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EFFECT OF HYDROGEL AMENDMENT ON GROWTH AND SURVIVAL OF PLANTS IN TWO TYPES OF SOILS

by
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AN ABSTRACT OF THE THESIS OF

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In this research a laboratory study was conducted to test the effect of SAP potassium polyacrilic acid (STOCKOSORB® 660) on water holding capacity of clay (C) and sandy clay (SC) soils. A field experiment was conducted at The Agricultural Reseach and Educational Center of the American University of Beirut in the Bekaa, where Carob trees (*Ceratonia siliqua*), South European flowering ash (*Fraxinus ornus*) and Juda's tree (*Cercis siliquastrum*) seedlings were planted in the field after mixing the soil with hydrogel rates of 0, 0.5, 1, 2, and 4 g hydrogel/kg of soil. Survival of trees in the different treatments was monitored. A greenhouse pot experiment on corn (*Zea mays*) was also run to study the effect of hydrogel on plant growth in SC and C soils. In the pot experiment, the rates of hydrogel were 0, 1, 2, 3 and 4 g hydrogel/kg of soil. Hydrogel was applied using two methods: banding (in one layer mixed with 20-20-20 fertilizers) and mixing where the hydrogel and fertilizers were thoroughly mixed with the soil. The growth was measured 7 weeks after planting. A second pot experiment was run on pine (*Pinus pinea*) trees to study the effect of hydrogel on the length of the survival period without any further irrigation. The rates of SAP used were 0, 2, 3 and 4 g hydrogel/kg of soil. Banding and mixing methods and clay and sandy clay were also used in this experiment.

Results of the laboratory study showed that hydrogel increased water holding capacity of the sandy clay soil but had minor effects in the clay soil. The negligible effects of SAP in clay soils were verified by the field experiment where the use of hydrogels did not significantly benefit tree survival. The corn pot experiment indicated that banding hydrogel was more efficient than mixing it with the soil, especially in sandy clay soil. These results were confirmed by the second pot experiment where banding hydrogels significantly helped prolong the life span of pine seedlings.

Therefore, it could be concluded that the use of hydrogel significantly helped plant growth and survival under water stress in sandy clay soil but was not significant in clay soil.

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ABREVIATIONS

A.D.	Anno Domini
AAc	Acrylic Acid
Am	Acrylamide
AREC	Agricultural and Research Education Center
AUB	American University of Beirut
B.C	Before Christ
C	Celsius
Ca	Calcium
CaCO3	Calcium Carbonate
Cl	Chloride
cm	centimeter
cm^3	cubic centimeter
- $CONH_2$	Amide group
dm^3	cubic decimeter
EC	Electrical Conductivity
et al.	*Et allii* (and others)
FAO	Food and Agricultural Organization
Fe	Iron
g	gram
ha	Hectare
HCl	Hydrochloric Acid
kg	kilogram
K	Potassium
l	Liter
LAI	Leaf Area Index
LRI	Lebanese Reforestation Initiative
m^3	cubic meters
mg/Kg	milligram per kilogram
ml	milliliter
mm	millimeter
mS/cm	milliSiemen per centimeter
mm	millimeter
MSDS	Materials Safety Data Sheet
M	Molar
Na	Sodium
NaCl	Sodium Chloride
NaOH	sodium hydroxide
NH_4OAc	Ammonium acetate

N	Nitrogen
OM	Organic Matter
P	Phosphorus
PAAc	Polyacrylate
PAAcK	Potassium polyacrylate
PAAm	Polyacrylamide
PAN	Polyacrylonitrile
Pb	Lead
Rpm	Rounds per minute
SAP	Super Absorbent Polymer
SCL	Sandy Clay
SPAN	Starch-Graft-Polyacrylonitrile
USAID	United States Agency for International Development
USFS	United States Forest Services
w/w	weight/weight

CHAPTER I

INTRODUCTION

Fresh water is a vital constituent of life on earth. In recent years, the demand for fresh water intensified due to a growing global population and increased standards of living. Food production is facing higher competition for land, water, and energy resources under pressures to meet the growing population demand. Moreover, the agricultural sector is the largest user of fresh water. It consumes 80–90% of global fresh water use (Bruinsma, 2009). Although the bigger fraction of agricultural land is rainfed, higher yields are found in irrigated areas which account for about 42% of global crop production. Further, water use efficiency in the agricultural sector is considered relatively low, with more than 50% water being wasted. Considerable water saving can be achieved in the agricultural sector by increasing water use efficiency through improved cultural practices and the adoption of new technologies (Hamdy et. al, 2003; Pereira et. al, 2009). The practices include among others: the adoption of drip and sprinkler irrigation, no-till farming, improved drainage, and the use of drought resistant varieties (Addams et. al, 2009).

Water saving can also be achieved through enhancing the water holding capacity of soils, especially in arid areas. This can be achieved through the incorporation of soil amendments such as Super Absorbent Polymers (SAPs).

Super Absorbent Polymers, more commonly known as hydrogels, are long chains of crosslinked polymers that can absorb and retain water up to 1000 times their own weight. The effects of the addition of SAPs to soils have shown differ according to soil types, regions, environment and crops used.

The detailed objectives of this research were:

1- Evaluate the effect of different rates of hydrogels on water holding capacity of two types of soils.

2- Investigate the effect of different rates and application methods of hydrogels on the growth of corn plants in two soil types.

3- Investigate the effect of different rates and application methods of hydrogels on prolonging the survival of tree seedlings.

One field experiment, two greenhouse pot experiments and a laboratory study were conducted to examine these effects.

CHAPTER II

LITERATURE REVIEW

This chapter will focus on water scarcity in the world in general and Lebanon specifically, highlighting the need for efficient methods for water use. Then, super absorbent polymers (SAP), commonly known as hydrogels, and their role in saving water for agriculture and reforestation will be presented. Finally the concerned plants will be briefly described.

A. Water Scarcity

According to FAO, the global use of water has been going up at more than twice the rate of population increase in the last century and an increasing number of regions are reaching the limit at which water services can be sustainably delivered (FAO, 2011).

Unparalleled pressures are being exerted on water resources, especially in arid regions, by an ever growing population and economic development. Recent projections indicate that world population will go from 6.9 billion people in 2011 to 9.1 billion in 2050 (FAO, 2011). Also according to the FAO's Natural Resources and Environment Department, by 2025, 1800 million people are forecasted to be living in countries or regions with "absolute" water scarcity which translates into less than 500 m^3 per year per capita. Water scarcity is measured by analyzing the population-water equation. An area is considered under "water stress" when annual water supplies drop below 1,700

m^3 per person. When the latter drops below 1,000 m^3 per person, the population faces water scarcity (FAO, 2007).

The agricultural sector is the largest consumer of water. On a consumptive use basis, 80–90% of all the fresh water is consumed in agriculture. Further, water use efficiency in this sector does not exceed 45% with more than 50% water losses; thus, enormous water saving could be achieved in the agricultural sector compared to other water uses (Hamdy et al., 2003; Pereira et al., 2009). In Lebanon, estimates vary, but on average, agriculture consumes 55 to 60% (8,000 to 9,000 m^3/ha) of all water with network efficiency varying between 52 and 70% (UN-ESCWA, 2012).

With projections of increased water shortages for agricultural uses due to population growth and climatic changes, many efforts are being exerted to find management practices, new technologies and innovative ways to alleviate the effects of water stress. Growing drought tolerant crops (Farré & Faci, 2006), crop rotations, the use of mulches, and new, efficient water delivery systems have been researched and are being implemented to increase the water use efficiency of crops.

Another way to improve the efficiency of water use in agriculture can be in altering soil water properties such as water holding capacity, hydraulic conductivity and infiltration. A possible way to alter the later properties is to incorporate hydrophilic polymer amendments into the soil (Baasiri et al., 1986). These super absorbent polymers (SAP) commonly referred to as hydrogels are capable of swelling and retaining water 400 - 1600 times their own weight (Kazanskii & Dubrovskii, 1992).

B. Superabsorbent Polymers (SAP): Hydrogels

Superabsorbent polymers, commonly referred to as hydrogels, are networks of polymer chains that are “three-dimensionally” cross-linked and can expand to absorb water up to 1000 times their own weight (Bhardwaj et al., 2007). Their use has been extended from hygienic products such as diapers to medicine and agriculture (M. Zohuriaan-mehr & J Kabiri, 2008).

The synthesis of the first water-absorbent polymer goes back to 1938 when acrylic acid (AA) and divinylbenzene were thermally polymerized in an aqueous medium. Then another generation of hydrogels appeared in the late 1950s and was mainly based on hydroxyalkyl methacrylate. These hydrogels could only swell up to 40-50% and they were used in the development of contact lenses which marked a revolution in ophthalmology (Kazanskii & Dubrovskii, 1992). The first commercial SAP was produced through alkaline hydrolysis of starch-graft-polyacrylonitrile (SPAN). However, these polymers did not have sufficient gel strength and were relatively expensive which caused their early market failure.

1. SAP classes and chemical structure.

Depending on the polymer charges, the SAPs may be categorized into two types: non-ionic, ionic (cationic or anionic). However, most commercial hydrogels contain negative backbone charges, so they are anionic. They can also be classified based on the type of monomer units used in their chemical structure, e.g., cross-linked polyacrylates or polyacrylamides, and hydrolyzed cellulose-polyacrylonitrile (PAN) or starch-PAN graft copolymers (Zohuriaan-Mehr, 2010).

2. *Hydrogels in Agriculture*

Agricultural hydrogels are mainly associated with “polyacrylamide (PAAm) hydrogels containing a certain amount of groups most often in the form of acrylic acid units (AAc) as well as with networks based on poly(acrylic acid) (PAAc), poly(methacrylic acid), or their alkali metal salts” (Kazanskii & Dubrovskii, 1992) . Acrylic acid (AAc) and its sodium or potassium salts, and acrylamide (Am) are most often used in the industrial production of SAPs whose structure consists of a carbon double bond and the - $CONH_2$ group, as well as suitable amounts of a type of crosslinker (Kim et al., 2010).

The presence of these ionic groups inside the gel network results in an osmotic pressure difference which constitutes the driving force behind its superior ability to absorb water. Also, hydrogen bonds are formed between water molecules and certain functional groups within the polymer form (Xie et al., 2009).

