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Article

Earthworms as soil quality indicators: A case study of Crissy Field and Bayview Hunters Point naval shipyard

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SUMMARY

Crissy Field (CF) and Bayview Hunters Point (BVHP) are both former military sites in San Francisco, California, USA, where chemical disposals occurred. Although CF, a former air coast defense station, was formally remediated in 1994, leading to low topsoil chemical remains, only haphazard remediations of BVHP, a former naval shipyard, occurred. Worms live in topsoil, and their health reflects that of their environment, thus indicating the health of other organisms who live on and around that soil, including humans. To investigate the differences in topsoil quality between CF and BVHP, topsoil toxicity was analyzed by taking soil samples along with *Lumbricus terrestris* (earthworm) counts. Topsoil sampling revealed heavy metals that influence human health, including arsenic, lead, chromium, and mercury. We hypothesized that fewer *L. terrestris* would be observed in BVHP and that BVHP would test positive for more heavy metals than CF. Our results aligned with our hypotheses as higher levels of contaminants and fewer worms were detected in BVHP topsoil compared to CF, underlining the need to remediate the soils of BVHP naval shipyard. Our findings support the poor ecological health and viability of BVHP topsoil and the dangers it poses, along with supporting claims surrounding illnesses attributed to BVHP toxins.

INTRODUCTION

Worms improve soil structure, water movement, nutrient cycling, and plant growth (1). Because of their ecosystem services, large quantities of healthy worms indicate a healthy soil system (2–4). Similar to humans, the environment in which an earthworm lives determines how successfully that organism will grow and thrive. Heavy metals in high concentrations can be lethal to organisms, and earthworms may consume contaminated soil and organic matter (5–8). As earthworms consume organic matter, toxic chemicals, and heavy metals in topsoil can affect their growth, structure, and metabolism through protein denaturation and destruction of cell membranes (9, 10).

In the USA, one source of soil contamination is the commercial hazardous waste facilities located in neighborhoods with higher percentages of people of color (11, 12). Environmental pollution in disenfranchised communities can be found in the Bay Area, which is detrimental to all interconnected ecosystems, including humans (13–16). In many cases, these instances of environmental injustice disproportionately impact people of color and lower-income people (17). Often, this pollution seeps into the soil and affects the organisms living in and on it (17). Environmental degradation in San Francisco leads to adverse health effects, including cancer, chronic lung diseases, high rates of children with asthma, and overall higher hospitalization rates due to asthma (18–20).

Our study focuses on two areas within San Francisco, California: Crissy Field (CF) and Bayview Hunters Point (BVHP). CF and BVHP vary vastly in their demographics; CF has a much higher percentage of white people and higher overall socioeconomic status (SES), whereas BVHP has a higher percentage of black, indigenous, and other people of color and lower overall SES (21–24). CF and BVHP were both military sites where chemical disposal occurred. However, CF was formally remediated using excavation and channel digging to manage and mitigate the human and environmental health risks from contaminated soil in 1994, which kept chemical remains low (25–27).

On the contrary, the Navy's shipbuilding and repair activities in BVHP from 1941 until 1976 contaminated soil, dust, sediments, surface water, and groundwater with petroleum fuels, pesticides, heavy metals, polychlorinated biphenyls, volatile organic compounds and radionuclides (28). The Navy established the BVHP Shipyard as a Naval Radiological Defense Laboratory in 1946, where they decontaminated and sandblasted radioactive ships exposed to nuclear weapon tests in the Pacific ("Operation Crossroads"), burned radioactive fuel, and studied the effects of radiation on animals and materials (28-30). Subsequently, the shipyard became a Superfund site, a location designated by the US Environmental Protection Agency (EPA) for intensive cleanup and remediation from hazardous contamination to protect human and environmental health, and it was also placed on the National Priorities List in 1989 (27, 29, 31, 33, 40).

