



Research Findings



Tea plantation in Western Ethiopia. Photo by B. Kassahun.

Potassium Availability in Selected Clayish Soils of the Ethiopian Central Highlands: Reassessment of Soil Testing Methods

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Abstract

For a long time, the importance of potassium (K) fertilization in Ethiopian soils has been incorrectly perceived to be unnecessary due to the misconception that K reserves in the soils were sufficient. This study was conducted with the aim of assessing four soil testing methods (NH_4OAc , CaCl_2 , Mehlich-3 [M-3], and Schofield-Woodruff [ΔF]) to determine plant available K in Ethiopian highland clay soils. Sixty composite (0-20 cm), geo-referenced surface soils were collected from 20 districts in 11 zones of Ethiopia's central highlands. While M-3 and NH_4OAc K extraction methods seem quite similar, but over-estimate soil

K availability, the CaCl_2 method mainly identifies the soluble K fraction, under-estimating exchangeable K. The ΔF method shows considerable agreement with the CaCl_2 method but has additional sensitivity to exchangeable K. ΔF results indicate that 60% of the soils sampled could be considered as sufficient K suppliers, depending in the crop species, while the rest are poor K suppliers. Preliminary mineralogical examination revealed a dominance

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of illite/smectite in most samples but the ratio between the two minerals, which might determine K fixation and release rates, is yet unknown. In the absence of any alternative proven chemical method to evaluate soil K availability, direct measurements of crops' K consumption should be integrated with simultaneous soil-K tests. Also, clay mineralogy should be further investigated on a local basis in order to determine and understand actual and possible dynamics of soil K status and availability, to establish a sufficient basis for practical recommendations.

Keywords: Illite; Mehlich-3; smectite; soil-K availability; soil-K extraction methods.

Introduction

The intensive fertilization approach emphasizes the need for fertilizer inputs to replace crop nutrient removal and to maintain soil nutrient reserves. In Ethiopia K fertilization was deemed to be unnecessary due to the misconception that K reserves in the soils were sufficient and, on the whole, in a form available to plants. Moreover, crops' response to K fertilization was inconsistent or insignificant (Murphy, 1968). In addition, the exchangeable K content of most agricultural soils exceeded the universally accepted critical level, as set by the index based on ammonium acetate extraction method, at 0.25 cmol kg⁻¹.

Analyses of both past and recent information on K status in different woredas (districts) of Ethiopia, however, show that there has been a gradual decline in K status due to continuous mining, leaching, and soil erosion (Wassie, 2009). In its national soil fertility survey initiative, the Ethiopian Soil Information System (EthioSIS, 2013-2016) found K deficiency in key areas that have Vertisols, Nitisols, and other soil types. This has also been supported by crop K response demonstrations. At the same time, crop response to K fertilizer has emerged in many highland Vertisols, despite soil analysis results that show K levels higher than the critical level of 195 ppm, adopted by EthioSIS.

Potassium's significance to plant nutrition is well recognized despite its complex and dynamic nature in soils (Zörb *et al.*, 2014). Long-term intensive cropping in the absence of K inputs, adversely affects K supply to crop plants and consequently reduces crop yields (Swarup and Ganeshmurthy, 1998). Next to nitrogen (N), crops absorb K in greater amounts than any other nutrient. It is indispensable in nearly all processes required to sustain adequate plant growth and reproduction. Potassium plays a basic role in a series of fundamental metabolic and physiological processes in the plant. Its accumulation rate during early growth stages precedes N accumulation. Therefore, its supply to plants seems to be decisive for N utilization. In turn, K significantly affects plant growth rates and governs the degree of realization of yield potential (Grzebisz *et al.*, 2012).

Soil K can be categorized into four main fractions: K in soil solution; exchangeable K; non-exchangeable K, which is fixed but potentially available; and K in the mineral matrix (Hoagland and Martin, 1933). Soil K availability to plants and microbes declines according to its chemical phase and location in the soil, as follows: soil solution > exchangeable K > fixed K (non-exchangeable) > mineral K (Sparks and Huang, 1985; Sparks, 1987; Sparks, 2000). According to Barbagelata (2006), these four categories give a general representation of the potential sources for plant-available K, but no distinct boundaries exist among them. The bulk of soil K is confined to the solid mineral soil phase (Sparks and Huang, 1985), while the exchangeable and the non-exchangeable K comprise a small portion of total soil K, located mostly at the soil solid-solution interphase. There are equilibria and kinetic reactions between the four soil K categories that affect the level of soil solution K at any particular time, hence determine the level of readily available K for plants. Although exchangeable K is widely used to evaluate soil K status and to predict K availability to crops (Krauss, 2003; Samaadi, 2006), such predictions have proven to be a difficult task due to the complexity of the dynamic equilibrium among the various forms of soil K (Barbagelata, 2006).

Potassium availability to plants is related in many ways to the structure and morphology of soil minerals, particularly clay (Zörb *et al.*, 2014). Clay minerals comprise significant diversity of composition, structure, and consequent chemical and physical traits (Barton and Karathanasis, 2002). Thus, K sorption and desorption in soil are largely influenced by the amount and proportions of different clay mineral types. Potassium is readily adsorbed by 2:1 smectite clay minerals, thus plants require a higher dosage of K fertilizer than on other clay minerals, such as 2:1:1, 1:1, oxide, and allophane. Nursyamsia *et al.* (2008) suggested that of the 2:1 clay mineral types, beidelite or smectite has the highest fixation capacity. Bajawa (1987) showed that K fixation declines in the order of smectite > vermiculite > hydrous mica = chlorite = halloysite. The contradiction between the complex, fuzzy dynamics of K soil status, on the one hand, and the need to quantify the soil's ability to supply K for current and future crops, on the other hand, calls for careful methodologies of soil testing. The relevance of total soil K as an indicator for plant nutrition, in many cases, therefore is quite small. However, quantifying K in soil solutions, and estimating the rates at which K is released from the exchangeable K pool, can provide enhanced diagnoses of the readily available K pool, thus supporting decisions regarding fertilizer application.

