The Soil Quality Triad as an ecological risk assessment tool for supporting soil management at contaminated sites

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RIVM
National institute for Public Health and the Environment

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- **Environment** (Infrastructure and Water Management; IenW)
- **Agriculture** (Agriculture, Nature and Food quality; LNV)

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- **Provinces**
- **Municipalities**
- **Waterboards**

We:
- RIVM employees: ~ 1450
- RIVM professors: ~ 28
Content

1. History and background
2. Ecological risk assessment in soil policy
3. WoE with the TRIAD
   - Scaling and weighing
   - 3x LoE
   - Tables, tiers and decisions
   - Example Brasil
   - Spatial aspects
4. Current status
Milestones in Dutch soil protection policy

1979: ‘LEKKERKERK’
first case of soil remediation

1987: **Soil Protection Act (SPA)**

*Art 1: soil organisms need to be protected because of functional role in soil quality*

1994: Revision SPA: Target + Intervention Values
Remediation priority system for contaminated sites

2006: Maximum values

2006: **Remediation criterion for contaminated sites**

2021: End of SPA
→ Environment and Planning Act
Contaminated sites

Potentially 425,000 sites seriously-contaminated

1518 ‘urgent’ sites (2014)

www.compendiumvoordeleefomgeving.nl

Bron: RIVM.
Overview current framework

‘suitable quality’ related to land use

(slightly) polluted

seriously polluted

* Maximum values are depending on land-use
‘Remediation Criterion’ for contaminated sites

Separate focus on three different ‘risks’:  
• human risks  
• ecological risks  
• potency for dispersion and migration of contaminants

There are risks, unless...... (precautionary principle)

Tiered procedure:  
1. Intervention Value is the threshold  
2. Standard site-specific risk assessment (generic set of tools)  
3. Tailored site-specific risk assessment
Tier 1: Ecotoxicological fundament to protect soil

Soil biodiversity model: SSD integrates multiple ecosystem attributes into a single risk number

**HC**x key tool in SPA


Tier 2: standard site-specific risk assessment
‘multi-substance risk assessment’

Criteria:

- Toxic Pressure of mixture (TP)*: 0.25 or 0.65 msPAF
- Surface area: 50, 500, 5000, 50000 m² *
- Ecological sensitivity: classes: 1, 2 or 3

Assessment:

0.25 or 0.65 msPAF contour exceeds specified surface area
(1.nature, 2.residential/agriculture/parks, 3.industrial/infra).

* Examples of TP calculations in RIVM report 711701072
## Decision criteria tier 2 Remediation Criterion

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Unsealed surface area</th>
<th>Unsealed surface area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TP &gt; 0.25</td>
<td>TP &gt; 0.65</td>
</tr>
<tr>
<td><strong>1. Nature</strong>, incl areas in the Ecological Main Structure and Natura-2000 areas</td>
<td>500 m²</td>
<td>50 m²</td>
</tr>
<tr>
<td><strong>2. Agriculture, garden</strong>, residential with garden, allotments, vegetable gardens, green areas with nature values (e.g. park)</td>
<td>5000 m²</td>
<td>500 m²</td>
</tr>
<tr>
<td><strong>3. Other green areas</strong>, urban areas, industry, infrastructure</td>
<td>50.000 m²</td>
<td>5000 m²</td>
</tr>
</tbody>
</table>
Drawing contours in tier 2
Tier 1 and 2: substance orientation (*bioavailability is not considered*)

**Tier 3: generic \(\rightarrow\) site-specific tools**

**Technical issues:**
- Specific land-use, ecosystem services, type of ecosystem, soil type, more impacts, ....
- Additional tools: exposure models, specific SSD, bioassays, biomarkers, field surveys, omics, ....

**Policy issues:**
- Shift of responsibility to local government
- Site-specific aspects: approval by national and local authorities

\(\rightarrow\) Negotiation required / policy decisions!
What is risk assessment?