To organize cleanup efforts, the Navy divided the BVHP Shipyard into parcels to determine which areas were clean and ready to be transferred to the city of San Francisco for residential housing development (32). According to the Navy, Parcel A, which includes a new housing development by Lennar, was primarily used for residential and commercial activities and was transferred to the city in 2004 with no further remediation action required in 1995 (33). The Navy claims Parcel A to be "remediated" because they cleaned up the site before transferring the site to the city of San Francisco (34). The Navy states they removed a contaminated underground storage tank, sandblasted to remove toxic soil, and also

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relocated contaminated soil (35). Parcel G was another place where we took samples of BVHP non-remediated areas. The Navy still needs to transfer Parcel G to the city and claims Parcel G is still remediating via excavation and pouring concrete covers over contaminated soil (36). Some contaminants remain in the shipyard today, though it is challenging to state the quantity due to the Navy keeping incomplete records of their hazardous waste dumping activities (17, 30).

Currently, the Lennar Corp apartment complex, adjacent to the BVHP Shipyard, is built directly on toxic topsoil and poses a risk to the residents (37, 38). In the spring of 2022, the shipyard homeowners won a court-approved $6.3 million settlement with Lennar and FivePoint, another BVHP developer, after the Navy's contractor falsified soil sampling results in a soil cleanup scandal (39–41).

To better understand the discrepancies between topsoil quality in CF versus BVHP influenced by systemic inequalities and SES differences, we collected data on *Lumbricus terrestris* (earthworm) abundance using mustard tests and took inventory of topsoil health by measuring contaminant levels in soil samples. As lab-grade soil testing can be costly, one inexpensive way of assessing the soil pollutant abundance is by measuring worm abundance using mustard tests (42). Farmers use 'mustard tests' to gauge their soil quality by counting the number of worms that move to the top of the soil profile in response to the mustard solution (43). While less precise, mustard tests utilize everyday household items and are more cost-effective than lab testing, which enables communities to perform their own tests.

In this current study, we aimed to determine the topsoil quality in CF and BVHP. By assessing soil samples for heavy metal testing and worm abundance, we hypothesized that BVHP will have a worse soil quality than CF due to haphazard remediation processes. Soil samples and mustard tests (worm abundance data collections) from CF generally showed fewer topsoil toxins. Significantly more worms were found in CF than in BVHP. Our findings highlight the intersection of environmental contamination and socioeconomic inequality, emphasizing the need for equitable remediation efforts and policies that address environmental injustices in underserved communities like BVHP.

RESULTS

Our data collection focused on three testing sites: CF (high SES neighborhood), the BVHP Parcel G (contaminated low SES area), and BVHP Parcel A (hypothetically less contaminated higher SES area surrounded by lower SES neighborhood) (**Figure 1, Table 1**). We tested each site for worm abundance and topsoil heavy metals. Eighteen mustard extraction tests were completed in the high SES neighborhood and 25 in the low SES neighborhood to count worms (**Figure 2**).

More worms and generally fewer amounts of contaminants were found in CF compared to both BVHP sites. In the first data collection, we performed seven mustard tests in CF, with a mean number of worms of 8.3 in trial #1 (*SD* = 6.3). In the second data collection, 11 additional mustard tests were carried out in CF, with an average mean of 9.6 worms in trial #2 (*SD* = 5.8). In CF, the arsenic concentration was undetectable (<0.5 parts per million (PPM) - mg/kg), chromium was 46.8 PPM, lead was 28.8 PPM, and mercury was 0.2 PPM. Cadmium was left out of the results for this data collection, as according to EPA guidelines, no significant traces of were found in any of the samples.

Five worm tests were conducted in the first data collection in BVHP, including remediated shipyard soil tests (BVHP trial #1 *M* = 1.2, *SD* = 2.7). In the second data collection, 20 mustard tests in BVHP non-remediated soil yielded an average worm count of zero. In both BVHP data collections, zero worms were found in the non-remediated soil. In general, worms in CF were much larger in circumference and length and darker in color than those found in BVHP-remediated soil (**Figure 3**). Furthermore, the soil in CF was darker and richer in nutrients, whereas the BVHP soil contained more sandy loam. Overall, the results indicated that CF had significantly higher worm abundance than BVHP (Mann-Whitney z = -5.45, p = < 0.001).

