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Research Article

Effects of Hydrogel Amendment to Different Soils on Plant Available Water and Survival of Trees under Drought Conditions

Dedicated to Aloys Hüttermann, to his honor and memory

The effect of super absorbent polyacrylate (SAP) hydrogel amendment to different soil types on plant available water (PAW), evapotranspiration and survival of *Eucalyptus grandis*, *Eucalyptus citriodora*, *Pinus caribaea*, *Araucaria cunninghamii*, *Melia volkensii*, *Grevillea robusta*, *Azadirachta indica*, *Maesopsis eminii* and *Terminalia superba* was investigated. The seedlings were potted in 3 kg size polythene bags filled with sand, loam, silt loam, sandy loam and clay soils, amended at 0 (control), 0.2 and 0.4% w/w hydrogel. The tree seedlings were allowed to grow normally with routine uniform watering in a glass house set up for a period of eight weeks, after which they were subjected to drought conditions by not watering any further. The 0.4% hydrogel amendment significantly ($p < 0.05$) increased the PAW by a factor of about three in sand, two fold in silt loam and one fold in sandy loam, loam and clay soils compared to the control. Similarly, the addition of either 0.2 or 0.4% hydrogel to the five soil types resulted in prolonged tree survival compared to the controls. *Araucaria cunninghammi* survived longest at 153 days, while *Maesopsis eminii* survived least (95 days) in sand amended at 0.4% after subjection to desiccation. Evapotranspiration was reduced in eight of the nine tree species grown in sandy loam, loam, silt loam and clay soils amended at 0.4% hydrogel. It is probable that soil amendment with SAP decreased the hydraulic soil conductivity that might reduce plant transpiration and soil evaporation.

Keywords: Drought; Hydrogel; Plant available water; Transpiration; Tree survival

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1 Introduction

Hydrogels, which were developed to increase the water holding capacity of amended media, have been used to aid plant establishment and growth in dry soils [1]. They have the potential to absorb water many times their weight, retain it and supply it to plant roots during water stress, thereby enhancing plant survival and growth [2 – 6]. The water absorbency of super absorbent polyacrylates (SAPs) depends on the degree of neutralization of monomer acid, the amount of initiator and the volume of polymerization mixture [7]. The addition of hydrogel to soils can improve not only its water holding capacity [1], but also the supply of plant available water [8, 9]. The addition of 4 – 6 g/kg of hydrogel to soil increased the available water content in sandyloam by a factor of 2.2 – 2.3, whereas in clay that factor was 1.1 – 1.2 [10, 11]. The plant available water (PAW) storage capacity of a soil provides a buffer which determines a plant's ability to withstand dry spells, hence its survival and growth [4 – 6, 12, 13]. An increase in plant available water of about 100% in sandy loam and loam soils when amended with hydrogels has been reported [6].

Most successful hydrogel studies have been conducted on sandy soils with a narrow range of tree species [4] and a few on sandy loam and loam soils using agricultural crops [6]. In a field trial by [14] to test tree survival and growth of *Eucalyptus grandis* clones grown on a hydrogel amended sandy clay loam soil, a highly significant ($p < 0.01$) interaction between hydrogel and water that had a positive impact on both transplant survival and growth was observed compared to water only treatments.

In spite of many success stories with hydrogel application, some responses of moisture requiring plants to hydrogels have been inconclusive and sometimes negative when used in field and container productions [11]. In a container production of *Betula pendula* (European birch), hydrogel addition into the medium showed reductions in the overall plant mass and the amount of available water in the plants [15]. The relative effectiveness of the hydrogels depends on its chemical properties, such as molecular weight, and it tends to have differing effects on various soil properties [11]. No studies have been done so far to compare hydrogel effects on a range

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Abbreviations: PAW, Plant available water; **SAP**, Super absorbent polyacrylate

Table 1. Analysis of the five soil types used in the experiment.

