Solid Earth, 8, 149–159, 2017
www.solid-earth.net/8/149/2017/
doi:10.5194/se-8-149-2017

Solid Earth

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

M. Abdulaha-Al Baquy[1,2], Jiu-Yu Li[1], Chen-Yang Xu[1,2], Khalid Mehmood[1,2], and Ren-Kou Xu[1]

[1]State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, 210008, China
[2]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100049, China

Correspondence to: Ren-Kou Xu (rkxu@issas.ac.cn)

Received: 26 August 2016 – Discussion started: 29 August 2016
Revised: 15 January 2017 – Accepted: 20 January 2017 – Published: 9 February 2017

Abstract. Soil acidity has become a principal 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. 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 is 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 (SE China) were conducted for wheat and canola crops in a controlled growth chamber. Aluminium sulfate ($Al_2(SO_4)_3$) and hydrated lime ($Ca(OH)_2$) were used to obtain the target soil pH levels from 3.7 (Hunan) and 3.97 (Anhui) to 6.5. 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 1.72 $cmol\,kg^{-1}$, 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, and 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.

1 Introduction

Soil is a key component of the Earth system as it controls the geochemical, biological, erosional and hydrological cycles and offers services, goods and resources for human kind (Keesstra et al., 2012; Brevik et al., 2015; Decock et al., 2015; Smith et al., 2015). Soils also play an important role in global food security, water security, biofuel security and human health (Brevik et al., 2015; Keesstra et al., 2016). However, many soils are under threat and unable to fulfil the food demand due to loss of soil fertility, erosion, drought and climate change (Muluneh et al., 2015; Tsozué et al., 2015; Mwango et al., 2016; Potopová et al., 2016; Singh et al., 2016). This situation might worsen due to increased population pressure on soil worldwide and thus enhance the degradation of soil. Moreover, soil degradation is due to intensive cropping, overgrazing, and unsustainable land use, and desertification further aggravates the soil, making it unfavourable for cropping (de Moraes Sá et al., 2015; Symeonakis et al., 2016; Yan and Cai, 2015). There is a need to find solutions to improve the crop yield. It is important to know the detrimental effect of intensive agricultural practices as well as their interaction with different kind of soils to ensure the security of food (Beyene, 2015).

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,

Published by Copernicus Publications on behalf of the European Geosciences Union.

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^+ ions on soil minerals are reactive and can dismantle the mineral lattices by reacting with structural Al^{3+}. The releases 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 resulting 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 (Behera and Shukla, 2015). Soil acidity is a principal 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 area 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; Eimil-Fraga et al., 2016; Elisa et al., 2016). 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; 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; 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; Mamedov et al., 2016). 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). The development of 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.

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

CEC: cation exchange capacity.

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.

Both Ultisols were derived from Quaternary red earth. Ultisols derived from Quaternary red earth are widely distributed in subtropical regions of southern China. The profile depth of this type of soils is normally more than 2 m or, sometimes, deeper than 10 m (Hseung and Li, 1990). The clay content in the soils was more than 40 %. Langxi, Anhui province, is located in the northern part of subtropical region in China. The average annual rainfall and temperature are 1300 mm and 15.5 °C at this sampling site. Qiyang, Hunan province, is located in the middle part of subtropical region in China. The average annual rainfall and temperature are 1431 mm and 18 °C at this sampling site. The greater precipitation and higher temperature at Qiyang led to higher weathering extent of the Ultisol from this site than that from Langxi. Therefore, the cation exchange capacity (CEC) of the Ultisol from Langxi is greater than that of the Ultisol from Qiyang (Table 1).

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 5 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 (Scout 66) and canola (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, distilled water, and then 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 har-

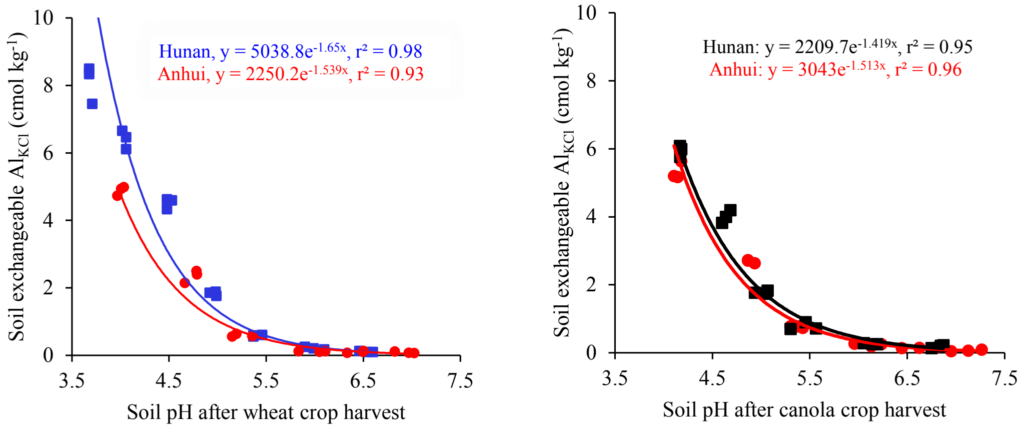

Figure 1. Relationship between soil pH and KCl extractable Al (cmol kg^{-1}). The fitted equations were significant at $P < 0.01$.

vested 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 analysis

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 and Gautheyrou, 2006). The exchangeable Al^{3+} was the difference between exchangeable acidity and exchangeable H^+ (Bertsch and Bloom, 1996).

