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The Environmental Science Education for Sustainable Human Health

in commemoration of Professor Armen Saghatelyan

6 – 13 September 2021

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Environmental Monitoring

Sampling Strategies, Sampling Design and Procedures

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“Environmental Monitoring and Measurement Devises” curriculum for Environmental Protection and Nature Management profession

This curriculum modernized by Dr. O. Belyaeva, Dr. C. Baldacchini and Dr. F.P. Carvalho

4 ESTC, 120 Hours

The overall **goal** of the curriculum is to develop students' knowledge about modern environmental monitoring programs, main analytical methods, familiarize with some field and laboratory devices and develop the ability to assess environmental pollution levels.

Topics of “Environmental Monitoring and Measurement Devises” curriculum

- Introduction
- Sampling in environmental monitoring
- Analytical provision of environmental monitoring
- Baseline monitoring
- Monitoring near-surface air quality
- Monitoring surface water
- Bottom/bed sediments and soils in environmental monitoring
- Biomonitoring and bioindicators
- Data treatment in environmental monitoring

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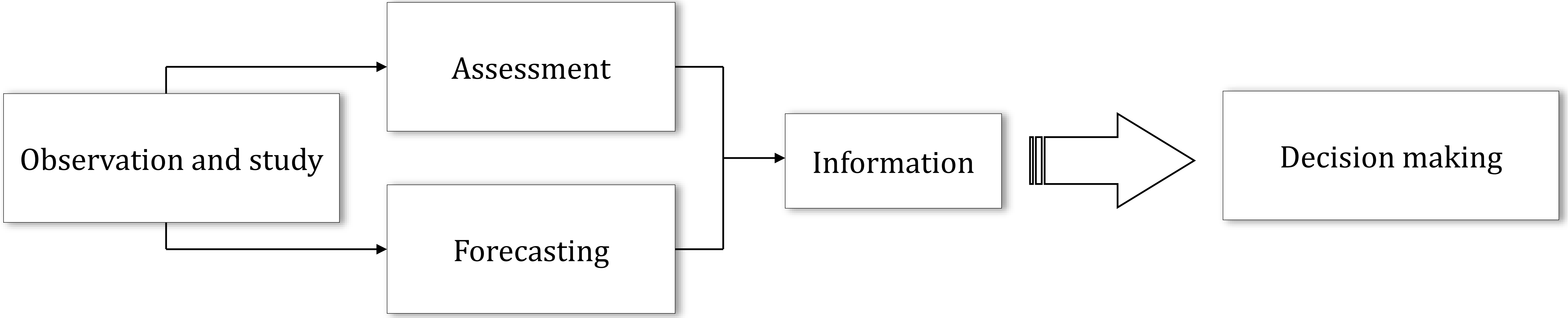
Environmental monitoring is the observation and study of the environment

Environmental monitoring



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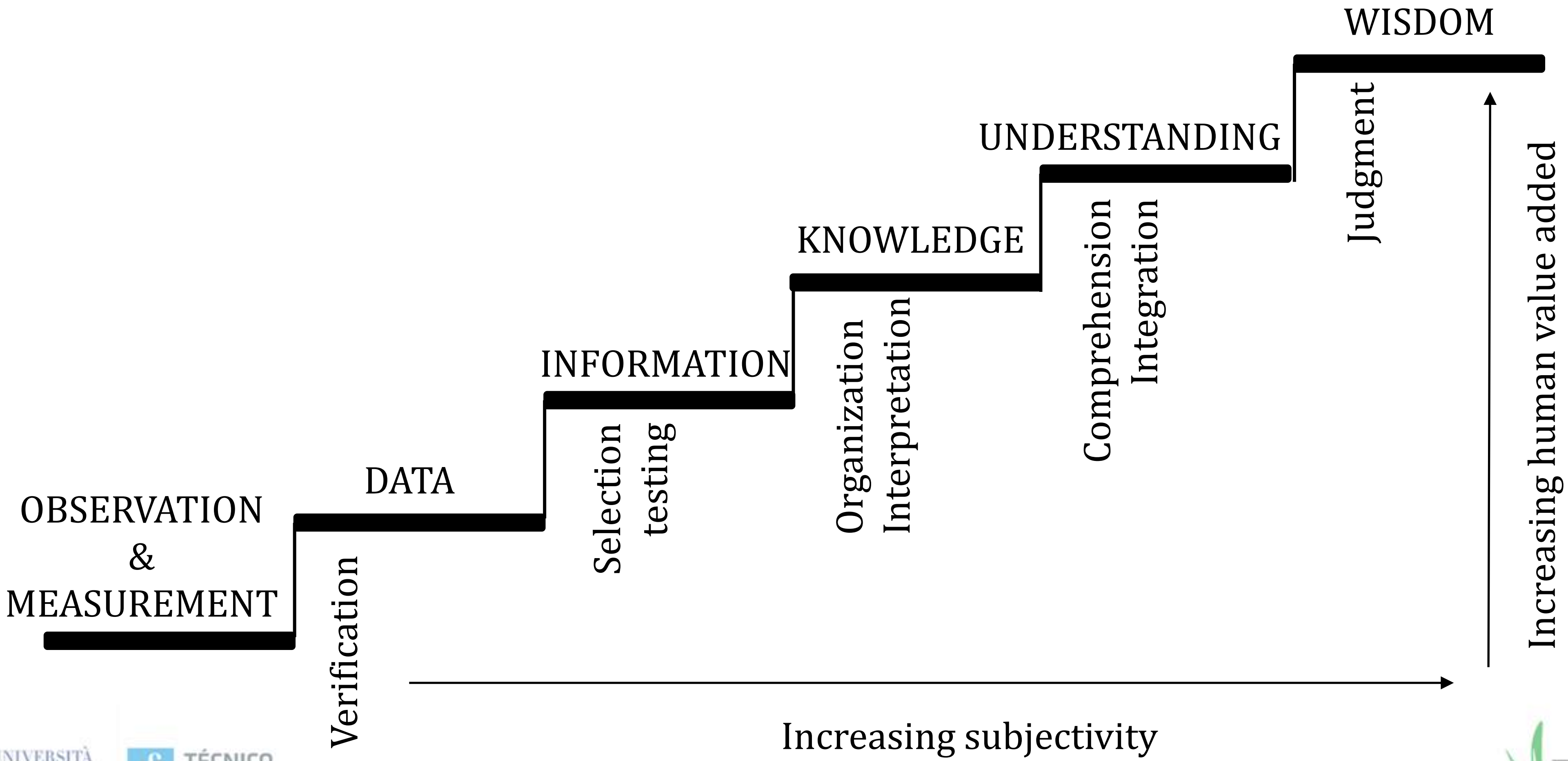
Science-based observations and measurements improve our understanding of the environment and lead to wise decision-making. (Roots, 1997)



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Steps of environmental monitoring

Planning	Project Goal	Schedule	QA Plan	
Data collection	Preliminary survey	QA review/ verification/ validation	Sampling campaign	Transportation
Analysis	QA review/ verification/ validation	Sample pretreatment and analysis	Analytical data quality assessment	
Reporting	Data treatment	Dissemination, communication, publication, etc.		

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Target population & Sampled population

Target population is the set of all units that comprise the items of interest in a scientific study.

The **sampled population** is that part of the target population that is accessible and available for sampling.

Target population: urban soil

Sampled population: soil of urban area that are not covered with structures, buildings and roads, etc.

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Sampling Unit, Sample Support, Sampling Design, Measurement Protocol

A **sampling unit** (or sample) is a member of the population that may be selected for sampling.

Sample support represents that portion of the sampling unit, such as an area, volume, mass, or other quantity, that is extracted in the field and subjected to the measurement protocol.

The **sampling design** specifies the number, type, and location (spatial and/or temporal) of sampling units to be selected for measurement

Measurement protocol is a specific procedure for making observations or performing analyses to determine the characteristics of interest for each sampling unit.

Sampling design

Sampling unit

Sample support

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Categories of sampling designs

Probability-based sampling design

- Provides ability to calculate uncertainty associated with estimates
- Provides reproducible results within uncertainty limits
- Provides ability to make statistical inferences
- Can handle decision error criteria

Judgmental sampling design

- Can be less expensive than probabilistic designs.
- Can be very efficient with knowledge of the site
- Easy to implement

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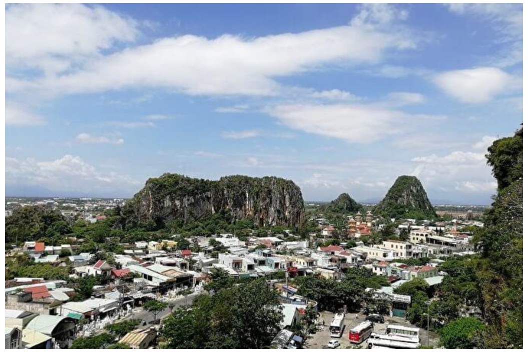
Main limitations

- **Budget**
- **Technical facilities**
- **Space**
- **Time**



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Sampling Designs

Random Sampling Design

- Simple Random Sampling Design

Systematic Sampling Design

- Triangular Grid Sampling Design
- Square Grid Sampling Design

Stratified Sampling Design

Adaptive Cluster Sampling Design

Composite Sampling Protocol

Judgmental Sampling

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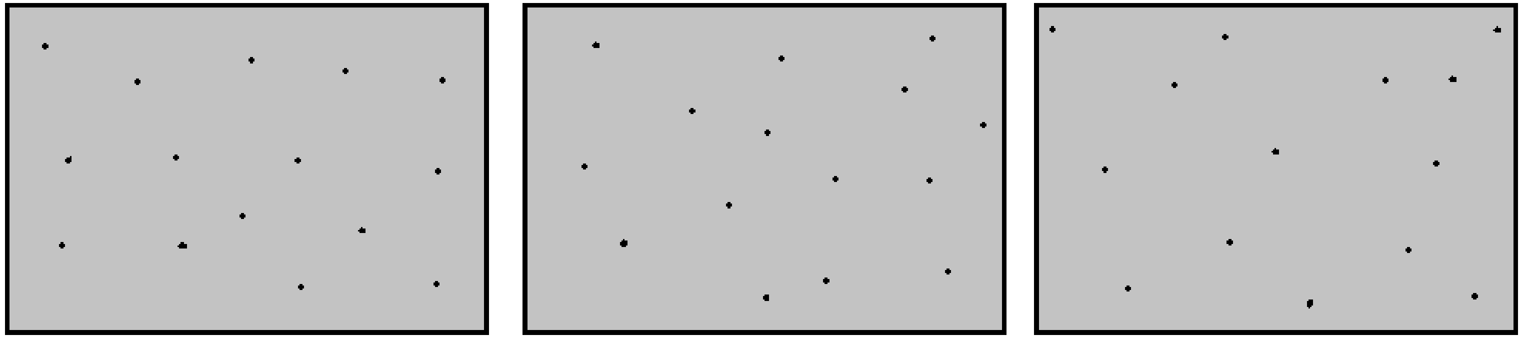
Simple Random Sampling Design

