Effects of Hydrogels on Tree Seedling Performance in Temperate Soils before and after Water Stress

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ABSTRACT

Super Absorbent Polyacrylate (SAP) hydrogels absorb and store water thereby aiding plant establishment when incorporated in the soil. The effect of cross-linked SAP hydrogel amendment on the performance of tree seedlings of Pinus sylvestris and Fagus sylvatica grown in temperate soils under water stress and non-water stress periods was investigated in a greenhouse. The objective was to compare the root and shoot biomass of seedlings of the three species grown in sand, loam and clay soils amended with 0.4% w/w hydrogel in non water stress conditions as well as survival, root and shoot biomass after subjection to water stress. The seedlings were grown for 16 weeks, harvested and shoot as well as root biomass determined before water stress. The seedlings were also subjected to water stress and their biomass assessed at death following the water stress. The results showed that root and shoot biomass were generally higher in hydrogel amended soils compared to the controls. Root and shoot biomass of Fagus sylvatica was lower compared to Pinus sylvestris and Pinus abies before water stress. The 0.4% hydrogel amendment significantly increased species’ survival in the different soils studied. Although root biomass was higher in hydrogel amended sandy soil compared to other soils, P. sylvestris and F. sylvatica shoot biomass were higher in hydrogel amended clay and loam soils compared to the sandy soil after water stress. Biomass was higher in sand compared to loam and clay soils under non-water and water stressed conditions. Since SAP hydrogel amendment improved the survival and biomass production of tree seedlings before and after water stress, use of SAPs could be promoted to enhance seedling production in water stress and non-water stress environments.

Keywords: Desiccation; Non-Water Stress; SAPs; Soil Amendment; Tree Species

1. Introduction

Water scarcity is a challenge to agriculture and plantation forestry in many parts of the tropical and temperate regions in the world. Water saving technologies that enhance plant establishment and growth in soils of different properties are required. Soils generally differ in moisture content, temperature and mineralogy [1] which may require different soil moisture conservation technologies. One available technology is the use of super absorbent hydrophilic polymers [2]. Super absorbent polymers (SAPs) are substances that can retain large quantities of water and nutrients when incorporated in the soil, making it available for plant growth whenever required. They can be linear or cross-linked hydrogels [3] based on the structure of the cross-linking agents. This study focused on the latter type that has a relatively higher water absorption capacity compared to the former. The soil water and nutrients stored in SAPs are released gradually for plant growth under water limiting conditions [4,5] whereas under non-water limiting conditions, they are reported to enhance nutrient uptake for plant growth [3].

Different soils and tree species exhibit varying responses to SAP hydrogel amendment. Several studies have shown that addition of hydrogels to growing media increased water holding capacity by up to 400% [6] and decreased water stress by delaying the onset of wilting.
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In water-stressed soils for instance, prolonged survival and improved growth have been recorded under drought conditions [8-12] and in sandy desert soils [13]. SAPs were reported to increase tree species survival and reduce evapo-transpiration in different soils under drought conditions [14]. Improved growth has also been reported in seedlings grown in well watered sandy soil [15] as well as tropical soils [16].

Since the effects of SAP hydrogels on trees grown in temperate soils and specifically under non-water stress conditions are not known, it is necessary to understand the behaviour of SAPs in a wide range of soils in order to recommend which trees for what type of soils. Most studies on hydrogel application have been conducted on sandy soils [17-22] with less attention to loamy and clayey soils. Thus, the behavior of hydrogels in the latter soils remains largely unexplored and could potentially limit their application over a wide range of agro-ecological zones. This study therefore investigated tree seedlings performance in temperate soils before and after water stress. The objective of the study was to compare survival and biomass of seedlings of the following tree species (Picea abies (L.) (H. Karst.) (Spruce), Pinus sylvestris L. (Pine) and Fagus sylvatica L. (Beech)) in temperate soils amended with SAPs before and after water stress. The following hypotheses were tested: 1) Hydrogel amendment increases the biomass of tree seedlings in sandy, loamy and clayey soils before water stress, 2) Hydrogel amendment prolongs the survival time of tree seedlings in sandy, loamy and clayey soils exposed to drought and 3) There is no difference in tree biomass between hydrogel amended soils before and after subjected to water stress.

