Measurement of xylem water pressure using High-Capacity Tensiometer and benchmarking against Pressure Chamber and Thermocouple Psychrometer

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Abstract. The response of the shallow portion of the ground (vadose zone) and of earth structures is affected by the interaction with the atmosphere. Rainwater infiltration and evapotranspiration affect the stability of man-made and natural slopes and cause shallow foundations and embankments to settle and heave. Very frequently, the ground surface is covered by vegetation and, as a result, transpiration plays a major role in ground-atmosphere interaction. The soil, the plant, and the atmosphere form a continuous hydraulic system, which is referred to as Soil-Plant-Atmosphere Continuum (SPAC). The SPAC actually represents the 'boundary condition' of the geotechnical water flow problem. Water flow in soil and plant takes place because of gradients in hydraulic head triggered by the negative water pressure (water tension) generated in the leaf stomata. To study the response of the SPAC, (negative) water pressure needs to be measured not only in the soil but also in the plant. The paper presents a novel technique to measure the xylem water pressure based on the use of the High-Capacity Tensiometer (HCT), which is benchmarked against conventional techniques for xylem water pressure measurements, i.e. the Pressure Chamber (PC) and the Thermocouple Psychrometer (TP).

1 Introduction

The response of the shallow portion of the ground (vadose zone) and of earth structures is affected by the interaction with the atmosphere. Rainwater infiltration and evapotranspiration cause settlement and heave in shallow foundations and embankments and control the stability of man-made and natural slopes.

Very frequently the ground surface is covered by vegetation and, as a result, transpiration plays a major role in the mechanisms of water removal by the atmosphere. Transpiration is the process of water movement taking place from the soil through the plant up to the leaves, where water eventually evaporates through the stomata. The soil, the plant, and the atmosphere form a continuous hydraulic system, which is referred to as Soil-Plant-Atmosphere Continuum (SPAC) [1]. The SPAC actually represents the 'boundary condition' of the water flow problem. Understanding its response is crucial to model the hydraulic boundary condition of any geotechnical system.

Water flow in the soil and plant takes place because of gradients in hydraulic head triggered by the negative water pressure (water tension) generated in the leaf stomata. To study the response of the SPAC, water pressure therefore needs to be measured not only in the soil but also in the plant.

The most common techniques to monitor xylem water pressure are the Pressure Chamber (PC) [2] and the Thermocouple Psychrometer (TP) [3]. The working principle of the Pressure Chamber is the same as the axis-translation technique used to measure or impose matric suction in soils [4]. Air pressure is increased around the xylem/leaf until water pressure is 'translated' from negative values to zero. The PC is often considered the 'reference' for xylem/leaf water pressure measurement [1, 5]. However, this is a destructive technique as it requires the trunk or branch to be cut or leaves to be excised. As a result, the PC is not suitable for continuous measurement and/or for monitoring leaf water pressure when a relatively small number of leaves is available, which is generally the case in laboratory experiments.

The Psychrometer is based on the use of a thermocouple, similarly to the instruments used to measure total suction in soils [6]. The psychrometer is widely used in the field for continuous monitoring of xylem/leaf water pressure. However, it measures total and not 'matric' water pressure, i.e. its measurement is affected by the presence of solutes in the xylem water. The common assumption that the osmotic component of

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xylem water pressure is negligible [7] does not always hold. [8, 9] have shown that the osmotic component of xylem suction may not be negligible and may vary over time. In addition, the Thermocouple Psychrometer is not accurate at low values of water tension (high relative humidity) and its response is strongly affected by temperature, which is a critical issue in field measurements [2].

The similarities between instruments used to measure water tension in soils and plants suggest that High-Capacity Tensiometers, which are widely used to monitor (negative) pore-water pressure in soils, could also be used to measure xylem water pressure in plants. Indeed, [10] have successfully attempted to measure xylem water pressure directly using a pressure probe made of a capillary tube filled with water and silicon oil. When the tip of the probe was inserted into a xylem channel, the xylem water pressure was transmitted through the liquid in the probe and measured by a pressure transducer. However, this pressure probe has never registered xylem water pressures below -0.65 MPa [11] and for no more than a few hours due to cavitation occurring in the probe [10]. This was probably due to the absence of a high-air-entry porous interface, which is actually incorporated into high-capacity tensiometer used to measure pore-water tension in soil [4]. This paper presents the use of High-Capacity Tensiometer (HCT) to monitor the negative xylem water pressure in plants. The measurement of the HCT was validated against the measurement of leaf water potential via the Pressure Chamber and the Transistor Psychrometer over a relatively wide range of xylem water pressures via field and laboratory experiments [12]. However, this paper only focuses on one single experiment carried out on a cherry tree in the laboratory.