A simple random sample of size *n* is defined as a set of *n* sampling units selected from a population (of objects or locations in space and/or time) so that all possible sets of *n* sampling units have the same chance of being selected



$n = 15$

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Simple Random Sampling: When to use

- when the population being sampled is relatively uniform or homogeneous;
- when the sampling design has more than one stage of sampling (at last stage of sampling)
- when preliminary survey is essential

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Simple Random Sampling: Benefits and Limitations

- protects against selection bias;
- design is simple;
- statistical analysis of the data is relatively straightforward;
- explicit formulae, as well as tables and charts in reference books, are available for estimating the minimum sample size needed to support many statistical analyses.

- sample points could, by random chance, not be uniformly dispersed in space and/or time;
- ignores all prior information

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Simple Random Sampling: Implementation

1. Define minimum sample size:

   1.1 Estimate a population mean

   - from pilot study of sample population
   - or another study conducted with a similar population
   - or an estimate based on a variance model combined with separate estimates for the individual variance components
   - or, in the absence of prior information, estimate the standard deviation (square root of the variance) by dividing the expected range of the population by six, i.e:
     $$\frac{Expected\ Max - Expected\ Min}{6}$$

   1.2 Use "SAMPLE SIZE TABLES FOR SIMPLE RANDOM SAMPLING DESIGNS" (from EPA QA/G-5S. Guidance on Choosing a Sampling Design for Environmental Data Collection, p. 44-49) to achieve specified precision for estimates of population means and proportions.

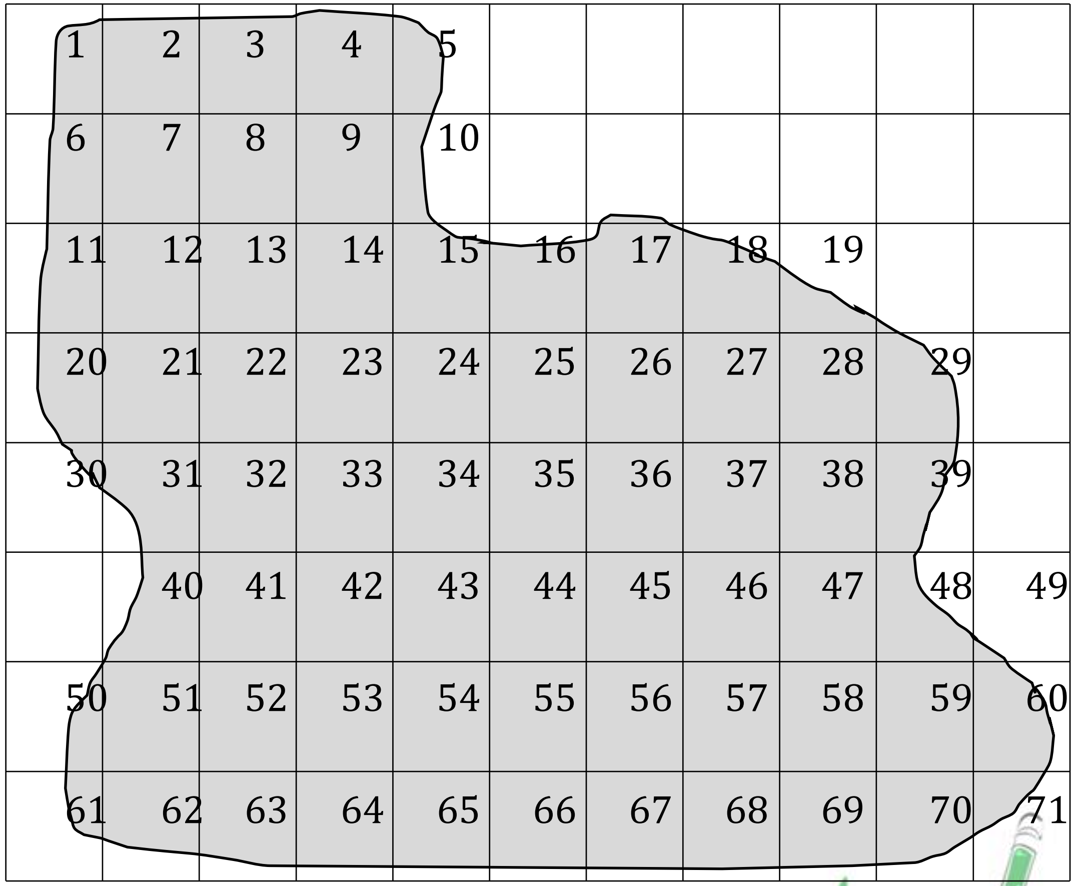
Simple Random Sampling: Implementation

2. Define sample units:

   2.1 Label the potential sampling units from *1* to *N*.

   2.2 Randomly select *n* integers from *1* to *N* from the list:

   - by using a table of random numbers,
   - or a applying computerized random number generator



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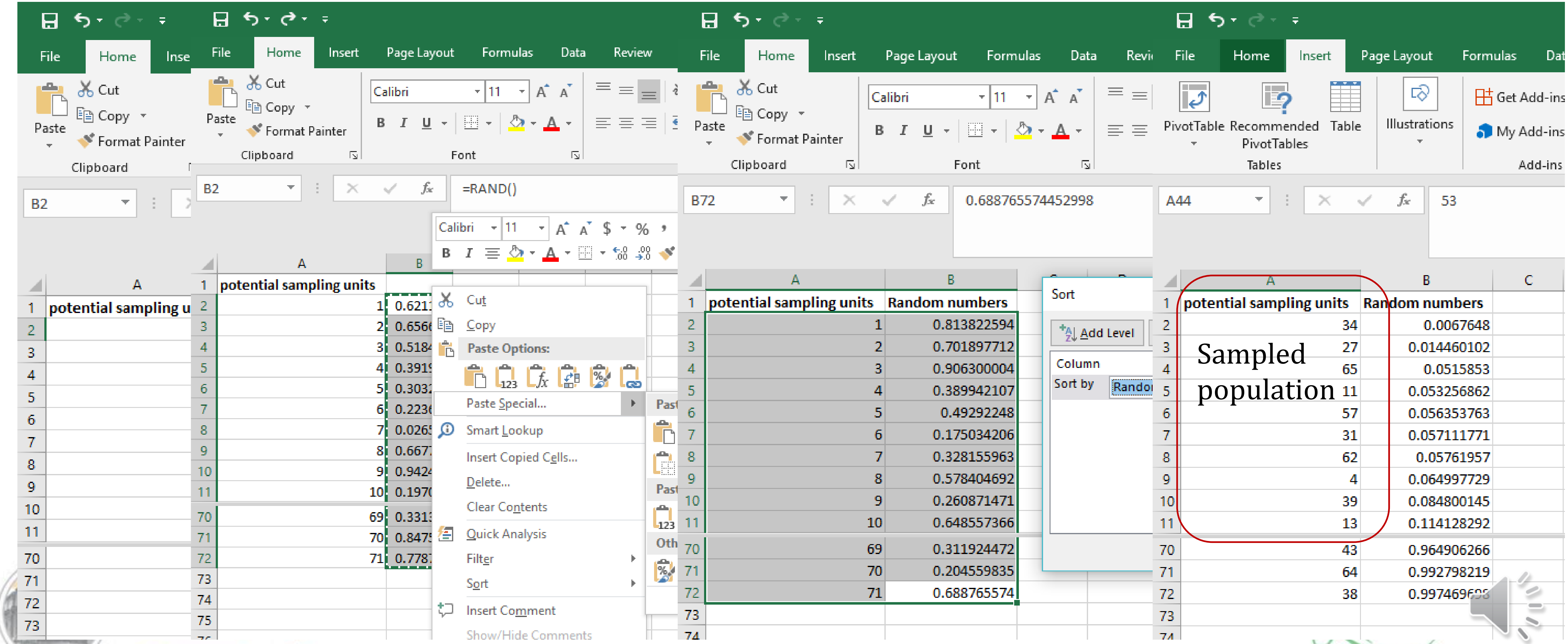
Example: Random Numbers in Excel



