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INVESTIGATION OF RELATIONSHIPS BETWEEN AVAILABLE BORON AND SOIL PROPERTIES

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ABSTRACT

Soil formation processes and cropping and management practices affect plant-available amounts of boron (B) in soils. Using Pearson's correlation and principal component analyses, this study investigated the relationships between soil properties and plant-available boron concentrations in 69 soil samples. In principal component analysis (PCA), 73.079% of the variance was explained with four components. Plant-available B in the soil was significantly correlated with phosphorus, potassium, pH, and electrical conductivity (EC), showing that phosphorus and potassium fertilizer producers would be adding boron to fertilizers, although it is not mentioned on their packages. Also, the tide correlation between B and either soil pH and EC was attributed to greater solubility B, pH and EC. The majority of the experimental soils were deficient in boron. Therefore, boron fertilizer must be added to the fertilization program to mitigate the losses caused by boron deficiency in low-input agricultural production fields.

Keywords: boron, plant nutrients, soil properties, chemometric relations, PCA.

INTRODUCTION

The continuity of sustainable agricultural production is possible by supplementing the nutrients removed by plants. Agricultural enterprises and farmers generally do not have much information about the deficiencies of micronutrients, while they regularly control the deficiencies of macronutrients such as nitrogen, phosphorus, and potassium. Boron, an essential micronutrient for plants, should be present in the soil in the range of 1-4 mg/kg. Plants' boron requirements differ, but the gap between sufficiency and toxicity is narrower than those of other nutrients. Therefore, both deficient and toxic levels of boron in soil solution can occur in a single growing season. The narrow deficiency and toxicity limits suggest that boron fertilization should be carefully monitored (Saha et al., 2017). The amount of boron available for plants in the soil depends on a variety of soil properties such as soil parent material, texture, reaction (pH), electrical conductivity (EC), organic matter content, lime content, clay content, type and amount of exchangeable cations, soil depth and horizontal differentiation, and topography (Dhaliwal et al., 2019; Gürel et al., 2019; Zhang et al., 2020) as well as the boron content of irrigation water, fertilization, and crop rotation, etc. and other agricultural practices (Nadeem et al., 2019; Vidal et al., 2019; Duboc et al., 2021). In this context, due to the fact that Turkey has more than 70% of the world's boron reserves, it has ecosystems where deficiency and toxicity extremes are frequently encountered.

Boron deficiency in soils has been reported in more than 80 countries worldwide (Padbhushan and Kumar, 2017). Boron deficiency is generally reported in coarse-textured acidic soils, soil rich in carbonates and/or Fe- and Al-oxides and hydroxides, and soils with low organic matter content (Niaz et al., 2011). Also, the monoculture of crops such as corn, sunflower, and alfalfa, which are of high commercial importance, exacerbates boron deficiency in low boron-content soils (Das et al., 2019).

The objective of this study was to assess the amount of plant available B content of the

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soils in relation to land cover and cropping pattern in Atabey Plain in Isparta of Türkiye.

MATERIAL AND METHODS

Soil sampling and analyses

A total of 69 composite soil samples were taken from 0-20 cm depth of representative soil series (Akgül et al., 2002) across the Atabey plain. The sampled soils' existing vegetation and land use patterns were recorded at the time of sampling. Land cover types of the sampled fields were; fallow/non-cropping land (FAL), pear (PE), sunflower (SNF), almond (ALM), grape (GRA), wheat (WHE), walnut (WAL), tomatoes (TOM), apple (APP), plum (PL), poplar (POP), cherry (CER), corn (COR), forest (FOR), aubergine (AUB), peach (PEA) and walnut (NUT).

