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Validation of a screening kit to identify environmental lead hazards

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ABSTRACT:

In many states, environmental lead hazards are evaluated only after a lead-poisoned child has been identified. This passive approach is problematic because only a small fraction of children are tested for lead and those with elevated blood lead levels may have irreversible developmental damage. In order to reverse this paradigm, a new lead screening kit was developed. In this study, we validated the accuracy of the kit compared to the conventional methods. Forty-five participants used the kit to collect 3 dust, 3 soil and 2 paint samples in their homes. A researcher performed an *in-situ* analysis of the lead content in the paint and soil using a portable X-ray fluorescence (XRF) spectrometer. The soil, paint, and dust samples collected by the participants were then analyzed by XRF *ex-situ*. A strong linear correlation was found between the *in-situ* and *ex-situ* measurements for soil and dust samples, and a reasonable correlation was obtained for lead content of paint samples. The kit had very high degrees of specificity (true negative rate) and sensitivity (true positive rate) for detecting hazardous levels of lead in soil and dust samples. The agreement was more moderate for paint samples because some of the paint chips provided gave different readings from the front or back surface, but *in-situ* XRF only reads from the front surface. Overall, the kit gave a sensitivity of 87%, a specificity of 98% and an accuracy of 96% for detection of environmental lead hazards in samples collected from the home by untrained citizens. This suggests that widespread and inexpensive lead screening could be used to successfully identify hazards and ultimately decrease environmental lead exposure in children.

1. Introduction

Childhood lead exposure is largely associated with the aging housing stock in the United States and is exacerbated by antiquated standards and regulations. Recently, for example, the National Guard and the New York City Housing Agency have both come under fire for their inaction and disregard of lead testing standards and regulations of public housing (Schneyer, 2018; Goodman et al., 2018). The Centers for Disease Control (CDC) estimates 83% (24 million) of all homes built before 1978 contain lead-based paint and that at least 4 million children under 5 are at risk of exposure (CDC, 1997, CDC, 2013). Residues from the use of leaded gasoline also contribute to the soil burden of lead and dust and may be the dominant lead exposure source in large cities (Mielke and Reagan, 1998). Over time, lead-based paint, defined as greater than 0.5% by weight, deteriorates usually at points of friction, such as windows and doors, resulting in lead-contaminated dust and soil, which can become major sources of lead exposure (Lanphear et al., 1998).

There is no safe level of lead (Flora et al., 2012). Unfortunately, the current *status quo* for locating environmental lead hazards is by screening children for elevated blood lead levels. This is an inhumane approach for locating environmental lead as this approach is unnecessarily wasting human life potential as lead exposure is devastating to the human body and brain. In particular, lead has neurological and physiological effects that interfere with brain development in children under the age of seven (Needleman, 2004; Chen et al., 2007). Lead poisoning, even at low levels of exposure, causes learning disabilities, behavioral problems, attention deficits, hearing problems, and speech impediments resulting in lower student achievement, lifetime earnings and IQ (Chen et al., 2007; CDC, 2012; Braun et al., 2006; Braun et al., 2008; Chen et al., 2005).

Residents have few choices to test their homes for lead, either by hiring a certified professional or by purchasing a commercial Do-it-Yourself (DIY) product. A Certified Risk Assessor may be hired to

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perform an on-site assessment utilizing an XRF analyzer. This option typically provides an in-depth analysis of the lead exposure risks in the home by collecting approximately 40 readings on-site for paint, while approximately 5–10 dust, soil, and water samples are sent to a laboratory and analyzed with inductively coupled plasma – optical emission or mass spectroscopy (ICP) which is time intensive and can be expensive for sample preparation and analysis. While XRF analysis requires less sample preparation and is therefore faster, it requires 1–3 h for a trained operator to collect data in a typical residence and it would be prohibitively expensive to send trained professionals and equipment to every house built before 1978 in any major city.