2.6 Data analysis

Data were analysed 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^{-1} 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 CEC 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 in 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.

Commonly, Al^{3+} is missing in soils with pH 5.3 or upper. However, the exchangeable Al^{3+} was still detected above pH 5.3 in present study. This may be due to the indirect method used, in which the exchangeable Al^{3+} was the difference between exchangeable acidity and exchangeable H^+ (Bertsch and Bloom, 1996).

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 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). We can also calculate the critical Al concentration from Fig. 1 based on the critical soil pH. It was 0.90 and 1.72 cmol kg^{-1} for the Ultisol from Hunan and An-

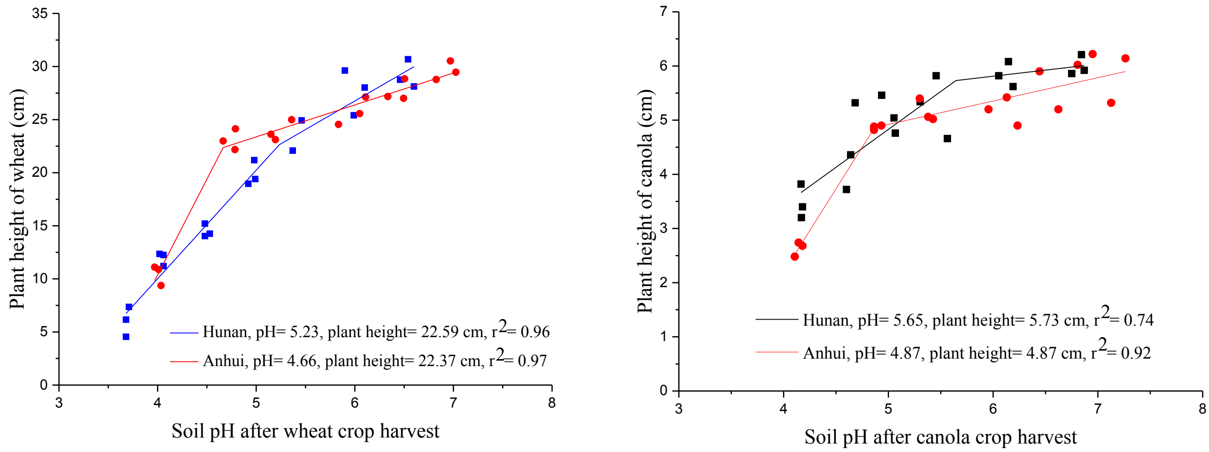

Figure 2. Plant heights of wheat and canola as a function of soil pH of the Ultisols from Hunan and Anhui. The fitted equations were significant at $P < 0.01$.

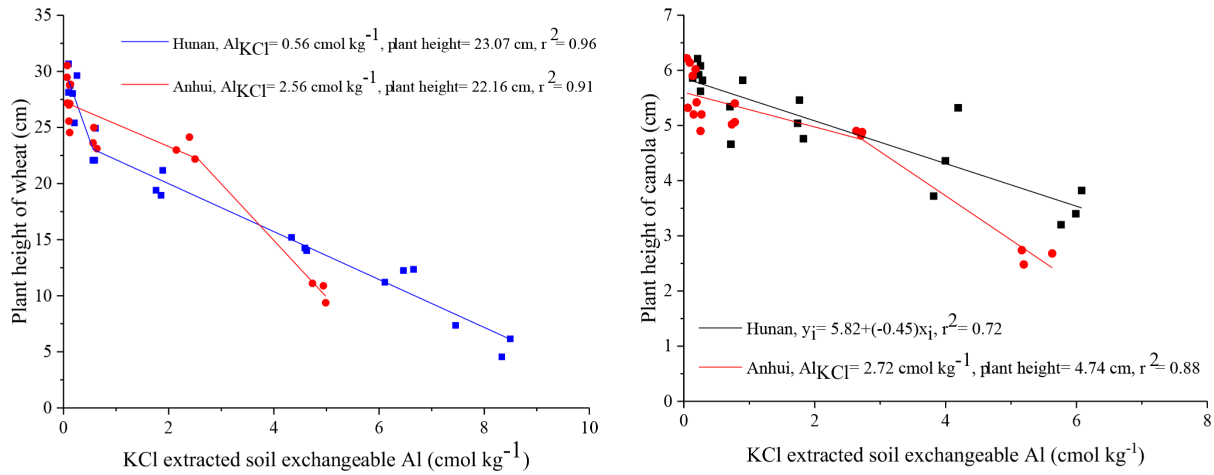

Figure 3. Plant heights of wheat and canola as a function of KCl extracted exchangeable Al of the Ultisols from Hunan and Anhui. The fitted equations were significant at $P < 0.01$.

hui, respectively. Therefore, 0.56 and 1.72 $cmol\,kg^{-1}$ were determined as the critical Al concentration for wheat in the two Ultisols.

Canola plant height ranged from 3.2 to 6.21 and 2.48 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 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.

