Introduction to Phytotecnologies and Phytomanagement

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Phytotechnologies

- The term phytotechnology describes the **application of science** and engineering to **solve problems** and provide solutions through **plants**.
- The term underlies the use of **plants** as **living technologies** to help address environmental challenges.

Phytotechnologies

- Phytotechnolgies involves **identifying** biological systems that are most adaptable to human needs.

Phytotechnologies

- Phytotechnology includes all plant-based pollution remediation and prevention systems, including, **phytoremediation**, constructed wetlands, green roofs, green walls and planted landfill caps.

Phytoremediation – What?

- Phytoremediation describes the **degradation** and/or **removal** and/or **stabilization** of a particular contaminant on a polluted site by a specific **plant** or group of plants, and their **associated microorganisms**.

Phytoremediation – Why?

Conventional remediation **techniques** show several weaknesses.

‘Pump-and-treat’ (cleaning polluted groundwater through extraction, filtration and recharge methods) and ‘dig-and-haul’ (where polluted soils are dug up and shipped off site), are:

- Expensive
- Single-outcome technologies
- Limited site-design potential beyond treatment
- Often extremely invasive and disruptive (soil quality)

Phytoremediation – Why?

OPPORTUNITIES

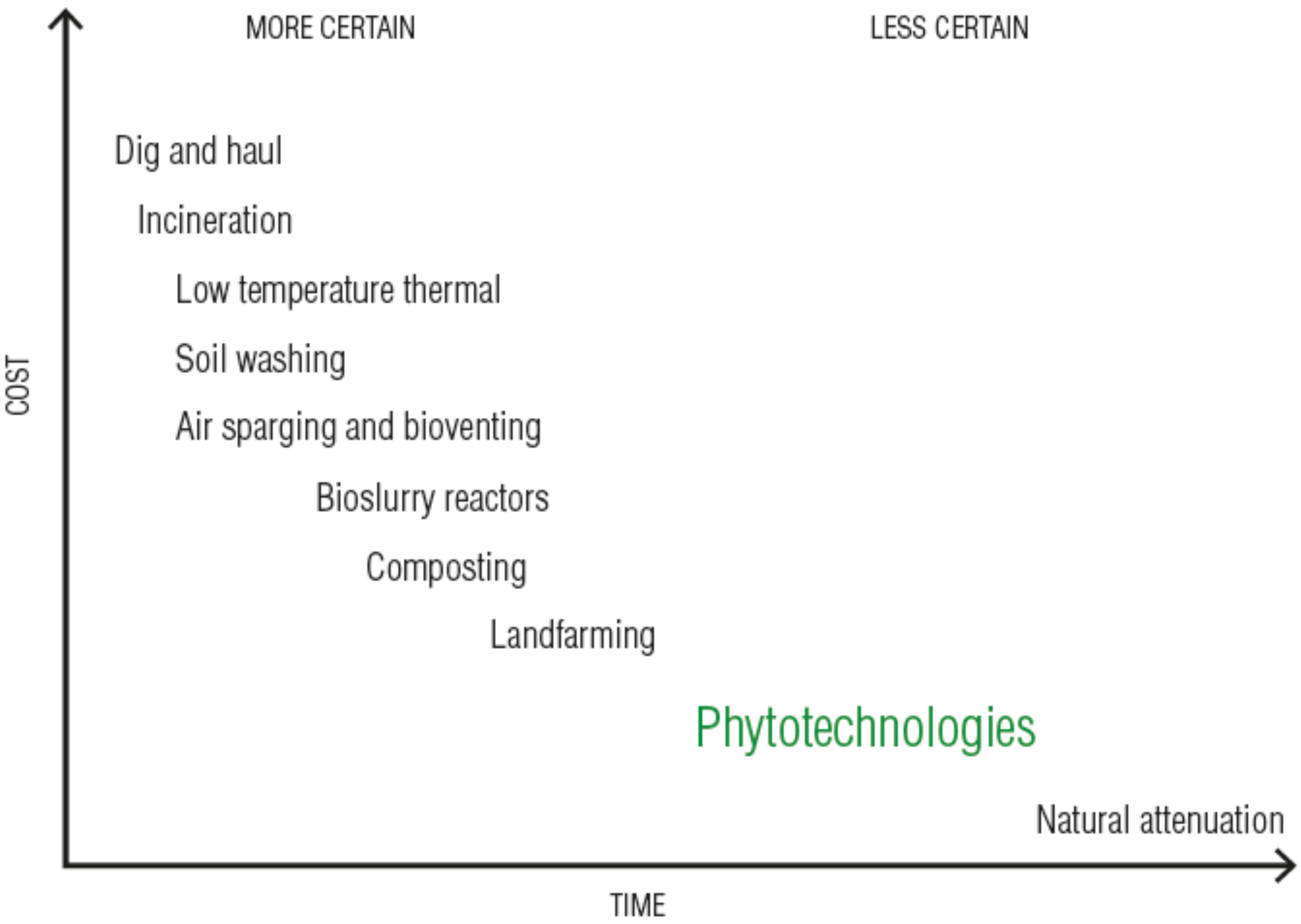
1- Vegetation-based remediation has been found to be **less expensive** in comparison with industry-based technologies and approaches.

Phytoremediation – Plus

Parameters	Incineration	Dig-and-Haul	Phytoremediation
Surface (m^2)	10 000	10 000	10 000
Depth (m)	0.2	0.2	0.2
Total soil volume (m^3)	2000	2000	2000
Average soil density ($t\ m^{-3}$)	2.6	2.6	2.6
Soil mass t	5200	5200	5200
Unit Cost ($\$\ t^{-1}$)	500-600	100-200	25-50
Total cost ($)	2.6 - 3 M$	0.5 -1 M$	130 -260 K$

From : Greenberg *et al* 2006 modified

Phytoremediation -Plus



Phytoremediation - Plus

2- Plant-based systems are **natural**, **passive**, **solar energy-driven** methods of addressing the **cleanup** and **regeneration** of several types of polluted sites

Phytoremediation - Plus

3 - Phytoremediation leaves the **soil intact**, even **improved**, unlike other, more invasive methods of remediation

Phytoremediation – Plus

4- High public acceptance, particularly if the site is located close to or within residential neighborhoods, (phytoremediation is a natural, visually and aesthetically pleasing remediation technology)

Phytoremediation – Plus

Ancillary potential benefits

Community use: The i**nvolvement** of **stakeholders** can offer opportunities to engage local communities with phytotechnology installations.

Phytoremediation – Plus

Educational use: providing an **outdoor classroom experience** for local students and people.

Phytoremediation – Plus?

Habitat creation: The introduction of vegetation as a natural remediation technique increases the amount and variety of habitat on a formerly polluted and abandoned site.

Phytoremediation – Plus

Biomass production: phytoremediation stands can be harvested and used for the production of biomass for **bioenergy**, creating an economic product that compensates remediation costs.

