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Impacts of Residual Boron on Wheat Applied To Previous Cotton Crop under Alkaline Calcareous Soils of Punjab

Abid Niaz[1]*, Allah Nawaz[1], Shabana Ehsan[1], Ifra Saleem[1], Muhammad Ilyas[1], Abdul Majeed[1], Atif Muhmood[1], Atta Muhammad Ranjha[2], Rahmatullah[2], Nazir Ahmed[2]

[1]Soil Chemistry Section, Institute of Soil Chemistry and Environmental Sciences, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[2]Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Abstract
Cotton and wheat are two most important crops of Pakistan. Food and Agriculture Organization of the United Nations reported that boron deficiency occurred widely in Pakistan, especially under cotton-wheat cropping system. High soil pH and $CaCO_3$ content are the major factors of low boron (B) availability in alkaline calcareous soils; therefore, this study was conducted to assess the leftover effects of B on wheat in these soils. For this purpose ten B treatments (0, 0.25, 0.50, 0.75, 1, 1.25, 1.50, 1.75, 2 and 3 kg B ha^{-1}) as boric acid were applied to cotton. After the harvesting of cotton, wheat was sown in the same plots as a test crop without B application, but all other nutrients were applied at recommended rates. Soil analysis showed that B concentration gradually increased from 0.17 mg kg^{-1} (at control) to 0.36 mg kg^{-1} (at 3 kg B ha^{-1}) after the cotton harvest in B application plots. The average highest soil B concentration of 0.24 mg kg^{-1} was obtained after first year cotton harvest followed by second year (0.21 mg B kg^{-1}) whilst the lowest soil B concentration of 0.19 mg kg^{-1} was obtained after the third season of cotton. This study revealed that residual B applied to previous cotton crop has a significant effect on wheat crop in terms of yield and growth. No toxic effect of residual B was observed in wheat. The highest grain yields of 4.70 t ha^{-1} and 4.58 t ha^{-1} were obtained from 1.50 kg B ha^{-1} treated plots during first and second years, respectively while the minimum was obtained from control. There was a highly significant linear relationship (P< 0.05) between residual B levels and plant B content of the first wheat crop (R^2= 0.96**) and second wheat crop (R^2= 0.93**) seasons.
Keywords Alkaline, boron, calcareous, residual effect, Pakistan.

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***Corresponding author** Abid Niaz **Email** draniazch@gmail.com
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Introduction

Boron chemistry is exceptionally complex and is similar to silicon [1]. Naturally, boron symbolized as B, but it never exists in the elemental form in an environment, rather it exists as a combination of the both isotopes, $_{10}B$ (19.78%) and $_{11}B$ (80.22%) [2]. At room temperature (~25^oC), elemental B persists as a solid form. The crystalline and amorphous structures of B have specific gravities of 2.34 and 2.37, respectively. It is a moderately inert metalloid in the absence of strong oxidizing associates. Hydrolytically unstable sodium perborates of B–O–O bonds react with H_2O to formulate H_2O_2 and sodium metaborate ($NaBO_2·nH_2O$) [3]. Very weak acid of boric acid (H_3BO_3; pKa of 9.15) and sodium borates, which originate generally as undissociated boric acid [$B(OH)_3$] in solution when the pH is less than 7, whereas metaborate anion $B(OH)_4$ species produce in solution at pH >10. B moves in all directions in the soil by mass flow of water, but its availability decreases with increasing pH, and most of the total soil B is unavailable to plants. A small quantity of B is gradually complexes within organic matter [4] or adsorbs on clays [5], and to some extent precipitates with $CaCO_3$ and unavailable for plant growth [6]. Therefore, B use efficiency is exceptionally low in Pakistan because the majority of soils are alkaline and calcareous in nature [7]. Cotton (*Gossypium hirsutum* L.), a white gold, is an important and renowned cash crop of Pakistan whereas wheat (*Triticum aestivum* L.) is the world's leading cereal crop. Food and agriculture organization of the United Nations (FAO) reported that about 49% area of Pakistan is B deficient. B deficiency is widespread owing to exhaustive cropping and more nutrient uptake than addition. Moderately high soil pH (≥ 7.5), use of fertilizers poor in B and low organic matter (OM) content (<1.0 %) of calcareous soils are major causes of low B availability to plants. Further, the majority of farmers indiscriminately use only macronutrients (N, P and rarely K) as fertilizer for irrigated wheat, cotton, sugarcane and rice crops [8].