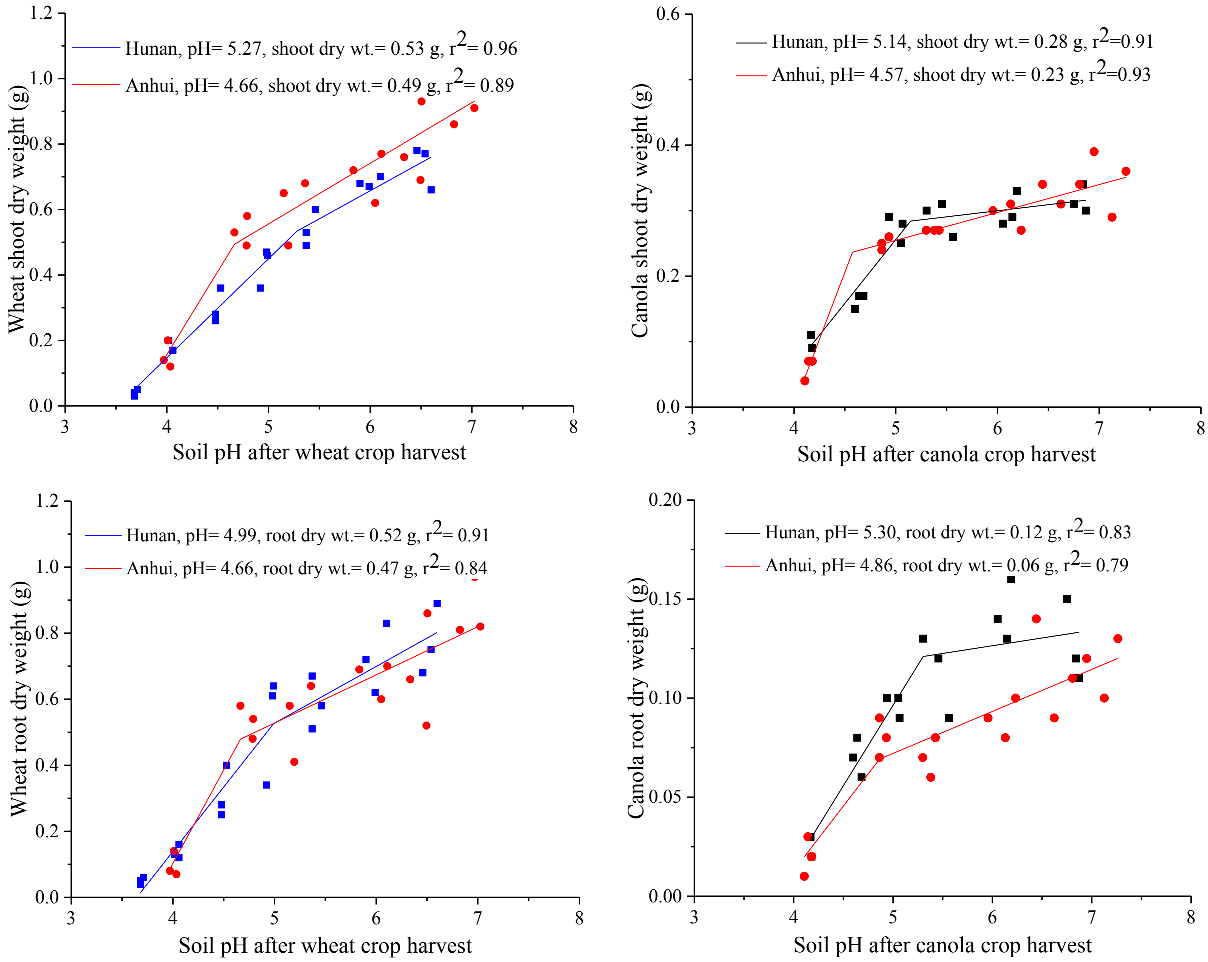

Figure 4. Dry weights of plant shoots and roots of wheat and canola as a function of soil pH of the Ultisols from Hunan and Anhui. The fitted equations were significant at $P < 0.01$.

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 and 0.12 to 1.10 g, respectively (Fig. 4). Similar 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).

Similar 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. This indicates 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