2. Materials and Methods

2.1. Soils

Sand, loam and clay soils were used in the study. The sand was obtained from a sand pit in Schöningen (Longitude 9°40’0” E Latitude: 51°38’0” N) in the Solling Mountains close to Göttingen, Germany. The loam soil was sampled from the field of the Institute for Tropical Agriculture, Georg August University Göttingen (Longitude 9°56’2” E Latitude 51°32’1” N). The clay soil was collected from the forest at the clay factory in Göttingen. Samples of the soils were collected from 30 cm deep 10 m × 10 m pits and separately mixed into one composite sample each of about 2 kg at the Fakultät für Forstwissenschaften und Waldökosysteme, Soil science laboratory, Georg August University.

All samples were air dried, sieved through a 2 mm sieve, oven dried at 80°C for 72 hours and their chemical characteristics analyzed. A pH meter was used to determine the soil pH [23] while organic C and N were determined by the Walkley-Black [24] and Kjeldahl [25] methods. Available phosphorus was analyzed using the Bray method [26,24]. Exchangeable cations (Ca²⁺, Mg²⁺, K⁺ and Na⁺) were extracted by shaking the soil sample for 2 hours with 1 M Ammonium acetate [27]. Concentrations of K and Na were then determined by a flame photometer whereas Ca and Mg were determined by Atomic Absorption Spectrophotometry [26]. The characteristics of the soils are presented in Table 1.

2.2. Plant Material

Six month old seedlings of Picea abies (Spruce), Pinus sylvestris (Pine) and Fagus sylvatica (Beech) obtained from a commercial tree nursery in Göttingen Germany were used in the experiment. The seedlings were healthy and free from pests and diseases. These species were chosen because they are widespread in Europe, are found in a large range of ecological conditions and have economic value. Picea abies for example, is one of the most common and economically important coniferous species in Europe and Scandinavia and tolerates acidic soils although it is not well suited for dry or nutrient deficient soils [28]. Pinus sylvestris is native to Europe and Asia. It is an important plantation forestry tree that is used to reforest degraded coal mines and burned sites. Seedlings of Pinus sylvestris establish best in soils with adequate moisture and some shade. Survival is best when the seedlings are planted on microsites close to the tops of hills, and lowest in overly moist depressions. Fagus sylvatica, the European Beech or Common Beech, is a deciduous tree that grows well in almost any type of soil. However, it grows best in fairly humid areas with well-drained soils found on moderately fertile ground, calcified or lightly acidic.

2.3. Hydrogel

Luquasorb hydrogel manufactured by the BASF SE Chemical Company, Ludwigshafen, Germany was used to amend the different soils at 0.4% hydrogel concentra-

### Table 1. Chemical characteristics of the soils used in the experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sand</th>
<th>Loam</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>4.37</td>
<td>6.20</td>
<td>5.80</td>
</tr>
<tr>
<td>Carbon (%)</td>
<td>0.06</td>
<td>0.70</td>
<td>0.40</td>
</tr>
<tr>
<td>Nitrogen (%)</td>
<td>0.01</td>
<td>0.21</td>
<td>0.12</td>
</tr>
<tr>
<td>Available Phosphorus (ppm)</td>
<td>9.81</td>
<td>14.80</td>
<td>10.14</td>
</tr>
<tr>
<td>Calcium (Meq/100g soil)</td>
<td>1.47</td>
<td>3.00</td>
<td>1.82</td>
</tr>
<tr>
<td>Magnesium (Meq/100g soil)</td>
<td>0.33</td>
<td>0.93</td>
<td>1.03</td>
</tr>
<tr>
<td>Potassium (Meq/100g soil)</td>
<td>0.08</td>
<td>0.32</td>
<td>0.25</td>
</tr>
<tr>
<td>Sodium (Meq/100g soil)</td>
<td>0.06</td>
<td>0.12</td>
<td>0.15</td>
</tr>
</tbody>
</table>
tion. The control had no hydrogel added. The 0.4% hy-
drogel concentration was made by mixing 4 kg of hy-
drogel powder with 1000 kg of soil prepared in a con-
crete mixer (Mini Concrete Mixer, Model: CM 180-MZ2;
Mixing capacity 180 L). The amount of hydrogel and the
mixing procedure followed previous studies [4] and rec-
ommendations by the manufacturer.

2.4. Treatments and Experimental Design

Thirty five seedlings each of *Picea abies*, *Pinus sylves-
tris* and *Fagus sylvatica* were transplanted into 3 kg
polythene pots each filled with sand, loam and clay soils
amended at either 0.4% hydrogel or a control (no hy-
drogel amendment). Altogether this made 18 treatment
combinations in a Randomized Factorial Design i.e.
(Sand + hydrogel × 3 tree species, Sand + control × 3
tree species; Loam + hydrogel × 3 tree species, Loam +
control × 3 tree species; Clay + hydrogel × 3 tree species,
Clay + control × 3 tree species). Each of the 18 treatment
combinations of seedlings in hydrogel amended or un
amended soils were randomly placed in a green house
and maintained at 25°C - 32°C and relative humidity of
50% - 95%. Depending on whether or not the soils were
saturated, the plants were watered for at least once a day
for 16 weeks until they were established. Proper estab-
lishment was indicated by the growth of new leaves or
needles and twigs.

