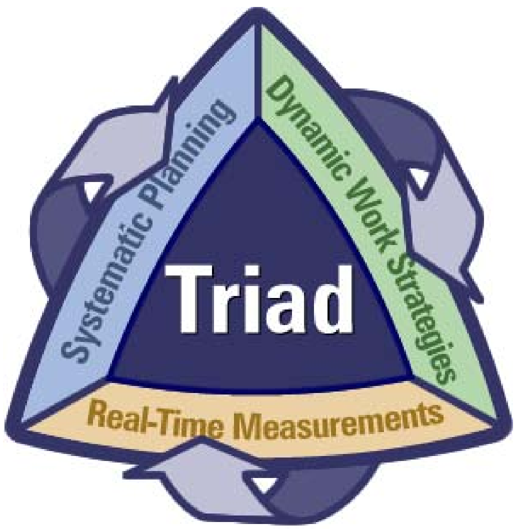
Sampling Design
Avoiding Pitfalls in Environmental Sampling

Part 1



Part of U.S. Environmental Protection Agency Technical Sessions

- **Employing Best Management and Technical Practices in Site Cleanup Programs**
  - » Introduction to the Tools and Mechanics of Systematic Planning
  - » Demonstration of Method Applicability and QC for XRF
  - » Green Remediation
  - » Critical Role of Data Management
  - » Best Management Practices: Conceptual Site Models
  - » Best Management Practices: Dynamic Work Strategies
  - » (EU Panel) Systematic planning, dynamic work plans, and real-time measurement techniques (the Triad) can help clarify and strengthen statistical analyses

U.S. EPA Technical Session Agenda

- Welcome
- Understanding: Where does decision uncertainty come from?
- Criteria: You can't find the answer if you don't know the question!
- Pitfalls: How to lie (or at least be completely wrong) with statistics…

- Solution Options: Truth serum for environmental decision-making

Understanding:
Where Does Decision Uncertainty Come From?

"Doubt is not a pleasant condition, but certainty is absurd."

Voltaire, humanist, rationalist, & satirist

(1694 - 1778)

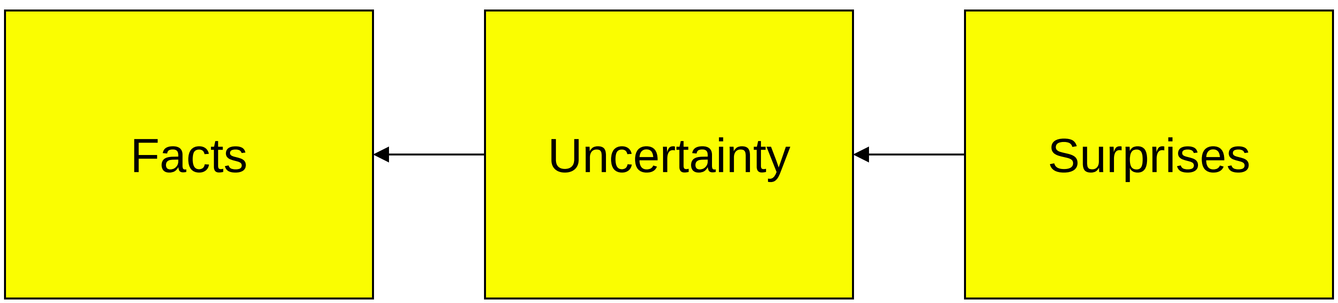
Common Questions Statistics Are Used to Address

- Does a site pose unacceptable human health risks?
- How much contaminated soil volume is there?
- Do our sample results differ from background?
- What risks do our sample results represent?
- How much contamination is present?
- Do our sample results meet cleanup goals?

"As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know."

Donald Rumsfeld, February 12, 2002,

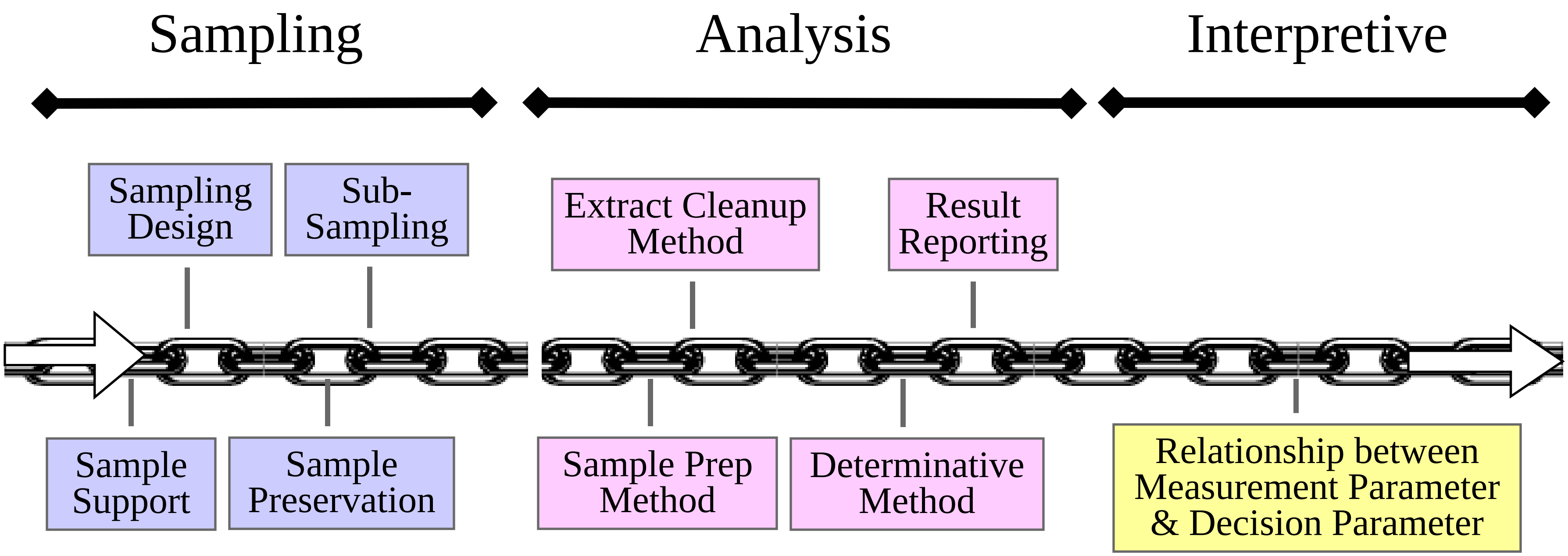
U.S. Department of Defense news briefing



