Impacts of Deicing on the Danforth Campus

ENST 405: Sustainability Exchange

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Introduction

Slippery sidewalks can be a significant safety hazard in any location which experiences frequent snowstorms or temperatures consistently below freezing (32°F). To combat the danger presented by icy roads and walkways, it has become common practice to apply deicing salts, or deicers, to lower the freezing point of water and mitigate snow and ice formation.[1] As such, Washington University regularly applies deicers in the winter to ensure the safety of their walkways for students and faculty. While these salts are quite effective in preventing ice from forming and keeping walkways safe, however, they also have some undesirable impacts which arise as a result of their application. The primary goal of this study was to assess these potential impacts and investigate methods by which they could be mitigated.

One major environmental concern which arises as a result of deicer application is damage to surrounding vegetation. When deicers runoff into soils, they directly increase the conductivity and salt concentration of the soil, which makes it more difficult for plants to uptake water. This causes plants to suffer dehydration and, in severe cases, ultimately die. In the best of cases, this can lead to temporary flaws in landscaping which may resolve themselves over time as the deicers dissipate. In the worst cases, this can cause serious damage to soils, making them less tenable and imposing significant economic costs associated with restoring damaged vegetation and improving soil health.[2]

Another potential detriment of deicer application is harm to microbial communities as a result of the osmotic stress imposed by increased salt concentrations. Since microbial communities participate in many processes vital to the functioning of ecosystems, any harm they experience from deicer application can further degrade soil health. This can inhibit the ability of plants to flourish and may necessitate the need for soils to be replaced or rejuvenated to support plant growth.[2]

Beyond the potentially damaging effects on plants and microbial communities, deicers can also impact man-made structures such as lampposts, benches, and vehicles. When deicers accumulate on these structures, they can accelerate rust formation. Over time, this damage necessitates that these structures be repaired and replaced, imposing additional economic burdens upon the parties responsible for maintaining them.

Due to the environmental and economic concerns which may arise as a result of overuse of deicing salts, it is important to assess how their application may be impacting an environment. In this study, this was achieved by testing soils on Washington University's campus for changes in pH and conductivity. As was previously mentioned, conductivity is a useful measure as it gives an indication of the ability of plants to uptake water and the health of microbial communities. Changes in pH are also significant as many environmental processes depend on pH. Because of this, monitoring pH can provide additional insight into soil health and how deicer application may be inciting harmful changes.[2]

As an ancillary objective of this study, the transport of deicers into soils on campus was preliminarily investigated by testing the pH and conductivity of soil samples taken at different depths. The purpose of this analysis was to provide insight on how deicers move in soils following their application. This information may be particularly important if there is any risk of deicers flowing into drinking waters as a result of runoff, as this may give rise to a human health hazard in addition to the previously mentioned environmental hazards.

Lastly, the final objective of this study was to investigate the effectiveness of several soil amendments, which are products applied to improve soil health. A total of five amendments consisting of biochar, encapsalt, C20, compost, and sulfur were investigated by assessing the impact they had on the pH and conductivity of soils treated with each amendment. To obtain a holistic view of each soil amendment, an abridged version of a house of quality (HOQ) analysis was conducted for each amendment to assess their costs, ease of application, and potential environmental impacts in addition to general performance.

Through analyzing weekly soil samples and testing for the presence of deicers at increasing soil depths, this study seeks to gain a sweeping view of how deicers affect soil health on Washington University's campus. When paired with the investigation of soil amendments which could be used to bolster and rejuvenate campus soils, this information will allow Washington University's landscaping department to make more informed decisions on how deicers should be applied and what actions may be taken to mitigate their impacts.

Experimental Procedures

Soil Sampling Analysis

Soil samples were taken throughout the semester on a semi-consistent basis (every other week, weather permitting). Samples were obtained from three locations on Washington University's Campus: Mudd Field, Oak Allée, and the East End. These locations were chosen due to their variations in soil type and amount of foot traffic. Mudd Field's soil is the least healthy. It is clay-like and experiences heavy foot traffic during the school year; this amount of foot traffic has been exacerbated in the past year with Mudd Field being a COVID-19 testing location for undergraduate students. Furthermore, the soil at Oak Allée has a traditional soil texture, intermediate foot traffic, and experiences significant water runoff because it is located near a drain. Finally, the East End has the healthiest soil because of relatively light foot traffic and soil of a sandy texture. It should be noted that on the first day of sampling, a single control sample was taken at Brookings Hall where there is minimal foot traffic and de-icer application. Figure 1 shows a map depicting each sampling site's location on campus.

Whenever possible, weekly sampling was scheduled to occur the day after any major weather events, which include rain and snow. On the day of sampling, weather conditions were recorded and photos were taken at each sampling site. Samples were taken at 0, 30, and 60 centimeters from the edge of the sidewalk to allow the migration of salts away from their application point to be studied. To obtain the samples at these distances, an auger was pushed into the ground and removed to collect approximately 20 grams of soil. Additionally, at each of the three sampling sites, an in-ground pH probe was utilized to measure the pH and the moisture level of the ground.

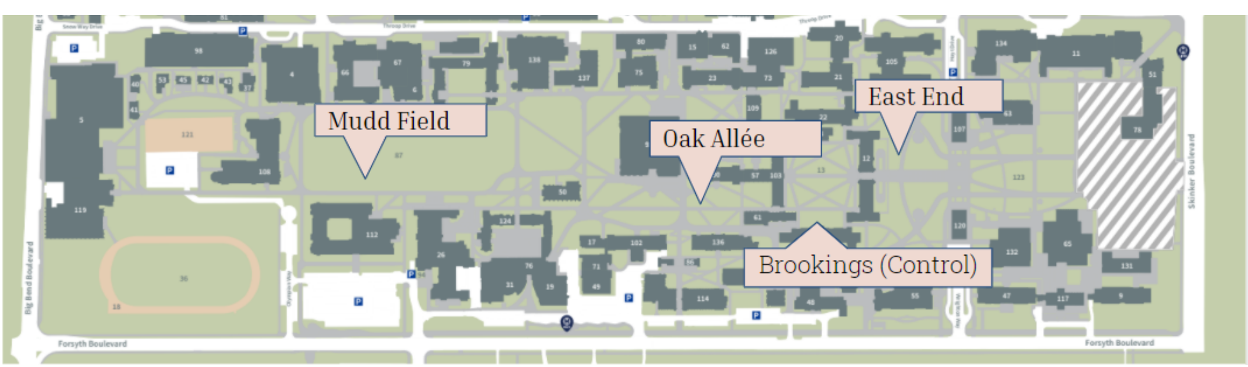

Figure 1 Locations of sampling sites on campus

As previously mentioned, during one sampling session, the above procedure was modified to evaluate how deicer impacts change with soil depth. This experiment could have been conducted at any of the three sampling locations, but the group selected Mudd Field because it has the highest amount of foot traffic and the worst soil health. Additionally, the East End would not be viable to do depth testing because there are fibers under the soil. For this experiment, a large auger full of soil was taken at each distance from the sidewalk as opposed to the typical, smaller amount of soil taken for weekly sampling. This large auger full of soil was then portioned into three increments so that the soil at different depths could be tested. Furthermore, this process was repeated once at the control site near Brookings Hall to obtain a basis for comparison.