Parameter	Soil type				
	Sand	Sandy Loam	Loam	Silt loam	Clay
Sand (%)	88	56	40	38	24
Silt (%)	4	20	50	54	12
Clay (%)	8	24	10	8	64
CEC C mol/kg (me/100g Soil)	4.6	13.8	40.0	38.0	24.0
pH	5.6	6.9	4.5	4.6	6.0
O.M (%)	0.12	4.35	3.40	4.02	0.55
N%	0.01	0.22	0.15	0.19	0.05
Available P (ppm)	43.11	72.42	11.76	13.60	3.50
Ca (Me/100g soil)	1.2	7.5	2.6	2.4	6.2
Mg (Me/100g soil)	0.35	2.36	0.88	0.96	2.11
K (Me/100g soil)	0.10	0.87	0.26	0.22	0.35
Na (Me/100g soil)	0.04	0.06	0.09	0.08	0.12
FWC[a)] (%)	15	25	25	25	N/A
Saturated Hydraulic Conductivity[a)] (cm/h)	4.39	0.48	2.71	3.38	N/A
Bulk Density[a)] (g/cm^3)	1.63	1.41	1.51	1.54	–

a) Calculated using the Module program (Soil Hydraulic Properties based on the US Texture Triangle) [41].

of soil textural classes using a wide range of tree species, resulting in difficulties in making recommendations on specific hydrogel concentrations and tree species suitable for growing in different soil types under water stress conditions. This study aims at evaluating the effect of hydrogel amendment to a range of particle soil types (i. e., sand, sandy loam, loam, silt loam and clay) on soil water retention and plant available water as they affect the survival of a range of tropical and temperate tree species subjected to drought conditions in a green house experimental set up.

2 Materials and Methods

2.1 Materials

2.1.1 Plant Material

Four month old seedlings of *Eucalyptus grandis* (Blue gum), *Eucalyptus citriodora* (Lemon scented gum), *Pinus caribaea* (Caribbean pine), *Araucaria cunninghamii* (Hoop pine), *Melia volkensii* (Melia), *Grevillea robusta* (Silk oak), *Azadirachta indica* (Indian neem), *Maesopsis eminii* (Musizi) and *Terminalia superba* (Limba) were obtained from the tree nurseries of the National Forestry Resources Research Institute and the National Forestry Authority in Uganda. The choice of these species was based on their frequent use in plantations and also on their perceived economic value.

2.1.2 Soil and Mineral Analysis

Five different soil types representative of the whole spectrum of particle soil sizes ranging from sand to clay were obtained from known sites and a sieve analysis was performed. The loam and sandy loam soils used were dug up from Mubende at the Kiganda site and Nakasongola at Kikoiro, respectively, where hydrogel trials for plantation establishment are ongoing. The sand was obtained from a sand pit in Mukono, while the clay was obtained from typical clay soils used by Uganda Clays in Kajansi.

Soil samples of each of the five soil types (sand, sandy loam, loam, silt loam and clay) were air dried and sieved through a 2 mm sieve and oven dried at 80°C before elemental analysis. The pH was determined in water using a pH meter [16]. Total Nitrogen was determined using standard laboratory methods following [17]. Available P was extracted by the Bray method [18] and determined by the chloromolybdate blue color method. Exchangeable cations K, Mg, Ca and Na were determined after extraction by shaking for 2 h with 1 M ammonium acetate [17], and concentrations of Na and K were determined by a flame photometer and Ca and Mg by Atomic Absorption Spectrophotometry [18]. Table 1 shows the soil textural classes and some hydraulic properties of the five soil types that were used in the experiment.

2.1.3 Hydrogel

Luquasorb hydrogel manufactured by the BASF SE Chemical Company, Ludwigshafen, Germany was used as the soil amendment at the following concentrations: 0 (control), 0.2 and 0.4%. The 0.2 and 0.4% hydrogel concentrations were made by mixing 2 and 4 kg of hydrogel powder, respectively, with 1000 kg of soil in a concrete mixer. The control had no hydrogel added. The amount of hydrogel used and the mixing procedures followed past research experience [4, 19].