3. *Limitations to swelling and water absorbing capacity.*

The swelling extent of the gel network is somehow limited. First, the cross-linked chains are insoluble and swelling capacity decreases the more the polymer is cross-linked (Liu & Guo, 2001). Grain size also has an effect on the water absorbing capacity of the polymers. In the free swelling systems, the absorbents’ water-absorbing capacity is inversely related to the average grain size. However, when mixed with soil, larger grain sizes performed better, mainly because of their higher resistance against the confining pressures of the soil particles. Water retention per gram of polymer also increased with increasing the rate of hydrogel in soil. The increase in granule number enhanced their ability to support the load of the soil particles thus enhanced their water absorption capacity (Bhardwaj et al., 2007).

In addition, gels composed of acrylamide (AM) and potassium acrylate swell much less in the presence of monovalent salts and can collapse in the presence of multivalent ions. Bowman et al. (1990) found that soluble salts dramatically affect absorption by hydrophilic polyacrylamide gels. The hydration of three commercial hydrogels in different concentrations of fertilizer salts was tested. It was found that monovalent cations as well as divalent cations inhibited the absorption of water significantly between 10 to 20% of maximum absorption. Subsequent, washing of the gel particles with deionized water reversed the inhibition by monovalent cations, but not divalent cations. Divalent cations were found to cause the irreversible collapse of the polymer chain (Bowman, Evans, & Paul, 1990). In addition, Bowman et al. found out that hydrogels did not have a significant effect on the physical properties of the medium, in the presence of fertilizer salts in a sandy growing medium.

Liu and Rempel (1997) explained the effect of salts on the absorption capacity of SAPs by the formation carboxylic anions in the polymer networks, which results in the development of strong electrostatic forces. These forces allow a higher Na^+ or other ions' concentration inside the polymer resulting in an ion gradient and an osmotic pressure difference (Z. S. Liu & Rempel, 1997). Another reason given for the decrease in absorption is what is known as "the polyelectrolyte effect". The anionic polymer contains charged groups along the chain to help maintain its structure by minimizing repulsion between the charges. When ions of opposite charge are present in the solution, these charges are neutralized which causes the polymer structure to collapse thus losing some of its absorption capacity.

Xie (2009) investigated the repeated absorbency of poly (acrylic acid-co-crylamide) (PAAM) in a solution of 0.9% NaCl. PAAM was immersed in the NaCl solution then dried repeatedly several times. As expected, the absorbency of PAAM decreased with each wetting cycle. The reduction in absorbance was explained by the fact that the combined water could not be taken off completely during the drying process of PAAM, causing the reduction of the osmotic pressure between the inside and outside of the network when the superabsorbent swells again. The decreasing swelling driving force induced a decrease in the absorbency. With the number of repeats, the PAAM absorbency decreases.

Studies show that the extent to which fertilizer salts affect hydrogel absorbency varies from one system to another and depends on the type, valence, and charge of fertilizer ions in addition to the gel functional groups (El-Rehim et al., 2004). Abd El-Rehim et al. (2004) studied the effect of different types and amounts of N, P and K fertilizers on the swelling behavior of hydrogels (polyelectrolyte polyacrylamide/potassium polyacrylate, PAAm/PAAcK). Results showed that under a given concentration of ions, water absorbency of the polymer decreases with the increase in ionic valence of the salt, resulting minimum in trivalent ions (Fe^{3+}) and maximum in monovalent ions (Na^{+}) solutions. It was reported that the amount of water retained in the gel is affected by chemicals or divalent cations present in the water. These cations develop strong interactions with the polymer gels and are able to displace water molecules trapped within the gel. Even though monovalent cations such as Na^{+} can replace water molecules, this effect is not as pronounced as with the divalent counterparts. The increase in fertilizer concentration also led to an increase in gel shrinkage

Polymers were also found to give away some moisture as the soil temperature would increase. This water could be lost by percolation or taken up by plant. Andry (2009) found that the water content value at field capacity for sandy soil-acrylamide mixture shifted from 0.21 to 0.10 cm^3 cm^{-3} for 0.1% and from 0.27 to 0.12 cm^3 cm^{-3} for 0.2%, as the soil temperature increased from 15 to 35 °C (Andry et al., 2009).

4. Stockosorb®

The superabsorbent polymer tested in this study represents the commercial hydrogel Stockosorb® 660 Medium, a crosslinked potassium polyacrilic acid. Stockosorb® is part of the wider brand of SAPs, Creasorb® which includes hydrogels for use outside the agricultural field (fire fighting, cable and packaging industries). Creasorb® is a product of Evonik Industries AG, Germany.

Table 1: Absorption capacities of Stockosorb660® as indicated by manufacturer.

	Absorption capacity	
	Free swelling conditions	In soil medium at 20 cm depth
0.125% NPK 12-14-12 2MgO	> 150 ml/g	> 80 g/g
Tap Water	> 100 ml/g	> 30 g/g
Synthetic soil solution	> 60 ml/g	> 20 g/g

Stockosorb® 660 Medium comes in the form of insoluble white granules, with a particle size of 0.2 to 0.8 mm. The granules swell upon contact with water and form a gel like substance. In water, at a rate of 1 g/L the measured pH varies between 7 and 8.

The technical sheet provided by the manufacturer claims that more than 95% of water absorbed is available for plants.

Also, the sheet provides values of the hydrogel's absorption capacity in free swelling and confined states. The different values are presented in

Table 1.

5. Safety & Environment

Health and environmental safety are of primary concern, especially when it comes to products interfering with the food supply chain. Although starting materials for SAPs are highly toxic, once polymerized, they cannot return to their starting monomers. The Stockosorb® Materials Safety Data Sheet (MSDS) states that the SAP is relatively inert in aerobic and anaerobic conditions. They are immobile in soil systems (>90% retention), with the mobile fraction showing biodegradability. Studies have also shown that hydrogels have little or no consistent adverse effect on soil microorganisms (Zohuriaan-mehr et al., 2008).

C. Hydrogels effect on soil properties

1. Effect on Water Holding Capacity

Because of the hydrophilic nature of the polymers, a higher rate of addition to the soil results in a greater increase in water holding capacity of soils. Higher rates of hydrogel addition to the soil result in an accentuation of the hysteresis effect (Bhardwaj et al., 2007). The hysteresis effect resulted in the soil-hydrogel mixture retaining more water during desorption than during wetting for a given suction. According to Bhardwaj (2007), this effect was more pronounced in soil-hydrogel mixtures for two possible reasons: first, the swelling and shrinking of the hydrogel particle alters the pore sizes in the soil thus accentuating the heterogeneity of the pore size distribution. The second reason could be related to the polymer itself and the way it was designed to adsorb and release water molecules.

The rise in water holding capacity of a certain soil starts declining with time due to the loss of effectiveness of hydrogels. Constant wetting and drying cycles deplete the water absorbing capacity of the polymer, to the point of losing "10% to 15% of their activity per year" (Al-Harbi et al., 1999).

A study conducted on several soil types showed that when sand treated with 0.7% gel, the soil water content during drying, decreased in a relatively uniform way throughout the entire drying period, whereas in black clay, water release rates were high initially and fell significantly afterwards (Narjary et al., 2012).

The time at which soil water content corresponding to 1 Bar was reached was studied in different soil types. Soil water content corresponding to 1 Bar with at 0.7% gel application, was reached approximately 7, 14, 22 and 4 days after watering in red sandy loam, alluvial sandy loam, sand and black clay soils, respectively. Hydrogels thus improved the water availability of sandy soils for longer period, while they were found unsuitable for black clay soil, in which the critical soil water content was reached significantly faster.

2. Effect on Hydraulic Conductivity

Higher rates of hydrogel mixed with soil further lower the saturated hydraulic conductivity (Andry et al., 2009).

In a study conducted by Bhardwaj et al. (2007), the saturated hydraulic conductivity of the soil–hydrogel mixtures initially decreased as previous studies found, only to thereafter increase. The increase was attributed to "the partial draining of the swollen polymer granules by the pressure exerted on the soil–polymer mixtures by the hydraulic head".

3. *Effect on Bulk Density*

The bulk density decreases with an increase in application rates of SAPs (Bai, et al., 2010). According to Al-Harbi et al. (1999), the initial bulk density of calcareous sandy loam mixed with 0.1%, 0.2%, 0.3%, and 0.4% sodium polyacrylamide, was reduced 6.8%, 19.2%, 31.5%, and 38.4% respectively. After the same pots were used five consecutive times for the same experiment the decrease in bulk density was 7.5%, 15.8%, 23.3%, and 26.7%. The difference was significant only in the 0.3 and 0.4% treatments between the first and the fifth time. The authors attributed the difference to decrease in efficiency of the polymer (Al-Harbi et al., April 1999; Andry et al., 2009).

4. *Effect on Infiltration*

The use of hydrogels can reduce water infiltration in soil therefore avoiding potential loss to deep percolation (Hüttermann et al., 2009) . Lentz et al. (2007) studied the role of cross-linked polyacrylamide (Stockosorb®) in inhibiting water infiltration in loam, silt loam, loamy sand and clay loam soils. In all soils, except loamy sand, water seepage decreased time and increased polymer rates. The seepage rates of soils treated with 10 g SAP/Kg of soil were reduced 82 to 92% for silt loam, 93% for loam and 51% for clay loam relative to control (Lentz, 2007).

5. Effect on Salinity

The presence of hydrogels has been found to mitigate the effect of soil salinity on plant growth, despite the fact that their water absorption is greatly reduced by a high electric conductivity. Improved performance of plants was shown for tomatoes, cucumbers and corn among others (Chen et al., 2004). A study conducted on the euphrat poplar (*Populus euphratica*) showed that plants treated with salt and a hydrogel amendment (cross-linked polyacrylamide) had a 2.7-fold higher biomass than those grown in soils treated with salt only (Chen et al., 2004). This study shows that hydrogel amendment in saline soil enhanced Ca^{2+} uptake and increased salt exclusion capacity of *P. euphratica*. As a result, the negative effects of salinity were eased and plant growth was eventually improved. The beneficial effects of polzymer amendment is most likely results from hydrogels covering and surrounding plant roots. Root aggregation allows good contact of roots with Ca^{2+} and reduces contact with Na^{+} and Cl^{-}, which most likely plays a major role in improving salt tolerance (Chen et al., 2004). Doraji et al. (2010) also studied the effect of different rates of hydrogels under various salinity levels on the growth of corn plants. The available water capacity of soils treated with hydrogels was reduced as salinity in irrigation water increased. However, for the same salinity level, higher rates of hydrogel, especially in loamy sand soils, gave higher roots and shoots biomass (Dorraji et al., 2010).

