the study of Faber et al.) and "Kasetsart NPK" was conducted by IFDC during 2002. The aim of the project was to generate information for simple and effective best-management scenarios providing attractive options for soil analyses in remote regions of Afghanistan that are lacking in functional soil analysis laboratories. The consumables and reagents

Table 1.6 Properties of rapid soil nutrient test kits evaluated by IFDC

Name	Type of analysis	Ease of use	Manufacturer	Price
Hach NPK-1	pH, nitrate-N, available P, exchangeable K. Additional reagents can be purchased separately.	Requires some laboratory skill and training	Hach Co., CO, USA	$600
LaMotte AST-5	pH, nitrate-N, available P, exchangeable K, humus (organic matter). Reagents can be purchased.	Same as above	LaMotte Co., CT, USA	$309
Kasetsart N-P-K	pH, ammonium-N, nitrate-N, available P, exchangeable K. Refill kit can be purchased.	Some training required	Kasetsart University-SM CRSP & Boon Din Thai Co. (Distributor), Thailand	$200

Table 1.7 Properties of soils used in IFDC's study of soil test kits

Soil name	Soil type	pH	Available P (Pi)
Houston	Vertisol	8.0	11.4
Vernon	Inceptisol	8.0	5.2
Hartselle	Ultisol	4.9	4.0
Hiwassee	Alfisol	5.4	4.4
Canyon	Entisol	8.4	29.8
Faunsdale	Inceptisol	7.3	9.0

Table 1.8 Correlation between rapid nutrient testing methods and wet chemistry

Rapid soil test kit	pH	N (NO_3^-)	P (available)	K (exchangeable)
Hach NPK-1	0.998	0.78	0.93	0.96
LaMotte AST-5	0.95	0.84	0.08	0.84
Kasetsart N-P-K	0.95	0.6	0.39	0.62

for the soil kits were obtained from the suppliers/manufacturers and are non-reusable. The kits are described further in Table 1.6. The soils used for evaluating the kits were sandy-clay in texture (Table 1.7), with a wide pH range (4.9 to 8.4) and available P (4 to 30 ppm). The result of that study, summarized as *r* values in Table 1.8, indicated that for pH, the Hach Soil Test Kit with a portable pH meter produced the most reliable values, compared to the laboratory-determined pH in water (ratio water:soil, 2:1). In contrast, the LaMotte and AccuGrow kits did not capture the full range of pH values compared to the laboratory standard, or the Hach Kit. The overall rating of the kits for pH measurements were as follows: Hach > Kasetsart > La Motte. For nitrate-N, most of the soils used in the study were low (2 to 5 ppm) in N, except for the

Canyon soil. The LaMotte and Hach kits identified the soils with high nitrate-N content, but were generally not very effective in separating the low N soils. The other kits gave less than satisfactory outcomes. In addition, it was found that doubling the amount of soil and $CaSO_4$ during extraction could improve the performance of the Hach Kit on soils with low nitrate-N. Results for P analysis indicated, with the exception of the Hach soil test kit, that the test kits were weak in P detectability. The researchers, however, did not find these results surprising, given that soil P extractants and associated methodology are dependent on the soil pH, so that in this study the pH and P determinations could be correlated. A similar pattern of accuracy was seen for K, where the Hach Kit outperformed others in correlating better with the laboratory-determined exchangeable K. On the basis of their findings, the IFDC investigators recommended the Hach kit as being more accurate for both NPK and pH, followed by the LaMotte AST-5 Kit, and the Thai-Kasetsart University Kit, in that order. However, they conceded that the Hach Kit was more difficult to use than the LaMotte, and would require some training by the user.

Taken together, these limited studies clearly demonstrate the potential differences obtainable among different rapid nutrient testing kits for different soil variables, even under similar experimental conditions. Notably, however, none of the studies determined the micronutrient status in the soil. The inability of certain nutrient testing applications to determine the micronutrient status of the soil or plant may be a minus for such kits given that micronutrients have increasingly assumed a significant role in boosting crop yield and quality, as observed in several recent studies (reviewed in Dimkpa and Bindraban 2016). With the renewed impetus being given to these nutrients based on the results of numerous field trials, the ability of rapid nutrient testing methods to detect and quantify micronutrients would be advantageous from the point of view of balanced fertilizer recommendations.