A wide range of soil extraction methods claim to quantify the readily available K soil fraction, however, each method holds advantages and drawbacks that are derived from the nature of the local soil. The most common soil test procedure at the global level is the use of neutral 1N ammonium acetate (NH₄OAc) extraction



Photo 1. Measuring Ca, Mg and Na from soil extract by AAS (Atomic Arbitration Spectroscopy).
Photo by E. Sokolowski.

on air- or oven-dried soil samples (Cox *et al.*, 1999). NH_4OAc extracts mainly soil solution K, exchangeable K, and a portion of interlayer K. This method uses a neutral salt solution to replace the cations present in the soil exchange complex. Therefore, the K concentration determined by this method is referred to as “exchangeable” for non-calcareous soils and “exchangeable plus soluble” for calcareous soils. Though this method mostly reflects the fertilizer K requirements of plants, there is some evidence that the NH_4OAc method is not sensitive enough for Vertisols. Cox *et al.* (1999) also claim that while 1N NH_4OAc soil test values work well for some soils, this approach is not reliable enough for soils with appreciable proportions of non-exchangeable interlayer K^+ , such as smectite mineral soils. The situation is even more problematic under intensively cropped agricultural systems (Bansal *et al.*, 2002).

A single soil extraction with 0.01 M CaCl_2 appears to be the simplest, most inexpensive, and environmentally-friendly method, the results of which display the least variability among laboratories, compared to some other

methods (Houba *et al.*, 1996). Water and weak salt solutions extract K ions in the soil solution that are in equilibrium with those on the exchangeable complex. It is assumed that this method extracts the most readily available K from the exchangeable phase. Together with K in soil solution, the results effectually represent the plant’s available soil K pool, providing more precise estimates, compared to methods extracting the total exchangeable K.

The concept of a nutrient potential as a measure of soil K status was first suggested by Schofield (1947). This method uses an indirect measure of the energy input required by a plant to remove nutrients from the soil. Woodruff (1955) related classical thermodynamics to soil exchangeable K^+ and calcium and magnesium ($\text{Ca}^{2+}+\text{Mg}^{2+}$) release to the soil solution for determining the free energy of K-Ca exchange equilibria in soils. According to Woodruff (1955), the energy of exchange is a measure of the chemical potential of K in the soil relative to the chemical potential of Ca in the same soil. The ability of a soil to supply K to plants is characterized by both the total amount of nutrient present (quantity,

Q) and the energy level at which it is supplied (potential, P). The K^+ potential (ΔGK) is a free energy measure of the soil’s nutrient availability, expressed as a ratio of the relative activity and exchange between K^+ and $\text{Ca}^{2+}+\text{Mg}^{2+}$ (Keene *et al.*, 2004). The Schofield-Woodruff (ΔF) method classifies soils according to their K supplying power as follows: soils with high K supplying power: $\Delta\text{F} > -2,000$ cal mole⁻¹; medium K supplying power: $-3,500 < \Delta\text{F} < -2,000$ cal mole⁻¹; and, poor K supplying soils: $\Delta\text{F} < -3,500$ cal mole⁻¹.

An alternative method is Mehlich-3 (M-3) (Mehlich, 1984), which has become very common, almost ‘universal’, as it suits a wide range of soils (Zbiral and Nemeč, 2000) and is relatively low cost. M-3 was developed as a multi-element (phosphorus [P], K, Ca, magnesium [Mg], sodium [Na], copper [Cu], zinc [Zn], manganese [Mn], Boron [B], aluminum [Al], and iron [Fe]) soil extraction and is widely used in agronomic studies to evaluate soil nutrient status and to establish fertilizer recommendations, mainly for P and K in humid regions. Several authors (Beegle and Oravec, 1990; Gartley *et al.*, 2002; Wang *et al.*, 2004) showed that both neutral 1N NH_4OAc and M-3 methods remove almost the same amount of K from the soil.

The M-3 soil test is widely accepted and employed throughout Africa, including Ethiopia. The debates that have recently been raised regarding the actual profile of K availability in selected Ethiopian clay soils, and the crucial consequences it might have on fertilization policy and on locally recommended practices, necessitates the reassessment of K extraction methods that are being employed. The objective of the present study, therefore, is to examine and compare various common methods and establish a starting point for further investigation, aiming to adopt the most appropriate method to evaluate K availability of selected Ethiopian highland clay soils.

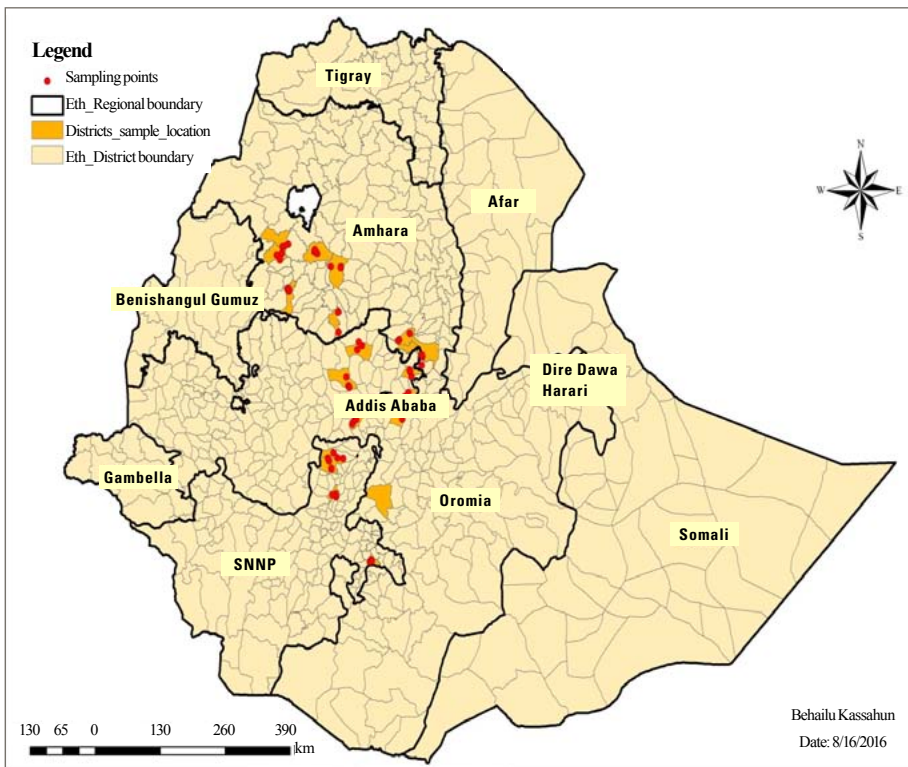


Fig. 1. Soil sampling locations in Ethiopia.

