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## Communication

# Amending Soils with Hydrogels Increases the Biomass of Nine Tree Species under Non-water Stress Conditions

The classical aim of the application of super absorbent polyacrylate (SAPs) hydrogels is the prolonging of plant survival under water stress. Their effect on plant growth during non-water stress conditions is not known. This study examined the root and shoot biomass of seedlings of nine tree species; *Eucalyptus grandis*, *Eucalyptus citriodora*, *Pinus caribaea*, *Araucaria cunninghamii*, *Melia volkensii*, *Grevillea robusta*, *Azadirachta indica*, *Maesopsis eminii* and *Terminalia superba*. The seedlings were potted in five soil types; sand, sandy loam, loam, silt loam and clay. These were amended at two hydrogel levels: 0.2 and 0.4% w/w and grown under controlled conditions in a green house. Root and shoot growth responses of the seedlings were determined by measuring the dry weight of the roots, stems, leaves and twigs. The addition of either 0.2 or 0.4% hydrogel to the five soil types resulted in a significant increase of the root dry weight ( $p < 0.001$ ) in eight tree species compared to the controls after 8 wk of routine watering. Also, the dry weight of stems and leaves and twigs were significantly ( $p < 0.001$ ) higher in the nine tree species potted in hydrogel amended soil types than in the hydrogel free controls. These results suggested that hydrogel amendment enhances the efficiency of water uptake and utilization of photosynthates of plants grown in soils which have water contents close to field capacity.

**Keywords:** Biomass; Hydrogels; Nine tree species; Non-water stress; Soil types; Super Absorbent Polyacrylate (SAPs)

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## 1 Introduction

Water is the most important soil physical factor that affects plant growth and quantification of such growth (e.g., height, biomass) is relevant for the understanding of the plant-water relationship [1]. Roots conduct water, nutrients, provide mechanical support to plants and are the primary sensors of water stress [2]. Roots are dependent on shoots for carbohydrates as shoots depend on roots for water and nutrients [2]. Optimum growth of plants depends on an efficient balance in the functions of roots and shoots [2]. A developed root system determines plant growth and survival in any soil type because rapid root development enhances lateral and vertical access of water in the layers of soil. The use of hydrophilic polymer (hydrogel) amendments is one known method of supplying additional water to plants (e.g., [3–11]) by increasing the stored water in the root zone for use by the plant.

Hydrogels maintain a conductive soil environment that facilitates water and nutrient absorption for plant root and shoot growth

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**Abbreviations:** ANOVA, Analysis of variance; CEC, Cation exchange capacity; SAP, Super absorbent polymers

in periods of water stress. The highly cross-linked polyacrylamide hydrogels (Super Absorbent Polymers (SAPs)) that can absorb and hold up to 400 times their weight of water [6, 11, 12] aid tree establishment in various media including degraded and polluted soils where water retention and root development are reduced [11].

Highly cross-linked hydrogels have been shown to favor good tree root development [6] and improve root growth during water stress conditions [6, 13–16]. It has been shown that hydrogels also increase root growth under saline conditions [17]. Experiments on the effects of hydrogels on plant growth indicate increased shoot biomass in terms of root collar diameter, height and number of leaves [14, 16, 18] under water stress conditions. It was found for the Hot-Dry Valleys in Yunnan, China, that several tree species had higher growth in hydrogel amended soils [19]. Increased root growth of *Photinia fraseri* plants in hydrogel amended media was shown during irrigation [20]. Increases in growth were also reported in citrus seedlings grown in well watered hydrogel amended sand soil [21]. Hydrogel induced plant growth under water stress conditions in sand, sandy loam and loam soils has been demonstrated for several tree species (e.g., [6, 7, 9, 22]).

However, the effects of SAPs on the biomass of a wide range of trees species in soils of different particle sizes has not yet been comprehensively studied under non-water stress conditions. In this study, the effects of different levels of hydrogels on the root and

**Table 1.** Soil analysis.

| Soil Parameters            | Soil Types |                 |       |           |      |
|----------------------------|------------|-----------------|-------|-----------|------|
|                            | Sand       | Sandy Clay Loam | Loam  | Silt Loam | Clay |
| Textural Class             |            |                 |       |           |      |
| Sand (%)                   | 88.0       | 56.0            | 40.0  | 38.0      | 24.0 |
| Silt (%)                   | 04.0       | 20.0            | 50.0  | 54.0      | 12.0 |
| Clay (%)                   | 08.0       | 24.0            | 10.0  | 08.0      | 64.0 |
| pH                         | 5.6        | 6.9             | 4.5   | 4.6       | 6.0  |
| Organic Matter (%)         | 0.12       | 4.35            | 3.40  | 4.02      | 0.55 |
| N (%)                      | 0.01       | 0.22            | 0.15  | 0.19      | 0.05 |
| Available Phosphorus (ppm) | 43.11      | 72.42           | 11.76 | 13.60     | 3.50 |
| Ca                         | 1.2        | 7.5             | 2.6   | 2.4       | 6.2  |
| Mg                         | 0.35       | 2.36            | 0.88  | 0.96      | 2.11 |
| K                          | 0.10       | 0.87            | 0.26  | 0.22      | 0.35 |
| Na                         | 0.04       | 0.06            | 0.09  | 0.08      | 0.12 |
| CEC (cmol/kg)              | 4.6        | 13.8            | 8.5   | 9.5       | 12.2 |

shoot biomass of nine different tree species growing on five different tropical soils under non-water stress conditions has been investigated.