Inarguably, the complete evaluation of the accuracy of a wide selection of the available rapid nutrient testing methods is still lacking; hence there is currently a limitation to their ability to provide significant data to better inform on both their specific and strategic effectiveness. To our knowledge, the few kits so far tested are limited to macronutrients detection, despite the increasing relevance of other nutrients, such as Zn and B, in crop responses in different soils. Thus, rapid nutrient testing methods able to determine both macro and micro nutrients in the soil and/or plant, as well as provide information on pH and other relevant soil physico-chemical parameters would be most ideal, as they will better permit the pursuit of comprehensive soil management strategies.

1.7 Matching Soil Tests with Fertilizers

Nutrients in soil are in a constant dynamic state, from being fixed to soil components, dissolved in the soil solution, and translocated into the root, enroute the shoot. However, classical approaches have tended to directly relate nutrients in soil extracts to their uptake in plants. This simple approach has proven inadequate to predict

nutrient availability to crops, as discussed for Zn bioavailability (Duffner et al. (2013). Therefore, more complex methods capable of systematically determining or predicting the partitioning of nutrients in the soil solid phase, their dissolution into the soil solution phase, interaction with root surfaces, and translocation into shoot could bridge the existing knowledge gap in the relationship between total soil nutrient content and crop responses to nutrients. Accordingly, previous studies in low Zn soils show that accounting for Zn fractions interacting with root surfaces would better predict Zn availability to crops than Zn in soil solution (Duffner et al. 2013). Subsequently, Duffner et al. (2014) found in low Zn soils that pH, and especially, organic matter, were major factors influencing the state of Zn (i.e., whether bound to solid phase, or existing as free Zn ions in solution). These authors further showed that by modulating (decreasing) the pH and organic matter, the free Zn ion concentration in the soil could be increased. Although these studies are specific for Zn, it is likely that by using similar modelling and experimental approaches, the truly bioavailable fractions of suites of nutrients can be predicted or determined for different soil and crop types, and with that, more accurate soil and crop-specific fertilizer recommendations can be made. Also, the ratios between nutrients should be considered (Bindraban et al. 2015). This is because an excess of one nutrient can dilute the amount of another nutrient that is present in a lower amount, while a limitation of a specific nutrient can inhibit the effect of another nutrient present even in adequate amounts. At the strategic level, this type of information is useful as a decision support tool for designing and implementing soil-based fertilizer regimes in the context of crop-specific fertilizer program, and would be especially valuable for relatively understudied staple crops such as cassava, yams, as well as several underutilized crops for which systems-based information about nutrient requirements, contents and yield responses are scarce or completely lacking (e.g., Kuzhivilayil et al. 2015).

Upon determining the state of soil fertility and related physico-chemical properties, the next logical step would be to make fertilizer and other crop management recommendations based on the test results. However, the process of matching soil fertility tests and fertilizer recommendations could be less straightforward in certain agro-ecoregions (e.g., in Sub-Saharan Africa) where multiple nutrient deficiencies occur simultaneously (Oliver and Gregory 2015; Voortman and Bindraban 2015). In such cases, finding the right balance in terms of nutrient composition and amounts, and meeting the soil conditions that best address the bioavailability of specific nutrients could pose new challenges. An example would be how best to address a simultaneous P and Zn deficiency in an alkaline soil, whereas each of these nutrients requires different pH regimes (alkaline for P, acidic for Zn) to be efficiently utilized by crops, in addition to potentially being mutually antagonistic for plant uptake, not to mention the formation of P-Zn precipitates that could complicate this interaction even further. Actualizing a balance between soil test results and balanced fertilizer recommendations may also be compounded in situations where a limited variety of macronutrient fertilizers are the only products readily available to farmers, which is the case in many places around the world. For instance, urea fertilizers are generally alkaline in nature, and thus could affect the availability of micronutrients such as Zn (Milani et al. 2015), and likely Cu and Mn, when blended together for use in other-