The alternative to hiring a professional is the purchase of a commercial DIY lead test kit. On September 1, 2010, the EPA set forth new kit requirements requiring test kits to meet both a positive and negative response criterion sensitivity of 95% and a specificity of 90% for paint (US EPA, 2018). To date, the EPA states no commercially available test kit meets these criteria, however there are three test kits that are recognized by the EPA that meet the requirements set forth prior to September 1, 2010 which require a negative response criterion (only a sensitivity of 95% with no requirements for specificity) (US EPA, 2018). Several kits offering quantitative results are available online (Environmental innovative technologies (EIT)), but at a cost of around $40 per sample, the cost is comparable to hiring a certified lead assessor. While qualitative paint test kits are inexpensive, there are significant limitations (Korfmacher and Dixon, 2007; Rossiter et al., 2000; US EPA, 2018; US DOL, 2003). Most notably, none of the test kits are designed to test for the presence of lead in dust or soil, which are major risk factors for young children (CDC, 2013; de Freitas et al., 2007).

While much is known about the sources of lead exposure, public policy in the US and many other countries has largely taken a reactive approach to the identification and investigation of lead by relying on the outcomes of children's blood lead tests. While lead screening guidelines exist, there are many gaps in state lead screening policies and laws. CDC recommends virtually every child should be tested for lead at age 12 and 24 months (CDC, 2012), however, US lead testing rates are generally low (Raymond et al., 2014). Only 10 states and the District of Columbia require universal screening of children, 8 states have targeted testing requirements, and 32 states have lead screening recommendations with no official policy and/or laws (Dickman, 2017). However, in each state when an elevated blood lead level (EBLL) is obtained that meets or exceeds an established threshold (EBLL thresholds differ by state), health department officials establish case management and work to identify the source(s) of lead exposure (Dickman, 2017). A Home Lead Risk Assessment is performed by a licensed risk assessor to assess and identify the source of lead exposure. In St Joseph County Indiana, USA which has ~28,000 (28%) homes built before 1950 and ~67,000 (65%) built before 1978 (US Census Bureau, 2017), the health department has historically conducted home hazard assessments on 50–100 homes per year. But given the low testing rates of children, few children are being identified and case managed while the majority of children in homes that contain lead sources are not being assessed (Beidinger-Burnett et al., 2019). We wanted to formulate a strategy to reverse the current testing paradigm by looking for lead exposure sources in the home in order to proactively identify children who may be at higher risk of lead poisoning. Given the importance of this public health issue, a citizen-science-based approach was chosen as the foundation for this study. Citizen science is a community-based participatory research method in which citizens are directly engaged in the scientific process to collect data with the goal of extending the researcher's reach (Bonney et al., 2014; Silvertown, 2009). As a result of their involvement in the research process, participants gain knowledge, increase awareness and help to solve community issues (Irwin, 1995).

The Filippelli group in Indianapolis has adopted the citizen science approach to study lead contamination in residential soils. Their citizen science efforts have led to the collection and analysis of thousands of soils from different property locations including dripline, roadside, and mid yard samples (Filippelli et al., 2018). Following this strategy, we have adopted similar guidelines for collecting soils from these property locations in our low-cost Lead Screening Kit that we have developed over the past two years. In addition to soils, this screening kit can be used to find lead in household dust and interior and exterior paint. The samples are returned to a laboratory for XRF analysis. Kit samples are collected by residents (citizen scientists) and analyzed rapidly with XRF spectrometry. Because XRF is a non-destructive technique, these samples can also be analyzed with ICP if one is available. However, while ICP methods are very accurate and remain the gold standard for testing trace metal concentrations in environmental samples, they are not suitable for a rapid screening method. The capital costs are expensive and the preparation time is too great to handle the sample load in any metropolitan area when there are tens of thousands of residences to be screened. Because XRF spectrometry does not require the samples to be in aqueous form prior to analysis, it is the only technology that can begin to approach the large sample numbers required to undertake residential lead screening. The technology has also improved considerably over the past two decades and is accepted by HUD and EPA for analysis of paint and soil samples in home lead hazard assessments. All the samples collected in the kit described here can be analyzed in less than 10 min, so a single XRF instrument could potentially screen a hundred homes per day. With participation of many community residents collecting samples, it becomes feasible to screen residences for lead exposure hazards on a large scale.