2.2 Methods

2.2.1 Experimental Procedure

Fifteen trees each of the nine selected species were planted in 3 kg pots filled with each of the 5 soil types amended with hydrogel at a concentration of 0.2, 0.4% and a control (no hydrogel added). The pot contents were weighed and placed in the green house in a completely randomized design. They were grown normally by watering with about 0.5 L of water 3 times a week for a period of 8 wk to ensure full establishment in the pots. This was indicated by the growth of new twigs and leaves. At this stage, the pot contents were watered to field capacity and weighed (W1). Field capacity was attained by immersing the pots with plants in a water tub for 24 h, and allowing excess water to drain gravimetrically. Drought conditions were simulated by not watering the trees any further, and the greenhouse was set to a relative humidity ranging from 50 – 90% and ambient temperature of about 25°C. The date (T1) when desiccation of plants was started was recorded, and the plants were monitored daily to identify when they died. Death of plants was monitored by observing on a daily basis the color change of leaves and branches from green to brown and grey. When all the leaves and stems turned brown and started shedding off, and branches becoming brittle, the plant was declared dead. Brittleness was checked by deliberately breaking a sample branch from a tree that appeared completely dry. At the point when each tree died, the pot contents were weighed (W2) and the date of death (T2) recorded.

2.2.2 Determination of Moisture Content and Water Holding Capacity of the Soils

Ten pots containing 3 kg of each soil type without plants but amended at 0, 0.2, 0.4% hydrogel were obtained and watered to field capacity. This was done by soaking the pots in a water tub for 24 h and letting excess water drain out gravimetrically from the perforated bottom of the pots. Each pot was weighed (W3) and put in a dry place. Their weight obtained by open air drying was monitored daily by weighing until they obtained a constant weight (W4). At this point, the remaining moisture content was determined by oven drying the soils in each pot at 105°C. The oven dry weight of the pots was also taken (W5). This gave data on the water holding capacity of the hydrogel amended and control soils without plants growing in it.

2.2.3 Determination of PAW

PAW was calculated as the difference in the weight of pots with plants at field capacity (W1) just before desiccation minus the weight of pots (W2) at death of the trees [10]. PAW was expressed in kg.

2.2.4 Determination of Evapotranspiration

Water loss through evapotranspiration by the plants was estimated as the weight loss of pots over the period that the plants survived since stoppage of watering. Thus, evapotranspiration by the plants was determined by dividing PAW in kg by the number of days the trees survived after subjection to drought conditions, i. e. (PAW/days survived). Determination of evapotranspiration by weighing pot contents was as according to [20].

2.2.5 Tree Survival

The time the trees survived after the initiation of drought conditions was calculated by subtracting the date of start of desiccation from the date of death of each individual tree, thus time taken in days was given by (T2 – T1). An average was then obtained for the 15 trees in a treatment block.

2.3 Data Analysis

Data on PAW and transpired water were subjected to Analysis of Variance (ANOVA) using the General Linear Model (GLM) procedure (SPSS Inc., Release 8.0, 1997) to determine the effects of hydrogel levels, soil types and the possible interaction between both factors on PAW and transpired water for each tree species. Differences between means of PAW and transpired water across the hydrogel levels and soil types were confirmed by Tukey's HSD test. Mean differences were regarded significant at $p = 0.05$.

3 Results

The results of PAW, tree survival and evapotranspiration of nine tree species grown in sand, sandy loam, loam, silt loam and clay soils amended with hydrogel are presented in Tabs. 2 – 6, respectively.

Table 2. PAW, tree survival and evapotranspiration of nine tree species in sand amended with hydrogel. Values in the same column followed by a different letter (a, b, c) are significantly different, and each value is the mean of 15 trees.

Tree species	Hydrogel Level	PAW (kg/pot)	Survival (days)	Evapotranspiration (kg/(pot day))
E. grandis	Control	0.552c	24	0.023b
	0.2%	1.048b	40	0.026a
	0.4%	1.593a	104	0.015c
G. robusta	Control	0.617c	27	0.023a
	0.2%	1.141b	74	0.015c
	0.4%	1.675a	104	0.016b
M. emimii	Control	0.576c	21	0.027a
	0.2%	1.197b	91	0.013c
	0.4%	1.144a	95	0.015b
M. volkensii	Control	0.552c	50	0.011c
	0.2%	1.089b	90	0.012b
	0.4%	1.566a	114	0.014a
P. caribaea	Control	0.558c	32	0.017b
	0.2%	1.160b	59	0.020a
	0.4%	1.588a	104	0.015c
T. superba	Control	0.488c	21	0.023a
	0.2%	1.017b	76	0.013c
	0.4%	1.624a	102	0.016b
A. indica	Control	0.497c	23	0.022a
	0.2%	1.112b	65	0.017b
	0.4%	1.548a	112	0.014c
A. cunninghamii	Control	0.687c	84	0.008b
	0.2%	1.091b	145	0.008c
	0.4%	1.643a	153	0.011a
E. citriodora	Control	0.559c	42	0.013b
	0.2%	1.085b	50	0.022a
	0.4%	1.520a	111	0.013b

