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Potassium (K)-to-magnesium (Mg) ratio, its spatial variability and implications to potential Mg-induced K deficiency in Nitisols of Southern Ethiopia

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Abstract

Background: Potassium (K) availability depends on exchangeable K and relative amounts of other cations. Yet, the latter has mostly been overlooked. Thus, this study was conducted to evaluate availability and spatial distribution of soil K in Nitisols of Wolaita area, southern Ethiopia, with particular regard to emphasis on assessing the potential for magnesium (Mg)-induced K deficiency. About 789 soil samples were investigated and mapped using ordinary kriging method.

Results: The result showed that 14.8% of the samples were K-deficient based on exchangeable K rating, whereas the K deficiency due to antagonistic effects of Mg was 54%. The spatial analysis also revealed that 68% of the study area (i.e., 57, 120 ha) has shown Mg-induced K deficiency. The finding is against the long belief that soils of the study area and the country contain sufficient quantity of K.

Conclusion: The findings of this study imply the need for inclusive approach while assessing the K status of soils and also call for greater attention toward K fertilizer intervention that was not in place in the study area. Nonetheless, further study including fertilizer application rates is suggested.

Keywords: Antagonism effect, Ethiopia, Geostatistics, Mapping

Introduction

Potassium (K^+) is an essential plant nutrient next to nitrogen (N) and phosphorous (P). It aids plants in the physiological processes such as transportation of water, nutrients and carbohydrates, photosynthesis, N utilization, stimulation of early growth, and in insect and disease resistance [1, 2]. It also helps plants regulate the opening and closing of stomata [1, 3] which is needed for efficient water use. In addition, a close relationship between K nutritional status and plant drought resistance has also been demonstrated [4].

Fertilizer-related interventions in Ethiopia were based on national soil survey that was conducted by FAO between 1950s and 1960s [5]. Consequently, the use of mineral fertilizer in the country had been focusing on N- and P-containing fertilizers in the form of urea (46-0-0) and di-ammonium phosphate (DAP) (18-46-0). Meanwhile, application of K as a commercial fertilizer in the country received little attention. This was due to the generalization that Ethiopian soils are believed to contain enough or sufficient quantity of the K nutrient. Such belief has emanated from the research of Murphy [6] conducted some five decades ago. Since then, pressure on land due to anthropogenic factors and farming practices has been changing. Some reports also indicated that continuous application of N and P fertilizers might have led to the depletion of other important nutrient elements such as K, magnesium (Mg), calcium

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(Ca), sulfur (S) and micronutrients in soils [7, 8]. If agricultural intensification and omission of K from the fertilizer regime continues, the risk of K limitation is expected to increase.

Currently, there is growing evidence of increasing K deficiency in different areas of Ethiopia. This is supported by research findings who reported the limitation of K under investigated soils [7, 9–15]. The depletion of K could be associated with continuous cultivation, complete removal of crop residues from farmlands, absence of crop rotation, unbalanced fertilizer application, soil erosion, loss of organic matter (OM) and inadequate fertilizer application (e.g., [5, 15, 16]).

Apart from the aforementioned reasons, the deficiency of K in Ethiopia has also been reported on soils having optimum amount of exchangeable K [14, 15, 17]. This might be connected with the disproportionate quantity of calcium (Ca^{2+}) and/or magnesium (Mg^{2+}) compared to K [14, 15, 17, 18]. This deficiency caused by a gross imbalance is known as induced deficiency [19]. According to Hoskins [19], there is usually an inverse and adverse relationship between a very high concentration of one cation in the soil and the availability and uptake of other cations by the plant. That is, if Ca and/or Mg dominate the exchange complex over K, it may reduce K availability and potentially result in K deficiency [14, 15, 17]. This implies that K availability does not solely depend on the K content of soils, but also depends on the relative amounts of other cations (Ca, Mg and K). Thus, knowledge on the relative proportion of cations (Ca, Mg, K) than single cation evaluation (e.g., K) has been suggested to explore nutrient antagonism and ensure sufficient supply of each nutrient [14, 15, 17–19]. Yet, this potential for induced limitation has been overlooked mostly by depending only on soil exchangeable K values to ascertain soil K status.

In Wolaita area, where this study was conducted, agriculture has been practiced under diverse slope positions (1–58%). In addition, continuous cultivation without fallow periods, complete crop residue removal from the farm and inadequate soil management were also common practices [16]. Fageria et al. [20] indicated that up to 70% of the total K accumulated in crops is found in crop residues. This has potentially important repercussions for soil K fertility in the cultivated fields of the study area where crop residues are removed under continuous cropping. However, limited information is documented with respect to the availability of soil K. Thus, the present study examined the hypothesis that K could be deficient in soils of Wolaita zone, southern Ethiopia, due to the presence of high amount of Mg relative to K. The objective of this study was to evaluate the availability and spatial variability of soil exchangeable K and Mg-induced potential K deficiency and generate K status map for the studied districts of Wolaita zone, southern Ethiopia.

