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Evaluation of atmospheric CO_2 sequestration by alkaline soils through simultaneous enhanced carbonation and biomass production

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ABSTRACT

A series of microcosm experiments were conducted. The objectives were to evaluate the effects of Ca/Mg-bearing materials on CO_2 sequestration in highly alkaline sodic soils (Sodosol) through carbonation and biomass production. Application of gypsum resulted in an increase in inorganic carbon and a decrease in organic carbon. The addition of talc did not significantly enhance carbonate formation. Soluble $CaCl_2$ and $MgCl_2$ did not have significantly better effects on soil carbonation, as compared to gypsum. The one-year growth experiment using five widely cultivated pasture grasses revealed that accumulation of carbonates following gypsum application could be inhibited by plant growth; the organic acids secreted from plant roots were likely to facilitate soil carbonate dissolution. In comparison with pedogenic carbonation, carbon sequestration by biomass production was much more evident. However, the biomass carbon gain varied markedly among the five species with *Digitaria eriantha* showing the highest biomass carbon gain. This further enhanced the accumulation of soil organic carbon. At the end of the experiment, an estimated CO_2 sequestering capacity of 93 t/ha was achieved. The research findings have implications for cost–benefit analysis of alkaline soil reclamation projects.

1. Introduction

Alkaline soils are referred to as the soils with a high pH (Van Beek and Van Breemen, 1973; Day and Ludeke, 1993). These soils have the potential to sequester CO_2 according to the following chemical equation:

$$M^{2+} + 2OH^{-} + CO_2 \rightarrow MCO_3 + H_2O. \quad (1)$$

M^{2+} in the above equation represents a divalent metal that can combine with CO_3^{2-} to form stable metal carbonates. In the Earth's surface environments, Mg and Ca are the two such binding metals that are present at substantial amounts under oxic conditions. Other binding metals are practically less important in terms of mineral carbonation for CO_2 sequestration. Under alkaline conditions, the available soluble Ca^{2+} and Mg^{2+} tend to be removed from the soil solution to form solid carbonate minerals (Eq. (1)). Therefore, the proportion of soluble Na^{+} in the soils increases, which may lead to soil sodification and the formation of alkaline sodic soils (Pessarakli, 1991; Singh et al., 2013a). The maintenance of high pH in alkaline soils indicates that the supply of binding divalent metals is limited. Therefore, the addition of substances containing soluble divalent metals into alkaline soils is likely to facilitate the sequestration of atmospheric CO_2.

Application of gypsum and other calcium-containing materials is a common agricultural practice to ameliorate sodic soils by reducing the exchangeable sodium percentage (ESP) (Chawla and Abrol, 1982; Mace et al., 1999; Hanay et al., 2004). Substantial amounts of research have been conducted to examine the effects of gypsum application on correcting soil sodicity and consequently enhancing crop growth (Hamza and Anderson, 2003; Abdel-Fattah, 2012; Rasouli et al., 2013). However, there has so far been no work reported with a focus on atmospheric CO_2 sequestration associated with these agricultural practices. The application of gypsum or other Ca- and Mg-bearing materials to alkaline soils could result in the fixation of atmospheric CO_2 by both carbonate formation (Han and Tokunaga, 2014) and organic matter production (Goel and Behl, 1995; Singh et al., 2013b), which has implications for mitigating climate change. Land use alteration can induce changes in soil carbonate systems (Sanderman, 2012). The potential carbon credit benefit from the amendment of alkaline soils may become a factor for consideration when developing plans for alkaline sodic soil reclamation. This is particularly relevant to situations where irrigation water becomes available from groundwater exploitation (Gijsbers and Loucks, 1999) or where there is a need for groundwater disposal due to e.g. coal seam gas extraction operations (Hamawand et al., 2013). Evaluation of carbon credit from the uses of improved alkaline soils for biomass production will provide useful information that can be used to assist in performing cost–benefit analysis for alkaline soil reclamation projects.