In BVHP remediated soil, the arsenic concentration was 5.1 PPM, chromium was 151.2 PPM, lead was 15.5 PPM, and mercury was 0.1 PPM. In BVHP non-remediated soil, the arsenic concentration was 5.7 PPM, chromium was 81.9 PPM, lead was 87.0 PPM, and mercury was 0.3 PPM. As before, cadmium was left out of the results for this data collection as no significant traces were found in any samples according to the EPA guidelines.

Overall, BVHP non-remediated soil had the highest mean concentration of contaminants and the lowest mean count of worms. Conversely, CF in the higher SES neighborhood has the lowest mean concentrations of heavy metals and the highest mean worms count (**Figure 1, Table 1**).

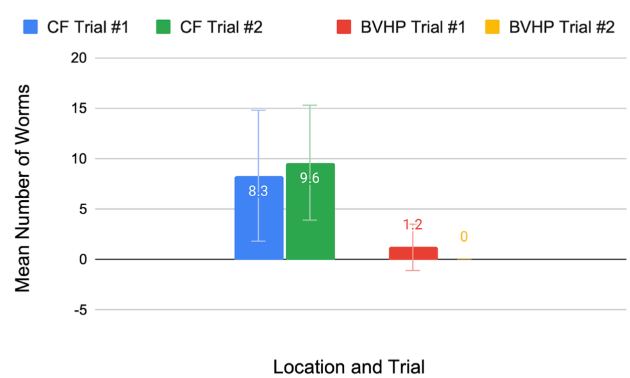

Figure 1: Mean earthworm count of CF and BVHP. Worm mustard tests from both trials. Comparisons were made between CF (n = 7) and BVHP (n = 5) in trial #1 (October to November 2020), followed by CF (n = 11) and BVHP (n = 20) in trial #2 (December 2020). Data shown as mean ± SD. Mustard tests revealed significantly more worms in CF than in BV (two-tailed Mann-Whitney U, p < 0.001). No worms were found in BVHP non-remediated soil (n = 25).

DISCUSSION

Our study used lab soil samples and mustard worm abundance tests to investigate topsoil quality differences in CF and BVHP. We hypothesized that we would find fewer heavy metal contaminants and more worms in CF than BVHP. Within BVHP, we hypothesized we would find fewer heavy metal contaminants and more worms in the remediated sites compared to the non-remediated sites. Our soil samples

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	BVHP (Oct. 30)	BVHP *Remediated* (Oct. 30)	CF (Nov 4. 2020)	EPA minimum amount for significance
Arsenic	5.725*	5.1*	0	5.0
Chromium	81.9*	151.2*	46.767*	2.0
Lead	86.98*	15.45*	28.833*	5.0
Mercury	0.27*	0.0565*	0.2*	0.03

Table 1: Lab soil samples. Averaged chromium, lead, and mercury levels, in PPM, from samples taken from three sites: CF, BVHP remediated, and BVHP non-remediated. Tests were conducted by RJ Lee Group, Inc. (29). RJ Lee states that their "internal QC" must fall within 10% (82). n=3 for CF, n=3 for BVHP non-remediated, and n=2 for BVHP remediated. *indicates significant result compared to EPA guidelines.

revealed that CF and BVHP remediated generally had fewer heavy metals and more worms than BVHP non-remediated. While we expected CF to have the lowest amounts of heavy metal contaminants, CF soil samples tested slightly higher in lead and mercury than BVHP remediated. However, CF still tested lower in all heavy metals than BVHP non-remediated. Furthermore, out of all three locations, we unexpectedly found the highest levels of chromium in BVHP remediated. There were significantly more worms in CF compared to both BVHP remediated and non-remediated.