Methodology

Description of the study area

The study was conducted during 2013 in Damot Gale, Damot Sore and Sodo Zuria districts located in Wolaita zone of Southern Nations', Nationalities' and Peoples' Regional State (SNNPRS) of Ethiopia (Fig. 1). The study districts from Wolaita zone were purposely selected because they have good potential for agriculture. The sites are located from 037°35′30″–037°58′36″E and 06°57′20″–07°04′31″N. The study area that covers about 84,000 hectare (ha) has a bimodal rainfall pattern with small rain in autumn (March–May) and major rain in summer (June–August) seasons. The long-term mean annual precipitation is 1355 mm and monthly temperature fluctuates between 17.7 and 21.7 °C with an average of 19.7 °C [21]. The elevation varies from 1473 to 2873 m.a.s.l (own survey data). The area is predominantly characterized by mid-highland agroecology. Eutric Nitisols associated with humic Nitisols are the most prevalent soils in the study area [22]. Agriculture is predominantly small-scale mixed crop-livestock subsistence farming. The farming system is mainly based on continuous cultivation without any fallow periods. The major crops grown in the study area include: tef (*Eragrostis tef* (Zucc.)Trotter), maize (*Zea mays* L.), bread wheat (*Triticum aestivum* L.), haricot bean (*Phaseolus vulgaris* L.), field pea (*Pisum sativum* L.), potato (*Solanum tuberosum* L.), sweet potato (*Ipomea batatas* (L) Lam.), taro (*Colocasia esculenta* (L.) schott.), enset (*Ensete ventricosum* (Welw.) chesman) and coffee (*Coffea arabica*).

Soil sampling procedure and laboratory analysis

Soil sampling procedure

Geographical information system (GIS) was employed to randomly assign predefined sampling locations following the Ethiopian Soil Information System (EthioSIS) sample distribution procedure [13]. Accordingly, 789 sampling points (243 in Damot Gale, 216 in Damot Sore and 330 in Sodo Zuria) were generated for sample collection. These sampling locations were randomly distributed at an average separation distance of 512 meters. During the survey work, the sample locations were navigated using geographical positioning system receiver (model Garmin GPSMAP 60Cx).

At each sampling point, 10–15 subsamples were taken based on the complexity of topography and heterogeneity of the soil to make one composite sample. Samples were collected using soil auger. Soil sampling depth for annual crops (e.g., tef, haricot bean, maize, wheat) was 0–20 cm, whereas it extended to 50 cm for perennial crops such as

