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Determination of critical pH and Al concentration of acidic Ultisols for wheat and canola crops

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Abstract. Soil acidity has become a serious constraint in dry land crop production systems of acidic Ultisols in tropical and subtropical regions of southern China, where winter wheat and canola are cultivated as important rotational crops. Regardless of other common existing concerns in acidic Ultisols of southern China, it needs to be investigated whether soil acidity has any effect on wheat and canola growth. There is little information on the determination of critical soil pH as well as aluminium (Al) concentration for wheat and canola crops. The objective of this study was to determine the critical soil pH and exchangeable aluminium concentration (Al_{KCl}) for wheat and canola production. Two pot cultures with two Ultisols from Hunan and Anhui were conducted for wheat and canola crops in a controlled growth chamber, with a completely randomized design. A soil pH gradient ranging from 3.7 (Hunan) and 3.97 (Anhui) to 6.5, with three replications, was used as a treatment. Aluminium sulfate ($Al_2(SO_4)_3$) and hydrated lime ($Ca(OH)_2$) were used to obtain the target soil pH levels. Plant height, shoot dry weight, root dry weight, and chlorophyll content (SPAD value) of wheat and canola were adversely affected by soil acidity in both locations. The critical soil pH and Al_{KCl} of the Ultisol from Hunan for wheat were 5.29 and 0.56 cmol kg^{-1}, respectively. At Anhui, the threshold soil pH and Al_{KCl} for wheat were 4.66 and 2.36 cmol kg^{-1}, respectively. On the other hand, the critical soil pH for canola was 5.65 and 4.87 for the Ultisols from Hunan and Anhui, respectively. The critical soil exchangeable Al for canola cannot be determined from the experiment of this study. The results suggested that the critical soil pH and Al_{KCl} varied between different locations for the same variety of crop, due to the different soil types and their other soil chemical properties. The critical soil pH for canola was higher than that for wheat for both Ultisols, thus canola was more sensitive to soil acidity. Therefore, we recommend that liming should be undertaken to increase soil pH if it falls below these critical soil pH levels for wheat and canola production.

Keywords: critical soil pH, soil acidity, soil exchangeable aluminium, Ultisol, wheat, canola

1 Introduction

Soils in tropical and subtropical regions undergo a natural acidification process due to intensive weathering and leaching under hot and humid climate conditions (Krug and Frink, 1983; Adams, 1984; Ulrich and Sumner, 1991). In the initial stage, prolonged intensive leaching and abundant precipitation deplete cations (especially base cations such as Na^+, K^+, Ca^{2+}, and Mg^{2+}) adsorbed on negatively charged sites of soil particles and then the leached ions are replaced by protons (H^+) originating from H_2O, H_2CO_3, or organic acids (van Breemen et al., 1984). The exchangeable H^+ on soil minerals are reactive and can dismantle the mineral lattices by reacting with structural Al^{3+}. The release of Al^{3+} ions from mineral structure occupy some soil cation exchangeable sites to form exchangeable Al^{3+} (Reuss and Johnson, 1986; Huang, 1997). Therefore, exchangeable Al^{3+} is the main form of exchangeable acidity in acidic soils (Yu, 1997). The rate of soil acidification process is generally very slow under natural conditions. However, in recent decades various anthropogenic activities have accelerated soil acidification to a great extent. Acid deposition resulted from air pollution is a major cause for increased soil acidity (Reuss and Johnson, 1986; Blake et al., 1999). At present, acid deposition is still a serious factor that accelerates soil acidification in China (Vogt et al., 2006; Zhao et al., 2009). Soil acidification can also be accelerated by applying excessive NH_4^+ or R-NH_2 based fertilizers (Bolan et al., 1991; Malhi et al., 1998; Xu et al., 2002; Schroder et al., 2011). Under the intensive land use in China, the sharp increase in application of N fertilizer in crop systems has greatly accelerated soil acidification in the last three decades (Guo et al., 2010).

Soil acidification is a serious process of agricultural land degradation, which leads to the decrease in soil pH and the increase in soil acidity. Soil acidity is a serious obstacle for crop production in many regions of the world (Sumner and Noble, 2003). Approximately 30 % of the world's total land area consists of acid soils and it has been estimated that over 50 % of the world's potential arable lands are acidic (von Uexküll and Mutert, 1995). There are 203 million km^2 of acid soils distributed in tropical and subtropical regions of southern China and account for about 21 % of arable land in the country (Hseung and Li, 1990). This huge acreage of land is needed for crop production to meet the demand of food. Intensive use of land for agriculture and clearing of vegetation for fuel further aggravate the degradation process by declining fertility of soil and changing dynamics of phosphorus (Wu and Tiessen, 2002). Typically, acidic Ultisols are low in organic matter content, cation exchange capacity and high in Al concentration which makes the soils more susceptible to acidification.