6. Effect on Heavy metals.

Heavy metals, salinity and fertilizers are all important for the soil-plant relationship. Hydrogels are well suited to bind some of these heavy metals and to reduce their plant availability. Hüttermann et al. (2009), states the structure of most hydrogels resembles that of humus in soil because they both possess functional groups which are hydrophilic and bind cations (Hejduk, 2012). However, hydrogels have a higher density of these groups and have no aromatic functional groups. SAPs are much more efficient than humic substances; plus they have the ability to hold more water under drought conditions as compared to humus which can become hydrophobic (Hüttermann et al., 2009).

As indicated by de Varennes & Torres (1999), in free solution several metal ions are trapped within the hydrogel polymer and cannot be released (Varennes & Torres, 1999). Guiwei et al. (2008) found out that after planting orchardgrass in Pb contaminated mine soil amended with hydrogels, Pb concentrations present in the amended soil were 15-66% of those in the unamended soil.

D. Hydrogel effect on plants yield, growth and water use efficiency.

One of the most sought after advantages of hydrogels is their ability to reduce the irrigation frequency especially in coarse-textured soils in arid and semi-arid regions (J. Abedi-Koupai, 2006, Chatzoudis & Rigas, 1999). Dorraji (2010) states that SAP amendments increase yield and water use efficiency of plants, translating into an increase in plant biomass (Dorraji et al., 2010). Hydrogels assist plant growth by increasing plant available water, inducing faster growth of plants and also prolonging their survival under harsh conditions (Beniwal et al. , 2010; Buchholz & Graham, 1998; Hüttermann, 1999).

El-Rehim et al. (2004) evaluated corn emergence, growth and wilting time in SAP amended sandy soil. Higher rates of polymers gave faster plant emergence than control soils. Also the study shows that corn grown on hydrogel amended soil gave 1.5 times higher total dry weight, taller plants at 12 weeks and larger leaf width than on control soil. Similar results have been reported in corn and bean crops by Lentz and Sojka (2009). Burke et al. (2010) have also found that hydrogel amended soil (mix of potting soil and sand) increased the biomass of rye grass by 30, 140 and 300% in normal, semi-arid and arid conditions. Dorraji (2010) found higher water use efficiency in corn plants in loamy sand and Sandy Clay where hydrogels were used.

In cucumber, water use efficiency at 40 Kg hydrogel / ha under 50% deficit irrigation was found to be around 2.37 times higher that of plants in untreated sandy soil (El-Hady, 2006). Other plants like tomatoes, lettuce, barley, wheat, chick pea and some tree species have also shown similar results in SAP amended soil (Akhter et al., 2004; Hüttermann et al., 2009).

Hydrogel amendments have been utilized for establishment of tree seedlings and transplanted trees in arid regions of Africa and Australia for their positive effect on plant survival (J. Abedi-Koupai, 2006). It has also been reported that SAPs have been used in the reforestation of barren soils of Uganda and China (Hüttermann et al., 2009). Hydrogels have been tried for grass restoration in arid regions where regular irrigation is a constraint (Lucero et al., 2010). The survival rate of plants in SAP amended soils doubles in the absence of irrigation (Abedi-Koupai, 2008; Rowe, 2005). Andry (2009) explains this beneficial effect by saying that when the surrounding temperature of the water swollen hydrogel granule increases, it releases this absorbed water, which could then be used by plants when needed.

Hydrogels have been found to enhance survival of pine trees in sandy loam soils. In soils treated with 0.4% hydrogels, pine seedlings survived around 82 days while control seedlings (no hydrogel) survived on average 49 days after a desiccation period at 30°C (Hüttermann, 1999).

A study has shown that even when there is enough water for the plants to grow, the presence of hydrogels promoted shoot and root growth. The results were drawn after measuring the growth of nine tree species grown in sandy, silty and clay soils with an adequate supply of water (Orikiriza et al., 2009). Higher rates (3 g/L) of hydrogels also gave a significantly higher wheat yield in soils that weren't subjected to any water stress, while under severe water stress no or low rates (0.1 g L^{-1}) gave higher yields (Geesing, 2004).

In other cases the use of hydrogels showed to be detrimental to plant health. Such as the case of Aleppo pine (*Pinus halepensis* Mill.) seedlings survival in loam soil in Spain. Higher survival rates were recorded in control than in hydrogel amended soils. This effect was attributed to higher root growth and seedling transpiration as hydrogel-amended soils show significantly higher soil water contents (Del Campo et al., 2011).

In strawberries planted in black (soil rich in humus mixed with clay) and sandy soils, the addition of hydrogels gave a significant increase in frost injuries in both soils compared to control. This effect was attributed to an increase in humidity. However the higheest strawberry yield was obtained from plants grown in soil treated with hydrogel addition of 3 g/dm^3. The fruit yield was over 40% higher than the yield obtained from plants grown in soil without hydrogel, while a hydrogel treatment of 6 g/dm^3 decreased the yield insignificantly compared to control (Makowska, 2004).

E. Reforestation Works

From 2600 B.C., documented by the earliest Egyptians and Mesopotamians, until around A.D. 138 the now Lebanese mountains were known for their valuable timber. Today, much of these forests have disappeared. Only patches survive of the formerly extensive and diverse forests (Mikesell, 1969).

Plans for the reforestation of Mount Lebanon began before the civil war but were hindered by many geographical, economical and societal issues. However, in the past decade, reforestation of Lebanon restarted and millions of tree seedlings have been planted across the country.

According to the Lebanese Reforestation Initiative (LRI) the reforestation process lasts 29 months from ordering seedlings to planting and irrigation.

Outplanting is done from November to January, and after that monitoring should be done on survival and proper establishment of the seedlings. Irrigation of the trees is done from May to September.

The role of hydrogels in the process begins from the nursery and continues to the field at transplanting. The preliminary studies done by Hüttermann et al. (1999) have shown that highly cross-linked polyacrylamide can be used effectively for the growth of ornamental trees both in the greenhouse and outdoors in the field or garden. The results indicate that amending soils with highly cross-linked polyacrylamide (Stockosorb®) significantly enhances the drought tolerance of the tree seedlings growing especially in sandy soils (Hüttermann, 1999; Mikesell, 1969) .

F. The Lebanon Reforestation Initiative (LRI)

This thesis is funded through and supported by the Lebanon Reforestation Initiative which will benefit from the recommendations deduced by the experiments' results.

LRI is a project funded by the United States Agency for International Development (USAID) and implemented by the United States Forest Services (USFS) that provides technical assistance and support for native tree reforestation and wildfire prevention.

One of the primary objectives of the LRI project is to support native tree planting on a large scale across all regions of Lebanon. Since 2011, working with local communities, more than 380,000 native tree seedlings of 25 different species, including cedar, fir, juniper and pine have been planted to restore biodiversity all around Lebanon (LRI, 2014).

Also, LRI works closely with native tree nurseries, providing them with advanced technologies and technical support to ensure the production of healthy vigorous seedlings with high after-planting survival rates.

Studying the effect of hydrogels on plant growth and survival will help in optimizing water use in the reforestation process from nursery to field planting.

G. Trees:

1. Stone Pine (Pinus Pinea) description

Native to the Mediterranean region, the stone pine has a somewhat flattened round canopy. The tree ultimately reaches 20 to 30 meters in height. The bright green, stiff, 15 cm long needles are arranged in slightly twisted bundles, and are joined by the heavy, cones which remain tightly closed on the tree for three years. The trunk is showy with narrow, 30 cm orange plates set off nicely by darker fissures.

Environmentally, the species is highly adapted to the high temperatures and drought characteristic of Mediterranean climates (IFAS, 2014). Stone pine is a slow growing tree which value comes mainly from its nuts which are the most important edible product of Mediterranean forests (Calama et al., 2008).

Nut yields vary annually and it has been demonstrated that these are mainly due to climatic factors the most limiting being water stress (Mutke et al., 2005). Flowering in a particular year depends on the winter of the previous year which has a direct effect on the formation and number of cone buds. Therefore, a good cone initiation year is linked to the previous year's rainfall. Rainfall in a certain season also affects the size of the harvested cones produced in the 3rd year. Nut /cone weights ratio depends upon precipitation from late spring to early summer of that year. Good cone initiations to a good harvest in the 3rd year occur when there are neither extreme temperatures nor droughts in the process (Calama et al. 2007).

a. ***Stone pine in Lebanon***

The status of stone pine (*Pinus pinea*) in Lebanon is controversial. It is believed that it is an introduced species, but other sources speculate that it can also be endemic (Mikesell, 1969).

In general, pine species are extensively used in reforestation works around the Mediterranean, and especially in Lebanon (Fallour et al., 1997; Roldán et al., 1996; SPAAK, 1995; Talhouk et al., 2001).

2. Carob (Ceratonia siliqua L.)

The Carob (*Ceratonia siliqua* L.) tree, which belongs to the Leguminaceae family, is native to southeastern Europe and western Asia. It is an evergreen tree with compound large rounded leaves, and can grow up to 15 meters high (Khan, 2010).

Carob trees grow best under Mediterranean climates, which are characterized by a long dry summer. Despite drought conditions and negligible rainfall, leaves of *C. siliqua* keep their green color and turgidity as water becomes scarce during the dry season, revealing the high adaptability of this tree to drought conditions (Correia et al., 2001). Root growth of *C. siliqua* seedlings was found to be minimally affected by soil drying, as a small amount of deep roots can supply enough water to the shoots, even when the upper soil layers were dried out. Carob leaves and vascular have well adapted responses to long periods of dryness (Correia et al., 2001; Rhizopoulou & Davies, 1991).

In Lebanon, carob trees can be found from the coastal areas up to 800m on the western slopes of Mount Lebanon. The importance of carob trees in Lebanon is economical as well as environmental. Trees are widely used in reforestation of arid and degraded areas (Haddarah et al., 2013).

3. Flowering ash (Fraxinus ornus)

The flowering ash or Manna ash (*F. ornus)*, which belongs to the Oleceae family, is a small, deciduous tree, native to southern Europe. The leaves of the ash tree are opposite, made of seven leaflets, and it produces creamy white flowers in clusters. Its height can reach 21 meters (Khare, 2007; Verdu et al., 2007).

4. Juda's tree (Cercis siliquastrum)

Cercis siliquastrum, Judas tree (Fabaceae) is native to eastern Mediterranean, and has a wide distribution in western Asia. It can reach a height of 5–10 m. The leaves are bluish green with rounded tips. *C. siliquastrum* flowers from March to April, flowers are pink, borne in. The tree is widely distributed in the Mediterranean at altitudes ranging from 0 to 800 m above sea level. *C. siliquastrum* grows has the ability to withstand hot dry summer conditions if enough moisture was stored in the soil during the rainy season (Zahreddine et al., 2007).