wise neutral soils. More generally, some nutrients could inhibit the availability to plants of other nutrients; examples of such negative nutrient interactions in soil being those of Zn vs. Fe, and Zn vs. Mn (Dimkpa et al. 2015), as well as P vs. Fe/Zn (Rietra et al. 2015). In other instance, an acidic soil treated with lime to correct for low pH may additionally provide Ca or Mg to the crop. However, the benefit of liming may be negated if an acidic fertilizer such as ammonium sulfate is available to supply N and S. This example can be contrasted with the acidifying benefits of ammonium-based fertilizers in the release of Zn and Fe when applied in alkaline soils. Because many of the available fertilizers do not consider such complex soil-nutrient scenarios, matching precise fertilizer recommendations and available fertilizer products have so far proven to be a difficult task, and clearly informs on the irrationality of blending just any set of nutrients together as fertilizers without considering soil complexities, nutrient interactions and potential constraints to plant uptake.

Accordingly, efforts are underway in the development of tailor-made fertilizer blends that match the needs of specific agro-ecosystems upon soil testing and agronomic studies involving nutrient omission trials (IFDC, ongoing activities in East Africa) and comprehensive soil physico-chemical analysis. For instance, fertilizer formulations containing specific levels of Zn, Cu, B and S, in combination with NPK have been demonstrated to act synergistically to provoke significant positive responses in multiple crops (see for e.g., Vanlauwe et al. 2014). Notably, the systematic omission of each nutrient provokes negative responses in the crop. In these examples, most of the crops show similar positive responses, without or with addition of dolomite (lime; average soil pH value = 5), indicating the lack of need for soil liming for such crops under the given growth conditions. The broader implication of these studies is that the recommendation and adoption of fertilizer regimes should be contingent upon the determination of the soil nutrient levels, as well as the factors influencing nutrient dynamics in the root zone for specific agricultural units (agro-ecological zones, or specific farm soils), to arrive at a sensible fertilizer regime.

As mentioned in a prior section, some of the rapid nutrient testing methods provide fertilizer recommendations upon soil testing. An example of such fertilizer and soil management recommendations for maize crop is presented in Fig. 1.3. This illustration, modified from SoilCares, is rather simplified, as it does not include micro and secondary nutrients and all the array of soil properties: only three major soil variables are considered, namely, pH, macronutrients (NPK) and organic matter. In the example in Fig. 1.3, the soil is acidic (pH 4.7), due to which an amendment with lime at the rate of 2000 kg/ha was recommended. Meanwhile, N and P are both present at low levels (1.9 g/kg and 5.4 mmole/kg, respectively) and, therefore, were recommended to be supplemented at 85 kg/ha of N:P (17:10) at sowing, followed by an additional 15 kg N/ha 6 weeks after. In contrast, K being sufficiently present (4.6 mmole/kg), was excluded from the recommendation. Furthermore, the soil contained 21.4 g/kg of organic matter (as organic C) which was optimal; however it was advised to supply 5000 kg/ha of compost or animal manure, to maintain the organic matter level. Additional advice from the fertilizer recommendation

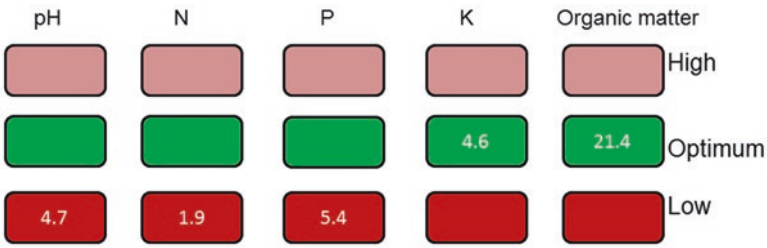

Fig. 1.3 Example of a fertilizer recommendation based on soil test result (modified from SoilCares). *Numbers* in *boxes* for high, optimum and low depict levels of pH, nutrients or organic matter determined from soil testing

included incorporating the lime into the soil before rainfall, but without mixing with the manure at the same time. From the above example, it is clear that as testing tools, although rapid nutrient testing methods may not resolve the problem of fertilizer availability and suitability for specific soils – suitable nutrient blends would have to be produced anyways, regardless of the testing method – they, like wet chemistry methods, can provide the basis upon which fertilizer recommendations can be made. A difference between the two systems is that the process can be more hastened in the case of rapid testing.

