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Development of a Qualitative Model for Predicting Soil Acidification due to Solid Rocket Motor Exhaust

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Increasing rocket launch rates coincide with growing concerns around climate change and pollution. Few prior efforts have attempted to assess the long-term environmental impacts of rocket launches, and those that did, primarily during the US Space Shuttle program, voiced concerns about HCl depositions from solid rocket motors. Despite solid rocket motors making up a small fraction of the market today, their HCl depositions can result in environmental acidification which disrupts food chains and destabilizes ecosystems. Modeling these effects holds value as some regions are more resilient to acidification than others. This work details a qualitative model which uses a small, readily available collection of data inputs, allowing the model to cover the majority of the continental United States. The results depict regions of resiliency/vulnerability to soil acidification relative to one another. Leveraging studies in adjacent fields (e.g., acid rain) aids in discerning what effects these regions would experience. A lack of information regarding the long-term impacts of acidification limits the scope of this effort. However, the qualitative results can still aid in guiding launch site selection processes.

I. Introduction

Since the Apollo program, generations of people have come to view rocket launch sites as symbols of human achievement. These sites serve as the starting point for the realization of countless scientific ventures. Therefore, it is not surprising that the demand and interest in rocket launches, and the facilities that enable them, continue to grow. The frequency of rocket launches experienced unprecedented increases between 2013 and 2023 [1]. These increases stagnated to some degree during the COVID-19 pandemic (2020), though the duration of that stagnation concluded by 2021 [2]. These increases in rocket launch frequency coincide with greater public interest in protecting the environment. Thus, it is important to consider the impacts of launch frequency on the environment surrounding rocket launch sites.

Currently, most launch sites in the United States reside on coastlines as these locations allow the rockets to ascend over unpopulated areas. Thus, one can assume that future launch sites will find themselves in similar locations. The nature of these locations—including Boca Chica, Texas and Cape Canaveral, Florida—means that they often coexist, or even overlap with conservation areas. Coastal ecosystems receive further attention due to their susceptibility to external influences, such as global warming, land use change, and pollution. These influences put the food chains, habitability, and stability of the ecosystem at risk. At present, the long-term ecological impacts of rocket launch sites remain uncertain, but prior studies suggest several possible avenues through which launches could impact the environment [3]. One such case pertains to damage stemming from the acidic depositions formed via chemical interactions between the exhaust of solid rocket motors and sound suppression water. The effects of such depositions range from visual damage of plants to the total collapse of the ecosystem and food chains [4–6]. Specifically, these depositions interrupt nutrient availability by depleting the supply of calcium. Calcium plays an essential role in bone formation, but also the reproductive cycle of avian species [7]. There are notable overlaps between launch sites and regions vital to migratory bird routes, including endangered species [8]. Thus, the adverse effects of these depositions, identified during the Space Shuttle program, deserve attention.

Works covering the Space Shuttle program provided insight into the deposition formation mechanisms [9], and detailed the expected and measured deposition concentrations [9, 10]. Associated environmental impact studies identified

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short-term ecological effects stemming from these depositions [3, 6, 11]. However, the launch rates achieved—just under once every two months—did not reach the thresholds required to cause long-term ecological harm. While these studies aid in determining a possible loading threshold, they fail to provide insight regarding the potential long-term effects of high-frequency launches [3]. Furthermore, their nature restricts their applicability to the region surrounding Kennedy Space Center. Despite the likelihood of future launch sites operating in regions with similar soil properties, it is unlikely that the specific environmental conditions will overlap entirely. Fortunately, studies covering acid rain and industrial emissions have examined the effects, both long and short term, of acidic depositions over a wide range of locations. Still, no effort to date has succeeded in estimating the long-term ecological effects of solid rocket launches, nor has any attempt defined the rate-dependent effects that one should expect to observe. This work seeks to take a first step towards rectifying both of the prior deficiencies by providing a qualitative evaluation of the impacts of solid rocket motor launches across the United States. This evaluation stems from the qualitative model presented in this work which estimates a region's resilience to acidification. Comparing the results of this model to prior cases of acidification indicates some of the responses that may arise following acidic loading.

II. Sources of Acidification

Developing a model to make this sort of qualitative evaluation requires an understanding of acidification. The foundation for this understanding rests upon the sources of ecological acidification. These sources fall into two primary categories: natural and anthropogenic. Both sources operate in a similar manner on the molecular and atomic levels with respect to the biogeochemical reactions that occur [12]. These reactions involve the transfer of anions and cations following the introduction of acidic compounds to the environment. Upon introduction to the environment, acidic compounds dissociate into their respective anions (e.g., Cl^-) and cations (e.g., H^+) [13]. The roles played by the anions depend heavily on the specific anion and the parent acid. This dependence arises since the ecosystem in question may capture and utilize some anions while allowing others to runoff into the watershed [14, 15]. The exact reactions involving anions usually play a minor role in ecological acidification and they are more difficult to detail [16–18]. Meanwhile, the cation reactions, revolving around the positively charged hydrogen ions, garner most of the attention. It is important to note that similar reactions occur when acidic compounds deposit onto vegetation and during soil acidification. For the purposes of this paper, and the model, this discussion shall only focus on soil reactions.

The prior mentioned hydrogen cations interact with the material they contact, the soil in this case, and begin replacing other cations. These original cations reside on a finite number of bonding sites within the soil, and soils with more of these sites prove more resilient to acidification as they contain higher concentrations of the original base cations. On a high level, soils with clay and organic matter have more bonding sites for cations than sandy and rocky soils [19]. These elevated concentrations of the original base cations slow the rate of acidification driven by hydrogen ion introduction. The original base cations include various species with notable examples including calcium, magnesium, potassium, and sodium [11]. These play key roles in nutritional cycles within ecosystems. The introduction of an excess of hydrogen ions leads to the replacement and subsequent removal, typically via leaching/runoff, of these original cations [11, 20]. These hydrogen ions also correspond to changes in the soil pH level which directly relates to the concentration of hydrogen ions. This lowering of pH values is at the core of ecological acidification [15]. Therefore, the rate at which hydrogen ion concentrations increase plays an important role, as does the area over which it occurs.

Returning to the topic of sources, natural sources of soil acidification operate on very long time scales ordering on hundreds to thousands of years, or even longer. Over these time frames, geological weathering alters the biogeochemical traits of the soil. Rocks break down via fragmentation and dissolution, due to weathering, which introduces new base cations into the soil. Meanwhile, ecological growth cycles and precipitation result in the root uptake and leaching of soil nutrients [15]. Eventually, the available cations within the rocks and soil decreases and the concentrations of hydrogen ions increase. Soil layers can also thin out over time due to weathering and erosion which further reduces the available base cation sites [21]. Thus, natural processes result in the long-term acidification of the environment over very large areas. However, natural acidification results in relatively minor environmental impacts as the time scales provide ample time for species to adapt to the changing conditions [22], or to leave the area in search of better living conditions.

On the other hand, anthropogenic sources of acidification operate on shorter timescales. These range from single deposition events spanning minutes to continuous deposition patterns spanning decades [23]. The long history of many industrial processes following the industrial revolution results in even longer range edge cases [24]. Regardless, these anthropogenic sources exhibit several notable differences with respect to natural ones. Primarily, these involve the introduction of large concentrations of acidic compounds over shorter time spans [25]. This results in similar chemical reactions to those of natural acidification, but the higher rates of acidification accelerate the resulting impacts.

These sources also afflict specific regions whose boundaries depend on the source's emission/deposition characteristics [24–26]. When considering rocket launches and the facilities that enable them, these characteristics become apparent.

Rocket launches result in the rapid expulsion of exhaust byproducts into the regions surrounding the launch pad. These byproducts form a ground cloud which emanates from the flame trenches built into the launch complex. These trenches often involve sound suppression systems which employ water deluge equipment to minimize vibrations and sound reflections. During rocket launches, the water from the deluge pumps interacts with the exhaust byproducts passing through the trench. These byproducts include alumina and chlorine particles for solid rocket motors (SRMs) [10], and nitrogen compounds for SRMs and liquid rocket engines (LREs). The reactions between the atomized water and these byproducts produces hydrochloric and nitric acid respectively. Meanwhile, the alumina particles react with HCl and water resulting in the formation of surface chloride salts on the alumina particles. The formation of the surface chlorides results in the alumina particles acting more like aluminum chlorides than aluminum oxides. One trait of aluminum chlorides is their tendency to dissolve in water, which aluminum oxide does not usually do. The implications of this include the release of HCl and aluminum (III) ions from these compounds when they dissolve [27].