According to a worldwide study on micronutrients, almost 49% area of Punjab, Pakistan is B deficient [6, 9]. In Pakistan, the climatic conditions are very severe, i.e., high temperature and low rainfall in arid and semi-arid areas of wheat-cotton cropping system, so a little amount of soil B is gradually complexes with organic matter [10] and also adsorbed on clay surfaces [11,12]. Further, it has also been revealed that somewhat boron is precipitated with $CaCO_3$ [13] and is quite unavailable for plant growth [6, 14, 15]. B is associated directly and indirectly with several plant functions, as it involves in growth of cells in newly emerging shoots and roots while in some plants it is crucial for boll formation, flowering, pollination, seed development and sugar transport synthesized by the different plant components [16, 17]. B plays a supportive role in cell wall synthesis, lignification [1] and cell wall structure [18]. In Pakistan, a number soil factors and farming practices are liable to stimulate B deficiency, comprising high soil pH, calcareous soils (high $CaCO_3$ content) and low OM. About 50% of the cotton area and cotton plants are thought to suffer from B deficiency [19]. B in soil system occurs in soil solution, from where it is taken up by plants through root via mass flow. It has a lot of reactions with soil properties like $CaCO_3$, pH, clay content (texture) and organic matter content. Further, boron in soil system can be added through irrigation water (either canal or tubewell waters). Therefore, in the soil system B has particular dynamics in alkaline calcareous soils, specifically when we study its availability under the wheat-cotton cropping system. So keeping in view the importance of B in crop nutrition, especially under the wheat-cotton cropping system, this research project was initiated to determine the residual or carry-over effects of B (if any) on wheat crop applied to previous cotton crop under alkaline calcareous soils of Pakistan.

Materials and methods

Wheat cultivation and soil sampling

This experiment was conducted during 2006-07 to 2008-2010 to determine the residual effects of boron by using wheat-cotton cropping system. For this purpose, cotton was supplied with ten B treatments (0, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2 and 3 kg B ha^{-1}) as a soil treatment and wheat was sown in the same plots after cotton harvesting. Prior to wheat sowing, composite soil samples (0-15 cm) were collected from the B treatment plots after the harvesting of cotton and subsequently analyzed for determining the physico-chemical properties of soil [21, 22]. Wheat (*Triticum aestivum* L.) cultivar Chenab-2000 was sown in the same plots after the harvest of cotton, but without B application on wheat. B was applied to cotton only once during the first year and after cotton only wheat crop was sown in the same plots. After wheat crop, the plots were kept fallow for both years. The cultural practices and other nutrients were applied to wheat (NPK @ 120, 80 and 50 kg ha^{-1}) as recommended by Agriculture Department. The wheat crop was harvested on the 2nd of May and grain and straw yields (t ha^{-1}) were recorded. Post harvest soil sampling was also done immediately after the harvest of wheat crop for the determination of residual B.

Plant B estimation

Analysis of B required extraordinary and exceptional attentions because it needs very sensitive instruments and apparatus. Further, ordinary glassware was not used during analysis because this glass contained boro-silicates (silica glass) and this glass-ware sometimes creates problems with the B concentration in minor ranges. So, for this purpose, we use special boron free glass-ware and polypropylene-ware like beakers, funnels, volumetric and conical flasks [23].

Plant tissue samples were collected from each treatment plot of wheat to assess the B concentration in plants. Plant and grain samples were collected at maturity stages. After washing with well-distilled and de-ionized water, these samples were oven dried at 70^{o}C in an air forced oven for 48-72 hours and subsequently ground with a plant grinding Willey mill. For dry ashing, 0.50-1.0 g of the ground plant material was added in porcelain crucibles, placed in a muffle furnace and the temperature was increased to 550◦C. The ashing process continued for 4.5 to 5 hours after attaining 550^{o}C. After 5 hours, the furnace was powered-off and the sample material was cooled. Soon-after that the samples were extracted by 0.36 N H_2SO_4, filtered through filter paper (Whattman No. 1) and then color was developed by Azomethine-H reagent. The absorbance of the colored material was noted at 420 nm on spectrophotometer [25]. Later, plants samples were passed through a 0.50 mm sieve and preserved to calculate the total B uptake by the following formula [24]:

$$\text{B uptake (g ha}^{-1}\text{)} = \text{B concentration (mg kg}^{-1}\text{)} \times \text{yield (t ha}^{-1}\text{)} \times 1000 / 1000$$