In summary, the success or otherwise of matching fertilizer products and soil chemical properties could make or mar the success of any fertilizer recommendation scheme aimed at establishing balanced nutrient regimes for specific soils. In some cases, proven rapid nutrient testing methods may provide the first line of action to address the soil fertility and fertilizer recommendation dilemma.

1.8 Rapid Nutrient Testing Applications for Plant Tissues

Like their soil counterparts, most available rapid nutrient testing methods for plant samples are based on colorimetry or nutrient meters (Table 1.9). Detection with these systems involve the collection of leaf tissues, dicing them into bits, and chemical extraction to assess nutrient levels. However, the presence and concentrations of nutrients in plants can also be evaluated using xylem sap (Alams et al. 2001; Dambrine et al. 1995). Although not included in the Table, SoilDoc, for instance, has the capacity of assessing N, P, K, and S in the sap of growing crops. As with soil testing, the result of a plant tissue colorimetric test is qualitative, but estimable by comparing color intensity with a pre-made color chart and associated values. Upon sample collection and preparation, the procedure for the actual nutrient measurement in plant tissue samples using rapid testing methods is generally similar to that for soil samples, dependent on whether it is colorimetry or meter based. In fact, some of the plant nutrient meters can also be applied in soil samples. For example, the CleanGrow's nutrient analyzer can simultaneous calibrate and measure up to six ions

Table 1.9 Plant nutrient test kits identified from web search

Product	Producer	Method	Nutrient detected	Rapidity	Complexity
Micronutrient Plant Tissue Test Kit Model PT-3R	LaMotte	Colorimetry (using plant tissue sap)	Fe (Fe^{2+}, Fe^{3+}), Zn, Cu, Mn, B	Min	Simple
Macronutrient Plant Tissue Test Kit Model PT-3R	LaMotte	Colorimetry (using diced leaf tissue extraction)	N (NO_3^-), P, K	Min	Simple
Nutrient analyzer	CleanGrow	Electrical conductivity of tissue extracts	Ca, Mg, Cl, K, Na, NO_3^--N, NH_4^+-N	Sec-min	Simple
Laqua Twin Nutrient Meters	Spectrum Technology	Electrical conductivity	NO_3^--N, Ca, K, Na, pH	Sec-min	Simple
Portable rapid plant tissue testing kit	Nagarjuna Agro Chemicals Pvt. Ltd.	No indication of method.	Multiple nutrients (not specified)	No info	

Product	Independent scrutiny	Country	Price/ Kit ($)	Sustain ability (Refill)	Web contact
Micronutrient Plant Tissue Test Kit Model PT-3R	None	USA	113.73	Refill available	www.lamotte.com
Macronutrient Plant Tissue Test Kit Model PT-3R	None	USA	114.99	Refill available	www.lamotte.com
Nutrient analyzer	None	USA; UK; Ireland	2662	Calibration solution refill available	http://www.cleangrow.com/nutrient-analyzer/
Laqua Twin Nutrient Meters	None	USA	435-495	Replacement sensors available	www.specmeters.com;
Portable rapid plant tissue testing kit	None	India		No info	www.nagarjunaagrochemicals.com

(NO_3^-, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Na^+, and Cl^-) in a tissue or soil sample extract using one meter. In this device, fast readout of output is achieved using a set of digital paraphernalia that includes Bluetooth-enabled smartphone, iPad, or iPod for displaying the result for each ion. The data can be recorded and stored, together with associated metadata such as date, time, location, co-ordinates and remarks for each sample. In contrast, the Laqua Twin products range includes individual meters that separately measure nitrate-N, K, and Ca ions in soil and plant tissue extracts. For more

information on ion-selective technologies and applications in nutrient management, readers are directed to Bamsey et al. (2012).