Decision Uncertainty Comes from a Variety of Sources

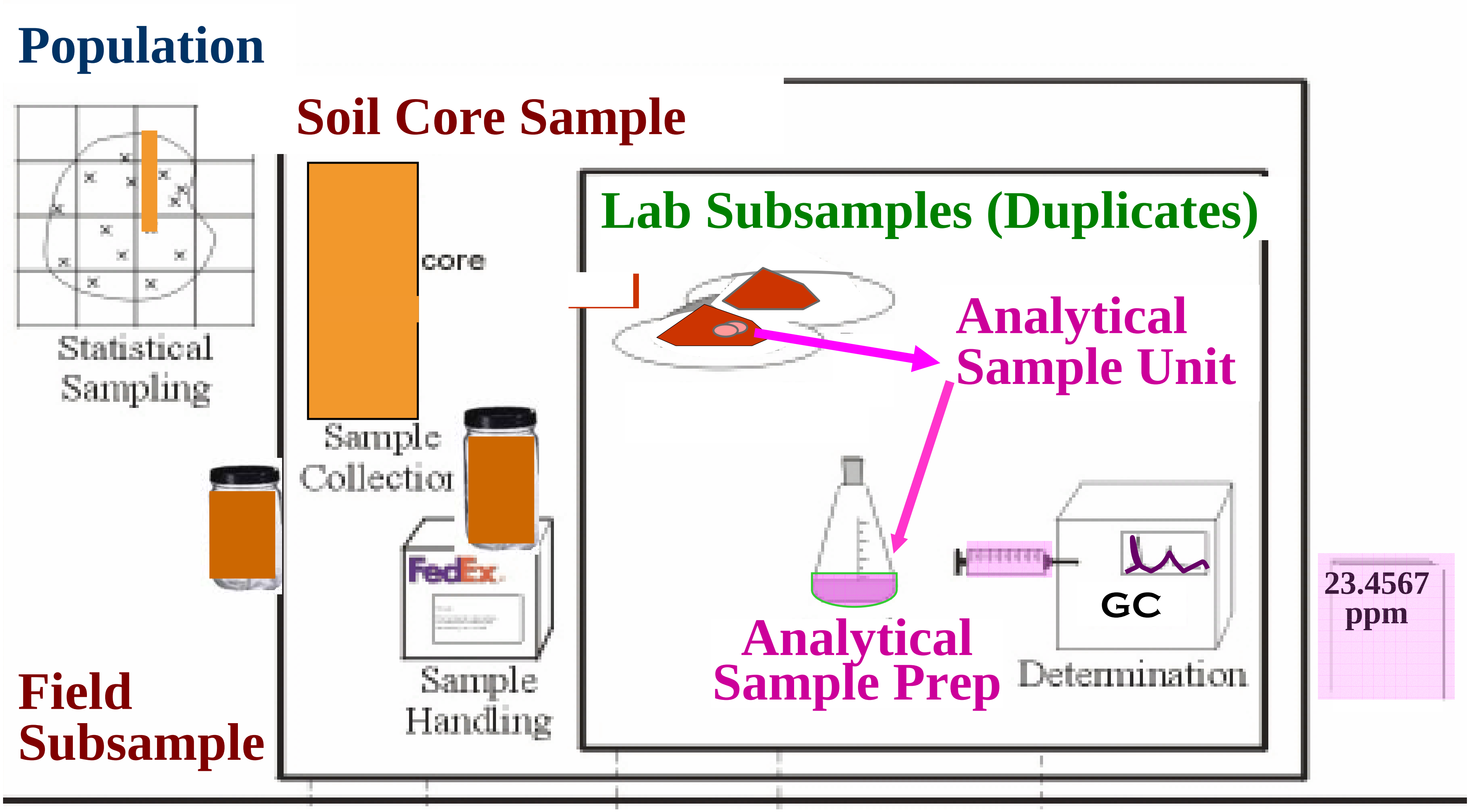
- Political, economic, organizational, and social uncertainty (outside scope).
- Model uncertainty (also outside scope).
- Data uncertainty: the uncertainty introduced into decision-making by uncertainty associated with data sets used to support decisions***…where statistics play a role.***

Decision Quality Only as Good as the Weakest Link in the Data Quality Chain



Each link represents a **variable** contributing toward the quality of the analytical result. All links in the **data quality chain** must be intact for data to be of decision-making quality!

Taking a Sample for Analysis



Historically Focus Has Been Analytical Quality

- Emphasis on fixed laboratory analyses following well-defined protocols
- Analytical costs driven to a large degree by QA/QC requirements
- Result:
  - » Analytical error typically on order of 30% for replicate analyses
  - » Traditional laboratory data treated as "definitive"…but definitive about what?