H. Crops

1. Corn (Zea mays) description

Corn (*Zea mays* L.) belongs to the Graminae family. It is one of the top three cereal crops grown in the world, along with rice (*Oryza sativa*) and wheat (*Triticum* spp.). In 2009, Lebanon produced 4,700 tons of corn, in an area covering 1,298 Ha, while importing 380,357 tons of corn (MoA, 2009).

a. ***Cultural Practices***

Z. mays may be grown in Lebanon with or without irrigation. Field corn sowing starts when soil temperatures reach 12°C; while sweet corn is sown later when temperatures go up to 14 – 16°. Planting can take place throughout the summer.

Maize plants grow best in well-draining, nutrient-rich soils with a pH between 5.5 and 7.0 and are not very tolerant of saline soils. Plant development depends greatly on variety, temperature, soil, water and radiation (Rhoads, 1990; Stewart & Nielsen, 1990), but on average grain maize needs around 125 to 180 days from planting to harvest (Critchley et al., 1991). Crop density for irrigated maize is typically around 60,000 – 80,000 plants per hectare (Birch et al., 2008).

b. ***Growth Stages***

Hanway (1963) proposed eleven stages of growth of maize, with stage 0 being germination and emergence and stages 6 – 10 occurring after silking. Germination and emergence occur 0-14 days after sowing, depending on surrounding conditions such as soil moisture and temperature, depth of seed and soil compaction. Fourteen to forty-two days after sowing, a permanent fibrous, thick, root system reaching down typically to 1 – 2 m forms. The tassel begins to differentiate when about 5 leaves have emerged, and lower leaves may start to senesce by the end of Stage 2.

In the late vegetative stage (42-60 days after planting), internode elongation produces a new leaf every three to four days. The production of leaves stops when the meristem starts converting into an inflorescence (Irish & Jegla, 1997). By the end of stage 3 the 16th leaf will have started to emerge, the tassel will have reached full size although will not have fully emerged and the ears within the husks will be a few centimeters long. Tillering (development of stalks from axillary buds) is cultivar dependent, with some cultivars forming few if any tillers under any conditions, and some forming numerous tillers under all conditions.

In terms of crop performance, growth refers to biomass accumulation and is measured by parameters such as leaf area, shoot/root weights and plant height.

c. ***Water Requirements of Corn***

Generally, maize is less water stress tolerant than other field crops, including sorghum. Water stress, could cause considerable yield losses and may even extend the vegetative growth period (Rhoads, 1990).

FAO globally estimates seasonal water use of maize to range between 500 and 800 mm of water (Critchley et al., 1991) while sweet corn may use up to 850 mm of water during the growing season (Srinivasan et al., 2004). In the Bekaa valley, seasonal evapotranspiration of maize was found to range between 540 to 570 mm (Karam et al., 2003).

Water stress during vegetative growth greatly affects the growth of stems and leaves which translates into reduced growth and Leaf Area Index (LAI) (Rhoads, 1990; Çakir, 2004a). At a deficit irrigation treatment of 60% of soil field capacity, Karam et al. (2003) noted a 25% reduction in LAI at silking.

Also, a 3-year study showed that corn growth and yield were significantly influenced by water stress due to absent irrigation during tasselling and cob formation. Limited water deficits during vegetative growth caused up to 32% loss of final dry matter weight, and more prolonged deficit during tasseling and ear formation caused 66-93% decrease in grain yield. Full irrigation and stress during vegetative growth stages gave the highest yields (Çakir, 2004b). Musick (1980) cited by Rhoad shows that the sensitivity of corn plant growth stages to water deficit declines in the following order: flowering and pollination > grain filling > vegetative growth (Musick & Dusek, 1980; Rhoads, 1990).

CHAPTER III

MATERIALS & METHODS

To study the effect of hydrogel on water availability and plant growth the following experiments were conducted between July 2012 and April 2014.

One field experiment, two greenhouse pot experiments and a laboratory study were conducted. The field experiment was conducted at Agricultural Research and Education Center (AREC) of the American University of Beirut (AUB) in the Central Bekaa Region and two soils were used in the laboratory study and the pot experiments. One of them was collected from site of the field experiment at AREC and the other was collected from a pine tree forest in Mount Lebanon. This chapter will explain the procedure followed in this study.

A. Methods of Soil Analysis

Soil analysis was carried out on the two types of soils used this study. Soil 1 was sampled from Block D at the AREC. Soil 2 was sampled from a pine tree forest located in Ain Saadeh, in Mount Lebanon. The soils were analyzed for selected physical and chemical properties according the procedures outlined by Bashour and Sayegh (2007).

1. Physical Analysis

The soil samples were air-dried for about three days, then ground to break up clods and obtain particles of uniform size. They were then sieved using a 2 mm-sieve and placed in a clean plastic container for analysis.

a. ***Soil Moisture Content***

Soil moisture content was determined using the gravimetric method. This method consists in oven drying the samples at 105 to 110°C for 24 hours then estimating moisture level in the soil from the difference between the air-dry and oven dry weights. The moisture content of the soil was used as a correction factor in subsequent analyses that are based on oven dry soils.

b. ***Soil Texture***

Soil texture analysis was done following the Bouyoucos hydrometer method (Bouyoucos, 1962).

A volume of 20 ml of Sodium Hexametaphosphate, used as a dispersing agent, and distilled water were added to 50 g of soil. The sample was then mixed using a blender until all aggregates were broken down then transferred into a settling cylinder. The Bouyoucos hydrometer was set to obtain two readings at 40 seconds and two hours. The temperature of the suspension was also taken to adjust readings. The textural class of the soil sample was obtained using the USDA textural triangle.

c. ***Bulk Density***

Since the soil samples were transported in bags and it was not possible to get a consolidated sample, the disturbed soil sample bulk density was measured. This method consists in filling a pre weighed graduated cylinder with air dry soil, compacting the soil by tapping the cylinder a few time to compact the soil, then recording the volume of the cylinder and weight of the soil.

2. *Chemical Analysis*

The chemical properties of soil samples that were analyzed are the following: pH, Electrical Conductivity (EC), total free calcium carbonates (CaCO3%), ammonium acetate extractable cations (Sodium (Na), calcium (Ca), and potassium (K)) and sodium bicarbonate extractable phosphorous (P).

a. ***Soil reaction (pH) and Electrical Conductivity (EC)***

Soil acidity and alkalinity are measured in terms of pH values of the soil's aqueous solution or extract. Soil pH significantly affects nutrient availability as well as the type and population size of microorganism in a certain soil. Electrical conductivity of a soil solution designated to measure the concentration of total soluble salts in the solution, revealing the level of soil salinity, which greatly affects the performance of hydrogels.

The pH and EC were obtained in a 1:2 ratio of soil: distilled water suspension that was shaken for 30 minutes on a mechanical shaker at 300 rpm. The solution was filtered with Whatman no. 40 filter papers. A pH-meter and an EC-meter were used to measure the pH and EC of the filtrate.

b. ***Total Calcium Carbonate ($CaCO_3$)***

Soils of arid and semi-arid regions are characterized by their considerable calcium carbonate content, which is largely caused by low rainfall and limited leaching. The amount of a $CaCO_3$ present in the soil affects its physical and chemical properties by acting as a cementing agent and increasing pH (Bashour & Sayegh, 2007).

The acid neutralization method was used to measure the free $CaCO_3$. Five grams of each soil sample were boiled with excess amount (100 ml) of 1 M Hydrochloric acid (HCl) for five minutes. The acid reacts with the carbonates and the acid not used in the process was back-titrated with 0.5M Sodium hydroxide (NaOH) solution using few drops of phenolphthalein indicator.

c. ***Ammonium Acetate Extractable Cations***

Five grams of the soil were mixed with 20 ml of 1M ammonium acetate (NH_4OAc) and shaken for 30 minutes. The suspension was then filtered using a Whatman no. 40 filter paper and Na, Ca and K were measured by Flame Photometer.

d. ***Sodium Bicarbonate Extractable Phosphorous or Available P (Olsen method)***

Available phosphorus was measured as outlined by Olsen (1965) using five grams of the soil that were extracted by 100 ml of the extracting solution (0.5 M sodium bicarbonate, NaHCO3).

B. Laboratory Study

The objective of this study was to assess the moisture characteristics of the two types of soils used in the field and pot experiments after mixing them with 5 rates of hydrogel (0, 1, 2, 3 and 4 grams of hydrogel per kilogram of soil).

A pressure plate apparatus was used to determine the effect of hydrogel on the soil moisture characteristic curves of the two soils. A sample of 20 grams of each soil were mixed with 0, 0.02, 0.04, 0.06 and 0.08 g of hydrogel. The samples were left to soak in distilled water for a minimal period of 12 hours, to secure reaching saturation stage. They were then placed on ceramic pressure plates inside a pressure chamber. After tightly closing the chamber, the required pressures (0.15, 0.3, 1, and 2 Bar) were applied. Driven by the applied pressure, water moved from the samples through the ceramic plate, and was collected outside the chamber. When water ceased to outflow from the chamber, the matric potential of the soil was considered to be in equilibrium with the applied pressure. Samples were then rapidly transferred to metallic cans, weighed and then placed inside an oven at 110°C. Water content of the samples was determined using the gravimetric method (Smith & Mullins, 2000).

C. Field Experiment:

1. Experimental Site

The experiment was conducted at AREC from July 2012 to November 2013. AREC is located in the central part of the Bekaa valley, with an elevation of 1000 m above sea level at 33°55’ latitude and 36°04’ longitude. The normal average annual rainfall is around 500 mm. The experiment took place in Block D (Figure 1) from which clay soil was sampled.

Figure 1: Map of AREC showing circled experimental plot (Block D).