2.5. Determination of Biomass before Water
Stress

After 16 weeks, the seedlings were watered to field ca-
pacity (when the water settled on the soil surface and
drainage became negligible). This ensured complete hy-
drogel expansion and soil saturation. Ten seedlings in
each treatment combination were harvested and cut into
two parts-roots and shoots, oven dried for 72 hours, then
weighed using a sensitive Sartorius weighing scale
(Model ED 8201-CW Extend Precision balance 8200 ×
0.1 g) to obtain the dry weight after water stress.

2.6. Determination of Survival and Biomass
after Water Stress

The remaining 25 were subjected to water stress by com-
plete termination of watering and monitored daily to ob-
serve initiation of wilting, desiccation and death. The
start date of desiccation was recorded (T1). The date
when a seedling died was recorded (T2). The seedlings
were monitored until the color of the stems, leaves,
branches and/or needles changed from green to brown or
grey. A plant was recorded as dead when all the leaves
and stems turned brown and started falling off as branch-
es became brittle. Brittleness was ascertained by break-
ing a sample branch which fell off confirming the brittle-
ness. Roots and shoots were also oven dried for 72 hours,
weighed using a sensitive Sartorius weighing scale
(Model ED 8201-CW Extend Precision balance 8200 ×
0.1 g) to obtain the dry weight after water stress.

2.7. Data Analysis

One-way Analysis of variance (ANOVA) was used to
test the effect of the factors (hydrogel and soil types) on
survival time and biomass production each tree species at
*p* < 0.05 in SPSS version 16. The mean root and shoot
biomass across hydrogel levels were compared between
soil types using paired *t*-tests. Biomass before and after
desiccation was also compared using paired *t*-tests. All
tests were carried out at *p* < 0.05 level of significance.

3. Results and Discussions

3.1. Effect of Hydrogel on Biomass in Non-Water
Stressed Soils

Root and shoot biomass of the three species were gener-
ally higher in hydrogel amended soils compared to the
controls. However, *Fagus sylvatica* root and shoot bio-
mass were generally lower than for *Picea abies* and
*Pinus sylvestris* in hydrogel amended soils (Figure 1).
Overall, root biomass was generally higher in hydrogel
amended sandy soil compared to other soils. In the case of
*P. sylvestris* and *F. sylvatica*, however, shoot biomass
was higher in hydrogel amended clay and loam soils
compared to the sandy soil (Figure 1).

These findings confirm that SAP hydrogel amend-
ments improve tree growth performance in non-water
stressed temperate soils. Hydrogel induced biomass re-
sponses between species and soils in this study concur
with those obtained from greenhouse experiments on
tropical soils in Uganda [16]. Differences in the species’
biomass accumulation responses to hydrogel amend-
ment for instance, the generally lower biomass of *Fagus sylva-
tica* relative to *Picea abies* and *Pinus sylvestris* could be
attributed to the different soil moisture requirements of
tree species caused by genotypic differences between the
species. Considering that soils with higher Cation Ex-
change Capacity (CEC) have the capacity to retain plant
nutrients better [29], the increase in biomass when water is
not limiting is possibly a result of improved nutrient
availability to the plants, following SAP hydrogel ap-
plication. It is possible that incorporation of hydrogels to
soils provided additional adsorption of cations to the
negative charges thereby increasing the soil base satu-
rion hence enhancing biomass.

The relatively high root biomass in hydrogel amended
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Figure 1. Root and shoot biomass responses of tree seedlings of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica* to hydrogel amendment in different soils before water stress. Each value is the mean of 5 plants. Different letters in the same bar cluster show significant differences.

sandy soil compared to other soils is related to the low water retention capacity of loam and clay soils. Divalent cations in soils (e.g. $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$) can destroy the polymer lattice of hydrogels thus diminishing water retention by the gel [18]. Hydration of gels in the presence of divalent ($\text{Ca}^{2+}$ and $\text{Mg}^{2+}$) and monovalent ($\text{K}^+$ and $\text{NH}_4^+$ at 20 meq. per liter) cations reduces from 10% and 20% mM [30]. The relatively high levels of these elements in loam and clay soils relative to sand (Table 1) therefore partly explain the observed biomass differences. However, the effect of calcium and magnesium cations on water absorption by loam and clay soils was not specifically investigated.