Technical scientific support for decision-making under uncertainty

- implies a decision (yes or no)
- implies goals
- implies alternative possible outcomes

Ecological risk assessment for contaminated sites. CRC press
Uncertainty in ecological risk assessment

1. Uncertainty from variation and lacking data
   - Spatial
   - Temporal
   - Reliability, confidence

2. Uncertainty from ignorance (model uncertainty)
   - Unknown effects
   - Undefined endpoints, criteria
   - Imperfection of indicators
   - System’s complexity
TRIAD (history)

1985: Edward Long and Peter Chapman introduced the Sediment Quality TRIAD
1995: Piet den Besten (RIZA) published TRIAD protocol for sediments in the Netherlands
1999: RIVM publication of Soil Quality TRIAD
2009: TRIAD in Soil Protection Act
2010: NEN 5737
2017: ISO 19204

TRIAD standards

TRIAD requirements

Fit for use in decision support

• Quantitative (...... for decision support)
• Tiered approach (...... cost effective: each step adds new info)
• Ecological relevant (...... for the land use: → antropocentric)

Ingredients

• Standard **scale**: 0 – 1 (no effect - maximum effect)
• integration per TRIAD LoE individually (**weight** issues)
• Decision after sufficient reduction of uncertainty
Scaling

- Process of putting information on an ‘effect’ ruler
- Ruler runs from 0 (no effect) to 1 (maximum effect level)
- 0.5 level is orientation for all TRIAD legs
Scaling

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- Process of putting information on an ‘effect’ ruler
- Ruler runs from 0 (no effect) to 1 (maximum effect level)
- 0.5 level is orientation for all TRIAD legs

![Diagram showing scaling process with effect ranging from 0 to 1 and indicators for % survival, % induction of stress genes, risk, toxicity, and ecology.]
Adaptation of scaling with SSD

\[ \text{NOEC} \rightarrow \text{EC50} \]

Species Sensitivity Distribution
Use of SSD in multi-substance modelling

Toxic Pressure calculation of mixture at EC50-level:

\[ msPAF_{EC50} = 1 - \left( (1 - PAF_1)(1 - PAF_2) \ldots (1 - PAF_n) \right) \]
Scaling bioassay information

• Assay with whole organisms
  → fraction of reduction, inhibition, etc

• Multi-species test, microcosm, model ecosystems,
  → follow ecology for scaling in multi-attribute systems

• Scaling depends on the level of the response:
  whole organism versus sub-cellular

• > 5 test results: SSD approach is possible
  (described in Posthuma et al. (2002))
Scaling ecological observations

Often multiple attributes are determined: for instance species composition

All responses determine the overall effect
Opt 1: Biological quality index*

All effects (+ and -) are considered as an impact

$$BQX = 1 - 10 \frac{\sum |\log X_n|}{n}$$ (REF = 1)

*Schouten et al. 2002
RIVM report 607604003
Opt 2. Multivariate space

Euclidean Distance between community compositions of contaminated and reference site*

$$ED = \sqrt{\sum_k (y_{ki} - y_{kj})^2}$$

* Data from transect Cu-Ni smelter (Kola peninsula, Russia; Naumova et al. 2004)
Weighing:

- Process of giving a relative importance to different sources of information: necessary for preparing a decision
- Example:
  Intervention value based on SSD:

  *Each species exhibits a different sensitivity for a contaminant, but is equally important for the risk assessment*

*(Posthuma, Suter and Traas. 2002)*
The issue of weighing

Between TRIAD LoEs

- (default) equal weights: chemistry = bioassays = ecology
- (alt) with highly disturbed sites give ecology a lower weight

Within a TRIAD LoE

- (default) all organisms are un-equal, but equally important’ (cf. SSD)
- (+) high weights for specific groups (functional, taxonomic)
- (+) high weights for target species (protected species)
- (+/-) low weights for untrustworthy results, high weights for clear results (provide arguments)

→ Using information(data) = (implicitly) weighing information
**TRIAD: tiers and tables (basic level; tier 3a)**

<table>
<thead>
<tr>
<th>Triad aspect</th>
<th>Parameter</th>
<th>Sample</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry</td>
<td>Sum TP metals</td>
<td>0.00</td>
<td>0.49</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>Microtox</td>
<td>0.00</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Ecology</td>
<td>nematodes biomass</td>
<td>0.00</td>
<td>0.00</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Integrated risk deviation</td>
<td>0.00</td>
<td>0.70</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Risk levels:
- 0 - 0.2: Green
- 0.2 - 0.5: Yellow
- 0.5 - 1: Red