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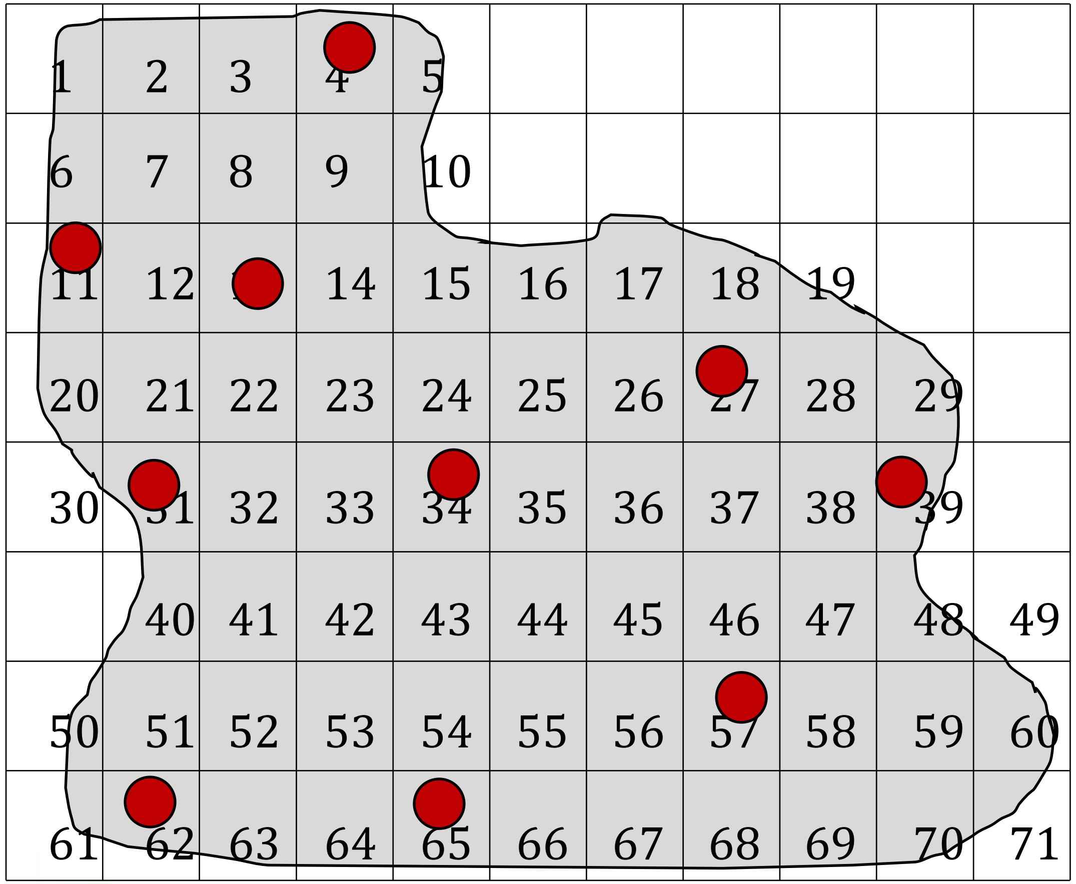
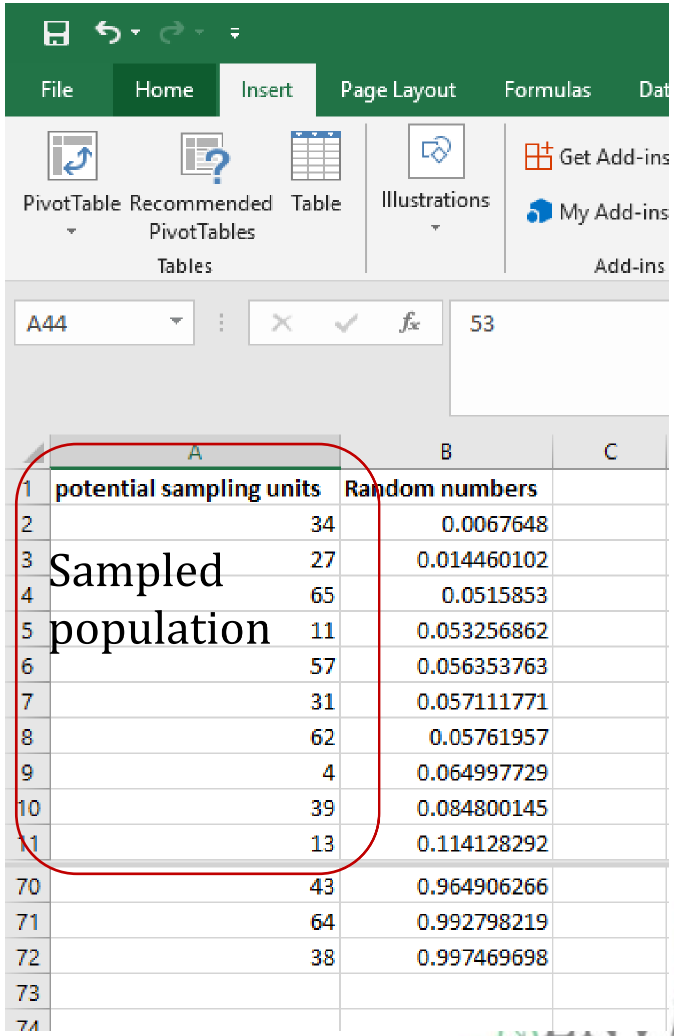
Example: Simple Random Sampling Design





	A	B	C
1	potential sampling units	Random numbers	
2	34	0.0067648	
3	27	0.014460102	
4	65	0.0515853	
5	11	0.053256862	
6	57	0.056353763	
7	31	0.057111771	
8	62	0.05761957	
9	4	0.064997729	
10	39	0.084800145	
11	13	0.114128292	
70	43	0.964906266	
71	64	0.992798219	
72	38	0.997469698	
73			

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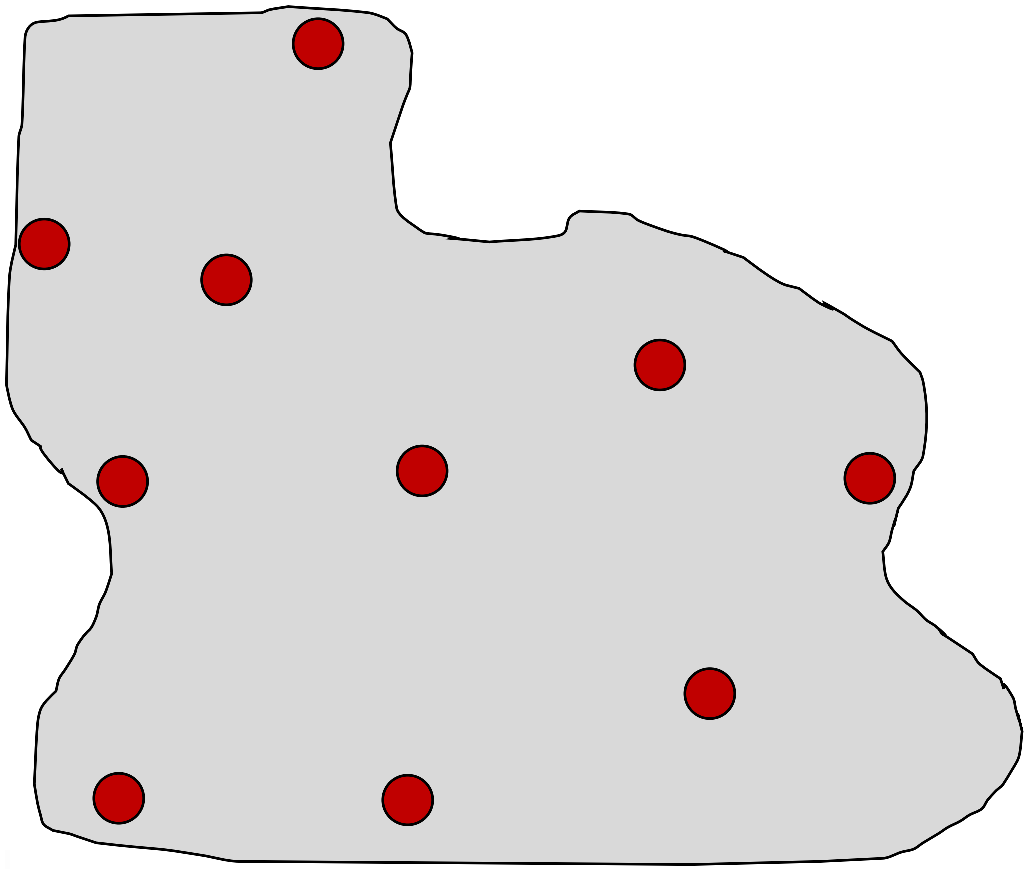
Example: Simple Random Sampling Design



Satisfied?

If yes, start sampling campaign

If no – repeat

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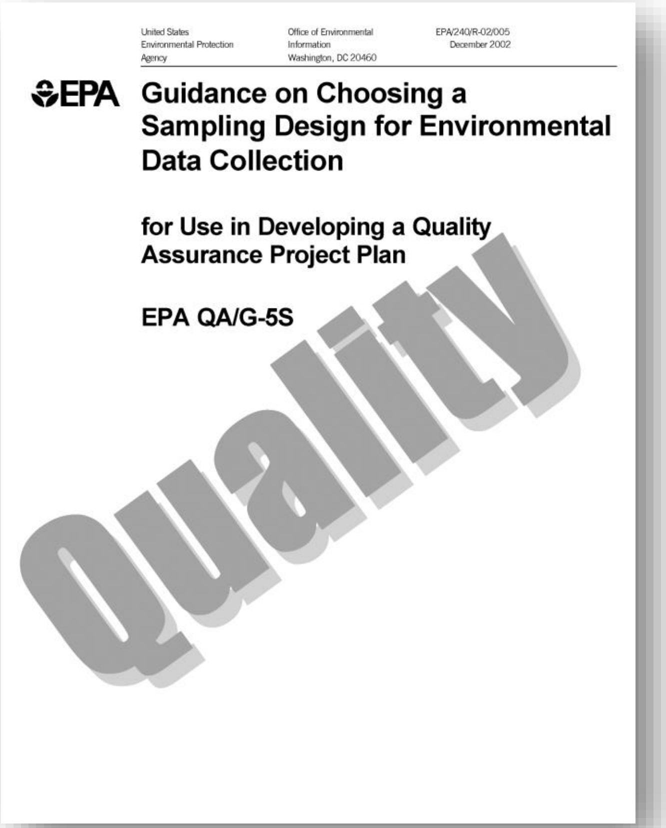
Simple Random Sampling: Implementation

3. Optimization of sample size to the fixed study costs and desired precision and accuracy of the final estimates
[EPA QA/G-5S. Guidance on Choosing a Sampling Design for Environmental Data Collection]