Within-Sample Variability: Interaction between Contaminant & Matrix Materials

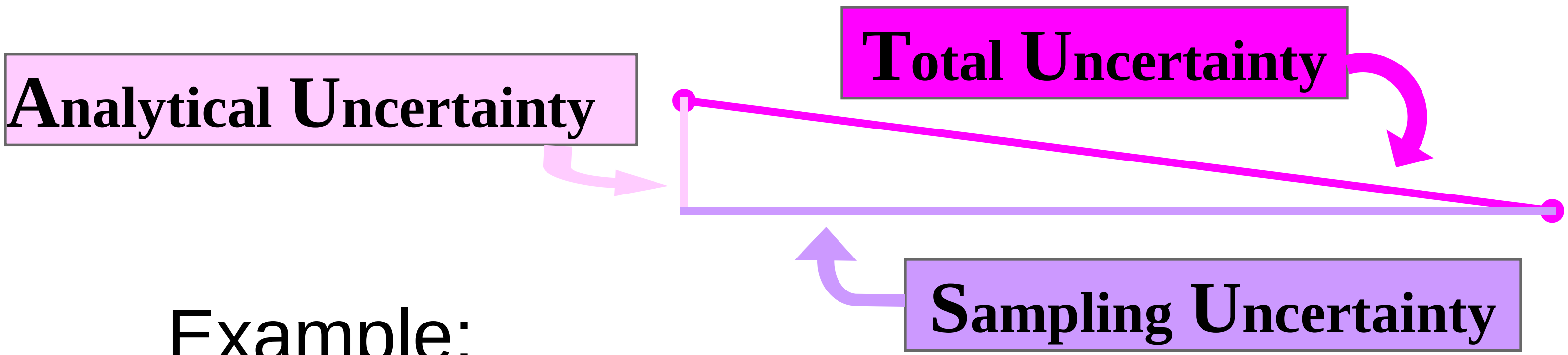
Firing Range Soil Grain Size (Std Sieve Mesh Size)	Pb Concentration in fraction by AA (mg/kg)
Greater than 3/8” (0.375”)	**10**
Between 3/8 and 4-mesh”	**50**
Between 4- and 10-mesh	**108**
Between 10- and 50-mesh	**165**
Between 50- and 200-mesh	**836**
Less than 200-mesh	**1,970**
Bulk Total	**927 (wt-averaged)**

Adapted from ITRC (2003)

The decision determines representativeness

Uncertainty Math Magnifies Weakest Link's Effects in Data Quality Chain

Uncertainties add according to ($a^2 + b^2 = c^2$)



<u>Example</u>:

- AU = 10 ppm, SU = 80 ppm: **TU = 81 ppm**
- AU = 5 ppm, SU = 80 ppm: **TU = 80 ppm**
- AU = 10 ppm, SU = 40 ppm: **TU = 41 ppm**
- AU = 20 ppm, SU = 40 ppm: **TU = 45 ppm**

How Do We Reduce Data Uncertainty?

- For analytical errors:
  - » Switch to a better analytical technique
  - » Improve QC on existing techniques
- For sample prep and handling errors:
  - » Improve sample preparation
- For sampling errors:
  - » Collect samples from more locations

Criteria:

You can't find the answer if you don't know the question!

Sometimes the Simplest Questions are the Most Complex…

» Does this site pose an unacceptable risk?

» Do ground water concentrations exceed drinking water standards?

» Do soil concentrations exceed cleanup requirements?

For Soils, Three Cleanup Requirement Definitions are Most Common:

- Never-to-Exceed Criteria: "Lead concentrations cannot be > 400 ppm"
- Hot-Spot Criteria: "Lead concentrations cannot be > 400 ppm averaged over 100 m^2"
- Averaged Criteria: "The average concentration of lead over an exposure unit cannot be > 400 ppm"

The Decision Unit is Often **Not** Well-Defined

"Lead should not exceed 400 ppm in soils"

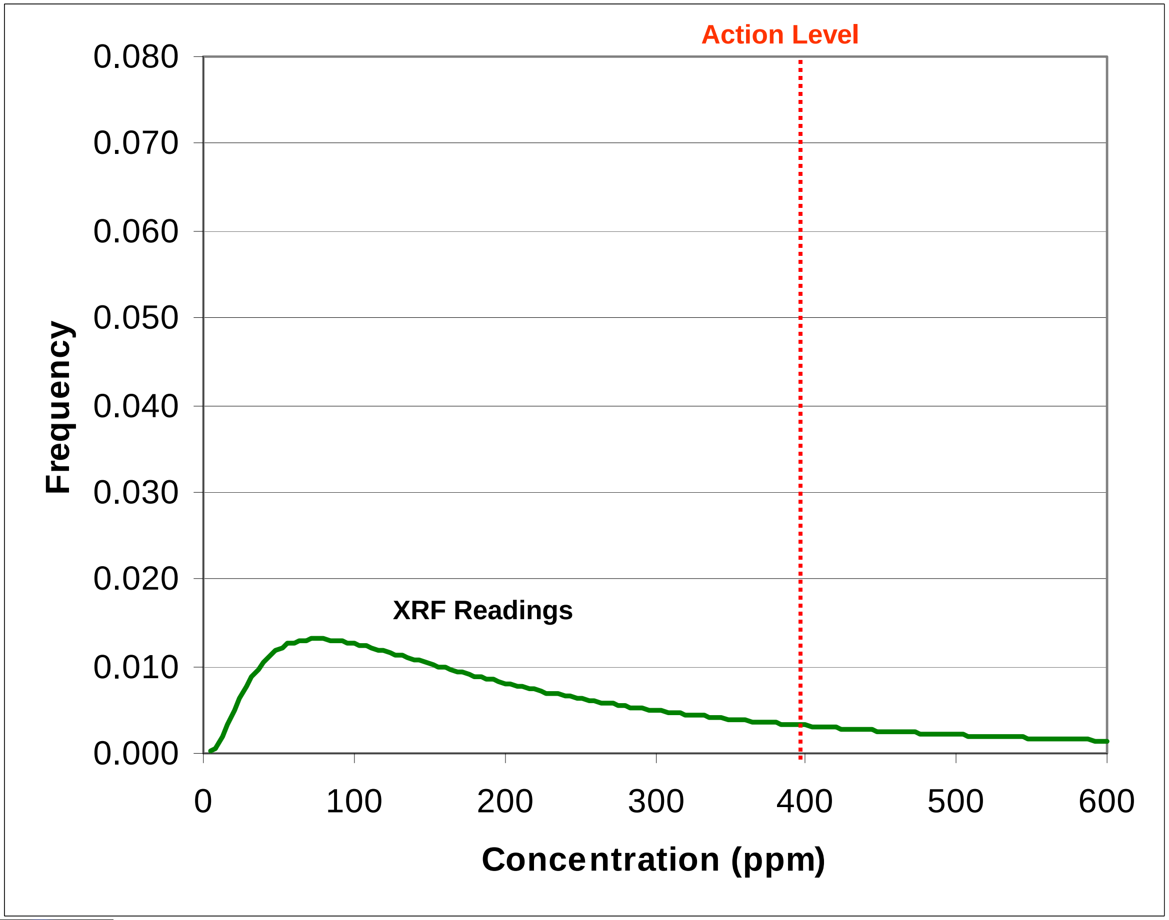
or

"TCE should not exceed 5 ppb in ground water"

Decisions are often ambiguous because cleanup criteria do not provide enough information to define the decision units.