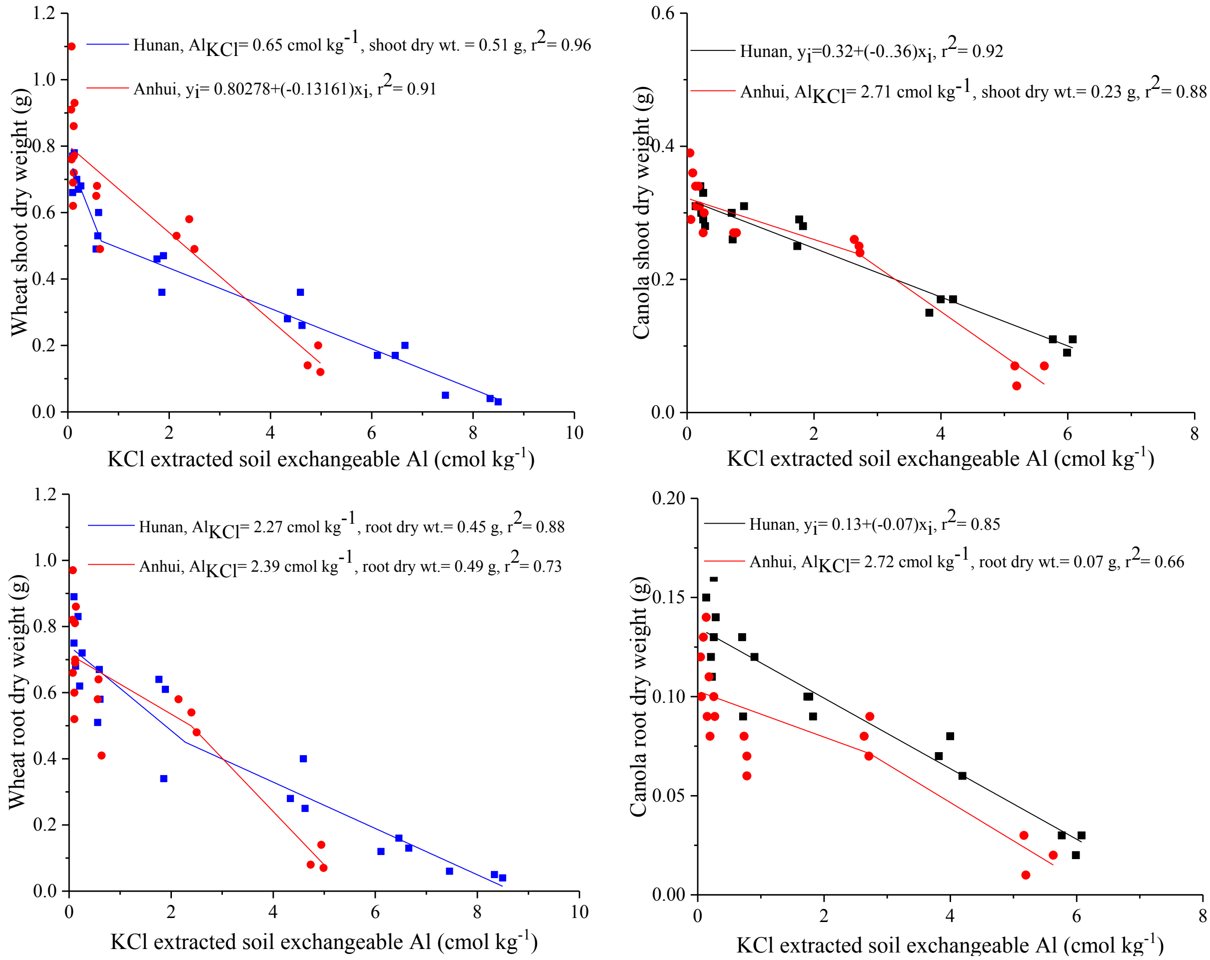

Figure 5. Dry weights of plant shoots and roots of wheat and canola as a function of KCl extracted exchangeable Al of the Ultisols from Hunan and Anhui. The fitted equations were significant at $P < 0.01$.

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 the 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} for Anhui (Fig. 5).

Similar 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 are 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. Low soil pH with high concentration of Al showed adverse effects on roots of both crops. Stunted, thick, bent, brownish roots, deformed root tips, and no or very few lateral roots were observed in our pot experiments.

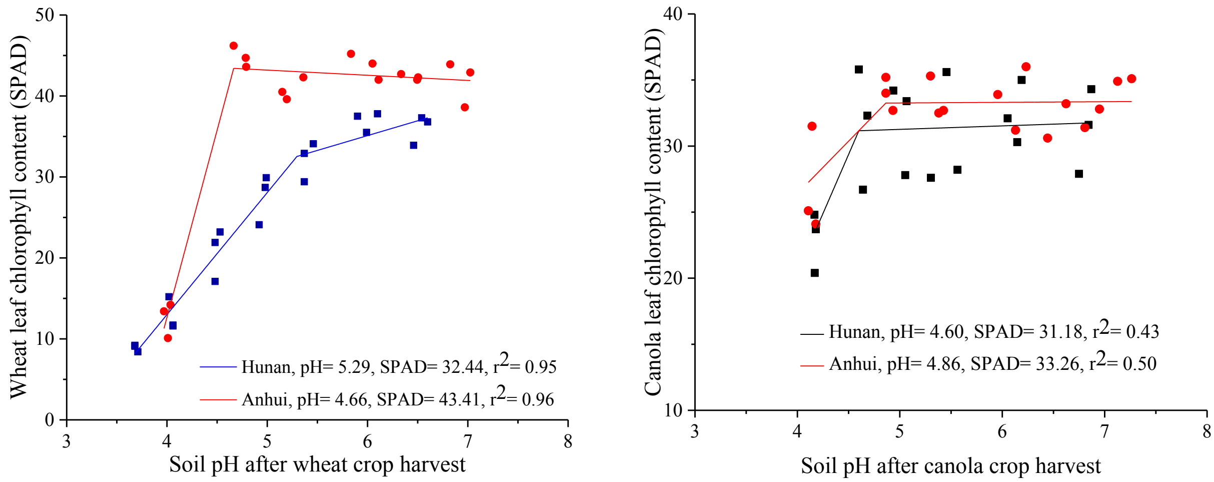

Figure 6. Leaf chlorophyll contents (SPAD value) of wheat and canola as a function of soil pH of the Ultisols from Hunan and Anhui. The fitted equations were significant at $P < 0.01$.