Phytoremediation - Drawbacks

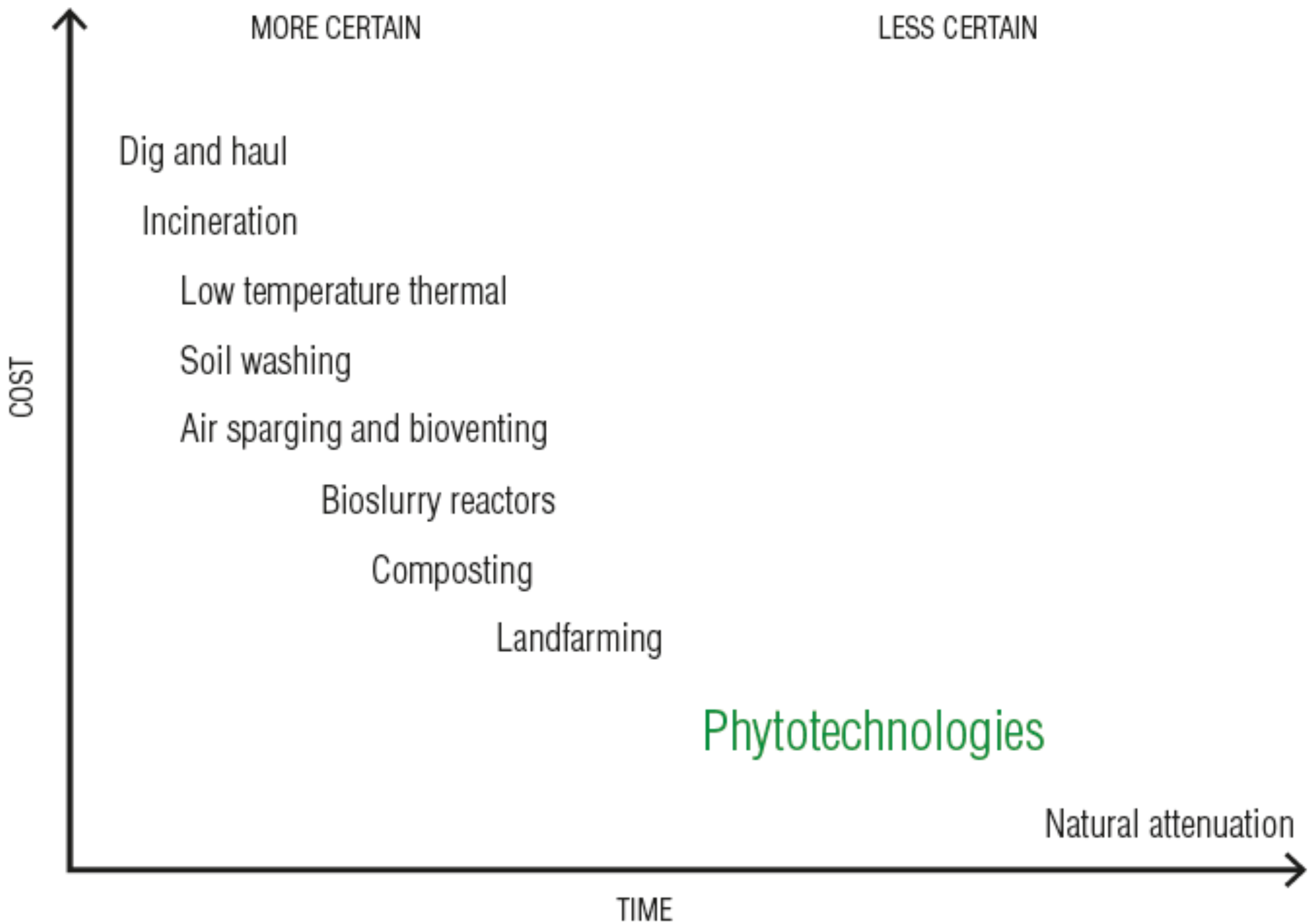
CONSTRAINTS

- Some soils may be **too toxic** or infertile for any plants to be grown.
- Phytoremediation is limited to relatively **shallow contaminated sites** and is dependent on the adaptability of the plants used.

Phytoremediation - Drawbacks

- The **elongated timescale** of phytoremediation may preclude its use in short-term site regeneration projects.
- Many projects take at least **5 years** or more to reach maturity and some could be designed as legacy projects, with lifespans of 50 years or more.

Phytoremediation - Drawbacks



Phytoremediation - Drawbacks

In some cases, plants may need to be **harvested** and **disposed** as a waste to remove a pollutant; this can be costly and energy intensive.

Phytoremediation - Drawbacks

Monitoring may be required and soil- and groundwater-testing practices may be **costly**

Phytoremediation - Drawbacks

Current legal and regulatory conditions surrounding phytoremediation may be difficult to navigate (missing in some countries).

Phytoremediation - Classification

ORGANIC CONTAMINANTS

Pollutants compounds containing bonds of carbon, oxygen and hydrogen

INORGANIC CONTAMINANTS

Elemental pollutants released into the environment

Phytoremediation - Classification

ORGANIC

Common Organic Pollutants **Successfully Targetable** by Phytoremediation

Pollutant	Typical Sources
Petroleum Hydrocarbons: Oil, Gasoline, Benzene, Toluene, PAHs, gas additive: MTBE: Methyl Tertiary Butyl Ether	Fuel spills, leaky underground or above-ground storage tanks
Chlorinated Solvents: such as TCE: trichloroethylene(most common pollutant of groundwater)	Industry and transportation, dry cleaners
Pesticides: Atrazine, Diazinon, Metolachlor,Temik (to name a few)	Herbicides, insecticides and fungicides from agricultural and landscape applications
Explosives: RDX	Military activities