After the samples were obtained from the field, they were analyzed in a laboratory on the same day. For each sample, approximately 20 grams of soil was mixed with 40 milliliters (mL) of reverse osmosis (RO) water in a clean beaker. A magnetic stir bar and a magnetic stir plate were used to stir the mixture for five minutes, followed by a two minute period during which the soil was allowed to settle. A calibrated pH probe was then used to measure the mixture's pH, while a handheld device was used to measure the conductivity. The results of these analyses for each sampling day can be found in the Results section.

Soil Amendment Analysis

As previously mentioned, to assess the effectiveness of the five soil amendments tested (biochar, compost, C20, Encapsalt, and sulfur), their impacts on pH and conductivity for selected soils were measured. The influence of the amendments could have been studied on soil samples from any of the three sampling locations, but the group selected to use Mudd Field soil because its health has the most room for improvement. The above sampling and soil analysis procedures were slightly altered for these experiments. A total of seven samples (each at the same depth) were taken 0 cm from the sidewalk to provide samples for each amendment, a control sample, and a sample to be used for a density analysis. When making the mixtures for this experiment, the amounts of soil and soil amendments given in Table 1 were added to clean beakers and mixed with 40 mL of RO water. This experiment was conducted twice over the course of two weeks to provide replicate data.

To evaluate the soil density, 50 mL of RO water was added into a graduated cylinder. Then, 20 g of soil was added to the cylinder and the change in water level was recorded; to find the density, 20 g was divided by the change in water level. The resulting density (1.65 g/mL) was used in calculating how much amendment should be added to the soil. By comparing the pH and conductivity of the amendment-treated soils to the control, the group could make conclusions about the effectiveness of the amendments.

In addition to evaluating the effectiveness of the amendments via experimentation, the group evaluated the soil amendments through the previously mentioned HOQ analysis to gain a more holistic view of their applicability. Each team member was assigned an amendment on which to do research and each amendment was evaluated based on factors such as effectiveness, cost, environmental impact, and overall sustainability. For the final HOQ assessment, see Appendix B.

Table 1 Amounts of soil and soil amendments to be mixed in a beaker with 40 mL of RO water

Amendment	Amount of Amendment	Mass of Soil (g)
None (Control)	0 g	20
Biochar[3]	5 g	15
Compost[4]	5 g	15
C20[5]	0.0475 g	20
Encapsalt[6]	20 μL	1 acre
Sulfur[7]	0.023 g	20

Results and Findings

Distance Sampling

As mentioned above, the main objective of the data collected from biweekly soil sampling was to quantify the spread of the deicers away from the sidewalk. The pH and Conductivity (μS) were analyzed from the samples and recorded for each distance from the walkway. Trends were then analyzed by plotting the pH and conductivity at each test distance for each sampling day. This was repeated for every sampling location to examine potential trends in the aforementioned variables. The results were then compared to the Control, taken at the Brookings Quadrangle, to see how much the soil had deviated from the unsalted case. Figures 2 through 7 on the following pages show the results of these tests. See Appendix A.3 for the raw data used in this analysis.

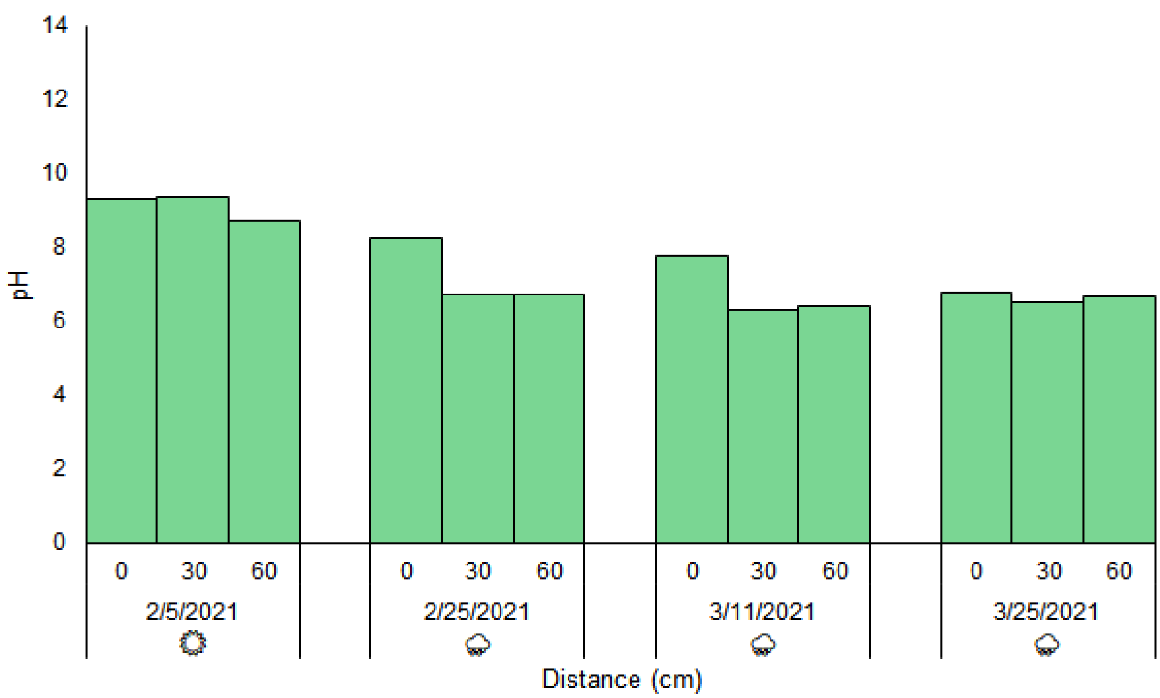

Figure 2 **East End pH data. Shown above are the pH values for each distance tested with relevant weather conditions for each sampling day illustrated by the icon below each dataset**