2. *Climatic Data*

Table 2: Average monthly weather data at AREC from July 2012 to November 2013

	Rainfall (mm)	Mean Max Temp	Mean Min Temp	Relative Humidity %	Wind Speed m/s
Jul-12	0	33.0	15.4	39.1	1.61
Aug-12	0	32.2	15.0	38.9	1.52
Sep-12	1.5	29.6	12.3	43.2	1.6
Oct-12	42	24.2	9.1	47.0	1.53
Nov-12	72.5	19.0	6.8	64.0	1.34
Dec-12	163.3	12.8	2.8	77.9	1.43
Jan-13	171.4	10.6	-0.4	77.3	1.42
Feb-13	52.7	13.6	2.7	74.2	1.58
Mar-13	9.6	17.2	4.0	54.6	1.91
Apr-13	25.9	19.8	5.8	57.0	1.68
May-13	9.5	26.7	10.3	44.7	1.56
Jun-13	0	29.8	12.9	35.7	1.85
Jul-13	0	33.0	15.4	39.1	1.61

Aug-13	0	32.2	15.0	38.9	1.52
Sep-13	1.5	29.6	12.3	43.2	1.6
Oct-13	4.2	24.2	9.1	47.0	1.53
Nov-13	9.4	19.0	6.8	64.0	1.34

3. Tree seedlings

The seedlings used in this experiment were from Carob tree (*Ceratonia siliqua*), South European flowering ash (*Fraxinus ornus*) and Juda's tree (*Cercis siliquastrum*). The seedlings were eight months old, planted in the nursery at AREC. Seventy-five seedling of each species were transplanted into the field at a spacing of one meter between trees.

4. Hydrogel Treatments

Pits of 60 cm radius and 40 cm depth were dug using a tractor operated auger. The amount of soil extracted was transported into a wheel barrow and weighed. The appropriate amount of hydrogel was then added and mixed according to weight. Hydrogel was mixed with the soil at the following rates: 0, 0.5, 1, 2 and 4 grams of hydrogel per kilogram of soil.

5. Experiment Design

The experiment design was a completely randomized design (CRD).

Hydrogel treatments: Five, at the rates of 0, 0.5, 1, 2 and 4 grams of hydrogel per kilogram of soil.

Replicates: Three (15 trees per replicate).

Trees: Three types (*C. siliqua, F. ornus* & *C. siliquastrum*).

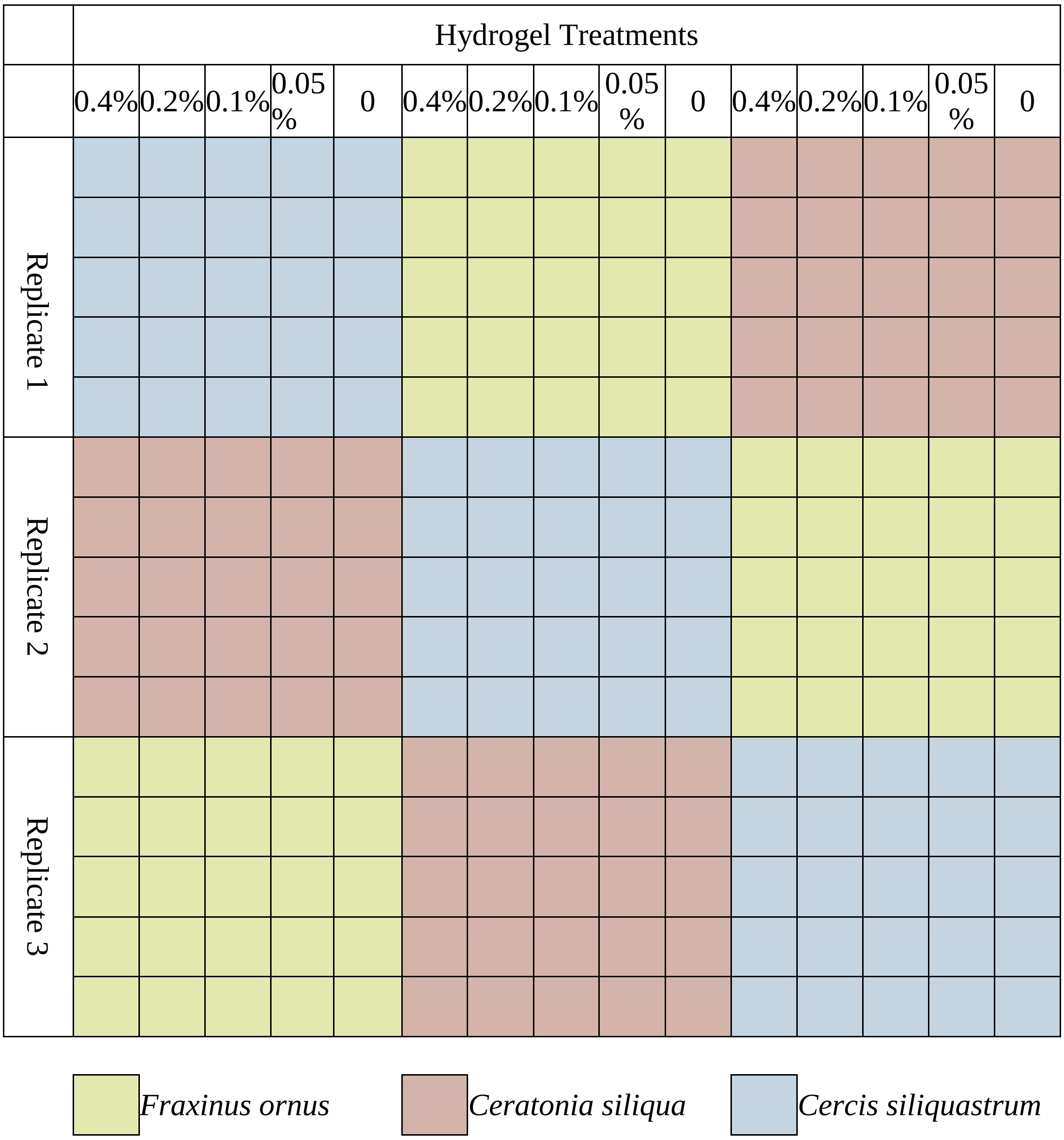

Figure 2: Experimental layout at AREC

6. Cultural Practices

Trees were planted on July 7, 2012. Following planting irrigation was done manually twice a week for the two subsequent weeks. Trees were subsequently left without artificial watering. Tree survival was then monitored regularly. The final tree survival assessment was done in November 2013.

7. Statistical Analysis

A One Way ANOVA analysis of the field experiment data was done using the Excel program Data Analysis Toolpack.

D. Pot Experiments:

Two pot experiments were conducted. The the first experiment (May-June 2013), corn was the test crop. The second experiment (October 2013-April 2014) studied the effect of hydrogel on pine seedlings' survival.

1. Corn Experiment

Corn experiment was carried out in pots placed inside a greenhouse in the AUB campus in Beirut, from May 7 to June 20, 2013.

a. ***Soil***

The same soil types used in the laboratory work were used in this experiment. Around 4 liters of each soil were placed in clean plastic pots.

b. ***Hydrogel treatments***

i. Rates

The rates of hydrogel that were mixed in soil are 0, 1, 2, 3 and 4 g hydrogel per kg of soil.

ii. Methods of Application

Hydrogels were applied using two methods (Figure 3):

- Banding: placed in one layer at a depth of 15 cm mixed with 1.5 gram of soluble 20-20-20 fertilizers.
- Incorporation: the same amounts of hydrogel and fertilizers were thoroughly mixed with the soil then filled in the pots.

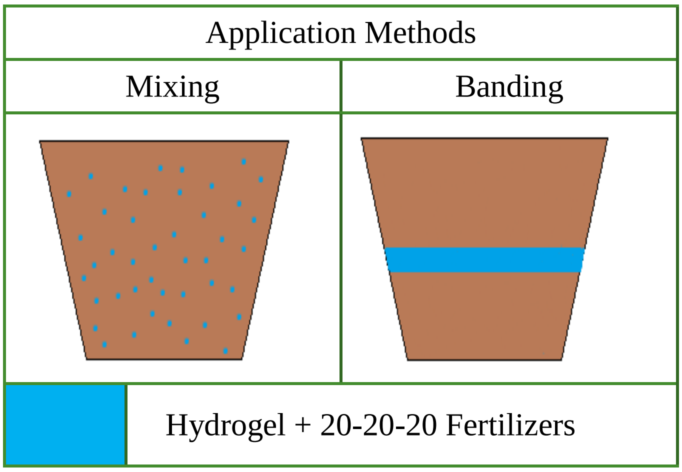

Figure 3: Hydrogel Application Methods.

c. ***<u>Crops</u>***

The tested crop was corn (*Zea mays*). Corn was chosen for its susceptibility to water stress as well as its practicality in pot experiments. Five seeds were directly sown in the pots. After germination plants were thinned to three seedlings per pot. Fresh and dry weights of areal parts were measured 7 weeks after planting.

d. ***<u>Irrigation</u>***

Pots were weighed and irrigated weekly. Around 600 ml (beginning of experiment) to one liter (before end of experiment) of water were added to all pots weekly. During the experiment, all pots received the same amount of water, which was measured with a graduated cylinder.

e. ***<u>Greenhouse Environment</u>***

The greenhouse was aerated by an automatic fan. Temperature was monitored and varied between 24 and 29°C throughout the experiment. Relative humidity also varied between 42 and 59% with an average of 48.5%.

f. ***<u>Experiment Design</u>***

A three way factorial arrangement of treatments (2x2x5) for soil type, hydrogel application method and application rate, and their two and three way interactions in a complete randomized design was used for this pot experiment.

The main factors are:

- Hydrogel treatments: Five rates of 0, 1, 2, 3 and 4 g hydrogel per kg of soil.
- Soils Type: Two types of soil (Clay and Sandy Clay).
- Application Method: Banding and mixing.

Replicates: Three.

Tested Crop: Corn.

2. Pine Seedling Experiment:

The pine seedling experiment was also carried out in pots placed inside a greenhouse in the AUB campus in Beirut.

a. ***Soil***

Soil 1 and Soil 2 were also used in this experiment. Around 15 liters of each soil were filled in clean plastic pots.

b. ***Hydrogel Treatments***

i. Rates

The rates of hydrogel were 0, 0.2, 0.3 and 0.4% w/w.

ii. Method of Application

Hydrogels were applied using two methods (Figure 3):

- Banding: placed in one layer at a depth of 25 cm.
- Incorporation: the whole amount of hydrogel was thoroughly mixed with the soil then filled in the pots.

c. ***Trees***

Pine tree seedlings (*Pinus pinea*) were used in this experiment. This type of tree was chosen for its extensive use in reforestation projects in the region. The three months old seedlings were provided by Lebanese Reforestation Initiative (LRI). Survival of trees was monitored weekly by their appearance. The trees were considered dead when the needles became grey and dry.

d. ***Irrigation***

Pots were thoroughly irrigated for one week after planting. Irrigation stopped to start the desiccation period which will determine which treatment most aided the survival of trees without artificial water addition.

e. ***Experimental Design***

A three way factorial arrangement of treatments (2x2x4) for soil type, hydrogel application method and application rate, and their two and three way interactions in a complete randomized design was used for this pot experiment.