Phytoremediation - Classification

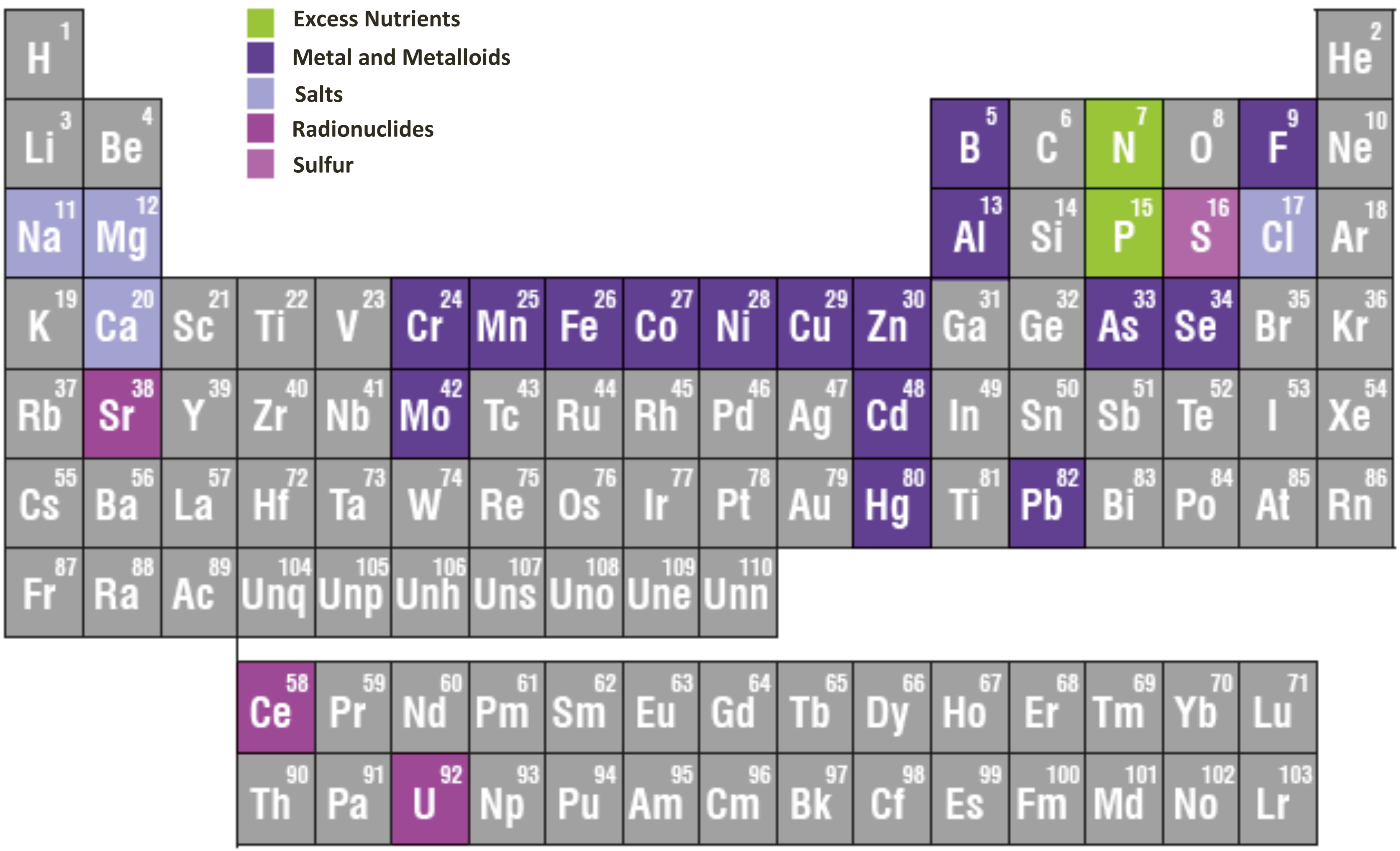
ORGANIC

Common Organic Pollutants **Not Easily Targetable** by Phytoremediation

Pollutant	Typical Sources
Persistent Organic Pollutants: Including DDT, Chlordane, PCBs	Historic use as pesticides or in products such as insulation and caulking
Explosives: TNT	Military activities

Phytoremediation - Classification

INORGANIC



Phytoremediation - Classification

INORGANIC

Common Inorganic Pollutants **Successfully Targetable** by Phytoremediation

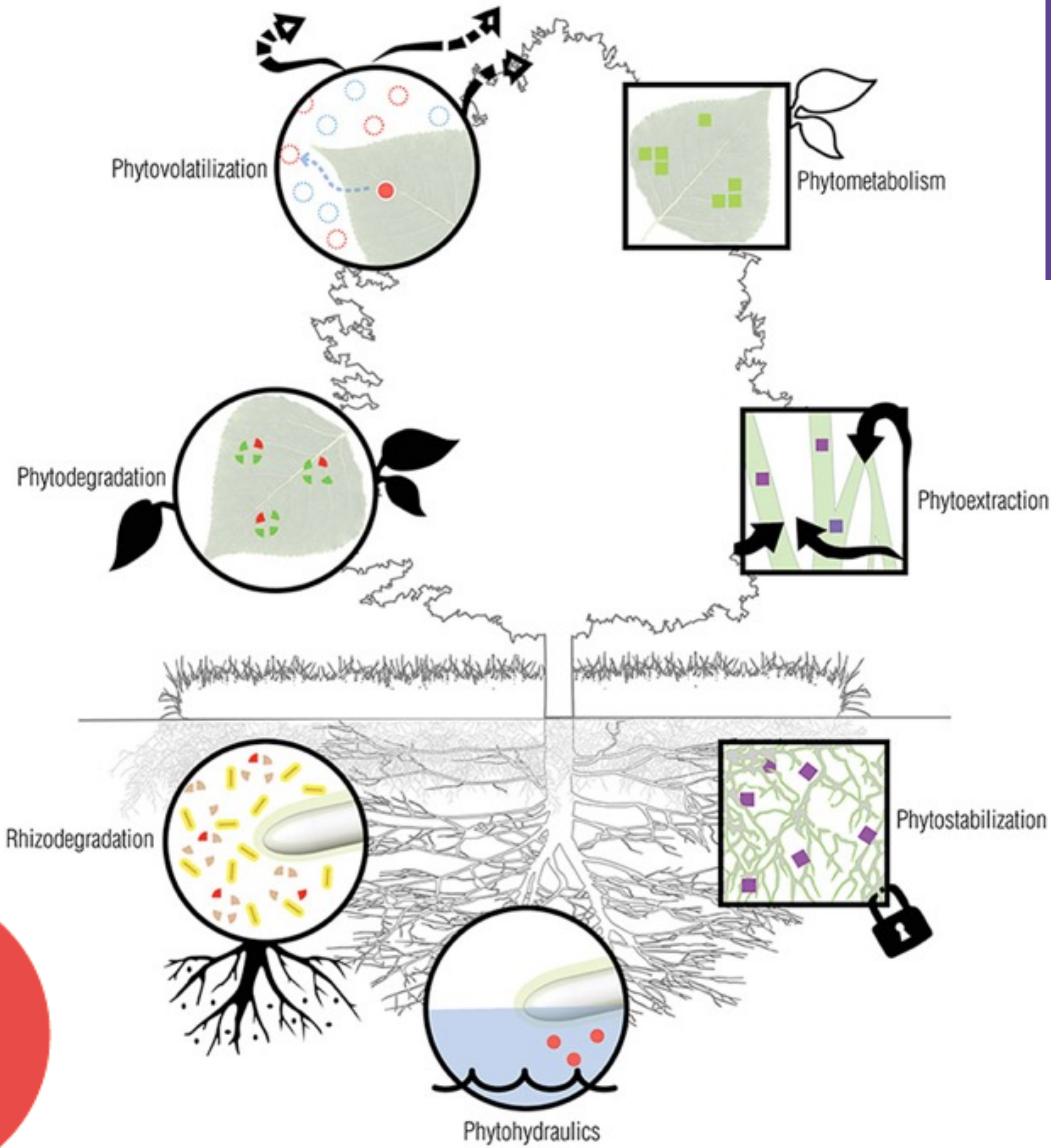
Pollutant	Typical Sources
Plant Macronutrients: Nitrogen and Phosphorus	Wastewater, landfills, agriculture and landscape practices
Metals/Metaolloids: Arsenic (As), Nickel (Ni), Selenium (Se) (shorter time frame) Cadmium (Cd) and Zinc (Zn) (longer time frame)	Mining, industry, emissions, automobiles and agriculture

