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Remediating Nuclear Contamination Through Phytoremediation

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Abstract: With the increasing threat of nuclear weapons and use of nuclear energy, the need for effective means of decontamination is also increasing. More specifically, an efficient means of decontaminating farmland is needed because this could negatively affect food supply if the soil is not decontaminated in a timely manner. Phytoremediation, the process of using plants to absorb contaminates from soil, has been used experimentally in different nuclear scenarios, namely Fukushima, but there is no verified way of modeling this process to know how well it can work given different parameters. Our research looks into modeling this process using systems dynamics modeling. In system dynamics modeling, all factors that can affect phytoremediation are accounted for, which can help responders to nuclear events make informed decisions on decontamination without wasting precious time.

Keywords: Phytoremediation, Isotope, Systems Dynamics

1. Introduction

Nuclear contamination is an ever-increasing threat. From hostile countries increasing their nuclear capabilities to unstable nuclear power plants, the possibility of radioactive material contaminating and harming essential aspects to human survival is higher than it has ever been. This applies especially to agricultural system. Radioactive contamination from nuclear waste will immediately render nutrient-filled soil useless. Nuclear contamination can affect the water supply and the soil itself, as radioisotopes from nuclear fallout contaminate the soil and remain there for years. This can have dire effects on human sustainability. With the help of modern-day technology, farms can support more people on a larger, economic scale. One farm can provide food for a whole city or produce food so that a country can export its product into the world market. If a farm's soil is contaminated, that threatens the sustainability of people that depend on a crop for food and income. It is important to find the best ways to remediate contaminated soil so that it can get back to producing healthy crops to sustain human life and the world economy.

1.1 Problem Statement

When nuclear waste contaminates soil, it renders the soil useless for agricultural purposes; it must be remediated. One possible method for remediation is phytoremediation, or using plants to absorb soil contaminants. This method of remediation is used for most inorganic compounds that contaminate soil, such as arsenic or iron (Chapter II will discuss this more in detail). In terms of nuclear contamination, phytoremediation was one of the methods used to remediate the contaminated soils of Chernobyl and the Japanese fields surrounding Fukushima. However, other than these two attempts, there is little literature on techniques to remediate nuclear-contaminated soil. Additionally, there is no validated computer model to predict the effectiveness of different plants given varying agricultural factors, such as soil type and climate. Furthermore, if such a model did exist, there is no value model to determine the best plant for phytoremediation given varying soil and climate conditions.

1.2: Background

This project is follow-on research from a capstone project from Academic Year 17. That team's research focused strictly on creating a computer model for phytoremediation. To model the effectiveness of phytoremediation, they used a system dynamics model, the same model we will use. With a system dynamics model, multiple factors and conditions can be set to certain processes. These processes are then connected through different one-way and two-way relationships to other processes.

Once the processes are connected properly, the system dynamics model can run a simulation and produce output that can be used to assess the systems performance. Last year's project team created a system dynamics model to model phytoremediation using corn on five of the most common isotopes. Although they had a model, it was not validated and the results were different than what literature and research suggested. The present project focuses on revising and validating the system dynamics model.

Additionally, based off our initial meetings with our main client, MAJ Samuel Heider representing the Defense Threat Reduction Agency (DTRA), it is also important that we determine which plants are best for phytoremediation, given certain soil and climate conditions. A value model can help us determine the plant, from a candidate list of plants, which would be the optimal solution of results to cost ratio. With the system dynamics model as part of the value model, all aspects of phytoremediation can be analyzed by clients to help them determine, given any plant or circumstance, which plant is best to choose for phytoremediation.

2. Literature Review

2.1 Phytoremediation explained

Cunningham and Ow define phytoremediation as "the use of plants to remediate contamination of soil with organic or inorganic wastes" (1996). Phytoremediation requires the contaminant to be within the growing area of the roots. This means that water, depth, nutrition of the soil, atmospheric conditions, physical texture of the soil, and the chemical properties of the soil's elements play a factor in how well a contaminant is extracted from the soil through phytoremediation.

One of the main factors in phytoremediation is the rhizosphere effect. This effect directly involves the rhizosphere, the area of soil around the roots. This effect involves nutrients and energy from the plant interjecting into the soil and creating more plant activity, especially in absorption of chemicals from the soil, in that area. Additionally, enzymes and soil conditions played a role in their study. These are many of the factors that need to be looked at when considering the remediation of nuclear compounds, especially soil type and weather.

Iman Tahmasbian and Ali Sinegani (2015) conducted a study that focused on polarizing plants, namely sunflowers, for phytoremediation in order to more effectively uptake different contaminants such as mine soil, poultry manure extract, cow manure, and acid. Phytoremediation has a very low efficiency of removing heavy metal-polluted soils. However, the results indicated that the application of negatively charged plants significantly increased the phytoremediation efficiency. This article is important because it can help refine the previous model that had little to no effect on nuclear contamination mitigation. Negatively charged plants could be a possible solution to phytoremediation in radioactive contaminated areas and should be considered in any modeling.