2 Background

2.1 Plant Structure

Plants are composed of rooting system, stem, and crown of leaves (Fig. 1a). Water is taken up from the soil by roots and transported through the stem up to the leaves, where it is released into the atmosphere in the form of vapour.

The stem is composed of different tissues, each one having its own specific role and structure. These include the outer bark, the cortex, the phloem, the cambium, and the inner xylem (Fig. 1c). The phloem and the xylem are the main pathways for solutes and water within the stem. The phloem is the tissue of the plant that redistributes downward the sugars synthesised in the leaves. The xylem is dedicated to the transport of water from the roots to the leaves and is characterized by a porous structure formed by tubes of reduced dimensions called *vessels* (diameter Ø~300 µm) or *tracheids* (diameter Ø~40 µm), which are similar to capillary tubes [13]. The water within this porous medium is continuous and under tension and this allows the ascent of water to considerable heights.

The leaf is the site of photosynthesis (Fig. 1b). The CO_2 and solar energy are converted into sugars and oxygen in the chloroplasts. The CO_2 enters the leaf through the *stomata*, apertures on the surface of the leaf. The guard cells can close or open the stomata, regulating the gas exchange and the water loss from the wet cells within the leaf, i.e. the *transpiration*. For most plants, stomata close during night-time, when no photosynthetic process and transpiration occur [14]. Plants are in a dilemma throughout their lives: photosynthesis requires intensive CO_2 ingress but in relatively dry conditions this exchange can result in excessive water vapour loss.

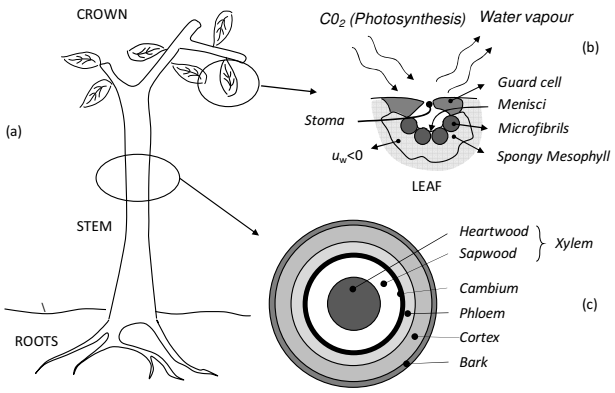


Fig. 1. (a) Structure of a tree: roots, stem, and crown. (b) Leaf structure: stomata and gas exchange; (c) xylem structure.

2.2 Transpiration

The loss of water through the stomata produces a movement of water up the plant to replace what is lost by evaporation. Transpiration in itself is neither an essential physiological function nor a direct result of the living process of the plants. It is mainly caused by a vapour pressure gradient between the normally saturated leaves and the often quite dry atmosphere. In fact, plants can thrive in a saturated or nearly-saturated atmosphere with very little transpiration [15]. In other words, it is the evaporative demand of the atmosphere in which the plants live that drives transpiration (and not the plant).

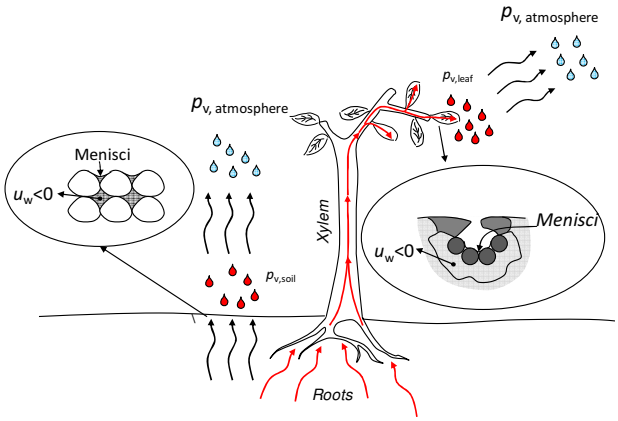


Fig. 2. Evaporation from bare soil and transpiration through plant.