3.2. Hydrogel Effect on Seedling Survival and Biomass in Water Stressed Soils

Survival time of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica* seedlings significantly increased in the 0.4% hydrogel amended sand, loam and clay soils compared to the controls (Figure 2). In hydrogel amended soils survival was 66, 71 and 57 days more in sand, 8, 11 and 3 days more in loam and 17, 3 and 4 days more in clay soils respectively for *Picea abies*, *Pinus sylvestris* and...
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Figure 2. Survival time after water stress of selected tree seedlings grown in different soils amended with hydrogel. Each value is the mean of 5 plants. Error bars indicate standard error of the mean.

Fagus sylvatica seedlings compared to the controls. Species’ root and shoot biomass was generally higher in hydrogel amended soils compared to the controls (Figure 3).

The higher duration of species’ seedling survival, root and shoot biomass responses in hydrogel amended soils compared to the controls, confirm that SAP hydrogel amendment improves survival and tree growth performance in water stressed temperate soils. Hydrogels enhance the water holding capacity of soils and thus provide supplementary plant available water to plant root zones in dry soils [13,31]. Whereas biomass was higher in hydrogel amended soils compared to the controls, the effect was higher in sand compared to loam and clay (i.e. overall, hydrogel had a marginal effect on root biomass in clay and loam soils). Our results on improved survival time, root and shoot biomass growth during water stress conditions agree with previous studies in different media, [11,32,33,34]. Despite the differences (e.g. in water retention) between hydrogel amended temperate soils [35], the relatively higher root and shoot biomass responses for P. abies and P. sylvestris compared to F. sylvatica may be explained by the genotypic differences between tree species [36]. Earlier studies (e.g. [18,36] report similar different plant responses to hydrogel treatments in drought stressed soils). The magnitude of increase in biomass following hydrogel amendment may be attributed to the differences in strategies of species in responding to water stress [37,38]. Although prolonged water stress inhibits plant growth through its effects on physiological processes such as CO2 assimilation [11] hydrogel amendment improves the photosynthetic rate, root growth, reducing CO2 assimilation and stomatal conductance inhibition caused by water stress [11]. It is thus likely that the species used in this experiment, strategically partitioned resources in response to water stress; with for instance Picea abies and Pinus sylvestris dramatically developing more root and shoot biomass, whereas Fagus sylvatica reduced root biomass. This is especially beneficial in dry environments where more root growth implies increased capacity to absorb the scarce water resources whereas increased shoot growth means a larger leaf area for photosynthesis with more growth [39] and enhanced water use efficiency. Hydrogel amended sandy soils have a higher water retention capacity [2,14]. It is also possible that large pore spaces in sandy soils allow more swelling of the hydrogel thereby providing more supplementary water available for plant growth compared to the loam and clay soils.

3.3. Change in Biomass during Water Stress

Total biomass (root and shoot) in hydrogel amended soils ranged from 5 to 45 times higher in hydrogel amended soils when compared to the controls after subjecting trees to water stress (Figure 4). However, total biomass gen-
Figure 3. Responses of different tree species to hydrogel amendment during water stress conditions. Each value is the mean of 5 plants. Different letters in the same bar cluster are significantly different.

erally reduced following water stress although some increases were recorded in hydrogel amended sand and loam soils (Figure 4).

Changes in total biomass for the species in hydrogel amended soils are signals of physiological adjustments to water stress. This partly accounts for the observed biomass increases in sand and loam soils amended with hydrogel during desiccation. Reduced biomass in hydrogel amended soils appears to be related to the ability of hydrogels to delay drought stress effects [33]. However, the fact that hydrogels enhanced total biomass in different soils before and after desiccation, implies that hydrogels can be applied in soils with different moisture contents (i.e. from dry to saturated at field capacity).

4. Conclusion

In conclusion, hydrogel amendment increased tree seedling root and shoot biomass of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica* seedlings in sand, loam and clay soils in non-water stressed soils. Under water stressed conditions, hydrogel amendment prolonged the species’ survival and improved biomass in sandy soils compared to other soils. Species’ biomass generally reduced the following water stress. Such effects of SAPs
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Figure 4. A comparison of the effect of hydrogel on total biomass (root and shoot) of selected species in different soils before and after desiccation. Each value indicated on the bars is the mean of 5 plants.

be used to promote tree seedling production and planting programmes especially in water stress and non-water stress environments.

5. Acknowledgements

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REFERENCES


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