While the release of HCl only contributes to the effects outlined in this work, the addition of aluminum (III) ions poses its own problems. Namely, elevated aluminum concentrations can be toxic to certain species. During soil acidification, aluminum (III) ions within the soil become more available for nutrient uptake as they leach out of the minerals in the soil. Thus, the effects of these aluminum chlorides fall within the coverage of soil acidification in general throughout this work. The newly formed compounds and all other particles and debris entering and residing in the flame trench exit at high speeds forming a rising ground cloud. At the mouth of the flame trench exit, the heaviest particles fallout quickly. The remainder fallout over time in a region defined by the ground cloud's coverage map. The concentration of fallout decays as the distance from the flame trench exit increases. This results in two sub-divisions within the affected area: the near field and far field [25]. The near field region refers to the local area within several hundred meters of the flame trench exit. The far field begins immediately afterward and extends until the concentrations of acidic fallout drop below detectable levels. The area and direction of the far field region varies significantly depending on the present weather conditions [5]. The acidic fallout alters the afflicted region's pH and base cation concentrations via the reactions outlined previously.

Prior to discussing the impacts of acidification, it is important to to recognize that the concentration of hydrochloric acid formed via a Space Shuttle launch (17,000 kg within the first 10 seconds after ignition) [9] is much much larger than that of nitric acid formed during a SRM or LRE launch (at most 1,000 kg within the first 10 kilometers of ascent for a simulated Falcon 9) [1, 28, 29]. The sources of the two compounds also differ somewhat as the chlorine comes from the fuel itself while nitrogen oxides come from combustion processes in general. This is why the latter applies to both SRMs and LREs, but the former only applies to SRMs. These differences in origin and scale explain why this work focuses on SRMs over LREs. The latter would require launch frequencies orders of magnitude higher than the former to produce similar concentrations. While LREs do not produce acidifying compounds in similar quantities, those utilizing UDMH or kerosene produce significant concentrations of soot. Elevated particulate matter concentrations pose a risk to the respiratory health of those nearby. Also, UDMH and hypergolic fuels are extremely toxic and require proper containment on the ground and during flight. Still, from now on the discussion of launches and the impacts that follow pertain specifically to SRMs.

III. Impact of Acidification

Understanding the sources of acidification and the associated mechanisms provides a useful background for discussing their impacts. These ecological impacts arise due to the changes in the chemical composition of the soil and its pH levels. The primary concern stemming from soil acidification pertains to the loss of base cations. As outlined in the prior section, introducing H^+ ions displaces the original base cations including crucial nutrients such as calcium. As these cations exit the nutrient pool, the effects first appear in insects, crustaceans, shellfish, and other low level members of the respective food chain [7, 22]. Most of these rely on ground-feeding for sourcing nutrients, thus the depreciation of nutrients due to acidic depositions impacts them quickly. The observed effects include reductions in overall biomass as well as weaker shells for species utilizing them. Weaker shells align with expectations as shell formation depends largely on calcium availability [22]. Unfortunately, disruptions near the bottom of the food chain often prove difficult to track due to challenges associated with collecting and studying adequately large populations. These difficulties result in an increased focus on species higher in the food chain and those slower to respond.

These higher level species of interest include small mammals, birds, and reptiles. Since these species feed on the lower level members discussed previously, they too exhibit effects of nutrient depreciation. Egg laying species rely on external calcium inputs to form their eggshells. As calcium supplies decrease, so too do the concentrations in the species that many egg-layers feed on [7, 22]. Prior studies observed that acidification correlated with decreased reproductive success in multiple bird species [30, 31]. The reliance of species at multiple levels on the calcium content in the local soil highlights that species in any ecosystem may prove susceptible to soil acidification. As these species begin to decline, the observed effects extend higher still along the food chain, but that is only one part of the problem.

Beyond animals and food chains, acidification also disrupts plant growth. Plants depend on these base cations and stable pH conditions for growth and maintaining their overall health [20, 32]. Disrupting these factors in the short term usually poses a problem for smaller plants, and/or those especially sensitive to acidity. However, prolonged depreciation in cation availability and semi-permanent pH reductions threaten a much broader population [33]. Prolonged shifts in nutrient availability and soil pH lead to root death for many species which corresponds to stunted growth and die-off events [34]. Reductions in growth and biomass compound with direct damage to vegetative surfaces due to acidic depositions, though those fall outside of the scope of this work. Compounding interactions play a key role in assessing the severity of these impacts.

As species at the bottom of the food chain decline in value and density, the effects spread up to larger species. As larger species begin to experience stresses stemming from food scarcity, they must also face a changing habitat. Plants that once provided refuge and food begin to die-off, further increasing the stress on already vulnerable species [31]. This cycle continues to climb the food chain in events where acidification continues and worsens. Thus, the general impacts following soil acidification include reductions in animal and plant species diversity [35]. These reductions lead to habitat loss and the depreciation of general biomass. However, the effects observed may lag behind the beginning of acidification and its impacts. One could expect that the process takes some time to start impacting the bottom of the food chain. Thus, it follows that the time to impact higher levels of the food chain will take longer still [32]. This raises some concern around stemming acidification early on. Any effort to stem the impacts of acidification relies to some extent on models designed to predict the impacts.

Several works detail efforts to quantitatively model acidification in an attempt to predict these impacts. These efforts provide useful insight regarding the keystone characteristic inputs for the models and how these interact [36–39]. However, they also outline the problems with quantitative models. Primarily, the models require large collections of inputs, many of which require extensive on-site sample collection and testing. The dependence on localized inputs leads to the second problem as some of these models try to simulate the responses of a very specific region/ecosystem which limits their applicability. By contrast, this work's modelling effort aims to provide coverage for the entire contiguous United States. The extent of this coverage effectively rules out any model that depends on site-specific input conditions. While quantitative models serve as a guide, they cannot fulfill this role.

IV. Model Development

The qualitative model outlined below attempts to assess regional susceptibility to acidification via a relatively small collection of ten inputs (from federal government SSURGO and STATSGO data sets [40]): cation exchange capacity (CEC), soil pH, organic matter concentration, calcium carbonate concentration, rock fragment percentage, soil depth, soil bulk density, sand percentage, silt percentage, and clay percentage. These inputs are biogeochemical traits which play essential roles in the prior mentioned quantitative models. However, their use here serves to provide a qualitative estimate of resiliency rather than detailing exact outcomes. In a perfect scenario, the model would use buffering capacity as the baseline for all regions and then define outcomes based on that. This trait alone can define how well a soil sample can resist acidification on a biogeochemical level. However, data for buffering capacity is not readily available as it requires on-site testing. Instead, this model estimates buffering capacity via the ten inputs outlined prior.

To assess the importance of each trait the model assigns weights to them depending on how closely tied they are to buffering capacity. These weights take into account whether a trait improves or worsens buffering capacity and the magnitude of this impact. Prior to starting the weighting process the model adjusts the scales of each trait such that they align. This is an important step in making the process easier as the original scales vary due to different units. In this case, the desired scale is from zero to one, but choosing the upper limit on the original scales for alteration is not trivial. The maximum value for a given trait may be much higher at a finer resolution. This becomes relevant when examining regional averages over large areas, such as counties or states. Thus, the upper limit may vary by an order of magnitude depending on the resolution involved. Accordingly, the upper level has several options: the resolution maximum and the area maximum. Using the resolution maximum, provides a more applicable result. On the other hand, an area (county, state, etc.) maximum gives a more intuitive result. Sometimes, these two maxima are the same value and in those cases this decision becomes a non-issue. Overall, the model utilizes the resolution maxima as these enable future application to smaller regions of interest. In cases where an area average takes precedence this normalization process also applies to the standard deviations such that they retain their relevance. Following the selection and initial scaling process, the model begins assigning weights to each trait.