Phytoremediation -Classification

INORGANIC

Common Inorganic Pollutants **Not Easily Targetable** by Phytoremediation

Pollutant	Typical Sources
Metals/Metalloids: Boron (B), Cobalt (Co), Copper (Cu), Chromium (Cr), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Lead (Pb), Fluorine (F), Mercury (Hg), Aluminum (Al)	Mining, industry, emissions, automobiles, agriculture, and lead paint
Salts: Sodium chloride, Magnesium chloride	Road de-icing, gas fracking and oil drilling, fertilizers, herbicides
Radioactive Isotopes: Cesium, Strontium, Uranium	Military and energy production activities



INORGANIC

ORGANIC

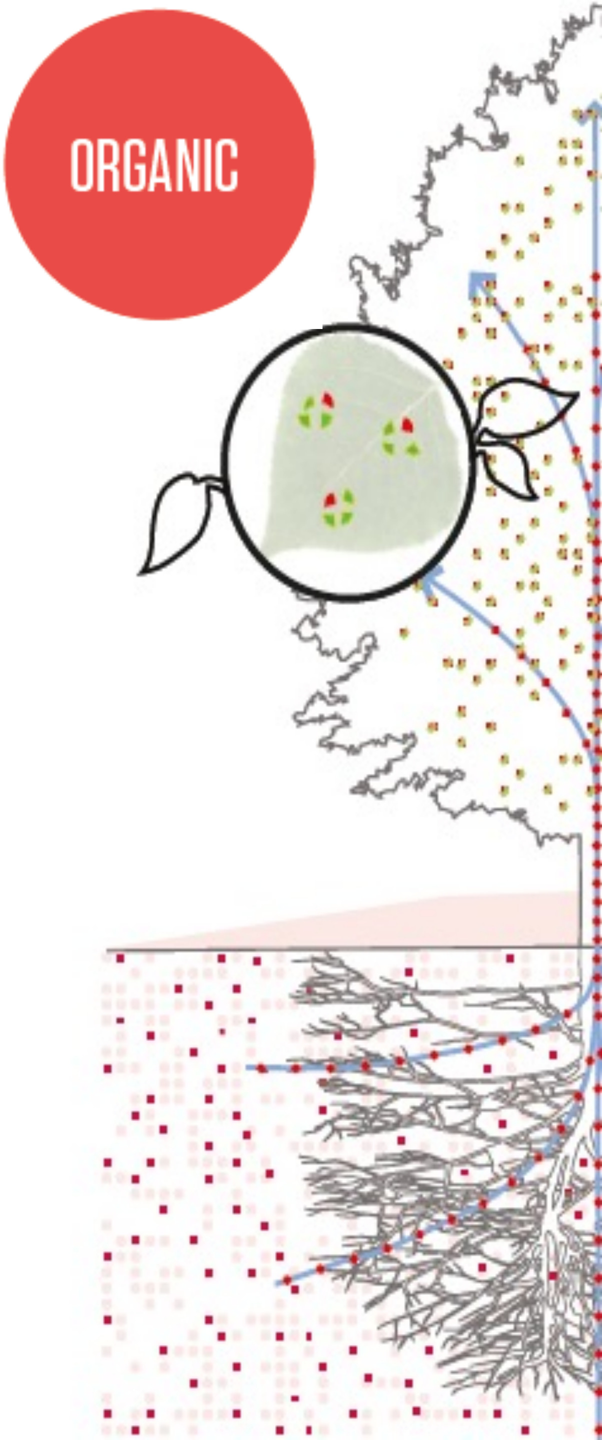
From: Kennen and Kirkwood, 2015

1. Phytodegradation

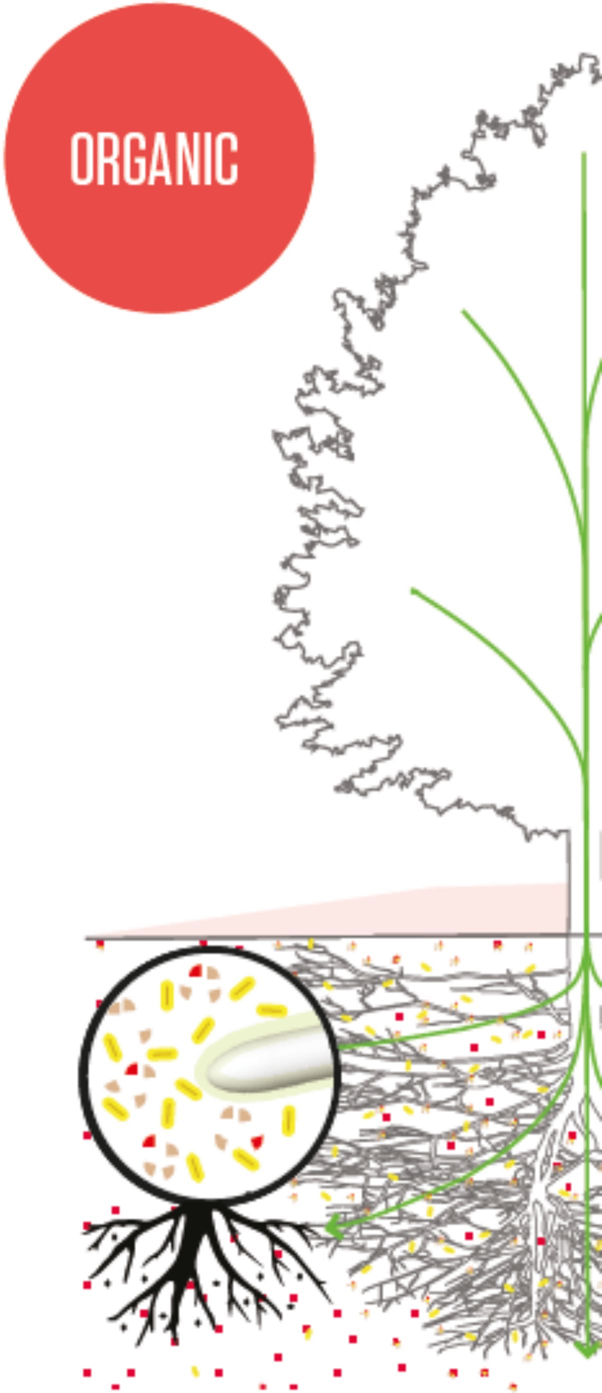
The contaminant is taken up by the plant's root and **broken down** into (often) non-toxic metabolites.