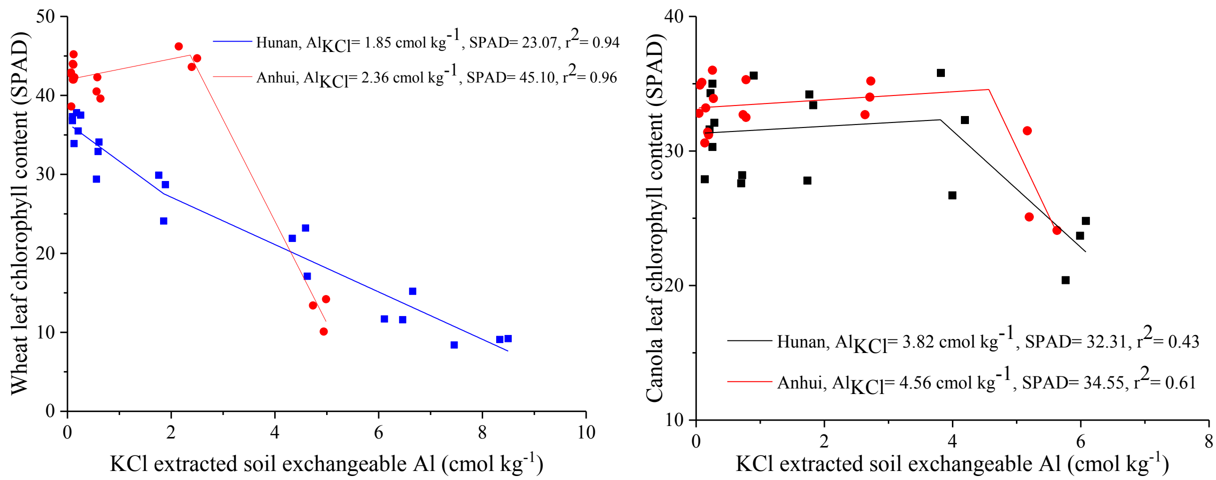

Figure 7. Leaf chlorophyll contents (SPAD value) of wheat and canola as a function of KCl extracted exchangeable Al of the Ultisols from Hunan and Anhui. The fitted equations were significant at $P < 0.01$.

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 leaf 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 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 high 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 suggest 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.

3.5 General discussion

The critical soil pH and Al concentrations were different for the same crop at different Ultisols. The growth of canola will not be affected at or above soil pH of 5.65 and 4.87 for Hunan and Anhui, respectively. On the other hand, wheat crop will not be damaged by acidity at or above soil pH of 5.29 and 4.66 for Hunan and Anhui, respectively. The difference was also found for critical exchangeable Al for wheat varied from 0.56 $cmol\,kg^{-1}$ in Hunan to 1.72 $cmol\,kg^{-1}$ in Anhui. The differences of critical values between two locations were mainly due to the difference in soil CEC. The CEC of the Ultisol from Anhui was greater than that from Hunan (Table 1). Thus, at the same exchangeable Al level, the Al saturation (percentage of exchangeable Al in CEC) was lower at the Ultisol from Anhui than that at the Ultisol from Hunan, while the base cation saturation (percentage of exchangeable base cation in CEC) was higher at the Ultisol from Anhui than that at the Ultisol from Hunan. Base cations can alleviate Al toxicity to plants (Meriño-Gergichevich et al., 2010; Liu and Xu, 2015). Therefore, the higher CEC and greater base cation saturation of the Ultisol from Anhui led to the lower critical values of soil pH and the higher exchangeable Al in the Ultisol from Anhui compared with that from Hunan. A similar relationship between plant growth and soil Al saturation was observed by other investigators (Lollato et al., 2013).

The critical values of soil pH and Al content varied with crop species. Canola was more sensitive to soil acidity than wheat and thus has higher critical soil pH in both locations than wheat. Canola was also more sensitive to Al toxicity and less tolerant to toxic Al. This may be the main reason why the critical soil Al contents were not obtained for canola in present study. The critical soil pH and Al values varied with soil types and crop species and thus the two parameters obtained in this study cannot be extended for other crops or the same crops for other soil types.

In the present study, the critical soil pH and Al levels for wheat and canola were obtained with pot experiments in only one crop season. Better Al and pH levels in a soil should be reasoned considering a crop rotation and not only one crop. Thus, better Al and pH levels will be defined for the more sensitive crop in the crop rotation adopted in future.

Soil pH and Al are important indicators of soil quality assessment in acidic Ultisols. Soil quality assessment is a large and challenging issue due to its high variability in properties and functions. According to Brevik and Sauer (2015), soil has a distinct impact on human health. The availability of food and contamination with various chemicals and pathogens from human input are influenced by soil. However, priority should be given to developing new technologies for maintaining soil quality not only for productivity but also human health (Zornoza et al., 2015). According to our results and findings, the critical values of soils vary among both locations for a particular crop. Different crop species have different sensitivity to soil acidity. These obtained critical values are only for specific soil types and crops. It is suggested that liming should be done according to the critical values for the growth of same species in different soil types. Hence, site-specific agricultural management practices including liming can be applied judiciously with proper crop selection, provided these are economically as well as environmentally sound. Judicious application of lime is necessary in order to protect not only the soil from degradation but also human health.