Advances in Sampling & Measurement Technologies Highlight

Representativeness Issues

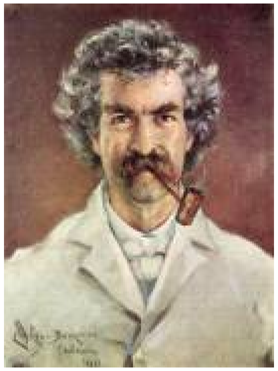


Pitfalls:
How to Lie (or at least be completely wrong) with Statistics

"He uses statistics like a drunk uses a lamp post….for support rather than illumination"

Mark Twain

1835-1910



Tools in Your Statistical Deception Arsenal

1. Obscure the question…
2. The representative sample that isn't…
3. Pretend the world is normal…
4. Assume we know when we don't…
5. Ignore short-scale heterogeneity…
6. Miss the forest because of the trees…
7. Regress instead of progress…
8. Statistical dilution is the solution…
9. Worship the laboratory…

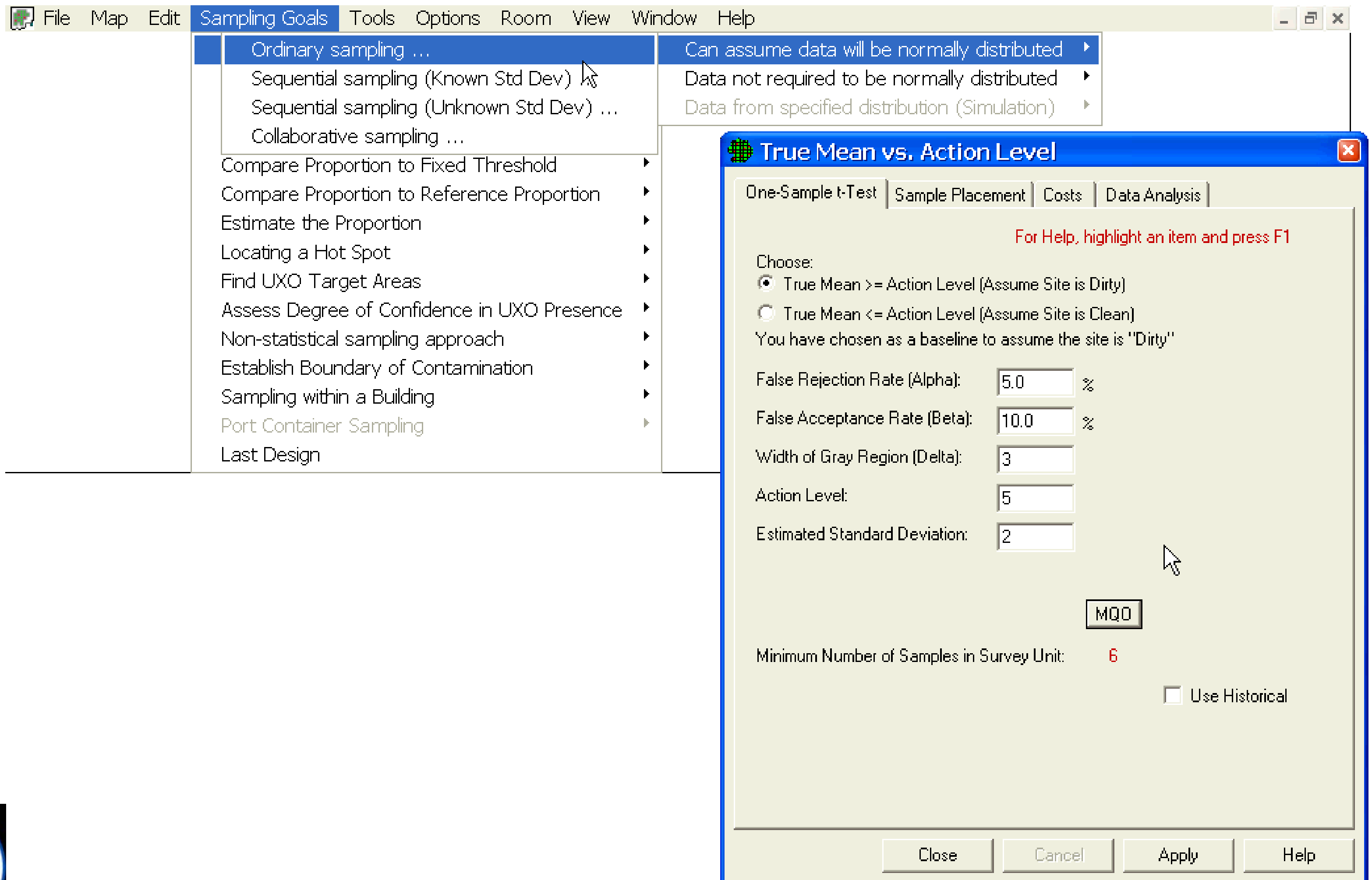
1. Obscure the Question

- Vague cleanup definitions and unclear decision statements will obscure the question:

Total PCB < 5 ppm

- Trying to hide contamination?
  - » Increase sample support/cut sample numbers!
- Trying to show contamination?
  - » Shrink sample support/increase sampling density!
- No technical basis for deriving sample numbers for this kind of question.