Soil contamination with heavy metals was highest in BVHP samples compared to CF samples. This suggests that the Navy still needs to thoroughly remediate BVHP soil from prior industrial activity. There are several plausible explanations for the presence of each heavy metal in the soil. In BVHP non-remediated soil, the Navy and other prior industrial activity illegally dumped large amounts of highly carcinogenic polychlorinated biphenyls and heavy metals at the site (44, 45). It is challenging to find historical records of the chemicals and other radioactive materials the Navy used because BVHP Navy operation documents were destroyed as Federal policies allowed it (46). The Navy has stated that we can expect to find arsenic in the shipyard because parts of it were filled with serpentine bedrock-derived fill material naturally consisting of minerals containing high concentrations of arsenic (47).

Other sources of heavy metal contaminants identified in our soil samples include disassembling and assembling shells and fuses during Naval Ordnance training on shipyard soil, as well as soil exposure to degraded heavy metals from casings, fillers, and projectiles, some of which contained arsenic (48, 49). Mercury was a component of military ordinance detonators for shells and bullets assembled, maintained, and decommissioned at the shipyard (50). Naval ships built with Krupps naval armor made of chromium alloyed steel were sandblasted, which generated residue clouds that dropped onto the soil (51). Furthermore, at the shipyard, the Navy coated machine guns and cannons with chromium which could be another source of the heavy metal (52).

One reason our soil samples revealed lower levels of lead in BVHP remediated sites compared to BVHP could be attributed to the Navy's remediation of Parcel G of the shipyard in 2009, which, according to their report, specifically addressed lead, manganese, and arsenic in the soil (47). The relatively high levels of arsenic in BVHP remediated soil samples suggest that the Navy's remediation methods for removing lead were more effective than those for arsenic.

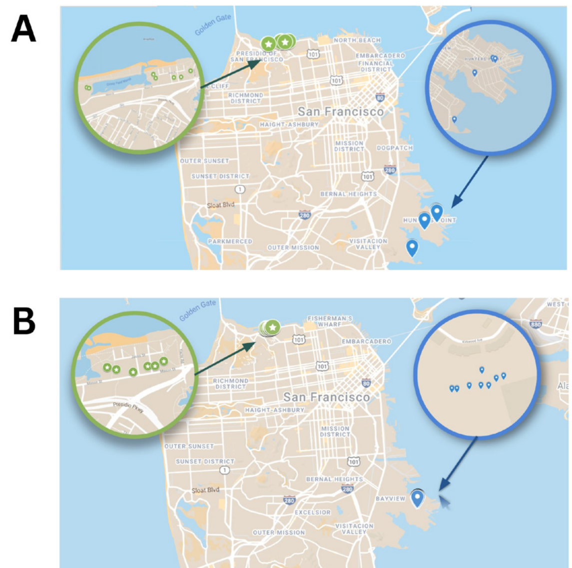

Figure 2: Data collection sites. A) Locations of the original eighteen worm tests conducted in CF and BVHP on October 30 and November 4, 2020, respectively. **B) L**ocations of an additional twenty-five worm tests carried out in CF and BVHP on December 12, 2020.

Other reasons why we did not find as much lead in the remediated soil could be due to the leaded gasoline that was gradually out-phased after the 1996 Clean Air Act, the lack of burning coal for ships after 1925, and the 1978 EPA regulation against leaded paint which was sandblasted off of boats (53–55). For example, deposits of leaded gasoline in the shipyard from industrial sources before 1996 could have contributed to increased lead levels in the soil (56).

The high levels of chromium in BVHP soil could be attributed to the Navy's 2009 remediation plan for Parcel G of the shipyard that sought to address chromium VI in below-ground aquifers, not in the topsoil where we took our samples. One reason we did not find as much mercury in our soil samples could be attributed to the Navy's 2017 *in situ* injections of an organosulfur compound to address mercury contamination (57).

Other historical heavy industrial activity, such as ship decontamination on the shipyard, may explain traces of heavy metals found in the soil today (58). The scarcity of cadmium during WWII is a plausible reason we did not find it in the soil samples from former military sites (CF and BVHP).

