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Research Article

An experimental comparison of silica gel and quartz sand grains as sediment media for growing vegetation at the laboratory scale

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Abstract. In this technical note we compare silica gel grains and quartz sand as sediment media for vegetation root growth in laboratory experiments for ecohydrology and ecohydraulics. Silica gel grains become quite transparent when saturated with water. This would be useful in order to non-invasively observe the rate of growth of plant roots and plan parallel laboratory experiments made in more typical sand sediments. In this work, we compare the results of preliminary tests conducted using quartz sand with the same grain size distribution of silica gel grains. We show that the complex microstructure of silica gel grains seems to influence the evaporation and, in turn, plant growth dynamics. The potential and limitations of the use of silica grains are accordingly discussed in light of more detailed experiments.

Key words. Silica gel; growth media; evaporation dynamics; microporosity; ecohydrology.

Introduction

Laboratory experiments have key roles to play in ecohydrological research investigating the interactions between riparian vegetation and river hydrology and morphodynamics (see Gran and Paola, 2001; Nilsson and Svedmark, 2002; Francis et al., 2005; Coulthard, 2005; Tal and Paola, 2007), in order to determine how vegetation may actively influence river systems and the implications this may have for river management, conservation and restoration (Corenblit et al., 2007; Hicks et al., 2007). Recent studies have addressed the role of plant root architecture in stabilising landforms and river morphology (Fitter and Stickland, 1992; Pollen, 2007; Docker and Hubble, 2008). Comprehensive laboratory experiments are then necessary for validating predicted relationships between the physical environment and plant root growth.

A long-standing limitation of laboratory experiments that involve examination or measurement of the rooting structures of plants is that the roots are covered by the growth medium. A range of techniques have been developed to attempt to address this limitation, ranging from growing plants in transparent containers and basing measurements on the visible portion of the root system (Berntsen, 1993), using transparent substrata without micro-porosity like small spherical glass beads (Futsaether and Oxaal, 2002), and whose effects of mechanical impedance on root growth have been investigated (Goss, 1977), to high-technology solutions such as the application of computed tomography (CT) scanning (Lontoc-Roy et al., 2006).

However, all of these methods have limitations. In transparent containers, much of the root remains hidden and destructive measurements of root systems

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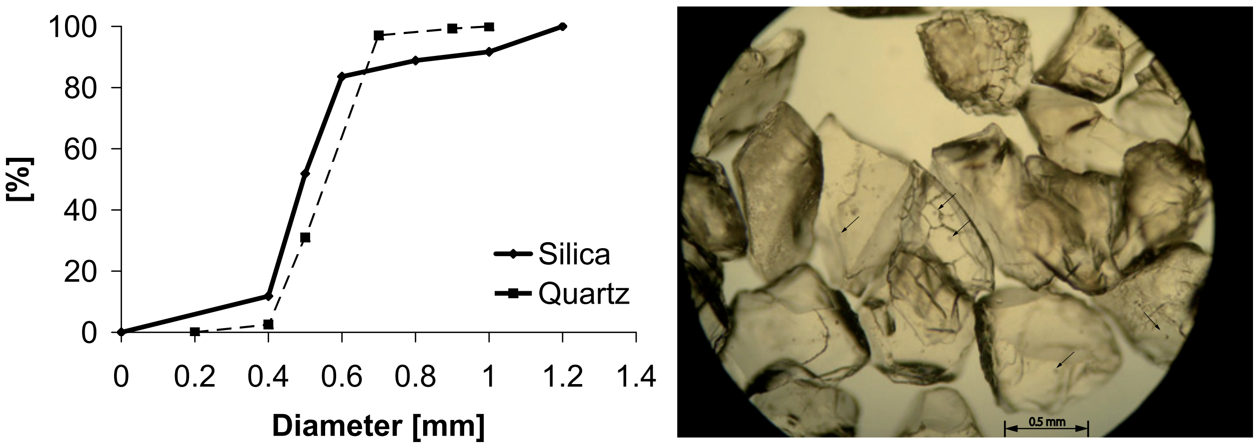