**Deviation factor is go/no-go trigger**

Bornia site; RIVM-report 711701026 (2001)
<table>
<thead>
<tr>
<th>Triad Aspect</th>
<th>Parameter</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<tbody>
<tr>
<td>Chemistry</td>
<td>TP bioavailable</td>
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<tr>
<td>Toxicology</td>
<td>Microtox</td>
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<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Bait lamina test</td>
<td>0.00</td>
<td>0.42</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Worms growth</td>
<td>0.00</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Worms survival</td>
<td>0.07</td>
<td>0.15</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Worms reproduction</td>
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<td>0.93</td>
<td>0.97</td>
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<td></td>
<td>Lettuce germination</td>
<td>0.00</td>
<td>0.52</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Lettuce growth</td>
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<td>0.26</td>
<td>0.60</td>
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<tr>
<td></td>
<td>integration</td>
<td>0.01</td>
<td>0.65</td>
<td>0.75</td>
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<tr>
<td>Ecology</td>
<td>Arthropods asex. reprod.</td>
<td>0.00</td>
<td>0.64</td>
<td>0.50</td>
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<tr>
<td></td>
<td>Arthropods fungiv. grazers</td>
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<td>0.00</td>
<td>0.86</td>
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<td>Arthropods predators</td>
<td>0.00</td>
<td>0.28</td>
<td>0.82</td>
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<td></td>
<td>MO thymidine incorp.</td>
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<td>0.72</td>
<td>0.99</td>
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<tr>
<td></td>
<td>MO biomass</td>
<td>0.00</td>
<td>0.81</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>MO nitrification</td>
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<td>0.50</td>
<td>0.00</td>
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<td>protozoans</td>
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<td>0.00</td>
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<tr>
<td></td>
<td>nematods biomass</td>
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<td>0.00</td>
<td>0.68</td>
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<td></td>
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<tr>
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<td>0.00</td>
<td>0.42</td>
<td>0.76</td>
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<tr>
<td></td>
<td>chemical risk:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>toxicity risk:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ecology risk:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Integrated risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>deviation</td>
<td>0.01</td>
<td>0.20</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Example from Brazil

Metal smelter, lead and other metals
Santo Amaro, Bahia, Brazil

The study site: location and history

Smelter area, 1990

Failed attempt to encapsulate the residues

"Encapsulated" taillings, 2002

500,000 metric tons of residues with 2-3% Pb

Images courtesy Prof. Fernando Carvalho
How the site looks today

Evidence of transport of contaminants

Images: Júlia Niemeyer
Sampling scheme
Tests tier 1:

**Chemistry:**
- Total concentrations
- Mixture modelling

**Toxicology:**
- Avoidance test *Folsomia candida*
- Avoidance test *Eisenia andrei*
- *Daphnia Magna* lethal test
- *Vibrio fischeri* (Microtox)

**Ecology:**
- Vegetation cover
- Bait lamina
- Basal soil respiration
## Risk calculations and results tier 1

### Table 4 Individual risk values for each parameter and combined risk for each line of evidence

<table>
<thead>
<tr>
<th>Soil groups</th>
<th>ChLoE</th>
<th>EcLoE</th>
<th>ELoE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>Cd</td>
<td>Cu</td>
<td>Zn</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1000T1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P20T3</td>
<td>0.08</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P400T3</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Group 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P0</td>
<td>0.29</td>
<td>0.00</td>
<td>0.12</td>
</tr>
<tr>
<td>P20T1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.07</td>
</tr>
<tr>
<td>P150T1</td>
<td>0.88</td>
<td>0.84</td>
<td>0.60</td>
</tr>
<tr>
<td>P50T3</td>
<td>0.83</td>
<td>0.45</td>
<td>0.90</td>
</tr>
<tr>
<td>Group 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P50T1</td>
<td>0.05</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td>P400T1</td>
<td>0.20</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>P150T3</td>
<td>0.30</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>P1000T3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
</tr>
</tbody>
</table>

For each sampling point, values are scaled between 0 and 1 and are given in relation to the respective reference soil (risk for reference soil is set to 0; see text for details).