Materials and methods

Soil sampling

Sixty geo-referenced composite surface (0-20 cm) soil samples were collected from 20 districts located in 11 zones within Ethiopia's central highlands (Fig. 1). These areas were Awi zone (Dangila district), East Gojam zone (Aneded, Huleteju Enense districts), East Showa zone (Adea, Gimbichu districts), Gurage zone (Cheha, Enemore Ener districts), Hadiya zone (Limo district), North Shewa zone (Basona Worena, Kimbibit, Kuyu, Moretena Jiru, Siyadeberna Wayu districts), Sidama zone (Hagere Selam district), South West Shewa zone (Becho district), West Arsi zone (Arsi Negele), West Gojam zone (Bure, South Achefer, Yilmana Densa districts) and West Shewa zone (Jeldu district). From each district, three sub-districts were selected based on K⁺ levels found (high, medium and low K) in a previous study, using the M-3 method. The present samples, however, were not taken from exactly the same sampling points as the previous study.

Sample preparation, analysis, and K extraction methods

Samples were air-dried, gently crushed and sieved using a 2 mm diameter sieve for analysis. Particle size was determined using a laser diffraction technique at Ethiopia's national soil testing center. Water and chemical extraction was conducted in the laboratories at Gilat Agricultural Research Center, ARO, in Israel. Water content was determined both from saturated paste and air-dried soil, and electrical conductivity (EC) and pH was measured from saturated paste extract. Cation exchange capacity (CEC) and exchangeable K percentage (EPP) were calculated after measuring Ca, Mg and Na from the NH₄OAc extract. Potassium, Ca, Mg and Na in all extracts were determined using atomic absorption spectroscopy (AAS).

Neutral ammonium-acetate extraction

Soil samples were dried and crushed to pass through a 2 mm sieve. Two grams of soil was extracted with 1:10 soil-solution

ratio of neutral 1M NH₄OAc at pH 7 after shaking for 15 minutes (Helmek and Sparks, 1996).

Calcium chloride extraction

Air-dried soil samples were extracted for 2 hours with a 0.01 M CaCl₂ solution at 20°C, at a 1:10 ratio of sample to extracting solution, respectively. After measuring the pH in the settling suspension, the concentrations of nutritional and polluting elements were measured in the clear filtrate (Houba *et al.*, 1996; Simonis and Setatou, 1996; Salomon, 1998).

ΔF method

This is based on determining the exchange energy of K (ΔF), with the prevalent divalent cations (Ca²⁺+Mg²⁺) (Schofield, 1947). The range of ΔF values is usually between -2,000 and -4,000 cal mole⁻¹, where the upper value (-2,000) indicates K sufficiency, and the lower (-4,000) K deficiency. The free energy of replacement (ΔF) is calculated using the formula proposed by Woodruff (1955) where R is gas constant, and T is the absolute temperature (°K):

$$-\Delta F = 2.303 RT \log \frac{a_K}{\sqrt{a_{Ca} + a_{Mg}}}$$

This concept simulates the measure of the energy a plant must invest to remove K from the soil, and thus can represent K availability to plants.

M-3 method

The M-3 extracting solution is comprised of 0.2 M acetic acid (CH₃COOH), 0.25 M ammonium nitrate (NH₄NO₃), 0.015 M ammonium fluoride (NH₄F), 0.013 M HNO₃, and 0.001 M ethylene di-amine tetra-acetic acid (EDTA). A soil sample of 2.5 g is mixed with the extracting solution at the ratio of 1:10, respectively, and shaken for 5 minutes (Mehlich, 1984).

Clay mineralogy

Clay mineralogy analysis was conducted for 11 selected soil samples in the Ministry of National Infrastructures, Energy and Water Resources Geological Survey

laboratory in Israel. These samples were disaggregated and passed through a 2 mm sieve. The clay fraction was collected from thin suspensions according to Stokes Law after carbonate minerals and salts were removed from samples by diluted HCl acid or buffered acetic acid, repeatedly washed, and treated by a low-intensity ultrasonic treatment for a few minutes. Clay suspension was pipetted onto glass slides and analyzed after air-drying, glycolation (at least 8 hours at 60°C and cooling overnight), and heating for 2 hours to 550°C (Moore and Reynolds, 1989). The mineralogical composition of the clay fraction was analyzed by X-ray diffraction.

Results and discussion

Analytical results for selected physical and chemical soil properties are summarized and presented in Table 1. Soil pH (H₂O) values varied from 4.68 to 8.07, normally categorized from very acidic to moderately alkaline (Bruce and Rayment, 1982). The lowest value (4.68) was observed in South Achefer district in west Gojam zone, while the highest one (8.07) was found in Dangilla district in Awi zone.

EC, measured from saturated soil paste extract (EC_e), ranged from non-saline (0.11 dS m⁻¹, at Hulet Ej Enese) to moderately saline (5.73 dS m⁻¹, at Yilmana Densa), based on Richards (1954) classification of soil salinity rates.

CEC values ranged from 3.1 at Becho (South West Shewa) to 41.8 meq 100⁻¹ g soil at Adea (East Shewa) district. These CEC values are rated as very low to very high. Soils with CEC < 3 meq 100⁻¹ g often display low fertility and susceptibility to soil acidification (Metson, 1961).

Soil clay content, determined using laser diffraction, ranged from 25% at Basanaworena district to 83% at Limo and Moretina Jiru districts. While there

Table 1. Physical and chemical soil properties of 60 samples collected from 20 Ethiopian districts.