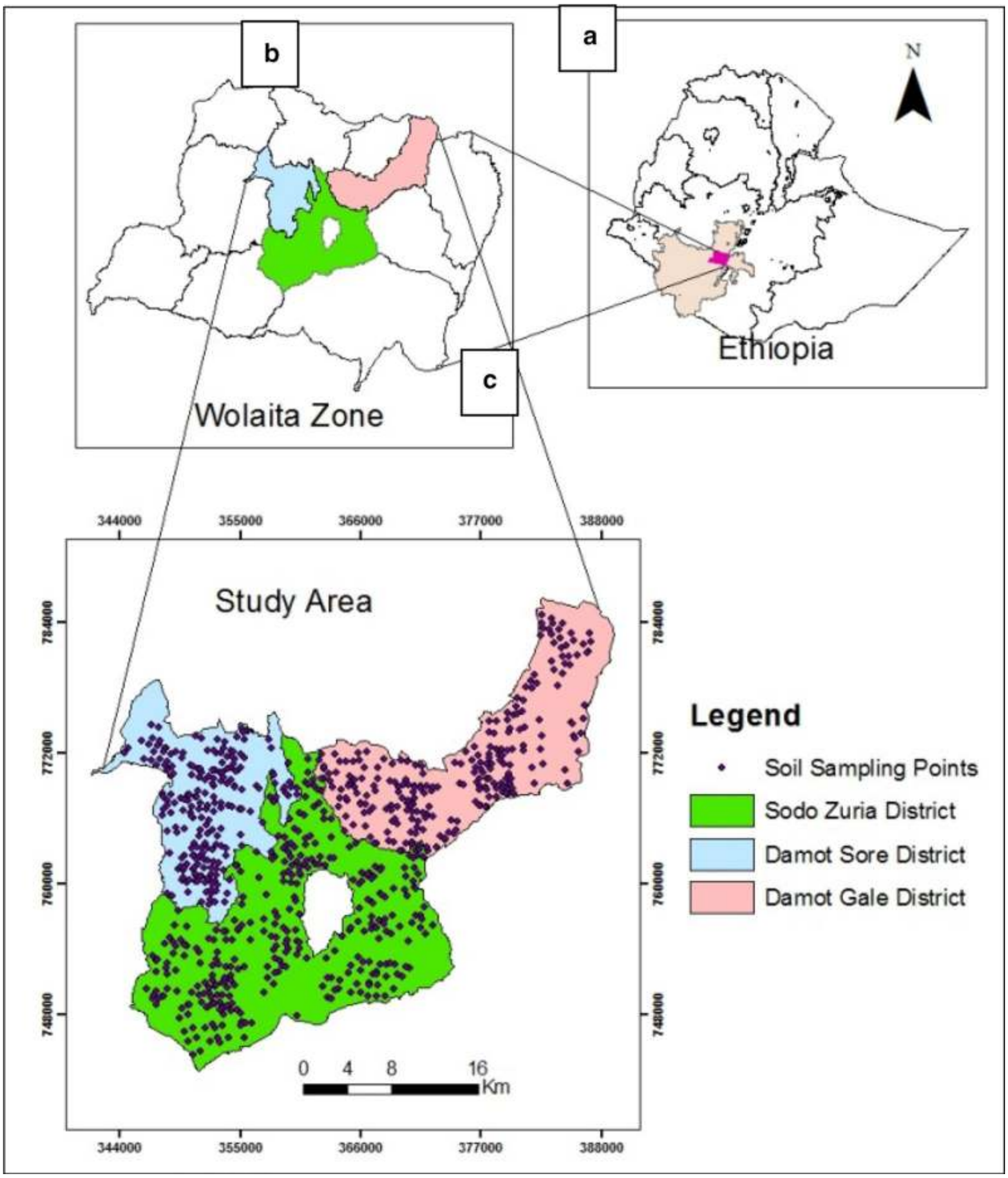

Fig. 1 Location map of SNNPRS in Ethiopia and Wolaita zone in SNNPRS: (**a**) the study districts in Wolaita zone (**b**) and soil sampling points in the study districts (**c**)

enset and coffee. From the composited sample, one kilogram (kg) of soil was taken with a labeled soil sample bag. To reduce the potential for cross-sample contamination, the soil auger and other sampling tools were cleaned before taking the next sample.

Soil sample preparation and analysis

Sample preparation (drying, grinding and sieving) was conducted at the National Soil Testing Center (NSTC), Addis Ababa, Ethiopia. Soil samples were analyzed for exchangeable K and Mg. Soil analysis was conducted in Altic B.V., Dronten, the Netherlands, using Mehlich-3 multi-nutrient soil extraction method at 1:10 (soil–solution ratio) [23]. The concentration of exchangeable K and Mg in the solution was measured using inductively coupled plasma (ICP) spectrometer. Mehlich-3 extraction was accomplished by mixing 2.5 g of soil and 25 ml of Mehlich 3 solution [0.2 M acetic acid (CH_3COOH), 0.25 M ammonium nitrate (NH_4NO_3), 0.015 M ammonium fluoride (NH_4F), 0.013 M nitric acid (HNO_3), and 0.001 M ethylene diamine tetra-acetic acid (EDTA)], shaking for 5 min, and filtering through a blue ribbon filter paper [23]. Mehlich-3 extraction which is adopted by EthioSIS as advised by AfSIS (Africa Soil Information System) is used in this study since it is cost-effective, less time-consuming, extracts multiple nutrients, and the method is being used by many regional organizations [24]. Furthermore, to highlight the soil environment conditions of studied districts, soil pH (1:2 soil/water suspension) and cation exchange capacity (CEC) were also measured using glass electrode and mid-infrared diffused reflectance (MIR) spectral analysis, respectively.

Geostatistical analysis and soil mapping

Ordinary kriging was performed to interpolate the values of un-sampled locations and produce maps of soil K status [25]. Semivariogram was constructed from the scatter point set to be interpolated, and the spatial variation was quantified from the input point dataset. Theoretically, the value of semivariogram for a separation distance of gamma *h* (referred to as the lag distance) is the average squared difference in Z value between sample points separated by *h* [26, 27]. The semivariogram was computed using Eq. 1 as:

$$\gamma(h) = \frac{1}{2n}\sum_{n=1}^{n}[Z(X_i) - Z(X_i + h)]^2 \quad (1)$$

where *n* is the number of pairs of sample points separated by the distance *h* and $Z(X_i)$'s are the values of the characteristic under study at *i*th location ($i = 1, 2, 3, \ldots, n$).