Figure 1. (Left panel) Grain size distributions of the silica gel grains and quartz sand samples selected in the experiments. (Right panel) Microstructure in the silica gel grains as seen under a common optical microscope (Nikon Eclipse 600). Arrows indicates cracks in the structure forming the microporosity that characterizes this material.

obtained via extraction are still common. Transparent substratum allow easy observation of roots under a variety of environments but do not expose the roots to the mechanical impedances experienced in soils. CT scanning technology requires highly specialized equipment, can be time-consuming, and can suffer from resolution and contrast problems. A fundamental step forward in improving laboratory experiments into root characteristics would be the possibility of growing vegetation in transparent material showing similar macroscopic characteristics to standard growth media (such as sand or soil).

In this paper we describe a number of experiments conducted with both synthetic silica gel grains and quartz sand in order to elect this material as a possible candidate for running parallel experiments in which the root status can be monitored over time. In particular, we first investigated the evaporation dynamics of silica gel and compared it to that occurring in quartz sand. Second, by growing plants within both silica gel and quartz sand, we obtained some initial measurements that allow us to ascribe the observed differences to the particular microporosity of silica gel grains.

Materials and methods

Common washed industrial quartz sand (Bernasconi AG, SB1-1.7) and silica gel grains (GRACE Davison, SP540-10364) with similar grain size distributions (Fig. 1) were selected as sediment media. Silica gel consists of sodium silicate that has been treated with an acid solution to form a colloidal solution of silicic acid. This is then heated under controlled conditions to form hard but highly porous grains (Tahat, 2001). This material is commonly used in a range of applications as an effective desiccant. Because of the similar grain size distribution, the samples of silica gel grains and quartz sand also show similar macrostructure and intra-grain porosity, both important to define the material volumetric porosity. However, the silica grains also show a characteristic microporosity due to cracks within the individual grains that affects their moisture-retention capacity (Fig. 1). A summary of the physical properties of the samples is given in Table 1.

Table 1. Physical properties of silica gel and quartz grains.

Material	d_{50} (mm)	d_{90} (mm)	Density (gcm^{-3})	Porosity
Silica grains	0.50	0.88	0.12	0.80
Quartz sand	0.56	0.68	0.40	0.44

Seeds of common *Avena sativa* L. were used to study how vegetation germinates and develops in both materials. This grass species is an alternative to others commonly used in laboratory experiments into eco-hydraulics (e.g., *alfalfa*) and it has recently been used in laboratory experiments described by Perona et al. (In revision). Avena sativa is a quick growing grass, which develops both primary and secondary roots within 2-3 days from seeding at a temperature of 18-20 °C. Then, the stem starts to appear and a characteristic 15-20 mm two-leafed branched structure will eventually grow within 8-10 days (Fig. 2). Interestingly, such plants grow up to their adult stage without the addition of nutrients, using only internal seed resources, provided that enough soil moisture is available.

Our two experiments (A and B) used a simple setup consisting of 1 transparent rectangular plastic

Table 2. Initial weights of the components related to sediment evaporation experiments: C1 represents the growth container 1, and so on. C1 and C2 were placed on the scale as controls for the evaporation dynamics, while C3 and C4 were planted with 10 seeds each, to determine how plant growth was affected by changes in sediment moisture.