## 2 Materials and Methods

### 2.1 Plant Material

Seedlings of four month old *Eucalyptus grandis* (Blue gum), *Eucalyptus citriodora* (Lemon scented gum), *Pinus caribaea* (Caribbean pine) and *Araucaria cunninghamii* (Hoop pine), three month old *Grevillea robusta* (Silk oak), five month old *Melia volkensii* (Melia), *Azadirachta indica* (Indian neem), *Maesopsis eminii* (Musizi), and *Terminalia superba* (Limba) were used. These species were selected based on their availability, fast growth, environmental and commercial value, both on farms and large scale forest plantations. The seedlings were obtained from the tree nurseries of the National Forestry Authority and National Forestry Resources Research Institute in Uganda.

### 2.2 Soils

Five soil types; sand, sandy loam, loam, silt loam and clay were used. The sand and sandy loam soils were dug from a sand pit in Mukono and Kikoiro in Nakasongola, respectively. Loam, silt loam and clay soils were dug from Kiganda in Mubende, Mukono and Kajansi, respectively. Analysis of the soils is presented in Tab. 1.

### 2.3 Experimental Design

The soils were mixed with three levels of Luquasorb hydrogel (manufactured by BASF SE, Chemical Company, Ludwigshafen, Germany) in a randomized factorial design with 15 treatment combinations. The three hydrogel levels used were; no hydrogel added (control), 0.2% w/w hydrogel and 0.4% w/w hydrogel. Fifteen seedlings of each of the nine tree species were transplanted into 3 kg pots each filled with one of the five soil types amended either with 0.2%, 0.4% hydrogel or with no hydrogel (control). The amount of Luquasorb used followed past research experiences [6, 23] and recommendations from the manufacturer. The 135 blocks of potted seedlings were randomly placed in the green house. They were maintained at a temperature of 25–32°C and a relative humidity of 50–95%. The seed-

lings were watered twice a day for 8 weeks. Proper seedling establishment was indicated by the growth of new leaves and twigs.

### 2.4 Determination of Growth Parameters

For each species, 15 seedlings of each of the three amendments were harvested at the end of the 8 wk period and separated into roots, stems, leaves and twigs. The roots were separated from the soil by gently washing in water. The biomass was dried in an oven at 60°C until they reached a constant weight.

### 2.5 Statistical Analysis

The data was analyzed using analysis of variance (ANOVA) with the general linear model (GLM) procedure (SPSS Inc., Release 8.0, 1997) to determine the effects of the factors; hydrogel levels, soil types and the possible interaction between both factors on biomass for each tree species. Whenever ANOVA indicated significant interactions for  $p < 0.05$ , one-way ANOVA was used to analyze the factors independently. Differences between the means of biomasses across the hydrogel levels and soil types were confirmed by the Tukey HSD test. Mean differences were regarded significant when  $p = 0.05$ .

## 3 Results

### 3.1 Hydrogel Effects on Biomass in Sand

Tree seedlings potted in 0.4% hydrogel amended sand had significantly ( $p < 0.001$ ) higher dry weight of roots, stems, leaves and twigs than the control in eight tree species except *Maesopsis eminii* (see Tab. 2). Addition of either 0.4 or 0.2% hydrogel increased the dry weight of the roots, stems, leaves and twigs of the nine tree species more than the control.

### 3.2 Hydrogel Effects on Biomass in Sandy Loam

The dry weights of the nine tree species were significantly ( $p < 0.001$ ) higher in either 0.2 or 0.4% hydrogel amended sandy loam than the control (see Tab. 3). Increasing the amount of hydrogel from 0.2 to 0.4% did not significantly ( $p > 0.05$ ) change the dry weight of the roots of *Eucalyptus citriodora*, stems of *Araucaria cunninghamii* and *Melia volkensii* and leaves and twigs of *Grevillea robusta* (Tab. 3).

**Table 2.** Growth of nine tree species potted in sand amended with different hydrogel levels. Different superscript letters in the same column are significantly different (post-hoc Tukey test,  $p < 0.05$ ).