Determining the relationships between each trait and buffering capacity to produce numerical weights immediately becomes complicated. While certain sources provide real world correlation coefficients between traits and buffering capacity, these are uncommon. Instead of relying upon such examples for each trait, this model first utilizes a partial analog for buffering capacity comprised of CEC and pH. The decision to use these inputs stems from prior works illustrating that they align very closely with buffering capacity. The sources agree that cation exchange capacity is the predominant factor in buffering capacity [41–43]. This follows expectations as the CEC buffering mechanism exists for soils with pH levels near and above four which covers most soils [44]. Additionally, one notable study identifies that CEC has a Pearson's correlation coefficient of 0.4897 with respect to buffering capacity [41]. The study notes that the tested soils are acidic to begin with which may indicate that the observed coefficient would be an underestimate for less acidic soils, such as the average for the contiguous United States. An underestimate in this scenario could arise as more acidic soils correlate with reduced CEC prevalence due to depletion while other buffering mechanisms still remain. Meanwhile, baseline pH is also a closely tied indicator of buffering capacity. Higher soil pH indicates that the buffering mechanisms have not depleted yet. The same source that provided an estimate for CEC states that the Pearson's correlation coefficient between soil pH and the buffering capacity is 0.2871 [41]. For the same reason mentioned prior, it seems likely that this would be an underestimate when compared to that for less acidic soils. Checking this value with respect to the United States as a whole relies upon considering the Pearson's correlation coefficients between pH and the buffering mechanisms: clay, $CaCO_3$, CEC, and organic material. These coefficients, in order of appearance are: 0.1219, 0.7195, 0.3914, and 0.0457 with the average being 0.3196. This supports the likelihood of an underestimate from the prior source for this case which aligns with expectations given the acidic soils in that study. Extending this to the CEC coefficient yields the following coefficients for use in this model: CEC (0.5000), and pH (0.3196). Together, these serve as a partial analog for buffering capacity which enables the weighting of other traits with respect to buffering capacity. The weights for each trait arise via the following equation which leverages the CEC and pH analog:

$$w_x = \frac{w_{\text{CEC}} r(\text{CEC}, x) + w_{\text{pH}} r(\text{pH}, x)}{w_{\text{CEC}} + w_{\text{pH}}}, \tag{1}$$

where x represents the trait in question, w_y represents the weight of trait y, and $r(y, x)$ is the Pearson's correlation coefficient between CEC or pH and the trait x. This method yields the weights shown in Table 1:

Table 1 Input parameter weights for the buffering capacity analog.

CEC	pH	Organic Matter	Calcium Carb.	Rock Frag.	Soil Depth	Bulk Density	Sand	Silt	Clay
0.5000	0.3196	0.2589	0.2571	-0.0356	-0.0410	-0.3432	-0.2765	0.1438	0.3173

The first step in verifying these weights pertains to confirming the expected trends for each trait. If the prevalence of a soil trait is inversely proportional to the quality of the response to acidification, then the weight for that trait should be negative. If increasing the trait's prevalence corresponds with an improved response to acidification, then its weight should be positive. The studies consulted for determining the traits' trends agree that cation exchange capacity, calcium carbonate concentration, baseline pH, and clay and silt content exhibit positive trends [19, 41–45]. These positive trends follow expectations as each of these traits, besides baseline pH, contributes to a soil's buffering capacity. It is important to note that pH exhibits a positive trend as it indicates the health of the buffering mechanisms rather than acting as one. Meanwhile, the cation exchange complex is the fundamental core of buffering capacity as it dictates the ability of the soil to trade base cations. Calcium carbonate concentrations play a vital role in resisting acidification for calcareous soils. The potency of calcium carbonate as a buffer to acidification means that these soils rarely experience acidification under normal conditions. The baseline pH of a soil corresponds with its buffering capacity though not necessarily in a linear relationship. Higher soil pH levels indicate that the soil still has multiple layers in its buffering capacity. These layers include calcium carbonate, organic matter, the cation exchange complex, and clay contents. As the pH lowers, the buffering capacity reaches saturation as each of these mechanisms exhausts itself. Clay forms the last part of the buffering capacity as it trades minerals, such as aluminum, for hydrogen ions during acidification.

The studies reviewed also consider the trends associated with bulk density, sand content, and soil depth. Each of these traits follows a negative trend during acidification [21, 45]. The negative trend with bulk density coincides with a strong relationship to the presence of sand. Bulk density also shares a negative trend when correlated with organic matter, clay, pH, and CEC. Soil depth exhibits a weak negative trend as deeper soil allows for greater opportunities to mitigate acidification, but buffering capacity worsens in deeper soil layers. This duality is likely responsible for the weak correlation overall. The negative trend from sand arises due its typical lack of charge which limits its affinity for cations, including base cations and hydrogen ions. Also, acidic depositions rapidly saturate the soil and deplete its buffering capacity more efficiently. This leaves two traits in their own state, organic matter, and rock fragments. The former receives extensive coverage [19, 41–44], but the results vary. Generally, the works conclude that higher organic matter concentrations correspond to increased buffering capacity. Rock fragments pose more of a challenge as they receive little to no coverage in the sources. They also exhibit negative correlation akin to soil depth with minimal correlation strength. This negative trend could occur for reasons similar to bulk density. The presence of rocks reduces the volume available for buffering mechanisms, such as clay, organic matter, and calcium carbonate. Thus, this negative correlation seems appropriate.

With the weights and trends identified, it is worth briefly recapping why they are what they are on a practical level. Starting with calcium carbonate provides a relatively simple case. The calcium carbonate in a soil usually acts as the first buffering mechanism. So, soils with high pH, thus not acidified, retain their calcium carbonate [44]. However, the relationship is not one to one as there are soils with high pH that completely lack calcium carbonate [40]. This compound is not universally prevalent, so this relationship makes sense. Moving on to the relationship between soil pH and CEC shows a perhaps unexpected result. Despite both being very closely tied to buffering capacity, they do not correlate with one another as much as one may expect. However, it is important to consider that CEC remains prevalent over a very wide soil pH range [44]. Also, it does not decrease with a linear relationship to pH during acidification due to other buffering mechanisms acting before, alongside, and after [42]. This is nearly the exact same case for clay, it is just more extreme as it is an inherent soil component. This means that clay remains present even in very acidic soils, despite still being a buffering mechanism. This leaves organic material as something of an outlier. While it is a buffering mechanism, it is more common in pine forests, swamps, and coastal wetlands. These regions have complex physical characteristics that often lead to more acidic soil. Pine forests often exist on sandy soil which has fewer bonding sites for cations which means they are often more acidic. Pine forests also lower the local pH as these species produce acidic litter-fall. Still, organic material helps resist external acidification, so it functions as a buffering mechanism despite the very weak correlation with pH.

With the analog weights established and justified, they provide the reference point for the correlation coefficients (weights) for each trait. After determining the positive and negative weights, they enter an array which maintains the same order as the traits that they apply to. Taking the sum of each weight, w, times its respective normalized value, v, for each region, or pixel, yields a raw score. The following equation depicts how the model estimates this raw score (akin to buffering capacity) using the prior determined weights:

$$\text{Score} = \sum_{i=1}^{10} w_i v_i . \tag{2}$$

It is important to note that at the resolution of the input data, the normalized value portion contains a trait value for each grid square, around 21 million in total. This equation applies the trait's weight to each of those values and repeats the process for each trait, summing the result. The score output remains dimensionless since this is only an estimate and cannot exactly define buffering capacity. However, this score is not in an intuitive form so the model re-scales the scores to range from zero to ten. The new minimum score is equal to the lowest raw score outlined above, and the maximum score of ten represents the largest raw score. If the model is set to calculate an area average for a region larger than the resolution it will also keep track of the standard deviation for each trait. The absolute value of the weights apply to the standard deviations as well. The model then takes each raw score and subtracts the weighted standard deviation. In that case, the minimum result of that operation serves as the 0-point. Then, it sums each raw score with its respective standard deviation such that the maximum is the 10-point.

Continuing in the area average case, the model then utilizes the average scores and their respective standard deviations to determine the probability that the actual score falls within a given interval. This process utilizes a cumulative distribution function and separates the likelihoods into integer bins from 0–1, 1–2, and so on. The bounds of these bins are easy to adjust to account for different levels of granularity, and the model includes a mask which filters out likelihoods below a certain percentage (one percent by default). The model stores the final scores (average or actual depending on the scenario), and the standard deviations and distributions if using the area average. Table 2 provides an example of the storage structure for a county area average data set. It retains position identifiers (GEOIDs) from the

Table 2 Data structure sample output by the qualitative model with truncated percentages.

County ID	County Name	State	Avg. Score	STD	Response Score Probability Distribution 0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
48053	Burnet	Texas	5.16	1.32	0.00	0.00	0.04	0.14	0.26	0.28	0.18	0.07	0.01	0.00

original input sets such that this information retains its value. At present, it would still remain difficult to interpret while in a large table. The model is set-up such that one could export this information in a format compatible with mapping software. This enables visualization of the results and improves one's understanding of the outlined trends.