Items (g)	C1 Quartz	C2 Silica	C3 Quartz and seeds	C4 Silica and seeds
Container weight	18.66	18.69	18.39	18.32
Sample weight	41.00	10.05	43.34	10.75
Dry seed weight	-	-	0.32	0.34
Water weight	11.29	20.38	11.42	21.51
Total weight	70.95	49.12	73.47	50.92

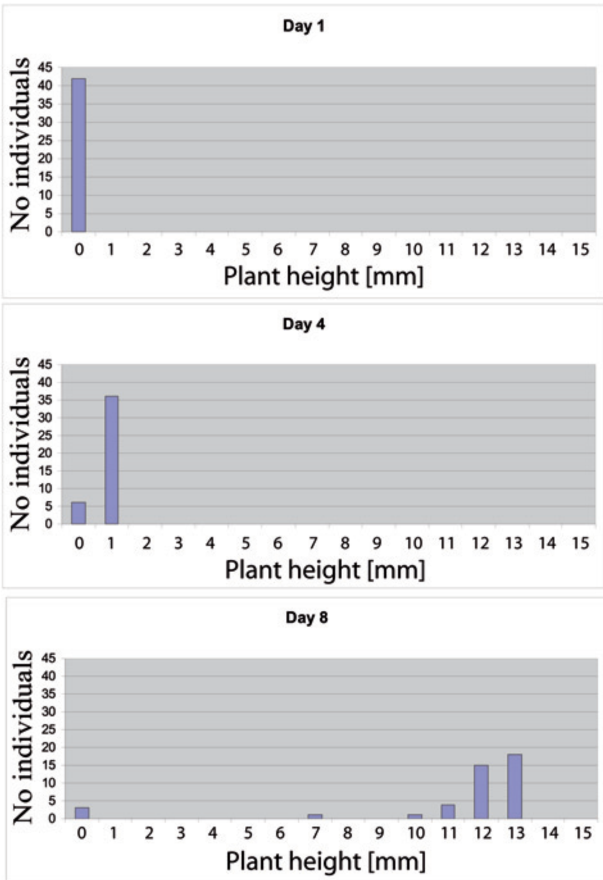

Figure 2. Growth dynamics of *Avena sativa* in quartz sand at about 19 °C. All seeds (40) correspond to a plant height of 0 mm at day 1. Then, they started growing leaves at day 4. Eight days after seeding nearly all seeds had germinated and reached a height of 11-13 mm.

box (87×28×37 mm), 4 cylindrical plastic containers (50 mm diameter; 13 mm height, hereafter referred to as growth containers), two electronic scales (OHAUS, 0.1mg-210g) complete with transparent protecting walls (20×20×32 cm), temperature button sensors (Omset Computer Corporation, S/N1235497), a desktop PC, and two beakers containing desiccant gel.

Experiment A. This experiment was conducted to test the transparency properties of the silica gel grains as far as the visibility of the root structure is concerned. The rectangular plastic box filled with silica gel grains was used for seeding the seeds at different distances from the front wall (5, 10, 15 mm, respectively) and at about 1 cm underneath the surface. As soon as seeds started to germinate and to produce roots, we took daily pictures of the box following saturation of the silica gel grains with water.

Experiment B. Two growth containers were filled with quartz sand and the other two with silica gel grains, resulting in a bulk density of 0.40 gcm^{-3} and 0.12 gcm^{-3}, respectively. For each growth medium only one container was seeded with *Avena sativa* (10 seeds), whereas the other container was used as a control for the evaporation dynamics. That is, only the container without seeds was put on the scale and its change in weight due to evaporation measured over time. In order to reduce the number of independent variables during the experiments, no nutrients were added to the sediment. Seeds were grown at room temperature of 21.5±1.5 °C. Both scales were connected to the computer, and the raw data corresponding to the sample weight was recorded over time. A temperature button sensor was placed inside the box and used to measure temperature. Finally, the beakers with desiccant gel were inserted within the boxes to keep the humidity inside the box approximately constant. A photograph of the setup with silica gel grains is shown in Figure 3. Also, the initial weights of components in the experiment are given in Table 2. We started the experiment by simultaneously and carefully saturating with water the corresponding sediment medium in all growth containers. This operation was only done once at the beginning of the experiment. After germination the plant stems were measured daily and the germinated plants were then carefully uprooted at the end of the experiment before plants died from water stress. The main root structure, the number of roots and the main root length were counted and their length measured as well at this time.