| Plant Species and Hydrogel Treatment | Biomass (Oven Dry Matter) |                   |                    |
|--------------------------------------|---------------------------|-------------------|--------------------|
|                                      | Root                      | Stem              | Leaves and Twigs   |
| <i>Eucalyptus grandis</i>            |                           |                   |                    |
| Control                              | 2.13 <sup>c</sup>         | 0.51 <sup>c</sup> | 2.88 <sup>c</sup>  |
| 0.2%                                 | 2.34 <sup>b</sup>         | 1.16 <sup>b</sup> | 5.82 <sup>b</sup>  |
| 0.4%                                 | 2.84 <sup>a</sup>         | 1.29 <sup>a</sup> | 6.56 <sup>a</sup>  |
| <i>Eucalyptus citriodora</i>         |                           |                   |                    |
| Control                              | 1.12 <sup>c</sup>         | 0.40 <sup>c</sup> | 3.06 <sup>c</sup>  |
| 0.2%                                 | 1.25 <sup>b</sup>         | 0.43 <sup>b</sup> | 4.00 <sup>b</sup>  |
| 0.4%                                 | 2.96 <sup>a</sup>         | 0.60 <sup>a</sup> | 12.25 <sup>a</sup> |
| <i>Pinus caribaea</i>                |                           |                   |                    |
| Control                              | 1.3 <sup>b</sup>          | 0.15 <sup>b</sup> | 1.28 <sup>c</sup>  |
| 0.2%                                 | 1.92 <sup>a</sup>         | 0.16 <sup>a</sup> | 1.38 <sup>b</sup>  |
| 0.4%                                 | 1.99 <sup>a</sup>         | 0.17 <sup>a</sup> | 1.68 <sup>a</sup>  |
| <i>Araucaria cunninghamii</i>        |                           |                   |                    |
| Control                              | 0.46 <sup>b</sup>         | 0.24 <sup>c</sup> | 2.18 <sup>c</sup>  |
| 0.2%                                 | 1.84 <sup>a</sup>         | 0.26 <sup>b</sup> | 2.96 <sup>b</sup>  |
| 0.4%                                 | 1.85 <sup>a</sup>         | 0.33 <sup>a</sup> | 3.09 <sup>a</sup>  |
| <i>Melia volkensii</i>               |                           |                   |                    |
| Control                              | 1.15 <sup>b</sup>         | 0.32 <sup>c</sup> | 0.31 <sup>c</sup>  |
| 0.2%                                 | 1.19 <sup>b</sup>         | 0.35 <sup>b</sup> | 0.53 <sup>b</sup>  |
| 0.4%                                 | 2.28 <sup>a</sup>         | 0.74 <sup>a</sup> | 1.63 <sup>a</sup>  |
| <i>Grevillea robusta</i>             |                           |                   |                    |
| Control                              | 3.15 <sup>c</sup>         | 0.98 <sup>c</sup> | 4.08 <sup>c</sup>  |
| 0.2%                                 | 4.94 <sup>b</sup>         | 1.45 <sup>b</sup> | 4.23 <sup>b</sup>  |
| 0.4%                                 | 5.68 <sup>a</sup>         | 1.81 <sup>a</sup> | 7.68 <sup>a</sup>  |
| <i>Azadirachta indica</i>            |                           |                   |                    |
| Control                              | 1.80 <sup>b</sup>         | 0.73 <sup>c</sup> | 1.15 <sup>c</sup>  |
| 0.2%                                 | 2.09 <sup>a</sup>         | 0.97 <sup>b</sup> | 1.19 <sup>b</sup>  |
| 0.4%                                 | 2.11 <sup>a</sup>         | 1.00 <sup>a</sup> | 1.57               |
| <i>Maesopsis eminii</i>              |                           |                   |                    |
| Control                              | 0.86 <sup>c</sup>         | 0.28 <sup>b</sup> | 0.51 <sup>c</sup>  |
| 0.2%                                 | 1.76 <sup>a</sup>         | 0.28 <sup>b</sup> | 0.66 <sup>b</sup>  |
| 0.4%                                 | 1.00 <sup>b</sup>         | 0.29 <sup>a</sup> | 0.68 <sup>a</sup>  |
| <i>Terminalia superba</i>            |                           |                   |                    |
| Control                              | 3.31 <sup>c</sup>         | 0.79 <sup>c</sup> | 0.74 <sup>c</sup>  |
| 0.2%                                 | 3.52 <sup>b</sup>         | 0.94 <sup>b</sup> | 0.93 <sup>b</sup>  |
| 0.4%                                 | 3.90 <sup>a</sup>         | 0.98 <sup>a</sup> | 0.96 <sup>a</sup>  |

**Table 3.** Growth of nine tree species potted in sandy loam amended with different hydrogel levels. Different superscript letters in the same column are significantly different (post-hoc Tukey test,  $p < 0.05$ ).

