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Mitigating a Sodium Bicarbonate Water Source with Calcium and Magnesium to Produce Container-Grown Live Oak Trees

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Abstract

The effect of alkaline water quality on live oak tree production was initiated at a nursery in Point Coupee Parish, Louisiana. Ca and Mg sources were used to study the impact of water quality on live oak tree container-growth and study the benefits of using different rates of lime and gypsum [0% dolomitic lime (Ca, Mg), 100% gypsum (Ca) + Epsom salt (Mg), 25% dolomitic lime (Ca, Mg), 75% gypsum (Ca) + Epsom salt (Mg), 50% dolomitic lime (Ca, Mg), 50% gypsum (Ca) + Epsom salt (Mg), 75% dolomitic lime (Ca, Mg), 25% gypsum (Ca) + Epsom salt (Mg), 100% dolomitic lime (Ca, Mg) + 0% dolomitic lime]. Live oak tree growth measurements increased with the reduction of dolomitic lime and increase of Epsom salt and gypsum applications. Leaf Na content was significantly reduced using higher proportions of gypsum and Epsom salt. Soil pH was also reduced by more than 1 pH unit after a growing season. Soil pH did increase when irrigated with highly alkaline water. Growers using alkaline water need to manage irrigation water and soil pH and consider using gypsum and Epsom salt reducing dolomitic lime rates as a source of Ca and Mg. All Ca and Mg sources provided greater than the threshold levels of leaf Ca and Mg content.

Keywords

Water Quality, Salinity, Sodic Soils, Amelioration

1. Introduction

Water sources for nurseries can sometimes be a hindrance when it comes to the health and quality of the plants being grown depending on what minerals/elements are present in them. This is consistent with the most common type of water source in Louisiana, sodium bicarbonate. Sodium bicarbonate in water can lead to negative effects on plants such as the buildup of Na in the media and the increase of pH [1] [2]. A common plant production problem around the world is having high salt levels within growing medium and water sources [3]. This is common among coastal regions and can significantly affect the growth of a variety of plants. High salt content can increase EC to levels at which ion imbalances occur rendering growing conditions for plants. Salinity stress also decreases photosynthesis [4], alters the mineral composition in plants and causes ion imbalance or toxicity [5]-[8]. Due to high salinity toxicity, soil water potential is decreased, so plants become incapable of absorbing sufficient extent of water from soil, ultimately reduction in plant growth rate occur [9]. Wilting occurs by constant salinity stress like drought symptoms, with waxed and thickened leaves and with a greenish blue color [10]. Increased salt concentration can affect senescence and photosynthetic ability of plants abridged to a level that growth of plant cannot endure [11]. Meaning the photosynthesis can be reduced to a point where growth of the plant ceases or is limited. There have been many salinity studies, but most have been concerned with NaCl-salinity [12]. Little attention has been given to other harmful salts, such as those caused by Na_2SO_4 and $NaHCO_3$ [13]-[15]. High pH can affect the physiological and cellular functions within plants leading to stress. The increase in pH reduces the availability of these nutrients and further cause problems in plant growth. These conditions are associated with high bicarbonate levels in the soil solution, which may directly induce iron (Fe) deficiency in plants by impairing Fe uptake and transport [16]-[18]. High carbonate content in soil generates alkalinity that limits Fe availability to roots, resulting in chlorosis symptomology [19] [20]. Alkaline irrigation water throughout Louisiana has reduced the quality of several horticultural crops. Container grown azaleas, poinsettias and bedding plants have been adversely affected by poor water quality. Increased N and Fe fertilization by nurserymen resulted in little or no effect on foliage chlorosis [21] [22]. For the amelioration of sodic irrigation effects, application of gypsum is commonly recommended [23].

Gypsum is the most common chemical amendment for saline-sodic and sodic soil reclamation because it is comparatively cheap, available, and easy to apply [24]. Gypsum, chemically known as calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), is commonly used in agriculture and horticulture to ameliorate soil or growing media that has a high Na content, often associated with a sodium bicarbonate ($NaHCO_3$) water source. Gypsum contains calcium ions (Ca^{2+}) that can effectively exchange with sodium ions (Na^+), in the soil or growing media. When gypsum is applied to the media, the Ca ions displace the sodium ions from the cation exchange sites on soil particles or organic matter. The released Na^+ ions can then leach from the medium in the form of sodium sulfate (Na_2SO_4). Gypsum has a slight acidifying effect on the media in which it is used. When gypsum dissolves in water, it releases Ca ions and sulfate ions (SO_4^{2-}). The sulfate ions can combine with hydrogen ions (H^+) in the soil solution, leading to the formation of sulfuric acid (H_2SO_4). This acidification process lowers the pH of the media, making it less alkaline. Lowering the pH is beneficial because high Na levels often coincide with elevated pH levels, which can be detrimental to plant growth. Gypsum application reduces Na and increases Ca availability in the media. Calcium is an essential nutrient for plant growth, and its availability can be limited in high-sodium soils. Dolomitic lime is typically used for Ca fertilization. Gypsum's role in improving Ca availability contributes to overall plant health. Besides these effects as a soil amendment, gypsum is highly suitable for practical use at field scales, because it is cost-effective, widely available, and easy to handle [25]. The experiment objective is to establish a basis for which different calcium (Ca) and magnesium (Mg) sources may be used to provide optimal nutrition for plants and negate the effects that sodium bicarbonate inflicts in a nursery setting.