In this respect, there is no difference between evaporation from bare ground and transpiration from plants. In bare ground, evaporation is triggered by the differential in vapour pressure between the ground surface and the atmosphere. The menisci forming at the ground surface due to the evaporation process generates negative pore-water pressures at the surface that uplift pore-water from the deeper layers (Fig. 2a). In a plant, it is the difference in vapour pressure between the leaf and the atmosphere that generates evaporation. The menisci forming in the leaf generate the negative water pressure that uplifts water from the soil through the xylem (Fig. 2b). The plant therefore moves the site of evaporation from the ground surface to the leaves.

2.3 Pressure Chamber

The working principle of the Pressure Chamber is analogous to the axis-translation technique used in soil testing [4]. Water in the leaf is under tension whereas the air surrounding the leaf is at atmospheric pressure (Fig. 3a). In order to measure the 'matric' water tension, the leaf is excised. Water tends to retract into the petiole and menisci form at the interface between the cut end of the petiole and the atmosphere (Fig. 3b). The leaf is inserted into a chamber and sealed inside it. Only the last part of the petiole is left outside in direct contact with the atmosphere (Fig. 3c). The air pressure in the chamber is then gradually incremented until water can be observed to form a flat meniscus on the excised end of the petiole. The air pressure is then taken equal to the water tension in the leaf before excision [16]. This technique is based on the assumption that the difference between the leaf water pressure and the surrounding air pressure is kept constant throughout the whole procedure (Fig. 3d-e) [2].

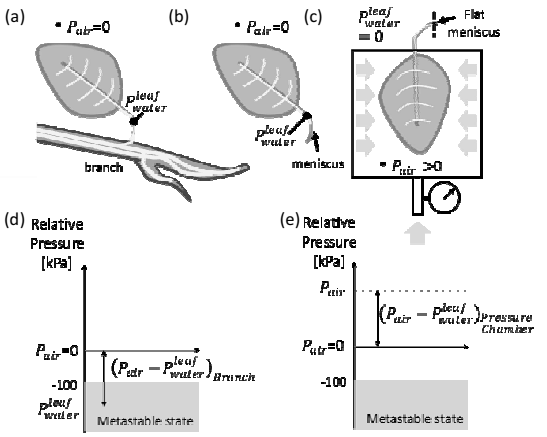


Fig. 3. Working principle of the Pressure Chamber (PC) technique for measurement of leaf water pressure. (a) leaf on the tree (water pressure is negative); (b) leaf excised (curved meniscus forming at the end of petiole); (c) air pressure increased around leaf (meniscus becomes flat).

The measurement of the PC is discontinuous and destructive; the frequency of the readings is therefore conditioned by the manpower and the sampling leaves available. The PC is a commonly used and trusted technique in plant science to measure the 'xylem' matric water pressure in plants and has been used as a benchmark to validate other techniques [10, 17, 18].

2.4 Thermocouple Psychrometer

The psychrometer used for this study is produced by ICT international (PSY1 Stem Psychrometer). The working principle of the psychrometer is based on the measurement of the air relative humidity in equilibrium with the xylem water pressure, which is then converted to water pressure via the psychrometric law. The thermocouple is cooled until the temperature drops below the dew point and a drop condense on the junction. As soon as the thermocouple stops cooling, the drop starts evaporating into the surrounding air. The rate of evaporation is related to the relative humidity in the chamber: the higher the relative humidity, the longer the drop will take to evaporate [5]. The response of the psychrometer must be calibrated against solution of known vapour pressure and, hence, liquid total suction.

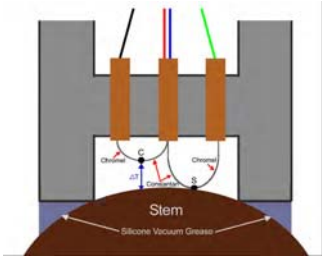


Fig. 4. PSY1 Stem Psychrometer schematic layout [18].

2.5 High-Capacity Tensiometer

The High-capacity Tensiometer (HCT) is shown in Fig. 5 and is composed of an integral strain gauge, a diaphragm 0.4 mm thick and a ceramic filter with nominal air-entry value of 1.5 MPa [20].

When the instrument is put in contact with the xylem, the tension of the xylem water is transferred to the water reservoir, deflecting the diaphragm and deforming the strain gauge. HCT measures the 'matric' water pressure in the sample, thanks to the free diffusion of ions through the porous ceramic [21].