Given the vast scope of the legacy lead problem in our community and across the US, new methods are needed to help families engage in primary prevention of lead poisoning. As stated above, current methods to test homes are labor intensive, costly and limited. This kit is a screening tool; the first step in identifying a lead hazard in the home environment. It was designed to be quick, low-cost (under $20) and scalable. Further, the origin of this kit was not born of a commercial interest nor as a way to replicate HUD and EPA testing, but rather to develop a screening tool to complement on-going state and federal lead risk reduction efforts. We anticipate that families could use this screening kit to see if lead hazards exist in their home environment and to help prevent lead poisoning of their children before it happens. Thus, the purpose of this study was to validate this kit as a method to reliably screen home environments for lead hazards.

2. Materials and methods

2.1. Ethical approvals

Institutional Review Board approval for the sample collections described in this work were obtained through the University of Notre Dame (IRB # 17-01-3522 08 June 2017–14 March 2018, IRB #18-03-4538 15 March 2018–14 March 2019).

2.2. Participant recruitment

Participants were recruited for this double-blinded study in Saint Joseph County, Indiana, USA. Recruitment primarily occurred through community organizations, medical practices, and word of mouth. A variety of recruitment materials such as postcards or flyers were distributed through community organizations. Medical practices were contacted directly by investigators and practices that believed this project was a beneficial service to their patients assisted in recruitment. Seminars were also given on campus and posted on the university website about the study. As the study progressed, participants contacted the study team after hearing about the screening testing process from previous participants.

Once contact was made with interested participants, an initial intake meeting (~1 h) was scheduled to obtain consent, gather data, and provide participants with additional information on the study. A key component of these visits was to inform the resident (either homeowner

Table 1
XRF vs. ICP-OES comparison for Pb in dust.

	ICP – Lead $> 40\ \mu g/ft^2$	ICP – Lead $< 40\ \mu g/ft^2$
XRF – Lead > 50 ppm	100 samples (true +)	7 samples (false +)
XRF – Lead < 50 ppm	7 samples (false -)	34 samples (true -)
Sensitivity	94%	
Specificity	83%	
Accuracy	91%	

Table 2
Lead classification categories used for recommendations to the residents. Soil and paint categories were adopted from EPA recommendations for lead safety (USEPA). The dust threshold was selected based on our comparison of ICP-OES and XRF measurements.

	Soil Lead (ppm)	Paint Lead (ppm)	Dust Lead (ppm)
Low lead	< 400	< 5000	< 50
Moderately leaded	400–2000		
Highly leaded	2000–5000	> 5000	> 50
Very highly leaded	> 5000		

or renter) that the results of this screening were neither a certification of a lack of lead risk or an actionable record of lead presence. A second visit (~1 h) was scheduled for the participant to perform the lead screening kit. In addition to the participant collecting samples for the kit during the second visit, the research team also performed *in-situ* XRF analyses in the home.

If actionable lead levels, defined in Table 2 in the Results section, were present in at least one sample type (paint, soil or dust) according to the lab team measurement, a thorough Home Lead Risk Assessment by the St. Joseph County Department of Health was recommended to the participant. A copy of the report sent to participants can be found in the Supporting Information.

2.3. Sample collection

During June, July and August of 2018, 45 homes were visited in St. Joseph County, IN, USA to screen participants' homes for lead exposure risks and observe the use of a "citizen science" lead screening kit. Residents were given the sample kit, Fig. 1, with written instructions contained within, and not provided oral instructions other than to follow the instructions while the research team observed and did *in-situ* testing at the sample site after the participant collected each sample. The kit allows for the collection of three soil samples, two paint samples and three composite dust samples. Prior to kit use, all components of the kit (tape, bags, paper or plastic) were analyzed by XRF to confirm their lead levels were below the detection limit of the XRF.

2.3.1. Soil collection

Soil samples were collected with small plastic spoons and placed into pre-labeled 0.002-inch thick resealable low-density polyethylene bags (Uline S-1291). Kit instructions guided the participants to collect up to three soil samples: one from the dripline of the house, one from the middle of the yard with exposed soil, and one from near the street.