2. Materials and Methods

This experiment was initiated to determine the effects of sodium bicarbonate in nursery growing conditions with live oak (*Q. virginiana*), seven-gallon liners of live oak were transplanted in March 2022 into 100-gallon wooden containers of which there were 100. Irrigation water source contained sodium bicarbonate having an average concentration of 220 milligrams per liter of dissolved solids and pH of 8.8. All were filled with a bark-based (3: bark, 1: sand, 1: peat) nursery media typical in the industry. Tree growth parameters of caliper (mm) and height (in) were measured, and trees were assigned to fertilizer treatments using random assignment to reduce variability. Ca fertilizer sources (gypsum and dolomitic lime), Mg fertilizer sources (dolomitic lime, Epsom salt [split applications]) and rates (0, 3, 6, 9 and 12 lbs./cubic yard) were established to form the five treatments as follows (**Table 1**):

Table 1. Treatments used in the 2022 Ducote Tree Farm experiment comparing live oak tree growth for using different Ca and Mg sources.

Ca and Mg Fertilizer Sources and Percentages		
Treatment 1	0% dolomitic lime (Ca, Mg)	100% gypsum (Ca) + Epsom salt (Mg)
Treatment 2	25% dolomitic lime (Ca, Mg)	75% gypsum (Ca) + Epsom salt (Mg)
Treatment 3	50% dolomitic lime (Ca, Mg)	50% gypsum (Ca) + Epsom salt (Mg)
Treatment 4	75% dolomitic lime (Ca, Mg)	25% gypsum (Ca) + Epsom salt (Mg)
Treatment 5	100% dolomitic lime (Ca, Mg)	0% gypsum (Ca) + Epsom salt (Mg)

The experiment compared 5 fertilizer treatments with 20 blocks, oak tree plants were randomized and arranged in a RCBD using random assignment to reduce variability. Each treatment contained 20 replications to account for all 100 trees. Drip irrigation was used to provide daily irrigation for all treatments as needed. This experiment was established at Ducote's Tree Farm in Lakeland, LA (30.56˚, −91.43˚) which provided ample space and the proper conditions for a nursery setting, outside in rows on top of ground cloth, as the experiment called for to be used. Data was collected from the trees every 2 months from April 2022 through April 2023. Growth parameters were established from collecting data on height (m) with a tape measure from the apex bud, canopy spread (m) with tape measure at base of tree crown, and caliper (mm) 6 inches above the soil line of the trees using digital calipers for the different treatments. Data was collected each month and means statistically compared using Duncan's Multiple Range Test. A leaf nutrient analysis was conducted by the LSU Soil Testing. Plant tissue nutrient analysis (P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo and Zn) was analyzed by the LSU Soil Testing Lab. Nutrient analysis was initiated by harvesting plants tops at the termination of the project, and dried at 60˚C. One gram of ground plant material was transferred into a 20 ml scintillation vial and placed in an oven at 50˚C for 1 h to remove residual moisture. Vials were transferred to desiccators for 1h to further remove moisture and cool the sample to room temperature. The caps of each sample were tightened upon removal from the desiccators to prevent moisture from re-entering. All elements were analyzed by placing 0.5 g of tissue into a 50 ml tube (SCP Scientific digiTUBE). Funnels were placed in each tube, and samples were placed into an automatic digester (Thomas Cain, DEENA) for digestion using nitric acid. During the digestion, the samples are heated for 6 s at 60˚C and 2.2 ml of distilled water is added. After 2 m, 5 ml nitric acid (SCP Science, 67% to 70% HNO_3, reagent grade) was dispensed into each tube, and the temperature was increased 10˚C every 10 m from 60˚C to 110˚C. The temperature was increased to 125˚C and held for 45 m, and then held for 50m at 128˚C, and cooled for 2 m. One ml of hydrogen peroxide (Macron Fine chemicals, 30% solution) was dispensed into each tube, cooled for 5 m and reheated for 5 m to 128˚C. One ml of hydrogen peroxide was dispensed, and another 1ml of hydrogen peroxide was dispensed into each tube. The samples were cooled for 5 minutes and heated for 30 minutes at 122˚C, cooled for 6 seconds to 20˚C and cooled for 1 more minute. The volume of each sample was brought to 20 ml using distilled water. Samples were removed from the digester and vacuum filtered using a 1.0-micron Teflon membrane filter (SCP Science) into another 20 ml tube. ICP was performed for the elements P, K, Ca, Mg, S, Al, B, Cu, Fe, Mn, Mo, Na, and Zn using a Spectro Arcos according to the LSU Soil Testing and Plant Analysis Lab's AgMetals procedure. The instrument was calibrated using one blank and 6 standard samples. Samples were run in sets of 60 (2 blanks included) with two National Institute of Standards and Technology (NIST) peach samples and an internal standard for every 20 samples. The data was verified to ensure it was within the tolerant ranges of the NIST and internal standards. Nutrient levels were reported as % (dry weight) for macronutrients and ppm (mg/kg dry weight) for micronutrients. pH was measured by mixing samples taken with water using a pH meter plus electrode to show if the different treatments influenced soil pH since all containers received water from the same source. Data was statistically analyzed using a Proc GLM at the 0.05 level.