In acidic soils, Al toxicity to plants and soil infertility are the main limiting factors for crop growth (Adams, 1984; Kochian, 1995; Ulrich and Sumner, 1991; Kidd and Proctor, 2000). Soil acidity directly affects crop growth through acidic reactions and shows indirect effects on crop growth by affecting nutrient availability. The concentrations of cations such as Al and Mn are high enough to be toxic to plants in acid soils, and the solubility of Al and Mn increases with increasing soil acidity (Pavan et al., 1982; Ritchie and Robson, 1989). On the other hand, N, K, S, Ca, Mg, Mo, and P are deficient in acid soils when the soil pH falls below 5.5. For these reasons, the majority of crop plants produce yields less than their potential. It is well documented that acid soils possess toxic concentrations of Al^{3+} and Mn^{2+}, deficient concentrations of P, and a low availability of bases, which together cause a reduction in crop yield (Adams, 1984; Ritchie and Robson, 1989; Schroder et al., 2011).

The issue of soil acidification is of principal concern when considering the sustainable agricultural crop production system. Liming of acid soils can increase soil pH and alleviate Al toxicity to plants, and thus maintain a suitable pH for the growth of a variety of crops (Slattery and Coventry, 1993; Mullen et al., 2006; Lollato et al., 2013). To establish which acid soils need to be ameliorated for plant growth and the target status of soil acidity after amelioration, the parameters of critical soil pH and soil Al concentration must be determined, and methods to achieve this need to be developed.

The threshold or critical soil pH value, defined as the highest soil pH level at which the addition of liming materials increases plant growth, as well as yield, varies among soil types, plant species, and cultivars of the same plant species (Adams, 1984; Rhoads and Manning, 1989). To advise growers on the need for liming, the identification of the critical soil pH for a particular crop species is essential (Adams, 1984). To develop crop varieties with an Al tolerance for a particular locality a critical soil pH is also crucial for plant breeders. The critical soil pH and KCl extractable Al for the same crop (wheat, sunflower, sorghum, and canola) varies with soil types and even between different cultivars within the same crop species (Kariuki et al., 2007; Lofton et al., 2010). The tolerable soil pH of winter wheat is 5.5 or lower, although this depends on the soil and weather characteristics, and crop growth failure usually occurs at a soil pH of 4 (Lollato et al., 2013). It is very important to know the effects of a wide range of soil pH values on crop growth. Ultisols are acidic and humid in nature and contain a high level of Al. It is believed that Al toxicity is a serious agricultural problem in Ultisols in southern China. However, there have been few investigations on the critical pH and Al concentration of these Ultisols reported for various crops. There has been a growing interest in wheat and canola crops in China and due to the combination of these above factors it is essential to investigate the critical soil pH and Al concentration for southern China. Therefore, the objective of this study was to investigate the critical soil pH and Al tolerance for wheat and canola crops using two Ultisols collected from Hunan and Anhui provinces, China.

2 Materials and methods

2.1 Site and soil characteristics

The two Ultisols used in this study were collected from cropland areas in Qiyang, Hunan province (26°45′12″ N, 111°52′32″ E) and Langxi, Anhui province (31°6′ N, 119°8′ E), China in 2015. Some of the initial soil properties are given in Table 1. The soil samples were collected from the top soil layer (0–15 cm), air-dried, and finally ground to pass through a 2 mm sieve.

2.2 Incubation experiment to obtain the target soil pH

A soil incubation experiment was executed for each location before conducting the pot culture to achieve the target soil pH level. To determine the actual amount of quick lime ($Ca(OH)_2$) and aluminum sulfate ($Al_2(SO_4)_3$) needed to reach a given target soil pH level, a soil incubation experiment in the laboratory was conducted to establish a standard curve. Briefly, 100 g air-dried and 2 mm ground soil was placed in a plastic cup and mixed with five incremental rates (0.1, 0.2, 0.3, 0.4, and 0.5 g) of $Ca(OH)_2$ and $Al_2(SO_4)_3$. The soils were then moistened with distilled water, with a field capacity of 60%, and placed under a polyethylene cover containing a hole. After 2 weeks, soil pH was measured. The relationships between soil pH and the amounts of $Ca(OH)_2$ and $Al_2(SO_4)_3$ were established.

2.3 Treatments, experimental design and pot culture

In this study, two pot experiments were conducted in a controlled environment and different soil pH gradients were considered as a treatment. There were seven target soil pH levels ranging from 3.7 to 6.5 (i.e., 3.7, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5) for the Ultisol from Hunan, and six target soil pH levels ranging from 3.97 to 6.5 (i.e., 3.97, 4.5, 5.0, 5.5, 6.0, and 6.5) for the Ultisol from Anhui. Each treatment was replicated three times and for the experimental design we used a complete randomized design. In each pot, 550 g soil from either Hunan or Anhui was amended with $Ca(OH)_2$ and $Al_2(SO_4)_3$ to obtain the target soil pH levels. After mixing the soil with $Ca(OH)_2$ or $Al_2(SO_4)_3$, the samples were incubated at 25°C. The mixtures were pulverized every five days to mix the $Ca(OH)_2$ and $Al_2(SO_4)_3$ with the soil. The field capacity of the incubated soil was maintained at about 60% throughout the 15-day incubation period.