Statistical Packages Can Give an Aura of Defensibility…

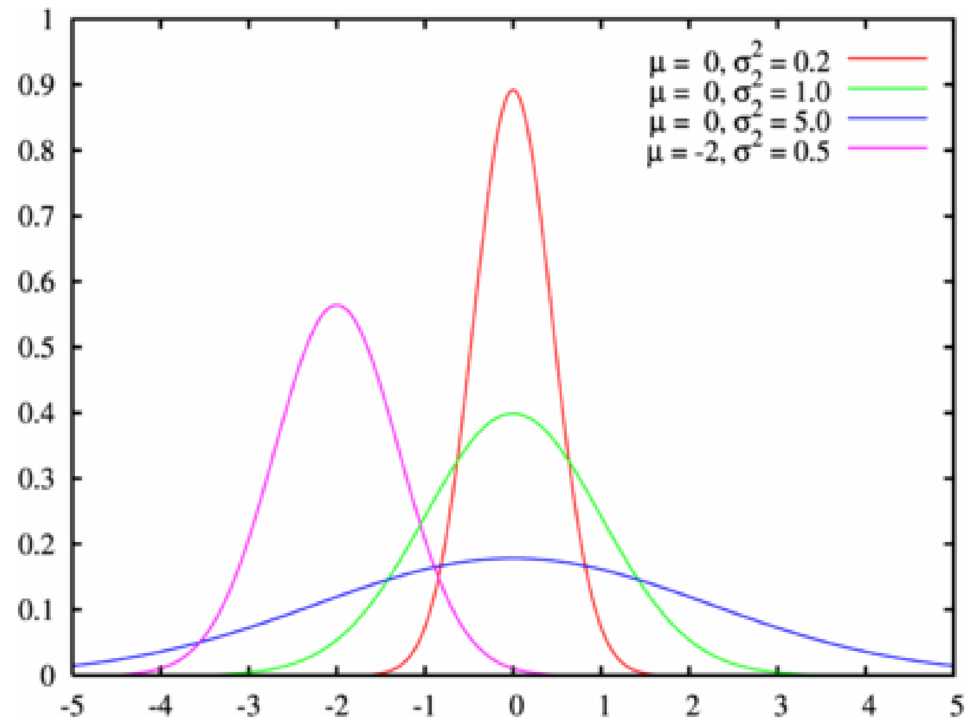


2. The Representative Sample that Isn't

- Mislead by feeding non-representative samples into statistical analyses:
  - » Select a non-representative vertical sampling interval
  - » Use spatially clustered locations or biased samples when calculating average concentrations
  - » Mis-match sample support with cleanup criteria

3. Pretend the World is Normal

- Normal is Nice!
- Normal distributions make statistics easy
- Can ignore complexities of spatial & non-random relationships
- Many common statistical tests (typical UCL calculation, Student t test, etc.) assume normality



Assuming Normality Can Under-estimate the 95% UCL on the Mean

- 4 lab lead results: 20, 24, 86, and 189 ppm
- Average of the 4 results: 80 ppm
- ProUCL 95%UCL calculation on the 80 ppm average:
  - » Normal distribution 95% UCL: 172 ppm
  - » Gamma distribution: 434 ppm
  - » Lognormal distribution: 246 – 33,835 ppm
  - » Non-parametric distribution: 144 – 472 ppm

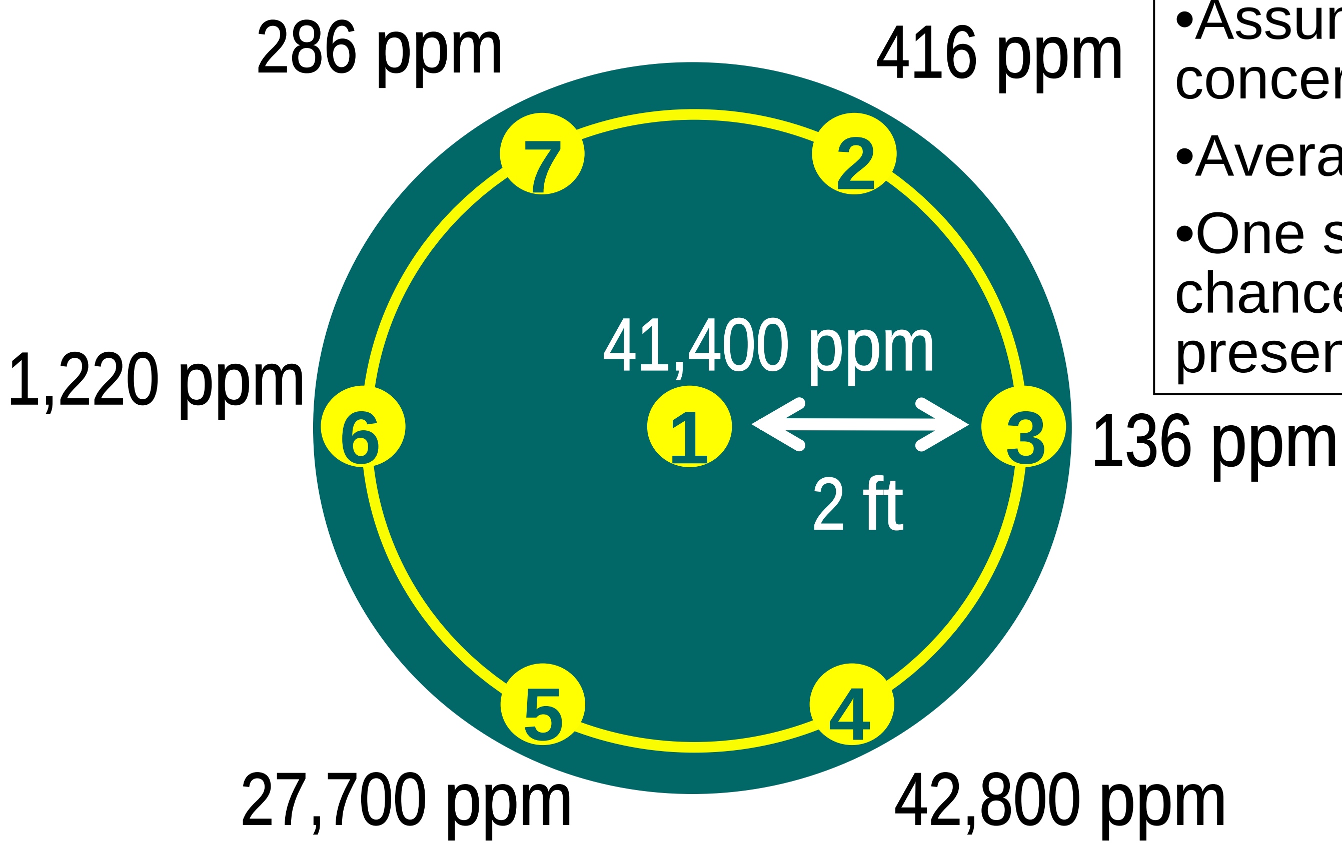
4. Assume We Know When We Don't

- A key question in the design of statistically-based sampling programs is: How many samples do we need?
- Information required when calculating sample numbers to determine if mean is above or below a threshold:
  - »Variability that will be present
  - »Gray region definition
  - »Underlying contaminant distribution

5. Ignore Short-Scale Heterogeneity

- Short-scale heterogeneity refers to variations in contaminant concentrations within a small radius (few feet to few yards)
- Assume discrete sample result from an area is "representative" of its immediate surroundings
- Particularly useful if we want to miss localized contamination
- Increases the chance that "hot spots" will be missed!