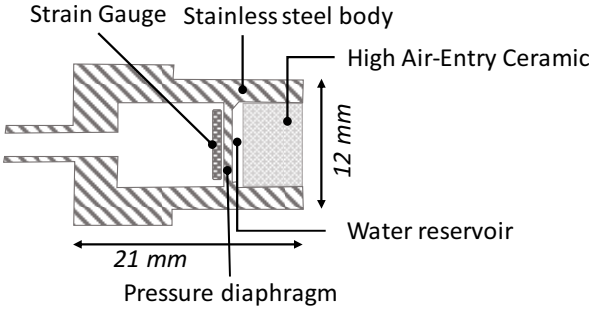


Fig. 5. High-Capacity Tensiometer (after [10]).

3 Materials

The experimental test presented in this paper was conducted on a cherry plant (*Bigarrau Burlat*), a broad-leaved species. The plant was selected for its stem diameter (stem diameter needs to be >20mm to allow proper installation of the high-capacity tensiometers and transistor psychrometer) and a sufficiently large number of leaves for pressure chamber measurements.

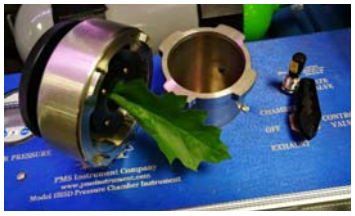
The plant was provided by an external nursery. Prior to the beginning of the experiment, it was kept in the laboratory at constant temperature and relative humidity, watered regularly with solar radiation mimicked through the use of a growth lamp. The oak tree had a height of 1.3 m and a stem diameter of 25 mm at 100 mm height from the soil surface.

4 Experimental procedures

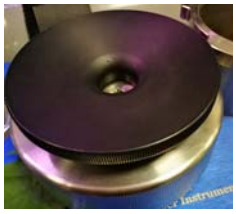
4.1 Pressure Chamber

The PMS 1515D Scholander Pressure Chamber [22] was used for the xylem water pressure measurement (Fig. 6a). Leaves were initially wrapped in aluminium foil for at least 2h. Leaf wrapping stops transpiration and allows water in the leaf to equilibrate with the branch. As a result, the water pressure recorded in the leaf is assumed to coincide with the water pressure in the branch at the base of the petiole.

(a)



(b)



(c)

Fig. 6. (a) PMS 1515D Scholander Pressure Chamber. (b) Leaf inserted into the sealing ring. (c) Sealing ring mounted on the pressure chamber.

The leaf was then excised with a sharp blade and promptly inserted into the sealing ring (in less than a minute), apart from the end of the excised petiole that was kept outside the sealing ring (Fig. 6b). The sealing ring was then mounted on the pressure chamber (Fig. 6c), with the leaf within the chamber and the petiole end kept at atmospheric pressure. Air in the chamber was gradually pressurised until a flat meniscus formed at the end of the excised petiole [23]. The air pressure in the chamber recorded when a flat meniscus appeared at the excised petiole surface was assumed to be equal to the negative water pressure in the leaf before excision. Each measurement was made in triplicate, with the leaves excised at time intervals of 3-5 min.

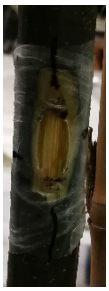
4.2 Thermocouple Psychrometer

Before installation, the psychrometer was observed at the microscope to check that the thermocouple S (Fig. 4) was in position and sufficiently extended to make contact with the xylem surface.

The psychrometer was then wrapped with Parafilm® to facilitate the removal (at the end of the test) of the silicone grease used to seal the sensor on the stem. Only the psychrometer chamber was not covered (Fig. 7a).

A small area of xylem was then exposed, cleaned with distilled water, wiped dry, and then wrapped with several layers of Parafilm® in order to avoid localized evaporation. A hole was made through the layers of Parafilm® to insert the psycrometer sensor (Fig. 7b). The psychrometer was mounted on a clamping device (Fig. 7c), which was in turn installed on the stem (Fig. 7d). The gap between the psychrometer and the stem was sealed with silicone grease.

(a)



(b)

(c)

(d)

Fig. 7. (a) PSY1 wrapping. (b) Xylem exposure and stem wrapping. (c) PSY1 screwed on the clamping device; d) PSY1 on the stem.