United States Environmental Protection Agency

Office of Environmental Information Washington, DC 20460

EPA/240/R-02/005 December 2002

EPA

Guidance on Choosing a Sampling Design for Environmental Data Collection

for Use in Developing a Quality Assurance Project Plan

EPA QA/G-5S

Quality

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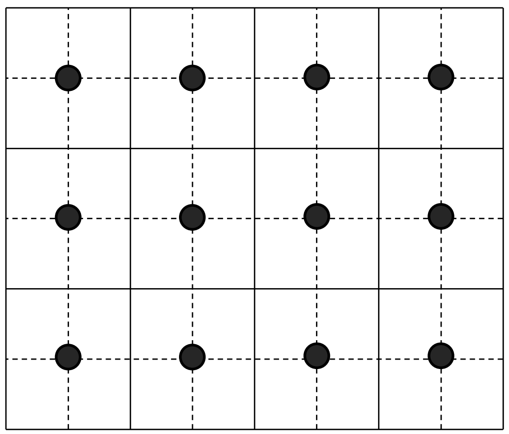
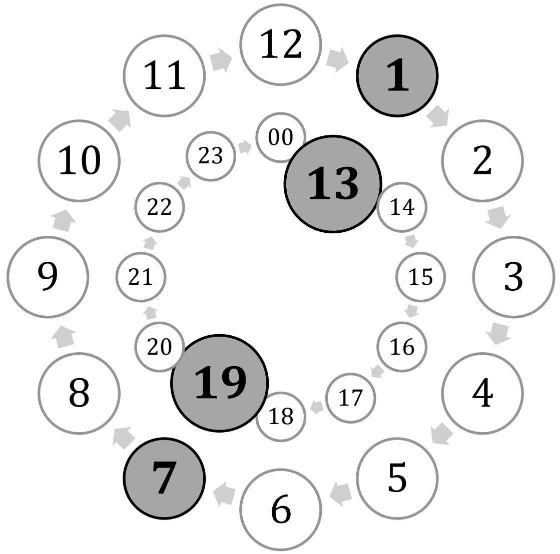
Systematic/Grid/Regular Sampling Design

Consists of collecting samples in a specified pattern: spatial or temporal



Central Aligned Square Grid



Temporal Sampling

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Systematic Sampling: When to use

- ✓ There is no information about a population and the objective is to determine if there is a pattern or correlation among units, or
- ✓ There is a suspected or known pattern or correlation among units at the site and the objective is to estimate the shape of the pattern or the strength of the correlation
- ✓ When making an inference about a population parameter when environmental measurements that are known to be heterogeneous
- ✓ When estimating a trend or identifying a spatial or temporal correlation
- ✓ When looking for a “hot spot” or making a statement about the maximum size object that could be missed with a given sampling design

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Systematic Sampling: Benefits and Limitations

- Uniform, known, complete spatial/temporal coverage of the target population is possible
- easy to implement
- allows calculation of spatial and temporal correlations
- can be implemented with little to no prior information about a site

- Invalid estimates can be got when choosing the incorrect scale of sampling
- costly and time-consuming

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Systematic Sampling: Implementation

1. Define minimum sample size

   1.1 Define scale of sampling based on the purpose of study:

   - regional (Sc: 1:1000000 – 1:200000)
   - medium-scale(Sc: 1:100000 – 1:25000)
   - large-scale (Sc: 1:10000 and more)

   1.2 In case of agricultural soil sampling use the Table provided by Wilson and Artiola (2004):

Area of agricultural land, ha	Sample size
0-2	1
2-5	2
5-10	3
10-15	4
15-20	5
20-30	6
>30	$n = 1 + \sqrt{A}$

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Systematic Sampling: Implementation

2. Choose grid geometry: square or triangular (the most common ones) or other: rectangles,, circles, and hexagons (less common)

3. Estimate the distance between sampling points (L) from the area A and the number of sampling units n using equations:

$$L = \sqrt{\frac{A}{0.866n}}$$ for triangular grid

$$L = \sqrt{\frac{A}{n}}$$ for squire grid

4. For squire grid design:

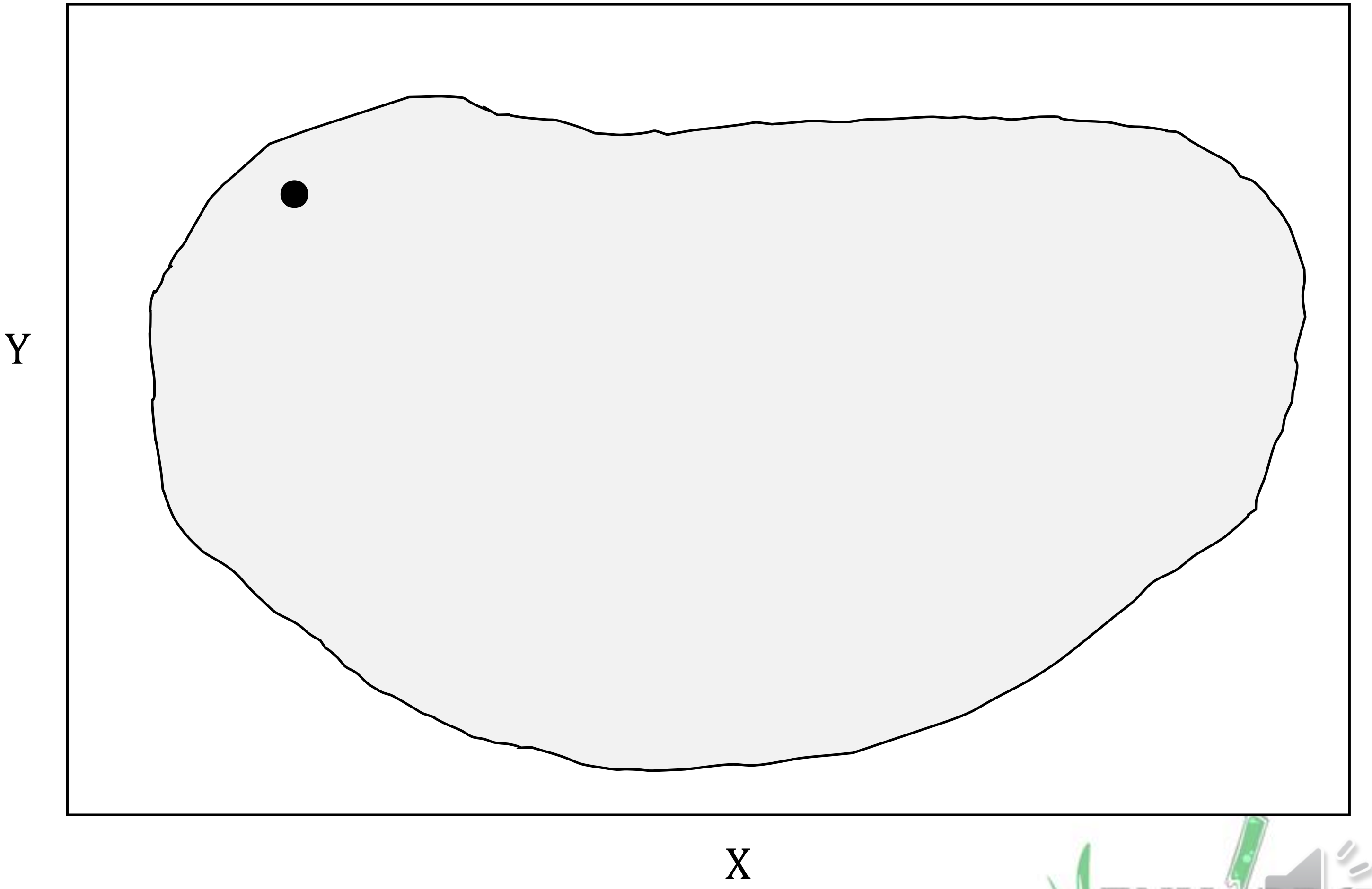
4.1 Select initial random point.
4.2 Construct coordinate axis going through initial point.
4.3 Construct lines parallel to vertical axis, separated by a distance of L.
4.4 Construct lines parallel to horizontal axis, separated by a distance of L

4. For triangular grid design:

4.1 Select initial random point.
4.2 Construct lines going through initial point at 30° and 120° grade angle
4.3 Construct lines parallel to the existing lines, separated by a distance of L.

Example: Squire Grid Sampling Design

Select initial random point.



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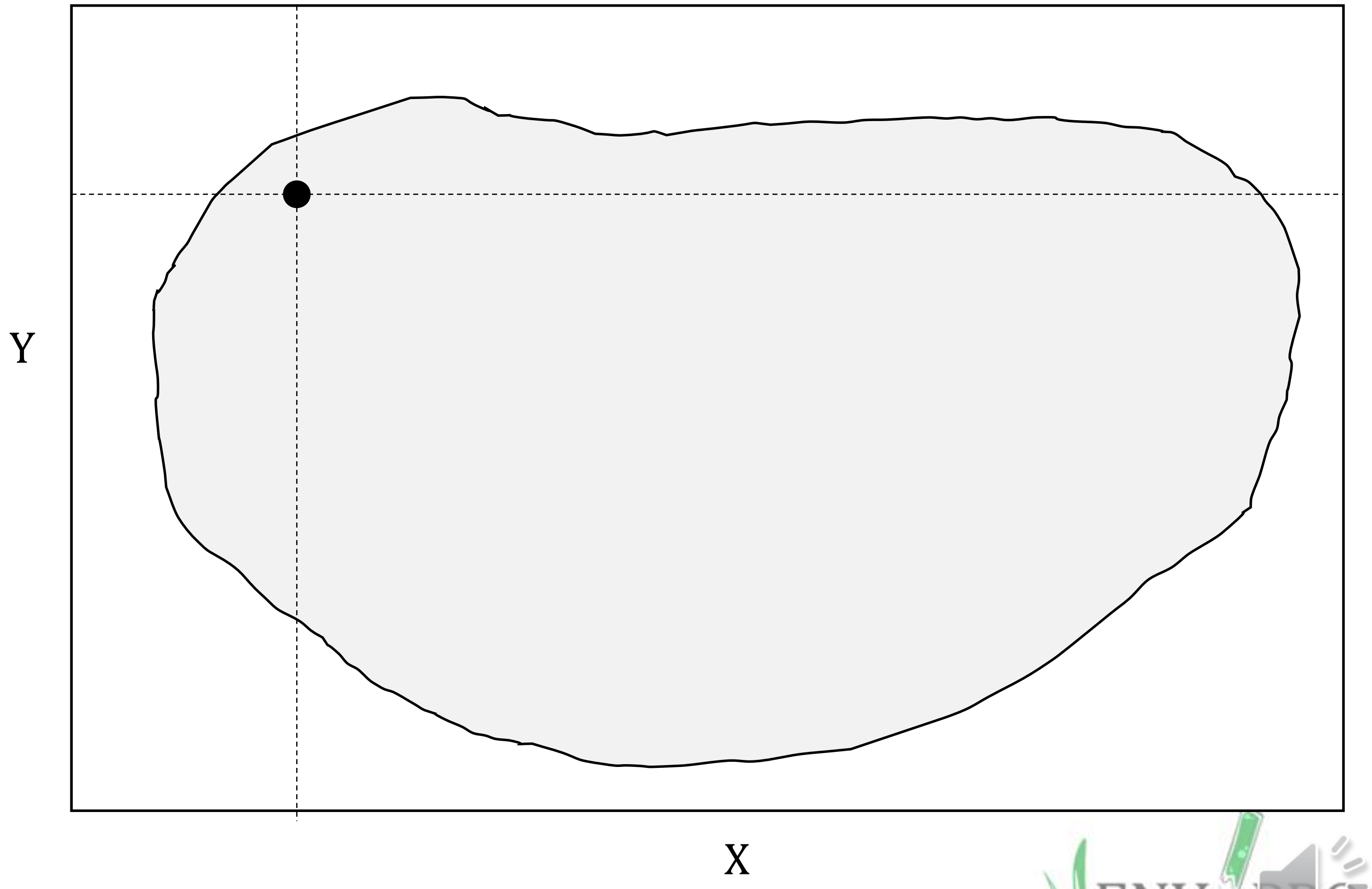
Example: Squire Grid Sampling Design