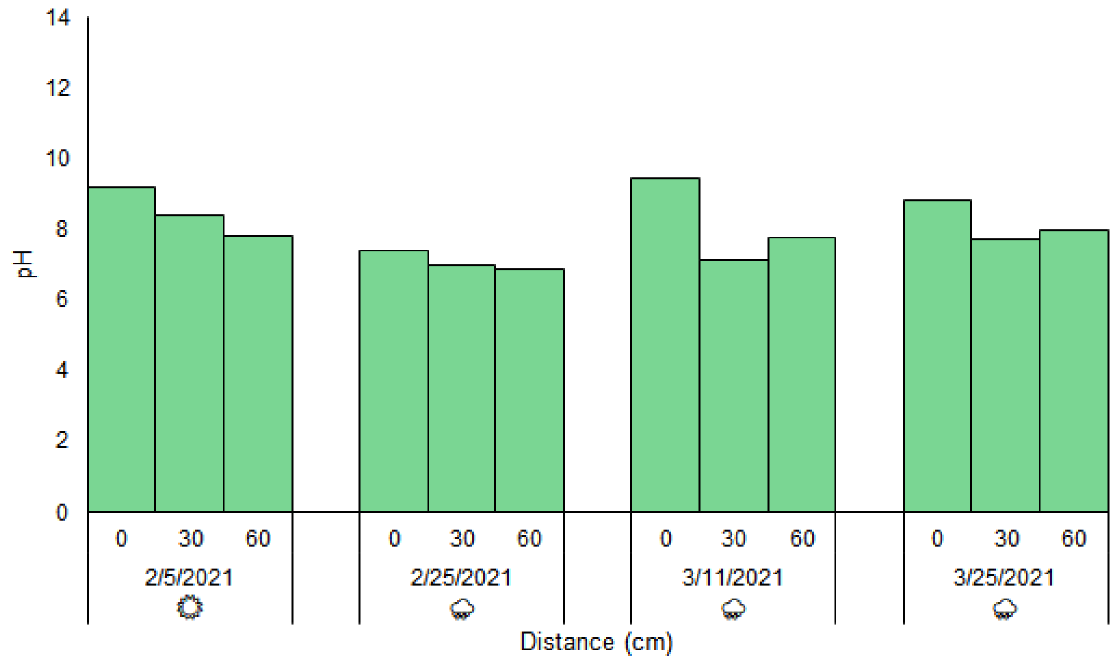

Figure 3 **Mudd Field pH data. Shown above are the pH values for each distance tested with relevant weather conditions for each sampling day illustrated by the icon below each dataset**

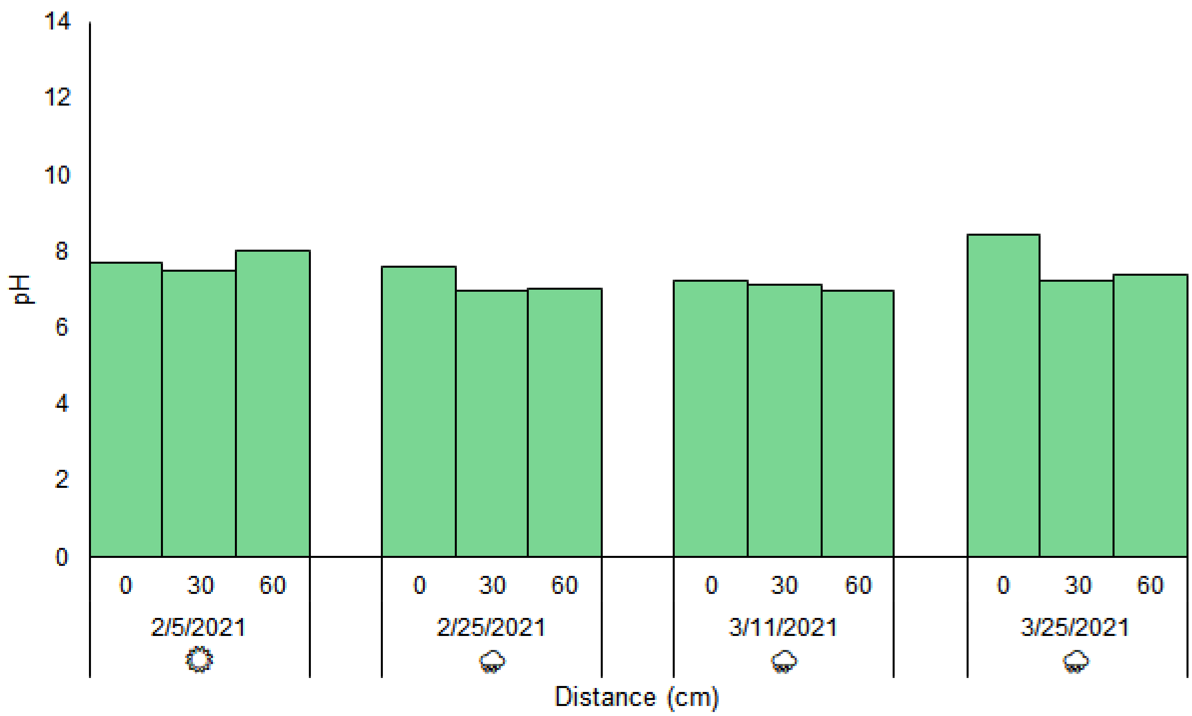

Figure 4 **Oak Allée pH data. Shown above are the pH values for each distance tested with relevant weather conditions for each sampling day illustrated by the icon below each dataset**

From these figures, it is apparent that there exists no clear trend in pH. Rather, the values at each location remain relatively constant. The East End seems to have a slight trend downwards, but there is not enough data to claim a source for this. For this reason, pH was used more as a general indicator for soil health rather than a measure of deicer presence. In other words, so long as drastic changes in pH were not observed, it was assumed that the application of deicers did not have a detrimental impact on soil pH. Each location hovers around a specific pH value, which is a product of the soil type, nutrition supply, and a multitude of external factors which were not quantified.

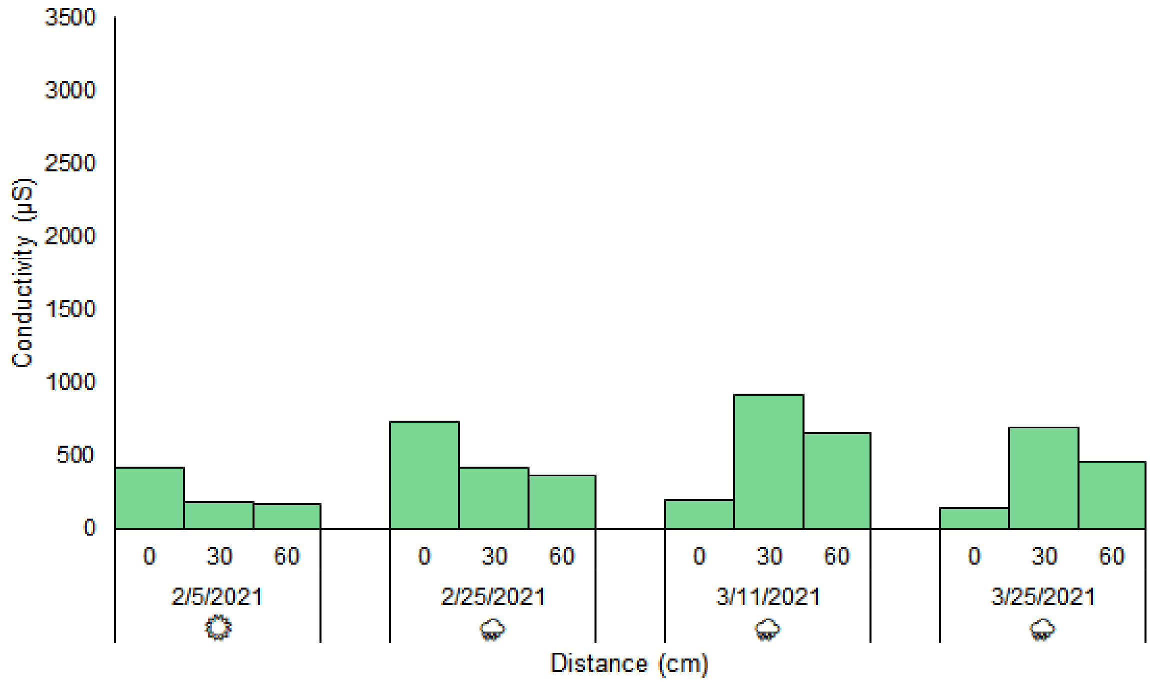

Figure 5 **East End conductivity data. Shown above are the conductivity values for each distance tested with relevant weather conditions for each sampling day illustrated by the icon below each dataset**