Figure 3: Visual worm comparisons. Worms from CF (left) and BVHP partially remediated on Lennar development (right). CF worms are visibly larger, more abundant, and robust.

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Cadmium was expensive and was used to protect steel, but it was substituted for zinc due to scarcity and cost (59).

Overall, we speculate that our results found high levels of heavy metals in remediated soil because the Navy, responsible for BVHP remediation under EPA supervision, hired third-party consultants that, according to lawsuits filed against them, allegedly falsified soil remediation claims (60–62). Furthermore, instead of removing all contaminants in BVHP in the remediation process, the Navy placed semi-permeable "cost-effective" plastic sheets under 2–3 feet of clean topsoil to protect humans from immediate exposure and enable residential development (47, 63). Plastic covers, a short-term and partial remediation strategy, can be breached by roots and burrowing animals, exposing the contaminants from prior industrial activity below the cover. The Navy's decision not to pursue the "highest cleanup standards" for the BVHP plan of excavating all contaminated soil after discovering higher-than-expected contamination levels in the shipyard in 1997 could explain why we found high traces of contaminants in remediated soil samples (63).

In addition to finding significantly higher levels of heavy metal contaminants in BVHP non-remediated, we also found fewer worms with the mustard tests, which supports our hypothesis of healthier soil quality in CF compared to BVHP. Overall, the few worms we found in BVHP (and the complete lack of worms found in BVHP non-remediated) support our conclusion that BVHP has poorer soil health. It makes sense that the BVHP worms were smaller in circumference and shorter than the worms in CF, as other studies show that lead, chromium, and arsenic (all contaminants our soil samples showed elevated levels of in BVHP non-remediated) can lead to earthworm infertility and weight loss (**Figure 3**) (10, 64). Our findings from our heavy metal and worm tests align and support current science highlighting BVHP's toxicity.

From mustard tests alone, we cannot conclude that BVHP is more contaminated than CF because each location had varying soil types and might, therefore, be a confound for the worm sample tests; BVHP sandy loam is less favorable for worms compared to dark nutrient-rich CF soil, which is suitable for worms (65, 66). Despite variation in soil types between sampling locations, we can still conclude that BVHP soil quality is poorer than CF because our lab-grade soil sample tests align with the mustard test results, showing how BVHP is more contaminated than CF.

Our study's limitations include that the varying soil types drain differently. Thus, the mustard seed solution may have unequally saturated soils, causing more worms to emerge from some soil types than others. In addition, since both studies were conducted in outdoor areas, some worms may be more predated on in some areas than others. Worm tests are a much more economical method to assess soil quality than lab-grade soil samples; one lab soil sample test costs 202 times as much as a < $1 mustard test. Our use of mustard powder and water to show soil toxicity in BVHP demonstrates that affordable environmental testing can be accessible to low-income communities. However, because of the varying soil types, lab-grade soil tests are a direct way to measure soil health and offer more specific data for remediation. More replicates using lab-grade tests would have increased the reliability of our test results, though testing was limited by cost.

The lack of worms and the higher levels of soil contaminants in BVHP are important because they show poor soil quality, which poses a health risk to the residents in the area. Our results emphasize the need for a full remediation of the BVHP Shipyard and point to the continuous neglect of BVHP and the surrounding neighborhood (31, 67). Furthermore, the higher average of contaminants found in BVHP non-remediated soil using both the expensive and accessible soil quality testing methods is concerning because pollutants in the soil may still pose risks to the health of the soil, worms, and ultimately humans leading to adverse health outcomes, such as cancer (68–70).