Soil B estimation

A total of 5 g soil was weighed in Polypropylene tubes and 10 ml 0.05 M HCl was added and kept for a few minutes and then samples were filtered through Whatman No.1 filter paper. The color was developed by adding 4 ml sample filtrate into test tube and then 4 ml buffer-masking reagent and 1 ml azomethine-H reagent were added. Samples were mixed up cautiously and thoroughly. Then samples were allowed to develop color for 40-50 minutes. After color development, these samples were measured for their absorbance at 420 nm using a Spectronic Genesis TM Spectrophotometer. B concentrations of sample were determined from the standard curve constructed by plotting absorbance versus concentration of standards in µg B ml^{-1} [26].

Statistical analysis

The collected data were analyzed by using Fisher's analysis of variance technique and LSD at 5% probability was used to compare the treatment means [27].

Results

Soil analysis

The basic soil analysis depicted that soil of the experimental site was sandy clay loam and pH was slightly higher (8.0) and indicated alkalinity of the soil. The electrical conductivity (EC_e) measured was (0.71 dS m^{-1}) and revealed that soil was normal, and there were no salinity or sodicity hazards found in the soil samples of the experimental site. Further, the soil analysis also reflected the intense calcareousness of the experimental site as it had high $CaCO_3$ content (11.05%), whereas fertility condition of soil was incredibly poor and OM content, total N, available P and extractable K of experimental site was 0.52%, 0.032%, 6.25 mg kg^{-1} and 116 mg kg^{-1}, respectively. In case of B concentration of soil, 0.05 M HCl extractable soil B in control plots was only 0.17, 0.16 and 0.16 mg kg^{-1} (average of three plots) during 1st year (after cotton harvest but before wheat sowing), 2nd year (after cotton and before wheat) and 3rd year (after wheat harvest), respectively.

The results depicted in Fig. 1 showed that soil B concentration before the start of the experiment was 0.17 mg kg^{-1} and it was significantly improved by B application to previous cotton crop with B application levels of 0, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00 and 3.00 kg B ha^{-1}. The results showed that soil B concentration gradually increased from 0.17 mg kg^{-1} (control) to 0.36 mg kg^{-1} (3 kg B ha^{-1}) after the cotton harvest (before start of wheat sowing). It was obvious that lower B treatment plots (0.25, 0.50, 0.75, 1.00 and 1.25 kg ha^{-1}) did not cause any strong buildup of B in the treatment plots, but afterward there was a significant increase in soil B concentration in B treated plots of 1.50 to 3.0 kg B ha^{-1}. The average highest soil B concentrations of 0.24 mg kg^{-1} was obtained from B treated plots of cotton after harvest during 1st season followed by second year (0.21 mg B kg^{-1}) whilst the lowest soil B concentration of 0.19 mg kg^{-1} were obtained during 3rd year (Fig. 1).

When we compared the soil B concentrations of all three year (three years averaged soil B), the data exhibited that the maximum soil B concentration was 0.31 mg kg^{-1} and it was found at B application level of 3 kg ha^{-1} while the minimum 0.16 mg kg^{-1} was obtained from control and 0.25 kg B ha^{-1}. The regression analysis and linear relationship depicted in Fig. 2 shows that B concentration significantly increased (P<0.05) from control to the highest B levels with utmost B concentration in soil during the 1st season (R^2 0.95), followed by 2nd season (R^2 0.95) and then the 3rd season (R^2 0.87). After wheat harvest, soil B concentration levels at 3 kg B ha^{-1} were 0.36 mg kg^{-1}, 0.30 mg kg^{-1} and 0.26 mg kg^{-1} during the 1st, 2nd and 3rd years, respectively, whereas in the case of control treatment, soil B level was gradually decreased from 0.17 mg kg^{-1} to 0.15 mg kg^{-1}. This soil boron concentration data clearly revealed that the original soil B concentrations were depleted with time and it directly depended on crop removal or uptake.