2.3.2. Paint collection

Paint samples were collected with a small piece of index card with a strip of double-sided tape and placed inside pre-labeled 0.002-inch thick resealable low-density polyethylene bags (Uline S-1291). Kit instructions guided the participants to remove the card from the bag, peel the tape backing from the card and apply the exposed sticky tape to a section of wall with paint in poor condition. When a visible paint chip was stuck to the tape, the participant was to place the card back in the bag it came from. Participants collected up to two paint samples: one from the interior of the house and one from the exterior of the house.

Fig. 1. Lead sample collection kit.

2.3.3. Dust collection

Dust wipes were collected with Ghost Wipes (Environmental Express SC4210) which are specially designed for analyzing metals in dust. The kit instructions guided the participants to keep the wipe completely folded upon opening the package and using a small surface area of the wipe to collect the dust. This sampling method was designed in order to collect the dust in a localized area that can be better tested with the XRF which has an approximately 1 cm^2 beam spot. Participants collected up to three dust wipes. The first wipe was used to collect a composite sample of sessile window dust from five windowsills around the house. This yields an overall composite measure of dust from a common source (frictional grinding of leaded paint on window trim). The second wipe was used to collect "old" sessile dust from an area that was rarely cleaned (a hard to reach shelf, the top of a fan, etc), giving information about a longer period of settling and potentially revealing past hazards. The third wipe was used to collect outside sessile dust from a surface on the front porch or the threshold of the house, yielding information about externally derived dust hazards. These screening locations and the composite nature of the dust samples are not meant to isolate the specific locations of hazards, but to determine if any hazards are likely to be present in the home.

2.7. Sampling protocol

The sampling was separated into two categories (Schneyer, 2018): an *in-situ* measurement where a field analyst tested on-site with an X-Ray Fluorescence (XRF) spectrometer, following the participant's sample collection locations as they used the kit and (Goodman et al., 2018) an *ex-situ* measurement where the kit samples were analyzed upon return to the laboratory with XRF by a different analyst. Dust samples did not have an *in-situ* measurement due to the necessity of using a dust wipe to collect the dust sample and thus do not have a corresponding Bland-Altman plot comparing the methods. The *in-situ* and *ex-situ* measurements were blinded (neither analyst knew the result of the other measurement until after the study data collection was done).

2.8. XRF analysis

All samples were analyzed with a handheld SciAps X-100 XRF Spectrometer which was calibrated each day with an alloy cap and regularly checked against a NIST leaded soil standard (NIST SRM 2586, 432 ppm Pb). For all *ex-situ* measurements of the collected samples, the spectrometer was set upright on a benchtop and each sample was placed on top of the device; all samples remained inside the 0.002" thick resealable bags during analysis. For all *in-situ* measurements, the XRF was held directly to the surface being analyzed. All measurements were taken in duplicate. The limit of detection for lead, reported by the SciAps software on this instrument was on average 12 ppm.

2.9. Dust wipe preparation and ICP-OES analysis

During kit development and before the study was initiated, the researchers established a method to test composite dust samples and validate the results. From previously collected samples prior to this study, 148 dust wipes were analyzed with both XRF and Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) and compared. The 1 ft^2 wiped surface area for each dust sample was recorded and the samples were collected without unfolding the dust wipes in order to obtain the most amount of dust o the smallest amount of area to concentrate the dust in an area that could easily be tested by the XRF's 1 cm^2 beam spot. The dirtiest spot of the wipe was first analyzed with XRF. The wipe was then placed in a 50 mL conical tube with 25 mL of 5% nitric acid to prepare for ICP-OES analysis. The tubes were placed on an orbital shaker for 2 h. The resulting liquid was then filtered and analyzed with ICP-OES.

2.10. Data analysis

Bland-Altman plots were created comparing the *in-situ* results to the *ex-situ* results to show the differences between the two sampling methods. To highlight the similarities between *in-situ* and *ex-situ* measurements linear regressions were performed. To convey the specificity (true negative rate), sensitivity (true positive rate), and overall accuracy of the Lead Screening Kit receiver operating characteristic (ROC) curves were utilized comparing the laboratory results to the standard of on-site testing. All analyses were conducted in R version 3.4.1, Microsoft Excel 2016, and MatLab 2018a edition.