3. Results and Discussion

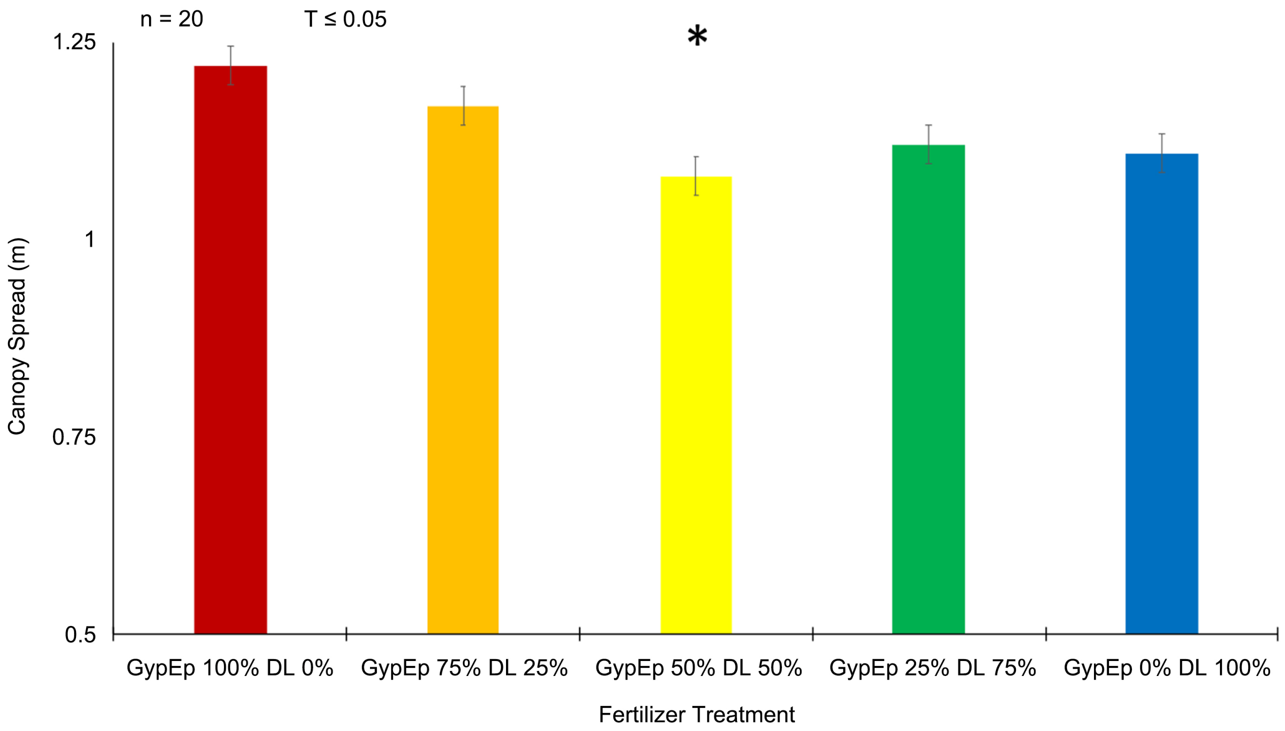

Figure 1. Canopy spread of live oak measured in meters after a 10-month growing season of 2022-2023 in a nursery production setting at Ducote's Tree Farm. NS = Not significant at the 0.05 level; * = Significantly different at the 0.05 level.

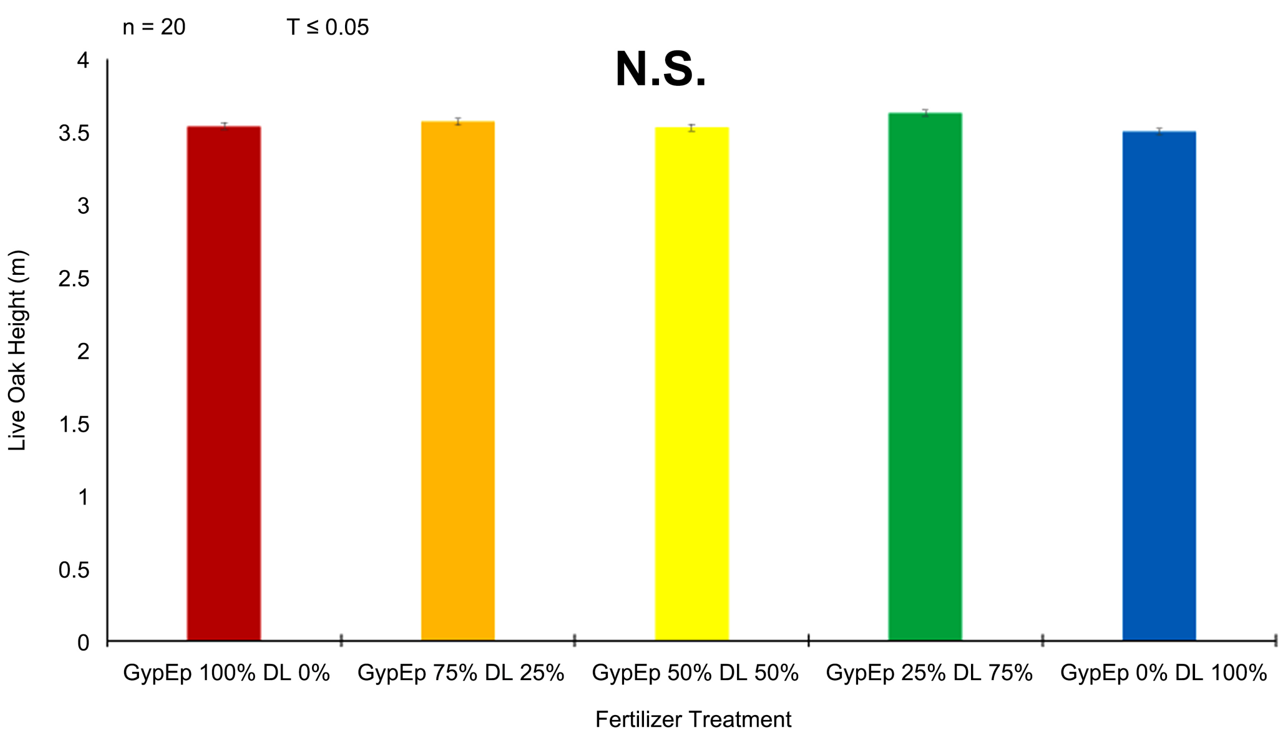

Figure 2. Height (m) of live oak measured after a 10-month growing season of 2022-2023 in a nursery production setting at Ducote's Tree Farm. NS = Not significant at the 0.05 level; * = Significantly different at the 0.05 level.