The experiments were repeated three times to increase confidence in the results.

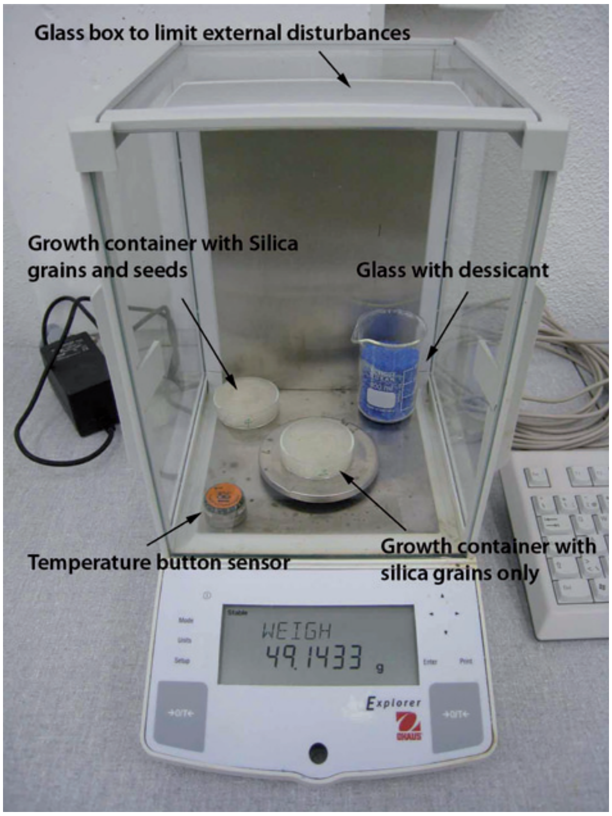

Figure 3. General arrangement of the experimental apparatus.

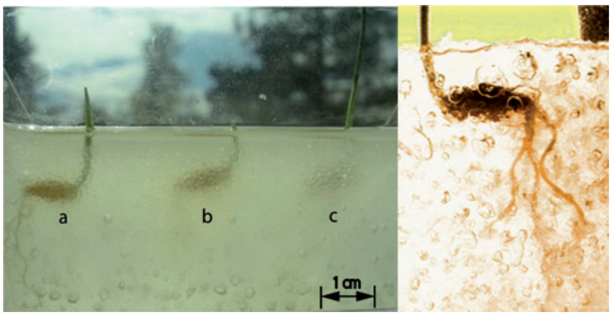

Figure 4. (Left) Detail of the root structure at different distances from the wall; (Right) Primary root branches of a plant sample within silica gel grains.

Results and discussion

Results of Experiment A are shown in Figure 4. In particular, the left panel shows that the spatial root structure is visible for plants (a) located near the front wall (5 mm). The right panel shows such a structure from a second experiment and after correcting both the brightness and contrast of the natural colors. This indicates that the transparency of saturated silica gel grains allows plant roots contained within to be clearly observed. However, the different light refraction index of water and silica gel reduces transparency dramatically when seeds are planted further away from the wall.

During Experiment B, we noticed that silica gel grains hosted much more water than quartz sand (i.e., 21.6g and 12g, respectively) to produce saturation (Table 2). This means that nearly 9.6g of water went stored into the cavities forming the microporosity of silica gel grains (Fig. 1), thus dictating an intrinsic different suction capacity of this medium. The role of this variable emerges from the results of Experiment B, which shows the change in the water content due to evaporation for both material samples (Fig. 5 Left). Apart from small fluctuations due to uncontrolled changes in the laboratory room temperature, such curves show a first phase (Phase 1) where the water content (in weight) of the samples decreases nearly linearly for both silica and sand, indicating a relatively constant average evaporation rate (Fig. 5 Right). Since we did not observe the negative exponential decrease that is well documented in the literature (Peter and Dani, 2008), this result indicates that evaporation practically proceeds at the potential rate in both media. We ascribe such a result to the rather high bulk porosity at both media (see Table 1) and the relatively small thickness (13 mm) of the sediment bed layer. The latter in particular being smaller than the characteristic length described (Peter and Dani, 2008).