1.8.1 Plant Tissue Testing for in Planta Nutrient Assessments

Unlike soil testing that indicates the potential availability of nutrients from soil, tissue sampling determines the nutrient levels actually present in the plant from the soil, and hence, provides direct indication of the plant's ability to acquire adequate amounts of available nutrients from the soil. Therefore, further discussion is appropriate about tissue sampling and its linkage to alternative nutrient delivery strategies such as foliar application. Tissue testing can serve a variety of purposes: (i) to determine the accumulation of nutrients by crops; (ii) to diagnose specific nutrient deficiencies, and (iii) to determine the compartmentalization of nutrients in different plant parts (root, stem, leaf and grain/seed), in both qualitative (i.e., which nutrient) and quantitative terms. In the first case, the concentration of a nutrient in a healthy crop tissue can provide an idea of the amount of that nutrient optimal for crop development, and for attaining an expected yield level (see for e.g., Daur et al. 2011; Kumar and Verma 1997). With respect to diagnosis, a notable change in the leaf color from green could be indicative of a nutrient deficiency: for example, purple along leaf margin for P; yellowing along leaf margin for K, and yellowing down the mid-vein for N. Along this line, the International Rice Research Institute, IRRI, developed the leaf color chart to aid in identifying and diagnosing N deficiency, and providing appropriate fertilizer recommendations. This is similar to the use of SPAD meter measurements as an indicator of plant chlorophyll status, which can be correlated with Fe, N or even Mg status of specific crops (Bindraban 1999; Bocchini et al. 2015; Ghasemi et al. 2011; Shaaban et al. 2002; Vasconcelos and Grusak 2014). Thus, in the event of crops manifesting tissue-specific nutrient deficiency symptoms, crop sampling for that nutrient can be directed towards the affected part of the crop; and by comparing test results between symptomatic and asymptomatic plants, nutrient deficiencies can be identified and resolved. Furthermore, since nutrients are differentially mobile in plants, and crops vary in the organs that are edible for human/animals, the goal of sampling may be to determine how nutrients are translocated and compartmentalized in the different organs. Thus, organ-specific sampling may particularly be relevant in human/animal nutrition-focused crop production, in which case the tissue sample of interest would depend on whether the crop is a root or tuber, stem, grain, leafy vegetable or fruit crop. For this reason, crop tissues may be sampled late in the growing season to determine the final nutrient contents that can be correlated with the crop's ultimate biomass production or grain/seed yield. This is especially relevant for fertilizer regimes that emphasize the enhancement of the nutritional quality of the final crop produce. With regards to their mobility, it is likely that sampling less mobile nutrients (namely B, Ca, Cu, Fe, Mn, S, Zn) from younger leaves would underestimate the result, as would sampling more mobile nutrients (namely N, P, K, Mg and Mo) from older leaves. Additionally,

tissue testing may be done as a prelude for using crop biomass as carriers for nutrients based on biosorption technologies, a novel area of research promoting bio-based technologies (Michalak et al. 2015).

From the foregoing discussion, it is apparent that an otherwise simple tissue sampling exercise could become complicated by several concerns such as (i) what tissue is appropriate for nutrient sampling for crop x and nutrient y; (ii) what time is best to conduct sampling in crop x; (iii) what age should crop x be sampled for nutrient y; (iv) whether plant size (stunted vs non-stunted) would obfuscate the accuracy, and therefore, the interpretation of tissue testing; and (v) whether different nutrients should be tested at different crop developmental stages. Clearly, the complications would vary for root crops (e.g., cassava) relative to grain crops (e.g., rice). In the case of legumes, sampling for Mo would present its own challenge: Mo is highly mobile, readily moving from root (soil) to shoot (Kaiser et al. 2005). Yet, it is required by plants mainly in the root-based N fixation process.

At the whole-plant level, stunting would likely produce a false positive due to the high concentration of nutrients in the small biomass, in contrast to the potential for a false negative arising from the low nutrient concentration caused by dilution effect in plants with larger biomass. Such false positives or negatives would over -or underestimate subsequent fertilizer recommendations, but can be corrected by determining nutrient uptake (Kaiser et al. 2013).

Taken together for all nutrients and different growth stages of different crops, the plant part to sample would, ultimately, depend on the purpose for which sampling is being done. Nevertheless, regardless of the plant part, timing of tissue testing, and nutrients to be measured, multiple plants should be sampled randomly from different locations of the farm. After sampling, if required, only samples from uniformly-sized plants should be pooled for analysis, to allow for a more representative result.