| Plant Species and Hydrogel Treatment | Biomass (Oven Dry Matter) |                   |                    |
|--------------------------------------|---------------------------|-------------------|--------------------|
|                                      | Root                      | Stem              | Leaves and Twigs   |
| <i>Eucalyptus grandis</i>            |                           |                   |                    |
| Control                              | 2.97 <sup>c</sup>         | 2.13 <sup>c</sup> | 12.85 <sup>c</sup> |
| 0.2%                                 | 7.21 <sup>b</sup>         | 2.55 <sup>b</sup> | 15.59 <sup>b</sup> |
| 0.4%                                 | 4.71 <sup>a</sup>         | 3.43 <sup>a</sup> | 15.94 <sup>a</sup> |
| <i>Eucalyptus citriodora</i>         |                           |                   |                    |
| Control                              | 1.66 <sup>b</sup>         | 1.35 <sup>c</sup> | 9.18 <sup>c</sup>  |
| 0.2%                                 | 1.90 <sup>a</sup>         | 1.69 <sup>b</sup> | 9.49 <sup>b</sup>  |
| 0.4%                                 | 1.93 <sup>a</sup>         | 2.09 <sup>a</sup> | 11.62 <sup>a</sup> |
| <i>Pinus caribaea</i>                |                           |                   |                    |
| Control                              | 1.73 <sup>b</sup>         | 0.29 <sup>c</sup> | 2.78 <sup>c</sup>  |
| 0.2%                                 | 2.25 <sup>a</sup>         | 0.32 <sup>b</sup> | 3.15 <sup>b</sup>  |
| 0.4%                                 | 2.27 <sup>a</sup>         | 0.38 <sup>a</sup> | 3.53 <sup>a</sup>  |
| <i>Araucaria cunninghamii</i>        |                           |                   |                    |
| Control                              | 1.26 <sup>c</sup>         | 0.40 <sup>b</sup> | 1.05 <sup>c</sup>  |
| 0.2%                                 | 1.52 <sup>b</sup>         | 0.42 <sup>a</sup> | 3.32 <sup>b</sup>  |
| 0.4%                                 | 1.72 <sup>a</sup>         | 0.42 <sup>a</sup> | 3.79 <sup>a</sup>  |
| <i>Melia volkensii</i>               |                           |                   |                    |
| Control                              | 3.98 <sup>c</sup>         | 2.50 <sup>b</sup> | 7.56 <sup>c</sup>  |
| 0.2%                                 | 4.85 <sup>a</sup>         | 2.77 <sup>a</sup> | 8.35 <sup>b</sup>  |
| 0.4%                                 | 4.22 <sup>b</sup>         | 2.77 <sup>a</sup> | 9.07 <sup>a</sup>  |
| <i>Grevillea robusta</i>             |                           |                   |                    |
| Control                              | 2.97 <sup>c</sup>         | 1.84 <sup>c</sup> | 8.41 <sup>b</sup>  |
| 0.2%                                 | 3.01 <sup>b</sup>         | 2.90 <sup>b</sup> | 11.07 <sup>a</sup> |
| 0.4%                                 | 4.56 <sup>a</sup>         | 3.15 <sup>a</sup> | 11.00 <sup>a</sup> |
| <i>Azadirachta indica</i>            |                           |                   |                    |
| Control                              | 2.27 <sup>c</sup>         | 1.10 <sup>c</sup> | 3.09 <sup>c</sup>  |
| 0.2%                                 | 3.86 <sup>a</sup>         | 1.94 <sup>a</sup> | 4.61 <sup>a</sup>  |
| 0.4%                                 | 2.81 <sup>b</sup>         | 1.69 <sup>b</sup> | 3.40 <sup>b</sup>  |
| <i>Maesopsis eminii</i>              |                           |                   |                    |
| Control                              | 2.14 <sup>c</sup>         | 0.50 <sup>c</sup> | 2.60 <sup>c</sup>  |
| 0.2%                                 | 3.82 <sup>b</sup>         | 0.66 <sup>b</sup> | 2.64 <sup>b</sup>  |
| 0.4%                                 | 4.33 <sup>a</sup>         | 0.75 <sup>a</sup> | 2.77 <sup>a</sup>  |
| <i>Terminalia superba</i>            |                           |                   |                    |
| Control                              | 3.87 <sup>c</sup>         | 1.76 <sup>c</sup> | 3.40 <sup>c</sup>  |
| 0.2%                                 | 6.01 <sup>b</sup>         | 1.83 <sup>b</sup> | 4.08 <sup>b</sup>  |
| 0.4%                                 | 7.43 <sup>a</sup>         | 1.85 <sup>a</sup> | 4.41 <sup>a</sup>  |

### 3.3 Hydrogel Effects on Biomass in Loam

The dry weight of the roots, stems and leaves and twigs of the nine tree species were significantly ( $p < 0.001$ ) higher in 0.4% hydrogel amended loam soil compared to the control (Tab. 4). Addition of 0.2% hydrogel did not significantly ( $p > 0.05$ ) change the root dry weight of *Eucalyptus citriodora* compared to the control. Increasing the amount of hydrogel from 0.2 to 0.4% reduced the root dry weight of *Melia volkensii* (Tab. 4).

### 3.4 Hydrogel Effects on Biomass in Silt Loam

Either 0.2 or 0.4% hydrogel significantly ( $p < 0.001$ ) increased the dry weight of the roots, stems and leaves and twigs of seven tree species more than the control silt loam soil except *Maesopsis eminii* and *Terminalia superba* (Tab. 5). Amending the soil with 0.4% hydrogel significantly reduced the dry weight of root, stem, leaves and twigs of *Pinus caribaea* compared to 0.2% hydrogel.