V. Results

Utilizing the soil parameter data sets outlined previously, this model yields results visualized via the map in Figure 1 [40]. As described in the previous section, the model prioritizes the resolution scale output, in this case that resolution is the input resolution of 800 by 800 meters per pixel. Every pixel displays a visual representation of the qualitative score. The scenario in Figure 1 does not utilize an area average, so this data set does not include any standard deviations, or probability distributions. As shown, the qualitative scores exist on a range of 0 to 10 where regions with higher scores are likely more resilient to acidic loading. Greater resiliency corresponds to a slower propagation of ecological decline. The regions shown in green represent areas in which the present soil data, often for CEC, is insufficient for scoring or outside of the data sets' scope (Canada and Mexico).

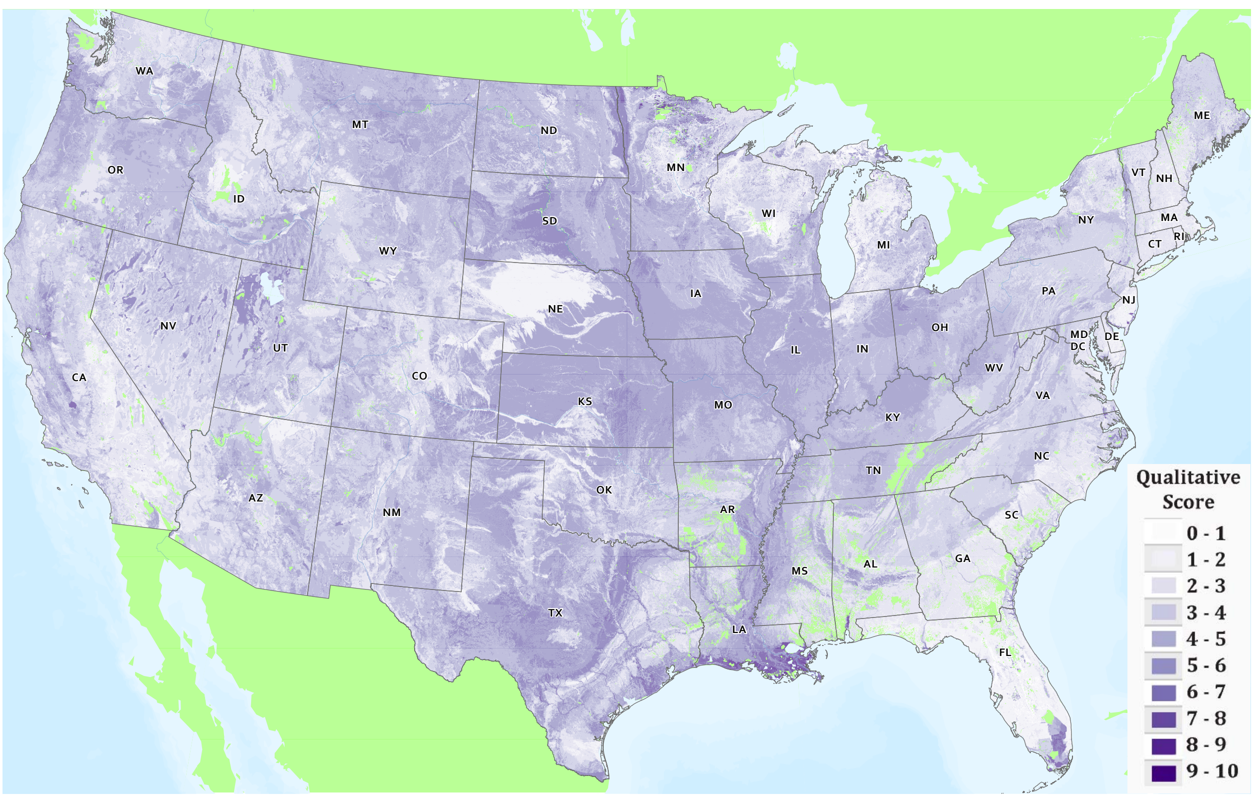

Fig. 1 Relative regional response to acidic loading for the contiguous United States. A higher score indicates a greater resiliency against acidification.

The next map shown in Figure 2 provides an example of regional average scores for the counties of the contiguous United States. This means it includes the area average scores and their respective standard deviations and probability distributions. When used alongside the prior map, this one shows the importance of tracking the standard deviations as

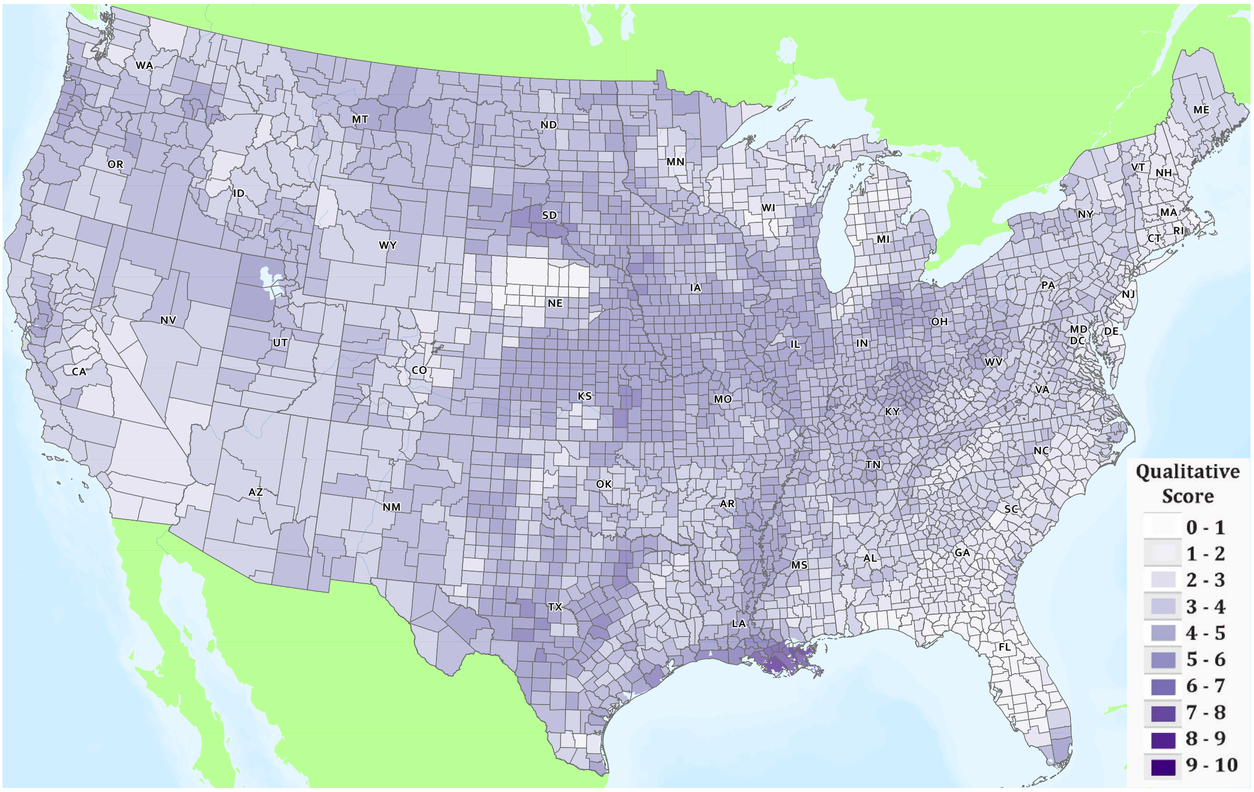

Fig. 2 Relative regional response to acidic loading for the counties of the continental United States.

some counties cover very diverse soil properties and vast land areas. It is important to note that the standard deviations and distribution functions do not appear on the visual directly, but one could find them via searching for the geographical identifiers in the exported data structure. The value of this particular map pertains to this model's possible integration with the facility location planning (FLP) model developed in Ref. [46]. The first scenario considered within that model identifies Humboldt, CA, Matagorda, TX, Monroe, FL, and Washington, ME as the optimal counties for future space port locations. It is important to consider that this scenario did not consider the scores outlined by the map in Figure 2. This map indicates that the scores for these counties in order of appearance are 4.15, 5.43, 4.98, and 3.78. Following the understanding that higher scores indicate more resilient regions, this map suggests that the best of the selected counties is Matagorda county in Texas.

