PLANT UPTAKE OF RADIONUCLIDES AND TOXIC CHEMICALS FROM CONTAMINATED SOILS BELOW A SHALLOW SOIL COVER

by

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There exist a number of naturally occurring processes that negate the functionality of a two foot[1] soil cover as a means of preventing exposure to the radioactive and chemical contamination at Hunters Point Shipyard (HPS). The extensive depth of roots, uptake of contaminants into plants, and various mechanisms of hydraulic redistribution allow vegetation to access materials such as toxic chemicals and radionuclides deep within soil layers. Once accessed, plants are capable of transferring those materials through their roots to the surface, providing several pathways for human exposure. These processes present problems for the remedy currently selected at HPS, which entails, rather than cleaning up contamination, leaving large quantities of pollutants beneath a thin soil cover.

Root Depths of Edible Plants Far Greater Than HPS Soil Cover

Most plant root systems extend further than one might think.[2] U.S. Department of Agriculture (USDA) data (Table 1) show that the roots of many plants commonly grown in home gardens extend well past two feet. According to the USDA data, watermelons and tomatoes, for example, can extend their roots 5 feet down into the soil, and asparagus roots can go down 6 feet. The roots of these crops, among others, could therefore reach far past the boundary of the "clean"[3] soil cover and deep into the contaminated soil at Hunters Point.

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Table 1. Maximum Root Depth of Crops (USDA)[4]

Crop	Maximum Root Depth (ft)	Crop	Maximum Root Depth (ft)
Artichoke	3	Melons	5
Asparagus	6	Parsnip	3
Beans (dry)	3	Peas	3.5
Beets	3.5	Peppers	3.5
Berries	4	Pumpkin	4
Cantaloupe	4	Soybeans	4.5
Carrots	3.5	Squash	3
Chard	3.5	Sunflower	5
Corn (sweet)	4	Sweet potatoes	5
Cucumber	4	Tomatoes	5
Eggplant	4	Turnip (white)	3
Grapes	6.5	Watermelon	5

Other sources report even deeper maximum root depth for edible plants. The seminal work on vegetable root development is Weaver and Bruner's *Root Development of Vegetable Crops.*[5] Cited widely in agricultural science, their data (summarized in Table 2) cover a wider array of common garden crops and show the potential for these plants to send their roots even deeper than those described in Table 1. For example, their study found that Swiss chard, carrot, and asparagus roots can reach depths of 7, 7.5, and 10.5 feet, respectively.

Table 2. Maximum Root Depth of Crops (Weaver and Bruner)[6]

Crop	Maximum Root Depth (ft)	Crop	Maximum Root Depth (ft)
Asparagus	10.5	Pea	3
Bean (Kidney)	4	Pepper	4
Bean (Lima)	5.5	Pumpkin	6
Beet	11	Radish (Early Long Scarlet)	3
Cabbage (Copenhagen Market)	5	Rhubarb	8
Carrot	7.5	Rutabaga	6
Cauliflower	4.5	Spinach	3.5
Cucumber	7	Squash	6
Eggplant	7	Strawberry	3
Kohlrabi	4	Sweet corn	5.5
Lettuce	3.75	Sweet potato	4.25
Muskmelon	3.75	Swiss Chard	7
Onion (Southport White Globe)	3	Tomato	4.25
Parsley	4	Turnip	5.5
Parsnip	9	Watermelon	4

Information compiled by the University of California Cooperative Extension for the UC Small Farm Program based at UC Davis further confirms that produce roots can reach depths greater than the two foot soil cover at HPS.[7] Roots of the following crops were found at average depths of 3 to 4 feet: bush and pole beans, cantaloupe, carrot, cucumber, eggplant, beets, peas, pepper, and summer squash. Other crops have roots that penetrate to average depths of over 4 feet include: asparagus, pumpkin, winter squash, seeded tomato, seeded watermelon, lima beans, and sweet potato. Note that these data concern root depth *averages* of mature plants, meaning the *maximum* vertical penetration of these roots can be even deeper.