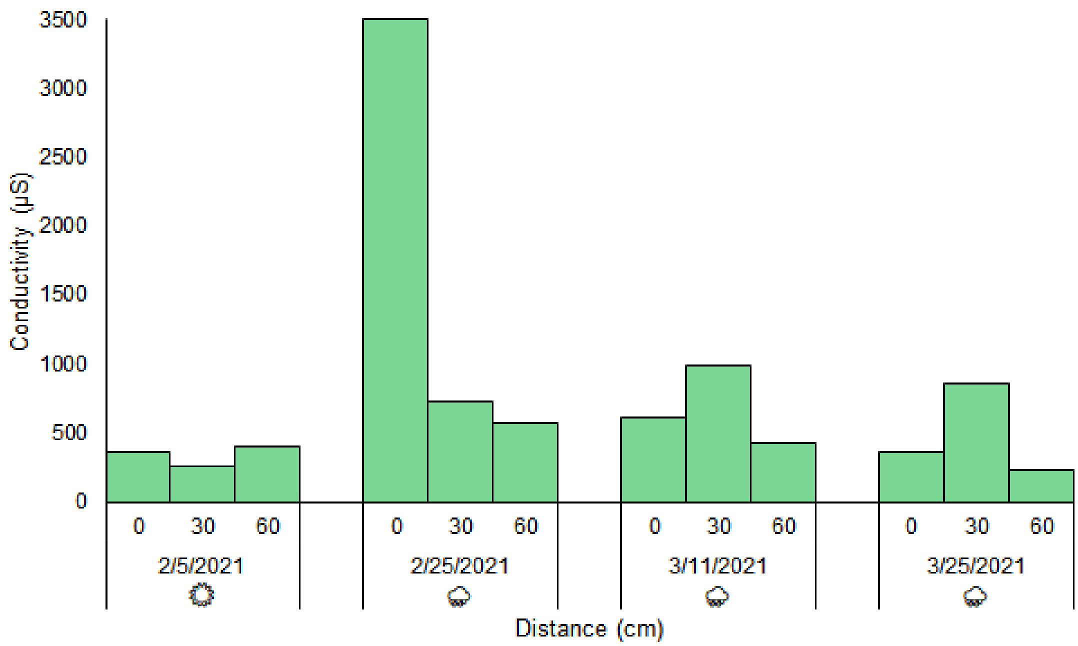

Figure 6 **Mudd Field conductivity data. Shown above are the conductivity values for each distance tested with relevant weather conditions for each sampling day illustrated by the icon below each dataset**

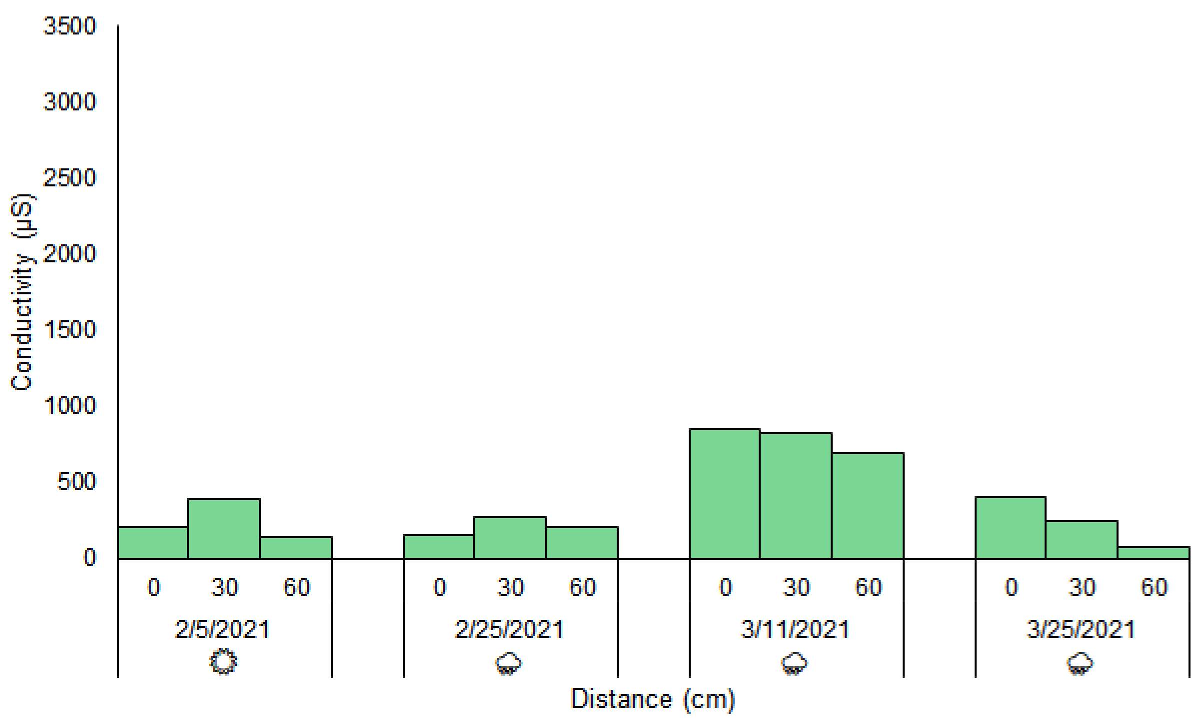

Figure 7 **Oak Allée conductivity data. Shown above are the conductivity values for each distance tested with relevant weather conditions for each sampling day illustrated by the icon below each dataset**

From Figs. 5-7, it can again be seen that no clear long term trends are present in the data. There are, however, several local trends worth noting. The most blatant result can be seen on Mudd Field's 2/25/2021 sample taken 0 cm from the walkway, which has a spike in conductivity much higher than any other recorded value. This was attributed to the application of deicers prior to sampling due to a weather event. With Mudd Field being a location of high foot traffic, it is safe to conclude a comparatively large amount was used on that walkway.

Expanding on the topic of weather events, it was generally observed that days with weather events exhibited higher conductivities than days without an event. While it is difficult to conclude this with certainty due to only one sampling day being on a non-event day, this does bring up interesting points as to what effects weather events may have on the conductivity of the soil, which is something future studies could investigate.