1.8.2 Plant Tissue Testing for Foliar Fertilizer Regimes

Obviously, the uptake of nutrients from soil into crops, determined by tissue testing, has implications for soil nutrient stocks, and the need or otherwise for replenishment through fertilization. However, complications from soil chemistry and associated effects on nutrient use efficiency have led to alternative or supplementary nutrient delivery strategies such as foliar application. In this section, the ramifications of plant tissue testing for foliar fertilization are briefly discussed. Firstly, foliar application can address concerns regarding nutrient mobility and tissue-specific accumulation, as nutrients applied through foliar are directly targeted to the aerial tissue of interest. Secondly, it presents a rapid response to nutrient deficiency diagnosed via tissue testing of above-ground plant parts. In essence, dependent on the nutrient, foliar- applied nutrients may be more readily available for uptake, compared to soil-applied nutrients that may be "lost" or fixed in the soil, resulting in less being taken up by the plant (Dimkpa and Bindraban 2016; Joy et al. 2015). Similarly, foliar application ensures more precision in nutrient delivery, compared to soil

application, since nutrient is directed towards the intended target, the plant, rather than the soil (Bindraban et al. 2015). Moreover, in mixed cropping systems, foliar application could also more easily permit conducting multiple fertilizer regimes for multiple crops on the same farm, since specific nutrients can be targeted to specific crops based on their individual needs.

In sum, plant tissue testing is relevant for both soil and foliar nutrient regimes, where they provide useful information on nutrient accumulation by crops, the diagnosis of specific nutrient deficiencies, or the mobility and compartmentalization of nutrients in different plant parts. However, compared to soil nutrient testing, relatively fewer rapid testing applications for tissue nutrient determination are commercially available. Thus, it is imperative that more rapid shoot nutrient testing methods be developed and evaluated for their robustness, especially given the increasing application of foliar fertilization to address both urgent and chronic plant nutrition issues.

1.9 Effect of Cultural Practices on Rational Fertilizer Recommendations

Assuming all other agronomic factors – water availability, improved seeds, pests, disease and weed management – have been optimized, crop response to fertilizer application is greatest when applied in soils whose nutrient levels are below optimum. As shown in Fig. 1.1, the benefits of fertilization can be significantly reduced in adequately fertile soils. Accordingly, except for the purposes discussed in the previous chapter, such as the need to rapidly diagnose nutrient deficiencies in the plant, soil testing should form the basis for rationale fertilizer recommendations. The advantage of soil-test based fertilizer recommendation was demonstrated in a cassava field study in different districts of India that spanned 6 years, in which comparisons were made between standard (blanket) and soil test-based fertilizer recommendations (Kuzhivilayil et al. 2015). In the study, the control field received the full blanket recommendations for cassava of NPK 100:50:100 (kg/ha) and 12.5 T of farm yard manure (FYM)/ha. In contrast, soil testing prior to fertilizer recommendation revealed that the soils did not require an amendment of P (hence, 0 kg/ha was applied), and required less amendments of organic matter, N and K, averaging 8 T FYM/ha, 92 kg N/ha, and 67 kg K/ha, respectively. When tuber yield was compared between the two treatments, it was observed that even with savings in N, P, K inputs averaging 8%, 100%, and 39%, respectively, as well as a 35% saving in organic manure, the tuber yields were similar between the treatments. This result clearly demonstrate the necessity of rationalizing fertilizer recommendations based on soil nutrient status.