As it stands, the qualitative scale from 0 to 10 is quite abstract in two regards. First, the exact response of a soil remains undefined with only a general relationship, which dictates that a score nearer to 0 indicates greater vulnerability to acidification than a score nearer to 10. Secondly, the scores apply to acidic depositions and acidification in general. This is useful for wider applicability, but it does not provide significant value when considering launch sites. So, the next step focuses on defining the effects described by the scores with respect to acidic loading from solid rocket motors. The studied effects of these rocket motors may aid in defining a given score and thus others from there. Generally, the scores should be able to describe the type of response and the deposition rates required to see notable effects. However, the scores cannot describe the impacts to specific species, nor how the impacts manifest differently between species. They also lack the capacity to describe the recovery time of the soil once the acidic loading concludes. A quantitative acidification model would better resolve these two deficiencies, but it would require significantly more data. Another factor to consider is the size of the scale itself. Currently, it utilizes ten intervals which improves model fidelity and region separation. However, it may prove challenging to find the difference between intervals. Examining test cases and comparing the results to the scores may aid in discerning these differences.

VI. Discussion

The test cases come in two varieties: those pertaining to rocket launch sites, and those in adjacent fields of study. The predominant case in the former comes from the Space Shuttle program's environmental impact assessments. This program exclusively used the launch facilities at Kennedy Space Center in Brevard County, Florida. The following coverage of this test case yields the most widely applicable results for the definition process. However, this example comes alongside several drawbacks due in large part to a slow launch rate. Following a discussion of the Space Shuttle program, the focus shifts to adjacent fields of study. These fields include works looking at acid rain and its associated ecological impacts as well as the impacts of large industrial processes. Industrial processes exhibit similar spatial deposition behavior to the Space Shuttle program. The key difference between these two cases comes from their respective emission behaviors. While the Space Shuttle program and present launch programs behave as pulsed emission sources, industrial processes behave as continuous emitters. Both sources act as point source emitters in producing characteristic near and far field regions. However, the distinction between these regions differs between pulsed and continuous sources. Still, the industrial emitters and their effects may reflect the emissions from rocket launches.

Comparing rocket launch emissions to any adjacent field poses several significant challenges. The test cases must contain two critical elements to ensure compatibility and applicability. The first element describes the deposition loading rate as the mass of H+ ions per unit area per time. This information already exists for general acid rain patterns, but finding similar results for industrial test cases poses a greater challenge. The second element identifies a target ecosystem response occurring due to soil acidification. This work focuses on examining plant health degradation and species loss. These indicators are relatively easy to track and they do not require extensive testing. With these two elements, a test case can contribute to defining the qualitative scale.

The first, and simplest test case is the Space Shuttle program which operated out of Kennedy Space Center (KSC) in Brevard County, Florida. Our model results show that the near-field region for KSC has an average score of approximately 3, which suggests that it would be susceptible to soil acidification. The local soil conditions show that this is a sandy region with relatively low calcium carbonate concentrations. Still, it has high CEC, adequate organic material concentrations, and a relatively high baseline pH. The low score arises, at least in part, due to the lack of clay relative to a dominant sand composition. The area occupied by KSC includes two primary launch pads used for the Space Shuttle program, 39A and 39B. The effects of near-field depositions from launch pad 39A covered between 10 and 15 hectares for any given launch [9]. This region typically extended to the north of the launch pad as its flame trench directed the solid rocket exhaust northward. These near-field effects usually reached no further than one kilometer in a given direction [5]. Deposition concentrations include two quantitative values pertaining to particulates and chlorides respectively. The near-field region experienced chloride depositions between several milligrams and 127 grams per square meter while particulate deposition concentrations reached as high as 246 grams per square meter [9]. The chloride depositions are the focus here and total up to 3,400 kg for the near-field region per launch [47]. It is worth noting that the trench's northward direction intersects the ocean. The ground cloud released from this trench sweeps across the ground for about one kilometer. Then, as it slows down, it rises into the atmosphere where prevailing conditions carry it along. The depositions following this rise fall under the far-field category and they reached as far as 22 km from the launch pad [5]. Accordingly, far-field depositions may reach farther when a trench points towards land.

The impacts of the near-field depositions included plant damage, plant death, and species die off for fish and plant populations. The extent of these impacts depends on both the concentration of depositions and the species. Generally, plants begin displaying signs of serious damage following depositions of one gram of HCl per square meter. Sensitive species may experience serious damage after 0.1 grams per square meter [5]. Thus, specimens in the transitory region between the near field and far field may also be at risk. Damaged plants have a chance of recovering unless they undergo defoliation. Defoliation occurred during deposition concentrations above 25 grams per square meter [48]. Species capable of re-foliating and repairing damages require rebound periods of several months. Plants suffering from visible damage, but without significant loss of leaf coverage, may only take weeks to recover. However, these recovery times only serve as estimates and would likely worsen with more frequent launches. Even with only a few launches per year during the Space Shuttle program, the near-field region suffered a loss in plant biodiversity [3]. Note that the most severe of these near-field effects arise due to chemical burns from acidic depositions. Thus, these do not pertain to the effects from soil acidification, though it is still important to keep them in mind. The environmental impact assessments for KSC do not find evidence of long-term damage. The relatively low launch rate, which peaked at just over once every two months, represents the most likely reason. The lack of observable long-term impacts due to the low launch rate restricts the comparative value of the Space Shuttle program itself. Instead, the value of the program's environmental impact studies comes from the Space Shuttle's emissions and deposition behaviors.

The Space Shuttle program environmental impact studies detail the mass deposition of HCl, whereas the test cases required for this work use only the mass of hydrogen cations. To leverage the Space Shuttle program results, we assume that the HCl depositions breakdown entirely into chloride and hydrogen ions [13]. Besides allowing for direct comparison, this enables the scaling of depositions depending on the launch rate. This conversion multiplies the hydrochloric acid depositions' mass by the hydrogen mass fraction. Using this conversion shows that the near-field hydrogen ion depositions peak at 3.518 grams per square meter, while the observed and predicted far field depositions cutoff at 0.0006925 grams per square meter [5]. The cutoff for defoliation events occurs at 0.6925 grams per square meter, and most plants sustain significant damage until 0.0277 grams per square meter [3]. Sensitive species exhibit serious damage down to 0.00277 grams per square meter [3, 5].

The adjacent field with the most extensive coverage focuses on acid rain. Any precipitation depositions with a pH under 5.6 constitute acid rain [13]. However, those attributed to anthropogenic sources usually range between a pH of 3.5 and 5.0 [33]. Many parties point to declines in ecosystem health on an international scale due to these depositions [13, 49]. These reactions depend on variations in soil composition, species diversity, and historical factors. Thus, an identical deposition load in one region may produce dramatically different results in another. This makes it difficult to predict how any region may react to acid rain. However, there are common signs of ecological damage from this source.

Acidic rainfall contributes to soil acidification which results in acidic runoff entering the watershed. These depositions harm the nutrient availability for plants and animals over time. Prolonged depletion of such nutrients increases the afflicted species' susceptibility to disease and other stresses [32]. Akin to the depositions from the shuttle program, acidic rain can also damage plants via surface contact. The mechanisms behind this surface damage and nutrient loss do not differ greatly. Over time, as fewer of these nutrients (base cations) remain, the buffering capacity of the soil becomes exhausted. At some point, aluminum within the soil also mobilizes to neutralize the acidic inputs. The concentration of mobilized aluminum could reach a phytotoxic level [20, 50]. Given its long history, acid rain and its impacts have been accumulating for decades. This makes it somewhat difficult to see the year over year changes that it has on a previously untouched ecosystem. However, that situation may not be necessary after identifying regions of interest. Afterwards, the only initial soil conditions of importance are those at the onset of reference studies.

These initial soil traits still correspond to some score. Also, estimates for acid rain deposition rates are available from the EPA. Together, these two details could enable an examination of observed impacts with respect to a score and loading rate. Many studies identify the northeastern portion of the U.S. as a region impacted significantly by acid rain. Of these, most reference an observed decline in red spruce trees within the Appalachian Mountains [18, 51–53]. However, despite the higher deposition concentrations in this area and the decline in red spruce, it seems that the former does not directly result in the latter. While, acidification leaches nutrients from the soil, it may not reach the levels required for these impacts to affect large scale ecosystems. This conclusion receives support from a three-part study [54–56]. Acidic depositions amplify the effects of other stressors by weakening the nutrient supply and damaging foliar surfaces [57]. Accordingly, studies pertaining to acid rain aid in identifying the mechanisms through which depositions can impact an ecosystem. But they provide minimal value when determining long-term impacts due to soil acidification caused by high loading conditions. Determining these impacts is easier when examining industrial operations.

