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Ca-amendment and tillage: Medium term synergies for improving key soil properties of acid soils

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ABSTRACT

Ca-amendments are routinely applied to improve acid soils, whilst no-tillage (NT) has been widely recommended in soils where traditional tillage (TT) has led to losses of organic matter. However, the potential interactions between the two treatments are only partially known. Our study was conducted on an annual forage crop agrosystem with a degraded Palexerult soil located in SW Spain, in order to assess if the combination of NT plus a Ca-amendment provides additional benefits to those of their separate use. To this end we analysed the effects of four different combinations of tillage and Ca-amendment on selected key soil properties, focusing on their relationships. The experimental design was a split-plot with four replicates. The main factor was tillage (NT versus TT) and the second factor was the application or not of a Ca-amendment, consisting of a mixture of sugar foam (SF) and red gypsum (RG). Soil samples were collected from 3 soil layers down to 50 cm after four years of treatment (2009). The use of the Ca-amendment improved pH and Al-toxicity down to 25 cm and increased exchangeable Ca^{2+} down to 50 cm, even under NT due to the combined effect of SF and RG. Both NT and the Ca-amendment had a beneficial effect on total organic carbon (TOC), especially on particulate organic carbon (POC), in the 0–5 cm layer, with the highest contents observed when both practices were combined. Unlike NT, the Ca-amendment failed to improve soil aggregation in spite of the carbon supplied. This carbon was not protected within the stable aggregates in the medium term, making it more susceptible to mineralization. We suggest that the fraction of Al extracted by oxalate from solid phase ($Al_{Oxa\text{-}Cu\text{-}K}$) and the glomalin-related soil proteins (GRSPs) are involved in the accumulation of carbon within water stable aggregates, probably through the formation of non-toxic stable Al-OM compounds, including those formed with GRSPs. NT alone decreased Al_K in the 0–5 cm soil layer, possibly by increasing POC, TOC and GRSPs, which were observed to play a role in reducing Al toxicity. From our findings, the combination of NT and Ca-amendment appears to be the best management practice to improve chemical and physical characteristics of acid soils degraded by tillage.

1. Introduction

Aluminium toxicity and Ca^{2+} deficiency are the main constraints for crop production in acid soils (Adams, 1984). Tillage, on the other hand, has been reported to decrease soil organic matter (SOM), thus affecting in turn other parameters related to soil quality (Reeves, 1997). The soils studied in our work (old Ultisols in the Cañamero's raña surface, SW of the Iberian Peninsula) suffer from both high acidity and degradation from tillage. Restoration of these degraded soils would require the use of a Ca-amendment to raise pH and alleviate Al toxicity, as well as the introduction of soil conservation practices such as no-tillage (NT).

Lime and gypsum amendments or the combination of both (Ca-amendment) are widely used to solve problems of soil acidity (Oates and Kamprath, 1983; Shainberg et al., 1989; Peregrina et al., 2006). Lime provides Ca^{2+} and generates OH^- ions that neutralize the acidity, thus raising the pH. This leads to the precipitation of aluminium from the soil solution in the form of insoluble hydroxides (Bohn et al., 1985). Lime is fairly insoluble, and thus to correct aluminium toxicity in deeper horizons gypsum addition is recommended due to its higher solubility (Reeves and Sumner, 1972). Gypsum delivers Ca^{2+} to the deeper horizons, increasing Ca^{2+} saturation in the exchange complex (Shainberg et al., 1989). At the same time it favours the formation of the non-toxic ionic pars $AlSO_4^+$ in the soil solution (Kinraide and Parker, 1987), thus

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reducing the activity of the toxic Al^{3+}. The increase of the Ca/Al ratio in the soil solution also helps to decrease the activity of the toxic Al^{3+} (Noble et al., 1988) while the sorption of SO_4^{2-} to the soil matrix liberates OH^- ions that raise the pH. This latter process is known as the "self liming effect" (Reeves and Sumner, 1972).

Whereas the effects of these amendments on pH, Al toxicity and biomass production are well documented (Pavan et al., 1982; Oates and Kamprath, 1983; Shainberg et al., 1989; Fageria and Baligar, 2008), their effects on SOM are contradictory (Haynes and Naidu, 1998). Variations in SOM content due to changes in soil management are normally slow and, therefore, monitoring changes on shorter time scales requires the selection of organic matter fractions that are easily degraded and mineralized. Such fractions include particulate organic matter (POM), which represents a labile fraction of the SOM and consists of particles between 0.053 and 2 mm (Cambardella and Elliott, 1992). We would expect Ca-amendments to promote the accumulation of SOM through the enhancement of biomass production (both root and above-ground biomass) as a result of a reduction of Al toxicity and nutrient supply (Haynes and Naidu, 1998). However, if the Ca-amendment also promotes microbial activity that effect may be counteracted by a higher SOM mineralization rate (Fuentes et al., 2006). In fact some authors (Marschner and Wilczynski, 1991; Chan and Heenan, 1999) have found lime to decrease organic carbon content, but the effect only occurs during the first few years following the application and vanishes with time (Caires et al., 2006).