Wheat cultivar (Scout 66) and canola cultivar (Qinyou 11) were used as test crops in this study. The seeds of both crops were surface sterilized with 10% H_2O_2 for 10 min, washed with running tap water, and then distilled water, and allowed to germinate without light at 25°C in distilled water. After 15 days of soil incubation, eight 1-day germinated seeds of wheat in the Ultisol from Hunan and nine seeds in the Ultisol from Anhui were sown at the same depth in each pot. In the case of canola crops, eight 1-day germinated seeds were sown in each pot and after coming out the seedlings from soil were thinned to five plants. Both crops were grown in a controlled environment growth chamber (Percival, Perry, IA, USA) with 60% field capacity, day/night temperatures of 20/15°C, a day length of 14 h, light intensity of 400 μmol photon m^{-2} s^{-1}, and day/night relative humidity of 70/60%.

2.4 Plant growth parameters

All the crop growth components were measured after 28 days. Plant height was measured using a ruler with an error of ± 0.1 cm. The chlorophyll content (SPAD value) was measured using a SPAD-502 plus chlorophyll meter (Konica Minolta Sensing, Tokyo, Japan). Shoots and roots were harvested separately, washed with running tap water and then distilled water, and finally dried in a forced-air oven at 80°C to constant weight and weighed.

2.5 Soil Analyses

After the crop harvest, soil samples were collected from each pot, air-dried, and finally ground to pass through a 0.3 mm sieve. Soil pH was determined with a pH combination electrode in a 1:2.5 soil:water suspension. The total soil exchangeable acidity (H^+ and Al^{3+}) was extracted with 1.0 M KCl and then titrated by 0.01 M NaOH to pH 7.0 (Pansu & Gautheyrou, 2007). The exchangeable Al^{3+} was the difference between exchangeable acidity and exchangeable H^+ (Bertsch and Bloom, 1996).

2.6 Data analyses

Data were analyzed using OriginPro 2015 software. To attain the critical points, piecewise models were evolved using a nonlinear curve fitting procedure. The Levenberg Marquardt method was used for the segmented linear function (PWL2).

3 Results and discussion

3.1 Relationship between soil pH and exchangeable Al

The range of KCl extractable Al was from 8.49 to 0.09 cmol/kg for the Ultisol from Hunan and from 4.98 to 0.06 cmol kg^{-1} for the Ultisol from Anhui, respectively (Fig. 1). There were differences in the Al content between the two Ultisols at a given pH. For example, at pH 4.5 the concentration of exchangeable Al was 3.0 and 2.30 cmol kg^{-1} for the Ultisols from Hunan and Anhui, respectively. This was probably due to the different soil types and other soil chemical properties, such as the organic matter content and cation exchange capacity of the soils.

There was an inverse exponential relationship between soil pH and KCl extracted exchangeable Al for both soils. The concentration of exchangeable Al decreased with increased soil pH, which was consistent with both theoretical prediction and previous reports (Evans and Kamprath, 1970; Chartres et al., 1990; Kariuki et al., 2007). With a decrease of soil pH, more Al ions were released from the soil mineral structure and occupied the exchangeable sites on soil surfaces; thus, increasing soil exchangeable Al (Yu, 1997). Therefore, the relationship between soil pH and exchangeable Al was quiet strong for both Ultisols, and the coefficient of the correlation was 0.95 for both soils.

3.2 Effect of soil acidity on plant height

Wheat plant height was adversely affected by soil acidity. The range of plant height was 4.55 to 30.67 cm and 9.37 to 30.52 cm for the Ultisols from Hunan and Anhui, respectively (Fig. 2). There was a negative response of plant height to the decreased soil pH. The plant height was also affected by the soil Al concentration. With the increased soil exchangeable Al concentration, the plant height was decreased. The breaking point was the threshold soil pH and exchangeable Al concentration, which was obtained by two intersected linear lines. For the Ultisol from Hunan, the breaking point occurred at pH 5.23. On the other hand, the threshold soil pH was at 4.66 for the Ultisol from Anhui. The breakpoints for the exchangeable Al concentration were detected at 0.56 and 2.56 cmol kg^{-1} for the Ultisol from Hunan and Anhui, respectively (Fig. 3).