Sample number	District	Particle size			EC	pH	CEC
		Sand	Silt	Clay			
		-----%-----			<i>ds m⁻¹</i>	<i>H₂O</i>	<i>meq 100 g⁻¹</i>
1	Adea	20	14	65	0.3	7.4	35.1
2	Adea	13	12	75	0.3	7.8	36.0
3	Adea	18	18	65	0.5	7.9	41.8
4	Aneded	19	25	57	0.1	7.2	32.9
5	Aneded	21	18	61	0.1	7.5	20.4
6	Aneded	20	37	43	0.4	6.5	12.2
7	Basona Worena	22	42	36	0.2	5.7	10.6
8	Basona Worena	52	24	25	0.2	6.1	7.2
9	Basona Worena	31	37	33	0.2	5.3	6.5
10	Becho	30	40	29	0.2	5.8	5.5
11	Becho	22	45	32	0.4	5.3	3.1
12	Becho	25	44	31	0.4	5.6	6.9
13	Bure	37	27	36	0.7	6.9	5.2
14	Bure	33	21	45	0.4	5.8	7.9
15	Bure	36	28	36	0.3	7.7	6.1
16	Cheha	26	38	37	0.5	5.4	7.4
17	Cheha	33	40	27	0.6	7.6	16.7
18	Cheha	33	34	33	0.8	7.8	20.5
19	Dangilla	23	25	52	0.3	7.5	22.4
20	Dangilla	15	23	61	0.4	8.1	25.1
21	Dangilla	28	31	41	0.3	5.2	6.6
22	Enemor Ener	25	37	38	0.3	5.1	6.0
23	Enemor Ener	28	29	43	0.2	5.8	7.0
24	Enemor Ener	28	31	41	0.2	5.7	4.5
25	Gimbichu	29	30	42	0.2	5.9	8.4
26	Gimbichu	29	35	37	0.2	6.0	9.7
27	Gimbichu	32	30	38	0.1	6.1	7.7
28	Hagere Selam	33	33	34	0.2	5.5	4.0
29	Hagere Selam	26	38	36	0.1	5.1	3.3
30	Hagere Selam	32	31	37	0.1	6.5	6.0
31	Hulet Ej Enese	34	33	33	0.1	6.2	4.9
32	Hulet Ej Enese	40	30	31	0.1	5.2	6.4
33	Hulet Ej Enese	26	31	43	0.3	6.5	4.8
34	Jeldu	31	30	39	1.5	6.6	15.5
35	Jeldu	28	32	40	1.8	5.9	11.9
36	Jeldu	23	30	47	1.8	5.7	9.0
37	Kimbibit	15	13	71	1.3	6.1	7.6
38	Kimbibit	14	24	62	1.2	5.3	8.7
39	Kimbibit	12	12	76	1.2	5.6	14.9
40	Kuyu	23	33	44	0.4	5.0	6.4
41	Kuyu	14	29	58	0.3	5.4	5.5
42	Kuyu	9	22	68	0.3	7.0	26.4
43	Limo	5	14	81	1.6	6.6	24.1
44	Limo	8	9	83	1.4	7.3	33.3
45	Limo	7	10	83	0.2	7.4	32.1
46	Moretina Jiru	8	9	83	0.2	7.4	31.7
47	Moretina Jiru	15	24	61	1.4	5.6	21.2
48	Moretina Jiru	6	23	71	0.6	5.9	20.1
49	South Achefer	16	34	50	0.5	5.4	12.1
50	South Achefer	19	27	54	0.8	5.7	16.6
51	South Achefer	19	26	54	0.6	4.7	15.7
52	Yilmana Densa	11	18	70	0.7	4.8	20.7
53	Yilmana Densa	12	13	74	0.4	5.0	17.7
54	Yilmana Densa	6	12	81	5.7	5.6	26.8
55	Arsi Negele	16	29	55	1.3	6.9	8.4
56	Arsi Negele	16	30	54	1.8	6.4	4.6
57	Arsi Negele	12	28	59	0.7	6.1	4.4
58	Siyadeberna Wayu	20	34	46	2.4	6.4	6.5
59	Siyadeberna Wayu	7	11	82	1.8	7.0	26.3
60	Siyadeberna Wayu	10	11	80	0.2	7.5	29.3

is a wide range of clay contents across districts (30-80%, as an average), the intra-district variation was much smaller, with several exceptions at Aneded, Kuyu and Siyadeberna Wayu (Table 1).

While soil clay content has appreciable positive effects on soil water retention at both situations - air-dried and saturated paste (Fig. 2) - its significance determining soil fertility, and in the present study (soil K availability), is questionable.

Each of the three common methods in use to evaluate soil K availability, namely CaCl_2 , NH_4OAc , and M-3, showed a very poor linkage between the estimated level of soil K availability and soil clay fraction, even at the wide range presented here (Fig. 3). Furthermore, the fourth method (ΔF), provided a slight indication that the greater the soil clay fraction, the energy required by plants to extract K tended to decrease (Fig. 3). Interestingly, the NH_4OAc and M-3 methods obtained quite similar results, which

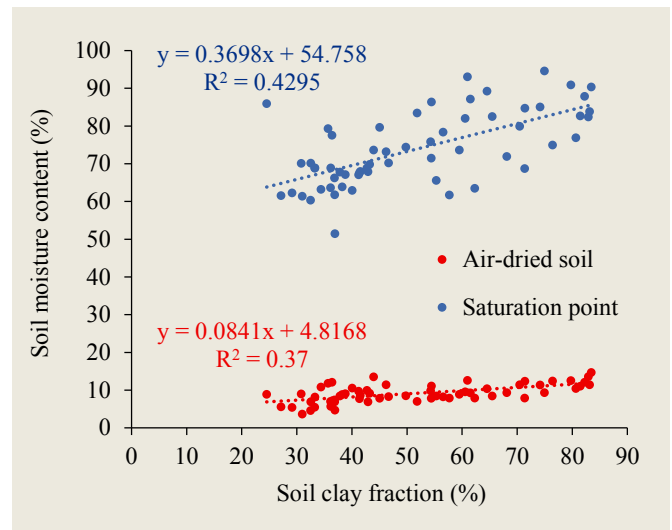


Fig. 2. The effects of soil clay content on water retention of air-dried soil, and saturated soil paste.