2.2 Nuclear Events

In 1986, a reactor Chernobyl nuclear plant in Ukraine exploded, sending radioactive debris into the surrounding area. Following the nuclear incident, most of the land within a 10 km radius around Chernobyl was contaminated with nuclear radiation. This event has been critical in the explorations of phytoremediation. There have been studies on the uses of willows, sunflowers, and hemp to remediate the soil. In a three-year study, beginning in 1998, willows proved to stabilize the contaminated lands by reducing the dispersion of radionuclides. The test of survival for the willows was conducted one year after the incident, and survival of the plants was extremely high and biomass production was low. Therefore, the willows were insignificant in their job to clean the soil. The willows did, however, help reduce the erosion of soil and sediment (2000).This study proves that phytoremediation can work as a means to decontaminate soil efficiently.

In a more recent nuclear incident, the nuclear fallout in Fukushima, Japan, phytoremediation was used again. After a tsunami hit their nuclear power plant in 2011, the area around the plant was radioactively contaminated with Cesium-137 (2003). The main goal of using phytoremediation, in this case, was to eliminate the radioactive isotopes from the farm land while avoiding the erosion of fertile topsoil from the hilly landscape. Sunflowers were the predominant plant used in the study. The removal of the radioisotopes from the contaminated area was significant because the sunflower's long roots allowed them to reach deep into the contaminated soil and cover more area. Additionally, phytoremediation was 25% less expensive than other methods cleaning the soil. Although this study was not as well documented as the Chernobyl case, this shows that phytoremediation can be used in different climates and soils.

2.3 Modeling Phytoremediation

Today's research on phytoremediation has produced mathematical models that focus on the chemical compounds involved, the plant types, and the conditions of the agricultural system. Individuals typically structure the models to depict the mass balance of the system. This includes the conservation of nutrients, water, and contaminants. Once in a system, objects flow into the plant by way of the roots.

Roose and Schnepf (2008) discussed multiple math models for plant systems, including root uptake of nutrients from soil. The focus of the nutrient uptake was only on single root systems. For these models, they assume that the solute in the soil quickly binds and unbinds to and from the solid particles in a fast equilibrium and that transport is given by diffusion and convection. Simply put, root uptake is a factor of the total amount of solute bound to soil particles and soil buffer power. Furthermore, it is also dependent on the size of the root, as this also affects water flux, which has a negative influence on rate. These are assumptions made in the model when the plant is a single-root system. This model for the uptake of nutrients provides us baseline modeling for phytoremediation.

Manzoni, Molini, and Porporato (2011), developed a stochastic model to model how contaminants move through the unsaturated zone. In contrast to models that use measured rainfall data, they treated rainfall depths and inter-arrival times as random variables. These variations allow the model to predict long-term state of contaminants. This allows the model to predict how the contaminants will behave in the system. Additionally, in “A Dynamic Model of Nutrient Uptake by Root hairs,” D. Leitner (2009) presents three models of root hair uptake. One of his models assumes that all nutrients within the zone of the root hairs is absorbed instantaneously. Applying this logic to the modeling research allows the expansion of the root system in order to maximize the uptake rates within the agricultural system. Determining how plants use and move contaminants is a barrier in the majority of mass balance and transportation based models. More recently, models have focused on the roots portion of the system, since the roots perform the initial and majority of the uptake in the system. This aspect of phytoremediation creates an issue for organizations implementing this technique, since this assumes contaminants will only be displaced, not necessarily removed.

2.4 Conclusion of Lit Review

Phytoremediation, although used primarily for biological waste in soil, is a method that has been tested for use in nuclear contaminated soil. Proxy elements and similar situations involving soil contaminants have been analyzed for their process and effectiveness, and phytoremediation has worked in these cases. For modeling nutrient uptake and phytoremediation, mass-balance equations, differential equations, and stochastic models are validated means in modeling the two processes of interest. Using this baseline knowledge of phytoremediation, nuclear disaster relief, and uptake modeling, we have sufficient reasons for and background info to validate a system dynamics model for nuclear remediation of soil through phytoremediation.