### 3.5 Hydrogel Effects on Biomass in Clay

The dry weight of the roots, stems, leaves and twigs of the nine tree species potted in clay soil amended with either 0.2 or 0.4% hydrogel were significantly ( $p < 0.001$ ) higher than the control (see Tab. 6). An increase in the hydrogel level from 0.2 to 0.4% significantly ( $p < 0.001$ ) reduced the root dry weight of *Eucalyptus grandis* as well as the dry weight of the root, stem, leaves and twigs of *Grevillea robusta*.

## 4 Discussion

### 4.1 Effectiveness of Hydrogel Levels

Incorporation of either 0.4 or 0.2% hydrogel significantly increased the biomass of roots, stems, leaves and twigs of nine tree species (*Eucalyptus grandis*, *Eucalyptus citriodora*, *Pinus caribaea*, *Araucaria cunninghamii*, *Grevillea robusta*, *Melia volkensii*, *Azadirachta indica*, *Maesopsis eminii*, and *Terminalia superba*) in sand, sandy loam, loam, clay and seven tree species (except *Maesopsis eminii* and *Terminalia superba*) in

**Table 4.** Growth of nine tree species potted in loam amended with different hydrogel levels. Different superscript letters in the same column are significantly different (post-hoc Tukey test,  $p < 0.05$ ).

| Plant Species and Hydrogel Treatment | Biomass (Oven Dry Matter) |                   |                    |
|--------------------------------------|---------------------------|-------------------|--------------------|
|                                      | Root                      | Stem              | Leaves and Twigs   |
| <i>Eucalyptus grandis</i>            |                           |                   |                    |
| Control                              | 1.69 <sup>c</sup>         | 1.18 <sup>c</sup> | 6.08 <sup>c</sup>  |
| 0.2%                                 | 2.26 <sup>b</sup>         | 1.64 <sup>b</sup> | 7.80 <sup>b</sup>  |
| 0.4%                                 | 3.89 <sup>a</sup>         | 3.69 <sup>a</sup> | 17.02 <sup>a</sup> |
| <i>Eucalyptus citriodora</i>         |                           |                   |                    |
| Control                              | 2.14 <sup>b</sup>         | 1.64 <sup>c</sup> | 10.45 <sup>c</sup> |
| 0.2%                                 | 2.29 <sup>b</sup>         | 2.09 <sup>b</sup> | 11.89 <sup>b</sup> |
| 0.4%                                 | 2.90 <sup>a</sup>         | 2.11 <sup>a</sup> | 13.30 <sup>a</sup> |
| <i>Pinus caribaea</i>                |                           |                   |                    |
| Control                              | 1.16 <sup>c</sup>         | 0.25 <sup>c</sup> | 2.56 <sup>c</sup>  |
| 0.2%                                 | 1.35 <sup>b</sup>         | 0.33 <sup>b</sup> | 3.47 <sup>b</sup>  |
| 0.4%                                 | 2.74 <sup>a</sup>         | 0.41 <sup>a</sup> | 4.02 <sup>a</sup>  |
| <i>Araucaria cunninghamii</i>        |                           |                   |                    |
| Control                              | 0.74 <sup>c</sup>         | 0.26 <sup>c</sup> | 2.78 <sup>c</sup>  |
| 0.2%                                 | 1.36 <sup>b</sup>         | 0.33 <sup>b</sup> | 3.23 <sup>b</sup>  |
| 0.4%                                 | 1.91 <sup>a</sup>         | 0.40 <sup>a</sup> | 4.13 <sup>a</sup>  |
| <i>Melia volkensii</i>               |                           |                   |                    |
| Control                              | 3.77 <sup>c</sup>         | 1.12 <sup>c</sup> | 3.48 <sup>c</sup>  |
| 0.2%                                 | 4.88 <sup>a</sup>         | 1.33 <sup>b</sup> | 3.65 <sup>b</sup>  |
| 0.4%                                 | 4.35 <sup>b</sup>         | 1.66 <sup>a</sup> | 5.03 <sup>a</sup>  |
| <i>Grevillea robusta</i>             |                           |                   |                    |
| Control                              | 1.03 <sup>c</sup>         | 1.66 <sup>c</sup> | 5.94 <sup>c</sup>  |
| 0.2%                                 | 2.38 <sup>b</sup>         | 1.68 <sup>b</sup> | 6.57 <sup>b</sup>  |
| 0.4%                                 | 3.11 <sup>a</sup>         | 1.89 <sup>a</sup> | 7.76 <sup>a</sup>  |
| <i>Azadirachta indica</i>            |                           |                   |                    |
| Control                              | 2.03 <sup>c</sup>         | 1.07 <sup>c</sup> | 1.98 <sup>c</sup>  |
| 0.2%                                 | 3.17 <sup>b</sup>         | 1.69 <sup>b</sup> | 3.72 <sup>b</sup>  |
| 0.4%                                 | 4.07 <sup>a</sup>         | 1.88 <sup>a</sup> | 3.97 <sup>a</sup>  |
| <i>Maesopsis eminii</i>              |                           |                   |                    |
| Control                              | 1.11 <sup>c</sup>         | 0.55 <sup>c</sup> | 2.37 <sup>c</sup>  |
| 0.2%                                 | 1.37 <sup>b</sup>         | 0.65 <sup>b</sup> | 3.40 <sup>b</sup>  |
| 0.4%                                 | 2.49 <sup>a</sup>         | 0.92 <sup>a</sup> | 2.42 <sup>a</sup>  |
| <i>Terminalia superba</i>            |                           |                   |                    |
| Control                              | 3.75 <sup>c</sup>         | 1.68 <sup>c</sup> | 3.51 <sup>c</sup>  |
| 0.2%                                 | 4.07 <sup>b</sup>         | 1.90 <sup>b</sup> | 4.01 <sup>b</sup>  |
| 0.4%                                 | 7.01 <sup>a</sup>         | 2.02 <sup>a</sup> | 4.05 <sup>a</sup>  |