Depth Sampling

As previously described, the methodology employed for analyzing the depth samples mimicked that of the distance sampling very closely. For the three depths tested at each distance from the sidewalk, the pH and conductivity were measured and plotted as a function of both distance and depth. These results are illustrated in Figs. 8 and 9 below.

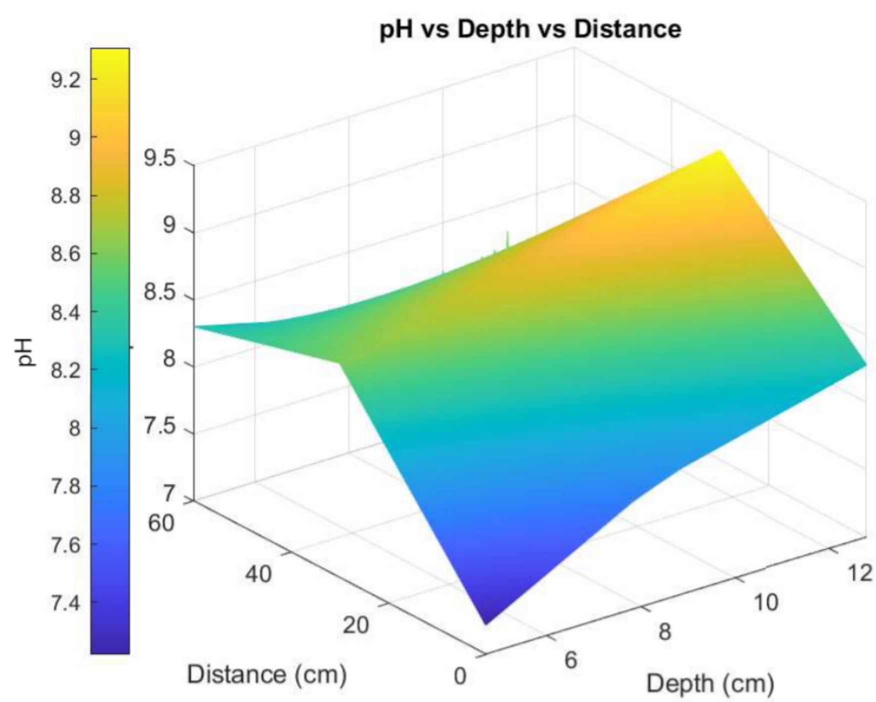

Figure 8 **Mudd Field pH vs depth and distance. The pH of the three samples taken at each distance from the sidewalk was plotted in MATLAB to yield the 3D plot shown above**

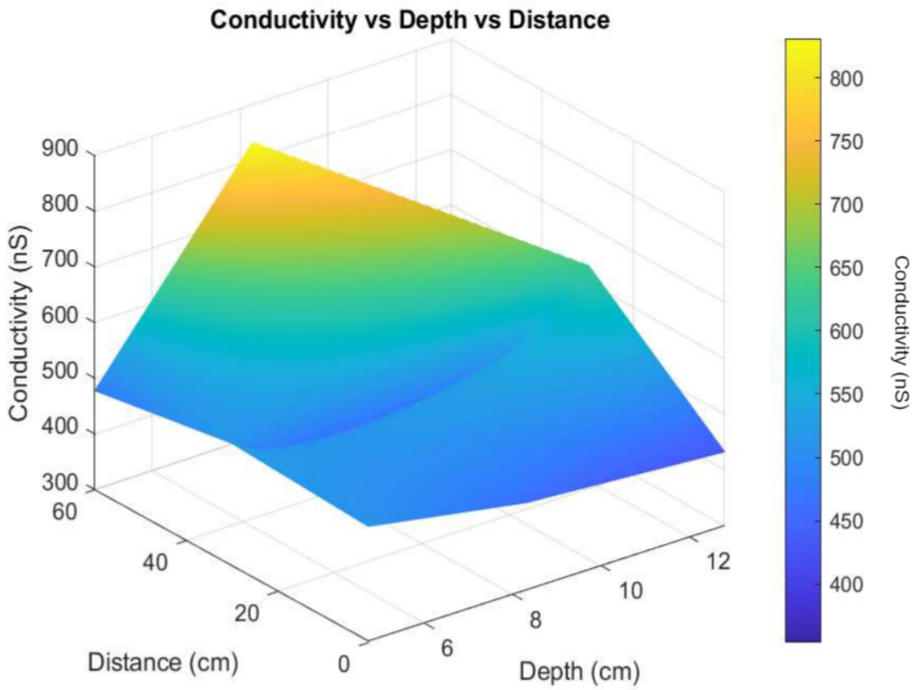

Figure 9 **Mudd Field conductivity vs depth and distance. The conductivity of the three samples taken at each distance from the sidewalk was plotted in MATLAB to yield the 3D plot shown above**

As shown by Fig. 8 above, it is again difficult to conclude what is causing the variations in pH. An observable change is present, however, as there is an upward trend in pH as depth increases, and slightly as you move further from the pavement. Additional analysis would be required to better understand the nature of this trend.

As for the conductivity data shown in Fig. 9, there does seem to be a trend in the values as depth and distance increase. Similar to pH, the conductivity tends to increase as both depth and distance from the sidewalk increase, as demonstrated by the yellow "peak" at high distance and depth. This finding begs the question of why might the soil be more conductive as both position variables increase. One possibility might be that the rocks and soil at that point might be more conductive, but a more pressing issue would be that the soil contains accumulated deicer from past application days. While both claims require more testing before they could be verified, this finding does bring awareness to an issue not previously discussed and can be used as a foundation for future research.

Amendment Testing

Figures 10 and 11 below show the relevant data collected when assessing the five soil amendments investigated in this analysis. The pH and conductivity of soil samples treated with each amendment were measured. These values were then compared to a control of the soil sample alone and percent relative changes in pH and conductivity were calculated for each amendment. These values were averaged across the two trials conducted to yield average percent changes for each amendment. Figure 10 shows the relative percent changes in the pH while Fig. 11 shows the percent changes in conductivity for each amendment. See Appendix A for the raw data utilized in this analysis.