The thermocouple signal depends on two parameters, the cooling time and the waiting time. The cooling time is the time whereby the current is circulated in the thermocouple. This causes cooling of the junction in proximity of the plant xylem due to the Peltier effect and condensation of a drop on the junction. The higher the

cooling time, the bigger is the drop the condenses on the cold junction. Once a water drop has condensed, the current is no longer circulated in the thermocouple. Because of the difference in temperature between the cold junction (carrying the condensed water drop) and the reference junction (at ambient temperature), an electrical potential is generated due to the Seebeck effect.

The water drop is subjected to an inward sensible heat flux because the temperature of the drop is lower than the air temperature surrounding the water drop. As a result, the temperature differential between the cold junction and the reference junction tends to decay and so does the electrical potential. This decay in temperature differential is faster for the case where the water drop is small in size. This can occur for either small cooling time or low relative humidity of the surrounding air (because faster evaporation reduces the water drop size more rapidly).

The response of the thermocouple psychrometer is shown in Fig. 8 for three different values of total suction (relative humidity) imposed via NaCl solution (0.45, 2.24, and 4.55 MPa respectively) and different cooling times (5, 8, 10, and 20 sec).

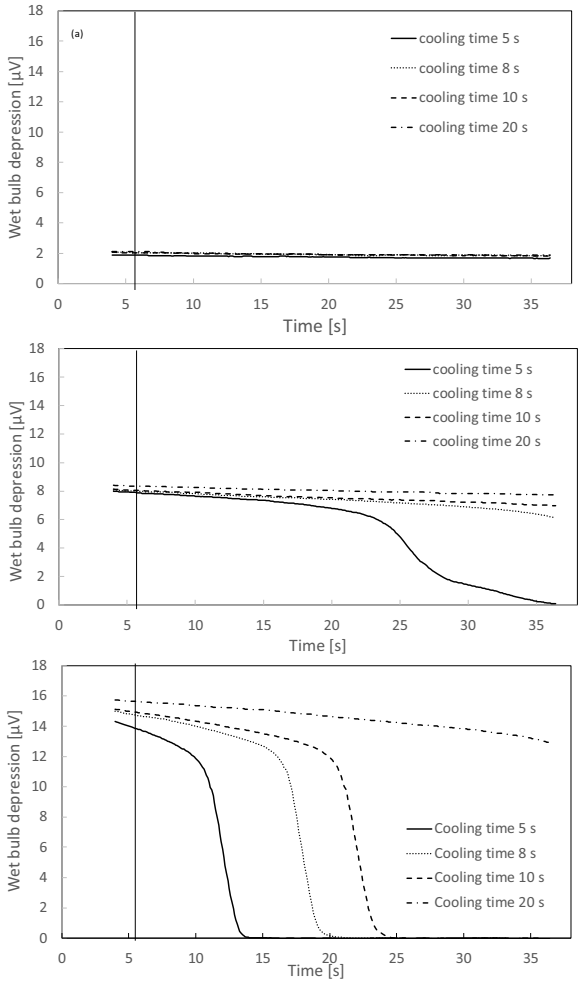


Fig. 8. (a) NaCl 0.1 mol (0.45 MPa suction. (b) NaCl 0.5 mol (2.24 MPa suction. (c) NaCl 1.0 mol (4.55 MPa suction).

The temperature depletion required to condense the water drop is lower when the relative humidity is higher (because the air temperature is closer to the dew point temperature). This explains why the initial signal is only about 2μV for the lowest 0.45 MPa suction (Fig. 8a) and in the range 14-16 μV for the highest suction 4.55 MPa (Fig. 8c). At given cooling time, the electrical signal drops more rapidly at higher suction (Fig. 8c). For the lower suction, the electrical signal drops so slowly that no significant variation is appreciated in the measurement time interval (Fig. 8a).

For a given suction, the higher the cooling time, the bigger is the water drop that condenses initially, and the slower is the decay in electrical potential due to the higher thermal inertia of the drop (Fig. 8c). Because the electrical signal depends on the cooling time and varies over time, a choice has to be made about the cooling time and the 'waiting time', i.e. the time lag between the start of drop evaporation and the record of the signal. The instrument was then calibrated for a waiting time of 6 s and the cooling time to 8 s and the same setting was maintained for the measurements.