Industrial processes include power generation, material processing, refining, and others. For the purposes of this work, smelteries are the primary facilities of interest. Smelting operations primarily emit sulfur dioxides, heavy metal particulates, and nitrogen oxides. The former two emissions are of greater interest than the latter due to their higher concentrations. The behaviors of sulfur dioxide and nitrogen oxides are similar to the depositions from acid rain. They can also cause acid rain. However, locations around smelteries exhibit significant environmental impacts near the emission point(s). The impacts are more severe and clearly defined than those from acid rain.

Early attempts at large scale smelting processes involved roasting massive quantities of ore in open air pits. The sulfide rich ore released a phytotoxic plume of ground level sulfur dioxide and heavy metals [58]. As processing methods progressed these pits disappeared, and operations began utilizing smokestacks. The deposition patterns from smokestacks follow point source emission behaviors. Smokestacks focused on moving the source farther from the ground, but they also allowed pollutants to travel farther [58]. This aids in understanding why industrial deposition areas cover a much larger area than those from the Space Shuttle program. Industrial operations produce nearly continuous depositions. A pulsed nature slows the rate of ecological degradation as it allows for multiple recovery periods. Smelteries do not allow for adequate recovery periods without human intervention [25]. The impacts from smelteries arise out of this long-term continuous nature and higher deposition rates. Due to their point source nature, smelteries produce a near field region, known as the barrens in this application, and a far field region. The former takes on a different shape than that produced by the Space Shuttle as the emissions can spread out radially. Wind conditions alter the exact profile of the barren region, but the particle physics of the metal depositions limit the coverage radius.

The acidic depositions can reach much farther than the metal particulates. The elevated emission point means they also reach farther than those observed in the Space Shuttle program. The increased deposition concentrations result in long-term damage within this far field region, though less severe than the barrens [24, 34, 58–60]. When considering these damages for use in defining the qualitative scale, it is important to consider the time lines in effect.

Two notable smelteries in Sudbury, Ontario [58] and Copper Basin, Tennessee [24] have surrounding regions which exhibit ecological damage stemming from their operations. The barren regions lack biomass and the root networks required to prevent erosion and have lost much of their topsoil. This reduces the likelihood of natural recovery without human intervention. Beyond the barren regions, the smokestacks enabled the expansion of deposition impacts [58]. These impacts ranged from a total lack of vegetation, to minimal over-story, to patchy forests, then relatively normal conditions [24, 58]. This gradient of effects aids in understanding the progression of ecological damages associated with point source emitters [34]. However, it is challenging to utilize these examples in defining the qualitative scale. Several studies show that after mitigation efforts took effect the surrounding ecosystem exhibited minimal recovery [24, 59, 60]. Reducing emissions aids in abating the worsening of conditions, but the extent of the damages in barren regions may take centuries to recover naturally [58, 60]. On the other hand, following the cessation of operations and extensive human intervention, these regions may recover within years to a few decades [24]. Prolonged degradation and intermittent data make it challenging to determine when certain impacts arose. Discerning changes in impacts becomes even more difficult due to external intervention. Human intervention within this space makes it almost impossible to assess impacts in reverse. That process would consider the observed impacts prior to a cut in emissions and again sometime after once a steady state occurs. Even this process faces significant challenges due to natural events and oddities [60]. Thus, again, industrial case studies help with recognizing the effects produced by acidic depositions. However, their complex and unique scenarios restrict their direct applicability.

VII. Conclusion

The present state of the model remains limited due to a lack of data on the long term impacts of exposing soil to HCl depositions. This limits the efficacy of any effort to define the effects of soil acidification for a given deposition rate. In turn, it becomes very difficult to tie the scores provided by the qualitative model to particular effects. Fortunately, the sources from adjacent fields suggest that the specific acid plays a lesser role to its concentration. Since acidification primarily depends on the introduction of H^+ cations, the ecological effects observed remain consistent.

This means that the output(s) of the present model generally describes a region's response to acidic loading. This response follows a general trend beginning with low level food chain interruptions. These worsen over time under continued or worsening loading conditions allowing them to expand to higher levels. Prolonged acidic soil conditions also deplete the nutrient pools available to plants. This nutrient deficiency may compound with direct foliar damage from acidic depositions. Sensitive species may decline or die out completely thereby creating additional ecological stresses. As plant biomass declines, the root network in the soil weakens which allows for significant erosion. Once the soil in a region washes away, natural recovery times escalate from years or decades to centuries or millennia. This is the general progression of the effects and impacts of soil acidification. This qualitative model generally indicates regions which should prove more resilient to decline. However, the extent, severity, and rapidity of this progression depends on several conditions.

These conditions include anthropogenic and ecological factors. The former includes land management, launch site design, and loading conditions. The loading conditions depend on the launch vehicles in use, and the launch schedule's frequency. In a scenario where sufficient data allows for a defined output scale, this model could relate loading rates to the expected effects. Returning to the latter, ecological conditions, this model already considers a sizeable number. Other conditions include natural weathering rates, precipitation patterns, and natural sources of acidification. While it would be useful to consider all of the conditions outlined above in this model, that acts in contrast to the goal of minimizing inputs. Instead, this model could integrate with other efforts to better refine the launch site planning process.

The qualitative model illustrates regions of relatively resistant soil. These illustrations could refine the areas of interest for a quantitative model. From there, this theoretical model would consider recovery and impact progression rates. This reduction in scope makes a quantitative model more feasible. Beyond theoretical models, this qualitative model can work with present efforts focusing on launch site selection.

For example, it could work in tandem with the facility location planning (FLP) model developed in Ref. [46]. That model aims to assign a cost estimate to any given launch site location. This guides the selection process by optimizing for various elements of that cost. As discussed elsewhere, this model cannot predict the exact effects for a given location. This means that it cannot provide a direct cost estimate with respect to ecological damages. However, the output score and distribution functions could serve as constraints for the FLP model. For instance, one could tell the FLP model to reject counties or regions where the output score falls below some threshold. Another option would restrict the selection process to avoid regions with large standard deviations. This would reduce uncertainty during the selection process. These two approaches could work together with differing weights depending on one's preference. When considering the theoretical quantitative model outlined previously, it seems better suited for estimating costs.

Another area of interest regarding launch site design and placement considers sociological elements. Ecological damage and acidic depositions pose a risk to public health and infrastructure. Reconstruction and ecological rehabilitation efforts would likely require public funding. Ecological disruptions and damages also impact local businesses and recreational opportunities. These issues raise potent and valid concerns within interest groups that hold influence over land use. Using this model to select regions with greater resiliency may aid in providing assurances when developing a launch site. It is feasible to imagine integrating this model with one that avoids placing the facility in underrepresented areas to further refine the selection process.

Between these three routes, the applicability and value of this model becomes more readily apparent. These also highlight the importance of trying to better define the qualitative scale. On its own, the model provides a high level understanding of which regions are more resilient. Combining this with the adjacent sources guides expectations regarding expected impacts. This highlights the importance of considering soil acidification during launch site planning procedures. Doing so will aid in mitigating the ecological, monetary, and sociological impacts of rocket launches.

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References

[1] Dallas, J. A., Raval, S., Gaitan, J. P. A., Saydam, S., and Dempster, A. G., "The Environmental Impact of Emissions from Space Launches: A Comprehensive Review," *Journal of Clear Production*, Vol. 255, 2020, pp. 2–10. https://doi.org/10.1016/j.jclepro.2020.120209.

[2] Space-Track.org, "Space Ops Tempo: Annual Launches," https://www.space-track.org/#annualLaunchesByNation, 2024. (Accessed: 5.15.2024).

[3] Hall, C. R., Schmalzer, P. A., Breininger, D. R., Duncan, B. W., Drese, J. H., Scheidt, D. A., Lowers, R. H., Reyier, E. A., Holloway-Adkins, K. G., Oddy, D. M., Cancro, N. R., Provancha, J. A., Foster, T. E., and Stolen, E. D., "Ecological Impacts of the Space Shuttle Program at John F. Kennedy Space Center, Florida," Tech. Rep. TM-2014–216639, National Aeronautics and Space Administration, 2014.

[4] Graveland, J., "Effects of Acid Precipitation on Reproduction in Birds," *Experientia*, Vol. 46, 1990, pp. 962–970. https://doi.org/10.1007/bf01939390.