The evaporation rate brings the water content in quartz sand down to zero in about 5 days. Interestingly, at this time, the water content in silica gel reached the value of about 9.6g, i.e., the water mass was stored in the grain cavities. From this time on, a second phase (Phase 2) starts for silica gel that is characterized by a nonlinear decrease, which suggests the onset of the evaporation process typically observed for compound soils. Eventually, silica gel would dry out nearly but not completely (i.e., the sample weight almost reaches the initial dry value) in 12 days. Our interpretation of this phenomenon cannot go further at this time than ascribing it to the documented presence of cracks (see Fig. 1) within grains. These cavities clearly augment the material's porosity, but because of their microscopic dimension they also affect the suction capacity, which is now strongly determined by capillary forces. Hence, in order to remove water completely from the inner cavities, more energy than the potential evaporation existing at room temperature is required. This explains why the water content decaying curve for silica gel approached but did not seem to reach 0 at the end of Phase 2 (Fig. 5).

The similar evaporation dynamics occurring in Phase 1 in the two sediment media would suggest that the two materials have similar mechanical impedance, and that vegetation can germinate and grow similarly

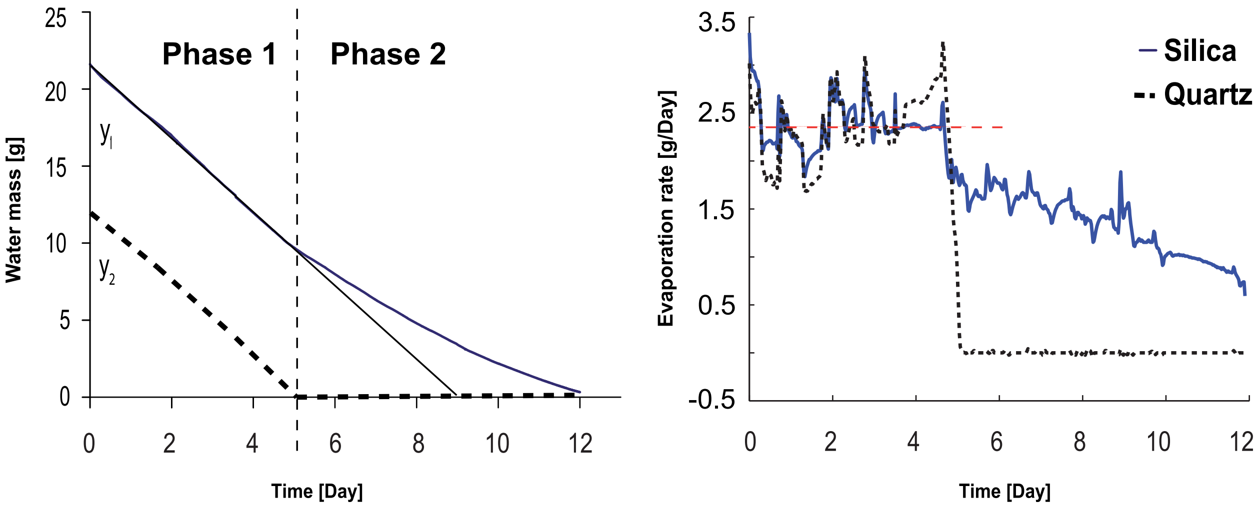

Figure 5. Comparison of moisture over time in both sediment media. (Left panel) Absolute water content in grain samples during evaporation; (Right panel) Average evaporation rates of both growth media.