Our two 2020 data collections showed significantly higher contamination in lower socioeconomic status (SES) neighborhoods near the BVHP than in higher SES neighborhoods (CF). Contamination variation between BVHP and CF supports broader trends of systemic environmental inequalities in the Bay Area; communities of color and low SES communities are much more likely to live closer to hazardous sites, including power plants, sewage treatment plants, and refineries (71). Other research that shows adverse health outcomes for low SES individuals who live near Superfund sites aligns with our data collection (72, 73). Our results show that environmental disparities between CF and BVHP are part of a more significant trend of ongoing environmental injustice, which is outlined in San Francisco's Department of Public Health's 2006 report on BVHP (74).

Further research on the worms within their habitats would contribute to this study. Furthermore, given that this study was done during late fall and early winter, it would need to be done during various seasons to see if the same results would occur. Since we only compared the BVHP Naval Shipyard to one higher SES neighborhood, collecting data in other lower and higher SES areas would also be beneficial to further examine systemic inequalities in San Francisco. Furthermore, blood tests for heavy metals in the residents of these three locations: BVHP remediated, BVHP non-remediated, and CF could express a direct link between environmental health and public health. The Hunters Point Community: Biomonitoring Program Medical Screening Clinic is working with the BVHP community to monitor human health due to shipyard and other BVHP contaminants (75).

This study on topsoil quality disparities may have an overall helpful impact on BVHP residents by bringing awareness to the shipyard's toxicity, which directly affects their community's health, inspiring further remediation. This study's findings could also benefit broader environmental science and environmental justice organizations, locally and globally, by further emphasizing the relationship between the environment and public health.

MATERIALS AND METHODS

Our study used two methods, soil samples and earthworms, to look at soil quality differences between two San Francisco regions with different demographics. There were two worm sampling periods. The first trial was on October 30, 2020 (BVHP) and November 4, 2020 (CF). The second trial was on December 12 (CF) and 18 (BVHP) of 2020. Soil samples were obtained during the first trial only.

Contaminant soil analysis

Three full vials of soil were collected from CF and five total from the remediated and non-remediate BVHP sites. In

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addition, one sample was taken at Candlestick Recreation Park located in Bayview and was represented under the Bayview non-remediated data as the park has never been remediated, and it is located directly downwind to the BVHP Naval Shipyard (**Table 1, Figure 2**). Sample locations were randomly selected within each site.

Samples were sent to RJ Lee, Inc Group for arsenic, cadmium, chromium, lead, and mercury testing, and compared to EPA contamination standards. RJ Lee uses two methods, EPA Method 200.8 and NIOSH Method 7300 to measure heavy metals (76). EPA Method 200.8 utilizes acid to extract metals into a solution for analysis and then uses inductively coupled plasma-mass spectrometry (ICP-MS), to measure multiple metals simultaneously with high sensitivity and accuracy (77). NIOSH 7300 similarly uses acid to release metals into a measurable solution and then employs inductively coupled plasma atomic emission spectroscopy (ICP-AES) (78). Both ICP-AES and ICP-MS involve introducing a sample into a high-temperature plasma to excite its atoms, but while ICP-AES measures the light emitted at characteristic wavelengths to determine elemental concentrations, ICP-MS detects and quantifies ions based on their mass-to-charge ratio for greater sensitivity and specificity (79).

Mustard test

We used mustard tests to extract worms from soil and examine/count them (43). The ground mustard seed was mixed 1:10 with water, and 600 mL of this solution was poured over 0.3 m^2 of soil. We used a pre-made quadrat square to choose a consistent area measure in each data collection. Worms that appeared on the surface were counted for 2 minutes (80). After we counted the worms, they were rinsed to remove the irritating mustard powder from their skin and placed back on top of a patch of soil adjacent to the mustard patch.

Statistical analyses

Worm counts were analyzed with a Mann-Whitney U, non-parametric statistic test for abnormally distributed data. We used a Mann-Whitney U test over a t-test because an uneven number of samples were taken at each field site. On a basic level, a t-test and a Mann-Whitney U test compare two sets of data to see if the difference between the means is likely to be repeatable or due to random chance. However, the math behind the Mann-Whitney U is slightly different in accurately measuring abnormally distributed data. To conduct our Mann Whitney U test, we used socscistatistics.com (81).

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