Select initial random point.

Construct coordinate axis going through initial point.



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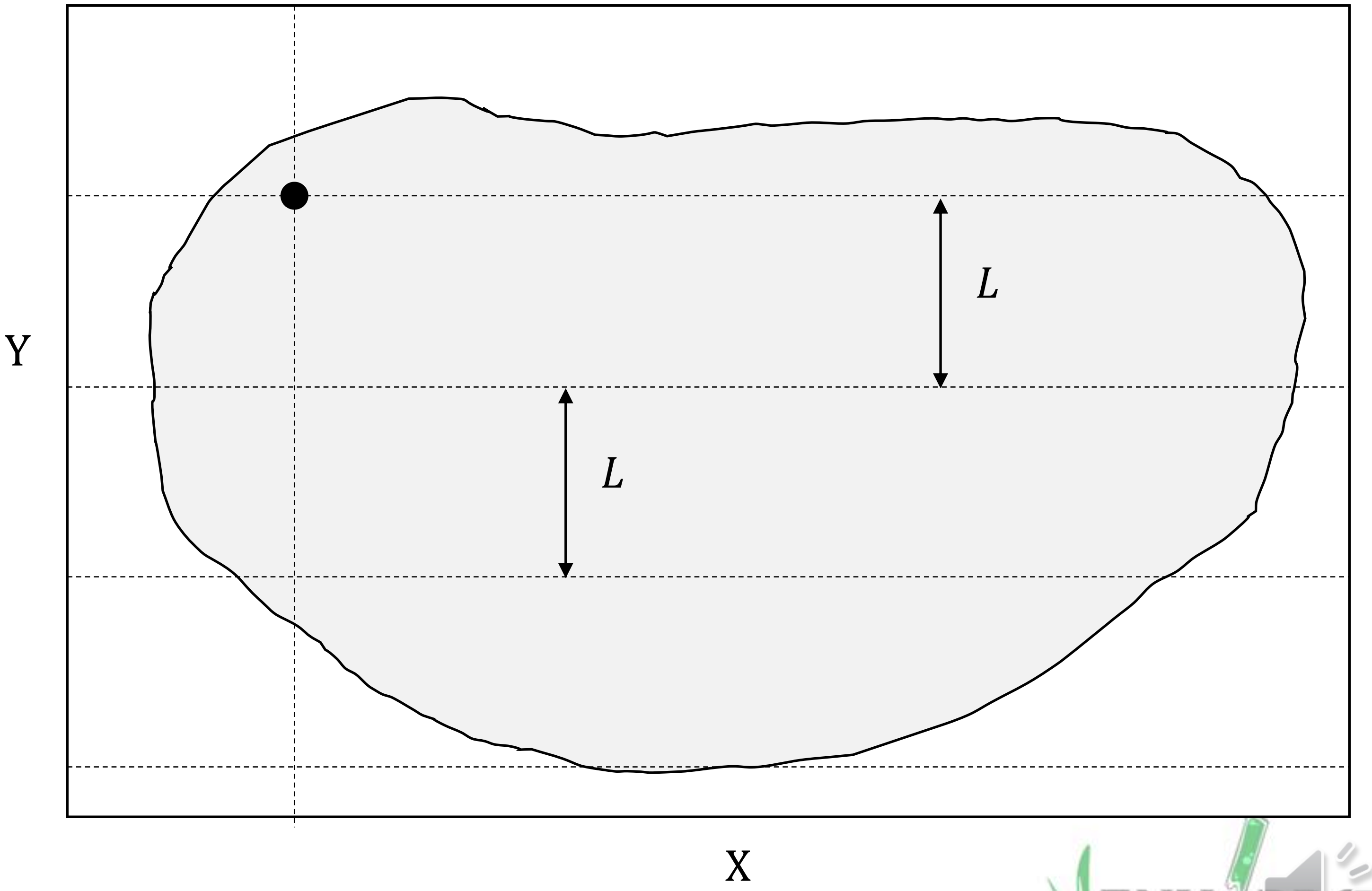
Example: Squire Grid Sampling Design

Select initial random point.

Construct coordinate axis going through initial point.

Construct lines parallel to horizontal axis, separated by a distance of *L*.



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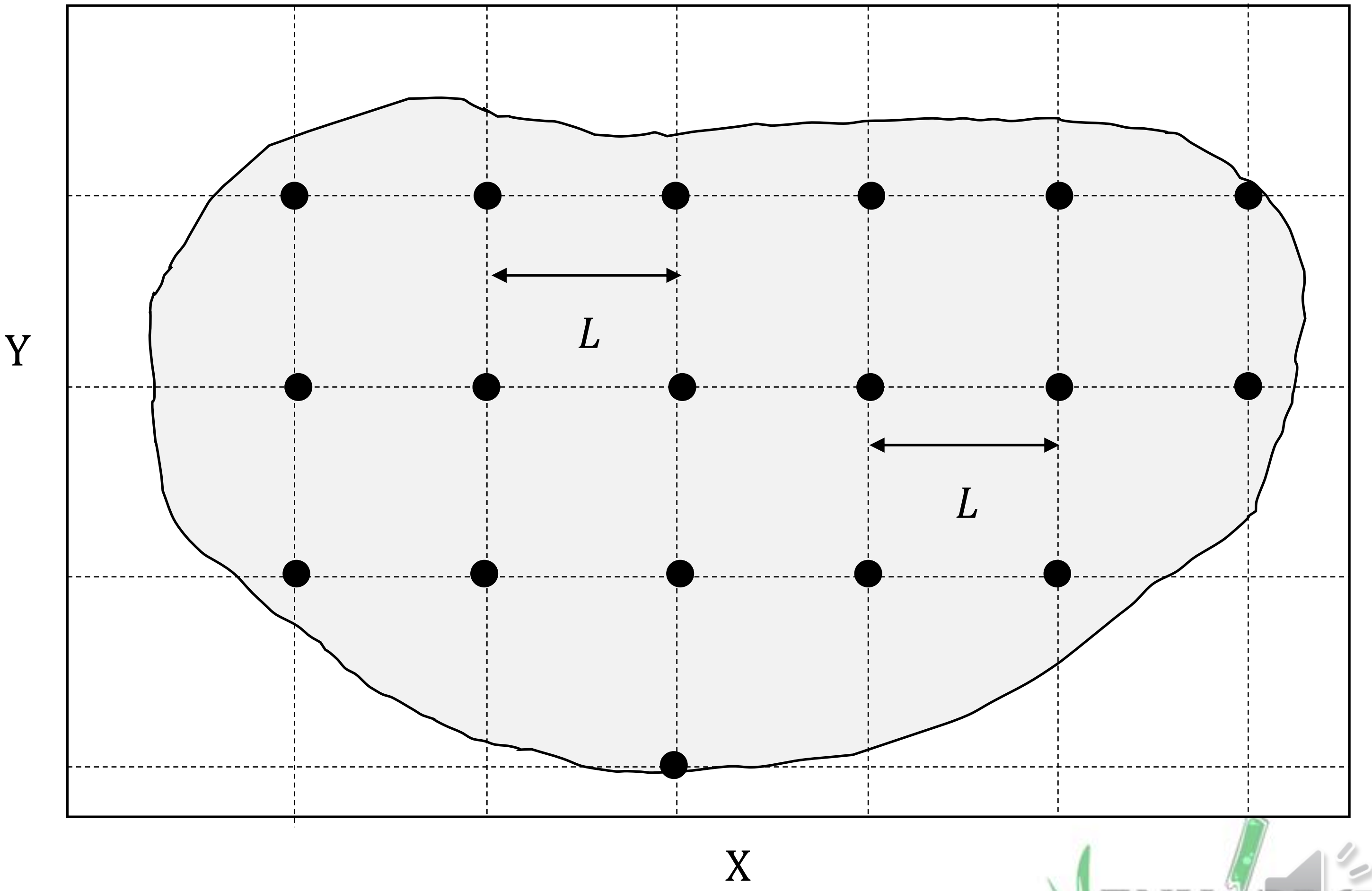
Example: Squire Grid Sampling Design

Select initial random point.

Construct coordinate axis going through initial point.

Construct lines parallel to horizontal axis, separated by a distance of *L*.