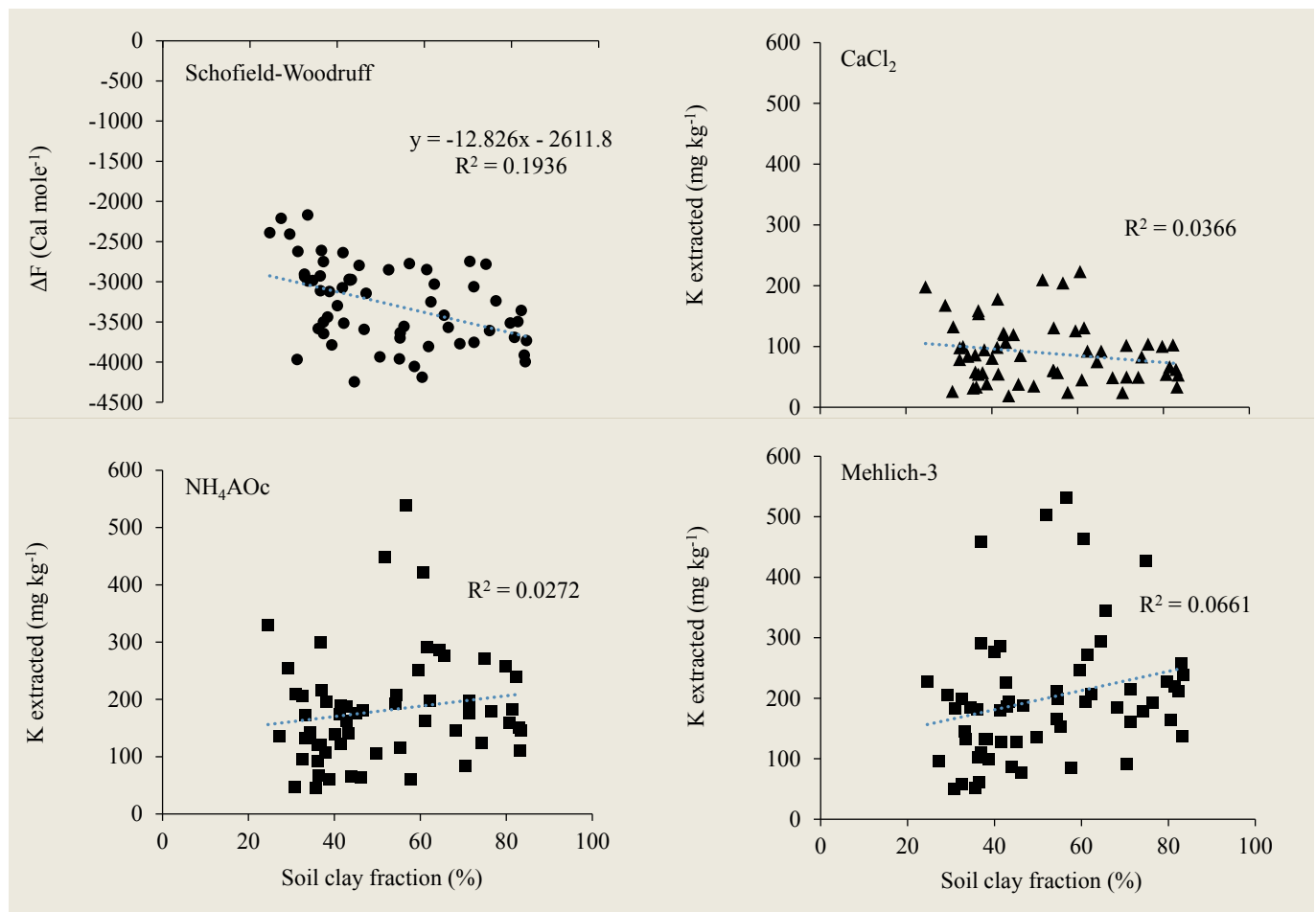


Fig. 3. Relationship between soil clay fraction and K availability, as measured using four distinct extraction methods.

were roughly two-fold higher than the K values obtained using the CaCl₂ method.

Indeed, direct pair-comparisons between the soil K extraction methods revealed a very high correlation between M-3 and NH₄OAc, with a coefficient of 0.85 (Fig. 4A). These results indicate that M-3 is somewhat more stringent than NH₄OAc at forcing K ions out from some clay minerals. However, together with their close chemical nature, these two methods appear to have similar chemical mechanisms of mining K out of clay minerals. This is in agreement with previous findings (Beegle and Oravec, 1990; Gartley *et al.*, 2002; Wang *et al.*, 2004), including on Ethiopian soils (Mamo *et al.*, 1996). Unequivocally, the K extraction ability of the CaCl₂ method is about 35% and 43% below those of the M-3 and NH₄OAc methods, respectively (Fig. 4B, C). It remains unclear, however, which of the three methods provides a better indication of K availability for plants. While M-3 and NH₄OAc might appear too stringent, releasing a portion of the non-exchangeable K, CaCl₂ might be too mild in representing the soluble K, with only a slight depiction of exchangeable K (Houba, *et al.*, 1996; Cox *et al.*, 1999).



Photo 2. Describing soil profile pit in Ethiopia. Photo by B. Kassahun.