At this point, a brief discussion of the effect of prevailing cultural practices on the precision of fertilizer recommendations is warranted, given the diversity of farming systems in different regions of the globe. In an intensive monoculture sys-

tem such as the one used by Kuzhivilayil et al. (2015) and practiced by most large scale farms, soil testing for the cultivation of a specific crop would provide a direct and specific fertilizer recommendation for that soil and crop; even in-field soil variations can be addressed by variable rate nutrient treatments. In contrast, mixed or intercropping as practiced in most Sub-Sahara African farming systems implies that the different crops in a farm have different physiological needs, with their nutrient requirements varying accordingly. For example, maize would respond more positively to N than a legume, since the later meets some of its N needs by root interaction with N-fixing bacteria. Moreover, competition among crops for nutrient uptake occurs (Zhu et al. 2016). As such, crops in a mixed cropping system would respond differently to soil nutrients, dependent on their competitiveness fitness in terms of nutrient uptake. Hence, in such systems, directly relating soil testing to crop-specific fertilizer recommendations is difficult, compared to mono-cropping systems, and thus may require additional approaches, such as cultivar-based plant tissue testing. Undoubtedly, prevailing farm cultural practices such as fertilizer application practice and cropping system could have profound impacts on fertilizer use and effectiveness as a production factor.

1.10 Concluding Remarks

Considerable technological advances have been made throughout human history. One of such technological advancements, the mobile telephony, has steadily permeated the fabrics of most agricultural activities in different parts of the globe in recent years, and has the potential to contribute in leapfrogging soil fertility management practices. In Africa, for instance, farmers could be seen communicating with colleagues, farming input marketers and produce buyers using mobile phones right from their farms located in far-flung places (VFRC 2016). With the increasing widespread deployment of rapid nutrient testing methods in different places, technological advancements such as smart mobile telephony will only enhance the efficiency of their application for soil and plant testing, especially for those applications amenable to mobile digital capabilities. Still, the slow mobile data speed experienced in many places, especially in Sub Saharan Africa, may limit the efficiency of the process of sending soil test inputs and receiving data from digital analysis, and remains an important issue to be resolved. Similarly, infrastructural challenges such as lack of constant electricity may impede the operations of rapid nutrient testing applications operating with rechargeable battery packs. Inevitably, the poor financial conditions of most smallholder farmers in less developed regions of the world would continue to impede the successful deployment and adoption of technologies, including rapid nutrient testing. One way to address this could be pooling resources by contiguous farmers with similar soil characteristics, farming operations and cropping history, for the communal procurement and sustainable use of these technologies.

Regardless, promising rapid nutrient testing methods, especially those with broader capabilities for capturing all nutrients and soil chemistry types should con-

tinue to be identified, and existing ones should be refined as problems and impediments militating against their efficient use are identified. Importantly, for each soil variable, these products should undergo independent evaluation in different soils, and compared to wet chemistry, as the latter is the largest reference source of soil data currently available in soil databases for soil mapping (see for e.g., www.isric.org). Among the nutrient testing methods, spectroscopy-based applications and others with digital output and storage capabilities hold some of the strongest promise, even though initial investment in them may be significant for many small scale farmers. However, such spectroscopic applications may be limited by their inability to determine bioavailable fractions of nutrients. In this regard, progress is needed on methods calibration based on advanced modelling and state-of-the-art soil analysis techniques for relating spectroscopic outputs with nutrient bioavailability.

Accordingly, a second and no less important aspect of this review have dealt with the difficulty in reconciling the lack of relationship often existing between bioavailable fraction of a nutrient and amount taken up by different crop species, under different soil and environmental conditions. This has impeded the efficiency and accuracy of translating soil test results into nutrient recommendation for different crops, or for the same crop grown in different soils. In addition, the myriad of nutrient-nutrient interactions, as well as the fact that different crops require different fertilizer regimes add to the mix. Among packages of principles and/or technologies that could be useful in disentangling the contradictions between bioavailable and plant accumulated fractions of nutrients include: (i) modelling to predict nutrient dynamics from the soil solid phase, through the soil solution, to root surfaces, and ultimate translocation into the shoot; (ii) use of nutrient-specific indicator crops that, when grown in a soil, would yield a response that indicates the level of that nutrient bioavailable to the crop; and (iii) investigating crop responses to nutrient omission trials to reveal what specific nutrients and soil chemistry are relevant for the growth of specific crops. Ultimately, these packages would yield the much needed basic outcomes that would, subsequently, engender the deployment of appropriate and available soil and plant testing systems, including rapid nutrient testing applications.

Acknowledgements Funding for this work is provided, in part, by the United States Agency for International Development (USAID). We would like to thank Susan Yiapan for assistance with internal editorial review of this manuscript.

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