Construct lines parallel to vertical axis, separated by a distance of *L*



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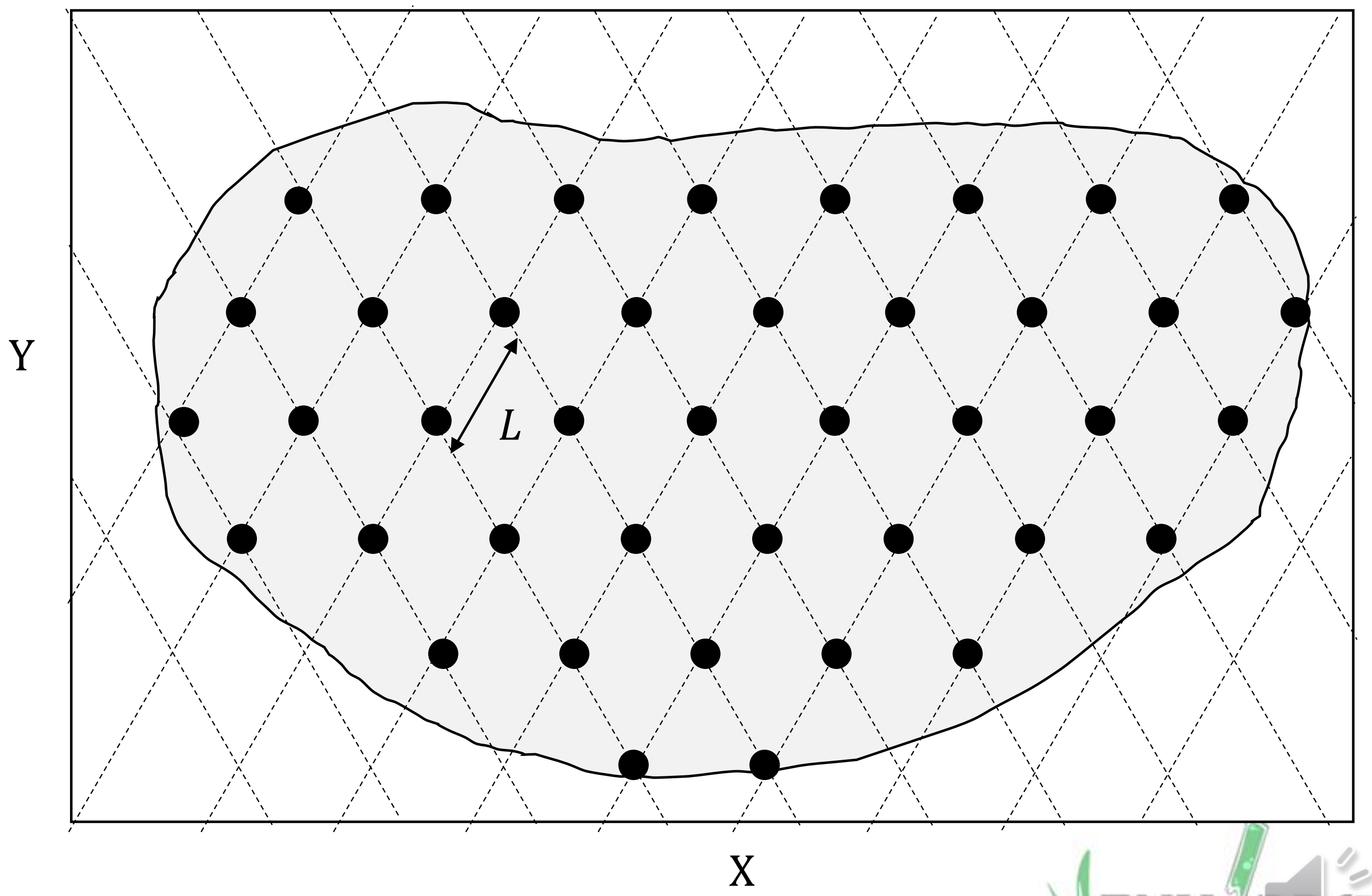
Example: Triangular Grid Sampling Design

For triangular grid design:

- Select initial random point.
- Construct lines going through initial point at 60° and 120° grade angle
- Construct lines parallel to the existing lines, separated by a distance of *L*.



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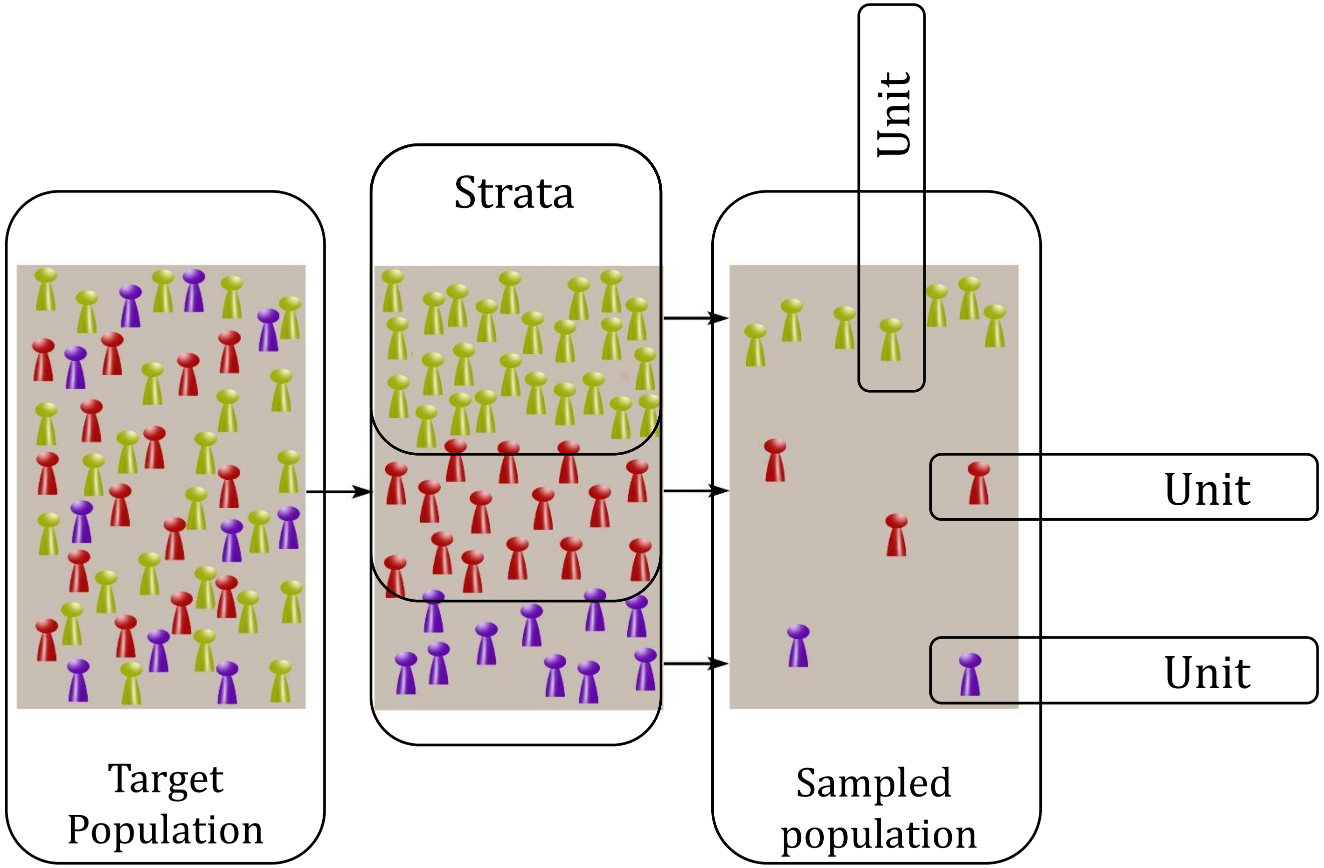
Stratified Sampling Design

Prior information about the population is used to determine groups (called strata) that are sampled independently.



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Stratified Sampling: When to use

The method of defining the strata depends on the purpose of the stratification. Use it when:

- population is subdivided into groups and certain information is desired separately for each group
- stratification can ensure a more representative sample by distributing the sample throughout the spatial and/or temporal dimensions of the population;
- stratification may produce gains in precision in the estimates of population characteristics;
- if different parts of a population present different sampling issues that may need to be addressed separately

Stratified Sampling: Benefits and Limitations

- cost effective
- more reliable results could be obtained within strata
- allows use auxiliary variables

- needs reliable prior knowledge of the population

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Stratified Sampling: Implementation

1. Choose the stratification factor and define strata

   1.1 based on reliable preliminary information, or

   1.2 If auxiliary variable is applied use the DALENIUS-HODGES STRATIFICATION PROCEDURE (from EPA QA/G-5S. Guidance on Choosing a Sampling Design for Environmental Data Collection, p. 59)

2. Define sample size within each stratum using:

   - equal allocation, to assign the same number of samples to be selected within each stratum: $n_h = \frac{n}{L}$, where n_h – number of units sampled in stratum h; n – total number of units sampled ($n = \sum_{h=1}^{L} n_h$); L – number of strata.
   - proportional allocation, to allocate the samples to the strata so that the proportion of the total sampling units allocated to a stratum is the same as the proportion of sampling units in the population that are classified in that stratum: $n_h = nW_h$, where W_h - stratum weight, ($W_h = N_h/N$, where N_h and N are sample unit number in stratum h and in population respectively).

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Stratified Sampling: Implementation

3. Optimize the sample size within each stratum for a fixed study cost:

$$n_h = \frac{(C - C_0) W_h \delta_h / \sqrt{C_h}}{\sum_{h=1}^{n} W_h \delta_h / \sqrt{C_h}}$$

where C – total budget; C_0 – initial fixed costs; C_h – cost per sample for stratum h δ_h - prior known standard deviation in stratum h, which in practice often replaced with the ordinary estimated variance of stratum h.