The air-dry soil samples were passed through a 2 mm sieve for analysis. Descriptive analyses of soil samples were performed using methods given in (Sparks and Bartels, 1996) commonly used in neutral-alkaline soils. The pH and electrical conductivity (EC) of the soils were determined in a 1:2.5 soil: water suspension; organic matter (OM) by the modified Walkley-Black method (Nelson and Sommers, 1996); calcium carbonate ($CaCO_3$) content with Scheibler calcimeter; texture fractions with a hydrometer (Gee and Bauder, 1986); available phosphorus (P) by the Olsen method (Kuo et al., 1996); plant available K, Na, Ca and Mg extracted with neutral molar ammonium acetate (Sumner and Miller, 1996); and cation exchange capacity (CEC) by molar sodium acetate at pH 8.2. The plant-available boron was extracted with 0.01 M $CaCl_2$ + 0.05 M by shaking at 20°C for 16 h and measured spectrophotometrically (PG Instruments, T80) at 420 nm wavelength by coloring azomethine-H reagent (Cartwright et al., 1983).

Statistical analyses

All statistical analyses were carried out in the SPSS 17 package program. Descriptive statistics were calculated to evaluate the distribution of data for each of the soil variables. The parameter is assumed to have a normal distribution when the kurtosis and/or skewness coefficient is≤2 x standard deviation (Berkman and Reise, 2011). Pearson's correlation analysis was performed after the parameters were approximated to normal distribution.

Principal component analysis (PCA) was conducted (Landau and Everitt, 2003). In this context, PCA is the expression of the structure explained by *p* number of variables that are correlated with variables that are linear components of the original variables, which have not correlated with each other and are less in number than the number of original variables. At this stage, no transformation was applied to CEC, Ca, pH, sand, and silt in the data set in order to reduce the skewness coefficient; whereas square root transformation to $CaCO_3$, K, Mg, Na, and B; Log transformation to OM, EC and clay parameters were applied. Then, the principal components were extracted using the "correlation matrix". Varimax rotation was applied to decrease the multiple loading of variables.

RESULTS AND DISCUSSION

Descriptive soil properties

Descriptive statistics of the investigated soil properties are given in Table 1.

Table 1. Descriptive statistics of the experimental soil properties

Soil Parameters	Min.	Max.	Mean	Std. Deviation	Variance	Skewness	Kurtosis
P (mg/kg)	2.5	368.0	44.3	53.37	2848.1	3.980	20.67
$CaCO_3$ (%)	0.7	41.5	11.4	10.81	116.90	1.117	0.421
CEC ($mmol_+$/ kg)	112.0	629.3	332.9	101.2	10244.0	0.476	0.218
Ca ($mmol_+$/ kg)	69.2	416.0	251.5	7.873	6199.0	-0.496	-0.174
K ($mmol_+$/ kg)	4.1	36.0	16.0	0.804	64.7	0.829	-0.172
Mg ($mmol_+$/ kg)	12.0	158.4	55.1	3.131	980.1	1.128	1.051
Na ($mmol_+$/ kg)	0.5	21.5	6.18	0.261	6.8	2.518	17.400
OM (%)	0.5	6.9	2.09	0.979	0.958	2.211	8.527
pH	6.8	8.0	7.69	0.286	0.082	-1.635	2.051
EC (mS/cm)	105.2	762.0	292	119.6	14305	1.078	2.318
B (mg/kg)	0.0	1.9	0.661	0.347	0.121	1.142	2.008
Sand (g/kg)	5.7	694.9	3901	161.0	25922	-0.189	-0.385
Clay (g/kg)	118.0	667.0	249	96.98	9405.9	1.410	3.748
Silt (g/kg)	146.9	699.1	361	119.2	14219.7	0.516	0.078

The standard error of skewness is 0.289, and the standard error of kurtosis is 0.570 for N: 69.