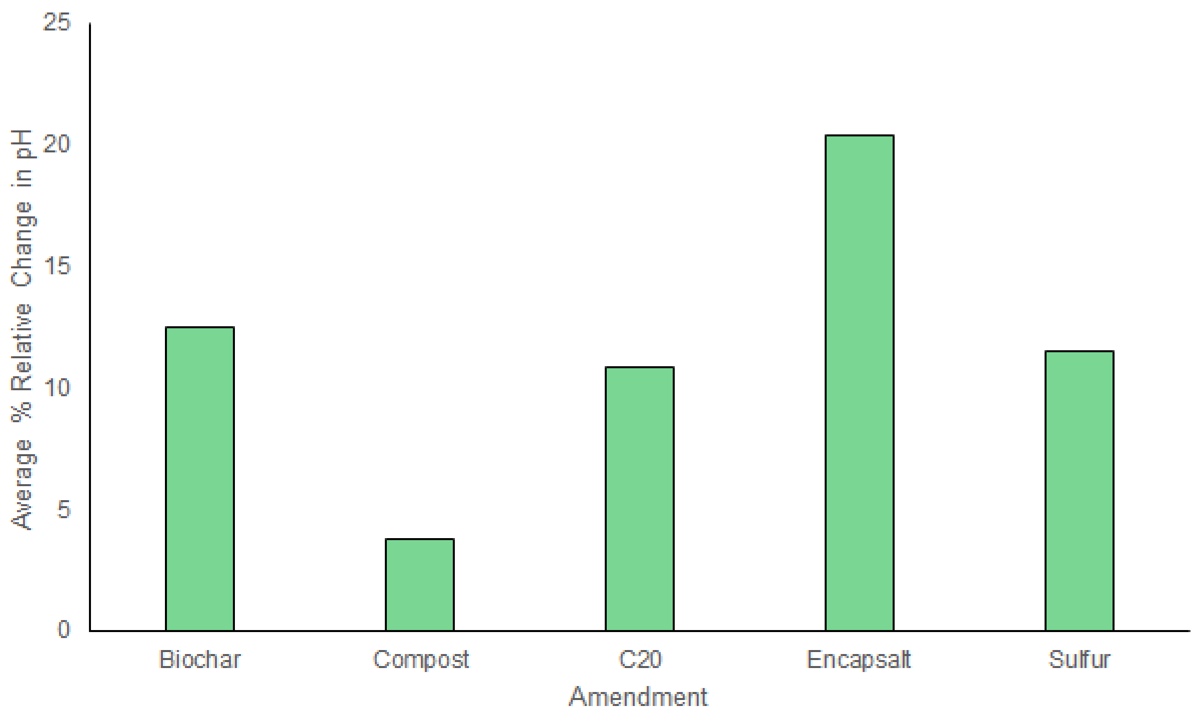

Figure 10 Percent changes in pH for each amendment. The average percent change between the amended soil and the control was calculated and plotted for each amendment tested

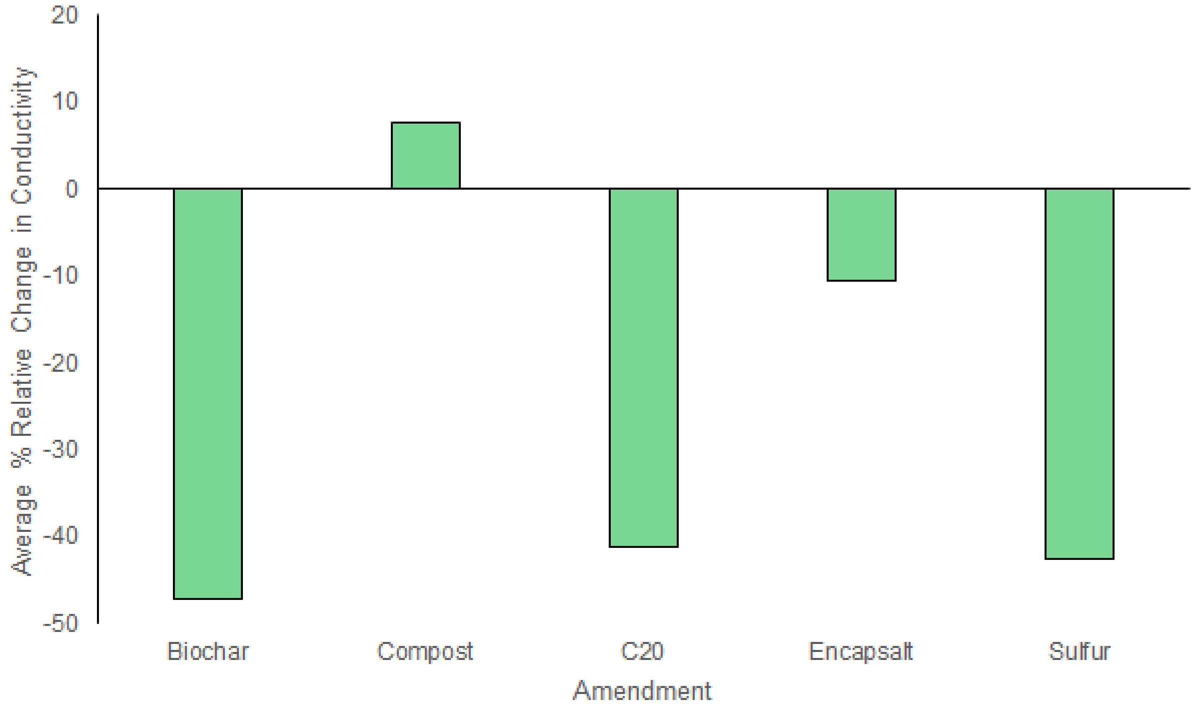

Figure 11 **Percent changes in conductivity for each amendment. The average percent change between the amended soil and the control was calculated and plotted for each amendment tested**

As can be seen by Fig. 10, all amendments had a positive effect on the pH, meaning the soil became more basic after the amendment was added. Of the amendments tested, Encapsalt provided the highest change in pH. It is again important to note that this change gives little insight into how this will affect the soil's ability to maintain its moisture. It can be said that these tests give us an estimate of the acidity of the amendment itself, which can be an important factor for some, but not for the deicer impact case.

As shown by Fig. 11, with the exception of compost, all amendments were able to reduce the soil's conductivity, with biochar exhibiting the largest percent decrease. With conductivity having a more direct relationship on presence of deicers, it is probable that biochar stands to be the most effective in mitigating the effect of oversalting.

A more complete description of how soil amendments were analyzed and the factors which were considered when comparing amendments can be found in Appendix B, which contains the full HOQ analysis conducted for all amendments.

Discussion and Recommendations

Biweekly Sampling Data

Between the pH and conductivity data collected, the group was most concerned with conductivity. As previously explained, this is because the ability of deicing salts to increase the conductivity of soils is the cause of many of the negative consequences associated with deicers. The impact of deicers on pH, on the other hand, is more difficult to quantify. That being said, the group was still interested in the pH results to examine if deicers have any significant impact on the pH of soils on Washington University's campus. However, the group was unable to draw any clear conclusions on the effect of deicers on pH.

With regard to the conductivity data, the group did find some notable data points. For instance, the measured conductivity at 0 cm from the sidewalk at Mudd Field on February 25th was 3500 µS, which is an extremely high value. This is notable because February 25th came a few days after a large snowstorm during which deicers were applied. The soil at 0 cm from the sidewalk would be most affected by this event as it would be in closest proximity to where deicers were applied. Thus, the situation shows a good example of how deicers can have a significant impact on soil conductivity.