In Reality, It May Look Like This…



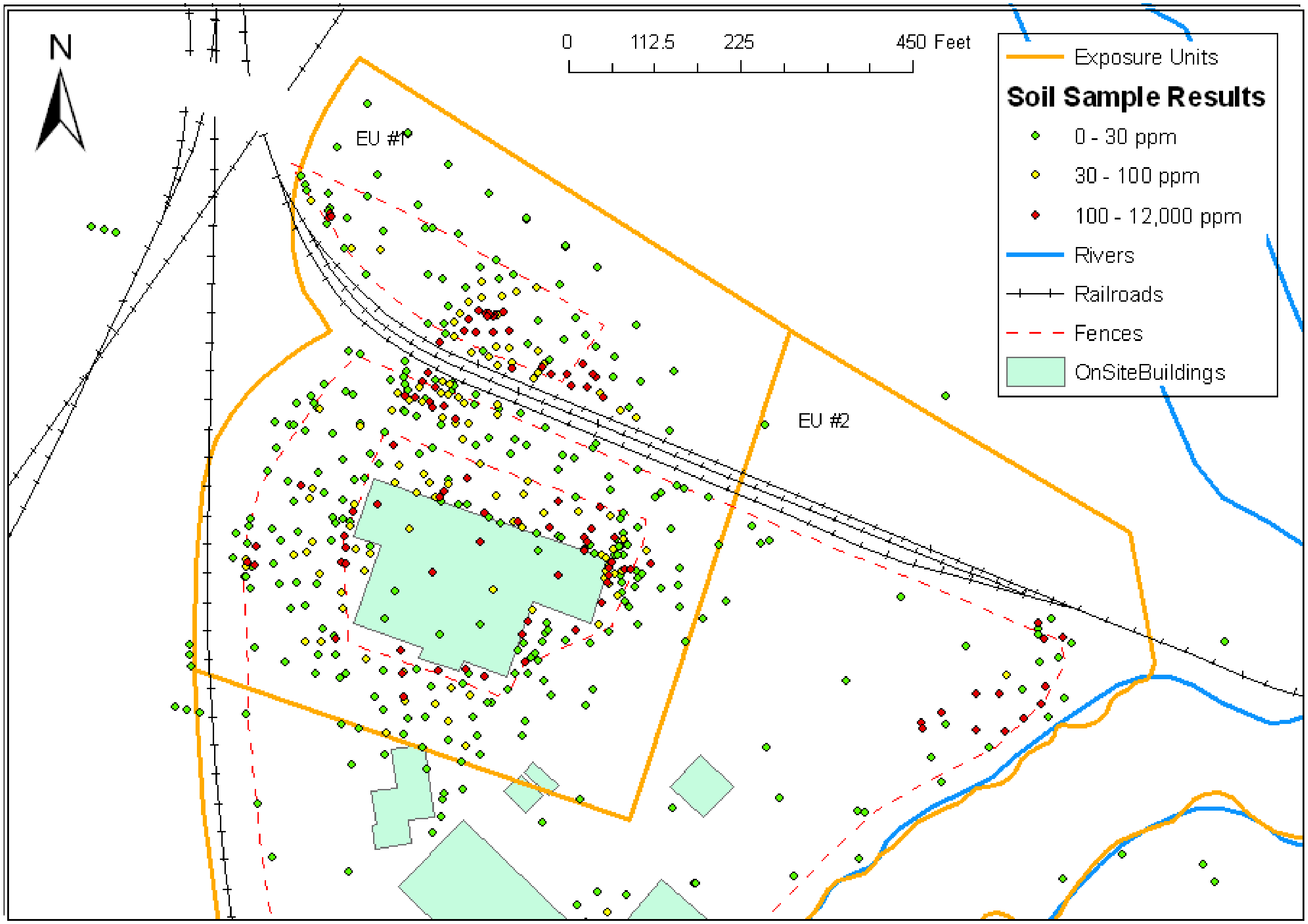
- Assume level of concern: 1,000 ppm
- Average: 16,280 ppm
- One sample has a 43% chance of missing the presence of a hot spot

Figure adapted from Jenkins (CRREL), 1996

6. Miss the Forest Because of the Trees

- Base decisions on only handful of laboratory results plus statistical analysis of those results
- Under-invest in collecting other forms of pertinent information (CSM and weight-of-evidence lacking)
- Use statistical tests to remove "outliers" from the data set
  - » Actual outliers can be very important - you may be discarding evidence telling you <u>the CSM is wrong</u>
- Reject field techniques that may be cheaper and build accurate CSM, but are not traditional and may have lower analytical quality and different QC