3. Methodology

3.1 System Dynamics Model in Vensim

In order to answer central question of modeling phytoremediation, Vensim was used to develop a system dynamics model to simulate the overall behavior of phytoremediation can reduce the time that the soil is contaminated. Model development begins by establishing the key variables in the system, known as stocks. Cesium-137, Iodine-125, and Ruthenium-106 (Cs-137, I-125, and Ru-106) are the three stocks in the system because they are the most common radioisotopes. Each represents the amount of the respective isotope within the system. Next, plant factors are identified, such as the plant growth rate and the plant uptake rate, as driving forces in the phytoremediation process. The plant growth rate is a function of the growth stage of the plant and the region quality of the contaminated area. The plant growth rate directly affects the plant uptake rate, since the plant will uptake nutrients faster or slower depending on the how fast the plant is moving through the growth stages. The plant uptake rate is only a function of the growth rate and the rate that the plant uptakes each isotope. The plant uptake rate will affect each isotope differently, since the plant will uptake each isotope as if it were a different necessary nutrient. Lastly, the biological decay rate was the final key variable. The biological decay rate is a function of nearly all key variables. The biological decay rate is the rate that the isotope leaves the system given the effects of phytoremediation and its natural decay.

After analyzing the relationships of the key variables, we began developing the systems dynamic model. We began by developing a basic model demonstrating the natural decay of the isotopes. We established the three isotopes and their components as the initial stock and flow systems. The initial model was composed of only the isotope, the half-life, and the biological decay rate. Once we established the isotopes’ natural behavior, we expanded the model, variable by variable. We began with plant uptake as a constant. Next, we added the growth rate, as a constant, while creating variability in the uptake rate. Lastly, we added the region quality as a determinate of the growth rate and yield of the total planting session.

3.2 Stochastic Excel Model

This model is a stochastic model that only focuses on the isotope and a compound that is similar in atomic make-up. In this model, different plants are listed with their uptake of an atomic compound that is in the same group on the periodic table as one of the three radioisotopes. In order to model its uptake, the amount of contaminants (in pounds) per acre is used as an input to begin the model. Then, knowing that not all the contaminants will be taken up at once, but rather with the uptake of the atomic similar compound, the amount of contaminants is linked proportionally to the uptake of the compound.

This uptake is then added on top of the natural decay of the contaminant. Once these two formulas are put together, the total decay rate, similar to biological decay rate in the systems dynamics model, is found. For how much of the compound is taken up, any distribution can be linked to the amount of uptake, therefore, making the model stochastic. Each year is iterated until the contaminated area is “decontaminated.” This time is compared to the natural decay rate of the isotope.

4. Analysis and Results

4.1 Analysis of Vensim and Excel model.

The analysis is taken from our Vensim and an Excel file that show the time it takes for the radioactive isotope to be absorbed by the plant. The results are displayed as typical line graphs that show the decay of the radioisotope over a period of years. The three radioisotopes, Cs-137, I-125, and Ru-106, are substituted into both the Vensim model and the Excel program using the half-life equation (1) for radioactive isotopes.

$$N(t) = N_0 e^{\frac{t}{t_{1/2}}} \tag{1}$$

$N(t)$ represents the amount of isotope still left, N_0 is the initial amount of isotope, and $t_{1/2}$ is the half -life of the element, or the amount of time it takes for half of the isotope amount to decay. This formula, and the corresponding half-lives of each of the radioisotopes, was added into our Vensim model, as well as our excel model. Additionally, for biological decay rate, all the factors mentioned above were added in with notional measurements to produce our results. The model specifically predicts the time it takes to clean an area, per acre, of radioactive contamination. The Excel model, uses the same equation and half-life for each isotope, but it also accounts for the uptake rate of elements that correspond to the same group on the periodic table as the isotope. For example, Cs-137 is in the same group as potassium. In the system dynamics model, all factors were taken into account to model the decay rate, including potassium oxide. In the Excel model, the uptake rate of potassium oxide was directly related to the uptake rate for Cs-137, under the assumption that Cs-137 followed the uptake rate of potassium oxide, and nothing else.

4.2 Results

The results from just the Cs-137 on the system dynamics and the Excel models showed phytoremediation worked better than just natural decay, but with differing degrees of significance. Each area has different plants that can survive in those areas based on soil, sunlight, rain fall, and every factor that goes into the ability for a plant to thrive. The program will generate a date at which the area is clean, clear, and safe to be used again. The cross over check with the excel program built by our team give us even more efficiency in predicting the day the area is clear because it is attached to another element that is similar in atomic structure to the isotope.. The importance of our team is to give the user a plant, a date of clean soil, and accuracy. Additionally, both models are easily adjustable, as all that needs to be done is a simple number change in the Excel model and a selection of different variables in the Vensim model. Although we are only using notional numbers, especially in the Vensim model, the model is verified because it does what we want it to depict, as seen in Figure 1, using grams (per acre) and months. The Excel model, which uses pounds per acre and years, is depicted in Figure 2.