The plant often uses such by-product metabolites in its growth process, so little contamination remains.

The degradation occurs during photosynthesis or by internal enzymes and/or microorganisms (endophytes) living within the plant.



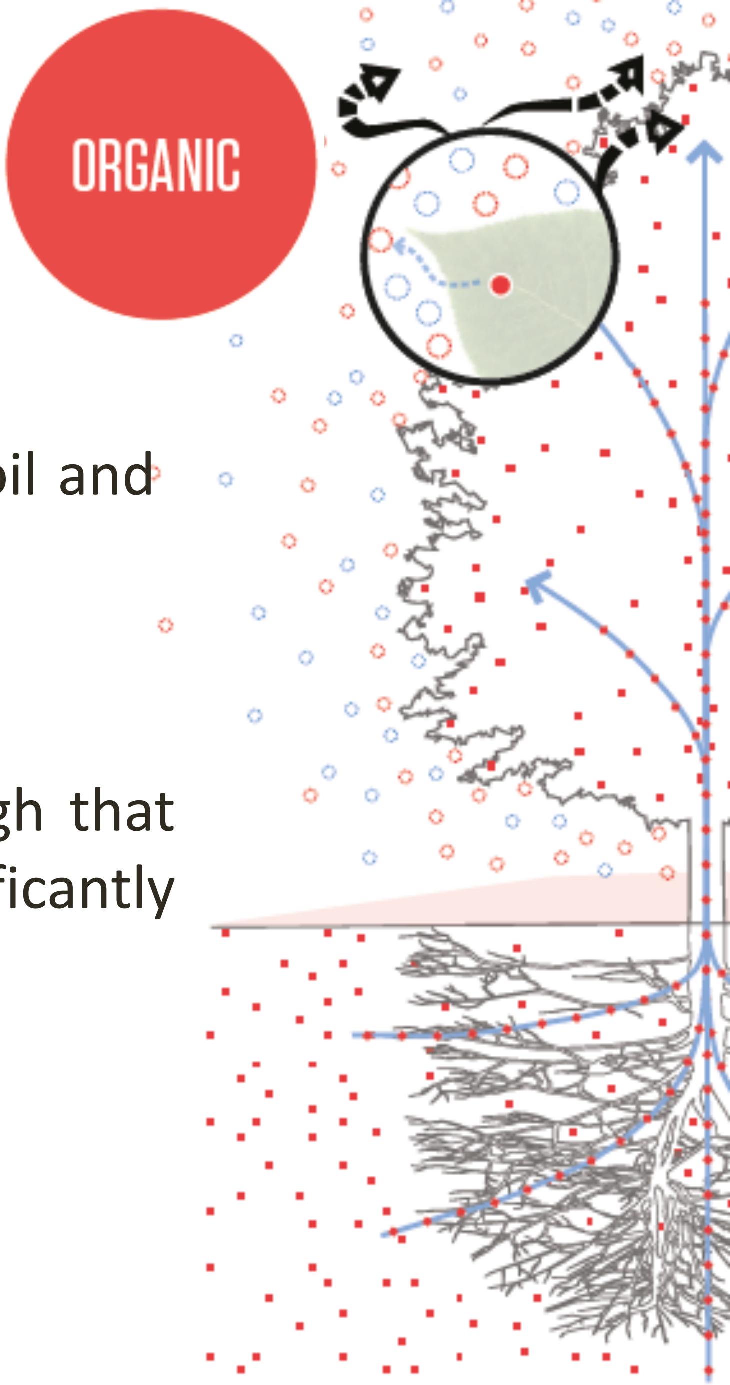
2. Rhizodegradation



- The **root exudates** released by the plant and/or the **soil microorganisms** around the roots **break down** the contaminant.

- The **plant** essentially acts as a **reactor** by helping to increase numbers of microorganisms and sometimes encouraging the growth of specific degrading communities of microbes

3. Phytovolatilization

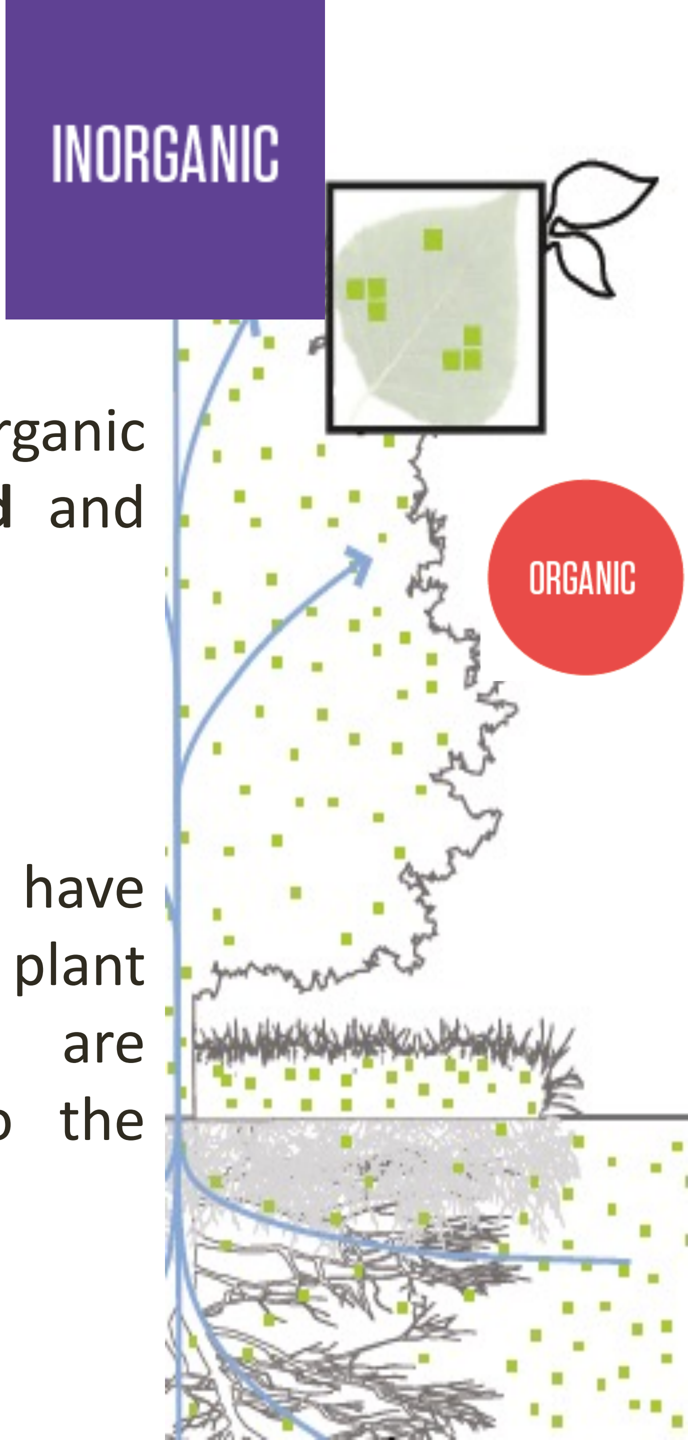


- The plant takes up the pollutant in the soil and **transpires** it to the atmosphere as a gas.