4 Conclusions

The results of this study demonstrate that wheat and canola growth were significantly reduced 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 1.72 $cmol\,kg^{-1}$, 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, and 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.

5 Data availability

The data are not publicly available due to copyright issues. However, the data set can be obtained from the corresponding author through e-mail (rkxu@issas.ac.cn).

Author contributions. M. Abdulaha-Al Baquy and Ren-Kou Xu designed the experiments and M. Abdulaha-Al Baquy carried them out. M. Abdulaha-Al Baquy and Ren-Kou Xu prepared the manuscript with all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This study was supported by the National Key Basic Research Program of China (grant number: 2014CB441003) and the National Natural Science Foundation of China (grant number: 41230855). The first author gratefully acknowledges the Chinese Academy of Sciences – The World Academy of Sciences President's Fellowship for his PhD studies in China.

Edited by: A. Jordán
Reviewed by: A. Cerdà and two anonymous referees

References

Adams, F.: Soil Acidity and Liming, 2nd Edn., Am. Soc. Agron., Crop Sci. Soc. Am. and Soil Sci. Soc. Am., Madison, Wisconsin, USA, 1984.

Behera, S. K. and Shukla, A. K.: Spatial distribution of surface soil acidity, electrical conductivity, soil organic carbon content and exchangeable potassium, calcium and magnesium in some cropped acid soils of India, Land Degrad. Dev., 26, 71–79, 2015.

Bertsch, P. M. and Bloom, P. R.: Aluminum, in: Methods of Soil Analysis. Part 3 – Chemical Methods, Soil Sci. Soc. Am. Book Ser. 5, edited by: Sparks, D. L., Am. Soc. Agron. and Soil Sci. Soc. Am., Madison, WI, USA, 1996.

Beyene, S. T.: Rangeland degradation in a semi-arid communal savannah of Swaziland: Long-term DIP-tank use effects on woody plant structure, cover and their indigenous use in three soil types, Land Degrad. Dev., 26, 311–323, 2015.

Blake, L., Goulding, K., Mott C., and Johnston, A.: Changes in soil chemistry accompanying acidification over more than 100 years under woodland and grass at Rothamsted Experimental Station, UK, Eur. J. Soil Sci., 50, 401–412, 1999.

Bolan, N. S., Hedeley, M. J., and White, R. E.: Processes of soil acidification during nitrogen cycling with emphasis on legume based pastures, Plant Soil, 134, 53–63, 1991.

Brevik, E. C. and Sauer, T. J.: The past, present, and future of soils and human health studies, SOIL, 1, 35–46, doi:10.5194/soil-1-35-2015, 2015.

Brevik, E. C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, J. N., Six, J., and Van Oost, K.: The interdisciplinary nature of SOIL, SOIL, 1, 117–129, doi:10.5194/soil-1-117-2015, 2015.

Chartres, C., Cumming, R., Beattie, J., Bowman, G., and Wood, J.: Acidification of soils on a transect from plains to slopes, south western New-South-Wales, Aust. J. Soil Res., 28, 539–548, 1990.

Decock, C., Lee, J., Necpalova, M., Pereira, E. I. P., Tendall, D. M., and Six, J.: Mitigating N_2O emissions from soil: from patching leaks to transformative action, SOIL, 1, 687–694, doi:10.5194/soil-1-687-2015, 2015.

de Moraes Sá, J. C., Séguy, L., Tivet, F., Lal, R., Bouzinac, S., Borszowskei, P. R., Briedis, C., dos Santos, J. B., da Cruz Hartman, D., Bertoloni, C. G., Rosa, I., and Triedrich T.: Carbon depletion by plowing and its restoration by no-till cropping systems in Oxisols of subtropical and tropical agro-ecoregions in Brazil, Land Degrad. Dev., 26, 531–543, 2015.

Eimil-Fraga, C., Fernández-Sanjurjo, M. J., Rodríguez-Soalleiro, R., and Álvarez-Rodríguez, E.: Aluminium toxicity risk for *Pinus pinaster* in acid soils (Galicia, NW Spain). Land Degrad. Dev., 27, 1731–1739, 2016.

Elisa, A. A., Ninomiya, S., Shamshuddin, J., and Roslan, I.: Alleviating aluminum toxicity in an acid sulfate soil from Peninsular Malaysia by calcium silicate application, Solid Earth, 7, 367–374, doi:10.5194/se-7-367-2016, 2016.

Evans, C. E. and Kamprath, E.: Lime response as related to percent Al saturation, solution Al, and organic matter content, Soil Sci. Soc. Am. J., 34, 893–896, 1970.

Guo, J., Liu, X., Zhang, Y., Shen, J., Han, W., Zhang, W., Christie, P., Goulding, K., Vitousek, P., and Zhang, F.: Significant acidification in major Chinese croplands, Science, 327, 1008–1010, 2010.