The main factors are:

- Hydrogel treatments: Four rates of 0, 2, 3 and 4 g hydrogel per kg of soil.
- Soils Type: Two types of soil (Clay and Sandy Clay).
- Application Method: Banding and mixing.

Replicates: Three.

Plant: Pine seedling *Pinus pinea*

E. Statistical Analysis of Pot Experiments

The General Linear Model procedure of SAS program was used for analyzing the data collected by Student Newman Keuls where appropriate with a significant difference of $P<0.05$.

CHAPTER IV

RESULTS AND DISCUSSION

This research focuses on the effect of a hydrogel amendment on soil moisture and plant growth and survival of plants in two types of soils. It also evaluates different rates of hydrogel additiona as well as two methods of application (mixing or layering). In this chapter, results of soil analysis, laboratory study, field and two pot experiments will be illustrated and discussed.

A. Soil Characteristics

The soil samples used in this study were collected from Block D at the Agricultural Research and Education Center (AREC) in the Central Bekaa Region (Soil 1) and from a pine tree forest located in Ain Saadeh, Mount Lebanon (Soil 2). The results of physical and chemical analysis are presented in Table 3.

Table 3: Physical and chemical properties of the soils soils included in the study.

Characteristic	**Value**	
	Soil 1	**Soil 2**
Texture	Clay (26.6% sand, 28.7% silt and 44.7% clay)	Sandy clay (47.1% sand, 17.1% silt and 35.8% clay)
pH (1:2 soil: water ratio)	8.02	7.87
EC (mS/cm) (1:2 soil: water ratio)	0.48	0.72
Na (mg/kg) (NH_4OAc extract)	115	95

K(mg/kg) (NH_4OAc extract)	550	120
P (mg/kg) (NaHCO3 extract)	31	25
Ca (mg/kg) (NH_4OAc extract)	2,975	685
OM% (Furnace burning)	2.11	1.9
$CaCO_3$ % (acid neutralization method)	21	12
Bulk density (g/cm^3) (cylinder method)	1.34	1.5
Field Capacity (% Moisture Content at 0.3 bar)	31.5%	19.1%

The results indicate that:

Soil 1 is Clay (C), highly calcareous, alkaline non saline and contains medium quantity of organic matter. It has sufficient levels of nutrients to support good plant growth.

Soil 2 is Sandy clay (SC), it is lighter in texture than soil 1, is calcareous, alkaline, non-saline with medium quantity of organic matter. Its content in nutrients is little lower than soil 1 because it has a coarser texture.

In general, both soils are suitable for plant growth if provided with sufficient amounts of water.

B. Laboratory Study

The laboratory study was conducted to observe the effect of different hydrogel treatments on the water retention curve of two soils. Each type of soil was treated with 0, 0.1, 0.2, 0.3 and 0.4% hydrogel (0, 1, 2, 3 and 4 grams of hydrogel per kilogram of soil). Soil moisture content of the treated samples was measured when subjected to different pressures ranging from 0.15 to 2 bars.

1. Water Retention

The results of water retention (Table 4, Figure 4, Figure 5) show that there was a general increase in moisture content at any given pressure with an increasing amount of applied hydrogel in both types of soils. However the increase relative to control treatment was more prominent in the coarser textured soil (SC) than in the fine textured soil (C).

Table 4: Effect of hydrogel treatments on water retention levels of the two soils (%).

Soil Type	Hydrogel Treatments (%)	Pressure (Bar)			
		0.15	0.3	1	2
Sandy Clay	Control	24.1%	19.1%	17.8%	15.3%
	0.1	24.7%	20.5%	17.9%	15.5%
	0.2	25.4%	20.9%	18.9%	16.7%
	0.3	28.5%	21.1%	20.3%	17.3%
	0.4	29.3%	23.9%	23.5%	18.4%
Clay	Control	37.5%	31.5%	24.1%	22.4%
	0.1	38.3%	31.5%	24.3%	22.8%
	0.2	39.3%	31.7%	24.5%	22.7%
	0.3	40.4%	32.6%	24.7%	22.8%
	0.4	41.4%	33.0%	25.1%	23.0%

The above table reports the moisture percentages of the treated soils as average values of two replicates.

Table 5: Effect of hydrogel treatments on soils reported as percentage difference from control.

Soil Type	Hydrogel Treatments (%)	Pressure (Bar)			
		0.15	0.3	1	2
Sandy Clay	0.1	2.5%	7.3%	0.6%	1.3%
	0.2	5.4%	9.4%	6.2%	9.2%
	0.3	18.3%	10.5%	14.0%	13.1%
	0.4	21.6%	25.1%	32.0%	20.3%
Clay	0.1	2.1%	0.0%	0.8%	1.8%
	0.2	4.8%	0.6%	1.7%	1.3%
	0.3	7.7%	3.5%	2.5%	1.8%
	0.4	10.4%	4.8%	4.1%	2.7%

a. ***Clay Soil***

The changes in the water retention levels as a result of mixing the soils with hydrogels at different concentrations are presented in Table 4. Figure 4 shows the water retention curve of the clay soil used at different rates of hydrogel. Field capacity for both soils was related to a 0.3 bar pressure. At the application rate of 0.4% (4 g/kg), clay soil retained on average 4.8% more water than control at field capacity. The same treatment retained on average 10.4% more water than control at 0.15 bar pressure. Treatment of 2 and 3 g/kg increased water retention of clay soil 0.6% and 3.5% respectively at field capacity when compared to control.

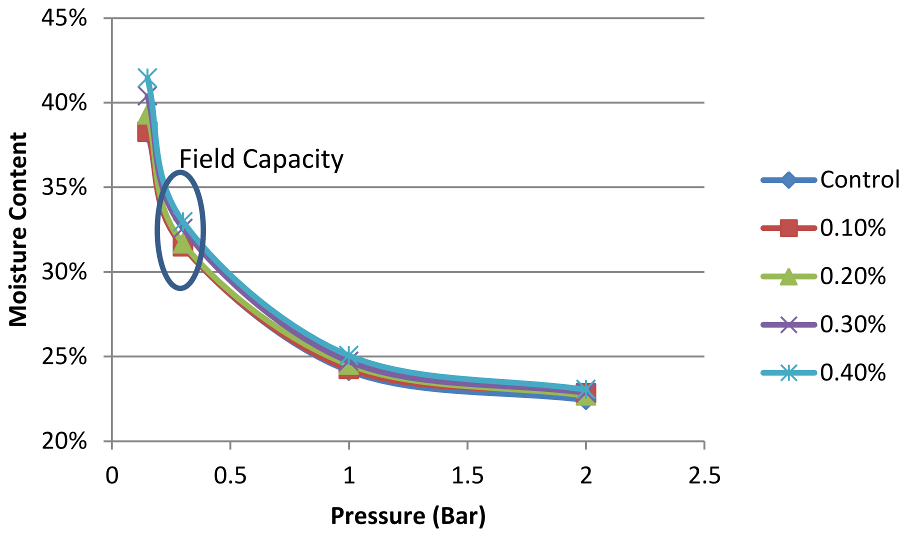

Figure 4: Water retention curve of Clay soil at different hydrogel levels

b. ***<u>Sandy Clay soil</u>***

Figure 5 shows the moisture retention curve of Sandy Clay soil at different levels of hydrogel. The maximum increases were obtained at treatments of 0.3% and 0.4% where SC retained on average 25.1% more water than control at field capacity.

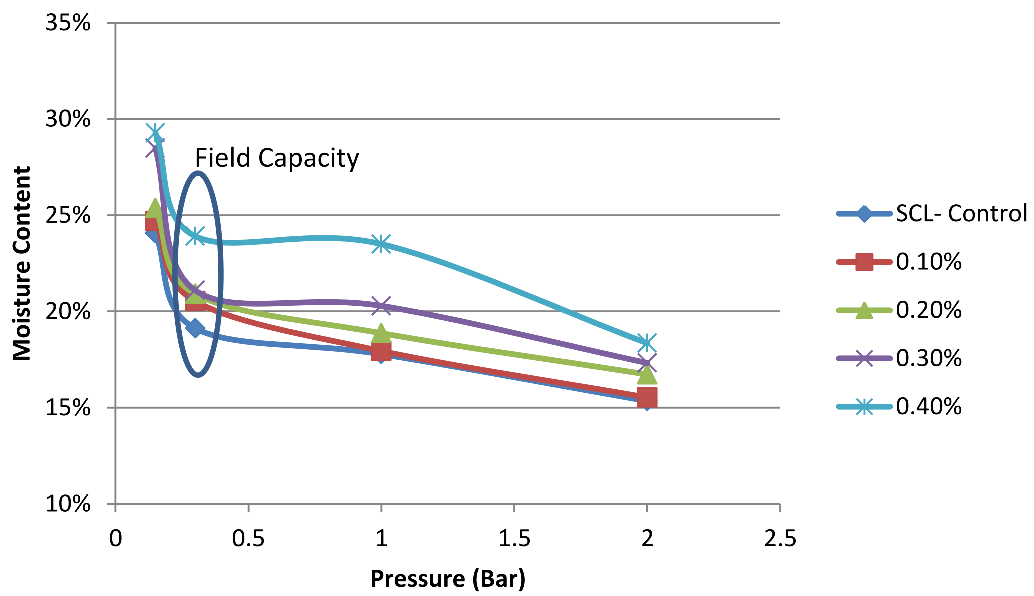

Figure 5: Water retention curves of Sandy Clay soil at different hydrogel levels.

The difference between treatments and control was more pronounced in Sandy Clay when compared to clay soil. Larger differences between treatments and control were recorded in SC than C.

2. Water Availability

The difference in soil moisture retention between hydrogel treatments and control decreased as pressure increased in both soils. Table 5 shows the percent difference in moisture between each treatment and control at different pressures.

In Clay soil the percent differences between treatments and control at the highest pressure (2 bars) ranged from 1.8 to 2.7%. In Sandy Clay, the percent differences between treatments and control were larger, ranging from 1.3% at 0.1% hydrogel to 20.3% for the highest rate of 0.4%.

This indicates that the majority of the water retained inside the hydrogel particles is released prior to the permanent wilting point.

These results show that as soil matric potential decreases, or as soil dries, hydrogel particles are able give off most of their absorbed water. Moisture content values of soils in all treatments came closer to control value at a pressure of 2 Bars, especially in Clay soil. The decrease in moisture content with increased pressure was more pronounced in higher rates of hydrogels.