Prior to geostatistical analysis, three semivariogram models (spherical, Gaussian and exponential models) were tested to select the model that best fits to the data. The models provide information about the spatial structure as well as the input parameters for interpolation. Predictive performances of the fitted models were checked on the basis of error values computed from the entire dataset [28–30]. In this regard, the values of root-mean-square standardized error (RMSSE) (Eq. 2), mean standard error (MSE) (Eq. 3), and root-mean-square error (RMSE) (Eq. 4) were estimated to ascertain the fitted model. Thereafter, the model showing RMSE close to the MSE and RMSSE value close to one was selected as best fitting model for prediction [28–30]. Finally, kriged maps showing the values of un-sampled locations were generated. The maps provided a visual representation of the distribution of the soil parameters.

$$\text{RMSSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\{Z(X_i) - \check{Z}(X_i)\}/\sigma(X_i))^2} \quad (2)$$

$$\text{MSE} = \sqrt{\frac{1}{n}\sum_{n=1}^{n}\sigma^2(X_i)} \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z(X_i) - \check{Z}(X_i))^2} \quad (4)$$

where $Z(X_i)$ is the value of the variable *Z* at location X_i, $\check{Z}(X_i)$ is the predicted value at location *i*, *n* is the sample size, and $\sigma^2(X_i)$ is the kriging variance for location X_i.

The effectiveness of the interpolation was evaluated based on goodness of prediction estimate (*G*) (Eq. 5) [31, 32]. A "*G*" value equal to 100% indicates a perfect prediction, positive values (i.e., from 0 to 100%) indicate that the predictions are more reliable than the use of the sample mean, and negative values indicate that the predictions are less reliable than the use of the sample mean.

$$G = 1 - \frac{\sum_{i=1}^{n}(Z(X_i) - \check{Z}(X_i)^2}{\sum_{i=1}^{n}(Z(X_i) - Y)^2} \times 100 \quad (5)$$

where $Z(X_i)$ is the observed value at location *i*, $\check{Z}(X_i)$ is the predicted value at location *i*, *n* is the sample size, and *Y* is the sample mean.

The corresponding nugget (C_0), sill (C_0 + partial sill (C)) and range values of the model were used to evaluate spatial distribution of soil variables. Nugget represents the experimental variability that is not detectable at the sampling scale than the sampling interval [27]. Range is the lag distance between measurements at which the values of variables become spatially independent of one another. The magnitude of spatial dependence of soil variables was estimated from the ratio of nugget to sill ($C_0/(C + C_0)$) [33]. If the ratio is less than 25%, the variable is characterized by strong spatial dependence; if the ratio is between 25 and 75%, it indicates moderate spatial dependence and if it is greater than 75%, a variable shows weak spatial dependence [33]. Universal Transverse Mercator (UTM), Zone 37 N projection and Datum of WGS_1984 were employed for map projection. All the tasks were done using GIS software (Arc Map version 10).

Data analysis

Descriptive statistics were employed. Variation of soil exchangeable K, Mg and K–Mg (Table 1) was determined using the coefficient of variation (CV) and rated as low (< 20%), moderate (20–50%) and highly variable (> 50%) as indicated in [34]. Data analysis was carried out using

Microsoft excel and Statistical Package for Social Sciences (SPSS) software version 20. Geospatial analysis was performed using GIS software (Arc Map version 10).

Results and discussion

Soil pH and CEC

Soil pH-H_2O in the study areas ranged from 4.5 to 8.0 where acidic soil reaction was prevalent. About 3.3, 60, 31.3 and 5.3% of the soil samples in the Damot Gale district are categorized as strongly acidic (pH < 5.5), moderately acidic (5.6–6.5), neutral (6.6–7.3) and moderately alkaline (7.4–8.4), respectively, as per the ratings of EthioSIS [13]. In Damot Sore district, about 33, 42, 22 and 3% of the soil samples are rated as strongly acidic, moderately acidic, neutral and moderately alkaline soils, respectively, whereas in Sodo Zuria district, the soil pH was under strongly acidic (26.7%), moderately alkaline (58.0%), neutral (14.5%) and moderately alkaline (0.9%) ranges. Overall, 21% of total samples were under strongly acidic reaction. The CEC of sampled soils vary between 3.3 and 50.5 cmol(+) kg^{-1}. According to Landon [35], majority (83.4%) of the soil samples across the three districts were under moderate (15–25 cmol(+) kg^{-1}) CEC category, whereas the remaining soil sample proportion such as 0.1,3.2, 12 and 1.3% was qualified under very low (< 5), low (5–15), high (25–40) and very high (> 40 cmol(+) kg^{-1}) CEC levels, respectively.