The objective of this study was to (a) examine the effects of gypsum application rate on carbon dynamics and alkalinity reduction in the test

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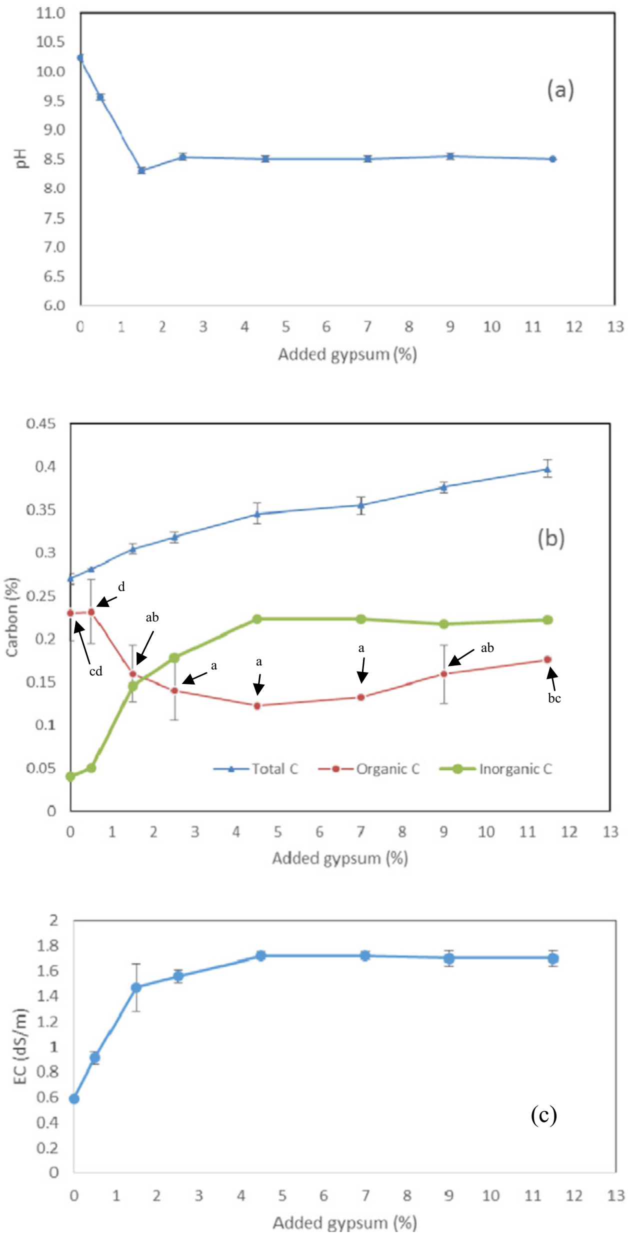

Fig. 1. Plots of gypsum application rate versus (a) soil pH, (b) total carbon, organic carbon and inorganic carbon, and (c) electrical conductivity (EC) in the soils. Means with different letters (appeared next to the data points) for organic carbon indicate that there was a statistically significant difference ($P < 0.05$) between the two treatments.

alkaline soil; (b) compare the effects of various Ca- and Mg-bearing materials on pedogenic carbonation, and (c) compare the effects of gypsum application-derived reduction in the alkalinity on the biomass production, and consequently carbon sequestration among different plant species.

2. Materials and methods

2.1. The experimental materials

The alkaline soil material used for various experiments was collected from Yelarbon, southern Queensland, Australia. The soil was locally known as Sodosol (Isbell, 2002). Approximately 190 kg of the soil material was taken from the upper 30 cm of the soil profile. In the laboratory, the soil material was air-dried and crushed to pass a 2 mm sieve. Gravel particles greater than 2 mm were discarded. The <2 mm soil fraction was thoroughly mixed. The soil sample had a pH of 10.2 and a value of electrical conductivity (EC) of 1.366 dS/m (1:5, soil:water extract). The soil contained no detectable soluble Ca. Soluble concentration of Na, K and Mg was 1190, 107 and 19 mg/kg, respectively. The soil had an organic carbon content of 0.23%. The concentration of total nitrogen and total phosphorus was 600 mg/kg and 90 mg/kg, respectively.