Whether the data showed a normal distribution or not was evaluated over the skewness and kurtosis coefficients. In this respect, organic matter (2.221), $CaCO_3$ (1.117), EC (1.078), K (0.829), Mg (1.128), Na (2.518), B (1.142), clay (1.410) and P (3.980) parameters showed a positively skewed distribution. The higher the skewness value, the more a deviation from the normal distribution, indicating the presence of some extremely high values of the corresponding variables. The skewness values for organic matter content indicate that some extremely high-valued localities were the case for OM content. Positive tailing in $CaCO_3$ and NH_4-acetate extractable-K, -Mg, -Na content may be attributed to local differences in parent material and topography and fertilizer use to some extent. The presence of calcareous parent materials in the study area may cause a positive tailing in the distribution of $CaCO_3$ data. Also, positively skewed distribution in variables such as EC and Na may be attributed to differences in topography, climate, and type of irrigation, and properties of irrigation water. The study area soils are formed on physiographic units such as high hills and ridges, colluvial piedmont, alluvial fans, bajadas, foothills, and young stream beds (Akgül et al., 2002). Highly variable topography would induce differences in soil depth and nutrient concentration due to differences in topography-driven erosion and deposition processes. Leaching may cause nutrient depression on some sites during enrichment on others. Positive skewness of P and B distribution may be attributed to the non-homogenous use of P and B fertilizers in the study area. Because when the frequency distribution graph of the boron content of the soils is considered (Figure 1), it is seen that a significant part of the soils is at the level of sufficiency according to the Azometin-H method corresponding to P and K availability.

Negative skewness for a variable refers to the presence of extremely low-valued localities. pH had a negatively skewed frequency distribution. However, the skewness coefficient of pH is too high (in absolute value) to have a normal distribution (Table 1) because of “–log” expression is included in the pH. This shows that soil pH decreases in some areas during soil formation. Considering that the parent material of the soils is Mesozoic-Tertiary limestone transported by the effect of water and/or gravity, one of the most important reasons for the differentiation in soils is different physiographic units (Akgül et al., 2002). Soil pH decreases with the progress of soil formation or with an increase in horizontal development (Usta, 1995). Also, acids used to prevent clogging of drip irrigation systems, especially in orchards, can have a pronounced effect on soils with low lime content and light texture.

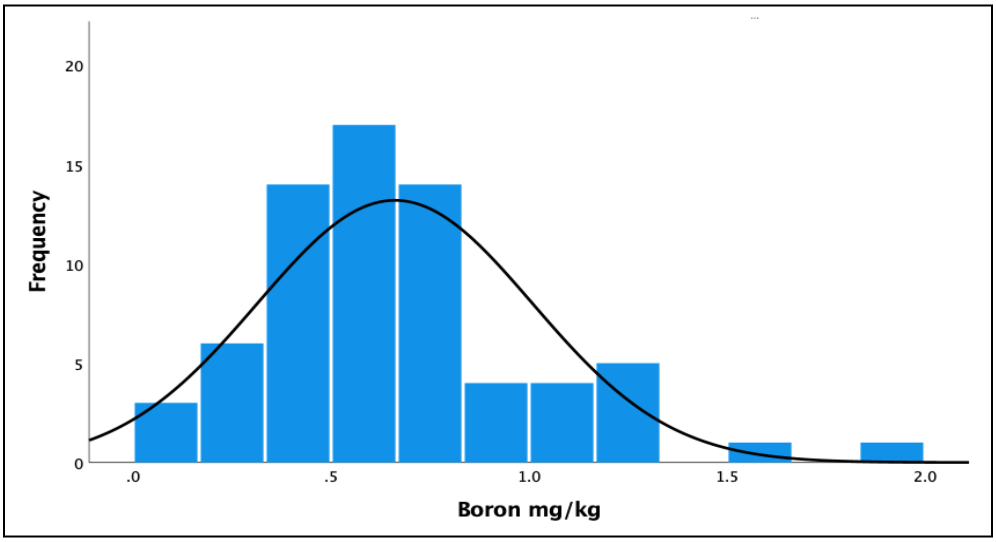

Figure 1. Frequency distribution of plant-available boron concentration in the soils

When the kurtosis coefficient is<2 x standard error of kurtosis (2 x 0.570 = 1.14), it is accepted that the dataset has a normal distribution, and positive values indicate a peak-like distribution and negative values indicate a flat distribution (Berkman and Reise, 2011). While the positive kurtosis value shows the tendency of the data to gather around the mode value; the negative kurtosis value indicates the variability of the soils in terms of the relevant feature (Berkman and Reise, 2011). Calcium carbonate equivalent (0.421), CEC (0.218), sand (-0.385), silt 0.078), Ca (-0.174), K (-0.172), and Mg (1.051) parameters of the soils showed normal distribution. The highest kurtosis value was determined in the available phosphorus content (20.669), followed by Na (17.40), organic matter (8.527), clay (3.748), EC (2.318), and pH (2.051). After transformation procedures, the kurtosis value was within normal distribution limits (Table 1).