Exchangeable K

The soil exchangeable K across districts varied from 0.1 to 6.2 Cmol(+) kg^{-1} in which higher variability among samples was observed. The range of values recorded in Damot Gale, Damot Sore and Sodo Zuria districts were 0.1–3.9, 0.2–6.2 and 0.2–4.5 Cmol(+) kg^{-1}, respectively (Table 1). Based on rating suggested for Ethiopian soils [13], about 0.4, 5.8, 64.2, 17.3 and 12.3% of sampled soils in Damot Gale qualified under very low (< 0.2), low (0.2–0.5), optimum (0.51–1.5), high (1.51–2.3) and very high (> 2.31 Cmol(+) kg^{-1}), respectively, in exchangeable K. In Damot Sore district, exchangeable K in the soils was in the range of low (17.6%), optimum (48.1%), high (15.7%) and very high (18.5%). Additionally, 19.4, 59.1, 12.4 and 9.1% of the samples in Sodo Zuria district qualified under low, optimum, high and very high exchangeable K level, respectively. Overall, 0.1, 14.7, 57.7, 14.8 and 12.7% of the soil samples across the three districts were categorized as very low, low, optimum, high and very high in their soil exchangeable K, respectively.

Exchangeable Mg

Exchangeable Mg showed moderate variability. The range of values were between 0.2 and 9.5 Cmol(+) kg^{-1} (Table 1). Landon [35] rated exchangeable Mg as very low (< 0.5), low (0.5–1.5), medium (1.5–3.3), high (3.3–8.3) and very high (> 8.3 Cmol (+) kg^{-1}) levels. In view of that, about 0.8, 28.4, 70.0 and 0.8 of the soil samples in Damot Gale district were regarded under very low, low, medium and high exchangeable Mg levels, respectively. In Damot Sore district, the status and sample proportion of exchangeable Mg showed low (32.9%), medium (54.2%), high (12.0%) and very high (0.9%) levels. The soil exchangeable Mg in Sodo Zuria district also indicates that about 0.9, 57.9, 89.4 and 4.6% of the soil samples were rated under very low, low, medium and high levels, respectively. Overall, about 0.5, 33.6, 60.8, 4.8 and 0.3% of the soil samples across the three districts were qualified under very low (< 0.3), low (0.3–1.0), medium (1.0–3.0), high (3.0–8.0) and very high (> 8.0 Cmol(+) kg^{-1}) soil exchangeable Mg levels, respectively.

Table 1 Descriptive statistics of soil exchangeable K, Mg and K–Mg in the study districts

District	Descriptive statistics	K (Cmol(+)kg^{-1})	Mg	K–Mg
Damot Gale (*N* = 243)	Mean	1.4	1.9	0.7
	SD	0.8	0.6	0.3
	Median	1.1	1.9	0.7
	Minimum	0.1	0.2	0.2
	Maximum	3.9	4.2	1.6
	CV (%)	57	32	40
Damot Sore (*N* = 216)	Mean	1.4	2.3	0.6
	SD	1.0	1.4	0.3
	Median	1.0	2.0	0.6
	Minimum	0.2	0.5	0.1
	Maximum	6.2	9.5	1.5
	CV (%)	71	61	43
Sodo Zuria (*N* = 330)	Mean	1.1	1.8	0.6
	SD	0.7	0.7	0.2
	Median	0.9	1.8	0.6
	Minimum	0.2	0.2	0.1
	Maximum	4.5	4.6	1.3
	CV (%)	64	39	40
Total (*N* = 789)	Mean	1.3	2.0	0.6
	SD	0.9	0.9	0.3
	Median	1.0	1.9	0.6
	Minimum	0.1	0.2	0.1
	Maximum	6.2	9.5	1.6
	CV (%)	69	45	41
	F_{value}	***	***	***

Number in brackets refers to sample size, *** significant at $p < 0.001$

Potassium-to-Mg ratio

The K–Mg ratio in soils of Damot Gale district varied from 0.2:1 to 1.6:1 where silty loam is the dominant soil texture (data not shown). On the other hand, in Damot Sore and Sodo Zuria districts that are clay in soil textural class (data not shown), the K–Mg ratio ranged between 0.1:1 and 1:1. To determine nutrient status, a variety of K–Mg thresholds have been reported by different authors in different soils (e.g. [18], Kundler et al. (1989) cited in Loide [18, 36, 37]). While studying fertilizer requirement in soils of Germany, the K–Mg values used by Kundler et al. (1989) cited in Loide [18] were 2:1 (sandy soil), 1.8:1 (sandy loam soil), 1.7:1 (loam soil), 1.2:1 (clay soil) and 3.6:1 (peat soil). The extraction method reported by the authors was double lactate (DL) for K and $CaCl_2$ solution for Mg. On the other hand, Loide [18] and Loide [36] extracting K in DL; and Mg in ammonium lactate (AL) method reported K–Mg values of 1.2:1 (sandy soil), 1:1 (sandy loam and loamy soils), 0.7:1 (clay soils) and 2.2:1 (peat soil). Hannan [37] suggested a K–Mg concentration between 0.40 and 0.50, regardless of soil texture, to avoid Mg-induced K deficiency.