3. Results

3.1. Comparison of XRF and ICP-OES analysis of lead in dust

Dust wipes from previous home visits were analyzed with both XRF and ICP-OES. As EPA action levels for lead in dust wipes are regulated in μg/ft^2, ICP-OES is used as the standard measurement method to detect lead in dust. The EPA regulates that lead should not exceed 40 μg/ft^2 on floors or counter surfaces. This level was recently lowered to 10 μg/ft^2 but has not yet taken effect (McClain-Vanderpool, 2019). The XRF and ICP-OES measurements were compared, setting the ICP-OES threshold at 40 μg/ft^2, per EPA recommendation at the time. When the XRF measurement indicated a lead concentration of 50 ppm or larger, the sample was classified as a lead exposure risk. Using this metric, the XRF measurement gave a sensitivity of 94%, a specificity of 83%, and an overall accuracy of 91% when compared to the ICP-OES classifications of the same samples which can be seen in Table 1.

Going forward in this study, XRF was used to measure lead in the dust wipe samples because it requires no sample preparation and less analysis time as compared to ICP-OES. Our goal for the XRF measurement was not to quantify the areal loading of lead (μg/ft^2), which was the outcome of the ICP-OES experiment. Rather, we aimed to decide whether the level of lead in composite dust samples indicated a probable environmental exposure hazard to children in the home.

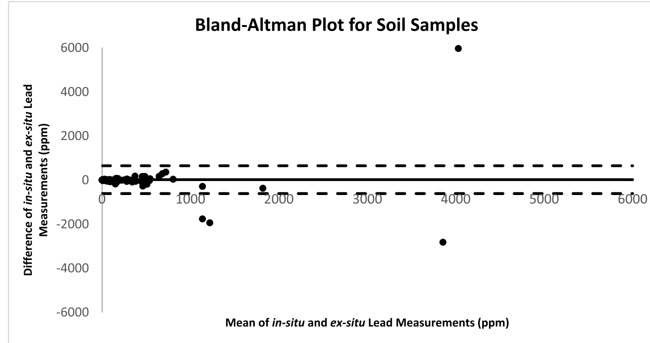

Fig. 2. A Bland-Altman Plot comparing XRF measurements between soil samples measured *in-situ* and *ex-situ*. Bias = −33.3.

3.2. Comparison of in-situ measurements and ex-situ laboratory measurements

To compare the *in-situ* analyses and the *ex-situ* analyses of the collected samples, Bland-Altman plots were made for soil and paint to investigate any discrepancies (Figs. 2 and 3, respectively). Bland-Altman plots are commonly used to visually represent the agreement between two analysis methods. On the x-axis lies the average value of the data points from the two measurements and on the y-axis lies the difference between those values. Ideally, all the points would lie very close to zero on the y-axis showing that there is strong agreement between the two measurements. This type of plot can also be useful in identifying outliers because it highlights when the two methods do not agree. Comparisons of all the *in-situ* and *ex-situ* measurements can all be found in the supplementary information. Ninety-five percent confidence intervals were calculated to highlight any samples that fell outside of a normal distribution. Inconsistencies between methods could imply a degree of instrument error, human error, or, the most probable, sample inhomogeneity. These plots highlight the variability between our lead testing method of utilizing a low-cost citizen science screening kit and an *in-situ* lead measurement. Dust samples did not have an *in-situ* measurement as the dust sample was a composite sample from multiple locations, thus a Bland-Altman plot was not appropriate.

As predicted, the biases in these plots are small, which shows that the average difference between the *in-situ* and *ex-situ* measurements was minimal. After eliminating the samples in each case that fell outside of the 95% confidence intervals (the dashed lines on the plots), scatter plots comparing the *in-situ* and *ex-situ* measurements for the soil and paint were made (Figs. 4 and 5, respectively). The outliers in these plots are likely caused by the inhomogeneity of those particular samples.