Edible Plants Uptake Contaminants and Transfer Them to People Who Consume the Produce

Through their roots, plants extract materials like water, nutrients, and contaminants from the soil and transfer them into the plant body.[8] At HPS, various harmful materials have been deposited in the soil by the U.S. Navy, including hazardous chemicals and long-lived radionuclides. Plants are able to take up *all* elements on the periodic table, to varying degrees, through their roots and leaves, including radioactive isotopes.[9] Therefore, when the roots of edible plants extend below the thin soil cover and into the contaminated soil at HPS, they have the ability to transport contaminants they find there up into the edible portions. When consumed, this contaminated produce would expose members of the public to contamination that is supposed to remain isolated beneath the cover.

Roots of Non-edible Plants Reach Even Deeper

The roots of non-edible plants also have deep roots that could easily reach far below a two-foot soil cover. In a widely-cited 1996 review of the maximum rooting depths for 253 species across the globe, the authors found that "deep root habits are quite common in woody and herbaceous species across most of the terrestrial biomes, far deeper than the traditional view has held up to now."[10] The study includes root depth data[11] for several species of trees and shrubs that were approved for planting at Parcel

A,[12] such as Manzanita (*Arctostaphylos spp.*), which roots to depths of 8.2 - 17 feet, Coyote Brush (*Baccharis pilularis*), which roots to depths of 10.5 feet, and the Coast Live Oak (*Quercus agrifolia*), which roots to depths of 35 feet. Eucalyptus (*Eucalyptus spp.*) trees are present at Parcel A, common throughout the San Francisco Bay Area, and root to depths of 8.9 - 131 feet. The species that will be planted during the Phase 2 redevelopment of the rest of HPS are not yet fully known. However, we do know that extensive vegetation is part of the plan for parts of the remainder of the site, as evidenced by the strong emphasis on parkland and open space in recent presentations by FivePoint and the San Francisco Office of Community Investment and Infrastructure (OCII).[13] Given that the global average for root depths of vegetative plants is 15+/-1.6 feet,[14] it must be presumed that the roots of trees and shrubs planted at HPS will grow much deeper than the two-foot soil cover.

Non-Edible Plants Transfer Contaminants to the Soil Surface

Consumption of edible plants is not the only pathway by which plants could expose people to contamination from beneath the soil cover at HPS. The deep roots of non-edible vegetation such as trees and bushes also have the potential to draw up pollutants and deposit them on the soil surface as contaminated leaf litter and dead plant material.[15] Plants are, in fact, so effective at taking up contamination deep in the soil profile that they have been used at waste burial sites for a process known as phytoremediation.

Phytoremediation, and more specifically phytoextraction, is a remediation process that relies on the plants' extraction of contaminants in soil and their concentration in the biomass of plants. When used as a remediation technique, the contaminated plants are removed from the site to leave cleaner soil behind.[16] This would not be the case at HPS, as the plant landscaping will be permanently installed after the Navy has declared the cleanup over despite contamination remaining in the soil.

Future use plans[17] for the site repeatedly show vegetation of various sorts (e.g., trees, bushes, and other vegetation) intended to grow in the open space and residential areas.[18] Those plants have deep roots, far deeper than the soil covers, and will, in essence, "pump" contaminants from the polluted soil below the cover up to the surface.[19] When the plants die or their leaves fall, the resulting organic matter on the soil surface will be contaminated, exposing the public to harmful chemicals and radionuclides. Humans wouldn't be the only organisms threatened by this: other animals could be at particular risk due to ingestion of contaminated leaves or seeds.[20]