Relationships between soil properties and plant-available boron

The results of the Pearson's correlation analyses between soil properties and B content are given in Table 2. Boron was significantly positively correlated with soil content in K, P, electrical conductivity, and soil pH. The plants uptake those nutrients mostly from the soil solution. It is well known that optimum plant growth and crop yield depend not only on the total amount of nutrients in the soil at a given time, but also on their availability controlled by soil physicochemical properties such as texture, organic carbon and calcium carbonate, cation exchange capacity, pH and EC (Bell and Dell, 2008). Similarly, it has been reported that the amount of available boron is related to K, P, Mg, and Na concentrations in sugar cane soils. In this context, the trace amount of B found in nitrogen, phosphorus, and potassium fertilizers (Pişkin, 2021) can explain the high correlation between B, P, and K.

On the other hand, the relationship with EC indicates that due to the fact that B is not strongly retained in soils (Terraza et al., 2018; Tlili et al., 2019), it may move from the washing zones to the accumulation zones (Zhang et al., 2020). Soil soluble B content has been correlated with soil pH (Elrashidi and O'Connor, 1982; Dridi et al., 2018) and EC (Dridi et al., 2018). Tkaczyk et al. (2017) reported that the amount of available B can be expressed by a multiple regression equation as a function of SO_4-S, Mn, pH, and Fe. This situation can indirectly indicate the relationship with EC, considering that SO_4-S has the highest share in the regression, and the experimental soils are located in the arid-semi-arid climate zone, which can lead to SO_4 accumulation in the soils.

Table 2. Pearson's correlation coefficient's matrix of soil properties (N=69)

Soil Parameters	P	$CaCO_3$	K	Mg	Na	OM	EC	B	Clay	CEC	Ca	pH
$CaCO_3$ (%)	0.169											
K (mmol/ kg)	0.387**	0.059										
Mg (mmol/ kg)	0.236	0.046	0.256*									
Na (mmol/ kg)	0.153	-0.032	-0.147	-0.319**								
OM (%)	0.318**	0.251*	0.329**	0.139	0.049							
EC (mS/cm)	0.381**	0.349**	0.623**	0.377**	-0.034	0.272*						
B (mg/kg)	**0.426****	0.205	**0.380****	0.232	0.006	0.037	**0.467****					
Clay (g/kg)	0.110	0.572**	0.216	0.245*	-0.114	0.147	0.300*	0.036				
CEC (mmol/ kg)	-0.034	0.000	0.512**	0.473**	-0.412**	0.225	0.539**	0.095	0.314**			
Ca (mmol/ kg)	-0.045	0.560**	0.488**	0.309**	-0.281*	0.224	0.666**	0.144	0.542**	0.708**		
pH	0.177	0.530**	0.240*	0.416**	-0.182	-0.158	0.355**	**0.344****	0.390**	0.092	0.515**	
Sand (g/kg)	0.176	-0.250*	-0.330**	-0.325**	0.327**	-0.024	-0.379**	0.019	-0.717**	-0.692**	-0.690**	-0.246*
Silt (g/kg)	-0.295*	-0.091	0.327**	0.228	-0.376**	-0.073	0.295*	-0.023	0.179	0.676**	0.515**	0.044

* Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

Chemometric relations of boron

As a result of the PCA performed after the normalization of 14 parameters determined in the soils, four principal components (PCs) were extracted with eigenvalues greater than 1. The eigenvalues of these PCs and the variances explained by the PCs are given in Table 3. Those 4 PCs explained 73.079% of the variance in data.

The soil properties associated with the extracted PCs are given in Table 4. Accordingly, it is seen that the PC 3 has high positive loading values with P, K, Mg, pH, and EC parameters. When the chemometric relationships between soil properties are considered, it is observed that the PCs 1, 2, and 3 significantly explain the variations. In Figure 2, the effect directions of the PCs 1 and 3 and the soil properties with high loading values are given in the scatter diagram. It is clear that the results revealed in the Pearson correlation analysis are also in agreement with the PCA. The PC 1, which explained 35.085% of the total variance in the data set, and PC 3, on which B content was loaded, showed that P, K, pH, and EC affected B content in the same direction. On the other hand, the amount of silt and Na concentration had an inverse relationship with the amount of available B.