Hseung, Y. and Li, Q. K.: Soils of China, Science Press, Beijing, China, 1990.

Huang, P. M.: Mechanism of soil acidification, in: Agro's Ann. Rev. of Crop Ecology, edited by: Dahama, A. K., Agro Botanica, Bikaner, India, 1997.

Joris, H. A. W., Caires, E. F., Bini, A. R., Scharr, D. A., and Haliski, A.: Effects of soil acidity and water stress on corn and soybean performance under a no-till system, Plant Soil, 365, 409–424, 2013.

Kariuki, S. K., Zhang, H., Schroder, J. L., Edwards, J., Payton, M., Carver, B. F., Raun, W. R., and Krenzer, E.G.: Hard red winter wheat cultivar responses to a pH and aluminum concentration gradient, Agron. J., 99, 88–98, 2007.

Keesstra, S. D., Geissen, V., van Schaik, L., Mosse, K., and Piiranen, S.: Soil as a filter for groundwater quality, Current Opinions in Environmental Sustainability, 4, 507–516, 2012.

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., van der Putten, W. H., Bardgett, R. D., Moolenaar, S., Mol, G., Jansen, B., and Fresco, L. O.: The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals, SOIL, 2, 111–128, doi:10.5194/soil-2-111-2016, 2016.

Kidd, P. S. and Proctor, J.: Effects of aluminium on the growth and mineral composition of *Betula pendula Roth*, J. Exp. Bot., 51, 1057–1066, 2000.

Kochian, L. V.: Cellular mechanisms of aluminum toxicity and resistance in plants, Annu. Rev. Plant Biol., 46, 237–260, 1995.

Krug, E. C. and Frink, C. R.: Acid rain on acid soil: A new perspective, Science, 221, 520–525, 1983.

Liu, Y. and Xu, R. K.: The forms and distribution of aluminum adsorbed onto maize and soybean root surfaces, J. Soils Sediments, 15, 491–502, 2015.

Lofton, J., Godsey, C. B., and Zhang, H.: Determining aluminum tolerance and critical soil pH for winter canola production for acidic soils in temperate regions, Agron. J., 102, 327–332, 2010.

Lollato, R. P., Edwards, J. T., and Zhang, H.: Effect of alternative soil acidity amelioration strategies on soil pH distribution and wheat agronomic response, Soil Sci. Soc. Am. J., 177, 1831–1841, 2013.

Malhi, S. S., Nyborg, M., and Harapiak, J. T.: Effects of long-term N fertilizer-induced acidification and liming on micronutrients in soil and in bromegrass hay, Soil Till. Res., 48, 91–101, 1998.

Mamedov, A. I., Bar-Yosef, B., Levkovich, I., Rosenberg, R., Silber, A., Fine, P., and Levy, G. J.: Amending soil with sludge, manure, humic acid, orthophosphate and phytic acid: Effects on infiltration, runoff and sediment loss, Land Degrad. Dev. 27, 1629–1639, 2016.

Meriño-Gergichevich, C., Alberdi, M., Ivanov, A., and Reyes-Díaz, M.: Al^{3+}-Ca^{2+} Interaction in plants growing in acid soils: Al-phytotoxicity response to calcareous amendments, J. Soil Sci. Plant Nutr., 10, 217–243, 2010.

Mullen, C., Scott, B., Evans, C., and Conyers, M.: Effect of soil acidity and liming on lucerne and following crops in central-western New South Wales, Anim. Prod. Sci., 46, 1291–1300, 2006.

Muluneh, A., Biazin, B., Stroosnijder, L., Bewket, W., and Keesstra, S.: Impact of predicted changes in rainfall and atmospheric carbon dioxide on maize and wheat yields in the Central Rift Valley of Ethiopia, Reg. Environ. Change, 15, 1105–1119, 2015.

Mwango, S. B., Msanya, B. M., Mtakwa, P. W., Kimaro, D. N., Deckers, J., and Poesen, J.: Effectiveness of mulching under miraba in controlling soil erosion, fertility restoration and crop yield in the Usambara Mountains, Tanzania, Land Degrad. Dev., 27, 1266–1275, 2016.

Pansu, M. and Gautheyrou, J.: Handbook of soil analysis: mineralogical, organic and inorganic methods, Springer, Berlin, Germany, 2006.

Pavan, M. A., Bingham, F., and Pratt, P.: Toxicity of aluminum to coffee in Ultisols and Oxisols amended with $CaCO_3$, $MgCO_3$, and $CaSO_4 \cdot 2H_2O$, Soil Sci. Soc. Am. J., 46, 1201–1207, 1982.

Poolpipatana, S. and Hue, N.: Differential acidity tolerance of tropical legumes grown for green manure in acid sulfate soils, Plant Soil, 163, 131–139, 1994.

Potopová, V., Štěpánek, P., Farda, A., Türkott, L., Zahradníček, P., and Soukup, J.: Drought stress impact on vegetable crop yields in the Elbe River Lowland between 1961 and 2014, Cuadernos De Investigacion Geografica, 42, 127–143, 2016.

Rengel, Z. and Zhang, W. H.: Role of dynamics of intracellular calcium in aluminium–toxicity syndrome, New Phytol., 159, 295–314, 2003.