**Table 5.** Growth of nine tree species potted in silt loam amended with different hydrogel levels. Different superscript letters in the same column are significantly different (post-hoc Tukey test,  $p < 0.05$ ).

| Plant Species and Hydrogel Treatment | Biomass (Oven Dry Matter) |                   |                    |
|--------------------------------------|---------------------------|-------------------|--------------------|
|                                      | Root                      | Stem              | Leaves and Twigs   |
| <i>Eucalyptus grandis</i>            |                           |                   |                    |
| Control                              | 2.30 <sup>c</sup>         | 0.91 <sup>c</sup> | 4.58 <sup>c</sup>  |
| 0.2%                                 | 5.13 <sup>b</sup>         | 1.74 <sup>b</sup> | 7.80 <sup>b</sup>  |
| 0.4%                                 | 6.25 <sup>a</sup>         | 2.21 <sup>a</sup> | 9.31 <sup>a</sup>  |
| <i>Eucalyptus citriodora</i>         |                           |                   |                    |
| Control                              | 1.00 <sup>c</sup>         | 0.70 <sup>c</sup> | 4.56 <sup>c</sup>  |
| 0.2%                                 | 1.98 <sup>b</sup>         | 1.54 <sup>b</sup> | 9.63 <sup>b</sup>  |
| 0.4%                                 | 5.27 <sup>a</sup>         | 2.23 <sup>a</sup> | 11.52 <sup>a</sup> |
| <i>Pinus caribaea</i>                |                           |                   |                    |
| Control                              | 4.23 <sup>c</sup>         | 0.26 <sup>c</sup> | 2.71 <sup>c</sup>  |
| 0.2%                                 | 6.57 <sup>a</sup>         | 0.37 <sup>a</sup> | 3.36 <sup>a</sup>  |
| 0.4%                                 | 5.20 <sup>b</sup>         | 0.29 <sup>b</sup> | 2.95 <sup>b</sup>  |
| <i>Araucaria cunninghamii</i>        |                           |                   |                    |
| Control                              | 1.45 <sup>c</sup>         | 0.29 <sup>b</sup> | 3.09 <sup>c</sup>  |
| 0.2%                                 | 1.60 <sup>b</sup>         | 0.30 <sup>b</sup> | 3.64 <sup>b</sup>  |
| 0.4%                                 | 1.93 <sup>a</sup>         | 0.32 <sup>a</sup> | 3.69 <sup>a</sup>  |
| <i>Melia volkensii</i>               |                           |                   |                    |
| Control                              | 2.36 <sup>c</sup>         | 0.75 <sup>c</sup> | 1.76 <sup>c</sup>  |
| 0.2%                                 | 3.16 <sup>a</sup>         | 0.86 <sup>b</sup> | 2.50 <sup>b</sup>  |
| 0.4%                                 | 3.46 <sup>a</sup>         | 1.10 <sup>a</sup> | 3.94 <sup>a</sup>  |
| <i>Grevillea robusta</i>             |                           |                   |                    |
| Control                              | 3.16 <sup>c</sup>         | 2.15 <sup>c</sup> | 9.22 <sup>c</sup>  |
| 0.2%                                 | 3.42 <sup>b</sup>         | 2.19 <sup>b</sup> | 9.66 <sup>b</sup>  |
| 0.4%                                 | 5.12 <sup>a</sup>         | 2.32 <sup>a</sup> | 9.87 <sup>a</sup>  |
| <i>Azadirachta indica</i>            |                           |                   |                    |
| Control                              | 1.07 <sup>c</sup>         | 0.51 <sup>c</sup> | 1.15 <sup>c</sup>  |
| 0.2%                                 | 2.51 <sup>b</sup>         | 1.15 <sup>b</sup> | 1.99 <sup>b</sup>  |
| 0.4%                                 | 4.42 <sup>a</sup>         | 1.17 <sup>a</sup> | 2.47 <sup>a</sup>  |
| <i>Maesopsis eminii</i>              |                           |                   |                    |
| Control                              | 1.65 <sup>c</sup>         | 0.44 <sup>c</sup> | 1.48 <sup>c</sup>  |
| 0.2%                                 | 1.67 <sup>b</sup>         | 0.45 <sup>b</sup> | 1.50 <sup>b</sup>  |
| 0.4%                                 | 2.50 <sup>a</sup>         | 0.50 <sup>a</sup> | 1.77 <sup>a</sup>  |
| <i>Terminalia superba</i>            |                           |                   |                    |
| Control                              | 5.76 <sup>c</sup>         | 1.30 <sup>b</sup> | 2.82 <sup>c</sup>  |
| 0.2%                                 | 6.47 <sup>a</sup>         | 1.74 <sup>a</sup> | 3.49 <sup>a</sup>  |
| 0.4%                                 | 6.05 <sup>b</sup>         | 1.30 <sup>b</sup> | 3.28 <sup>b</sup>  |