- The gas is usually released slowly enough that the surrounding air quality is not significantly affected.

4. Phytometabolism

- The nutrients needed by plants (inorganic elements such as N, P, K) are **processed** and turned into **plant biomass**.
- Sometimes when **organic contaminants** have been broken down by a plant (phytodegradation), the metabolites are **phytometabolized** and incorporated into the plant's biomass.



5. Phytoextraction

INORGANIC

- Phytoextraction is the ability of the plant to **take up** a pollutant from soils and water and **store it into the biomass**.

- To remove pollutants from the site, **biomass** must be **harvested** before the leaf drop.

- The harvested plant material can be **burned**, followed by disposal in a landfill, reused for biomass or burned and smelted into ore to collect valuable metals (called **phytomining**)

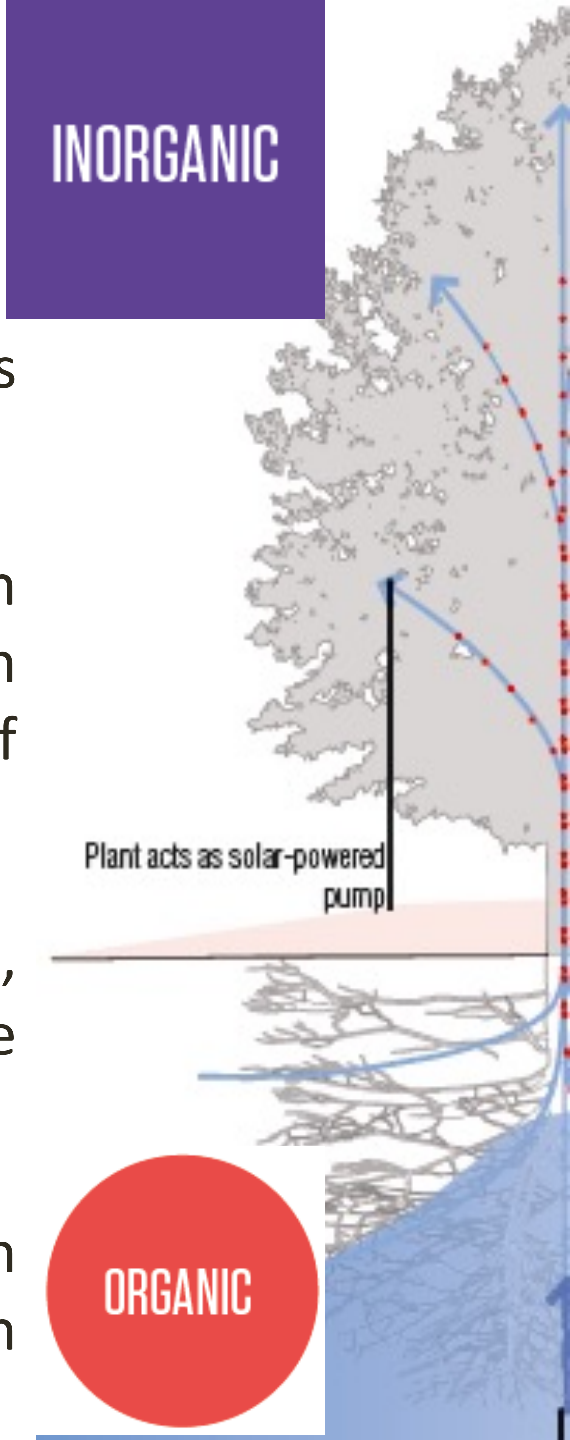
6. Phytohydraulics

- Phytohydraulics is the **pull** created as water is brought into the roots.

- The pull can be so strong that groundwater can be drawn towards a plant and many plants can actually **change** the **direction** or stop the flow of **groundwater**.

- If the groundwater is contaminated, phytohydraulics may be able to attenuate plume movements.

- This technique coupled with phytodegradation/phytovolatilization can eliminate the pollutant.



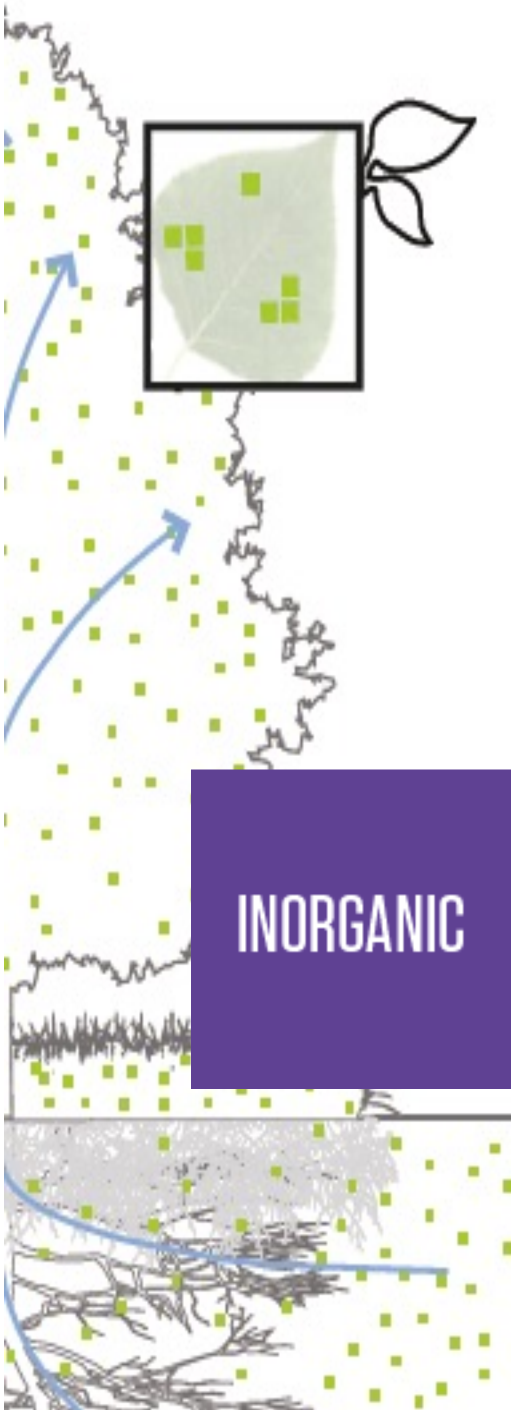
7. Phytostabilization

- The plant **holds** the contaminant in place so that it does not move off site.