Soil Amendment Testing

All 5 amendments (compost, biochar, sulfur, C20, and Encapsalt) and the control soil samples were tested under the same environmental conditions. When it came to pH data, all 5 amendments had the effect of raising the pH within a general range of 4%-20% from that of the control soils. Unfortunately, there are few conclusions we can draw from this data, other than that all of the amendments are perhaps slightly more basic than the non-amended soil at Mudd Field. This slight increase in pH shouldn't have any notable effects on the soil's health.

The conductivity results, on the other hand, yield more meaningful implications. The range of changes in conductivity values was much larger than that of pH, ranging from -47% to +8%. More specifically, biochar, C20, and sulfur all decreased conductivity by 40+% while Encapsalt only reduced conductivity by about 10% and compost actually slightly increased the conductivity. One of the main goals of this project is to find ways to mitigate increases in soil conductivity resulting from the application of deicers. In that regard, biochar, C20, and sulfur all perform extremely well. On the contrary, Encapsalt seems to have a relatively weak performance and compost does not seem to mitigate high conductivity levels at all.

The group's initial lab tests on the different soil amendments would seem to suggest that the most effective amendment at mitigating the negative effects of deicers is biochar, closely followed by sulfur and C20. However, the lab data only looks at the raw performance of the amendments and doesn't consider other factors. Other considerations that may affect the quality of each amendment include cost of application, the amount of resources required for production, environmental impact, rate of application, and ease of application. The HOQ analysis conducted by the group was utilized to assess the importance of these other factors. Scores were assigned to each amendment by following the procedure outlined in Appendix B to compare amendments. The resulting scores were as follows: 16.2 for biochar, 15.4 for sulfur, 14.3 for C20, 11.5 for encapsalt, and 10.5. For a more detailed explanation of the HOQ analysis, including the specific data for each amendment, please refer to Appendix B.

Ultimately, even when considering other factors in addition to ability to lower conductivity, the group still determined that biochar was the best amendment, closely followed by sulfur and C20. Based on this information, the group recommends that our clients further investigate the feasibility of applying biochar, sulfur, and C20. Since each amendment proved effective in reducing conductivity, a more detailed analysis pertaining to how effectively each amendment could be employed on campus would be a useful line of inquiry for making a final decision regarding amendment use on campus.

Additional Considerations

There were also other areas of deicing research that our clients and/or future deicing groups could look at in the future to improve the use of deicers on campus. One of these areas could be a further analysis on the potential contamination of drinking water from deicing salts from both groundwater seepage and runoff. The contamination of drinking water is a possible negative impact of deicing that we have previously mentioned but did not explicitly study this semester. Future research in this area would be extremely salient as drinking water is something that affects all of us.

Another future area of research with regard to deicing could be social equity. Although social equity was considered as a potential line of inquiry for the project this semester, it was ultimately decided that any measures which could sufficiently consider this factor were beyond the scope of the project. There are several ways that deicing and our deicing project could affect social equity. For one, runoff from deicers on WashU's campus could potentially harm the roads, walkways, and environments of other communities in the St. Louis area. This point was one of the driving factors for conducting the previously described depth tests; however, the results of this analysis did not yield conclusive results and would require further investigation to make any concrete assertions. Our project itself also has social equity implications. The workers who carry-out deicing on campus could potentially be negatively affected by changes to WashU's deicing procedure that result from this study. It is therefore pertinent for their voices to be considered when officially making changes to the soil or deicing on WashU's campus. The possibility of interviewing WashU groundworkers to get their input on this study was considered to account for this matter, but was ultimately decided beyond the scope of the project at this time.

Conclusion and Future Plans

This study seeked to assess the impacts of deicers on Washington University's campus and investigate ways in which these impacts could be mitigated. Based on the biweekly sampling data collected, the pH of campus soils seems to remain fairly constant across different sampling locations and distances from the sidewalk, with results consistently falling within the 6-8 range. The conductivity at each sampling location also showed relatively consistent values, with few trends emerging besides slight increases observed following weather events. Moving forward, it is recommended that this data be used as a baseline for soil health on Washington University's campus to be compared against in future years.

Based on the conductivity results obtained from the depth testing conducted at Mudd field, it was also preliminarily observed that rainwater may be carrying deicers deeper into the soil and away from the sidewalk. This result could have implications on how deicers may be accumulating in the runoff waters collected through the drainage systems on Washington University's campus. However, as only one test was conducted in this analysis, it is recommended that these results be considered preliminary and that more extensive studies be conducted to investigate how deicers may be seeping into water reservoirs on campus.

Finally, through the HOQ analysis conducted for biochar, encapsalt, C20, compost, and sulfur, it was found that biochar yielded the most promising results. However, due to the high cost associated with biochar as a result of its high rate of application, it may be worth exploring sulfur and C20 as well, which yielded similar performance results but have a lower associated cost. Therefore, it is recommended that all three of these soil amendments be further investigated through a more robust study which can better assess the feasibility of applying each amendment on Washington University's campus.

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Appendix A: Raw Data

Table A1 Amendment Testing Data from Two Trials

	pH (Trial 1)	pH (Trial 2)	Conductivity (µs) (Trial 1)	Conductivity (µs) (Trial 2)
Control	9.07	7.34	491	931
Biochar	7.94	8.58	486	499
Compost	8.75	8.15	352	1337
C20	9.16	8.86	251	619
Encapsalt	8.83	8.84	950	717
Sulfur	9.3	8.84	243	608

Table A2 Depth Sampling Data

Distance (cm)	Depth (cm)	pH	Conductivity (µs)
0	4.7	7.22	509
	8.3	7.87	458
	12.8	8.28	432
30	4.7	8.6	521
	8.3	8.8	342
	12.8	9.31	631
60	4.7	8.3	478
	8.3	7.98	832
Control*	4.7	6.53	82.6
	8.3	6.65	56.2
	12.8	6.48	50.2

*Control location in Brookings Quadrangle, distance not applicable due to isolation from path

Table A3 Distance Sampling Data

Date	Location	Distance (cm)	pH	Conductivity (μs)
2/5/2021	East End	0	9.33	417
		30	9.38	181.5
		60	8.75	170.4
	Oak Allee	0	7.7	212
		30	7.51	393
		60	8	139
	Mudd Field	0	9.17	365
		30	8.42	251
		60	7.8	400
	Brookings*	N/A	7.44	313
2/25/2021	East End	0	8.26	735
		30	6.75	422
		60	6.7	359
	Oak Allee	0	7.62	154.1
		30	6.97	270
		60	7	206
	Mudd Field	0	7.41	3500
		30	6.96	731
		60	6.86	570
3/11/2021	East End	0	7.76	196.5
		30	6.3	923
		60	6.4	651
	Oak Allee	0	7.22	857
		30	7.12	830
		60	6.96	687
	Mudd Field	0	9.46	605
		30	7.14	996
		60	7.74	430
3/25/2021	East End	0	6.79	144.5
		30	6.49	696
		60	6.65	453
	Oak Allee	0	8.44	401
		30	7.22	248
		60	7.41	82.3
	Mudd Field	0	8.8	363
		30	7.71	858
		60	7.98	234