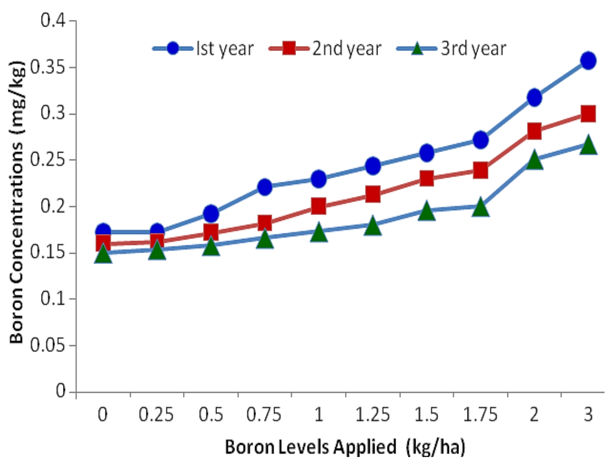

Fig. 1 Residual soil B concentrations at the experimental site after cotton, before wheat sowing for first two years (2008-09) and after wheat harvest in the third year (2010).

Moreover, soil B application significantly improved the soil B status and there was a definite B buildup in B treated plots in the case of 2 to 3 kg B ha^{-1} applied to previous cotton crop, resulted in increased soil B concentration from 0.17 mg kg^{-1} to 0.36 mg kg^{-1} after first year, 0.16 mg kg^{-1} to 0.30 mg kg^{-1} after second year and 0.15 mg kg^{-1} to 0.31 mg kg^{-1} after the third year. However, 0.05 M HCl extractable soil B levels indicated that soil B was increased, but it could not reach the critical soil B level of 0.50 mg kg^{-1}.

Grain and straw yields (t ha^{-1}) of wheat

The data exhibited (Fig. 2) that the uppermost wheat grain yield of 4.70 t ha^{-1} was obtained with plot of B treatment 1.50 kg B ha^{-1} applied to cotton and the minimum wheat grain yield (3.71 t ha^{-1}) was obtained from control plot and the highest B application plot. The difference in yield was statistically significant ($P \leq 0.01$) and grain yield increased from 3.71 t ha^{-1} in B lacking (control) treatment to 4.70 t ha^{-1} in B treatment plots. A further appealing observation was that residual B did not cause any toxicity symptoms either on vegetative crop stand or on yield response parameters. In addition, wheat responded to B only at lower levels as compared to higher residual B levels. During 2nd year, this grain yield data again showed the significant responses of residual B on wheat grain yield increased from 3.95 t ha^{-1} in control plots to 4.58 t ha^{-1} at 1.50 kg B ha^{-1} application level plots of cotton (Fig. 3). Actually, yield increased trend started with B application level of 1 kg ha^{-1} and it remained up to 1.75 kg B ha^{-1} level and these four treatments (T_1, T_2, T_3, and T_4) were statistically at par with each other.

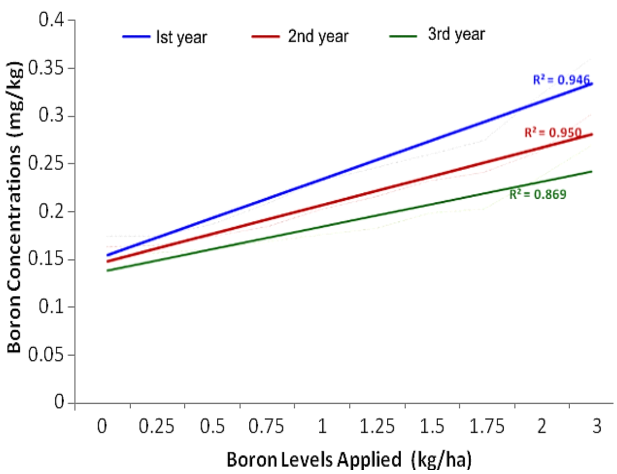

Fig. 2 Regression analysis along with R^2-values showing the linear relationship between boron treatments applied and B concentration (mg/kg) in soil during three years (2008-2010).