Among threshold values, a K–Mg value of 0.7 which is described by Loide [18, 36] was temporarily adopted in this study to demonstrate the potential Mg-induced K deficiency due to the following reasons:

1. Mehlich-3 extraction solution that was used in this study was reported to yield significantly ($p < 0.01$) and linearly correlated result with DL extraction solution for K ($r = 0.955$) and AL extraction solution for Mg ($r = 0.916$) [38].
2. In Ethiopia, an indication of Mg-induced K deficiency in wheat [14] and maize plant [15] was reported considering the threshold of Loide [18, 36].
3. There is also insufficient evidence to support the use of threshold value as a hard cutoff point for identifying soils likely to exhibit Mg-induced K limitation.

Accordingly, about 47, 57 and 54% of the silty loam soils, clay soils and total soil samples, respectively, have shown an indication that they are prone to Mg-induced K deficiency (Fig. 2). Potassium deficiency has not been reported and is overlooked in the study area due to exclusive reliance of the soil testing on soil exchangeable K concentration to indicate soil K status. Intensive cropping, complete removal of crop residue, wide spread use of fertilizers (DAP and urea) which contain no K and nonuse of mineral K fertilizer in soils of the study area might have resulted in the occurrence of K depletion [9, 14–16, 39].

In Vertisols of central highlands of Ethiopia, Hillete et al. [14] also reported K deficiency in soils having very high exchangeable K. The authors associated the deficiency with the disproportionate quantities of exchangeable Mg. In addition, Abayneh et al. [17] reported

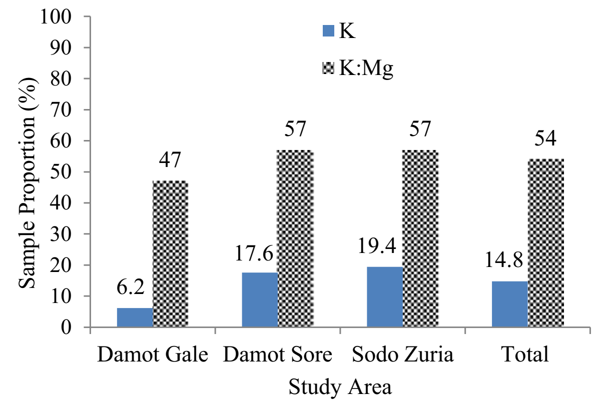

Fig. 2 Actual and Mg-induced K deficiency proportion in soils of Damot Gale, Damot Sore, Sodo Zuria and total area

K deficiency on soils having an optimum amount of exchangeable K. Moreover, Hillete et al. [14] also noted low foliar K on 70% of wheat flag leave samples, despite the high soil K and high soil Mg. Similar to this, the study by Fanuel et al. [15] in Nitisols of southern Ethiopia also documented lower K tissue concentration on 54% of sampled maize leaves despite having adequate levels of soil K. Furthermore, soil exchangeable cation availability in the present study was in the order of Ca > Mg > K > Na (data not shown). These examples support the importance of considering Mg concentration as potentially important factor controlling K availability.

Soil spatial variability analysis and mapping

The spatial variation of exchangeable K and Mg in the semivariogram was best described by the Gaussian and exponential models, respectively (Table 2). In line with the present findings, Behera and Shukla [40] also reported Gaussian and exponential models for K and Mg, respectively. The spatial dependence of K was weak (> 75%). Exchangeable Mg exhibited moderate spatial dependence (25–75%), while K–Mg was relatively strong (< 25%). Strong spatial dependence indicates that random factors have less influence on K–Mg ratio, while internal factors associated with inherent variations of soil characteristics are more influential. Weak spatial dependence shows a more random distribution [27]. In agreement, weak spatial dependence on K [41–43] was reported. Moderate spatial dependence was attributed to both intrinsic and extrinsic factors [40]. The value which indicates spatial autocorrelation (range) varied from 843 m (K–Mg) to 4466 m (K) which is more than 512 m (average sampling distance). This indicates that the sampling interval used in this study was adequate to capture the variability. Besides this, the RMSSE value

Table 2 Model performance and semivariogram characteristics of exchangeable K, Mg and K–Mg ratio

Semivariogram characteristics	K	Mg	K–Mg
Model	Gaussian	Exponential	Exponential
Data transformation	Log	Log	No
Nugget (m) (C_0)	0.37	0.11	0.004
Partial sill (m) (C)	0.04	0.07	0.06
Sill (m) ($C_0 + C$)	0.41	0.18	0.064
Lag size	372.16	266.17	124.19
Range (m)	4465.9	1833.8	843.4
Spatial dependence $C_0/(C + C_0)$ (%)	90	61	6.0
Spatial dependence status	Weak	Moderate	Strong
RMSE	0.86	0.81	0.25
RMSSE	1.03	0.95	1.01
MSE	0.95	0.91	0.25
G (%)	99.0	23.0	100

RMSE root-mean-square error, *RMSSE* root-mean-square standardize error, *MSE* mean standard error, *G* goodness of prediction

of prediction was close to one with the nearest values of RMSE to MSE. Goodness of prediction varied from 23 to 100% where the value of Mg, K and K–Mg was 23, 99 and 100%, respectively. All these confirm a good prediction performance. Generally, the stronger spatial dependence and smaller spatial autocorrelation of K–Mg than soil K and Mg suggest that the concentration of soil Mg is more patchily distributed than K, and hence, perhaps a better indicator of the potential for Mg-induced K deficiency.