Canola plant height ranged from 3.2 cm to 6.21 cm and 2.48 cm to 6.22 cm for the Ultisol from Hunan and Anhui, respectively (Fig. 2). The critical soil pH obtained from Fig. 2 was 5.65 for the Ultisol from Hunan and 4.87 for the Ultisol from Anhui. The breaking point of exchangeable Al was 2.72 cmol kg^{-1} for the Ultisol from Anhui, and no critical point was found from Fig. 3 for the Ultisol from Hunan.

The results of a comparison between the two soils indicated that there was a different threshold soil pH and exchangeable Al concentration in wheat and canola production. This was probably due to the different Al content in the soil as well as the cation exchange capacity. The plant root system is affected by high Al concentrations because of Al interferes with the uptake, transport, and utilization of essential plant nutrients such as P, K, Ca, Mg, and water, as well as enzyme activity in the roots (Lofton et al., 2010). Wallace and Anderson (1984) reported that DNA synthesis in plant roots was inhibited by Al and was followed by root elongation. Due to the lower cation exchange capacity and higher Al content of the Ultisol from Hunan, compared with the Ultisol from Anhui at the same soil pH, the threshold soil pH differed and was higher for the Ultisol from

Hunan. Moreover, the results also indicated that the critical soil pH values for canola in two Ultisols were higher than these for wheat in the same soils, which suggested that canola was more sensitive to soil acidity than wheat.

3.3 Effect of soil acidity on the dry weight of shoots and roots

Soil acidity had a negative impact on the biomass dry weight of the wheat and canola crops. The range of wheat shoot dry weights for the Ultisols from Hunan and Anhui was 0.03 to 0.78 g and 0.12 to 1.10 g, respectively (Fig. 4). Similarly to plant height, shoot dry weight increased with the increased soil pH. The reverse trend was observed in the case of soil exchangeable Al. Shoot dry weight was enhanced with the reduced soil Al concentration. At a soil pH of 5.27, the breaking point was obtained for the Ultisol from Hunan. In contrast, the breaking point for the exchangeable Al concentration was 0.65 cmol kg^{-1} in the same location. On the other hand, the threshold soil pH was at 4.66 for the Ultisol from Anhui, but there was no breaking point for exchangeable Al. A negative linear response was identified with increased soil exchangeable Al (Fig. 5).

Similarly to plant height and shoot dry weight, there was a negative impact of soil acidity on wheat root dry weight. The root dry weight for the Ultisols from Hunan and Anhui at the different soil pH gradients was 0.04 to 0.89 g and 0.07 to 0.97 g, respectively (Fig. 4). Root dry weight increased with an increase in soil pH in both locations. At a soil pH of 4.99, the breaking point was reached for soil from Hunan. In contrast, for soil from Anhui, the breaking point was observed at a soil pH of 4.66. Root dry weight decreased with an increase in exchangeable Al for both locations (Fig. 5). At Hunan, the breaking point was found at 2.27 cmol kg^{-1} of exchangeable Al, while the breaking point was 2.39 cmol kg^{-1} for soil from Anhui.

Canola shoot growth had also a negative response to soil acidity. Shoot dry matter yield ranged from 0.09 to 0.34 g for the Ultisol from Hunan and 0.04 to 0.39 g for the soil from Anhui (Fig. 4). The critical soil pH of Hunan and Anhui was 5.14 and 4.57, respectively. It indicated that there was a strong relationship between soil pH and shoot dry weight. The shoot dry weight was reduced at lower soil pH due to soil acidity for both the Ultisols. A negative linear response was observed with the increased soil exchangeable Al for Hunan. The threshold point of soil exchangeable Al at 2.71 cmol kg^{-1} was identified for Anhui (Fig. 5).

Canola root dry matter yield ranged from 0.02 to 0.16 g for Hunan and 0.01 to 0.13 g for Anhui, respectively (Fig. 4). For Hunan, the critical soil pH was obtained at 5.30 in case of root dry weight. On the other hand, at soil pH 4.86, the breaking point for Anhui was found. Root dry matter yield was greatly affected by soil exchangeable Al for both the Ultisols. At Hunan, the response of root biomass yield to Al concentration followed a negative linear trend, with higher Al concentration resulting in higher reduction in root dry matter yield. A threshold point for soil exchangeable Al was acquired at 2.72 cmol kg^{-1} (Fig. 5).

Similarly to plant height, the threshold pH of the Ultisol from Hunan was higher than for the Ultisol from Anhui. This was probably due to the high Al concentration as well as the low cation exchange capacity in Hunan soil. Because Al interferes with root growth and then nutrient and water uptake, plant growth was reduced at a lower soil pH due to the high solubility of Al, and ultimately plant shoot dry weight was also reduced at a lower soil pH. A previous study conducted by Joris et al. (2013) reported that the density of root length, shoot biomass, grain yield, and the nutrition of corn were increased due to the reduction of soil acidity through liming. Poolpipatana and Hue (1994) reported that the dry matter yield of legume crops was decreased at lower soil pH values due to the presence of a high Al concentration. These findings were in agreement with those of our study.