*Control location in Brookings Quadrangle, distance not applicable due to isolation from path

Table A4 HOQ Raw Data

	Performance (pH) (average % relative change)	Performance (conductivity) (average % relative change)	Cost Per Unit Area ($/m^2)	Resources	Environmental Impact	Application Rate (g/m^2)	Ease of Application (times per year)	Ease of Application (application method)
Biochar	12.5	-47.1	$39/m^2 [8]	Biomass[8]	Pyrolysis produces biochar and bio-oil [8]; heat energy released can be converted to electricity	13,700g/m^2	Application ~1x/year. [10]	Apply over the ground and rake it in thoroughly; Established lawns will need to be aerated.[10]
Compost	3.8	7.6	$1.38/m^2 [4,,12,13]	Green matter and brown matter[16]	The materials in compost are all organic matter and biodegradable waste[11]	27,400g/m^2 [4,12]	Once per year in cool climates, twice per year in warm climates[17]	Apply 1-2 inch thick layer over soil and incorporate to a depth of 6-8 inches. Can apply by hand, by rake, or mechanically (spreader, grading blade,etc.)[12]
C20	10.9	-41.2	$0.24/m^2	Grain products and inert binding agents [5]	SDS gives a warning about excessive groundwater release; None of the ingredients are toxic[18]	98 g/m^2 [5]	Annual application 1x/year should be sufficient[15]	Put the amendment in a turf application spreader and apply it along all soils.[15]
Encapsalt	20.4	-10.5	$0.002/m^2 [20]	5 active, cheap components[2] [1]	Active ingredients are dilute but very toxic; if too concentrated it will have negative health effects[21]	0.25 g/m^2 [6]	Apply every 15-20 days until satisfied with turf [6]	Apply to top of soil (light mixing is encouraged, not required)[6]
Sulfur	11.5	-42.6	$0.11/m^2 [22]	From reactions for Claus Process, H2S and O2 are reacted to form sulfur[23]	In the Claus process, the elemental sulfur is recovered from petroleum refineries, natural gas plants, and coking plants.[24] The Claus Process reduces the environmental impact of these processes by 52.34%[25]	44.8 g/m^2 [26]	Should be applied every 3 months at most.[26]	Elemental soil should be incorporated (mixed into the soil) into the top 1-2 inches of soil to maximize oxidation. The soil should be aerated throughout the year.[26]

Appendix B: House of Quality (HOQ) Analysis

To more holistically evaluate the soil amendments, the group did a HOQ analysis that considered factors like performance (found through lab testing), cost per unit area, resources to produce the amendment, the environmental impact, the rate of application, and the ease of application. The research used to construct this HOQ analysis can be found in Appendix A.

Based on the information found through research, the scoring cutoffs were set for each category, and the weighting was set based on the clients' priorities. The ++ correlates to a score of 4, the + correlates to a score of 3, the 0 correlates to a score of 2, the - correlates to a score of 1, and the -- correlates to a score of 0. To obtain the overall scores found below, Equation 1 was utilized.

$$Overall\ Score\ =\ \sum_{0}^{n}(weighting_0 * score_0) + ... + (weighting_n * score_n) \qquad (1)$$

Based on the final scores, Biochar is ranked first with a score of 16.2, the Sulfur is ranked second with a score of 15.4, and the C20 is ranked third with a score of 14.3. For future analysis, it may be beneficial to evaluate the amendments in terms of equity. To evaluate equity in a simplistic fashion, the metric of accessibility of the amendments would be a good choice.

Following the overall scoring of each amendment, correlations were assigned based on the scoring patterns between technical characteristics. To demonstrate a positive correlation, an asterisk (*) was put into the matrix. To demonstrate a negative correlation, a tilde symbol (~) was put into the matrix. For a correlation to be assigned between two technical characteristics, at least three amendments needed to correlate in the same way. If only three or four amendments related in the same way and the remaining amendment(s) had at least one neutral relationship, a correlation was assigned. If no symbol is placed into the matrix, there is not a notable correlation between the two characteristics. It is important to note that the correlations do not influence our recommendations in any way and only serve to illustrate the relationships between scoring categories.

Table B1 Summary of HOQ parameters and score assignments

Technical characteristic	Abbreviation	Weighting	Metric	++	+	0	-	--
Performance (pH)	PH	0.4	% relative change in pH.	16-20	12-16	8-12	4-8	0-4
Performance (conductivity)	PC	0.8	% relative change in conductivity.	-50 - -38	-38 - -26	-26 - -14	-14 - -2	-2 - 10
Cost Per Unit Area	C	0.8	$\$/m^2$	0-0.10	0.10-0.20	0.20-0.50	0.50-1.50	>1.50
Resources	R	1.1	"number of inputs or number of resources". This assumes that water and/or electricity are also used in production and they are not included in the count.	1	2	3	4	5

Technical characteristic	Abbreviation	Weighting	Metric	++	+	0	-	--
Environmental impact	EI	1.1	This category is defined by the extent to which an amendment	Mitigates another process's environmental impact with minimal production of undesirable byproduct(s)	Mitigates another process's environmental impact with production of undesirable byproduct(s)	Does not reduce impact of another process but produces minimal undesirable byproduct(s)	Does not reduce impact of another process but produces a considerable amount of undesirable byproduct(s)	Does not reduce the impact of another process and produces undesirable byproducts that require remediation
Application Rate	AR	0.7	g needed per m^2	0-1	1-10	10-100	100-1000	>1000
Ease of application (times per year)	EOAT	0.5	The number of times per year it is recommended that the amendment is applied.	1	1-2	2-3	3-4	>4
Ease of application (method of application)	EOAM	0.5	The way in which the soil amendment is applied	Spread on top of soil.	Spread on top of soil and light mixing recommended.	Rake into soil.	Uniformly mix into soil.	Uniform mixing and aeration

Table B2 HOQ Results and Correlation Matrix. The correlation matrix is shown in the upper half of the table with all score assignments shown in the lower half.

			PH	PC	C	R	EI	AR	EOAT	EOAM	Score
			0.4	**0.8**	**0.8**	**1.1**	**1.1**	**0.7**	**0.5**	**0.5**	
Technical Characteristics	Performance (pH)	PH						*			
	Performance (Conductivity)	PC				*			*		
	Cost	C				~	~	*	~		
	Resources	R		*	~		*	~	*	~	
	Environmental Impact	EI			~	*		~	*	~	
	Application Rate	AR	*		*	~	~		~		
	Ease of Application (times per year)	EOAT		*	~	*	*	~			
	Ease of Application (method)	EOAM				~	~				
Technologies	Biochar (spent hops)		+	++	--	++	++	--	++	0	**16.2**
	Compost		--	--	-	+	++	--	+	-	**10.5**
	C20		0	++	0	+	--	0	++	++	**14.3**
	Encapsalt		++	-	++	--	-	++	--	++	**11.5**
	Sulfur		0	++	+	+	+	0	0	--	**15.4**