Reuss, J. O. and Johnson, D. W.: Acid Deposition and the Acidification of Soils and Waters, Springer-Verlag, Berlin, Germany, 1986.

Rhoads, F. and Manning, A.: Soybean, corn, and wheat yields with variable soil pH on Plinthic Acrisols, Fertil. Res., 19, 137–142, 1989.

Robson, A. D.: Soil Acidity and Plant Growth, Academic Press, Sydney, Australia, 1989.

Schroder, J. L., Zhang, H. L., Girma, K., Raun, W. R., Penn, C. J., and Payton, M. E.: Soil acidification from long-term use of nitrogen fertilizers on winter wheat, Soil Sci. Soc. Am. J., 75, 957–964, 2011.

Slattery, W. J. and Coventry, D. R.: Response of wheat, triticale, barley, and canola to lime on 4 soil types in north-eastern Victoria, Aust. J. Exp. Agr., 33, 609–618, 1993.

Singh, K., Mishra, A. K., Singh, B., Singh, R. P., and Patra, D. D.: Tillage effects on crop yield and physicochemical properties of sodic soils, Land Degrad. Dev., 27, 223–230, 2016.

Smith, P., Cotrufo, M. F., Rumpel, C., Paustian, K., Kuikman, P. J., Elliott, J. A., McDowell, R., Griffiths, R. I., Asakawa, S., Bustamante, M., House, J. I., Sobocká, J., Harper, R., Pan, G., West, P. C., Gerber, J. S., Clark, J. M., Adhya, T., Scholes, R. J., and Scholes, M. C.: Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils, SOIL, 1, 665–685, doi:10.5194/soil-1-665-2015, 2015.

Sumner, M. E. and Noble, A. D.: Soil acidification: the world story, in: Handbook of Soil Acidity, edited by: Rengel, Z., Marcel Dekker, New York, USA, 2003.

Symeonakis, E., Karathanasis, N., Koukoulas, S., and Panagopoulos, G.: Monitoring sensitivity to land degradation and desertification with the environmentally sensitive area index: The case of Lesvos Island, Land Degrad. Dev., 27, 1562–1573, 2016.

Tsozué, D., Nghonda, J. P., and Mekem, D. L.: Impact of land management system on crop yields and soil fertility in Cameroon, Solid Earth, 6, 1087–1101, doi:10.5194/se-6-1087-2015, 2015.

Ulrich, B. and Sumner, M. E.: Soil Acidity. Springer-Verlag, Berlin, Germany, 1991.

van Breemen, N., Driscoll, C. T., and Mulder, J.: Acidic deposition and internal proton sources in acidification of soils and waters, Nature, 307, 599–604, 1984.

Vogt, R. D., Seip, H. M., Larssen, T., Zhao, D. W., Xiang, R. J., Xiao, J. S., Luo, J. H., and Zhao, Y.: Potential acidifying capacity of deposition-experiences from regions with high NH_4^+ and dry deposition in China, Sci. Total Environ., 367, 394–404, 2006.

Von Uexküll, H. R. and Mutert, E.: Global extent, development and economic impact of acid soils, in: Plant-soil interaction at low pH: principles and management, edited by: Date, R. A., Grundon, N. J., Raymet, G. E., and Probert, M. E., Kluwer Academic Publishers, Dordrecht, the Netherlands, 1995.

Wallace, S. and Anderson, I.: Aluminum toxicity and DNA synthesis in wheat roots, Agron. J., 76, 5–8, 1984.

Watanabe, T., Osaki, M., Yano, H., and Rao, I. M.: Internal mechanisms of plant adaptation to aluminum toxicity and phosphorus starvation in three tropical forages, J. Plant Nutr., 29, 1243–1255, 2006.

Wu, R. and Tiessen, H.: Effect of land use on soil degradation in alpine grassland soil, China, Soil Sci. Soc. Am. J., 66, 1648–1655, 2002.

Xu, R. K., Coventry, D. R., Farhoodi, A., and Schultz, J. E.: Soil acidification as influenced by crop rotations, stubble management, and application of nitrogenous fertiliser, Tarlee, South Australia, Aust. J. Soil Res., 40, 483–496, 2002.

Yan, X. and Cai, Y. L.: Multi-scale anthropogenic driving forces of karst rocky desertification in Southwest China, Land Degrad. Dev., 26, 193–200, 2015.

Yu, T. R.: Chemistry of Variable Charge Soils, Oxford University Press, New York, USA, 1997.

Zhang, X. B., Liu, P., Yang, Y., and Xu, G. D.: Effect of Al in soil on photosynthesis and related morphological and physiological characteristics of two soybean genotypes, Bot. Stud., 48, 435–444, 2007.

Zhao, Y., Duan, L., Xing, J., Larssen, T., Nielsen, C. P., and Hao, J. M.: Soil acidification in China: Is controlling SO_2 emissions enough? Environ. Sci. Technol., 43, 8021–8026, 2009.

Zornoza, R., Acosta, J. A., Bastida, F., Domínguez, S. G., Toledo, D. M., and Faz, A.: Identification of sensitive indicators to assess the interrelationship between soil quality, management practices and human health, SOIL, 1, 173–185, doi:10.5194/soil-1-173-2015, 2015.