3.1 Effect of Hydrogel Amendment in Sand

3.1.1 Evapotranspiration

Six of the nine tree species (*Eucalyptus grandis*, *Grevillea robusta*, *Maesopsis eminii*, *Pinus caribaea*, *Terminalia superba* and *Azadrachta indica*) had their evapotranspiration significantly reduced (almost twofold) when grown in sand amended with 0.4% hydrogel compared to the control (see Tab. 2). However, evapotranspiration values increased as hydrogel amendment increased for *Melia volkensii* and *Araucaria cunninghamii*, but was not changed for *Eucalyptus citriodora* (see Tab. 2).

3.1.2 Plant Available Water and Tree Survival

Amending sand with 0.4% hydrogel significantly ($p < 0.05$) increased the plant available water by about three fold in eight of the nine tree species (*Eucalyptus grandis*, *Grevillea robusta*, *Melia volkensii*, *Pinus caribaea*, *Terminalia superba*, *Azadirachta indica* and *Eucalyptus citriodora*) compared to the control. Amendment at 0.2% hydrogel had a significant two fold increase in plant available water in all the nine tree species compared to the control. Sand amendment at either 0.2 or 0.4% hydrogel registered prolonged survival for all the nine tree species compared to the control. *Araucaria cunninghammi* survived longest at 153 days while *Maesopsis eminii* survived least (95 days) in sand amended at 0.4% after subjection to desiccation.

Table 3. PAW, tree survival and transpiration of nine tree species in sandy loam amended with hydrogel. Values in the same column followed by a different letter (a, b, c) are significantly different, and each value is the mean of 15 trees.

Tree species	Hydrogel level	PAW (kg/pot)	Survival (%)	Evapotranspiration (kg/(pot day))
E. grandis	Control	0.872b	25	0.035a
	0.2%	0.904b	27	0.033b
	0.4%	1.025a	62	0.017c
G. robusta	Control	0.947b	22	0.043a
	0.2%	1.065a	51	0.021b
	0.4%	1.104a	61	0.018c
M. emimii	Control	0.813b	23	0.035a
	0.2%	0.885b	36	0.025b
	0.4%	0.920ab	42	0.022c
M. volkensii	Control	0.924c	38	0.024a
	0.2%	0.967b	50	0.019b
	0.4%	1.008a	62	0.016c
P. caribaea	Control	0.884a	39	0.023a
	0.2%	0.895a	42	0.021b
	0.4%	0.953a	44	0.022ab
T. superba	Control	0.922b	21	0.044a
	0.2%	0.955b	41	0.023b
	0.4%	0.961ab	42	0.023c
A. indica	Control	0.812c	25	0.032a
	0.2%	0.864b	50	0.017b
	0.4%	1.069a	114	0.009c
A. cunninghamii	Control	0.673b	57	0.012a
	0.2%	1.041a	106	0.010b
	0.4%	1.069a	115	0.009b
E. citriodora	Control	0.797a	22	0.036a
	0.2%	0.844a	27	0.031a
	0.4%	0.889a	39	0.023b

Table 4. PAW, tree survival and transpiration of nine tree species in loam amended with hydrogel. Values in the same column followed by a different letter (a, b, c) are significantly different, and each value is the mean of 15 trees.