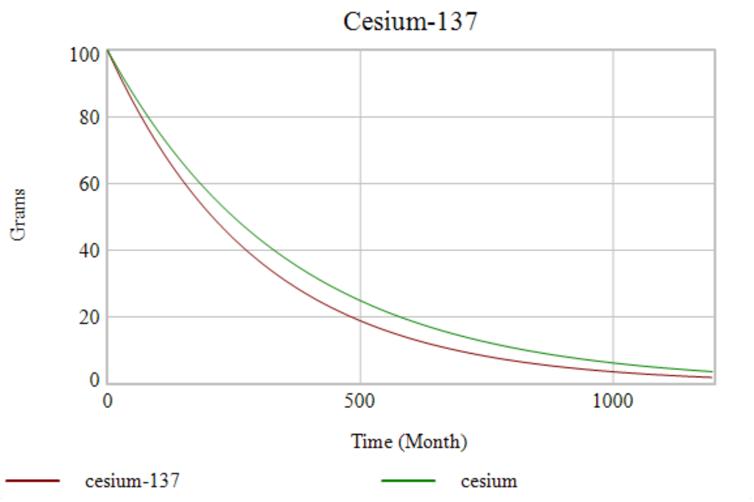

Figure 1. This chart shows the time with/without phytoremediation in our Vensim model. "Cesium-137" represents the decay with phytoremediation, while "cesium" is only the natural decay rate of Cs-137.

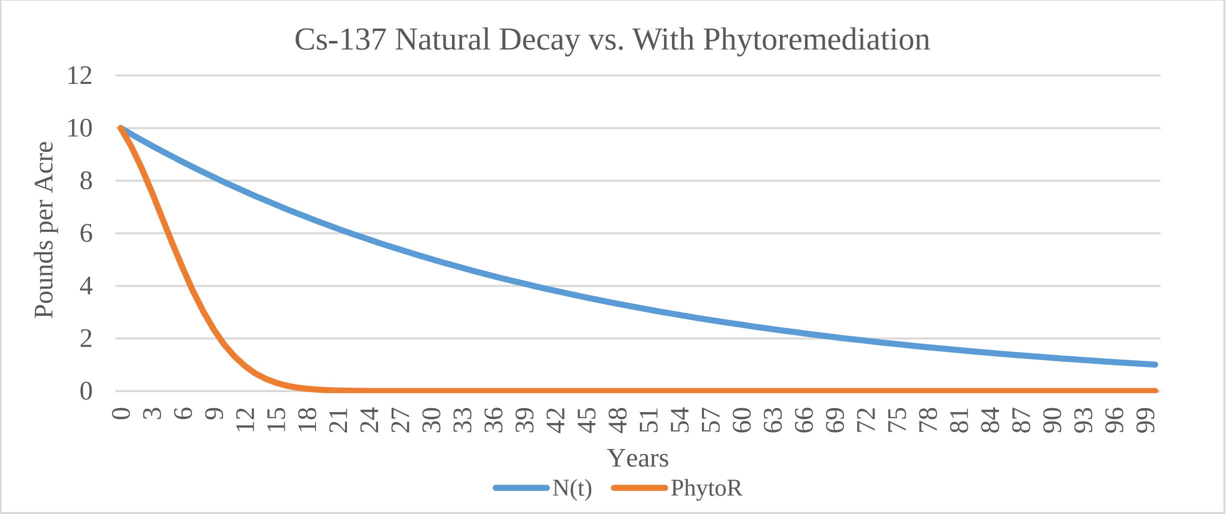

Figure 2. This chart shows the time with/without phytoremediation in our excel model. The efficiency can be seen here with the use of phytoremediation in an area that is infected with radioactive isotopes.

As depicted, the decay of Cs-137 per acre decreases much quicker with phytoremediation as compared to natural decay. This is supported by the fact that phytoremediation has worked in different areas of Fukushima, even if the measurements were not as quantified as our model.

5. Conclusion

5.1 Further Research

Although we are able to model the actual decay of various isotopes and the predicted affect phytoremediation would have on these isotopes, it is impossible to validate our model without an experiment that would look to model the affect certain plan types would have on various radioactive isotopes given certain environmental parameters. Dr. Preston Miles, a professor of chemistry at Centre College, commented that, even looking at a graph, he could not tell us whether or not our model was valid. Further research would have to involve conducting a controlled experiment of phytoremediation's effect on radioactive decay. The experiment would have to involve controlling for the different factors of our model, as this would validate the system dynamics model. Our model is verified in that it is doing what we want it to do, but we need to verify it to make the model useful for future modeling.

5.2 Discussion

With the threat of nuclear weapons and the use of nuclear energy increasing, it is important to be ready in the event of nuclear contamination. We can predict which isotopes are most likely to contaminate, so it is easier to focus efforts on helping remediate these isotopes as best we can. Furthermore, it is important to be able to support the community that is affected by nuclear contamination, which means food. Farmland must be clear of radioactive contamination in order to continue growing crops for human consumption. Our model, if validated, can help provide insight on how to quickly decontaminate soil using phytoremediation, which will help continue the research and development of quickly decontaminating our world in the event of nuclear disaster

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