The scatter diagram of the principal components 1 and 3 shows that most of the sampling sites with perennial vegetation are distributed depending on the soil properties that have a positive loading value with the PC 3 (Figure 3). In this region, variables of pH and EC and P, K, Mg, and B contents are closely related to agricultural practices. Soils scattered in the negative zone are generally those where low input management is practiced, and high silt content is thought to play an important role in this behavior that facilitate its leaching. It is observed that the soils that are generally under fallow and the forest management had lower boron contents and fell apart from other soils with these characteristics. On the other hand, soils with a high B concentration, where mainly fruit orchards are located, were located in the positive region of the diagram, and this supported the assessment that it was a result of the relatively high amount of fertilization as a function of vegetation and the addition of boron (0.1-0.8%) in the fertilizers (Pişkin, 2021).

On the other hand, there is a general trend of an increase in soil organic matter due to perennial plants in these soils. Although correlation analyses do not reveal a strong relationship between B and OM, OM is an important soil feature that increases B availability in soils (Dhaliwal et al., 2019). It can be thought that the relatively high B uptake of crops and fruits (Eriksson, 2001) would overshadow the positive effect of OM content on the plant available B content of those soils.

Table 3. Explained variances by the extracted principal components

Components	Initial Eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	4.912	35.083	35.083	4.912	35.083	35.083	3.620	25.854	25.854
2	2.377	16.979	52.062	2.377	16.979	52.062	2.574	18.388	44.242
3	1.653	11.809	63.871	1.653	11.809	63.871	2.530	18.072	62.314
4	1.289	9.208	73.079	1.289	9.208	73.079	1.507	10.765	73.079
5	0.941	6.724	79.804						

Extraction Method: Principal Component Analysis.

Table 4. Loading matrix for soil properties vs. rotated principal components

Soil Parameters	Principal components			
	1	2	3	4
Silt (g/kg)	0.894			
CEC (mmol/ kg)	0.877			
Sand (g/kg)	-0.812	-0.460		
Ca (mmol/ kg)	0.625	0.625		
Na (mmol/ kg)	-0.557			
$CaCO_3$ (%)		0.903		
Clay (g/kg)		0.799		
pH		0.624	0.497	-0.443
B (mg/kg)			0.791	
P (mg/kg)			0.705	
EC (mS/cm)			0.628	
K (mmol/ kg)	0.435		0.588	0.400
Mg (mmol/ kg)	0.416		0.535	
OM (%)				0.826

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser. Normalization. Rotation converged in 6 iterations.