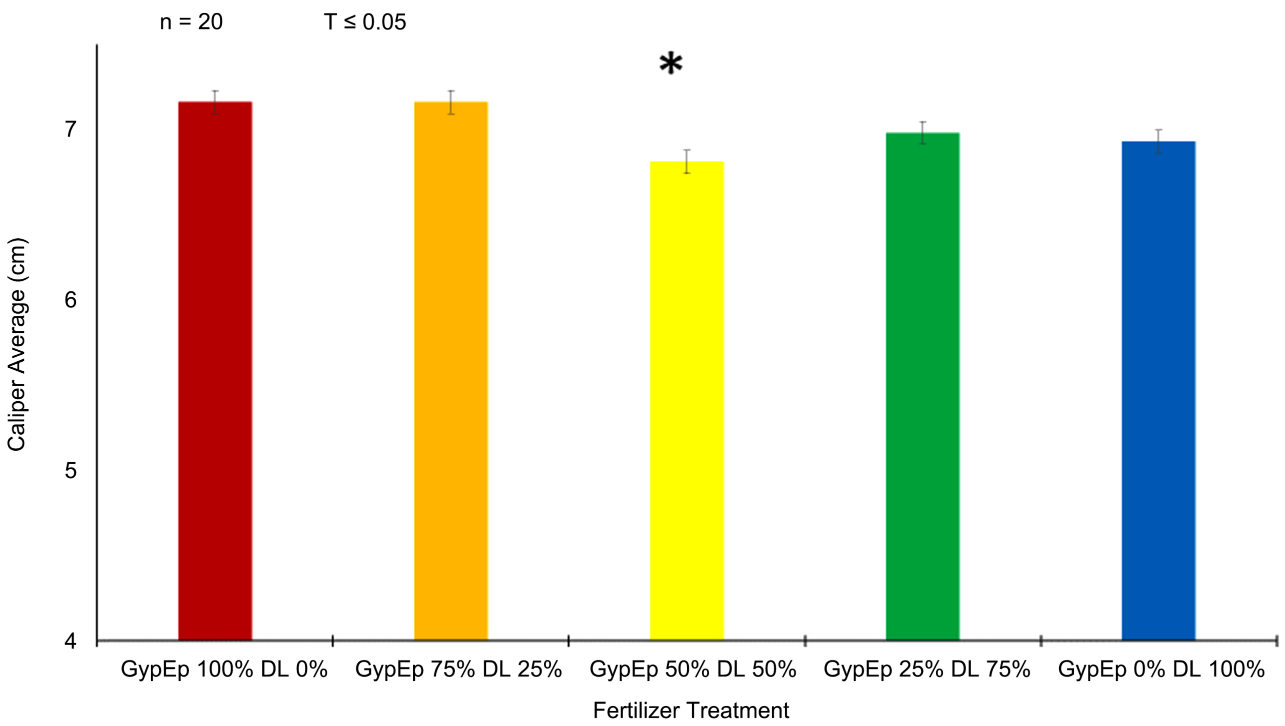

Figure 3. Average stem caliper (cm) of live oak measured after a 10-month growing season of 2022-2023 in nursery production settings at Ducote's Tree Farm. NS = Not significant at the 0.05 level; * = Significantly different at the 0.05 level.

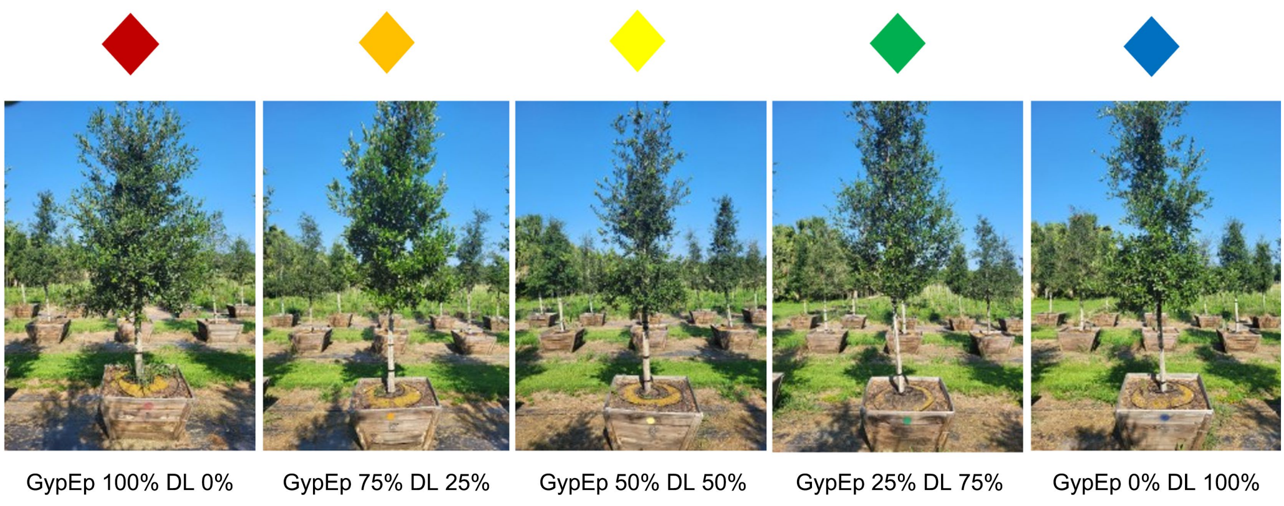

Figure 4. Visual representation of the different treatments at the end of the experiment in 2023 at Ducote's Tree Farm. The trees shown are an example of the treatment effects.