Calcium sulfate dehydrate ($CaSO_4{\cdot}H_2O$, gypsum) used in Experiments 1 and 2 and calcium chloride and magnesium chloride used in Experiment 2 were of analytical reagent grade. Powdered talc ($Mg_3Si_4O_{10}(OH)_2$) used in Experiment 2 was purchased from a commercial source. Ultrapure water (18.2 MΩ/cm) was used throughout the entire course of the laboratory incubation experiments.

Since Experiment 3 (Greenhouse experiment) required large amounts of gypsum, it is too costly to use gypsum of analytical reagent grade for this experiment. Cheaper agricultural gypsum was used instead. The product was purchased from a commercial source and contained 67% of gypsum.

Aquasol soluble fertilizer used for the growth experiment contained 23% of nitrogen, 3.95% of phosphorus, 14% of potassium, 6.6% of sulfur, 0.15% of magnesium, 0.13% of manganese, 0.06% of copper Cu, 0.06% of iron, 0.04% of zinc, 0.01% boron, and 0.001 of molybdenum.

For the greenhouse plant growth experiment, five widely cultivated pasture grass species in the area where the soil sample was collected were selected: *Panicum maximum* (common name: Gatton panic; variety: Gatton), *Panicum coloratum* (common name: Bambatsi panic; variety: Bambatsi), *Digitaria eriantha* (common name: Digit grass, variety: Premier), *Chloris gayana* (common name: Rhodes grass; variety: pioneer) and *Bothriochloa insculpta* (common name: Bluegrass; variety: hatch). Seeds of the grass species were purchased from a local seed supplier. According to the supplier, the cultivar of these grass species appeared to have a medium level of salt tolerance with Rhodes grass being more salt-tolerant than the other grass species.

2.2. Experiment 1: effect of gypsum dosage on CO_2 sequestration

The alkaline soil material was amended with gypsum at varying application rates. Seven treatments were set with 500 g of the soil material being mixed with the gypsum at the following rate: 0.5, 1.5, 2.5, 4.5, 7, 9 and 11.5%. The amended soil of each treatment was placed in a plastic container with dimensions of 19.5 cm (length) × 12 cm (width) × 6 cm (height). The soil material with no added gypsum was used to serve as the control of the experiment. At the beginning of the experiment, the soils were saturated with deionized water (moisture content: 33%) and then exposed to ambient air. An appropriate amount of deionized water was added to the soil in each incubation chamber to compensate soil water loss due to evaporation at times when the surface soil layer dried out. Pre-experiment test showed that soil pH tended to become stable after initial drop within 25 days for all the treatments. Therefore, the duration of the incubation experiment was set at 30 days to ensure that the equilibrium for the reaction (Eq. (1)) was approached. The experiment was run in triplicate. At the end of the experiment, the soil in each incubation chamber was air-dried, crushed and homogenized. A sample from each incubation chamber was used to determine pH, electrical conductivity (EC), organic carbon, total carbon, water-extractable and exchangeable basic cations (Ca, Na, Mg and K).

2.3. Experiment 2: comparison among different Ca- or Mg-containing materials

This experiment aimed to examine the effects of different Ca- or Mg-containing materials on CO_2 sequestration by the alkaline soil material. Four treatments were set: (a) Treatment 1 (T1): addition of powdered talc; (b) Treatment 2 (T2): addition of gypsum; (c) Treatment 3 (T3): addition of $MgCl_2$; and (d) Treatment 4 (T4): addition of $CaCl_2$. 200 mL plastic beakers were used as incubation chambers. In each of the incubation