After that, as B application increased as in case of treatment plots where B application rates were 2 and 3 kg B ha^{-1}, the grain yield decreased abruptly and both of these treatments exhibited statistically significant variation in grain yield (Fig. 3 & 4). This yield reduction trend was another clear indication of B toxicity at higher levels that might be due to the low B requirement of wheat crop and disturbance in the nutrient balance within the wheat plants which ultimately appeared as low grain setting and grain development. The results regarding straw yield also exhibited the significant response of residual B on wheat (Fig. 4). The results also indicated that grain and straw yields did not badly affected by higher B levels during both years. Highest straw yield during both years was obtained with B treatment plots of 1.5 kg B ha^{-1} (8.38 t ha^{-1}) and 2 kg B ha^{-1} (8.56 t ha^{-1}), respectively, while lowest straw yields (6.78 and 5.97 t ha^{-1}) were obtained from control plots, respectively.

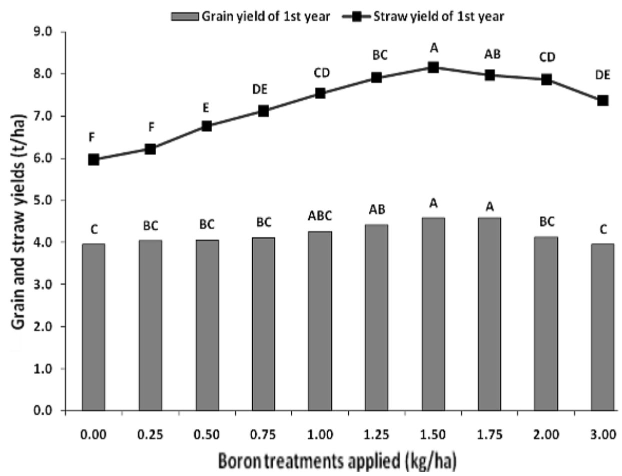

Fig. 3 Residual effect of B on grain and straw yields (t/ha) of wheat during 1st year (2008-09).

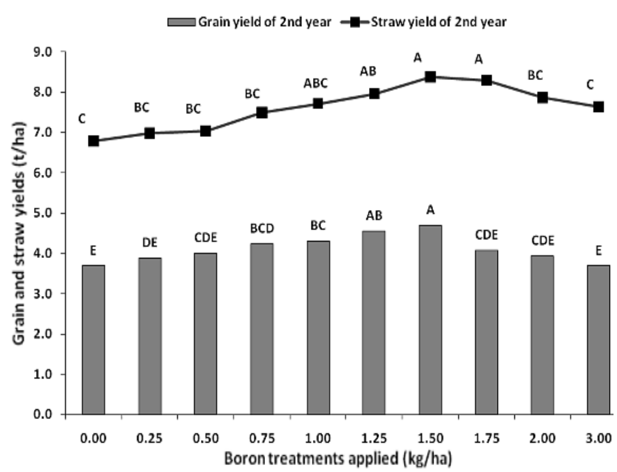

Fig. 4 Residual effect of B on grain and straw yields (t/ha) of wheat during 2nd year (2009-10).

Leaf B concentration and uptake by wheat crop

The results illustrated (Fig. 5) that B concentration in plant leaves was improved with B application and the maximum B concentration was observed where B was applied to cotton at the rate of 3 kg ha^{-1} in both years. The B concentration in leaves at first three treatments were statistically at par pertaining to each other, but soon after that level, B concentration increased significantly due to higher B application rates. Likewise, the data showed that the highest B applications (to previous cotton crop) evidently resulted into more B uptake by wheat plants. The results of total B uptake by wheat plants showed (Fig. 5) that the B uptake was more during the first year as compared to second year and it might be due to the more B availability during the first year then 2nd year. The results exhibited that the highest B uptake was obtained from the treatment where 3 kg B ha^{-1} was applied during both years while the lowest was obtained from the control.

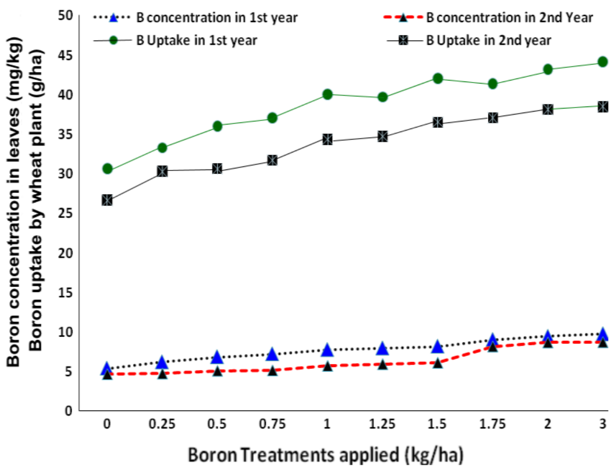

Fig. 5 Average boron concentration in leaves and total boron uptake by wheat crop during both years (2008-2010).