There were significant statistical differences at the 0.05 level using a Proc GLM between treatments (Figures 1-7) display growth parameter differences in live oak tree growth between the various Ca and Mg treatments. The canopy spread for Treatments 1 and 2 (red and orange) were significantly greater than all other treatments (Figure 1). No significant differences were measured between treatments for tree height (Figure 2). However, there were significant differences between the highest gypsum/Epsom salt treatments for stem diameters (Figure 3).

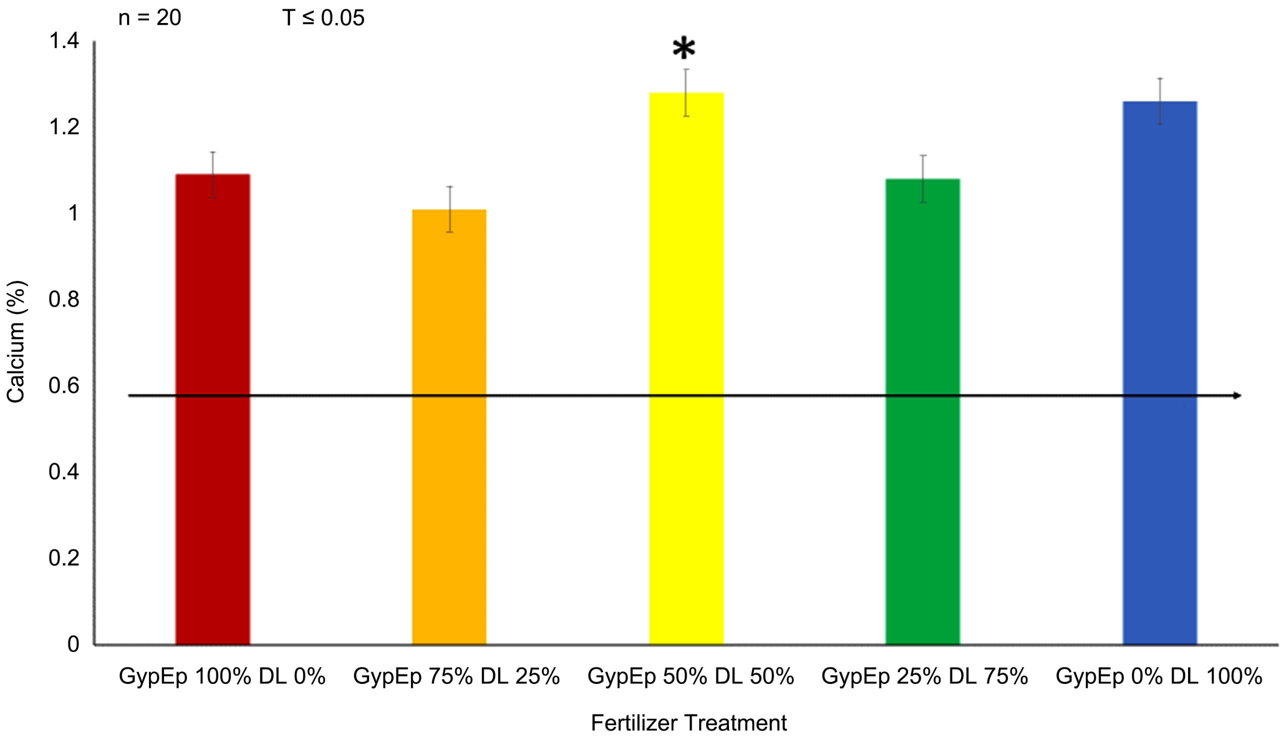

Figure 5. Calcium (%) leaf tissue content of live oaks from the Ca and Mg treatments in the LSU study at Ducote Tree Farm in the years 2022-2023. The arrowed line represents the sufficiency threshold. NS = Not significant at the 0.05 level; * = Significantly different at the 0.05 level.