Tree species	Hydrogel level	PAW (kg/pot)	Survival (%)	Evapotranspiration (kg/pot day))
E. grandis	Control	0.792c	21	0.038a
	0.2%	0.975b	35	0.028c
	0.4%	1.285a	41	0.031b
G. robusta	Control	0.901c	28	0.032a
	0.2%	1.048b	62	0.017b
	0.4%	1.324a	74	0.018b
M. emimii	Control	0.805c	20	0.040a
	0.2%	0.929b	27	0.034b
	0.4%	1.24a	39	0.032c
M. volkensii	Control	0.891c	36	0.025a
	0.2%	1.056b	42	0.025a
	0.4%	1.187a	59	0.020b
P. caribaea	Control	0.757c	29	0.026b
	0.2%	0.969b	39	0.025b
	0.4%	1.391a	44	0.032a
T. superba	Control	0.891b	24	0.037a
	0.2%	0.929b	39	0.024c
	0.4%	1.32a	44	0.030b
A. indica	Control	0.827c	25	0.033a
	0.2%	0.921b	32	0.029b
	0.4%	1.239a	36	0.034a
A. cunninghamii	Control	0.992c	68	0.015a
	0.2%	1.119b	86	0.013b
	0.4%	1.297a	103	0.013b
E. citriodora	Control	0.915b	29	0.032a
	0.2%	0.967b	36	0.027b
	0.4%	1.161a	42	0.028b

3.2 Effect of Hydrogel Amendment in Sandy Loam

3.2.1 Evapotranspiration

Eight of the nine tree species (*Eucalyptus grandis*, *Grevillea robusta*, *Maesopsis eminii*, *Melia volkensii*, *Terminalia superba*, *Azadirachta indica*, *Araucaria cunninghamii* and *Eucalyptus citriodora*) had their evapotranspiration significantly reduced by an average of 0.015 kg/(pot day) when grown in sandy loam amended with 0.4% hydrogel (see Tab. 3).

3.2.2 PAW and Tree Survival

The 0.4% hydrogel amendment significantly increased PAW in seven of the nine tree species except for *Pinus caribaea* and *Eucalyptus citriodora* (see Tab. 3). About 44% of the tree species had their plant available water increased with 0.2% hydrogel amendment. *Araucaria cunninghamii* and *Azadrachta indica* survived more days (115 and 114, respectively) than the other tree species in sandy loam amended at 0.4% hydrogel (see Tab. 3).

3.3 Effect of Hydrogel Amendment in Loam

3.3.1 Evapotranspiration

Eight of the nine tree species (*Eucalyptus grandis*, *Grevillea robusta*, *Maesopsis eminii*, *Melia volkensii*, *Pinus caribaea*, *Terminalia superba*, *Araucaria cunninghamii* and *Eucalyptus citriodora*) had their evapotranspiration significantly reduced on average by 0.0067 kg/(pot day) when amended with 0.4% hydrogel as compared to the control, but significantly increased for *Pinus caribaea* (0.026 ± 0.003 in 0.4% hydrogel compared to 0.032 ± 0.001 in the control) (see Tab. 4). The differences in evapotranspiration for *Azadrachta indica* were significant for the 0.2% hydrogel compared to the control, but insignificant when comparing the 0.4% to the control (see Tab. 4).

3.3.2 PAW and Tree Survival

There was a significant increase in PAW with increasing hydrogel concentration except for *Terminalia superba* and *Eucalyptus citriodora* in loam soil at 0.2% hydrogel amendment. Similarly, prolonged tree survival was observed with increasing plant available water, with trees surviving longest in the higher hydrogel amendments (see Tab. 4).

3.4 Effect of Hydrogel Amendment in Silt Loam

3.4.1 Evapotranspiration

Eight of the nine tree species had their evapotranspiration reduced by an average of 0.0068 kg/(pot day) when grown in silt loam amended with 0.4% hydrogel, except *Eucalyptus grandis* which had its evapotranspiration increased by both 0.2 and 0.4% hydrogel amendment by 0.004 and 0.003 kg/(pot day), respectively (see Tab. 5).

3.4.2 PAW and Tree Survival

There was a significant increase in plant available water with increasing hydrogel concentration except for *Pinus caribaea* and *Terminalia superba* in silt loam soil at 0.2% hydrogel amendment (see

Table 5. PAW, tree survival and transpiration of nine tree species in silt loam amended with hydrogel. Values in the same column followed by a different letter (a, b, c) are significantly different, and each value is the mean of 15 trees.