4.3 High-Capacity Tensiometer

The HCTs were kept in the saturation chamber at 4 MPa bars for at least 24 hours; The tensiometers were then removed from the saturation chamber and placed in free water at atmospheric pressure. Once equalisation in free water was achieved, negative water pressure was generated by wiping the tensiometer porous ceramic filter. Water pressure was let to drop to about -1000 kPa and the tensiometer was then replaced in free water. This procedure was repeated twice [19, 20]. The tensiometer reading was then zeroed.

The tensiometers were installed on the stem of the plant by exposing an appropriate section of the xylem by means of a cutter blade (Fig. 9a). Any material released from damaged cells was cleaned with distilled water and wiped using tissue paper. The xylem surface was kept moist during the installation to avoid excessive dehydration of the tissues. To ensure proper hydraulic contact between the tensiometer porous ceramic filter and the xylem, a small amount of kaolin clay paste was placed on the tip of the porous ceramic filter (Fig. 9b).

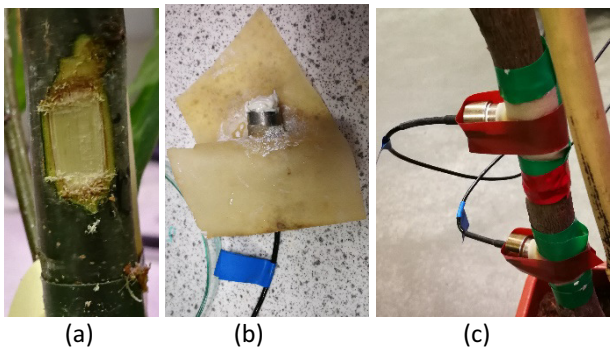


Fig. 9. HCT installation on stem. (a) Exposure of xylem tissues. (b) Kaolin paste on HCT. (c) Application to stem and sealing with latex membrane.

The paste was prepared at a water content sufficiently high to give enough plasticity to the paste and ensure good contact between the HCT and the xylem. Excessive water content was avoided due to the longer time that would have been required for the paste to equilibrate with the xylem water pressure. A latex membrane was used to seal the tensiometers on the stem and to avoid measurement errors due to localised evaporation from the paste (Fig. 9c).

5 Results

The xylem water pressure measurement was carried out for about 30 days. However, only the measurement carried over 2 days (from day 23 to day 25) is presented here. Day and night cycles were mimicked by switching on (from 6am to 8pm) and off (from 8pm to 6am) a growth lamp. As shown in Fig. 10, water pressure tends to decrease during day time (when stomata are open and evaporation is ongoing) and increase during night time (when the stomata tend to close and transpiration reduces significantly). The two High-Capacity Tensiometers show an excellent agreement with each other and, in turn, their measurement is consistent with the ones carried out using the transistor psycrometer and the pressure chamber on leaves excised from branches.

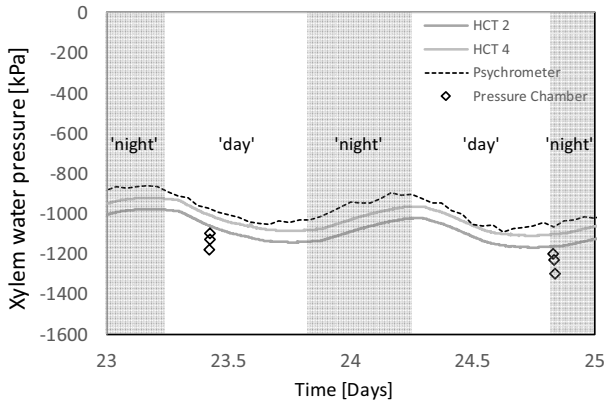


Fig. 10. Measurement of xylem water pressure using HCT2, HCT4, and transistor psychrometer (at 115 mm, 250 mm 400 mm above soil surface respectively) and pressure chamber (on leaves excised from tree branches).

6 Conclusions

The paper has demonstrated the use of High-Capacity Tensiometer (HCT) for measuring xylem water pressure in plants. The use of HCT on plants is a step change in the understanding and modelling the effect of plant transpiration on suction and moisture regime in a vegetated ground. HTCs have been used for more than 20 years in geotechnical engineering and this instrument is available in many research laboratories. Installing HCTs on stems and branches is quite straightforward and this will allow analysing the soil and the plant as a continuum in the same experimental setup rather than borrowing transpiration models developed by plant scientists for their specific applications.

Acknowledgements

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