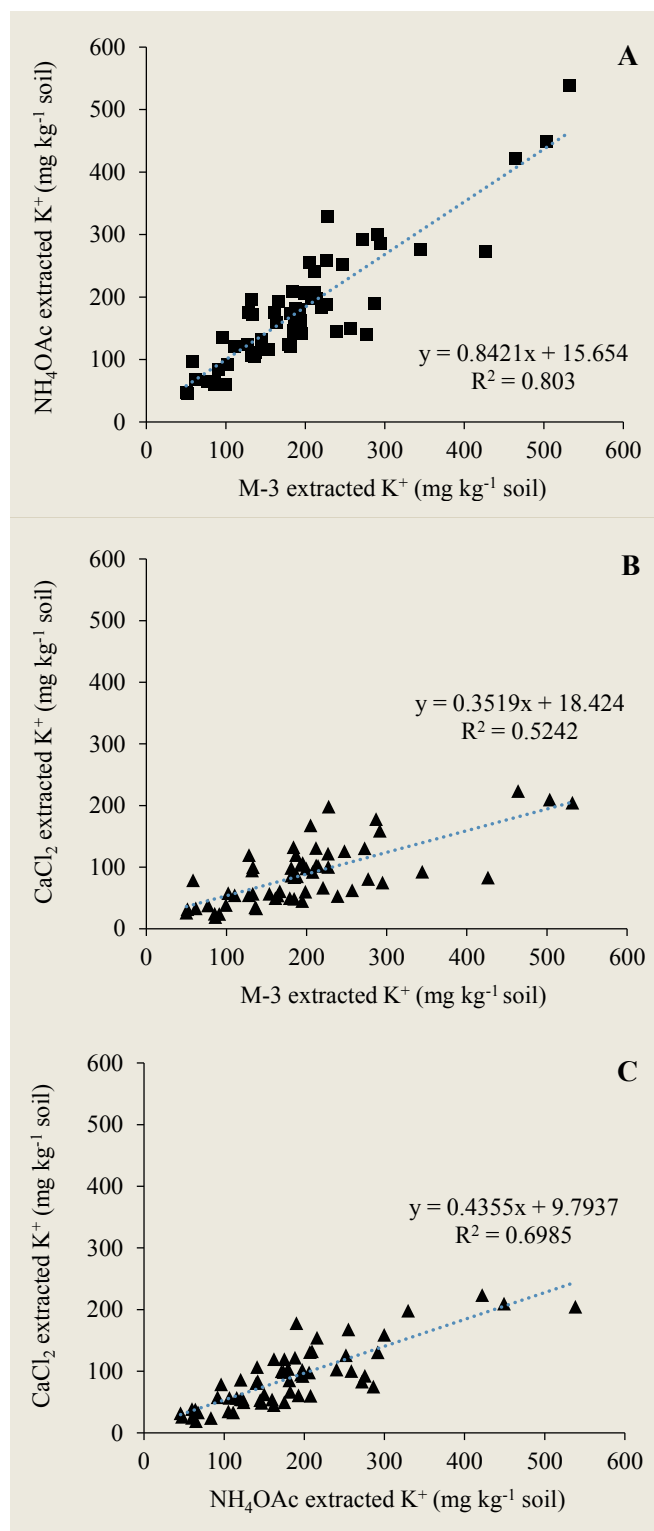


Fig. 4. Pair-comparisons between soil K extraction methods: A) NH₄OAc vs. M-3; B) CaCl₂ vs. M-3; and C) CaCl₂ vs. NH₄OAc.

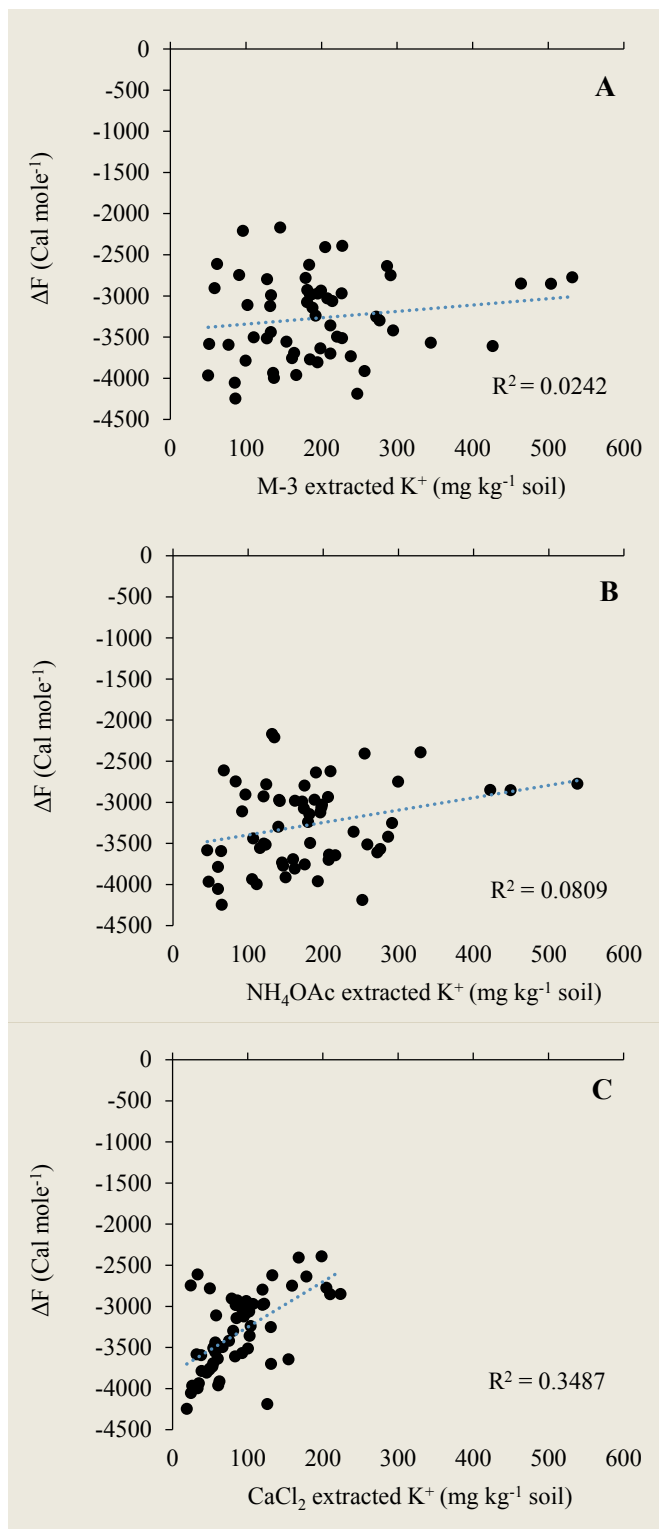


Fig. 5. The ΔF method confronted with K extracted from corresponding soil samples using the M-3 (A), NH₄OAc (B), and CaCl₂ (C) methods.