Tree species	Hydrogel level	PAW (kg/pot)	Survival (%)	Evapotranspiration (kg/(pot day))
E. grandis	Control	0.741c	23	0.032c
	0.2%	0.963b	27	0.036a
	0.4%	1.175a	34	0.035b
G. robusta	Control	0.941c	22	0.043a
	0.2%	1.075b	56	0.019b
	0.4%	1.397a	74	0.019b
M. emimii	Control	0.788c	21	0.038a
	0.2%	0.94b	25	0.038a
	0.4%	1.416a	41	0.035b
M. volkensii	Control	1.017c	44	0.023a
	0.2%	1.075b	50	0.021b
	0.4%	1.529a	90	0.017c
P. caribaea	Control	0.967b	27	0.036a
	0.2%	1.005b	39	0.026c
	0.4%	1.383a	43	0.032b
T. superba	Control	1.004b	26	0.039a
	0.2%	1.025b	32	0.032b
	0.4%	1.38a	42	0.033b
A. indica	Control	0.716c	25	0.029a
	0.2%	1.121b	62	0.018c
	0.4%	1.505a	75	0.020b
A. cunninghamii	Control	0.893c	62	0.014a
	0.2%	1.128b	93	0.012c
	0.4%	1.497a	112	0.013b
E. citriodora	Control	0.725c	21	0.035a
	0.2%	0.937b	27	0.035a
	0.4%	1.435a	44	0.033b

Tab. 5). Similarly, prolonged tree survival was in the order of increasing available water, with trees surviving longest in the higher hydrogel amendments (see Tab. 5).

3.5 Effect of Hydrogel Amendment in Clay

3.5.1 Evapotranspiration

Eight of the nine tree species (*Eucalyptus grandis*, *Grevillea robusta*, *Maesopsis eminii*, *Melia volkensii*, *Pinus caribaea*, *Terminalia superba*, *Azadrachta indica*, and *Araucaria cunninghamii*) had their transpiration significantly reduced by an average of 0.0065 kg/(pot day) when grown in clay amended at 0.4% hydrogel (see Tab. 6).

3.4.2 PAW and Tree Survival

There was no significant increase in PAW for *Azadrachta indica* and *Eucalyptus citriodora* at either 0.2 or 0.4% hydrogel amendment in clay (see Tab. 6). Considering the 0.4% hydrogel amendment, the shortest duration of tree survival was observed in clay soil in contrast to sand, sandy loam, loam and silt loam soils. Similarly, water retention with regard to hydrogel amendment was lowest in clay compared to the other soils (see Tabs. 2 – 6).

4 Discussion

The amount of additional water retention in the hydrogel amended soils was dependent on the soil type. In sand, amendment of 0.4% hydrogel increased PAW by almost three times, whereas the effect of hydrogel amendment was much lower in loamy soils and in clay (see Fig. 1).These results are different from the findings of Akhter et al. [6], where amendment with a polyacrylamide-acrylate gel increased PAW by about 100% in loam and sandy loam. At the same time, no significant difference was found in the water uptake of sand and loam for four different types of commercial SAPs [21]. For Superab A200, a significant difference was found between the increase in available water content in amended sandy loam and

Table 6. PAW, tree survival and transpiration of nine tree species in clay amended with hydrogel. Values in the same column followed by a different letter (a, b, c) are significantly different, and each value is the mean of 15 trees.

Tree species	Hydrogel level	PAW (kg/pot)	Survival (%)	Evapotranspiration (kg/(pot day))
E. grandis	Control	0.781b	20	0.039a
	0.2%	0.788b	28	0.028b
	0.4%	0.936ab	34	0.028b
G. robusta	Control	0.684c	23	0.030b
	0.2%	0.859b	27	0.032a
	0.4%	0.979a	64	0.015c
M. emimii	Control	0.651c	21	0.031a
	0.2%	0.669b	25	0.027c
	0.4%	0.769a	27	0.028b
M. volkensii	Control	0.720c	40	0.018b
	0.2%	0.875b	44	0.020a
	0.4%	0.979a	74	0.013c
P. caribaea	Control	0.695c	20	0.035a
	0.2%	0.759b	25	0.030b
	0.4%	0.903a	32	0.028c
T. superba	Control	0.608c	21	0.029a
	0.2%	0.74b	25	0.030a
	0.4%	0.848a	33	0.026b
A. indica	Control	0.769a	26	0.030a
	0.2%	0.816a	30	0.027a
	0.4%	0.884a	43	0.021b
A. cunninghamii	Control	0.82b	76	0.010a
	0.2%	0.823a	83	0.011a
	0.4%	0.937a	104	0.009b
E. citriodora	Control	0.716a	27	0.027b
	0.2%	0.704a	21	0.034a
	0.4%	0.729a	28	0.026b