silt loam soils, respectively, more than the control. The effect of hydrogels on biomass growth was not only influenced by the differences in properties of the hydrogel levels, but also tree species-specific soil requirements for their growth. Such hydrogel induced growth has been reported so far only for citrus seedlings grown in well watered sand soil [21].

Comparing the hydrogel levels, 0.4% displayed the best growth effects in sand, sandy loam and loam soils for *Eucalyptus grandis*, *Eucalyptus citriodora*, *Grevillea robusta*, *Maesopsis eminii* and *Terminalia superba* more than 0.2% hydrogel. 0.2% hydrogel showed the best growth effects for *Azadirachta indica* in sandy loam, *Pinus caribaea* and *Terminalia superba* in silt loam. Each of the hydrogel levels displayed best growth effects in four tree species potted in clay soil.

## 4.2 Possible Mechanism of SAP Induced Growth

The development of the total biomass with regard to the amendment with 0.4% hydrogel to the different soils is given in Fig. 1. It shows that the average hydrogel induced growth compared to the

tree growth in control soils without hydrogel amendment for the nine tree species was between 150% and 220%. The values shown in Fig. 1 indicate that the effect of growth promotion by the hydrogel amendment cannot be directly correlated to the concomitant increase in plant available water. The amendment of a sandy loam with hydrogels results into a 3.2 fold higher increase in plant available water compared to a 1.8 fold increase in clay [24]. The average hydrogel induced growth in these two soils, however, differs only by 16% (Fig. 1).

It is a well known fact in soil science, that the fertility of a soil is highly dependent on its cation exchange capacity (CEC) [25]. The higher the CEC is, the better the fertility of soils, provided that no other factors like soil acidity or poisonous ions [26–29] counteract the positive effect of the CEC. The CEC of organic substances of the soil is in the range of 1.8–3.0 mval/g, the inorganic part of the soil is in the range of 0.03 (coarse silt)–0.55 (clay) mval/g [25].

With SAP, an additional cation exchange system enters the soil which in its hydrated form takes about 10% of the soil volume in a well watered soil. Compared to the natural soil components, it has a much higher CEC; 13.9 mval/g (the value is calculated for a poly-

**Table 6.** Growth of nine tree species potted in clay amended with different hydrogel levels. Different superscript letters in the same column are significantly different (post-hoc Tukey test,  $p < 0.05$ ).