These results are in accordance with Hüttermann (1999), who found that when subjected to high pressures from the pressure plate apparatus, soil treated with hydrogels released 90% of their absorbed water; suggesting that theoretically this water would be fully available for plant uptake.

C. Field Study

The field study conducted at AREC was done to test the effect of mixing five levels of hydrogels grown in a clay soil in open field conditions on the survival of three types of trees.

Five levels of hydrogel (0, 0.05%, 0.1%, 0.2% and 0.4%) were used in this experiment on three types of trees (*F. ornus, C. siliquastrum* and *C. siliqua)*. The trees were fully irrigated after planting. The survival of the seedlings was monitored from July 2012 till November 2013. The design was a Completely Randomized Design, with each treatment for replicated three times.

The results for this experiment are presented in Table 6. The survival rates among the tree types were different and are discussed in the following.

Table 6: Effect of hydrogel on survival of trees in the field. The table reports the number of surviving trees per treatment and tree type.

	Control	0.05%	0.1%	0.2%	0.4%	**Total**
Fraxinus ornus	1	0	1	0	1	***3***
Ceratonia siliqua	5	4	2	3	1	***15***
Cercis siliquatrum	14	12	12	12	9	***59***

1. *Fraxinus ornus*

Survival of *F. ornus* was low across all treatments, only three seedlings out of 75 survived from July 2012 to November 2013.

Figure 6: Live *Fraxinus ornus* seedling, taken on October 14, 2013

2. Ceratonia siliqua

Total mortality of *C. siliqua* averaged at about 80%. On average, 7% of the trees treated with 0.4% hydrogel survived until the end of the experiment, while 33% of control trees stayed alive. However this difference proved to be statistically insignificant.

Figure 7: *Ceratonia siliqua* seedling, taken October 14, 2013.

3. Cercis siliquastrum

Lowest mortality and highest growth were recorded in *C. siliquastrum* trees, with only 16 dead seedlings out of 75.

Figure 8: *Cercis siliquastrum* seedling, taken October 14, 2013.

4. Effect of hydrogel treatments on tree survival

Despite the fact that the lowest survival rate was recorded in treatments of 0.4% hydrogel in *C. siliquastrum* and *C. siliqua*, a One Way ANOVA analysis ($p < 0.05\%$) showed that differences between treatments were not significant for the three types of trees.

These results confirm that in clay soils the effect of hydrogels is weak, especially when drought tolerant species are being planted. These trees are well adapted to the periods of drought that are characteristic of the Lebanese climate and survive in its forests without any supplemental irrigation as grown trees.

In contrast, *C. siliquastrum* seedlings grew considerably in all treatments with only 21.6% of trees having died.

D. Pot Experiments

1. Corn Experiment

The same two soils used in the laboratory study were used in this experiment (clay and Sandy Clay). Four rates of hydrogel were tested 0, 0.1%, 0.2% 0.3%, and 0.4% (0, 1, 2, 3 and 4 grams of hydrogel per kilogram of soil). Two application methods (banding and mixing) were used for each treatment.

The study evaluated the effect of these treatments on the weights of corn plants' areal parts. At the end of the experiment the 3 corn plants that were planted in each pot were cut at 1 cm from soil surface. Fresh and dry weights of plants per pot were recorded. The data were analyzed using the SAS program, three factors were introduced in the experiment: hydrogel application rates, application method and soil type.

The Analysis of variance (ANOVA) was done to determine the significance and interactions between factors based on dry weight and moisture content at the 5% significance level.

Table 7 and Table 8 show the general results of the pot experiment as averages of three replicates.

Table 7: Effect of hydrogel on dry and fresh weight, and moisture content of corn plants (per pot) planted in SC.

Soil Type	Application Method	Hydrogel Application Rate	Fresh Weight (g)	Dry Weight (g)	Moisture Content (%)
Sandy Clay	Layering	Control	132.6	40.9	67
		0.10%	133.9	41.7	69
		0.20%	144.3	42.2	71
		0.30%	172.2	46.0	73
		0.40%	181.0	46.7	74
	Mixing	Control	116.7	38.4	67
		0.10%	101.1	37.6	63
		0.20%	119.3	40.6	65
		0.30%	119.2	38.4	68
		0.40%	103.7	37.8	65

Table 8: Effect of hydrogel on dry and fresh weight and moisture content of corn plants (per pot) planted in Clay

Soil Type	Application Method	Hydrogel Application Rate	Fresh Weight (g)	Dry Weight (g)	Moisture Content (%)
Clay	Layering	Control	162.4	43.1	71.7
		0.10%	156.2	42.4	71.0
		0.20%	162.5	42.9	73.3
		0.30%	165.2	43.2	73.7
		0.40%	174.0	44.8	74.0
	Mixing	Control	170.6	45.2	73.3
		0.10%	181.9	45.8	74.3
		0.20%	173.0	45.8	72.7
		0.30%	169.8	44.9	72.7
		0.40%	168.5	45.2	72.3

a. ***<u>Soil Type</u>***

Table 9 shows the average fresh weight, dry weight and moisture content of three corn plants in Clay and Sandy Clay soils irrespective of hydrogel treatment and application method. Clay soils gave a significantly higher dry plant weight than Sandy Clay.. This difference is largely expected, knowing that clay soils are more fertile than Sandy Clay soils and because naturally retain more water which increased growth and water uptake.

Table 9: Comparing average weights of corn plants/pot grown in clay and sandy clay soils (Dry weight SEM=0.52).

Soil Type	Dry weight (g)
Clay	44.6[a]
Sandy Clay	41.0[b]

b. ***Application Method of Hydrogel***

Table 10 shows the average fresh and dry weights of corn plants per pot with regards to application method irrespective of soil type and rate of hydrogel. Placing the hydrogel in one layer inside the soil lead to an increase of the fresh weight of corn plants by 19% and their dry weight by 9% when compared to mixing the granules with soil. Mixing distributed the polymer’s quantity somehow uniformly in the pot. These results indicate that the application method can have a significant effect on increasing the efficiency of use of superabsorbent polymers. A closer look at the interactions between the different factors of the experiment shows a significant interaction between soil type and hydrogel application method.

Table 10: Fresh weights of corn plants/pot with two application methods (SEM= 2.77)

Application Method	Fresh Weight (g)
Banding	164.4[a]
Mixing	138.7[b]

Table 11: Dry weights of corn plants/pot with two application methods (SEM=0.51).

Application Method	Dry weight (g)
Banding	44.5[a]
Mixing	40.9[b]

c. ***Rate of Application***

Table 12 shows the average fresh weight, dry weight and moisture content of three corn plants as affected by the rates of application of hydrogels, irrespective of soil type and application method.

High application rates, 0.3 and 0.4% gave significantly higher dry weight than control, with no significant difference between them. Rate of 0.4% gave significantly higher plant dry matter than control and rates of 0.1% and 0.2%. There was no significant difference between rates of 0.1%, 0.2% and 0.3%.

Table 12: Weights of corn plants per pot at different hydrogel levels (SEM=0.81).

	Control	0.1%	0.2%	0.3%	0.4%
Dry Weight (g)	40.7[c]	41.5[bc]	42.4[bc]	43.6[ab]	45.0[a]

The results of Table 12 show that the dry weight of plants significantly increased by applying high rates of polymer, fresh weight and moisture content of plants were not significantly affected by these treatments. These results indicate that only high rates of hydrogel (0.3% and 0.4%) can have a significant effect on plant growth and production of dry matter.

d. ***Significant Interactions***

The three way interaction term was not significant in this experiment. A two way interaction interaction between soil type and method of application was found to be significant.

i. Interaction between Type of Soil and Method of Application

Irrespective of the rate of application, mixing hydrogel in Sandy Clay resulted in a 38.4 g dry plant weight per pot, which was increased by 5.3 g when gel banding was utilized. This magnitude was not observed in Clay soil, as the difference was only 1.5 g.

Corn plants grown in clay soil had significantly higher moisture content than plants growing in Sandy Clay. Also, banding hydrogel in Sandy Clay soil led to in a significant increase in plant moisture content than mixing in the soil, irrespective of application rate.

Table 13: Dry weights of corn plants/pot as affected by soil type and hydrogel application method (SEM=0.86)

		Mixing	Banding
Dry Weight (g)	Sandy Clay	38.4[b]	43.7[a]
	Clay	43.8[a]	45.3[a]

Table 14: Moisture content of corn plants/pot as affected by soil type and hydrogel application method (SEM=0.80)

		Mixing	Banding
Moisture Content (%)	Sandy Clay	65.5%[c]	70.8%[b]
	Clay	73.5%[a]	73.3%[a]

The previous results are partially explained by Figure 9 where mean water content percentages of both types of soils under two application methods are displayed. The same trend observed in Figure 6 can be seen in this chart. Pots were weighed, irrigated abundantly with water then left to drain for three days until draining stopped. Pots were weighed again and their water content was measured.

This study’s results can be explained by the results obtained by the reported data Bhardwaj et al. (2007) on their study of the water retention by SAP in sandy soils. They found that the higher the hydrogels content of soil, the higher was their ablity to absorb water. This was explained by the fact that when confined by the soil matrix and under load, a single granule’s absorbing capacity can be significantly reduced; while at a higher concentration or when grouped together in a layer, granules can better withstand the pressure load of soil thus absorb more water. Thus, when applying SAPs in one layer, the granules are less restricted by the load of the soil matrix which enables them to absorb more water.

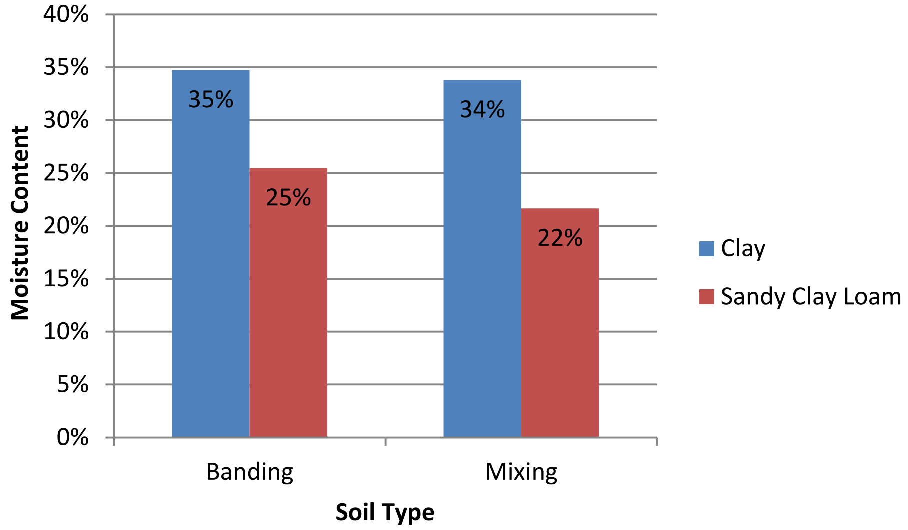

Figure 9: Mean moisture contents of soil in pots three days after first irrigation.