Testing the ΔF method against either M-3 or NH₄OAc revealed an absence of any correlation between them (Fig. 5A, B). In fact, there was a complete discrepancy between the methods in evaluating soil K status, and hence soil fertility. This result suggests intrinsic differences in the mode of action between the methods. While M-3/NH₄OAc methods might indiscriminately pull out K⁺ from relevant as well as irrelevant soil phases, the ΔF method seemingly offers a finer approach, which possibly distinguishes between clay minerals corresponding to their chemical affinity to K⁺. Thus, soils obtaining relatively low K status according M-3 might significantly differ in their K availability, according to the ΔF method, and vice versa. Excluding a few exceptions, a much better concurrence was found between ΔF and the CaCl₂ methods (Fig. 5C), which may indicate the dominance of the soluble K fraction, the most available one, in the results of ΔF .

Sorting the 60 Ethiopian soil samples by their K supplying potential, as determined using the ΔF method revealed that about 60% of them would be considered medium, while the rest are poor K suppliers (Table 2). Note that this sorting method significantly discriminates between neighboring soils, in some cases sending them to distant locations on the list. No linkage between ECe, soil pH or CEC and ΔF can be observed, indicating for the small relevance of these measures (at their detected range here) to the soil K supplying potential. As already mentioned and clearly noticed in Table 2, the relationships between soil total K, as determined by the M-3 or NH₄OAc methods, and ΔF , are absolutely coincidental as long as additional information is provided.

The mineral composition of clay fractions in each soil may provide the information required to interpret differences in K status and availability among them. The dominant minerals (>50%) in most of the 11 samples examined were interstratified illite and smectite (Table 3). Unfortunately, the ratio between the two in each sample was not resolved with the methods employed. While both minerals belong to the 2:1 clay class, they significantly differ in their ability to bind and release K ions (Barton and Karathanasis, 2002). Compared to illite and other clay minerals, smectite has a significantly higher tendency to fix K (Brady, 1984). Furthermore, many clay soils possess a relatively rapid dynamic transformation between the two minerals, which is influenced by temperature, moisture, pH, soil-K status, and plant roots (Scherer *et al.*, 2003). Plant roots display remarkable ability to rapidly absorb K from the rhizosphere (Hinsinger, 2015; Adamo *et al.*, 2016), thus strongly affecting the dynamic transformation between illite and smectite. Crops grown in the absence of K fertilization induced a rapid transformation of illite to smectite, accompanied by accelerated K fixation (Tributh *et al.*, 1987). This situation is quite typical of many arable clay soils in Ethiopia's central highlands; decades of inadequate K supply may have affected the clay mineral composition, favored increased K fixation and

Table 2. The 60 selected Ethiopian soil samples sorted according to the results of the ΔF method (soils with medium K supplying potential [$-3,500 > \Delta F > -2,000$ Cal mole⁻¹] are marked in blue.