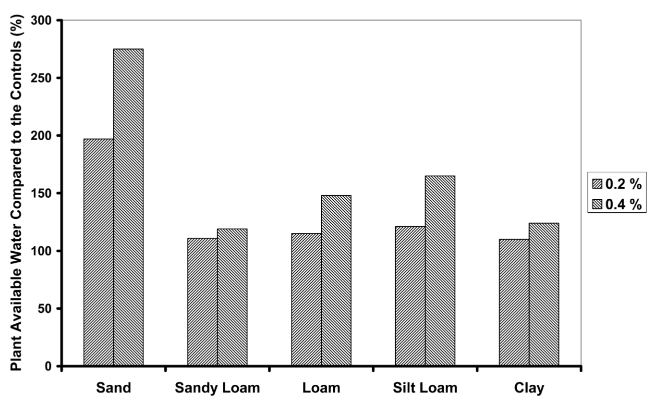

Figure 1. Plant available water in hydrogel amended soils compared to the control soils. The data shown are the means of the nine tree species planted in the different soils. The data are given as a percent of the control soils.

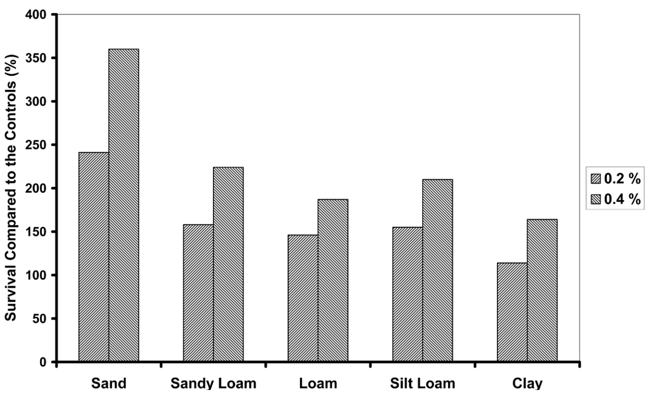

Figure 2. Survival of the trees in the different hydrogel amended soils compared to the controls. The data shown are the means of the nine tree species planted in the different soils. They are given as a percent of the survival of the trees in the control soils.

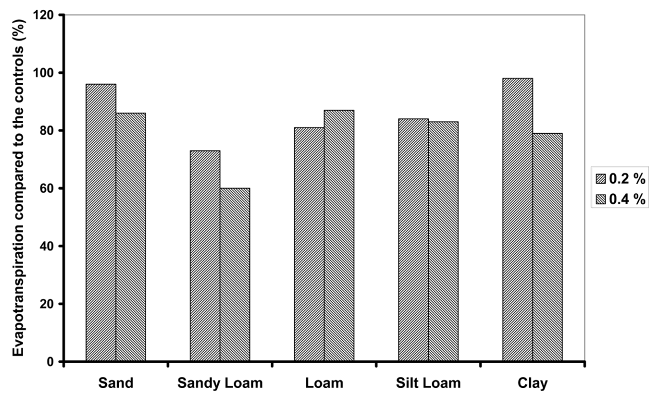

Figure 3. Evapotranspiration of the different hydrogel amended soils compared to control soils. The data are the means of the soils planted with the nine different tree species. The data are given as a percent of the control soils.

clay. The addition of 4 – 6 g/kg soil increased the available water content in sandy loam by a factor of 2.2 – 2.3, whereas in clay that factor was 1.1 – 1.2 [10, 11].

The reason for this discrepancy is probably due to the differences in the macromolecular design of the different gels [22]. It has been shown that the concentration of cross linkers in the gel determines the swelling of the gels [23]. The water absorbency of SAPs also depends on the degree of neutralization of monomer acid, the amount of initiator and the volume of polymerization mixture [7]. Since the chemical details of Luquasorb have not been published so far, it is not possible to discern the specific reasons for this unexpected result. The results for tree survival (see Fig. 2) are in agreement with earlier publications on the effect of SAPs on the survival of trees under water stress [4, 11, 24 – 27].