The primary and most evident symptom of Al toxicity is that the root growth of plants decreases (Rengel and Zhang, 2003), which reduces the plant uptake of nutrients from soils. Watanabe et al. (2006) reported that the absence of phosphate due to the presence of Al decreased the weight of roots. These findings are consistent with the results of this study, in which the dry matter yield of roots was reduced at high Al concentrations.

3.4 Effect of soil acidity on chlorophyll content

As well as the growth components, the chlorophyll contents in wheat and canola leaves were also affected by soil acidity. Wheat lead chlorophyll content (SPAD value) range for the Ultisols from Hunan and Anhui was from 8.4 to 37.8 and 10.1 to 46.2, respectively, for the different soil pH treatments (Fig. 6). At a soil pH of 5.29, the breaking point was achieved for the Ultisol from Hunan location. For Anhui, at a soil pH of 4.66 a linear plateau was found, which indicated that there was little response in the chlorophyll content at higher soil pH values. At Hunan, the threshold soil exchangeable Al was 1.85 cmol kg^{-1}, while for Anhui it was found at 2.36 cmol kg^{-1} (Fig. 7).

The range of chlorophyll content (SPAD) in the leaf of canola varied from 20.4 to 35.6 for the Ultisol from Hunan, whereas it was 24.1 to 36.0 for the Ultisol from Anhui (Fig. 6). The threshold soil pH was detected at 4.60 for the Ultisol from Hunan. In contrast, the critical soil pH was observed at 4.86 for the Ultisol from Anhui. The breaking point for soil exchangeable Al was 3.82 cmol kg^{-1} and 4.56 cmol kg^{-1} for the two Ultisol from Hunan and Anhui, respectively (Fig. 7). However, these values of soil exchangeable Al were too higher for canola growth and cannot be set as the critical soil exchangeable Al for canola.

The presence of Al in plant tissues interferes with Ca and Mg uptake from soil, as well as damaging the chloroplast and mitochondrial membrane (Meriño-Gergichevich et al., 2010). The results of this study suggested that the chlorophyll content in leaves was lower at a lower soil pH and higher at a higher soil pH. Zhang et al. (2007) also found that chlorophyll content in leaves was reduced due to the presence of a high Al concentration in soils, which confirms the findings of this study.

4 Conclusions

The results of this study demonstrate that there was a significant reduction of wheat and canola growth at low soil pH values and high Al concentrations. Plant height, shoot dry weight, root dry weight, and chlorophyll content in leaves were significantly decreased below the critical soil pH. A negative correlation was found between plant growth parameters and soil exchangeable Al. Plant height, shoot dry weight, root dry weight, and the chlorophyll content in leaves were decreased below the threshold soil Al concentration. The critical soil pH and Al concentration differed between locations as well as crop species. At the Hunan site, the critical soil pH and Al concentration for wheat were 5.29 and 0.56 cmol kg^{-1}, respectively. For Anhui, the critical soil pH and Al concentration for wheat were 4.66 and 2.36 cmol kg^{-1}, respectively. The threshold soil pH for the Ultisol from Hunan (5.65) was also higher than that from Anhui (4.87) for canola crop. The critical soil pH for canola was higher than that for wheat, thus canola was more sensitive to soil acidity. The difference in the critical soil pH and Al concentration of both sites was probably due to the different Al content at different soil pH values, the different soil types or other inherent soil chemical properties, such as organic matter content and cation exchange capacity. Based on the findings of this study we suggest that liming should be considered if soil pH remains below the critical level for wheat and canola production. We hope these findings also help to protect the soils from degradation by reducing the excess use of lime in the studied location.

Author contribution

M.A. Baquy and R.K. Xu designed the experiments and M.A. Baquy carried them out. M.A. Baquy and R.K. Xu prepared the manuscript with all co-authors.

Competing interests

We declare that I and any of co-authors of this paper have no conflict of interest.

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Table 1 Some initial properties of the two Ultisols from Hunan and Anhui

Location	Soil pH (Soil:Water=1:2.5)	Organic matter ($g\ kg^{-1}$)	CEC	Exchangeable H^+	Exchangeable Al^{3+}
			($cmol_{(+)}\ kg^{-1}$)		
Hunan	4.06	15.5	13.5	0.40	6.41
Anhui	3.97	18.1	15.5	0.40	4.88