Data Only Become Meaningful When Site Information is Viewed Holistically

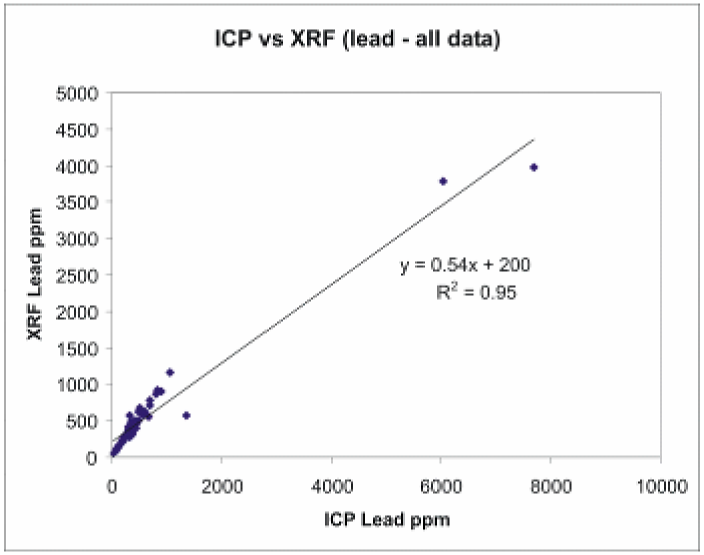


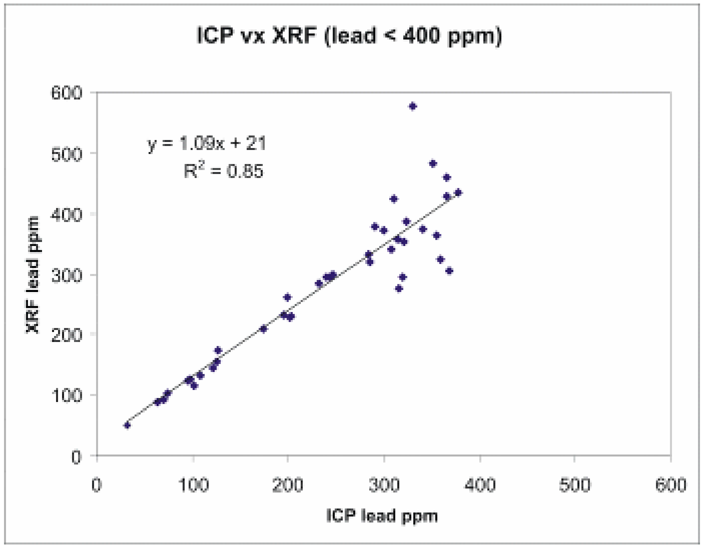
7. Regress Instead of Progress

- Require numerical regression comparability between paired field analytic and lab data. Hold field data to a higher standard than lab data.
  - » Reject the field data if R^2 not “good enough,” even when ***lab*** duplicates show same or worse comparability ***to each other***
  - » Pretend that 2 different labs could pass the regression test
  - » Ignore field analytics QC in project design and in data review
- Base data comparability on regression’s R^2, ignoring better regression indicators, such as slope and intercept.
- Include <u>all</u> paired data in the regression (ignoring artifacts at concentration extremes and relevance to decision-making).
- Pretend that quantitative comparability is required for the decision, even when it is not.

Example: XRF and Lead

- Full data set:
  - » Wonderful R^2
  - » Unbalanced data
  - » Correlated residuals
  - » Apparently poor calibration
- Trimmed data set:
  - » Balanced data
  - » Correlation gone from residuals
  - » Excellent calibration
  - » R^2 drops significantly

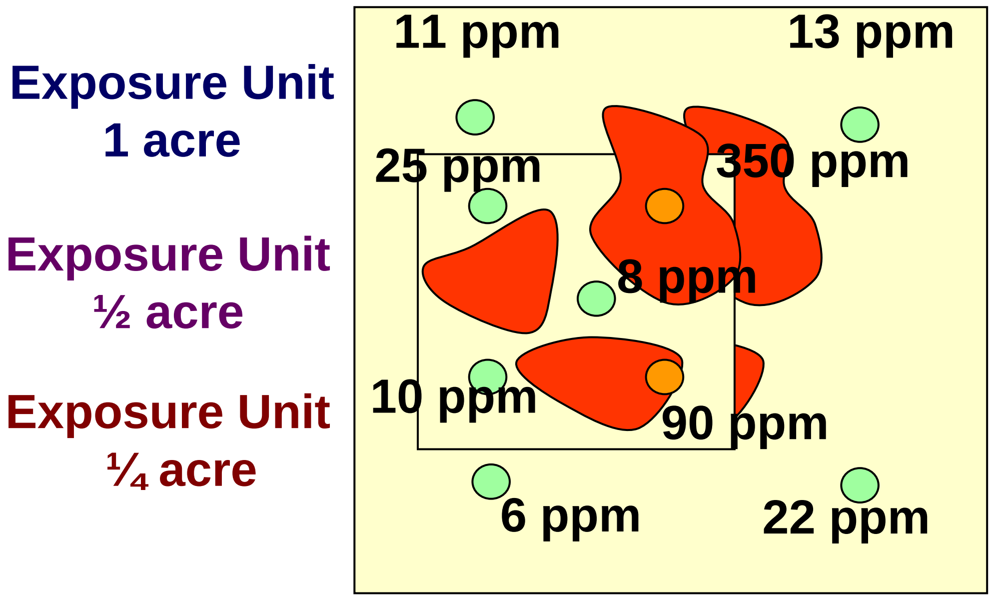




8. Statistical Dilution is the Solution

- Common **error of statistics users**: calculate sample numbers (n) using an averaging program, but then compare each individual sample result to the action level (a do-not-exceed decision), rather than compare data set's average
- **Statistics software users** routinely use software without realizing the statistical calculations do not take area size into account when predicting n.
  - » When designing investigations, using inappropriately large decision units dilutes sample density (fails to predict enough samples per unit area), making it less likely to find contamination
  - » When analyzing data, using large decision units will dilute averages and potentially dilute standard deviation estimates (artificially lowering the 95% UCL)

An Example of the Dilution Effect...



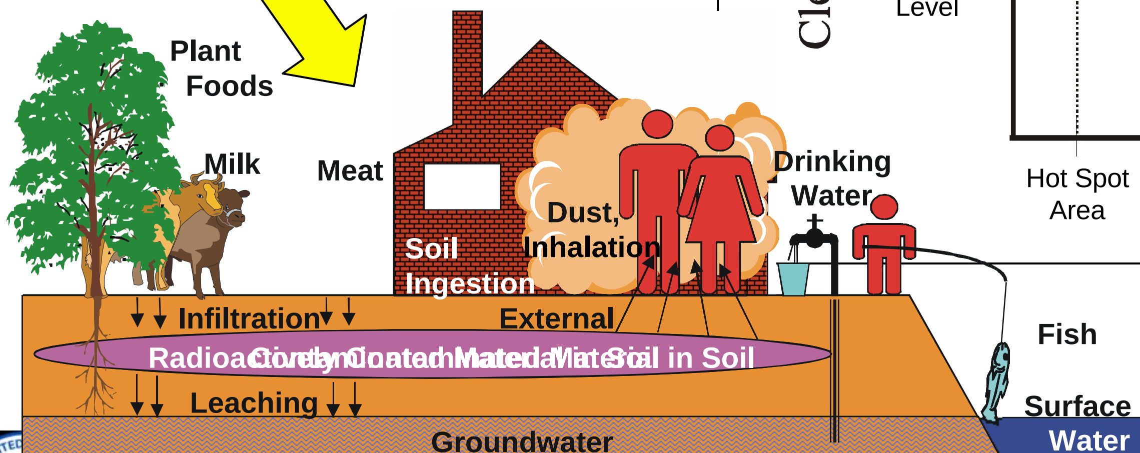
EU Area: ¼ **acre**
Average: 97 ppm
St Dev: 146 ppm