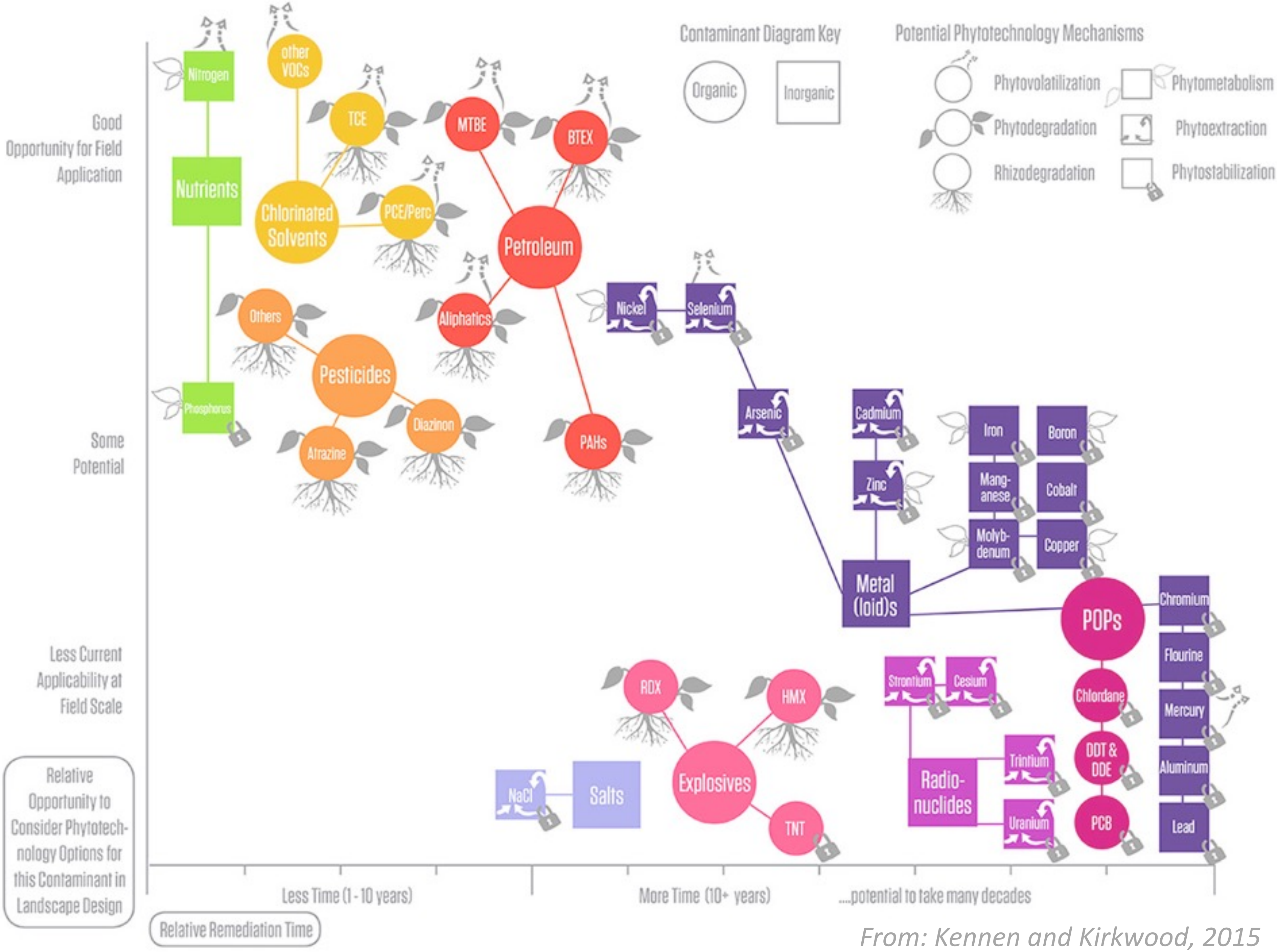
- The plant **releases phytochemicals** into the soil that **bind contaminants** making them less bioavailable.

8. Rhizofiltration

- In constructed wetlands and stormwater filters, (e.g. willow vegetation filters) the roots of plants **filter** out pollutants from the **water**.



Name	Description	Pollutant
Phytodegradation	Plant destroys it	ORGANIC
Rhizodegradation	Soil biology destroys it	ORGANIC
Phytovolatilization	Plant turns it into a gas	ORGANIC, INORGANIC
Phytometabolism	Plant uses it in growth, incorporates it into biomass	ORGANIC, INORGANIC
Phytoextraction	Plant takes it up, stores it and is harvested	ORGANIC, INORGANIC
Phytohydraulics	Plant draws it close and contains it with water	ORGANIC, INORGANIC
Phytostabilization/ Phytosequestration	Plant caps and holds it in place	ORGANIC, INORGANIC
Rhizofiltration	Contaminant is filtered from water by roots and soil	ORGANIC, INORGANIC