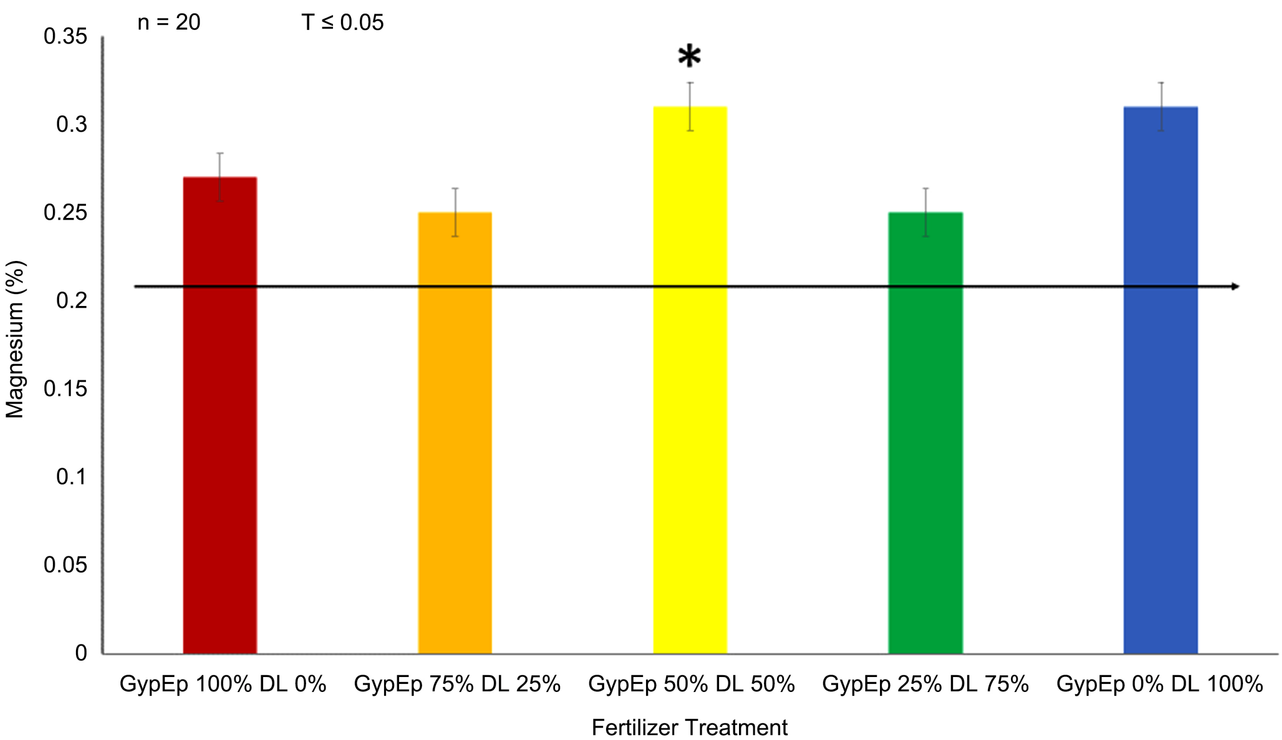

Figure 6. Magnesium (%) leaf tissue content of live oaks from the Ca and Mg treatments in the LSU study at Ducote Tree Farm in the years 2022-2023. The arrowed line represents the sufficiency threshold. NS = Not significant at the 0.05 level; * = Significantly different at the 0.05 level.

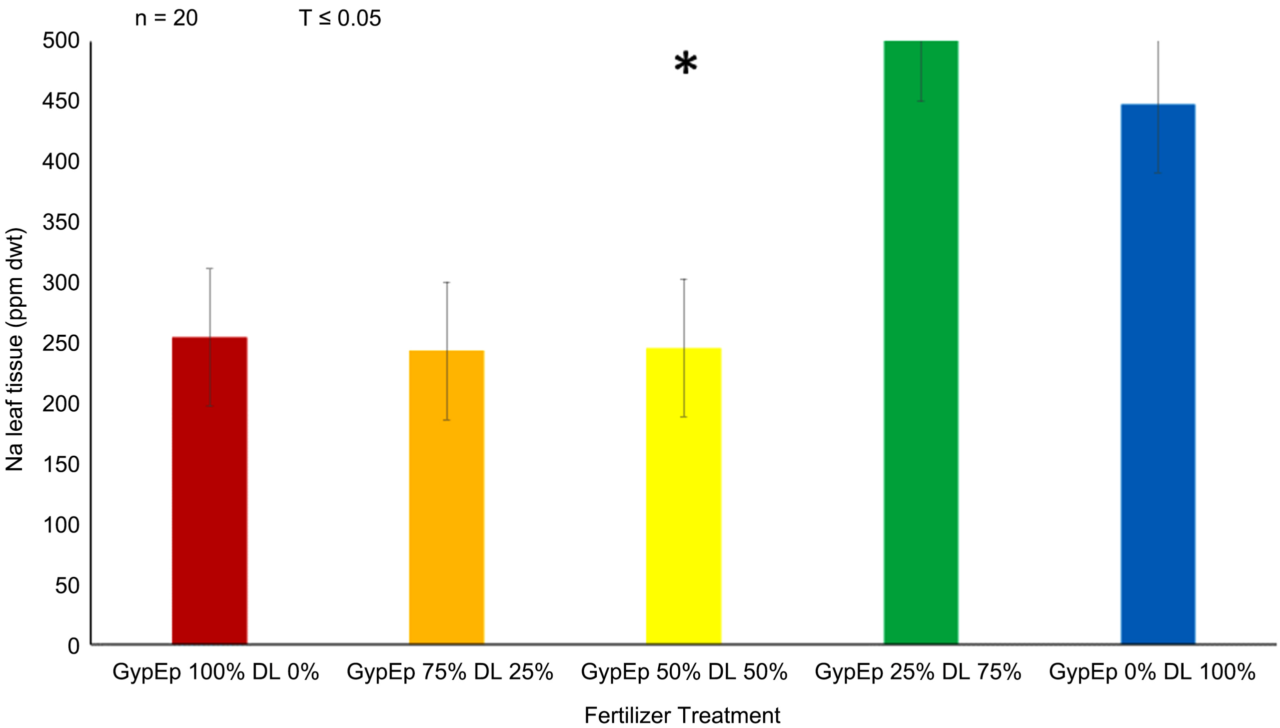

Figure 7. Sodium (ppm) leaf tissue content of live oaks from the Ca and Mg treatments in the LSU study at Ducote Tree Farm in the years 2022-2023 measured in ppm dry weight. NS = Not significant at the 0.05 level; * = Significantly different at the 0.05 level.

The results in **Figures 5-7** indicate that nutrient absorption of the live oaks had significant differences and would affect the growth parameters measured. The % Ca found in leaf tissue of the trees exceeded minimum threshold requirements (**Figure 5**). Similar findings are found in **Figure 6** where Mg leaf content exceeded sufficient levels. All trees, therefore, received optimum amounts of Ca and Mg from the various fertilizer treatments. Sodium absorption, as shown in **Figure 7**, is affected by the presence of gypsum. A significant difference occurred between treatments was expected between the first three treatments and the latter two treatments in **Figure 7**. The effect of gypsum and Epsom salts reduced the absorption of sodium compared to dolomitic lime as a Ca and Mg source. This result demonstrated the effectiveness of gypsum/Epsom salts combined by increased spread and caliper. Nursery managers can use gypsum/Epsom salts to mitigate the negative effects of soil Na by reducing plant uptake and possibly leaching Na while increasing soil pH affected by the alkaline water.