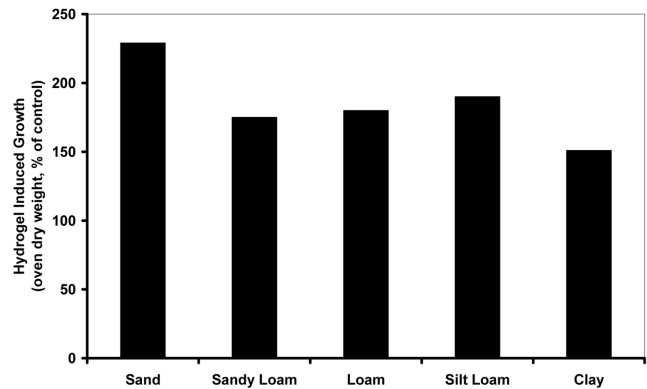
| Plant Species and Hydrogel Treatment | Biomass (Oven Dry Matter) |                   |                   |
|--------------------------------------|---------------------------|-------------------|-------------------|
|                                      | Root                      | Stem              | Leaves and Twigs  |
| <i>Eucalyptus grandis</i>            |                           |                   |                   |
| Control                              | 1.03 <sup>c</sup>         | 0.51 <sup>c</sup> | 3.53 <sup>c</sup> |
| 0.2%                                 | 1.59 <sup>a</sup>         | 0.59 <sup>b</sup> | 5.39 <sup>b</sup> |
| 0.4%                                 | 1.53 <sup>b</sup>         | 1.09 <sup>a</sup> | 7.67 <sup>a</sup> |
| <i>Eucalyptus citriodora</i>         |                           |                   |                   |
| Control                              | 0.75 <sup>c</sup>         | 0.36 <sup>c</sup> | 3.07 <sup>c</sup> |
| 0.2%                                 | 1.54 <sup>b</sup>         | 0.50 <sup>b</sup> | 3.64 <sup>b</sup> |
| 0.4%                                 | 2.08 <sup>a</sup>         | 0.92 <sup>a</sup> | 6.17 <sup>a</sup> |
| <i>Pinus caribaea</i>                |                           |                   |                   |
| Control                              | 1.00 <sup>b</sup>         | 0.20 <sup>c</sup> | 1.61 <sup>c</sup> |
| 0.2%                                 | 1.92 <sup>a</sup>         | 0.26 <sup>a</sup> | 1.92 <sup>a</sup> |
| 0.4%                                 | 1.01 <sup>b</sup>         | 0.23 <sup>b</sup> | 1.83 <sup>b</sup> |
| <i>Araucaria cunninghamii</i>        |                           |                   |                   |
| Control                              | 0.42 <sup>c</sup>         | 0.20 <sup>b</sup> | 2.27 <sup>c</sup> |
| 0.2%                                 | 0.56 <sup>a</sup>         | 0.25 <sup>a</sup> | 2.77 <sup>a</sup> |
| 0.4%                                 | 0.44 <sup>b</sup>         | 0.21 <sup>b</sup> | 2.63 <sup>b</sup> |
| <i>Melia volkensii</i>               |                           |                   |                   |
| Control                              | 2.94 <sup>c</sup>         | 1.13 <sup>c</sup> | 2.84 <sup>c</sup> |
| 0.2%                                 | 3.45 <sup>a</sup>         | 1.23 <sup>b</sup> | 3.52 <sup>a</sup> |
| 0.4%                                 | 3.34 <sup>b</sup>         | 1.19 <sup>a</sup> | 3.19 <sup>b</sup> |
| <i>Grevillea robusta</i>             |                           |                   |                   |
| Control                              | 2.27 <sup>c</sup>         | 1.44 <sup>c</sup> | 5.03 <sup>c</sup> |
| 0.2%                                 | 4.10 <sup>a</sup>         | 1.66 <sup>a</sup> | 6.29 <sup>a</sup> |
| 0.4%                                 | 3.78 <sup>b</sup>         | 1.51 <sup>b</sup> | 5.64 <sup>b</sup> |
| <i>Azadirachta indica</i>            |                           |                   |                   |
| Control                              | 2.15 <sup>c</sup>         | 0.81 <sup>c</sup> | 0.93 <sup>c</sup> |
| 0.2%                                 | 2.94 <sup>a</sup>         | 1.09 <sup>a</sup> | 1.35 <sup>a</sup> |
| 0.4%                                 | 2.48 <sup>b</sup>         | 0.88 <sup>b</sup> | 1.21 <sup>b</sup> |
| <i>Maesopsis eminii</i>              |                           |                   |                   |
| Control                              | 0.24 <sup>c</sup>         | 0.17 <sup>b</sup> | 0.50 <sup>c</sup> |
| 0.2%                                 | 0.43 <sup>b</sup>         | 0.18 <sup>b</sup> | 0.65 <sup>b</sup> |
| 0.4%                                 | 1.21 <sup>a</sup>         | 0.20 <sup>a</sup> | 0.79 <sup>a</sup> |
| <i>Terminalia superba</i>            |                           |                   |                   |
| Control                              | 4.67 <sup>c</sup>         | 0.89 <sup>c</sup> | 1.10 <sup>c</sup> |
| 0.2%                                 | 4.73 <sup>b</sup>         | 0.95 <sup>b</sup> | 1.40 <sup>b</sup> |
| 0.4%                                 | 4.93 <sup>a</sup>         | 1.05 <sup>a</sup> | 1.82 <sup>a</sup> |

acrylic acid polymer). As has been shown before [17], such a potent cation exchange system in soils can change completely the ion composition of the soil water.

The effect of the resulting additional cation exchange system that enters the soil when amended with 0.4% hydrogel on the growth of the trees in this system was not always higher than the 0.2% hydrogel amendment in the same soil. This probably depends on the soil requirements of the different tree species.

### 4.3 Economic Considerations

In afforestations, between 20 and 40 g of hydrogel is given per tree into the plant hole [19]. With a tree number of 1600, this amounts to 32–64 kg per ha. One kilogram of hydrogel will cost between \$ 2–4 depending on the country where it is sold. The cost of the machinery for the application of hydrogels during the planting of trees is low. In our field experiments we had no trouble in converting conventional planting machines in such a way that the desired amount of hydrogel was applied to the plant holes. Thus, the maximal price per hectare would be about \$ 250.



**Figure 1.** The average growth induction of the nine different tree species in the five different soils amended with 0.4% Luquasorb.

If one compares this value with the typical costs for afforestations around the world (Austria: 3500 \$/ha [30], Canada: 1750 \$/ha [31], China: 90 \$/ha [32]) a hydrogel induced twofold growth increase would raise the internal rate of return considerably (Austria: from –6.6 to –3.8%, Canada: 5.1 to 15.5%, China: 41 to 65% (authors calculation)). Thus, it is very profitable to also apply hydrogels in afforestations where the survival of the planted trees is not a major problem.

In conclusion, hydrogel amendment clearly increased the biomass of the nine tree species potted in the five soil types. This effect should be exploited both in tree seedling production in the nursery and in afforestations.

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