For linear regression plots, an R^2 value close to 1 indicates a strong linear trend in the data, and a slope close to 1 indicates similar results between the two methods. The correlation coefficient of 0.93 and the

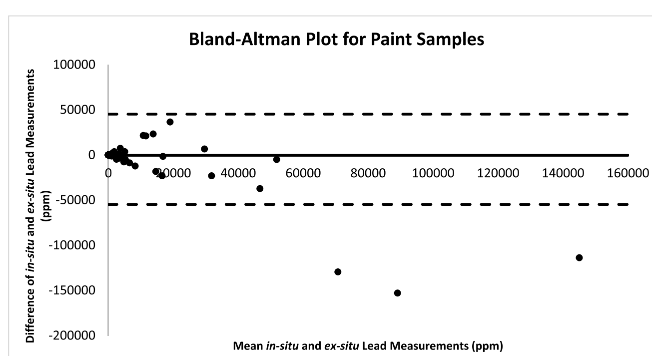

Fig. 3. A Bland-Altman Plot comparing XRF measurements between paint samples measured *in-situ* and *ex-situ*. Bias = −307.8.

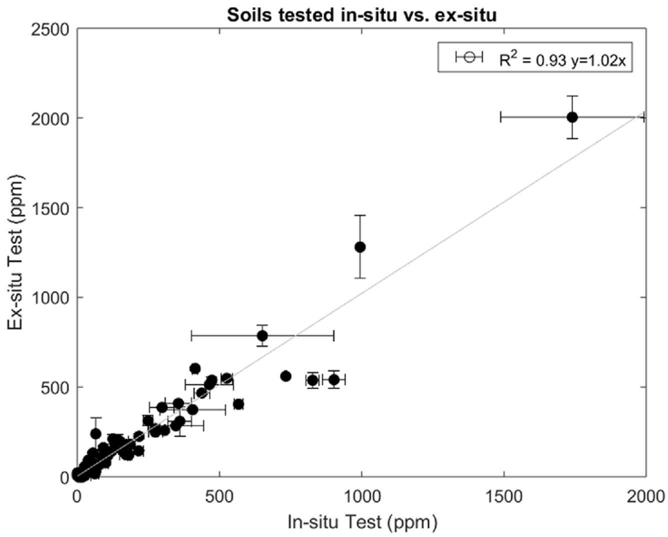

Fig. 4. Scatter plot with linear regression comparing XRF measurements between soil samples measured *in-situ* and *ex-situ*. N = 132.

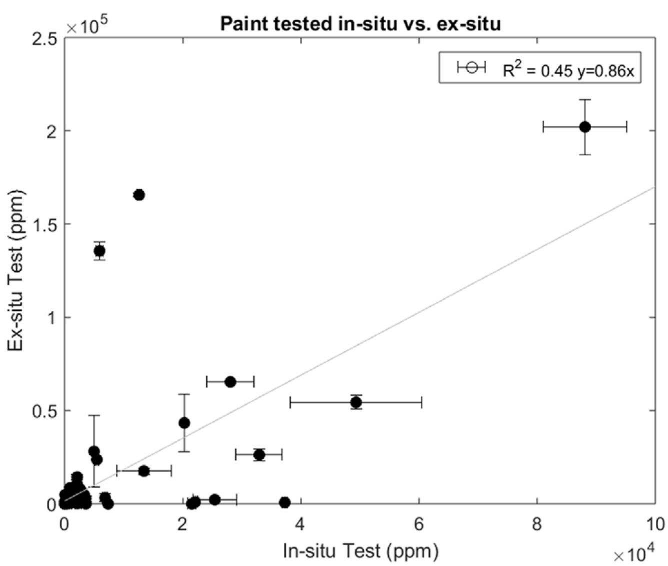

Fig. 5. Scatter plot with linear regression comparing XRF measurements between paint samples measured *in-situ* and *ex-situ*. N = 87.

slope of 1.02 for the soil samples shows there is a strong correlation and match in concentration between measurement methods between the *in-situ* and *ex-situ* measurements.