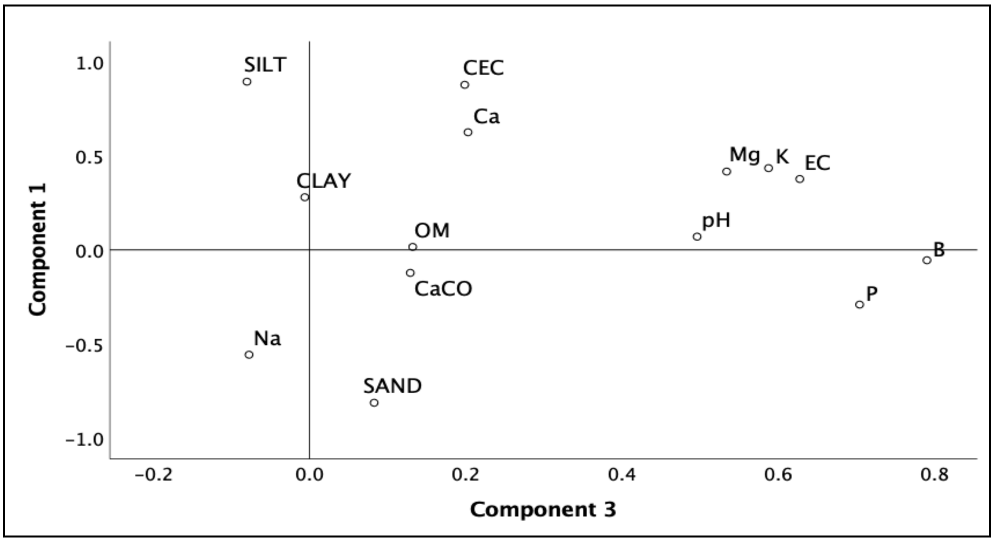

Figure 2. Scatter diagram for soil properties related to PC1 vs PC3

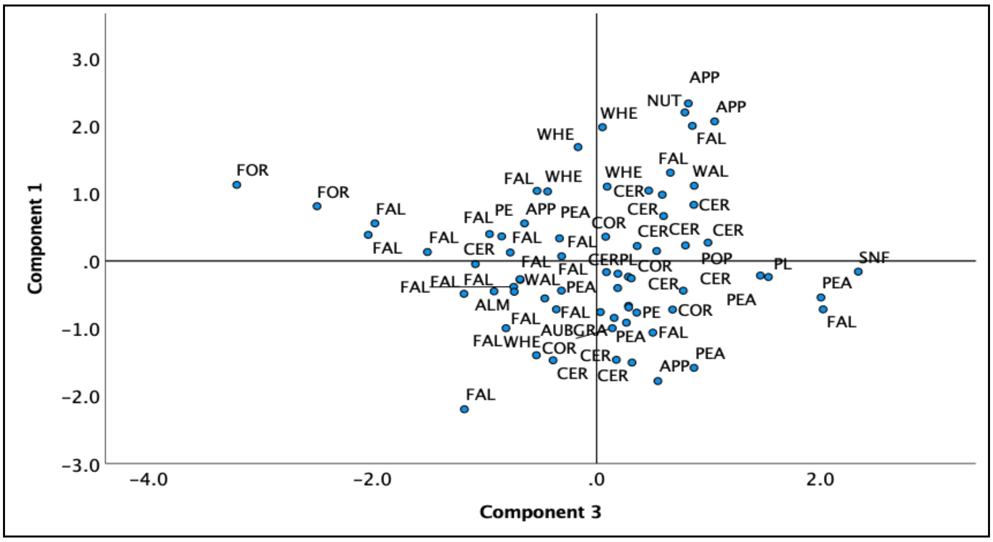

Figure 3. Scatter diagram for PC1 vs. PC3. Crop /land use types of the sampled fields were: fallow/non-cropping land (FAL), Pear (PE), sunflower (SNF), almond (ALM), grape (GRA), wheat (WHE), walnut (WAL), tomatoes (TOM), apple (APP), plum (PL), poplar (POP), cherry (CER), corn (COR), forest (FOR), aubergine (AUB), peach (PEA) and walnut (NUT)

The scatter diagram of plant available B concentrations of the soil's vs. PC3 is given in Figure 4. The distribution of soil samples resenting different crops in the Figure shows that the amount of available B in the soil can be estimated using parameters associated with PC3.