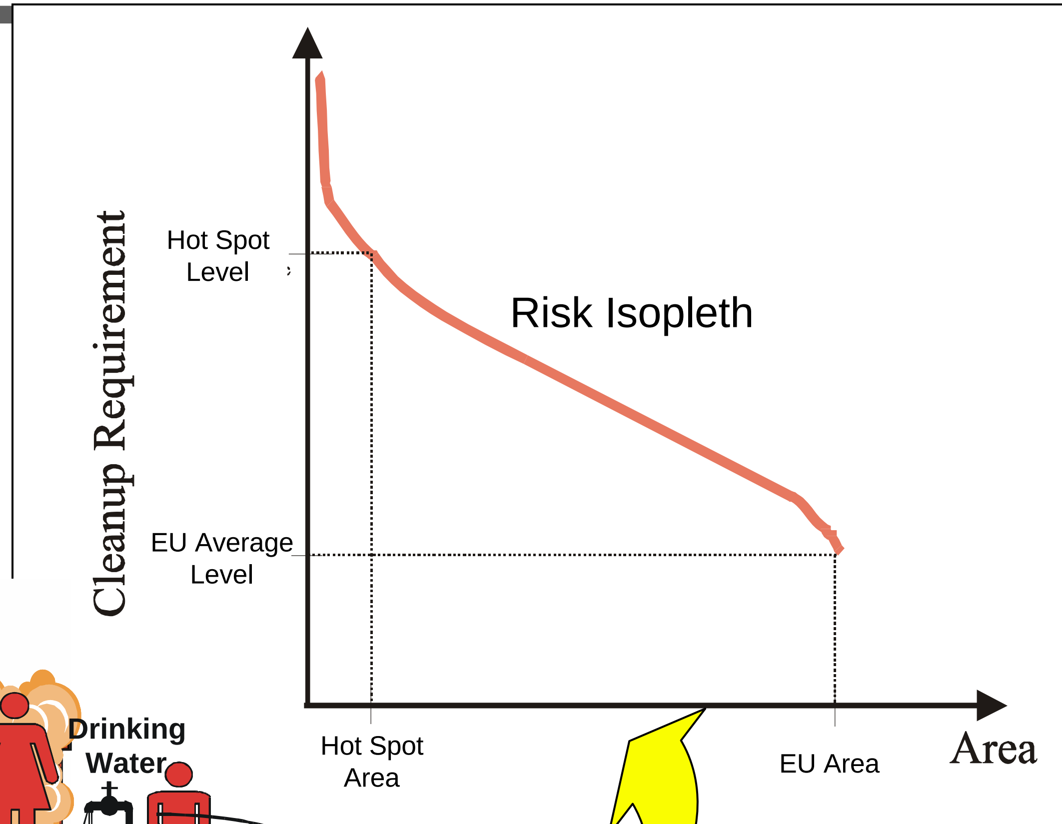
EU Area: ½ **acre**
Average: 57 ppm
St Dev: 102 ppm

EU Area: **1 acre**
Average: 12 ppm
St Dev: 6 ppm

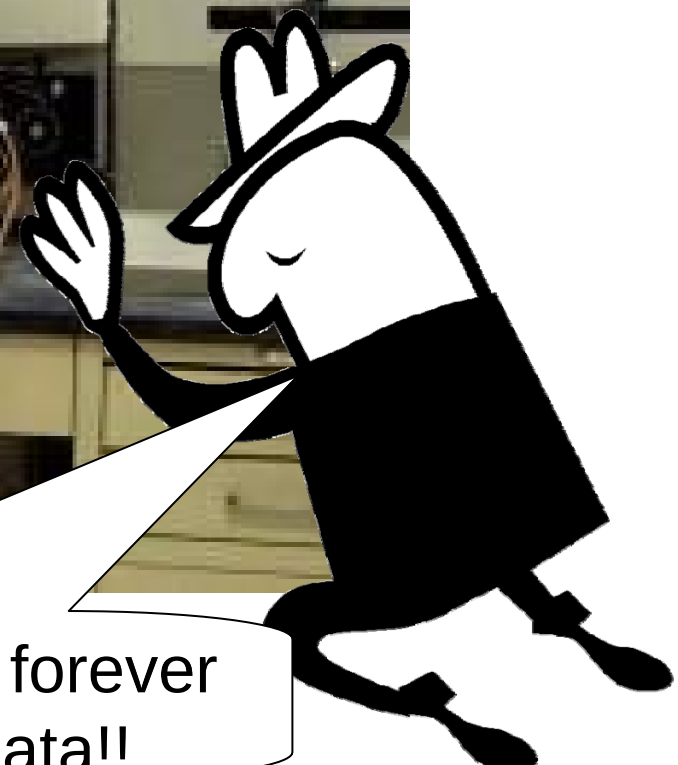
The Real Issue is That Exposure Unit Size & Cleanup Requirement Should be Linked

Site Specific Risk or Dose-Based Requirements





9. Worship the Laboratory



Assume the Lab is Infallible

- Focus on laboratories' analytical data quality and assume laboratory data has no error
  - » Assumed corollary: a few expensive lab results are much better than a bunch of cheaper field results
- Base decisions strictly on a handful (since that's all we can afford) of "definitive" expensive laboratory results

Triad Data Collection Design and Analysis Built On:

- **Planning systematically** (CSM)
- **Improving representativeness**
- **Increasing information** available for decision-making via real-time methods
- **Addressing the unknown** with dynamic work strategies