4. Apply any sampling design to select the samples within each stratum

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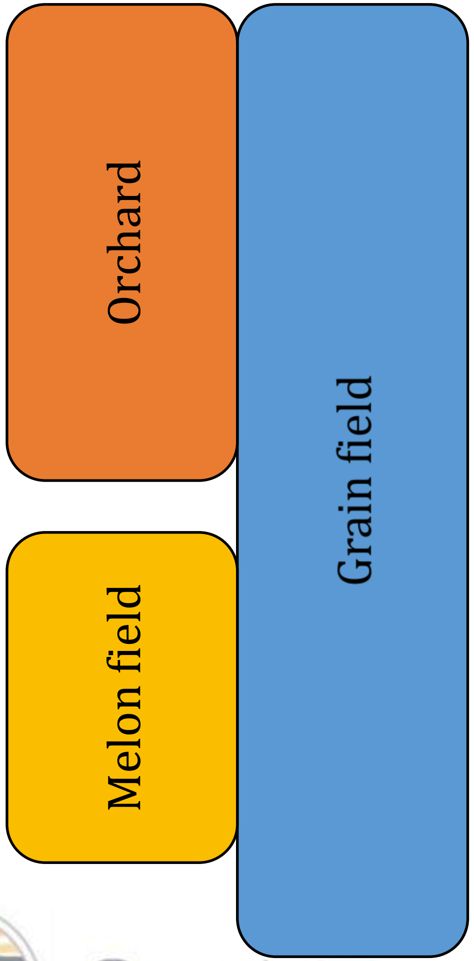
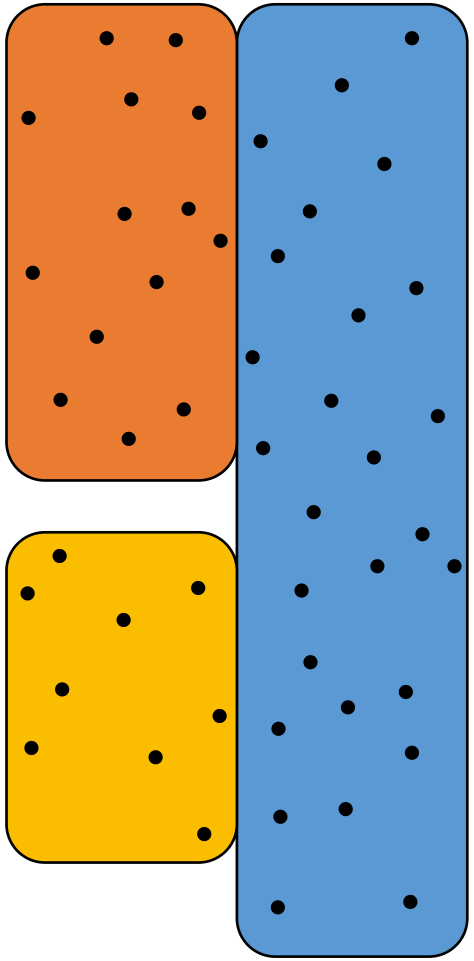
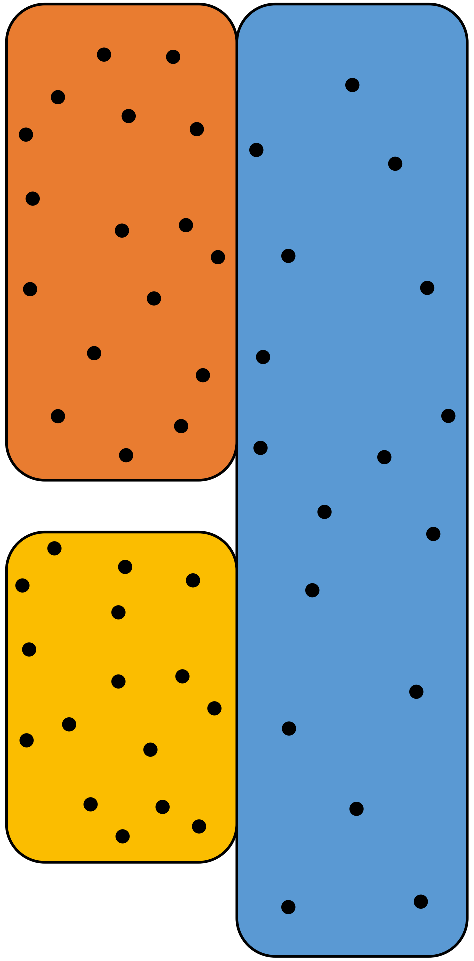
Example: Stratified Sampling Design





$n=50$
$W_{\text{Grain field}} = 0.54$
$W_{\text{Orchard}} = 0.27$
$W_{\text{Melon field}} = 0.18$
$N_{\text{Grain field}} = 27$
$N_{\text{Orchard}} = 14$
$N_{\text{Melon field}} = 9$

Proportional allocation,
Simple random sampling



$n=50$
$N_{\text{Grain field}} = 17$
$N_{\text{Orchard}} = 17$
$N_{\text{Melon field}} = 16$

Equal allocation,
Simple random sampling

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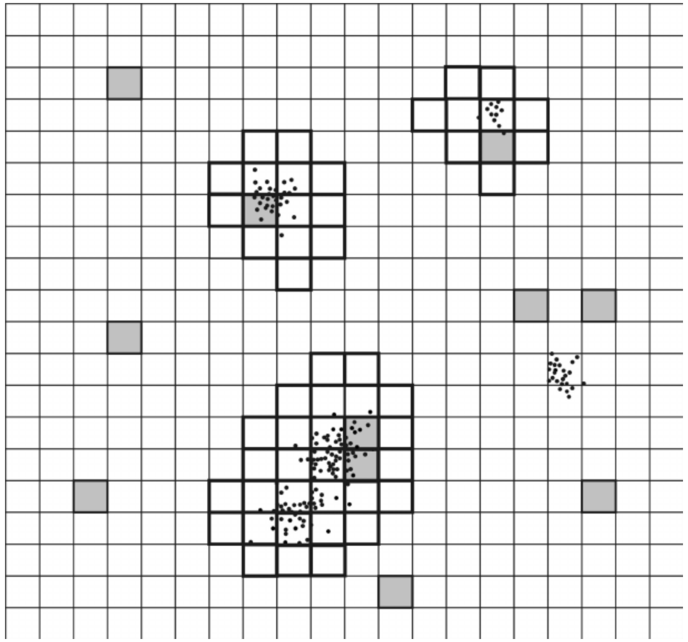
Adaptive Cluster Sampling Design

Adaptive sampling designs are designs in which additional units or sites for observation are selected depending on the interpretation of observations made during the survey. Additional sampling is driven by the results observed from the initial sample



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Adaptive Cluster Sampling: When and where to use

- ✓ where the characteristic of interest is sparsely distributed but highly aggregated
- ✓ quick turnaround of analytical results is possible
- ✓ applicable for detailed survey, when the main hotspots were identified but further details are essential

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Adaptive Cluster Sampling: Benefits and Limitations

- simultaneously addresses the objective of estimating the mean concentration and the objective of determining the extent of contamination
- allows hot spot investigation
- provide quick turnaround time on test results

- Time-consuming
- unbiased estimators of the population mean and variance could be problematic
- initial reliable information is required

Adaptive Cluster Sampling: Implementation

1. Select the initial probability-based sample
2. Specify a rule or criterion for performing additional sampling
3. Define the neighborhood of a sampling unit

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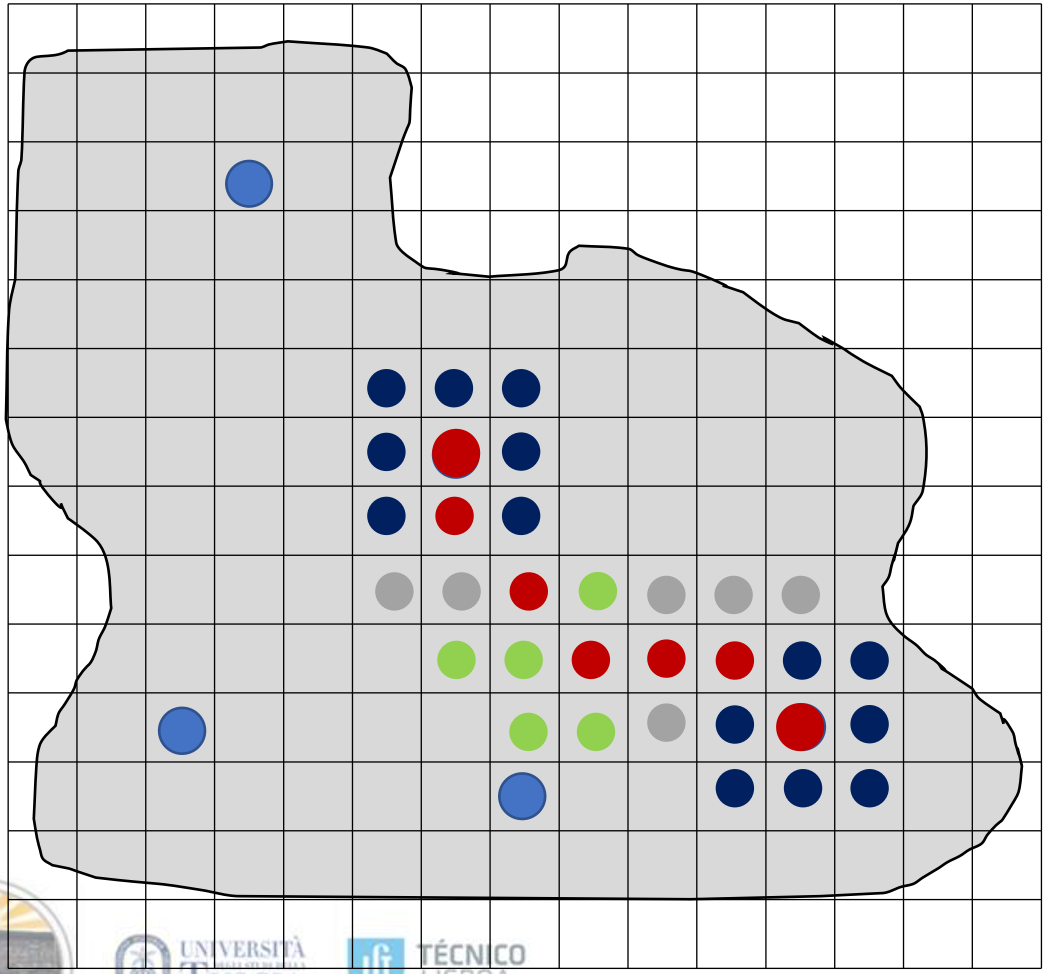
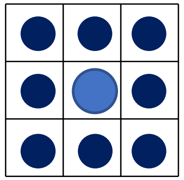
Example: Adaptive Cluster Sampling Design