The exchangeable K content of the interpolated map (Fig. 3) varied from 0.46 to 2.55 Cmol (+) kg^{-1}. Spatially, about 0.3, 92, 6.7 and 1% from the total area were found to have low (0.2–0.5), optimum (0.5–1.5), high (1.5–2.3) and very high (> 2.31 Cmol(+) kg^{-1}) levels of soil exchangeable K. The observed exchangeable K values were above the critical limits (K > 0.5 Cmol(+) kg^{-1}) adopted for Ethiopian soils [13] and would seem to satisfy the K demand by crops with the exception of very small areas in Sodo Zuria district that showed K deficiency.

Soil exchangeable Mg content of interpolated map was between 0.7 and 6 Cmol(+) kg^{-1}) (Fig. 4). In terms of area coverage, about 14, 84 and 1% of total study area were having low (0.5–1.5), medium (1.5–3.3) and high (3.3–8.3 Cmol(+) kg^{-1}) Mg contents, as rated by Landon [35]. Acidic nature of the soil, continuous Mg removal with crop harvest and low soil OM could explain the low level of exchangeable Mg. In addition, the prevalence of moderate to strong leaching on 32% of the soil samples across the three districts, according to leaching criterion of [44], would also contribute to lower soil exchangeable Mg. In line with this finding, Adesodun et al. [45] reported that continuous cultivation led to reduction, uptake and leaching of exchangeable cations, especially in acidic tropical soils.

Data on K–Mg ratio of the interpolated map indicated values that varied from 0.14:1 to 1.48:1. Using the K–Mg of 0.7 [18, 36], spatially 68% of the studied area (i.e., 57, 120 ha) showed a potential risk of K deficiency due to antagonistic effects of relatively high exchangeable Mg (Fig. 5). This might also be mainly attributed to inadequate soil management practices in the study areas, e.g., no K fertilizer application, inadequate and unbalanced fertilization (i.e., only N and P), and complete crop removal [15, 16]. In general, K deficiency in the vast area needs attention as it would limit the efforts of improving crop productivity of the study area.

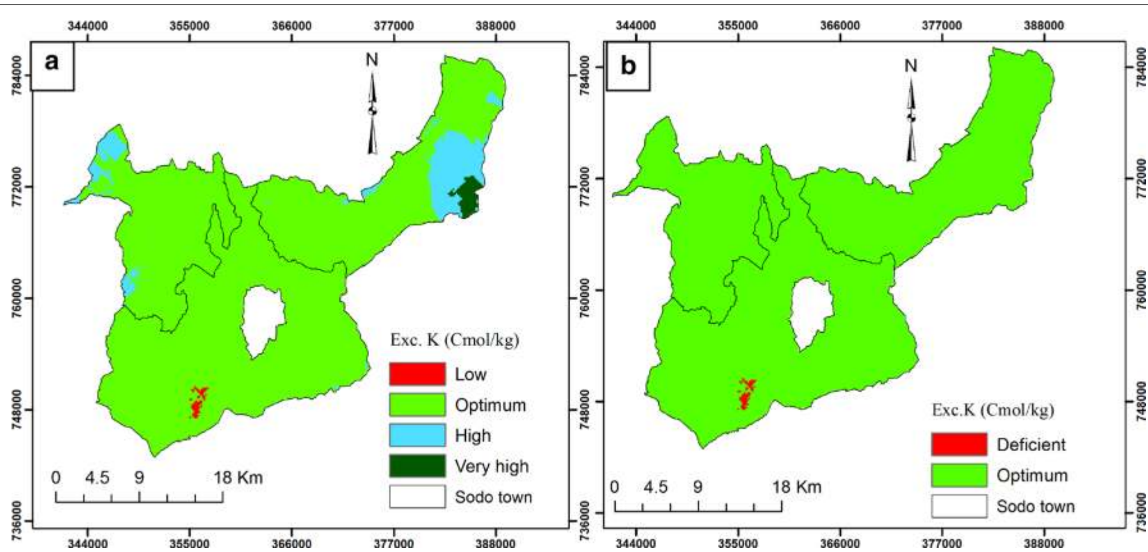

Fig. 3 Soil exchangeable K: **a** status and **b** management-based map of Damot Gale, Damot Sore and Sodo Zuria districts