For the paint samples, however, the *in-situ* and *ex-situ* measurements showed poor agreement with a R^2 value of only 0.45. The large discrepancy can be attributed to the sample collection method. Participants used a small paper card with double-sided tape attached, peeled off the backing of the double-sided tape, and placed the sticky side of the tape to their wall to obtain a small portion of paint to send back with the kit. This method exposes the underside of the paint allowing the lab to test the previously unexposed portion of the paint chip, unlike the *in-situ* measurement which tests the exposed side of the paint while still attached to the wall. This can lead to a significant measurement discrepancy if the outermost layer of paint was not leaded, but the underside was lead-based paint, which can lead to the lab measurement being higher than the *in-situ* measurement. Conversely, if the tape retrieves only a very small paint chip, or an oddly shaped paint chip, that does not encompass the whole beam area (approximately 1 cm^2), the lab measurement may be lower than the *in-situ* measurement where the entire beam-spot was covered by leaded paint instead of only a fraction of the beam-spot. This issue will be remediated by requiring participants to obtain larger paint chips that fulfill the 1 cm^2 beam-spot size requirement and if not will be reported as non-sufficient sample.

Based on the categories specified in Table 2, adapted from EPA recommendations, only 3.6% of soil samples did not agree. The portion of soil samples that were misclassified can be attributed to sample inhomogeneity and collection location. Nearly all the samples that were misclassified were highly leaded; the samples were categorized as either (a) 2000 ppm–5000 ppm or (b) > 5000 ppm. Given all the misclassified soil samples were collected from the dripline, this suggests solid lead may be mixed into the soil (*i.e.* a solid paint chip falling from the side of the house). Although misclassification occurred between the two categories, the recommendation to the participant was the same.

Based on the categories specified in Table 2 for paint, either greater than 5000 ppm or less than 5000 ppm, 13.0% of paint samples fell into different categories based on the *in-situ* vs *ex-situ* measurements. There were also 2 paint samples that gave false negatives by failing to show any lead in the *ex-situ* readings, where the *in-situ* measurement had shown greater than 5000 ppm lead. In both cases this was attributed to a sampling error because the participants returned the sampling card without a visible paint chip attached. In the future this should be reported as insufficient sample in the final report. The remaining categorization discrepancies between *in-situ* paint measurements and *ex-situ* measurements can likely be attributed to which side of the paint chip was analyzed as discussed previously.

To accommodate the lack of an *in-situ* reading for dust, the field analyst tested by XRF each dust sample immediately after collection by the homeowner. Comparing this measurement to the standard laboratory *ex-situ* measurement only 2.2% of dust samples fell into the different categories of less than or greater than 50 ppm.

Overall, using the *in-situ* XRF measurement as the "standard" for soil and paint, and the field analyst's in-home XRF measurement as the "standard" for dust, it was found that the kit presented a sensitivity of 87%, a specificity of 98% and accuracy of 96%. The sensitivity is the percentage leaded of samples correctly identified as leaded, specificity is the percentage of non-leaded samples correctly identified as non-leaded, and accuracy is the percentage of all samples that were correctly categorized as leaded or non-leaded. These results can be seen in Table 3.

3.3. *Age of home as a predictor for lead*

The age of the home was found to be a strong predictor for the presence of environmental lead in the home. Of the 45 homes tested, 17 were built prior to 1950, 11 were built between 1950 and 1978 and 17 were built after 1978. Of homes built prior to 1950, 100% had multiple samples with elevated lead levels. Of homes built between 1950 and 1978, 45% had at least one sample with an elevated lead level. Of homes built after 1978, 0% had a sample with an elevated lead level. Furthermore, of all the paint samples that had over 5000 ppm lead, 73% were from the exterior of the home which suggests less regular painting upkeep on the exterior of the homes compared to the interior of the homes. It was also found that of all the soil samples that had over 400 ppm lead, 79% were from the dripline of the house. Unsurprisingly,

Table 3
Sensitivity, specificity and accuracy of kit to detect lead in soil, paint and dust.