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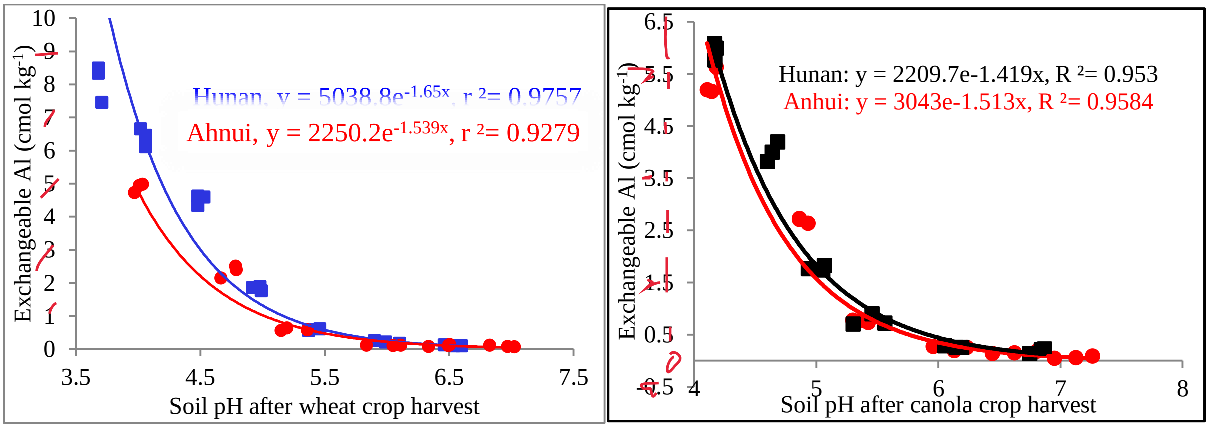
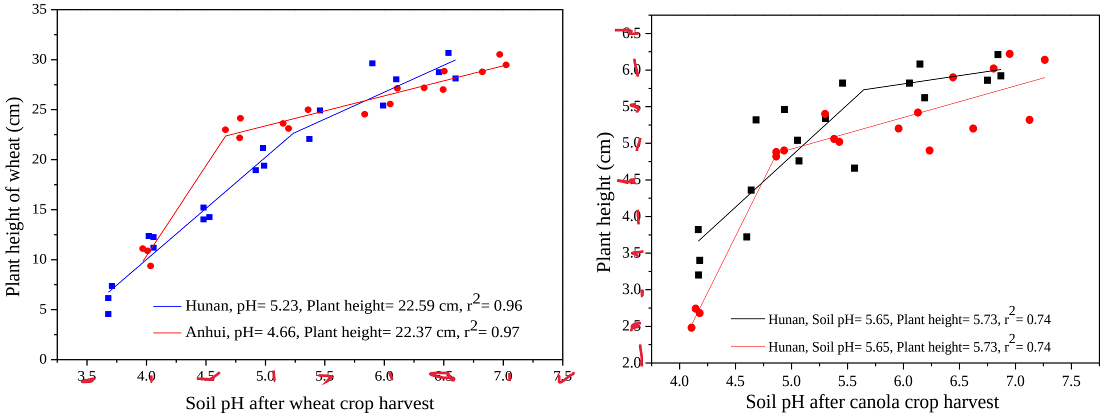


Figure 1: Relationship between soil pH and KCl extractable Al after wheat and canola harvest



5 **Figure 2: Plant heights of wheat and canola as a function of the soil pH of the Ultisols from Hunan and Anhui**

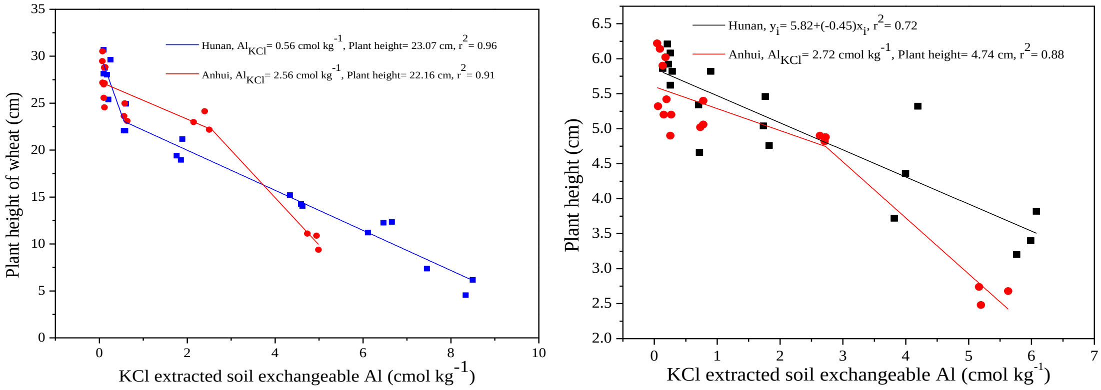


Figure 3: Plant heights of wheat and canola as a function of KCl extracted exchangeable Al of the Ultisols from Hunan and Anhui

