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Effects of atmospheric CO_2 concentration on soil-water retention and induced suction in vegetated soil

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ABSTRACT

Current atmospheric CO_2 (400 ppm) is increasing 2 ppm annually and might reach up-to 1000 ppm by year 2100 due to global climate change. Different plant growth was observed under elevated CO_2 in the previous studies. However, plant induced soil suction besides plants growth due to increasing atmospheric CO_2 concentration in heavily compacted soil remain elusive. The objective of this study is to quantify transpiration and evapo-transpiration induced soil suction by *Schefflera heptaphylla* in heavily compacted soil under different atmospheric CO_2 concentration. Three replicates of the plant were grown, and their characteristics were measured under 400 ppm and 1000 ppm CO_2 concentration for three months. Leaf area index of plants decreased by 35% under 1000 ppm CO_2 concentration due to soil nitrogen scarcity which impedes the plants ability to metabolize increased atmospheric CO_2 concentration. Despite having LAI of 0.5–0.7, plant induced suction decreased by 10–25 kPa during transpiration and evapo-transpiration test under 1000 ppm CO_2 concentration. Although a strong positive linear correlation ($R^2 = 0.8–0.9$; P-value < 0.1) of LAI and root-shoot biomass ratio with induced peak soil suction under 400 ppm CO_2 concentration, a weak linear correlation ($R^2 = 0.6–0.8$; P-value > 0.1) of the same plant traits under 1000 ppm CO_2 concentration was observed. This is because leaves cannot open stomata wide enough to transpire more water when they absorb more CO_2 from the atmosphere resulting in soil suction reduction. This implies that the effects of atmospheric CO_2 concentration on plant induced soil suction must be considered in vegetated soils.

1. Introduction

Effects of the increasing atmospheric CO_2 concentration on plants have been quite important for forest management, botany, agronomy and water management in agricultural research. Previous botany and agricultural studies found increased root and shoot growth across many plant species under elevated atmospheric CO_2 (Rogers et al., 1996; Bernacchi et al., 2000; Prior et al., 1994). In contrast, elevated CO_2 effects varied among different plants (based on photosynthesis and carbohydrate storage) i.e., 60% of the studied plants showed increased root-shoot ratio (Rogers et al., 1996). A functional-structural (FS) plant model is presented by Fourcaud et al. (2008) (Fig. 1), a schematic representation of interactions between plant and its environment which considers physiological processes in organs (i.e., water absorption by roots, transportation by stem, transpiration and photosynthesis by leaves). Based on this model, plant growth is driven by basic input elements to the plant (i.e. C, N, P, K) and used by organs (i.e. leaves, roots etc. known as sinks) within 3-D architecture of plant (Fig. 1), considering output or losses. Input, investment and output variables are spatially and temporally under environmental control, i.e., both climate and soil, and variables can interact with and influence each-other. Due to climatic influence, plants displayed reductions in stomatal conductance, which also reduced their transpiration rate (Wullschleger and Norby, 2001; Dugas et al., 2001; Dong-Xiu et al., 2002) and evapo-transpiration rate under elevated CO_2 concentration (Dijkstra et al., 1999; Conley et al., 2001; Hungate et al., 2002). In contrast, differences in transpiration rate were not significant when atmospheric temperature increased (Apple et al., 2000; Lewis et al., 2002) and differences in evapo-transpiration rate also reduced over time (Grunzweig and Korner, 2001) or in different soil (i.e., calcareous soil) (Bucher-Wallin et al., 2000). However, some plants responded to elevated atmospheric CO_2 concentration while some plants did not respond.

Research on the vegetation effects on slope stability and landfill cover has become more widespread in the last few decades (Smethurst et al., 2015; Sinnathamby et al., 2013). Positive influence of vegetation (hydrological effects) is now more recognized. This is due to an increase in plant-induced soil suction upon evapo-transpiration which leads to an increase in soil shear strength and decrease in water permeability

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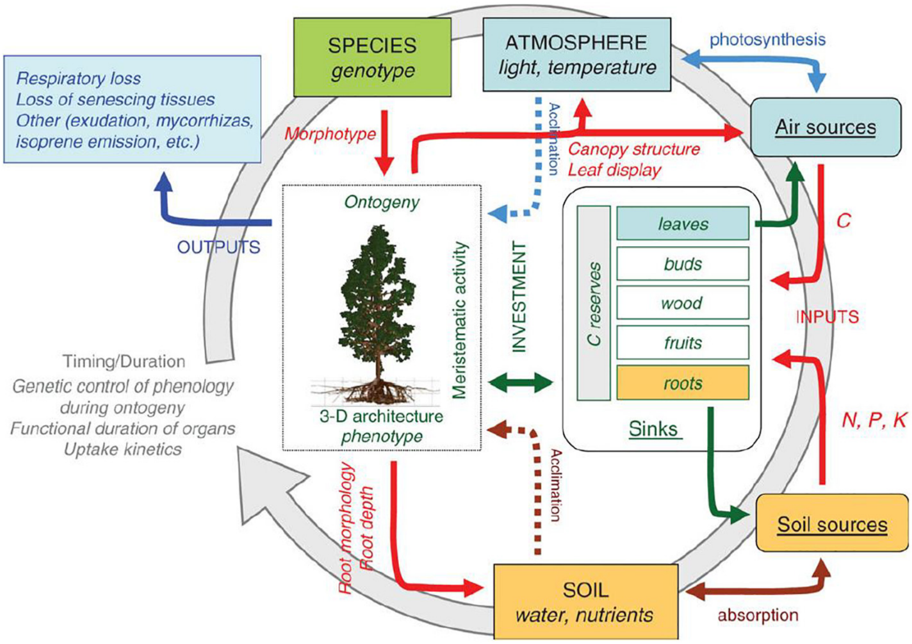