Evidence abounds of uptake of contaminants by non-edible plants. For example, at the 200-East Area of the Hanford site, "Russian thistle was absorbing and emitting several fission elements, including Sr^{90}, Y^{90}, Ce^{144}, Pr^{144}, Cs^{137}, Ru^{106}, and Zr^{95}." The study further "determined that the roots penetrated through at least a 1.1-m [3.6 foot] thick protective layer."[21] The same review references a study by Klepper et al., which reported that the roots of gray rabbitbrush "penetrated to depths of at least 2.4 m [6.5 feet] to reach the radionuclides associated with the waste," resulting in their shoot samples being "often more than 10 times greater than background levels."[22] A 2017 study observed preferential uptake of Ra-226 in trees, "particularly by trees of the *Quercus* species."[23] *Eucalyptus* has been found to accumulate U-238, Th-230, Ra-226, and Pb-21.[24] The EPA states that "transpiration of plants with large root systems may also substantially contribute to tritium re-emission."[25] A study, "Uptake of Nuclides by Plants," by Maria Greger of Stockholm University provides further detailed information about uptake of the a large number of radionuclides in a wide array of plants.[26]

Plants Create Upward Gradients for Contaminants Below the Root Zone

Edible and non-edible plants alike use their roots to extract water, nutrients, and other materials such as contaminants. In doing so, they create concentration and pressure gradients in the soil.[27] Since water and nutrients must be in contact with the roots to be taken up, these gradients are a key component of plant nourishment.

Nutrients come in contact with root surfaces in three main ways: *root interception*, whereby roots grow into nutrient and water zones; *mass flow*, whereby water moves into the root zone due to a pressure gradient created by root moisture uptake and transpiration from leaf and other plant surfaces; and *diffusion*, whereby root nutrient uptake creates a concentration gradient such that nutrients will tend to move toward the root zone.[28] In other words, as plant roots suck up water, nutrients, and other materials, the soil around the root zone becomes depleted of these components and gradients are formed which transport water, nutrients, and contaminants from beyond the root zone to the root surface. These processes present additional pathways whereby contamination beneath the soil cover, even in regions beyond the root zone, could be accessed and subsequently transferred to the plant body or topsoil.

Additional processes exist which mobilize the movement of water upward in the soil profile. Evaporation at the soil surface creates an upward gradient for soil water. As moisture evaporates from the soil surface, the soil surface dries out, inducing moisture to move upward from wetter, lower layers.[29] Transpiration of moisture through plant leaves adds to the effect. Evapotranspiration thus is a key factor producing hydraulic redistribution in soils and the potential for bringing contaminated soil water to the surface.

As moisture travels, contaminants can travel with it. Strontium-90, for example, is particularly water soluble, and thus gets "accumulated within plants."[30] Therefore, the aforementioned processes can result in contaminants being pulled upward from the profile beneath the thin soil cover and transferred to the surface soil. Indeed, this is part of how soil-building occurs—materials from deeper in the profile are brought to the surface by plants, and as they drop leaves or die, their organic material builds up in the top soil. In the case at hand, that mechanism can also bring with it HPS subsurface contaminants.

These Pathways are Significant and Raise Serious Questions About Cleanup Approaches at Hunters Point Shipyard

One can readily imagine the problems that would arise for gardens grown in this insubstantial two-foot soil cover layer: as a garden develops, so will the root systems of its crops, penetrating into the contaminated soil beneath the cover and drawing moisture and contaminants into and from the root zone. Radioactivity and toxic chemicals can accumulate in the plant body, leading to contaminated vegetables being ingested by the public. Further, if a garden employs a compost system (as many do), any contaminants in plant bodies would be re-applied to the garden beds as compost, thus further concentrating contamination in the garden soil for future consumption as produce. Even if the community were not to consume vegetables grown on-site, the non-edible vegetation to be planted for redevelopment may still bring contamination up to the surface, thus exposing residents.

Conclusion

The Navy's basis for shifting the HPS remedy from cleaning up the contamination to covering it with two or three feet of clean soil is questionable based on the above analysis. This thin cover is vulnerable to many processes that render it ineffective in preventing exposure to the radioactive and toxic chemical contamination. Due to the substantial contamination at the Shipyard and the associated risks to human and environmental health, these plans should be reconsidered in light of the issues raised above.