Sample number	District	Clay	EC	pH (H ₂ O)	CEC	K-soil test results			
						CaCl ₂	NH ₄ OAc	M-3	ΔF
		%	ds m ⁻¹		meq 100 g ⁻¹	----K conc. soil mg kg ⁻¹ ----		Cal mole ⁻¹	
18	Cheha	33	0.8	7.8	20.5		131.8	145.2	-2,169
17	Cheha	27	0.6	7.6	16.7		134.9	96.0	-2,209
8	Basonaworena	25	0.2	6.1	7.2	198.1	329.5	227.4	-2,390
10	Becho	29	0.2	5.8	5.5	167.8	255.0	204.8	-2,406
15	Bure	36	0.3	7.7	6.1	33.2	67.5	61.7	-2,611
12	Becho	31	0.4	5.6	6.9	132.5	209.6	183.7	-2,621
24	Enemor Ener	41	0.2	5.7	4.5	177.9	190.1	286.6	-2,636
52	Yilmana	70	0.7	4.8	20.7	24.2	83.4	91.0	-2,745
26	Densa								
	Gimbichu	37	0.2	6.0	9.7	159.0	299.6	291.3	-2,748
4	Aneded	57	0.1	7.2	32.9	204.5	538.1	531.7	-2,773
53	Yilmana	74	0.4	5.0	17.7	49.5	124.2	179.0	-2,781
14	Densa								
	Bure	45	0.4	5.8	7.9	119.7	175.0	128.0	-2,797
5	Aneded	61	0.1	7.5	20.4	223.4	422.0	463.9	-2,848
19	Dangilla	52	0.3	7.5	22.4	209.7	449.1	503.5	-2,851
11	Becho	32	0.4	5.3	3.1	78.8	96.3	58.4	-2,904
29	Hagere Selam	36	0.1	5.1	3.3	86.2	120.5	181.1	-2,928
9	Basonaworena	33	0.2	5.3	6.5	98.0	206.1	199.4	-2,935
23	Enemor Ener	43	0.2	5.8	7.0	121.9	188.3	226.7	-2,969
33	Hulet Ej	43	0.3	6.5	4.8	106.8	141.1	195.0	-2,971
6	Enese								
	Aneded	43	0.4	6.5	12.2	119.6	162.2	186.7	-2,981
28	Hagere Selam	34	0.2	5.5	4.0	83.8	142.0	184.8	-2,983
31	Hulet Ej	33	0.1	6.2	4.9	99.8	171.8	133.1	-2,990
38	Enese								
	Kimbibit	62	1.2	5.3	8.7	92.4	198.1	207.6	-3,030
37	Kimbibit	71	1.3	6.1	7.6	101.9	197.4	214.3	-3,061
21	Dangilla	41	0.3	5.2	6.6	98.5	174.1	180.9	-3,075
7	Basonaworena	36	0.2	5.7	10.6	57.9	91.9	102.1	-3,111
27	Gimbichu	38	0.1	6.1	7.7	94.6	195.9	132.0	-3,121
36	Jeldu	47	1.8	5.7	9.0	85.1	181.2	188.0	-3,143
39	Kimbibit	76	1.2	5.6	14.9	103.8	179.7	192.3	-3,239
20	Dangilla	61	0.4	8.1	25.1	130.8	291.5	272.4	-3,251
35	Jeldu	40	1.8	5.9	11.9	80.6	140.0	276.9	-3,297
59	Siyadeberna	82	1.8	7.0	26.3	102.6	240.2	211.8	-3,357
3	Wayu								
	Adea	65	0.5	7.9	41.8	75.0	286.3	294.7	-3,417
22	Enemor Ener	38	0.3	5.1	6.0	56.9	106.6	132.8	-3,439
54	Yilmana	81	5.7	5.6	26.8	66.6	182.5	220.4	-3,495
30	Densa								
	Hagere Selam	37	0.1	6.5	6.0	54.4	120.6	110.2	-3,502
60	Siyadeberna	80	0.2	7.5	29.3	100.3	258.7	227.0	-3,513
25	Wayu								
	Gimbichu	42	0.2	5.9	8.4	54.6	123.1	127.8	-3,515
55	Arsi Negele	55	1.3	6.9	8.4	56.9	115.8	153.4	-3,555
1	Adea	65	0.3	7.4	35.1	92.5	275.6	344.4	-3,568
13	Bure	36	0.7	6.9	5.2	31.8	45.5	51.2	-3,582
58	Siyadeberna	46	2.4	6.4	6.5	37.9	64.1	76.9	-3,593
2	Wayu								
	Adea	75	0.3	7.8	36.0	83.0	272.0	426.3	-3,609
50	South Achefer	54	0.8	5.7	16.6	60.2	207.7	198.5	-3,635
16	Cheha	37	0.5	5.4	7.4	154.2	215.9		-3,644
43	Limo	81	1.6	6.6	24.1	54.1	159.7	163.9	-3,693
56	Arsi Negele	54	1.8	6.4	4.6	130.9	207.1	211.8	-3,700
44	Limo	83	1.4	7.3	33.3	53.0	145.1	238.6	-3,733
48	Moretna Jiru	71	0.6	5.9	20.1	49.7	175.1	161.0	-3,755
42	Kuyu	68	0.3	7.0	26.4	48.8	146.5	184.6	-3,771
34	Jeldu	39	1.5	6.6	15.5	38.6	59.9	99.4	-3,786
47	Moretna Jiru	61	1.4	5.6	21.2	45.1	161.9	194.5	-3,807
46	Moretna Jiru	83	0.2	7.4	31.7	62.4	149.9	256.9	-3,912
49	South Achefer	50	0.5	5.4	12.1	34.8	105.2	135.9	-3,936
51	South Achefer	54	0.6	4.7	15.7	60.8	192.7	166.5	-3,960
32	Hulet Ej	31	0.1	5.2	6.4	26.0	47.3	50.0	-3,966
45	Enese								
	Limo	83	0.2	7.4	32.1	33.3	111.3	137.1	-3,995
41	Kuyu	58	0.3	5.4	5.5	24.5	59.9	85.3	-4,053
57	Arsi Negele	59	0.7	6.1	4.4	126.0	251.9	247.2	-4,189
40	Kuyu	44	0.4	5.0	6.4	18.9	64.7	86.2	-4,246

reduced K availability to crops (Abiye *et al.*, 2004).

Concluding remarks

M-3 and NH₄OAc K extraction methods seem quite similar in their ability to partially extract non-exchangeable K, in addition to soluble and exchangeable K. Thus, both methods provide an over-estimate of soil K availability. The CaCl₂ method, on the contrary, mainly identifies the soluble K fraction, under-estimating exchangeable K. The ΔF method shows considerable agreement with the CaCl₂ method but has additional sensitivity to exchangeable K. Nevertheless, in the absence of any alternative proven chemical method to evaluate soil K availability (Wang *et al.*, 2016) to compare with, the ΔF results only provide indications, not reliable recommendations. A possible solution appears to be integrating chemical methods with biological tests, namely, direct measurements of K consumption by crops with simultaneous soil-K tests, as suggested by Affinnih *et al.* (2014), and more recently by Li *et al.* (2016). In addition, clay mineralogy should be further investigated on a local basis in order to determine and understand actual and possible dynamics of soil K status and availability, to establish a sufficient basis for practical recommendations.

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Table 3. Mineralogical composition of the clay fraction of 11 soil samples and the corresponding K-soil tests results (clay minerals: I, illite; S, smectite; Ka, kaolinite; Q, quartz; AM, amorphous material, probably transformed from I/S mixture).

Sample number	Soil properties		Clay mineral composition					K-soil tests			
	Clay %	CEC meq 100 g ⁻¹	Dominant >50%	Major 20-50%	Minor 5-20%	Traces <5	Saddle	CaCl ₂	NH ₄ OAc	M-3	ΔF Cal mole ⁻¹
57	59.5	4.4	AM		I, Ka, Q	-	-	126.0	251.9	247.2	-4,189
54	81.4	26.8	I/S		I, Ka	Q	1	60.8	192.7	166.5	-3,960
46	82.9	31.7	I/S		Ka	Q, I	0.8	62.4	149.9	256.9	-3,912
42	68.1	26.4	I/S		Ka	Q	>1	48.8	146.5	184.6	-3,771
44	83.4	33.3	I/S		Ka	Q	0.7	53.0	145.1	238.6	-3,733
2	74.9	36.0	I/S		I, Ka	Q	0.9	83.0	272.0	426.3	-3,609
59	82.2	26.3	I/S		I, Ka	Q	>1	102.6	240.2	211.8	-3,357
39	76.4	14.9	I/S		I, Ka, Q	-	>1	103.8	179.7	192.3	-3,239
19	51.8	22.4	AM		I, I/S	Q, Ka	-	209.7	449.1	503.5	-2,851
5	60.7	20.4	I/S	I	Ka	Q	>1	223.4	422.0	463.9	-2,848
8	24.5	7.2	AM		I, Ka	Q	-	198.1	329.5	227.4	-2,390

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