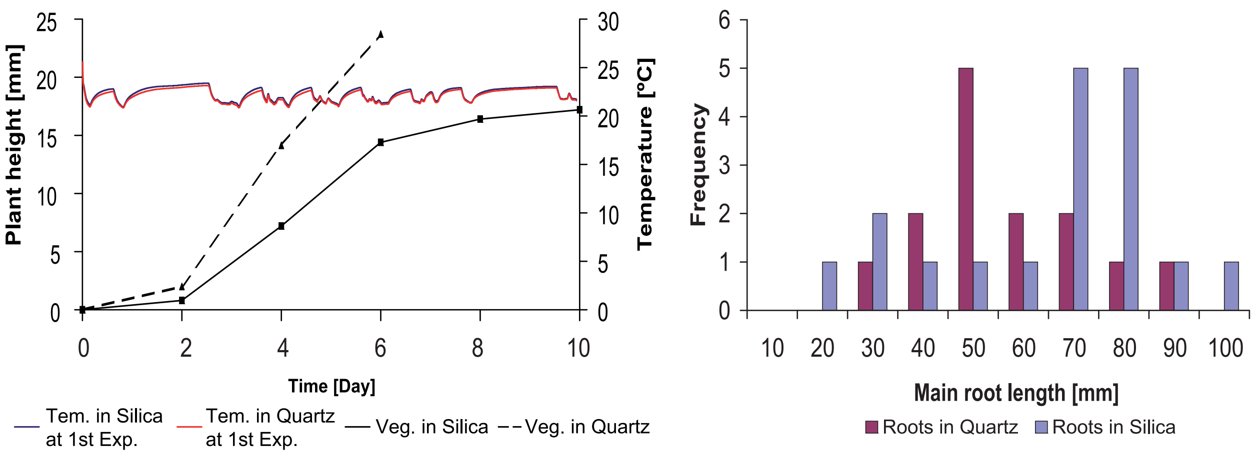

Figure 6. (Left panel) Comparisons of vegetation growth (average plant height) in both sediment media at nearly constant temperature conditions. (Right panel) Histogram of root dynamics of plants growing in both sediment media.

both in sand and in silica gel in this period of time. As well, the fact that silica gel holds more water and for a longer time suggests a longer survival time for vegetation in silica gel than in sand. However, Figure 6 shows that different vegetation growth rates resulted starting from the same seedling density (10 seeds per container) and same average room temperature. Seeds in quartz sand seemed to grow faster than those in silica gel grains. In total, 9 seeds germinated in the quartz sand, whilst only 8 seeds grew in the silica gel. The average plant height in the quartz grains reached 23.71 mm at day 6, after which plants died. The growing rate is somehow slower in silica gel grains, but vegetation kept growing until day 10 to an average height of 17.2 mm. This behaviour is therefore in accordance with the decreasing soil moisture curves described before. It also proves that water retention in both materials provided enough water for seed germination and growth in Phase 1. Figure 6 right shows the histograms of the main root length for both samples by collecting together all the results from three repeatable experiments that we performed at similar room temperature in the range of 21/23 °C. In general, a much more complicated root system was observed for the plants growing in the silica gel container, thus leading us to conjecture that water uptake from silica gel grains is somehow more difficult due to the increased suction capacity of this material. A final propositional comment concerns the role of light conditions, which of course could penetrate the silica gel medium and potentially influence growth dynamics. This variable was not controlled in our experiments and it would be an important aspect to investigate in forthcoming experiments.

Conclusions

In this paper, explorative experiments were described with the purpose of electing silica gel grains as a potential medium for growing vegetation and continuously monitoring its rooting status. This idea originates from silica gel's interesting property of becoming transparent when saturated with water.

At this point, and considering the evaporation dynamics that characterize Phase 1, one could conclude that the material is suitable for incorporating into experiments in ecohydrology and ecohydraulics. However, our results also confirm that root formation and consequent vegetation development is not only related to the sediment moisture dynamics. This aspect does not make possible a direct use of such a material unless further studies are conducted. In particular, interesting points for future investigations include clarifying the water uptake mechanism in relation to the suction capacity of silica gel when thicker sediment layers are used, as well as the role of penetrating light condition on the root growth dynamics.

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