Another important aspect is the effect of the Ca-amendments on arbuscular mycorrhizal fungi (AMF), which have been reported to increase the access of plant roots to limiting nutrients and to enhance stress resistance in acidic environments (Cumming and Ning, 2003). AMF are also responsible for the production of glomalin, a glycoprotein that has been reported to play a role in soil aggregation (Wright and Upadhyaya, 1998) and to help reduce Al toxicity in acid soils (González-Chávez et al., 2004; Etcheverría, 2009; Aguilera et al., 2011). When referring to glomalin we use the term glomalin-related soil protein (GRSP) proposed by Rillig (2004), since some other heat-stable proteins of non-AMF origin may be extracted in the process (Rosier et al., 2006), although GRSPs are largely of AMF origin (Rillig, 2004). We also distinguish between the total fraction (GRSP) and the easily extractable fraction (EE-GRSP), which is supposed to represent recent deposits (Wright and Upadhyaya, 1998). Soil management practices influence AMF, thus modifications of the soil pH can alter the distribution of AMF species (Abbott and Robson, 1977) and spore production (Raznikiewicz et al., 1994), although in the study by Wang et al. (1993) lime hardly affected root colonization. To our knowledge, no studies have reported the direct effects of Ca-amendments on GRSPs.

The effect of the Ca-amendments on soil aggregation is also unclear (Haynes and Naidu, 1998). It would be expected to have a favourable effect by increasing the amount of residual biomass (Tisdall and Oades, 1982), adding calcium (Chan and Heenan, 1999), favouring the precipitation of aluminium as hydroxides (El-Swaify and Emerson, 1975) and promoting biological activity, which results in the production of polysaccharides and other microbially-derived binding agents (Six et al., 2004). However, it can also have adverse effects, such as the dispersion of clay by repulsion as a result of increasing negative charges in the exchange complex due to the pH increase and reduced Al^{3+} activity (Haynes and Naidu, 1998). Increased SOM mineralization as a consequence of the stimulated microbial activity (Haynes and Swift, 1988) could also reduce aggregate stability in the short term (Chan and Heenan, 1999). These opposing effects can explain the contradictory results obtained in both laboratory and field studies. These studies have reported positive effects (Chan and Heenan, 1999; Briedis et al., 2012b), negative effects (Roth and Pavan, 1991; Koutika et al., 1997; Westerhof et al., 1999), variable effects depending on soil type (Castro and Logan, 1991) and even insubstantial effects (Stenberg et al., 2000).

With regards to tillage, its negative impact on SOM is mainly due to (i) aeration enhancing mineralization (Reicosky et al., 1995) and (ii) the mechanical breakdown that exposes the SOM that was previously physically protected within the aggregates against microbial degradation (Six et al., 2000). The benefits of NT on SOM have been described in a wide range of studies (Paustian et al., 1997; West and Post, 2002). No-tillage promotes the formation of macroaggregates and helps to stabilize and store soil carbon through the formation of microaggregates within the macroaggregates (Six et al., 1998). AMF have been reported to decrease with tillage mainly due to mechanical disturbances (Wright et al., 1999; Kabir, 2005), which cause the direct disruption of roots and hyphas, whereas NT practices favour fungal development (Kabir et al., 1998; Galvez et al., 2001). We would expect, therefore, that GRSPs are sensitive to management changes in the same direction. Indeed, a higher concentration of these proteins has been found in soils under NT compared with tilled ones (Borie et al., 2006; Curaqueo et al., 2011).

In addition, NT improves soil aggregation by stopping the mechanical breakdown and by the promotion of SOM (Paustian et al., 2000; Six et al., 2000). The POM fraction is, above all, reported to be important for the formation and stabilization of microaggregates within macroaggregates (Jastrow, 1996; Six et al., 2002). No-tillage also favours fungal development, which increases soil aggregation through hyphal trapping and the production of binding substances (Six et al., 2004). Such substances include GRSPs, which have been associated with aggregate stability since they are reported to act as a glue stabilizing aggregates, possibly due to their recalcitrant nature and hydrophobic characteristics (Wright and Upadhyaya, 1998; Rillig et al., 2002).

The increase of both SOM and GRSPs under NT would not only enhance soil aggregation, but could also help to alleviate Al toxicity. The role of SOM in this process has been widely reported (Hargrove and Thomas, 1981a; Haynes and Mokolobate, 2001; Wong and Swift, 2003) and has been attributed to (i) the increase of pH resulting from the decomposition of SOM, which leads to the precipitation of exchangeable and soluble aluminium, and (ii) the production of non-toxic stable complexes formed by the SOM and the aluminium. More recently, GRSPs have been reported to be a response by AMF to reduce Al toxicity in acid soils (Seguel et al., 2013). Due to their high cation exchange capacity and high affinity for polyvalent cations (Etcheverría, 2009), GRSPs have the capacity to sequester substantial quantities of Al by forming stable compounds (Aguilera et al., 2011).

The combination of NT with Ca-amendment, therefore, seems to be a suitable management approach for acid soils degraded by an excess of tillage, such as the soils studied here. Some studies have examined the combined use of these practices (Arshad et al., 1999; Stenberg et al., 2000; Conyers et al., 2003; Soon and Arshad, 2005), although they have only focused on a few variables and none of them have studied the combined use of lime and gypsum. Regarding the role of SOM in reducing Al toxicity, this has mainly been investigated in laboratory studies (Hargrove and Thomas, 1981b; Mokolobate and Haynes, 2002; Naramabuye and Haynes, 2007), and only occasionally in the field (Godsey et al., 2007; Brown et al., 2008). The role of GRSPs in reducing Al toxicity has only been reported recently and further research is needed to confirm its relevance under different conditions.

We hypothesized that NT could: (i) compensate the possible negative effects of the Ca-amendment on SOM content and soil aggregation; (ii) contribute to decrease aluminium toxicity through the enrichment of SOM and GRSPs. We sought to