Sample Type	Sensitivity	Specificity	Accuracy
Soil	100%	98%	99%
Paint	69%	95%	90%
Dust	92%	99%	98%
Overall	87%	98%	96%

of all the addresses that showed elevated exterior paint, two thirds also showed elevated dripline soils suggesting that much of the elevated lead levels in the soils comes from leaded exterior paint in St. Joseph County. However, it is still important to consider multiple sources of lead in soils, like legacy leaded gasoline; it is just indicative that exterior leaded paint is the largest contributor of lead in dripline soils.

4. Discussion

As presented in Table 3, these results suggest the kit is a reliable screening tool to detect lead hazards in the home when in fact lead is present in the home. The implications of this research are significant and far-reaching. First, as discussed, there are few options available to families to test their home environment for lead which are affordable and readily available. Additionally, EPA recognized DIY test kits focus on the absence or presence of lead in paint only, and for a few kits, the paint tested must be of light color for the test to work. The lead screening kit described here costs about $10 to manufacture, the majority of which can be re-used multiple times, and includes quantitative results for paint (any color), soil, and dust. Additionally, due to the minimal sample preparation and fast analysis time, the full cost of the kit is still under $20 for all supplies, transportation, and analysis.

Second, the kit may provide a way to prioritize homes that should receive a Home Lead Risk Assessment. At present, the St. Joseph County Health Department (SJCHD) conducts a Home Lead Risk Assessment when case management is initiated or if a parental request is made. The risk assessment is conducted by a certified Lead Risk Assessor employed by the SJCHD. Risk assessments adhere to EPA guidelines, are labor intensive and often, there is a backlog of requests. As a result of our research and findings, SJCHD has agreed to allow participants who present with an elevated kit result to be prioritized for a risk assessment. Consequently, the screening kit allows SJCHD to effectively allocate their limited resources to serve those with a demonstrated risk first. This model could be implemented elsewhere and could improve the reach and resource utilization of underfunded health departments.

Third, the kit has the potential to significantly improve reach and prevention of lead poisoning in children. There are nearly 68,000 homes built before 1978 in Saint Joseph County (Dickman, 2017). Given the labor-intensive nature of the SJCHD's risk assessment (approximately 6 person hours are required per home to collect samples and write reports), 408,000 h or over 200 person-years would be necessary to test all homes for environmental lead hazards. Given these parameters and shrinking health department budgets, we arrive at the *status quo*, in which the vast majority of homes remain untested. An alternative method could be to distribute these screening kits to residents directly, which would engage families in the process of testing their homes. Analysis would still be done by trained personnel and automated XRF systems in a centralized location, but these tools exist and could be adapted to address the environmental lead problems in this county.

It must be noted that the regulatory levels were set at a time when blood lead levels of 25 μg/dL or 10 μg/dL were the guidelines for excessive lead exposure; they may be reduced in future from the current 5 μg/dL recommended by the CDC (CDC, 2019), because the level of concern for lead poisoning has increased. The regulatory limit for lead in dust has also since been reduced from 40 $\mu g/ft^2$ to 10 $\mu g/ft^2$ and the kit report will be adjusted to match updated regulatory limits. While it is commendable that the actionable levels for blood lead and dust have been reduced, it is also important to note that the regulatory limits for soils have not changed, as soils are still a major contributor to elevated BLLs. Even if the regulations for elevated BLLs are lowered, overall BLLs cannot be expected to decrease if actionable lead levels for housing through paint, dust, and soils are not similarly decreased and enforced.

While the kit, due to sampling limitations, is not perfect at replicating exact lead concentrations in paint, it is reliable at screening whether leaded paint is present or absent. This by itself is useful, since paint is usually the largest environmental lead contributor in homes in St. Joseph County. The kit is very reliable at detecting dangerously high lead concentrations in soil and house dust. This is critical since soil and dust are the larger sources of lead exposure through accidental ingestion than painted walls in good condition.

The Lead Screening Kit has the potential to significantly change the way we identify environmental lead thereby preventing exposure. The kit provides a method for parents to initiate and engage in primary prevention of lead poisoning. After decades of using a child's elevated blood result to find environmental lead, the kit provides a more humane, proactive, and effective way to identify lead hazards before children are exposed.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envres.2019.108892.

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