ChLoE chemical line of evidence, EcLoE ecotoxicological line of evidence, ELoE ecological line of evidence, n.d. not determined.
Results tier 1 (infographics)
Tier 2, additional tests

**Chemistry:**
- Total concentrations
- Mixture modelling
- Extractable metal concentrations

**Toxicology:**
- Reproduction test *Folsomia candida*
- Reproduction test *Eisenia andrei*
- Reproduction test *Enchytraeus*
- *Daphnia magna* reproduction test
- Microalgea growth test
- Plant growth test *(Avena)*

**Ecology:**
- Surface dwelling invertebrates
- Microbial biomass C and N
- Enzyme activities
- Litter bags
# Risk calculation and results  tier 2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Group 1</strong></td>
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<td></td>
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<tr>
<td>1000T1</td>
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<td>0.91</td>
<td>0.96</td>
<td><strong>0.63</strong></td>
<td><strong>0.37</strong></td>
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<tr>
<td>20T3</td>
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<td>0.00</td>
<td>0.00</td>
<td><strong>0.32</strong></td>
<td><strong>0.46</strong></td>
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<td>400T3</td>
<td>0.05</td>
<td>0.00</td>
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<td>0.00</td>
<td><strong>0.28</strong></td>
<td><strong>0.44</strong></td>
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<td>P0</td>
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<td>0.06</td>
<td>0.03</td>
<td><strong>0.12</strong></td>
<td><strong>0.69</strong></td>
</tr>
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<td>0.25</td>
<td>0.00</td>
<td>0.12</td>
<td>0.06</td>
<td><strong>0.16</strong></td>
<td><strong>0.63</strong></td>
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<td>1.00</td>
<td>1.00</td>
<td>0.32</td>
<td>0.99</td>
<td><strong>0.71</strong></td>
<td><strong>0.69</strong></td>
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<tr>
<td>50T3</td>
<td>1.00</td>
<td>0.44</td>
<td>0.04</td>
<td>0.27</td>
<td><strong>0.29</strong></td>
<td><strong>0.62</strong></td>
</tr>
<tr>
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</tr>
<tr>
<td>50T1</td>
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<td>0.00</td>
<td>0.10</td>
<td>0.05</td>
<td><strong>0.17</strong></td>
<td><strong>0.67</strong></td>
</tr>
<tr>
<td>400T1</td>
<td>0.49</td>
<td>0.00</td>
<td>0.07</td>
<td>0.03</td>
<td><strong>0.02</strong></td>
<td><strong>0.37</strong></td>
</tr>
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<td>150T3</td>
<td>0.72</td>
<td>0.00</td>
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<td>0.02</td>
<td><strong>0.41</strong></td>
<td><strong>0.47</strong></td>
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<tr>
<td>1000T3</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td><strong>0.21</strong></td>
<td><strong>0.38</strong></td>
</tr>
</tbody>
</table>
Ecological risk inside the smelter area

- Metal rich tailings
  - Failed encapsulation
  - Impact on establishment of vegetation
  - Simplification of habitat structure
  - Impact on organic matter input

- Impairment of soil processes

- Direct toxicity
  - Lack of favorable conditions for microorganisms and soil invertebrates
Conclusions Santo Amaro

- Uncertainty reduction through Weight of Evidence (WoE) confirmed for Santo Amaro site
- Many tests are applicable:
  - no inherent difference between Europe (NL) and Brazil!
- TRIAD approach substantiates risk assessment:
  - ecotoxicological and ecological observations more convincing for stakeholders
  - clues to better solutions
Spatial extrapolation of TRIAD response data
Precautionary principle less stringent

'standard curve' TRIAD effects

Toxic Pressure (TRIAD)

Toxic Pressure contaminants (msPAF-ec50)
Current status of soil quality TRIAD

- **NL:** TRIAD is part of the Remediation criterion in the SPA
- **NL:** 55 TRIADs performed in the Netherlands (until 2008)
  - 85% were useful for decision support
  - 60% of the sites had unacceptable ecological effects
- **Many scientific improvements, e.g.:**
  - Chen et al. 2014. ET&C 33: 900-909
  - Gutiérrez, et. al. 2015. STOTEN 514: 49-59
  - Ribe et al. 2012. JHazMat 207/208: 15-20
- **Technical guidance document (RIVM report 607711003)**
- **ISO and NEN process standards for TRIAD**

*SKB 2009 report PTS 808*
“Ignorance is inevitable, continuous learning is key” (Aristoteles)

Thanks to our contributors!

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Abroad
- John Jensen
- Antonio Marcomini
- Andrea Critto
- Elena Semenzin
- Júlia Niemeyer
- José Paulo Sousa
- Jörg Römbke

Contact: Michiel.Rutgers@rivm.nl
Data from 38 sites: Van Wezel et al. (2007) report 500122002 (www.rivm.nl)