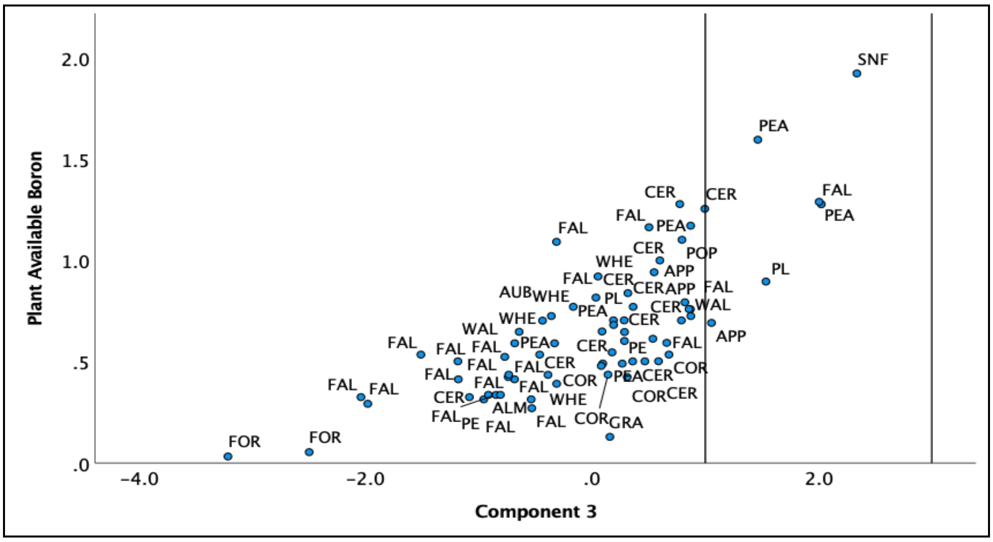

Figure 4. Scatter diagram for PC3 vs. plant-available boron concentrations. Crop /land use types of the sampled fields were: fallow/non-cropping land (FAL), Pear (PE), sunflower (SNF), almond (ALM), grape (GRA), wheat (WHE), walnut (WAL), tomatoes (TOM), apple (APP), plum (PL), poplar (POP), cherry (CER), corn (COR), forest (FOR), aubergine (AUB), peach (PEA) and walnut (NUT)

CONCLUSIONS

This study determined that the available B concentration of some soils in the Isparta region changes between 0 and 1.9 B mg/kg and the mean concentration was 0.661 B mg/kg in the depth of 0-20 cm. Boron was positively correlated with soil content in K, P, electrical conductivity, and soil pH. While 58 of the study soils were below the boron sufficiency level, 11 of them (1<B<4 mg/kg) were below 2 mg/kg within the threshold values. It has been considered that B deficiency is quite common in the soils due mainly to the nonexistence of a specific B fertilization program, very low B content of the parent material, and/or leaching away during the soil formation processes due to its weak adsorption on soil components in alkaline conditions. Also, B can be easily washed on due to rough topography (even in high amounts of B-containing parent materials such as limestone). Two forest soil samples with extremely low B content supported this notion. This means a source of boron from the parent material is insufficient, and it strengthens the idea that the boron found in other samples may come from the boron added to the chemical fertilizers. Even though calcareous parent materials generally contain higher total B than other parent materials, this advantage may not be effective on a rough topography. When normal commercial fertilization is made in these soils, the B requirements of many plants can be met without any risk due to the B content of the fertilizer. Specific B fertilization programs may be necessary for soils with low B content where macro element fertilizer input is low.

REFERENCES

Akgül, M., Başyiğit, L., Uçar, Y., 2002. *Atabey ovası topraklarının genel özellikleri ve sınıflandırılması*. Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 6(1): 1-13.

Bell, R.W., and Dell. B., 2008. *Micronutrients for sustainable food, feed, fibre and bioenergy production*: International Fertilizer Industry Association (IFA).

Berkman, E.T., and Reise, S.P., 2011. *A conceptual guide to statistics using SPSS*. Sage.

Cartwright, B., Tiller, K.G., Zarcinas, B.A., Spouncer, L.R., 1983. *The chemical assessment of the boron status of soils*. Soil Research, 21(3): 321-332.

Das, R., Mandal, B., Sarkar, D., Pradhan, A.K., Datta, A., Padhan, D., Seth, A., Kumar, R., De, N., Mishra, V.N., 2019. *Boron availability in soils and its nutrition of crops under long-term fertility experiments in India*. Geoderma, 351: 116-129.

Dhaliwal, S.S., Naresh, R.K., Mandal, A., Singh, R., Dhaliwal, M.K., 2019. *Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review*. Environmental and Sustainability Indicators, 1: 100007.

Dridi, I., Tlili, A., Fatnassi, S., Hamrouni, H., Gueddari, M., 2018. *Effects of boron distribution on sugar beet crop yield in two Tunisian soils*. Arabian Journal of Geosciences, 11(15): 1-7.

Duboc, O., Steiner, K., Radosits, F., Wenzel, W.W., Goessler, W., Tiefenbacher, A., Strauss, P., Eigner, H., Horn, D., Santner, J., 2021. *Field evaluation of a boron recycling fertiliser*. Plant, Soil and Environment, 67(2): 110-119.