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[1] The Navy's selected remedy generally includes a two foot soil cover, or four inches of asphalt. In some cases, the soil cover is three feet. Additionally, in some cases, the Navy is setting a condition that edible vegetables and berries be grown in a raised bed, which would add approximately 2-8 inches to the "clean" soil depth. The information presented here applies as readily to a three-foot-eight-inch soil layer as it does to two feet. Please see the main report for references to Navy documentation of their remedy and the soil cover thickness.

[2] The data from the sources cited herein generally reflect root depths in agricultural settings, rather than home gardens. This can mean root depths can vary from what we have listed since some home gardens may be under-irrigated and under-fertilized. However, the data clearly demonstrate that roots for the kinds of edible plants grown in backyard and community gardens can penetrate far deeper than the thin "clean" soil cover contemplated for HPS.

[3] The Navy purports to be using clean soil to construct the two-foot cover layer. However, we have been unable to find a detailed description of the materials to be used, their physical, minerological, and chemical characteristics, or the levels of allowable contamination at which the soil will be considered 'clean.'

[4] *National Engineering Handbook, Part 623: Irrigation, Chapter 11: Sprinkler Irrigation,* United States Department of Agriculture, Natural Resources Conservation Service, August 2016, accessed April 15, 2019: p. 11-30, http://www.wcc.nrcs.usda.gov/ftpref/wntsc/waterMgt/irrigation/NEH15/ch11.pdf. The USDA source table provides a range of effective maximum root depths. Table 1 in our report presents the USDA's maximum value in the range for each crop.

[5] John Ernest Weaver and William Edward Bruner, *Root Development Of Vegetable Crops* (London: McGraw-Hill Book Co., 1927), chapters 2-14, https://www.soilandhealth.org/wp-content/uploads/01aglibrary/010137veg.roots/010137toc.html.

[6] The authors present root depth data across the full range of the life cycle of the plant. Accordingly, we have made our best efforts to report root depth at the normal time of harvest.

[7] "Tips on Irrigating Vegetables," University of California Agriculture and Natural Resources, UC Small Farm Program, Table 1, accessed April 15, 2019, http://sfp.ucdavis.edu/pubs/Family_Farm_Series/Veg/Irrigating.

[8] Horst Marschner, *Mineral Nutrition of Higher Plants* (San Diego: Elsevier Science & Technology, 1995), 484-486, ProQuest Ebook Central.

[9] Maria Greger, "Uptake of nuclides by plants," No. SKB-TR—04-14, Swedish Nuclear Fuel and Waste Management Co., April 2004, 11.

[10] Canadell et al., "Maximum rooting depth of vegetation types at the global scale," *Oecologia* 108, no. 4 (January 1996): 583, https://rd-springer-com.oca.ucsc.edu/content/pdf/10.1007%2FBF00329030.pdf.

[11] Canadell et al., "Maximum rooting depth," 588-92.

[12] "Hunters Point Shipyard Parcel A Phase 1 Open Space Schematic Design," San Francisco Redevelopment Agency and Lennar/BVHP, October 2, 2007, accessed April 15, 2019: p. 16, https://sfocii.org/Modules/ShowDocument.aspx?documentid=793.

[13] "Presentations on Proposed Revisions to the Hunters Point Shipyard Phase 2 Project," Office of Community Investment and Infrastructure, accessed April 12, 2019, https://sfocii.org/proposed-revisions-hunters-point-shipyard-phase-2-and-candlestick-point-project.

[14] Canadell et al., "Maximum rooting depth," 583.

[15] Tom Hakonson, "Review of Sandia National Laboratories/New Mexico Evapotranspiration Cap Closure Plans for the Mixed Waste Landfill," Citizen Action, February 15, 2002, accessed April 1, 2019, http://www.radfreenm.org/old_web/pages/hakonson_full.htm.