The trend shown from the figures indicates that using gypsum/Epsom salts in the presence of a sodium bicarbonate water source leads to more growth and development in live oaks versus using dolomitic limestone. As Na in the soil combines with sulfate it forms a leachable compound leached through the soil matrix reducing available sodium for the tree roots to assimilate. This can be attributed to reduced sodium absorption in the leaves of these trees even in treatments that were not 100% gypsum but still contained limestone. Improved growth height and caliper increases the value and grade of the tree for sale. These criteria are what trees are based on by landscape architects and horticultural contractors when buying nursery trees. Additionally, ecological benefits of efficient plant growth improves water and fertility usage. This in turn can reduce water waste and offsite fertilizer waste.

4. Conclusion

The experiment, which utilized varying levels of lime and gypsum/Epsom salt as sources of Mg and Ca in the presence of a sodium bicarbonate water source, has yielded significant findings regarding their influence on plant growth and Na absorption. The treatments with higher percentages of gypsum/Epsom salt have demonstrated distinct advantages in these aspects compared to the lime-heavy treatments. Adding gypsum and Epsom salts as Ca and Mg sources reduced the absorption of Na in the tree leaf tissue. It can be said from this the Na buildup within the media was reduced. Growth parameters showed a difference between the various treatments. Gypsum treatments have an overall better performance compared to the lime heavy treatments. A significant difference in Ca and Mg absorption occurred, but all treatments had absorption percentages above the optimum amount required by the trees. Notably, the treatments with higher percentages of gypsum/Epsom salt have consistently promoted superior plant growth compared to the lime-heavy treatments, despite both sources providing adequate Ca and Mg. This suggests that factors beyond the supply of Ca and Mg played a role in determining plant performance. Sulfate ions from gypsum and the specific Ca-to-Mg ratio in Epsom salt may favor better nutrient uptake or metabolic processes, resulting in improved growth [1] [26]. Findings show the gypsum/Epsom salt treatments' ability to effectively reduce Na absorption by plants [15]. Even when Ca and Mg levels were sufficient in both sets of treatments, the treatments with gypsum/Epsom salt exhibited a greater capacity to mitigate Na uptake by the plants. This suggests that the specific chemical properties of these substances contributed to their superior performance in preventing Na accumulation in plant tissues. These results highlight the complexity of nutrient interactions in plant growth and nutrient uptake. The choice of Ca and Mg sources can impact on overall plant health, growth, and Na regulation, beyond providing these essential nutrients in adequate quantities. What does this all mean for growers in Louisiana? The state has plenty of water sources, but not all are best suited for the growth of plants. The outcomes of this experiment have practical implications for growers and horticulturists dealing with sodium bicarbonate water sources. While both lime and gypsum/Epsom salt can supply the necessary Ca and Mg, the selection of these sources should be carefully considered, considering their additional chemical properties and potential impacts on plant performance. A sodium bicarbonate water source is commonly used and so plenty of growers must deal with the problems that come with it. Issues that arise if not considered such as ionic toxicity and pH increases will reduce plant growth. Media may be mixed to help combat the effects of a water source, but Na still can accumulate, and the water pH will still affect the pH of even the most acidic media mix. If it's a major issue causing problems with ionic toxicity and increase in pH, then the amelioration of Na via the use of gypsum can be implemented otherwise loss of crops will outweigh the cost that may come using one fertilizer source for Ca and Mg over another source. The application of gypsum can make a difference in plant growth that would give a nursery the competitive edge needed to succeed. This experiment could have benefitted more greatly from an extensive soil/media compositional analysis, but the main concern was of Na accumulation in the leaves hence the leaf tissue analysis. In the future, a look at a more extensive list of tree/shrub species undergoing this experiment should be investigated. Live oaks were chosen as an ideal candidate due to their tolerance to brackish water during transitory inundation from storms causing increases in soil sodium accumulation. But perhaps looking at less tolerant species would give greater insight into the effectiveness of the treatments. Also, the use of a sodium chloride water source versus a sodium bicarbonate source would be interesting to compare how gypsum could ameliorate these two similar yet different sources.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Carter, C.T., Grieve, C.M. and Poss, J.A. (2005) Salinity Effects on Emergence, Survival, and Ion Accumulation of *Limonium perezii*. *Journal of Plant Nutrition*, **28**, 1243-1257. https://doi.org/10.1081/pln-200063293

[2] Mohsenian, Y., Roosta, H.R., Karimi, H.R. and Esmaeilizade, M. (2012) Investigation of the Ameliorating Effects of Eggplant, Datura, Orange Nightshade, Local Iranian Tobacco, and Field Tomato as Rootstocks on Alkali Stress in Tomato Plants. *Photosynthetica*, **50**, 411-421. https://doi.org/10.1007/s11099-012-0054-2

[3] Rengasamy, P. (2006) World Salinization with Emphasis on Australia. *Journal of Experimental Botany*, **57**, 1017-1023. https://doi.org/10.1093/jxb/erj108

[4] Marschner, H. (1986) Mineral Nutrition of Higher Plants. Academic Press.