The average evapotranspiration was significantly reduced in most cases, with the 0.4% amendment with hydrogel having in almost all soil types a higher effect than the 0.2% amendment (see Fig. 3). In only a few cases (9%) did the 0.4% hydrogel treatment lead to more evapotranspiration than the control, e. g., *Melia volkensii* and *Araucaria cunninghamii* in sand (see Tab. 2), *P. caribaea* in loam (see Tab. 4) and *Eucalyptus grandis* in silt loam (see Tab. 5).

Comparing the increase in PAW due to the hydrogel amendments and the survival time of trees, it was clear that the survival time was positively correlated with the increase in PAW. In the case of *Maesopsis eminii* planted on sand, a twofold increase in PAW was found in pots containing 0.4% Luquasorb, whereas the trees growing on that substrate had a 4.5 fold longer survival under water stress during the desiccation period ($n = 15$, $r = 0.803$, critical value = 0.514) (see Tab. 2). The basis for that phenomenon is recorded in the last column of the same table. The rate of evapotranspiration was almost twofold lower in the trees growing on the hydrogel amended soils. The reduction of evapotranspiration was also recorded in the pots with clay, where only a small amount of water was stored in the hydrogel. Although the increase in PAW was rather low in most of the hydrogel amended soils (sand, sandy loam, loam silt loam and clay), a significant reduction of the evapotranspiration of up to 50% was found in eight of the nine tree species tested in sandy loam, loam, silt loam and clay soils (see Tabs. 3 – 6). Such a phenomenon has not yet been reported in the literature for hydrogel applications.

The physiological background of the reduction of evapotranspiration might be explained on the basis of hydraulic lift, hydraulic conductivity of the soil and the reaction of plants to partial root zone drying. Hydraulic lift is the nocturnal resupply of water in the upper soil layers which have been depleted during daytime [28]. This movement of water can go so far that even in trees water can move from the trunk via the roots back to the soil [29, 30] and the water may also be made available for neighboring plants [31, 32]. The hydraulic conductivity of the soil is influenced by the particle size distribution of the soil [32] and is a function of the soil texture [33]. Amendment with hydrogels decreases the hydraulic conductivity of soils [34].

Partial root zone drying (PRD) [35] is a technique where the roots of the plants are simultaneously exposed to both wet and dry zones. This results in the same productivity when compared to plants with full watering. The physiological explanation seems to be linked to the roots being exposed to dry zones that send abscisic acid to the leaves, thereby reducing the stomatal conductance [36] without changing the water status of the whole plant significantly. Originally developed for vineyards, this technique has so far proven useful for a variety of crops such as potatoes (*Ipomea batatus*) [37], tomatoes (*Solanum lycopersicum*) [38], oil seed rape (*Brassica napus*) [39], *Forsythia x intermedia* [40].

Based on the above observations, it can be said that the reduction in evapotranspiration of the trees growing on hydrogel amended soils was due to water storage in the soil matrix. During the day it was transpired by the plant into the air and during the night the soil sucked water back from the plant via the mechanism of hydraulic redistribution. By amending the soil with hydrogel, an additional system is incorporated into the soil which has both high water retention and a high water potential. An amendment with 0.4% hydrogel results in a hydrated hydrogel volume of about 10% with a particle size of up to 1 cm^3. Thus in these soils a significant heterogeneity with regard to its water potentials can be expected. Therefore, the water supply of the roots will be also heterogeneous with different water potentials and a patchy water supply from the root system. In these soils a similar situation is present as it is in the PRD system. The roots will send more abscisic acid into the shoot and leaves, indicating a localized drought thus reducing the transpiration of the leaf system compared to the control trees in spite of a good water supply.

It is worth noting that this study was conducted as a pot experiment under controlled conditions and hence its application in field conditions could be completely different. Studies have shown that the survival and early growth of young seedlings after establishment in the field is a key process for afforestation [1]. Observations have shown that the beneficial effects of hydrogel (Stockosorb K 410) normally last 3 – 5 years [1]. Since tree survival is normally critical in the first 1 – 2 years, hydrogel application could aid tree planting on marginal lands on a wide scale. Application of hydrogel for wide scale field planting needs to be assessed.

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