[5] Schmalzer, P. A., Hinkle, C. R., and Dreschel, T. W., "Far-Field Deposition from Space Shuttle Launches at John F. Kennedy Space Center, Florida," Tech. Rep. TM 83104, National Aeronautics and Space Administration, 1986.

[6] Zammit, C. A. and Zedler, P. H., "Germination Response to Extreme Acidity: Impact of Simulated Acid Deposition from a Single Shuttle Launch," *Environmental and Experimental Botany*, Vol. 28, No. 1, 1988, pp. 73–81. https://doi.org/10.1016/0098-8472(88)90048-2.

[7] Drent, P. J. and Woldendorp, J. W., "Acid Rain and Eggshells," *Nature*, Vol. 339, 1989, p. 431. https://doi.org/10.1038/339431a0.

[8] Smith, M., Mahoney, J., Knight, E., Taylor, L., Witko, C., Jimenez, M., Bailey, C., Seavy, N., DeLuca, W., Deppe, J., Wilsey, C., Carbone, M., O'Bryan, G., Rao, N., Gonzalez, N., Okanon, L., Possehl, A., Hanley, J., Kelly, S., Ashcroft, E., Paz, E., and Henry, N., "Audubon Bird Migration Explorer," https://explorer.audubon.org/home?sidebar=expand&layersPanel=collapse, 2020. (Accessed: 10.06.2023).

[9] Dreschel, T. W. and Hall, C. R., "Quantification of Hydrochloric Acid and Particulate Deposition Resulting from Space Shuttle Launches at John F. Kennedy Space Center, Florida, USA," *Environmental Management*, Vol. 14, 1990, pp. 501–507. https://doi.org/10.1007/bf02394138.

[10] Anderson, B. J. and Keller, V. W., "Space Shuttle Exhaust Cloud Properties," Tech. Rep. TP 2258, National Aeronautics and Space Administration, 1983.

[11] Marion, G. M., Black, C. H., and Zedler, P. H., "The Effect of Extreme HCL Deposition on Soil Acid Neutralization Following Simulated Shuttle Rocket Launches," *Water, Air, and Soil Pollution*, Vol. 43, 1989, pp. 345–363. https://doi.org/10.1007/bf00279201.

[12] Wiklander, L., "Interaction Between Cations and Anions Influencing Adsorption and Leaching," *Effects of Acid Precipitation on Terrestrial Ecosystems*, Springer, 1980, pp. 239–254. https://doi.org/10.1007/978-1-4613-3033-2_20.

[13] Likens, G. E., Wright, R. F., Galloway, J. N., and Butler, T. J., "Acid Rain," *Scientific American*, Vol. 241, No. 4, 1979, pp. 43–51.

[14] Reuss, J. O. and Johnson, D. W., *Acid Deposition and the Acidification of Soils and Waters*, Springer, 1986.

[15] Reuss, J. O., Cosby, B. J., and Wright, R. F., "Chemical Processes Governing Soil and Water Acidification," *Nature*, Vol. 329, 1987, pp. 27–32. https://doi.org/10.1038/329027a0.

[16] Öberg, G. M., "The Natural Chlorine Cycle – Fitting the Scattered Pieces," *Applied Microbiology and Biotechnology*, Vol. 58, 2002, pp. 565–581. https://doi.org/10.1007/s00253-001-0895-2.

[17] Öberg, G. M., *The Biogeochemistry of Chlorine in Soil*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2003, pp. 43–62. https://doi.org/10.1007/b10447.

[18] Sherman, R. E. and Fahey, T. J., "Solute Concentrations and Fluxes of Major Nutrients in Potted Red Spruce Saplings Exposed to Simulated Acid Rain Treatments," *Management of Nutrition in Forests under Stress*, Springer, Dordrecht, 1991, pp. 155–168. https://doi.org/10.1007/978-94-011-3252-7_14.

[19] Gazey, C. and Azam, G., "Soil pH Buffering," https://www.agric.wa.gov.au/soil-acidity/soil-ph?page=0%2C1, 2018. (Accessed: 10.15.2023).

[20] Shortle, W. C., Smith, K. T., Minocha, R., Lawrence, G. B., and David, M. B., "Acidic Deposition, Cation Mobilization, and Biochemical Indicators of Stress in Healthy Red Spruce," *Journal of Environmental Quality*, Vol. 26, No. 3, 1997, pp. 871–876. https://doi.org/10.2134/jeq1997.00472425002600030038x.

[21] EPA, "The Effects of Acid Rain on Ecosystems," https://www.epa.gov/acidrain/effects-acid-rain, 2023. (Accessed: 1.2.2024).

[22] Mänd, R., Tilgar, V., and Leivits, A., "Calcium, Snails, and Birds: A Case Study," *Web Ecology*, Vol. 1, No. 1, 2000, pp. 63–69. https://doi.org/10.5194/we-1-63-2000.

[23] Schmalzer, P., Hall, C., Hinkle, C., Duncan, B., William Knott, I., and Summerfield, B., "Environmental Monitoring of Space Shuttle Launches at Kennedy Space Center - The First Ten Years," *31st Aerospace Sciences Meeting*, AIAA, 1993. https://doi.org/10.2514/6.1993-303.

[24] Mathews, L. and Harden, C., "150 Years of Environmental Degradation and Reclamation in the Copper Basin, Tennessee," *Southeastern Geographer*, Vol. 39, No. 1, 1999, pp. 1–21. https://doi.org/10.1353/sgo.1999.0008.

[25] Schmalzer, P. A., Hinkle, C. R., and Breininger, D. R., "Effects of Space Shuttle Launches STS-1 through STS-9 on Terrestrial Vegetation of John F. Kennedy Space Center, Florida," Tech. Rep. TM 83103, National Aeronautics and Space Administration, 1985.

[26] Dudka, S. and Adriano, D. C., "Environmental Impacts of Metal Ore Mining and Processing: A Review," *Journal of Environmental Quality*, Vol. 26, No. 3, 1997, pp. 590–602. https://doi.org/10.2134/jeq1997.00472425002600030003x.

[27] III, W. R. C., Pellett, G. L., Sebacher, D. I., and Wakelyn, N. T., "Surface Chloride Salt Formation on Space Shuttle Exhaust Alumina," *Journal of Geophysical Research - Atmospheres*, Vol. 89, No. D2, 1984, pp. 2535–2540. https://doi.org/10.1029/JD089iD02p02535.

[28] Kokkinakis, I. W. and Drikakis, D., "Atmospheric Pollution from Rockets," *Physics of Fluids*, Vol. 34, No. 5, 2022, p. 056107. https://doi.org/10.1063/5.0090017.

[29] Ryan, R. G., Marais, E. A., Balhatchet, C. J., and Eastham, S. D., "Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate," *Earth's Future*, Vol. 10, No. 6, 2022. https://doi.org/10.1029/2021EF002612.

[30] Eriksson, M. O. G., “Acidification of Lakes: Effects on Waterbirds in Sweden,” *Ambio*, Vol. 13, No. 4, 1984, pp. 260–262. https://doi.org/stable/4313038.

[31] Hames, R. S., Rosenberg, K. V., Lowe, J. D., Barker, S. E., and Dhondt, A. A., “Adverse Effects of Acid Rain on the Distribution of the Wood Thrush <i>Hylocichla mustelina</i> in North America,” *Proceedings of the National Academy of Sciences*, Vol. 99, No. 17, 2002, pp. 11235–11240. https://doi.org/10.1073/pnas.172700199.

[32] Driscoll, C. T., Driscoll, K. M., Mitchell, M. J., and Raynal, D. J., “Effects of Acidic Deposition on Forest and Aquatic Ecosystems in New York State,” *Environmental Pollution*, Vol. 123, No. 3, 2003, pp. 327–336. https://doi.org/10.1016/S0269-7491(03)00019-8.

[33] Menz, F. C. and Seip, H. M., “Acid Rain in Europe and the United States: An Update,” *Environmental Science and Policy*, Vol. 7, No. 4, 2004, pp. 253–265. https://doi.org/10.1016/j.envsci.2004.05.005.

[34] Dawson, J. L. and III, T. H. N., “Effects of Air Pollution from Copper Smelters on a Desert Grassland Community,” *Environmental and Experimental Botany*, Vol. 20, No. 1, 1980, pp. 61–72. https://doi.org/10.1016/0098-8472(80)90221-X.