Fig. 1. A schematic representation of interactions between a plant and its environment (Functional-structural plant model). (Fourcaud et al., 2008).

(Ng and Menzies, 2007; Ng and Leung, 2012). Vegetation is also recognized as an effective way for mitigating soil surface erosion (Shen et al., 2017). Previous studies have shown that some plant traits such as- leaf area index (LAI) (Ng et al., 2016) and root-shoot biomass ratio (Boldrin et al., 2017) have a linear positive correlation with plant induced soil suction. Since atmospheric CO_2 concentration is increasing 2 ppm annually due to global climate change (Keeling and Whorf, 2005) and might reach 500–1000 ppm by year 2100 (IPCC, 2013), it might affect plants and hence plant induced soil suction which is crucial for slope stability and transient seepage analyses. Furthermore, there is a lack of understanding whether the previous correlations between plant traits and induced soil suction is still valid under elevated atmospheric CO_2 concentration. Moreover, in addition to 3-D plant architecture as an output of FS plant model (Fig. 1), plant-induced soil suction, volumetric water content and correlation of plant traits with suction due to uptake of more CO_2 from the atmosphere were not considered in heavily compacted soil. These need to be considered from an engineering point of view to ensure proper design of vegetated slopes, road and railway embankments and landfill covers with respect to climate change and increasing atmospheric CO_2 concentration.

In this study, a laboratory experiment was conducted to quantify and compare the magnitude and distribution of suction induced by transpiration and evapo-transpiration of *Schefflera heptaphylla*, in silty sand under current (400 ppm) and elevated (1000 ppm) CO_2 concentration. In addition, plant traits (e.g., LAI, leaf number, shoot and root length, shoot and root biomass) were quantified and correlated with plant induced soil suction as well as soil-water retention curves were also established.

2. Materials and methods

2.1. Test plan

In this study, two test series were conducted. First and second test series were intended to grow plants in heavily compacted soil under 400 ± 50 ppm and 1000 ± 50 ppm CO_2 concentration and to investigate transpiration and evapo-transpiration induced soil suction and volumetric water content (VWC). First series is a reference test since the current atmospheric CO_2 concentration is 410 ppm (Dlugokencky and Tans, 2018). Second series is to represent a scenario where CO_2 concentration might reach 500–1000 ppm by year 2100 (IPCC, 2013). Bare soil was also tested in both test series. Transpiration and evapo-transpiration induced soil suction was influenced by plant transpiration (covering the soil surface) and plant-soil system, respectively. Atmospheric CO_2 enrichment generally reduces leaf stomatal conductance in most plants, which reduces the amount of water they transpire. (de Boer et al., 2011; Lammertsma et al., 2011) At the same time, it often stimulates or inhibits the production of leaf area (Bernacchi et al., 2000; Tingey et al., 1996), which tend to increase or reduce the amount of water they convey to the atmosphere (Kelliher et al., 1995). Moreover, the stimulated or reduced leaf area shades or exposes more of the underlying ground from the direct rays of the sun, which could increase or reduce the amount of water evaporated from the soil. Hence, it is not immediately clear what the net effect of these several competing phenomena would be with respect to evapo-transpiration or the loss of water from the entire soil-plant system. Besides, Garg et al. (2015) observed 3%–47% difference between transpiration and evapo-transpiration induced soil suction. Therefore, in this study both transpiration and evapo-transpiration induced drying tests were conducted to investigate atmospheric CO_2 effect on plant induced soil suction by these two processes.

2.2. Test set-up and instrumentation

Fig. 2 shows the schematic setup of a vegetated test box. Four boxes were constructed with cross-section area of 300 mm × 300 mm and a height of 350 mm. Soil was compacted in boxes up-to 280 mm depth and an individual tree was transplanted at the centre of three boxes. Side boundaries were impermeable, free drainage was allowed through 5 mm diameter holes at the bottom of the box and top boundary was exposed to the environment. Three miniature tip tensiometers at depths of 30 mm, 80 mm and 140 mm (within initial root depth zone) and one tensiometer at depth of 210 mm were installed just below the tree at the centre of box. The measurement range of suction is limited by water cavitation in tensiometer when negative pore-water pressure in soil approaches 80–90 kPa (Fredlund and Rahardjo, 1993). One soil moisture probe (SM-300) was installed at 80 mm depth right next to the tensiometer to monitor VWC, to check the measurements of suction against VWC and to investigate the effects of CO_2 on root growth which might affect soil water retention behaviour. Since two moisture probes