rule for performing additional sampling

Initial random sampling units

“Positive” result

Sampling units of the second sampling campaign

Sampling units of the third sampling campaign

Sampling units of the forth sampling campaign

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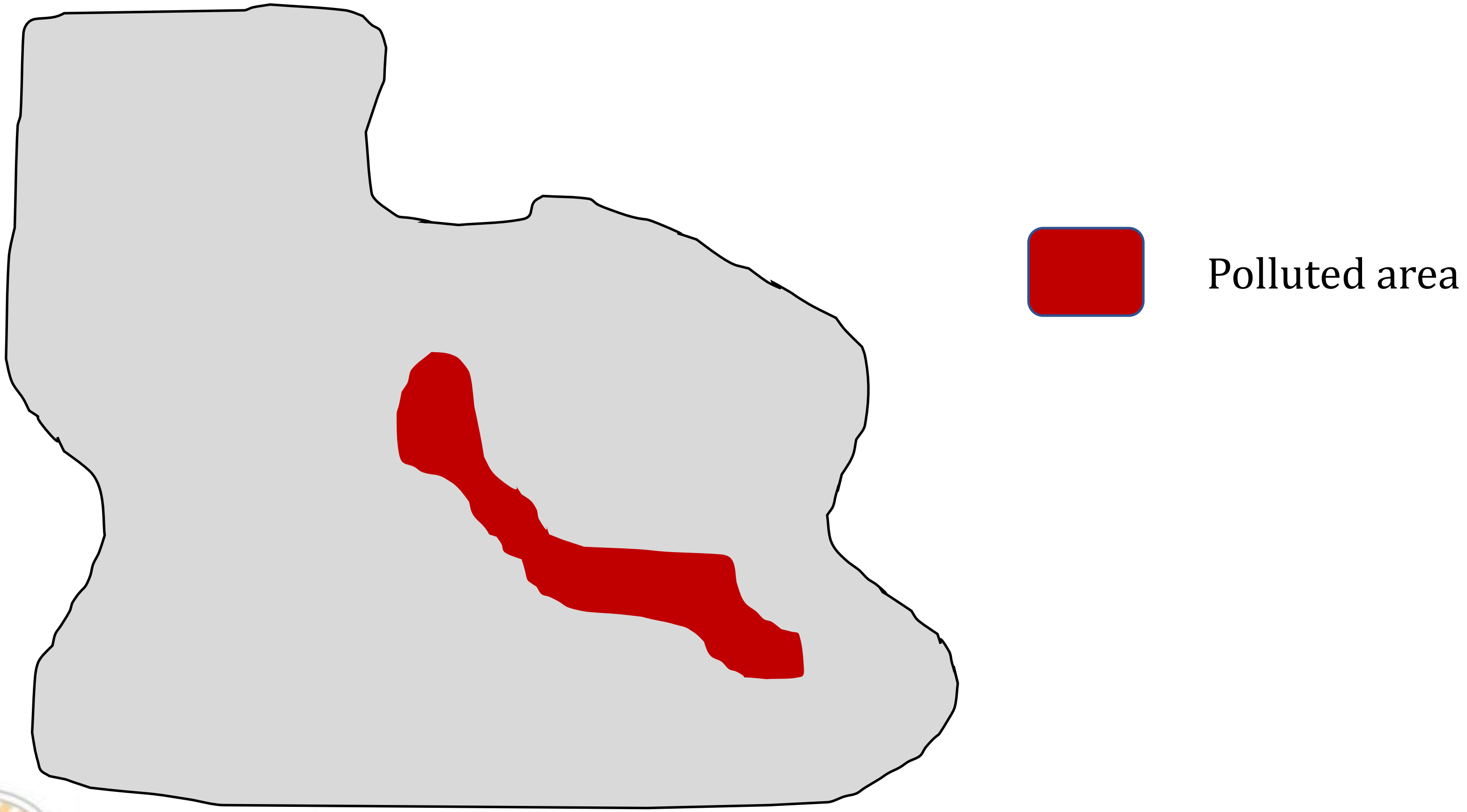
Example: Adaptive Cluster Sampling Design



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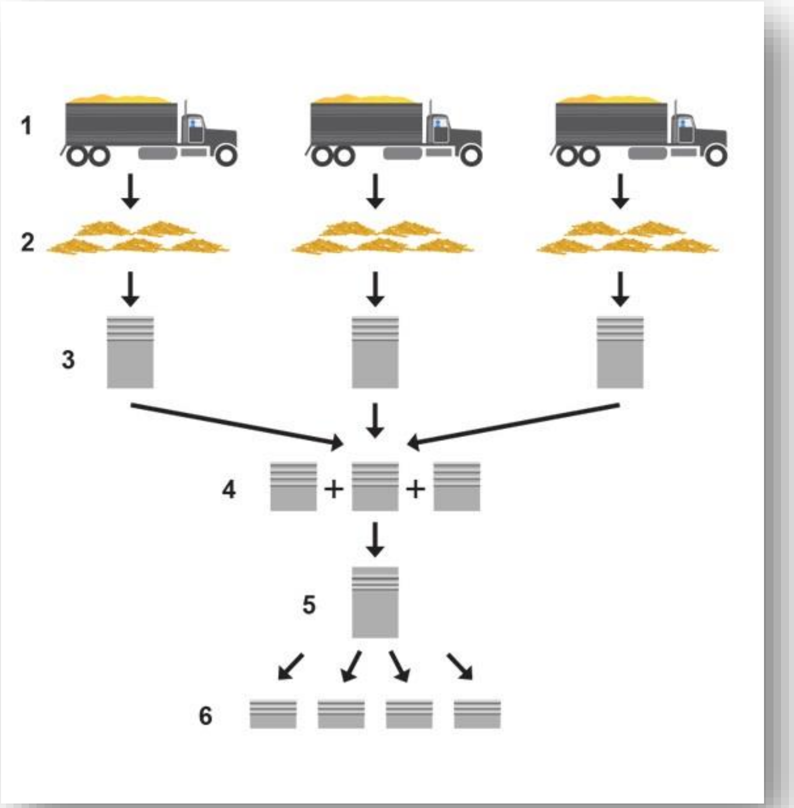
Composite Sampling Protocol

Composite sampling involves physically combining and homogenizing environmental samples or subsamples to form a new sample (i.e., a composite sample)



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Composite sampling: When to use

Application of composite sampling allows to reduce cost by having fewer analyses

Usable in case the study goal of estimating a population mean

Composite Sampling Protocol: Implementation

The individual samples comprising the composite are of equal size (in volume or mass) and shape.

The number of samples comprising each composite is the same.

A single subsample or aliquot is selected for analysis

A single analysis is performed on the subsample.

A large number of composite samples could potentially be formed, but the number to actually be formed is small relative to the number of potential composites.

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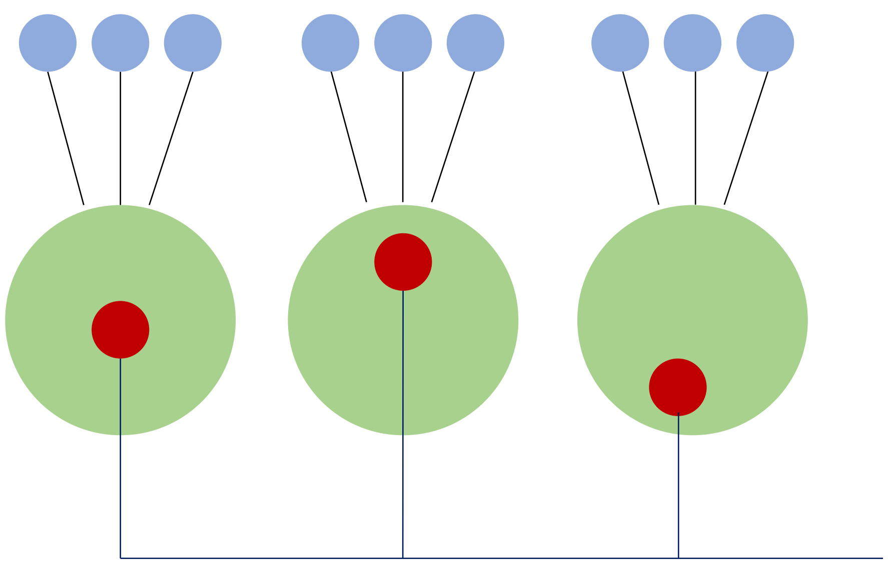
Example: Composite Sampling Protocol



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Judgmental sampling

Judgmental sampling refers to the selection of sample locations based on professional judgment alone, without any type of randomization. Judgmental sampling is useful when there is reliable historical and physical knowledge about a relatively small feature or condition

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Judgmental sampling: Implementation

- ✓ Judgmental sampling is implemented in a manner decided by the professional(s) establishing the sampling design.
- ✓ Specialized academic and professional training is needed before a professional is qualified to design a judgmental sampling program.

Judgmental sampling: Examples of successful applications

Investigation of subsurface soil contamination

Site-specific groundwater contamination issues

Investigation in the known contaminated area

Investigation in the area where potential location of the contaminant release is known

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Further reading

EPA QA/G-4. Guidance on Systematic Planning Using the Data Quality Objectives Process. http://www.epa.gov/QUALITY/qs-docs/g4-final.pdf

EPA QA/G-5S. Guidance on Choosing a Sampling Design for Environmental Data Collection: for Use in Developing a Quality Assurance Project Plan. http://www.epa.gov/QUALITY/qs-docs/g5s-final.pdf

Cochran W.G. (1977) Sampling techniques. 3rd Edition. John Welly and Sons

Brus D.J. (2011). Statistical Sampling Strategies for Survey of Soil Contamination. In: Dealing with Contaminated Sites: From Theory Towards Practical Application / Ed. by F.A. Swartjes. Springer: Dordrecht Heidelberg London New York, pp. 166-206.

Demetriades A., Birke, M. (2015) Urban Geochemical Mapping Manual: Sampling, Sample preparation, Laboratory analysis, Quality control check, Statistical processing and Map plotting. EuroGeoSurveys, Brussels, 2015, 162 pp

... and many others

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Thank you for your kind attention!

Olga Belyaeva

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