[16] Andreas D. Peuke and Heinz Rennenberg, "Phytoremediation: molecular biology, requirements for application, environmental protection, public attention and feasibility," *EMBO reports* 6, no. 6 (2005): 497, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1369103/.

[17] "Parks, Open Space, and Habitat Concept Plan," Appendix J to Disposition and Developer Agreement, FivePoint and San Francisco Office of Community Investment and Infrastructure, approved April 17, 2018. https://sfocii.org/candlestick-point-hunters-point-shipyard-phase-2-project-documents.

[18] Whereas for some parcels there is a restriction (which is difficult to imagine actually being effectively enforced) requiring fruit trees to be grown in containers with imported soil, there is no such restriction for trees and bushes that do not produce edible fruit.

[19] Hakonson, "Review of Sandia."

[20] Michele A. Parisien et al., “Ecological Risk Associated with Phytoextraction of Soil Contaminants,” *Journal of Environmental Chemical Engineering* 4.1 (2016): 651–656.

[21] Andrew G. Bowerman and Edward F. Redente, "Biointrusion of Protective Barriers at Hazardous Waste Sites," *Journal of Environment Quality* 27, no. 3 (1998): 627 - 628.

[22] E.L. Klepper, L.E. Rogers, J.D. Hedlund, and R.G. Schreckhise, "Radioactivity associated with biota and soils of the 216-A-24 crib,” Rep. PNL-1948, Pacific Northwest Lab, Richland, WA, 1979, cited in Andrew G. Bowerman and Edward F. Redente, "Biointrusion of Protective Barriers at Hazardous Waste Sites," *Journal of Environment Quality* 27, no. 3 (1998): 628.

[23] E. Charro and A. Moyano, “Soil and vegetation influence in plants natural radionuclides uptake at a uranium mining site,” *Radiation Physics and Chemistry* 141 (2017): 200.

[24] P. Blanco Rodriguez, F. Vera Tomé, J.C. Lozano, and M.A. Pérez Fernández, “Transfer of ^{238}U, ^{230}Th, ^{226}Ra, and ^{210}Pb from soils to tree and shrub species in a Mediterranean area,” *Applied Radiation and Isotopes* 68, no. 6 (2010): 1159.

[25] *Methods for Estimating Fugitive Air Emissions of Radionuclides from Diffuse Sources at DOE Facilities,* U.S. Environmental Protection Agency, Office of Radiation and Outdoor Air, Radiation Protection Division, September 3, 2004: xiv, https://www.epa.gov/sites/production/files/2015-05/documents/final_report_9_04.pdf.

[26] Maria Greger, “Uptake of nuclides by plants,” No. SKB-TR—04-14, Swedish Nuclear Fuel and Waste Management Co., April 2004.

[27] Marschner, *Mineral Nutrition*, 484-486.

[28] Marschner, *Mineral Nutrition*, 484-486.

[29] Gabriel G. Katul and Mario B. Siqueira, "Biotic and abiotic factors act in coordination to amplify hydraulic redistribution and lift,” *New Phytologist* 187, no. 1 (2010): 4.

[30] Alexey V. Yablokov, Vassily B. Nesterenko, and Alexey V. Nesterenko, “Atmospheric, Water, and Soil Contamination after Chernobyl,” *Annals of the New York Academy of Sciences* 1181, no. 1 (November 2009): 223-36, https://doi.org/10.1111/j.1749-6632.2009.04830.x, cited in Dharmendra K. Gupta, Utsab Deb, Clemens Walther, and Soumya Chatterjee. “Strontium in the Ecosystem: Transfer in Plants via Root System,” In *Behaviour of Strontium in Plants and the Environment*, edited by Gupta, Dharmendra K., and Clemens Walther, 1-18. Springer International Publishing, 2018. doi:10.1007/978-3-319-66574-0. pg. 2.