Elrashidi, M.A., and O'connor, G.A., 1982. *Boron sorption and desorption in soils*. Soil Science Society of America Journal, 46(1): 27-31.

Eriksson, J., 2001.*Concentrations of 61 trace elements in sewage sludge, farmyard manure, mineral fertiliser, precipitation and in oil and crops*. Vol. 5159: Citeseer.

Gee, G.W., and Bauder, J.W., 1986. *Particle-size analysis*. Agronomy (USA).

Gürel, S., Başar, H., Keskin, E., Dirim, M.S., 2019. *The determination of soil boron fractions, their relationships to soil properties and the availability to olive (Olea Europea L.) Trees.* Communications in Soil Science and Plant Analysis, 50(8): 1044-1062.

Kuo, S., Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., 1996. *Phosphorus. Methods of soil analysis. Part 3. Chemical methods. Madison.* Soil Science Society of America, Inc., American Society of Agronomy, Inc.

Landau, S., and Everitt, B.S., 2003. *A handbook of statistical analyses using SPSS*. Chapman and Hall/CRC.

Nadeem, F., Farooq, M., Nawaz, A., Ahmad. R., 2019. *Boron improves productivity and profitability of bread wheat under zero and plough tillage on alkaline calcareous soil.* Field Crops Research, 239: 1-9.

Nelson, D.W., Sommers, L.E., 1996. *Total carbon, organic carbon, and organic matter*. Methods of soil analysis: Part 3, Chemical methods, 5: 961-1010.

Niaz, A., Ahmad, W., Zia, M.H., Ranjha. A.M., 2011. *Relative efficiency of different extractants for available boron estimation in alkaline calcareous soils*. Communications in Soil Science and Plant Analysis, 42(16): 1934-1944.

Padbhushan, R., and Kumar, D., 2017. *Fractions of soil boron: A review.* The Journal of Agricultural Science, 155(7): 1023-1032.

Pişkin, A., 2021. *Farklı form ve bileşendeki kompoze gübre uygulamalarının şeker pancarı verim ve kalite değerleri üzerine etkisi ve ekonomik analizi*. Anadolu Tarım Bilimleri Dergisi, 36(2): 255-267.

Saha, A., Mani, P.K., Hazra, G.C., Mitran, T., 2017. *Assessing suitability of different extractants for determining available boron in soil*. Journal of Plant Nutrition, 40(19): 2651-2661.

Sparks, D.L., and Bartels, J.M., 1996. *Pt. 3: Chemical methods*. Soil Science Society of America Book Series.

Sumner, M.E., and Miller, W.P., 1996. *Cation exchange capacity and exchange coefficients*. Methods of Soil Analysis: Part 3, Chemical methods, 5: 1201-1229.

Terraza, P., Fernanda, M., Sumner, M.E., Cabrera, M.L., Thompson, A., 2018. *Boron adsorption and desorption on volcanic ash-derived soils*. Soil Science Society of America Journal, 82(1): 66-75.

Tkaczyk, P., Bednarek, W., Dresler, S., Krzyszczak, J., Baranowski, P., Sławiński, C., 2017. *Relationship between assimilable-nutrient content and physicochemical properties of topsoil*. International Agrophysics, 31(4): 551.

Tlili, A., Dridi, I., Attaya, R., Gueddari, M., 2019. *Boron characterization, distribution in particle-size fractions, and its adsorption-desorption process in a semiarid Tunisian soil.* Journal of Chemistry, 2019.

Usta, S., 1995. *Soil chemistry*. Agricultural Fac. Pub, 1387.

Vidal, Y.C., Baró, E.A., Gutiérrez, G.M., Gutierrez, A.S., Villazón, J.A., Fajardo, A.R., 2019. *Chemical properties that determine boron availability in sugar cane soils*. Agrisost, 25(2): 1-5.

Zhang, X., Li, M.J., Zhan, L.Q., Wu, W., Liu, H.B., 2020. *Boron availability in top-and sub-soils as affected by topography and climate*. Nutrient Cycling in Agroecosystems, 118(1): 91-101.