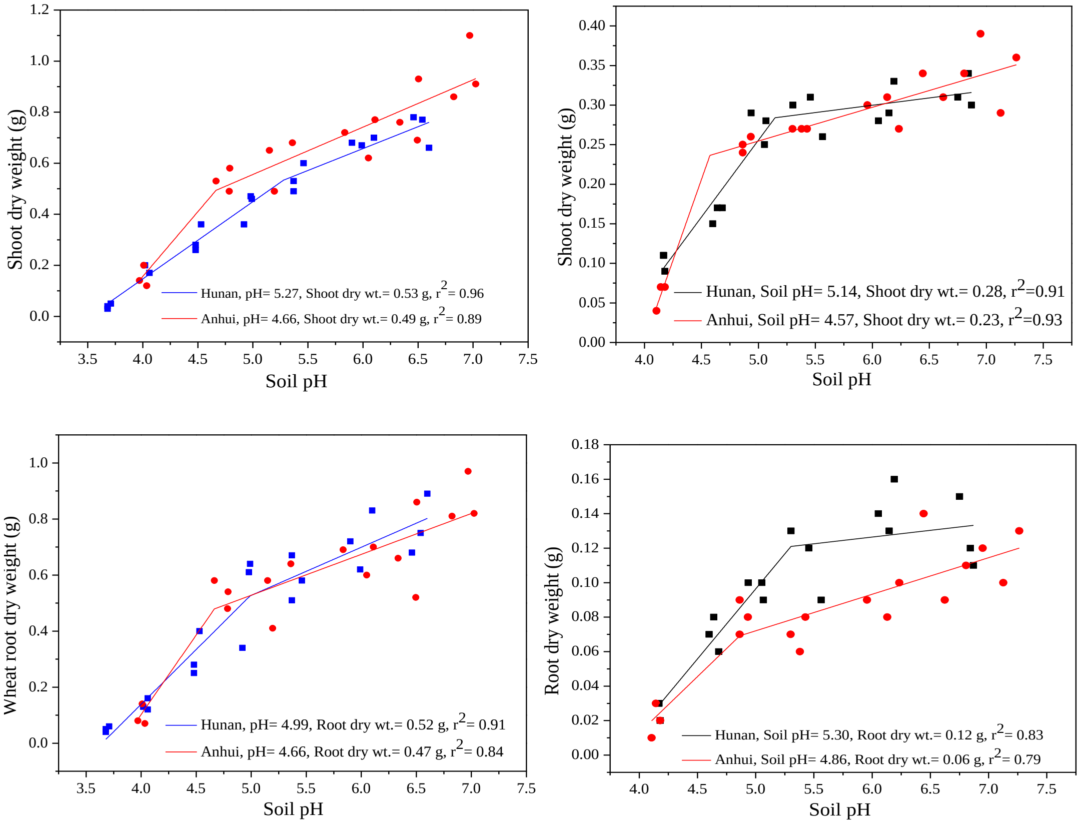


Figure 4: Dry weights of plant shoots and roots of wheat and canola as a function of the soil pH of the Ultisols from Hunan and Anhui