Discussion

The period of the carryover or residual effect of soil supplied B obviously depends on soil physico-chemical properties, predominantly those that had a significant role in leaching (i.e. soil texture), desorption or adsorption. Thus, it is impracticable to explicate length or interval of residual impacts of B, apart from the comprehensive localized experiments. Many researchers have reported toxic residual effects of B on different crops [28, 29]. Some other factors are also responsible for soil residual B availability like B application method, B doses and tillage practices [30]. Furthermore, B deficiency is extremely frequent in coarse or sandy textured soil. It was well established that B or borates are easily leached from surface soil to lower profiles. Therefore, researchers recommended that B applications for only one crop at the rate of 1 to 2 kg ha-1 were very effective with modest residual or carry-over impacts to a second crop of next year [6]. However, in case of specific crop rotations, B is required by just one crop, this signifies that the one such crop must be applied with B. Conversely, the adsorption of B by CaCO3 as well as fine or clayey textured soils can result in significant residual or carry-over effects [31, 32]. Earlier studies had also revealed that B remained in the soil in the adsorbed form on clay surfaces depending upon the amount of clay minerals [33]. Further, it has also been revealed that somewhat B is precipitated with CaCO3 and is quite unavailable for plant growth [34]. It is also a fact that climatic conditions are very harsh, i.e., high temperature and low rainfall in arid and semi-arid areas of wheat-cotton cropping system, so a little amount of soil B is gradually complexed with soil organic matter [11, 35]. In cereals like wheat, B deficiency limits plant reproductive growth more strictly than vegetative growth. B depletion, removal or absence from the root medium, for not more than three days, at pollen and anther development or elongation stages badly affected the plant structures and finally resulted in the collapse of pollen viability [36, 37]. The depressing effects on anther-length of wheat is owing to the B deficit in the form of its removal, and this also projected that B positively performs its role in the cell walls of reproductive structures which is identical to vegetative growth [38]. The results of the current study are in conformity with the findings of other researchers in which they elucidated that wheat genotypes responded positively to boron application whilst B toxicity encouraged 15 to 17 % decline in dry matter yield [39]. Whereas some researchers revealed that in few Asian countries (like India, China, Pakistan, Bangladesh, Nepal and Thailand) wheat sterility is a ubiquitous hindrance in rice-wheat farming systems that caused serious grain yield reductions [40]. In wheat, B deficiency resulted in the formation of sterile floret of wheat and this sterility was not only due to B, but some other factors may also take part in it like heat stress or elevated temperature, water scarcity and cold temperature [41-43]. Similarly, the low residual B concentration in the soil did not produce any toxic symptoms on wheat and this study was also in accordance with the findings of other researchers in which they suggested that B applications to first crop has residual impacts on the second crop [6, 31, 32]. The appropriate and most favorable B concentration in leaves of wheat is 1.20 mg kg-1 of dry matter and comparative B share in plant parts is 6% in stem, 10% in grains, 68% in leaves and 16 % in roots [44]. The increased wheat yield also attributed to the residual B in soil solution at low concentration which ultimately increased boronic acid mediated carbohydrate transport through cell membranes [45, 46]. Likewise, the data showed that the highest B applications (to previous cotton crop) evidently resulted into more B uptake by wheat plants. More or less comparable results were also obtained by other scientists and their findings are well-matched with present results in which they reported that B concentration was improved with B application [41, 43, 44]. Some researchers also reported that B application to triticale and wheat genotypes resulted in to higher B concentration and uptake [39].

Conclusions

This study clearly revealed that B remained in the soil for the next crop and its residual effects substantially increased the wheat growth and yield. This study also proved that B application to cotton crop has no toxic effect on wheat. There was a highly significant linear relationship ($P<0.05$) between residual B levels and plant B content of the first wheat crop and second wheat crop. This study clearly concluded that under the wheat-cotton cropping system, B fertilization to cotton had significant residual effect on next wheat crop.

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