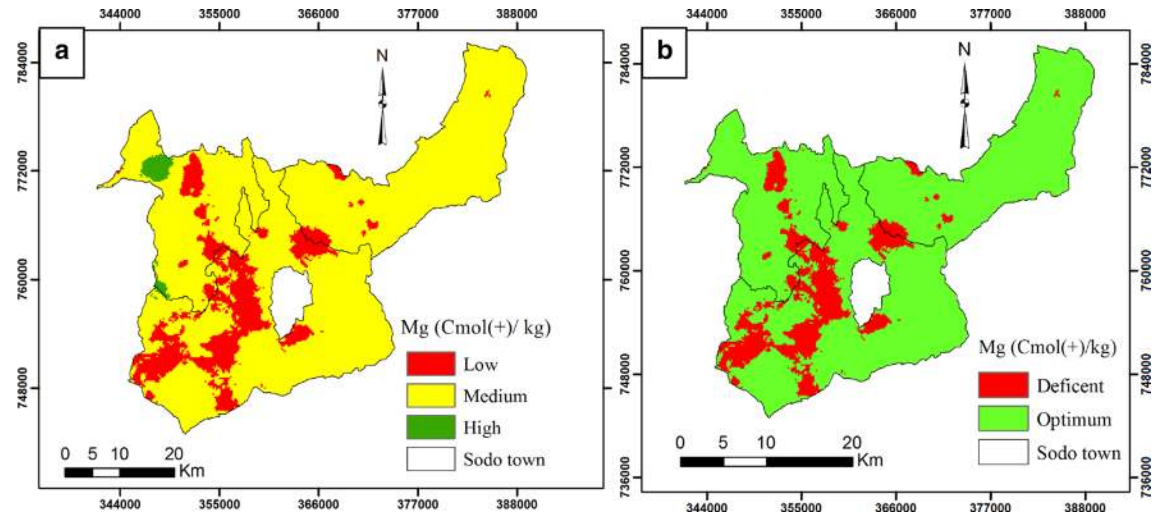

Fig. 4 Soil exchangeable Mg: **a** status and **b** management-based map of Damot Gale, Damot Sore and Sodo Zuria districts

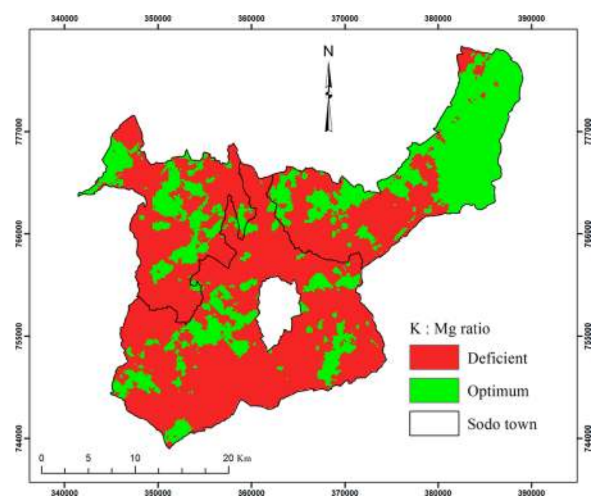

Fig. 5 Map of K status based on K–Mg ratio of the study area

To this end, recently K fertilization experiment on wheat crop grown in Nitisols of Sodo Zuria, Wolaita zone having high available soil K (0.96 Cmol(+) kg^{-1}) [46] but regarded as Mg-induced potential K deficiency in this study was conducted. The result revealed that K fertilizer application significantly influenced growth and yield of wheat. According to Tigist [46], the highest grain yield was recorded when 50 kg ha^{-1} KCl (0-0-60) was applied with 74.5 N-57 P_2O_5-10.5 SO_4^{-2} kg ha^{-1}.

Conclusion

The result showed that the proportion of the study area affected by Mg-induced K deficiency is by far higher than the K deficiency based on exchangeable K from soil test. This implies that soil exchangeable K values alone may not adequately indicate K availability in areas where soil exchangeable Mg concentration is relatively high enough to compete with exchangeable K and cause K deficiency. Hence, holistic approach is needed while assessing the K status instead of depending solely on values of exchangeable K. Furthermore, the present finding is against the generalization that Ethiopian soils are believed to contain sufficient quantity of K and calls for greater attention toward K in the Ethiopian national fertilizer agenda. It also recommends the need for site-specific research to determine the K–Mg threshold and consider this in determining the K availability.

Authors' contributions

Fanuel Laekemariam collected, analyzed and interpreted the data. Kibew Kibret helped to draft the manuscript. Hailu Shiferaw contributed to mapping. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

We declare that the data and materials presented in this manuscript can be made available as per the editorial policy of the journal.

Consent for publication
All data and information are generated and organized by the authors.

Ethics approval and consent to participate
Not applicable.

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