2. Pine Seedling Experiment

In the pine pot experiment, four rates of hydrogel were tested 0, 0.2% 0.3%, and 0.4% (0, 2, 3 and 4 grams of hydrogel per kilogram of soil). Two application methods (banding and mixing) were used for each treatment in the same soils used in the corn experiment (clay and Sandy Clay soils). The study evaluated the effect of these treatments on the survival of *Pinus pinea* seedlings after a desiccation period. Results of this experiment are reported in Table 15 Table 16.

Survival data in weeks was analyzed using the SAS program, three factors were introduced in the experiment: hydrogel application rates, application method and soil type.

The three way interaction term was not significant in this experiment, but all two way interactions terms were. Therefore data are presented and discussed in the following sections.

Table 15: Effect of hydrogel on pine seedlings survival time in Sandy Clay soil.

Soil Type	Application Method	Hydrogel Application Rate	Survival time after planting (weeks)
Sandy Clay	Mixing	Control	16
		0.20%	18
		0.30%	20
		0.40%	21
	Layering	Control	16
		0.20%	27
		0.30%	23
		0.40%	31

Table 16: Effect of hydrogel on pine seedlings survival time in Clay soil

Soil Type	Application Method	Hydrogel Application Rate	Survival time after planting (weeks)
Clay	Mixing	Control	22
		0.20%	23
		0.30%	27
		0.40%	27
	Layering	Control	22
		0.20%	27
		0.30%	28
		0.40%	31

a. ***Interaction between Rates and Method of Application***

Irrespective of soil type, banding hydrogel at the rate of 0.2% resulted in a significant 6.2 weeks increase in the life span of the seedlings, while mixing at this rate prolonged their survival by 0.5 weeks.

Table 17 shows the length of the survival period of pine seedlings as affected by four hydrogel rates and two application methods irrespective of soil type. Any addition of hydrogel using the banding method significantly extended the survival time of pine seedlings over control regardless of the type of the soil used. There was no significant difference between the lengths of the survival period between the three rates of hydrogel in both banding or mixing. However, only the rate of 0.4% gave significantly longer life span than control for the seedlings when hydrogels were mixed with soil.

Table 17: Survival of pine seedlings (weeks) at different hydrogel rates and application methods (SEM = 1.38)

	Control	0.2%	0.3%	0.4%
Banding	19.2^{d}	27.0^{ab}	27.6^{ab}	30.7^{a}
Mixing	19.0^{d}	20.5^{cd}	22.8^{bcd}	25.0^{bc}

(Pooled standard error of means SEM = 1.38)

These results also confirm that at higher rates, hydrogels are more effective than lower rates in absorbing water, especially when the mixing method is used.

Figure 10 shows the hydrogel layer in clay soils. The layer divided the soil into two parts that could be easily separated as soon as the dried soil block was removed from the pot. This thick layer had large pores and was not compacted at all due to the shrinking of hydrogel particles. Mixed treatment also left small air pockets in the soils, as seen in Figure 11. When the granules absorb water, they swell considerably, even when confined by soil particles. As hydrogels dry, the volume of the granules is strongly reduced, leaving large air pores in the soil.

Figure 10: The air pocket formed by the layer of hydrogel in clay soils 21 weeks after planting

Figure 11: Pores left by shrunken hydrogel particles in Sandy Clay soils21 weeks after planting.

b. ***Interactions between Soil Type and Rate of Application***

Irrespective of the application method, the addition of hydrogel to Sandy Clay soil, significantly increased the trees' life span by 5.7, 5.8 and 11.4 weeks for 0.2, 0.3 and 0.4% hydrogel respectively. This magnitude was not observed in Clay soils, as the difference was only 2.6, 5.3 and 6.5 weeks for 0.2, 0.3 and 0.4% hydrogel respectively.

There was no significant difference between control and 0.2 and 0.3% rates of hydrogel in Clay soil, where only the rate of 0.4% significantly increased tree survival by 6.5 weeks.

At each polymer application rate, there was no significant difference in survival time between the two types of soil; whereas in the survival time of control plants differed considerably between Clay and Sandy Clay. This observation may indicate that the addition of SAPs to Sandy Clay soil has the same effect of Clay on plants. Furthermore, these results point out clearly that hydrogels had a minor effect on plant survival in Clay soils.

Table 18: Survival of pine seedlings (weeks) at different hydrogel rates in Clay and Sandy Clay soil (SEM = 1.50)

	Control	0.2%	0.3%	0.4%
Clay	22.2[b]	24.8[ab]	27.5[ab]	28.7[a]
Sandy Clay	16.0[c]	22.7[ab]	21.8[b]	27.4[ab]

(Pooled standard error of means SEM = 1.50)

c. ***<u>Interaction between Soil Type and Method of Application</u>***

Table 19 shows the average number of weeks from transplanting until death of pine trees in Sandy Clay and clay soils treated by mixing and banding hydrogel amendments.

Irrespective of the rate of application, mixing hydrogel in SC resulted in tree survival of 18.1 weeks, which was increased by 6.9 weeks when gel banding was used. This magnitude was not observed in Clay soil as the difference was only 2.4 weeks.

Treatment of Sandy Clay with a layer of hydrogel resulted in a shorter tree life than clay but the difference was insignificant.

Table 19: Survival of pine seedlings (weeks) in clay and Sandy Clay soil with two application methods

	Banding	Mixing
Clay	27[a]	24.6[a]
Sandy Clay	25[a]	18.1[b]

(Pooled standard error of means SEM = 1.22)

These results show that not only the rate of hydrogel but the method of application too can have the same effect of clay soil on trees in Sandy Clay. Moreover, Figure 12 shows that banding treatments can allow roots to grow around hydrogel granules, which allows the plant to greatly benefit from the stored water.

Water saving is one of the most pressing issues that arid and semi arid areas are facing currently. With decreasing rainfall and sporadic distribution of precipitation events, practices should be implemented to save water as a precious resource.

The scope of this research was to find if the use of superabsorbent polymers with soil can achieve the purpose of assisting plant growth and survival by keeping water available for plant uptake for a longer period. Many studies reported that the addition of hydrogels has aided the development of plants; however more studies should be done on the economics of hydrogel use and its use under arid or severe drought conditions. In fact, currently the high cost of these polymers renders them impossible to use in large scale commercial agricultural production. Nonetheless, their limited use in landscaping, nurseries, ornamentals and even reforestation works only where the soil is majorly sandy.

Figure 12: Roots of a live tree growing around hydrogel granules.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. Summary

One field experiment, two greenhouse pot experiments and a laboratory study were conducted to test the effect of the use of superabsorbent polymer (hydrogel) Stockosorb660® on soil water retention and growth and survival of plants.

In the laboratory experiment, moisture content of clay and Sandy Clay soils treated with 0, 0.1%, 0.2%, 0.3% and 0.4% hydrogel was measured at several soil matric potentials. Treatments appeared to affect moisture content of sandy clay soil more than clay soil. Also hydrogels particles showed an ability to release most of their retained water as the soil dried.

The field experiment was conducted at the Agricultural Research and Educational Center (AREC) of the American University of Beirut (AUB) in the Bekaa Valley from July 2012 to November 2013, in order to study the effects of several rates of hydrogel use on survival of three types of trees. AREC's clay soil was treated with 0, 0.05%, 0.1%, 0.2% and 0.4% hydrogel before transplanting *C. siliqua*, *F. ornus* & *C. siliquastrum* trees. Irrigation was carried out only for two weeks after which tree survival was monitored. Results showed an insignificant survival rate with an increased rate of hydrogels. The lack of difference between control and treatments obtained in this field experiment can be highly attributed to the clay soil characteristic of AREC. Clay soils can hold enough water to sustain the drought tolerant trees for an elongated period of time. During this period water held inside polymer granules would have also been depleted due to heat and other factors. At the time when the plant needs the additional water all moisture and in the soil and SAP granule would be reduced causing tree necrosis.

The first greenhouse pot experiment was done to test how corn plants reacted to two application methods and five rates of application of hydrogels in clay and Sandy Clay. The rates of hydrogel used are 0, 0.1%, 0.2%, 0.3% and 0.4%, applied by layering or mixing with soil. Results showed that only the higher rate of application resulted in a significantly higher dry matter production when compared to control. None of the treatments gave a significant effect in clay soil. However, in Sandy Clay, treatments where SAPs were layered gave significantly higher plant water content than mixing.

The second greenhouse pot experiment was done on pine seedlings to test how SAP rates and application methods affect their survival. The rates of hydrogel used are 0, 0.2%, 0.3% and 0.4%, applied using the two previously mentioned application methods. Survival of plants was monitored after transplanting and irrigating a limited amount of times. Results showed that using SAPs in a layer in soils interacted positively with higher rates of hydrogels, especially in Sandy Clay soil. Higher rates as well as banding helped trees survive in Sandy Clay for a period of time similar to that in control treatments in clay soils.

B. Conclusions

It can be concluded from this study that:

1. Hydrogels enhance water retention properties of sandy clay soil, while keeping retained water available for plant uptake.
2. Hydrogels have a minor effect when used in clay soils.
3. Applying SAPs in a layer or band in soils significantly enhanced their efficiency in retaining water thus greatly benefiting plant dry matter production and survival under water stress.

C. Recommendations

It is recommended to:

- Use superabsorbent polymers in sandy clay soils rather than clay soils.
- Apply hydrogels in a single layer or band in soil rather than uniformly mixing them for better plant growth and survival.
- Conduct more studies on:
    a. Specific soil physical and chemical properties
    b. Fertilizer uptake efficiency
    c. Effect on spacing irrigation interval
    d. Water use efficiency of specific crops under water stress.
    e. Effects on soil erosion
    f. Effects in contaminated soils.
- More studies on the economics of hydrogel use.
- Establish pilot trial stations in reforestation sites to test hydrogels in real field conditions, in selected areas in Lebanon. Especially to assess the economic feasibility of the use of these hydrogels.

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