[35] DesGranges, J.-L., “Studies of the Effects of Acidification on Aquatic Wildlife in Canada: Lacustine Birds and their Habitats in Quebec,” Occasional Paper, 1989.

[36] Bonten, L. T. C., Reinds, G. J., and Posch, M., “A Model to Calculate Effects of Atmospheric Deposition on Soil Acidification, Eutrophication and Carbon Sequestration,” *Environmental Modelling and Software*, Vol. 79, 2016, pp. 75–84. https://doi.org/10.1016/j.envsoft.2016.01.009.

[37] Reuss, J. O., Christophersen, N., and Seip, H. M., “A Critique of Models for Freshwater and Soil Acidification,” *Water, Air, and Soil Pollution*, Vol. 30, 1986, pp. 909–930. https://doi.org/10.1038/329027a0.

[38] Posch, M. and Reinds, G. J., “A Very Simple Dynamic Soil Acidification Model for Scenario Analyses and Target Load Calculations,” *Environmental Modelling and Software*, Vol. 24, 2009, pp. 329–340. https://doi.org/10.1016/j.envsoft.2008.09.007.

[39] Xu, D., Zhu, Q., Ros, G. H., Xu, M., Wen, S., Zhang, F., and de Vries, W., “Model-based Optimal Management Strategies to Mitigate Soil Acidification and Minimize Nutrient Losses for Croplands,” *Field Crops Research*, Vol. 292, 2023. https://doi.org/10.1016/j.fcr.2023.108827.

[40] Walkinshaw, M. and A T O’Geen, D. E. B., “Soil Properties,” https://casoilresource.lawr.ucdavis.edu/soil-properties/, 2022. (Accessed: 10.15.2023).

[41] Lu, H., Li, K., Nkoh Nkoh, J., Shi, Y., He, X., Hong, Z., and Xu, R., “Effects of the Increases in Soil pH and pH Buffering Capacity Induced by Crop Residue Biochars on Available Cd Contents in Acidic Paddy Soils,” *Chemosphere*, Vol. 301, 2022. https://doi.org/10.1016/j.chemosphere.2022.134674.

[42] Meiwes, K. J., Khanna, P. K., and Ulrich, B., “Parameters for Describing Soil Acidification and their Relevance to the Stability of Forest Ecosystems,” *Forest Ecology and Management*, Vol. 15, No. 3, 1986, pp. 161–179. https://doi.org/10.1016/0378-1127(86)90064-2.

[43] Wu, Z., Sun, X., Sun, Y., Yan, J., Zhao, Y., and Chen, J., “Soil Acidification and Factors Controlling Topsoil pH Shift of Cropland in Central China from 2008 to 2018,” *Geoderma*, Vol. 408, 2022, p. 115586. https://doi.org/10.1016/j.geoderma.2021.115586.

[44] Blake, L., “Acid Rain and Soil Acidification,” *Encyclopedia of Soils in the Environment*, 2005, pp. 1–11. https://doi.org/10.1016/B0-12-348530-4/00083-7.

[45] Watmough, S. A., Whitfield, C. J., and Fenn, M. E., “The Importance of Atmospheric Base Cation Deposition for Preventing Soil Acidification in the Athabasca Oil Sands Region of Canada,” *Science of the Total Environment*, Vol. 493, 2014, pp. 1–11. https://doi.org/10.1016/j.scitotenv.2014.05.110.

[46] Wu, H., Sun, K. R., Miller, J. A., Jia-Richards, O., and Li, M. Z., “Spaceport Facility Location Planning within the US National Airspace System,” *International Conference on Research in Air Transportation*, United States Federal Aviation Administration and EUROCONTROL, Singapore, 2024.

[47] Duncan, B. W. and Schmalzer, P. A., “Using a Geographical Information System for Monitoring Space Shuttle Launches: Determining Cumulative Distribution of Deposition and an Empirical Test of a Spatial Model,” *Environmental Management*, Vol. 18, 1994, pp. 465–474. https://doi.org/10.1007/BF02393874.

[48] Schmalzer, P. A. and Hinkle, C. R., "Monitoring Biological Impacts of Space Shuttle Launches from Vandenberg Air Force Base: Establishment of Baseline Conditions," Tech. Rep. TM 100982, National Aeronautics and Space Administration, 1987.

[49] Driscoll, C. T., Lawrence, G. B., Bulger, A. J., Butler, T. J., Cronan, C. S., Eagar, C., Lambert, K. F., Likens, G. E., Stoddard, J. L., and Weathers, K. C., "Acidic Deposition in the Northeastern United States: Sources and Inputs, Ecosystem Effects, and Management Strategies," *BioScience*, Vol. 51, No. 3, 2001, pp. 180–198. https://doi.org/10.1641/0006-3568(2001)051[0180:ADITNU]2.0.CO;2.

[50] Singh, A. and Agrawal, M., "Acid Rain and its Ecological Consequences," *Journal of Environmental Biology*, Vol. 29, No. 1, 2008, pp. 15–24. https://doi.org/PMID:18831326.

[51] Craig, B. W. and Friedland, A. J., "Spatial Patterns in Forest Composition and Standing Dead Red Spruce in Montane Forests of the Adirondacks and Northern Appalachians," *Environmental Monitoring and Assessment*, Vol. 18, 1991, pp. 129–143. https://doi.org/10.1007/BF00394975.

[52] Feret, P. P., Diebel, K. E., and Sharik, T. L., "Effect of Simulated Acid Rain on Reproductive Attributes of Red Spruce (Picea rubens sarg.)," *Environmental and Experimental Botany*, Vol. 30, No. 3, 1990, pp. 309–312. https://doi.org/10.1016/0098-8472(90)90042-3.

[53] Johnson, A. H., Friedland, A. J., and Dushoff, J. G., "Recent and Historic Red Spruce Mortality: Evidence of Climatic Influence," *Acidic Precipitaion*, Springer, Dordrecht, 1986, pp. 319–330. https://doi.org/10.1007/978-94-009-3385-9_33.

[54] Johnson, A. H., Andersen, S. B., and Siccama, T. G., "Acid Rain and Soils of the Adirondacks. I. Changes in pH and Available Calcium, 1930–1984," *Canadian Journal of Forest Research*, Vol. 24, No. 1, 1994, pp. 39–45. https://doi.org/10.1139/x94-006.

[55] Johnson, A. H., Schwartzman, T. N., Battles, J. J., Miller, R., Miller, E. K., Friedland, A. J., and Vann, D. R., "Acid Rain and Soils of the Adirondacks. II. Evaluation of Calcium and Aluminum as Causes of Red Spruce Decline at Whiteface Mountain, New York," *Canadian Journal of Forest Research*, Vol. 24, No. 4, 1994, pp. 654–662. https://doi.org/10.1139/x94-088.

[56] Johnson, A. H., Friedland, A. J., Miller, E. K., and Siccama, T. G., "Acid Rain and Soils of the Adirondacks. III. Rates of Soil Acidification in a Montane Spruce–fir Forest at Whiteface Mountain, New York," *Canadian Journal of Forest Research*, Vol. 24, No. 4, 1994, pp. 663–669. https://doi.org/10.1139/x94-089.

[57] DeHayes, D. H., Schaberg, P. G., Hawley, G. J., and Strimbeck, G. R., "Acid Rain Impacts on Calcium Nutrition and Forest Health: Alteration of Membrane-associated Calcium Leads to Membrane Destabilization and Foliar Injury in Red Spruce," *BioScience*, Vol. 49, No. 10, 1999, pp. 789–800. https://doi.org/10.2307/1313570.

[58] Freedman, B. and Hutchinson, T. V., "Long-term Effects of Smelter Pollution at Sudbury, Ontario, on Forest Community Composition," *Canadian Journal of Botany*, Vol. 58, No. 19, 1980, pp. 2123–2143. https://doi.org/10.1139/b80-245.

[59] Lukina, N. and Nikonov, V., "Acidity of Podzolic Soils Subjected to Sulphur Pollution near a Cu-Ni Smelter at the Kola Peninsula," *Water, Air and Soil Pollution*, Vol. 85, 1995, pp. 1057–1062. https://doi.org/10.1007/BF00477121.

[60] Vorobeichik, E. L., Trubina, M. R., Khantemirova, E. V., and Bergman, I. E., "Long-term Dynamic of Forest Vegetation After Reduction of Copper Smelter Emissions," *Russian Journal of Ecology*, Vol. 45, No. 6, 2014, pp. 498–507. https://doi.org/10.1134/S1067413614060150.