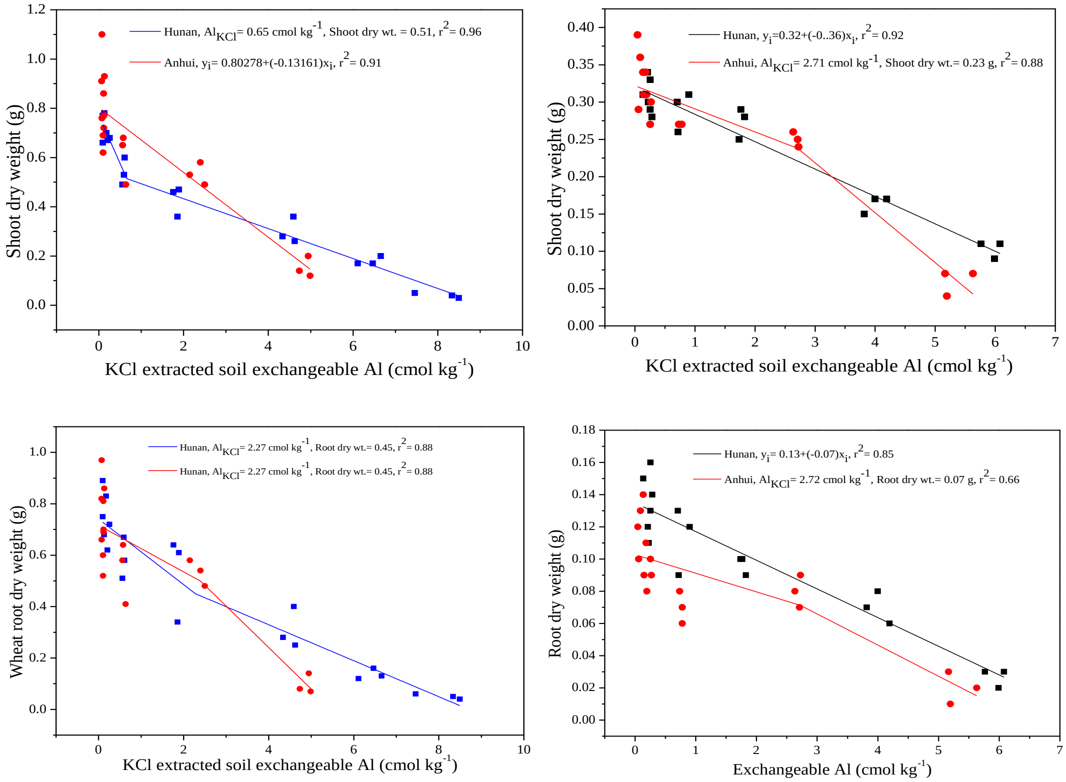


Figure 5: Dry weights of plant shoots and roots of wheat and canola a function of KCl extracted exchangeable Al of the Ultisols from Hunan and Anhui

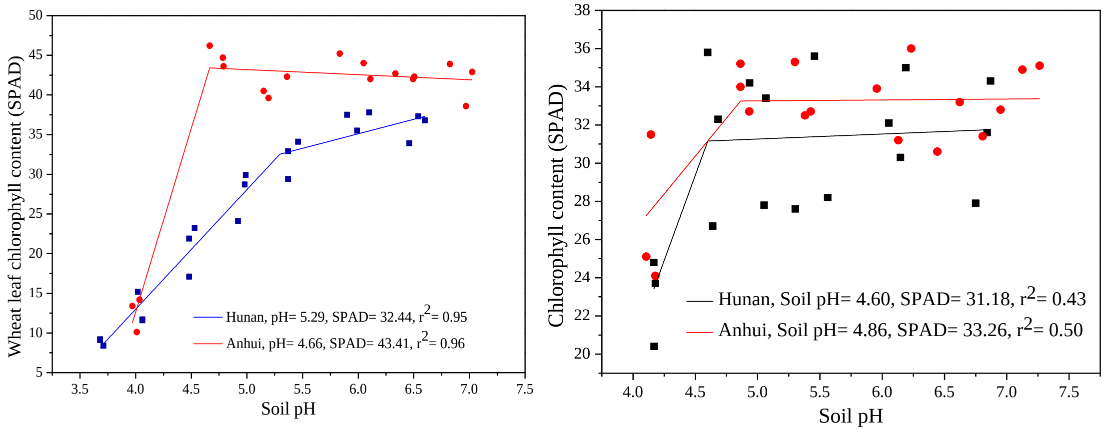


Figure 6: Leaf chlorophyll contents (SPAD value) of wheat and canola as a function of soil pH of the Ultisols from Hunan and Anhui

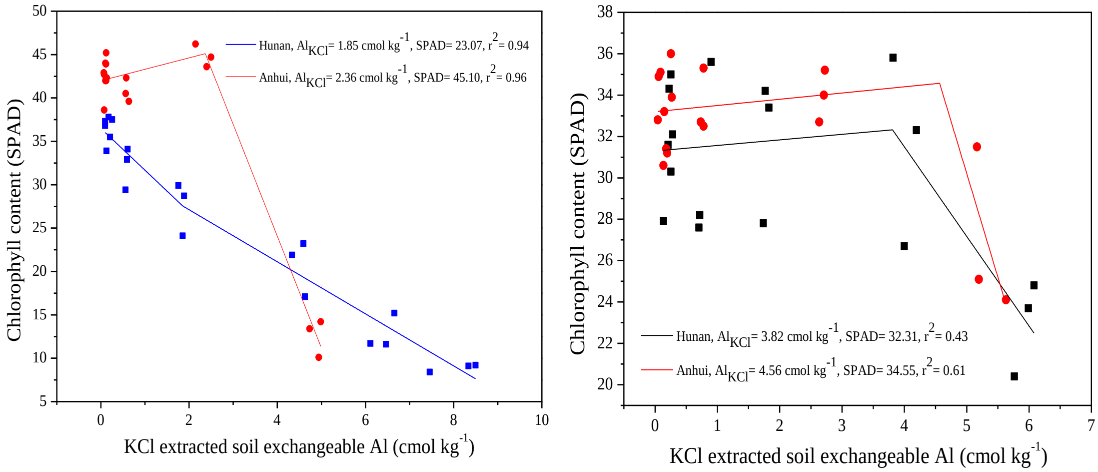


Figure 7: Leaf chlorophyll contents (SPAD value) of wheat and canola as a function of KCl extracted exchangeable Al of the Ultisols from Hunan and Anhui