[5] Greenway, H. and Munns, R. (1980) Mechanisms of Salt Tolerance in Nonhalophytes. *Annual Review of Plant Physiology*, **31**, 149-190. https://doi.org/10.1146/annurev.pp.31.060180.001053

[6] Wahome, P.K., Jesch, H.H. and Grittner, I. (2001) Mechanisms of Salt Stress Tolerance in Two Rose Rootstocks: *Rosa chinensis* 'Major' and *R. rubiginosa*. *Scientia Horticulturae*, **87**, 207-216. https://doi.org/10.1016/s0304-4238(00)00168-0

[7] Wright, G.C., Patten, K.D. and Drew, M.C. (1994) Mineral Composition of Young Rabbiteye and Southern Highbush Blueberry Exposed to Salinity and Supplemental Calcium. *Journal of the American Society for Horticultural Science*, **119**, 229-236. https://doi.org/10.21273/jashs.119.2.229

[8] Zekri, M. and Parsons, L.R. (1992) Salinity Tolerance of Citrus Rootstocks: Effects of Salt on Root and Leaf Mineral Concentrations. *Plant and Soil*, **147**, 171-181. https://doi.org/10.1007/bf00029069

[9] Tester, M. and Davenport. R. (2003) Na^+ Tolerance and Na^+ Transport in Higher

Plants. *Annals of Botany*, **91**, 503-527. https://doi.org/10.1093/aob/mcg058

[10] Fraga, T.I., de Campos Carmona, F., Anghinoni, I., Genro Junior, S.A. and Marcolin, E. (2010) Flooded Rice Yield as Affected by Levels of Water Salinity in Different Stages of Its Cycle. *Revista Brasileira de Ciência do Solo*, **34**, 175-182. https://doi.org/10.1590/s0100-06832010000100018

[11] Shereen, A., Mumtaz, S., Raza, S., Khan, M. and Solangi, S. (2005) Salinity Effects on Seedling Growth and Yield Components of Different Inbred Rice Line. *Pakistan Journal of Botany*, **37**, 131-139.

[12] Grattan, S.R. and Grieve, C.M. (1998) Salinity-Mineral Nutrient Relations in Horticultural Crops. *Scientia Horticulturae*, **78**, 127-157. https://doi.org/10.1016/s0304-4238(98)00192-7

[13] Gizaw, B. (1996) The Origin of High Bicarbonate and Fluoride Concentrations in Waters of the Main Ethiopian Rift Valley, East African Rift System. *Journal of African Earth Sciences*, **22**, 391-402. https://doi.org/10.1016/0899-5362(96)00029-2

[14] Haby, V.A., Patten, K.D., Cawthon, D.L., Krejsa, B.B., Neuendorff, E.W., Davis, J.V., *et al.* (1986) Response of Container-Grown Rabbiteye Blueberry Plants to Irrigation Water Quality and Soil Type. *Journal of the American Society for Horticultural Science*, **111**, 332-337. https://doi.org/10.21273/jashs.111.3.332

[15] Renault, S., Lait, C., Zwiazek, J.J. and MacKinnon, M. (1998) Effect of High Salinity Tailings Waters Produced from Gypsum Treatment of Oil Sands Tailings on Plants of the Boreal Forest. *Environmental Pollution*, **102**, 177-184. https://doi.org/10.1016/s0269-7491(98)00099-2

[16] Cinelli, F. (1995) Physiological Responses of Clonal Quince Root-Stocks to Iron-Deficiency Induced by Addition of Bicarbonate to Nutrient Solution. *Journal of Plant Nutrition*, **18**, 77-89. https://doi.org/10.1080/01904169509364886

[17] Coulombe, B.A., Chaney, R.L. and Wiebold, W.J. (1984) Bicarbonate Directly Induces Iron Chlorosis in Susceptible Soybean Cultivars. *Soil Science Society of America Journal*, **48**, 1297-1301. https://doi.org/10.2136/sssaj1984.03615995004800060019x

[18] White, P.F. and Robson, A.D. (1990) Response of Lupins (*Lupinus angustifolius* L.) and Peas (*Pisum sativum* L.) to Fe Deficiency Induced by Low Concentrations of Fe in Solution or by Addition of HCO_3^-. *Plant and Soil*, **125**, 39-47. https://doi.org/10.1007/bf00010742

[19] Korcak, R. (1987) Iron Deficiency Chlorosis. *Horticultural Reviews*, **9**, 133-186.

[20] Mengel, K., Planker, R. and Hoffmann, B. (1994) Relationship between Leaf Apoplast Ph and Iron Chlorosis of Sunflower (*Helianthus annuus* L.). *Journal of Plant Nutrition*, **17**, 1053-1065. https://doi.org/10.1080/01904169409364787

[21] Bailey, D.A. and Hammer, P.A. (1986) Growth and Nutritional Status of Petunia and Tomato Seedlings with Acidified Irrigation Water. *HortScience*, **21**, 423-425. https://doi.org/10.21273/hortsci.21.3.423

[22] Fuller, D., Bush, E. and Wall, D. (1991) Media and Water Quality Influence Growth of Container-Grown Azaleas. *Southern Nursery Association Conference*, **36**, 116-118.

[23] Ayers, R. and Westcot, D. (1985) Water Quality for Agriculture. Food and Agriculture Organization of the United Nations.

[24] Shainberg, I., Sumner, M.E., Miller, W.P., Farina, M.P.W., Pavan, M.A. and Fey, M.V. (1989) Use of Gypsum on Soils: A Review. In: Stewart, B.A., Ed., *Advances in Soil Science*, Springer, 1-111. https://doi.org/10.1007/978-1-4612-3532-3_1

[25] Qadir, M., Schubert, S., Ghafoor, A. and Murtaza, G. (2001) Amelioration Strategies for Sodic Soils: A Review. *Land Degradation & Development*, **12**, 357-386. https://doi.org/10.1002/ldr.458

[26] Lim, C., Kim, S. and Kim, P. (2011) Effect of Gypsum Application on Reducing Methane (CH_4) Emission in a Reclaimed Coastal Paddy Soil. *Korean Journal of Environmental Agriculture*, **30**, 243-251. https://doi.org/10.5338/kjea.2011.30.3.243