From: Kennen and Kirkwood, 2015

Plant characteristics and installation considerations

Plant characteristics and installation considerations

1 - TOLERANCE TO POLLUTION AND COMPETITIVENESS

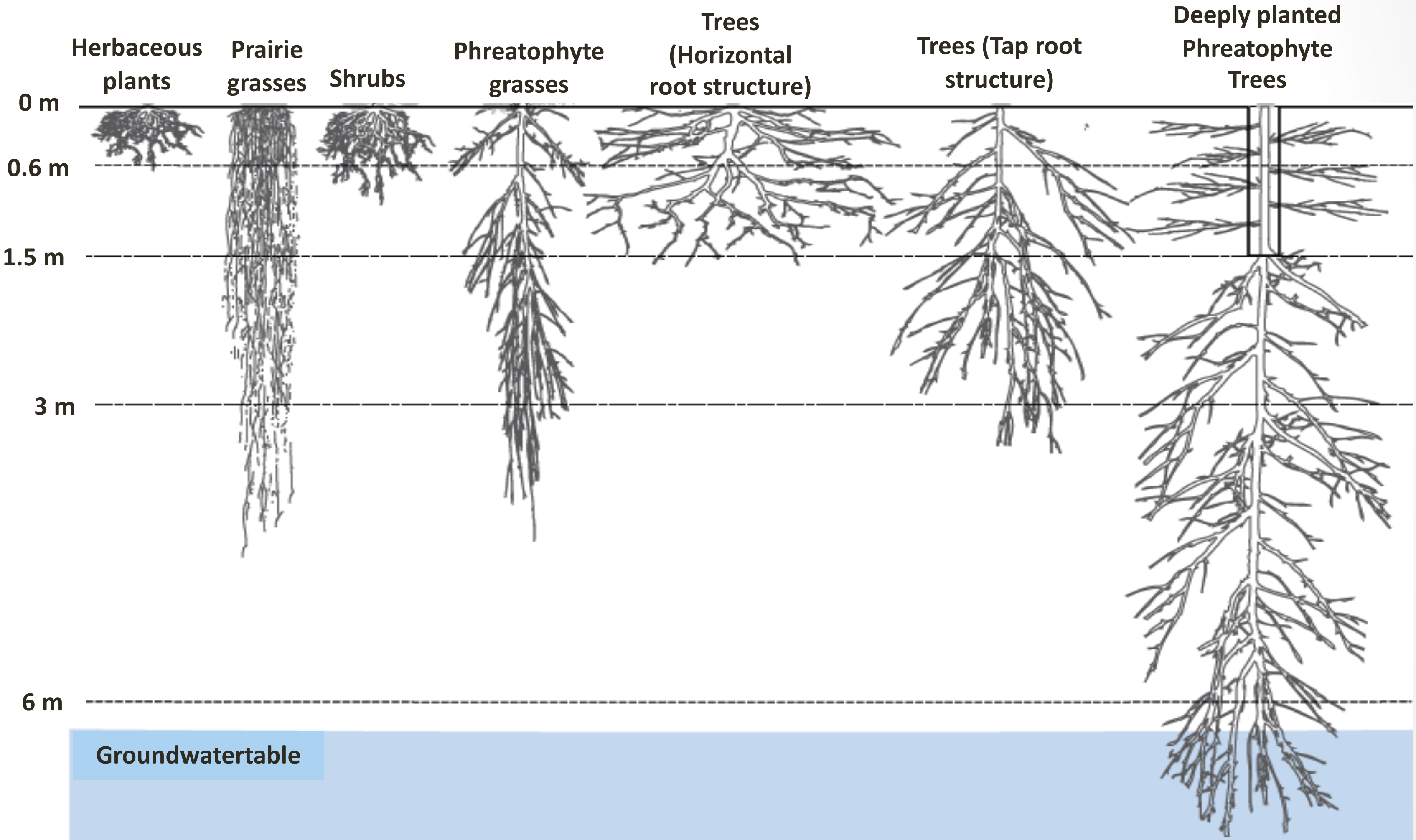
- If plants cannot grow on a site, it is impossible for a phytotechnology system to be successful.

- When selecting species, the very first qualifier to consider is whether it will **tolerate** the encountered concentrations of pollutants.

- Hardy perennials, which adapt to the local climate and aggressively outcompete weeds are preferred.

2 - ROOT DEPTH AND STRUCTURE

- Since the plant must be able to reach the pollutant, phytoremediation is limited by root depth.



Plant characteristics and installation considerations

Deep soil and/or groundwater pollution

- **Prairie perennial** species.

- **Phreatophytes** (usually they have at least a part of roots constantly in touch with water). These plants send long root systems in search of water and can reach depths of up to 6-8 m (e.g. poplar and willow).

Plant characteristics and installation considerations

Shallow soil pollution

- When contamination is near the surface, species with **fibrous root** zones are able to come in contact with contamination, because of the number of **small, dense roots** dispersed through the soil.

- Fibrous roots provide more surface area for **colonization by microorganisms** and allow close interaction between the contaminant and the microbiology associated with roots.

Plant Species for Phytoremediaion of Organic Compounds: Deep-rooted tree and shrub species in temperate regions

Latin	Common	Petroleum Category Targeted	Contaminant	Vegetation Type	Reference
Acer platanoides	Norway Maple	Easy	BTEX	Tree	Cook and Hesterberg, 2012
Alnus glutinosa	Black Alder	Both		Tree/Shrub	Tischer and Hubner, 2002
Betula pendula	European White Birch	Hard	PAH	Tree	Rezek et al., 2009
Celtis occidentalis	Hackberry	Both	BTEX-TPH-PAH	Tree	Cook and Hesterberg, 2012
Eucalyptus spp.	Eucalyptus	Easy	BTEX	Tree	Coltrain, 2004
Fraxinus pennsylvanica	Green Ash	Hard	PAH	Tree	Spriggs et al., 2005
Paulownia tomentosa	Princess Tree	Both	PAH	Tree	Macci et al., 2012
***Populus* spp**.	Poplar species and hybrids	Both	Aniline, Benzene, Ethylbenzene, Penol, Toluene, m-Xylene, PAH, BTEX, MTBE, DRO, TPH	Tree	Applied Natural Sciences, Inc., 1997 Barac et al., 2009 Burken and Schnoor, 1997a Coltrain, 2004 Cook et al., 2010 Cook and Hesterberg, 2012 El-Gendy et al., 2009 Euliss et al., 2008 Euliss, 2004 Fagiolo and Ferro, 2004 Ferro et al., 2013 Ferro, 2006 ITRC PHYTO 3 Kulakow, 2006b Kulakow, 2006 Luce, 2006 Ma et al., 2004 Olderbak and Erickson, 2004 Palmroth et al., 2006 Spriggs et al., 2005 Tossell, 2006 Unterbrunner et al., 2007 Weishaar et al., 2009 Widdowson et al., 2005
***Salix* spp.**	Willow	Both	DRO TPH BTEX PAH	Tree/Shrub	Carman et al., 1997, 1998 Coltrain, 2004 Cook and Hesterberg, 2012 Euliss et al., 2008

Hevy Metal phytoextraction

INORGANIC

Hyperaccumulators

Plus:

- actively accumulate several **percent of TEs** in the dry mass of their above-ground parts;

Minus

- they **may not produce enough biomass** to be useful for harvesting and extraction;
- they may not be native to a site and could be **weedy** or **invasive**, or difficult to cultivate;
- hyperaccumulators have been confirmed only for few TEs (Ni, Zn, Cd, Mn, As and Se)

Hevy Metal phytoextraction

INORGANIC

High-biomass species

Plus:

- more effective to use in field conditions than hyperaccumulators especially when paired with other amendments to change the soil chemistry;
- easier to grow, readily available as seeds/cutting and better adapted to soil conditions and climate;
- easier to harvest;

Minus

- Lower contaminant up-take rate than hyperaccumulators

Plant Species for Phytoremediaion of Heavy metals

Hyperaccumulators

Latin	Common	Targeted TEs	Vegetation Type	Reference
Arabidopsis halleri	Rockcress	Cd, Zn	Herbaceous	Banasova and Horak, 2008
Dichapetalum gelonoides	Gelonium Poison-Leaf	Zn	Herbaceous	Reeves, 2006
Minuartia verna	Spring Sandwort	Zn	Herbaceous	Reeves, 2006
Polycarpaea synandra	Polycarpaea	Zn	Herbaceous	Reeves, 2006
Thlaspi caerulescens	Alpine Pennycress	Cd, Zn	Herbaceous	Baker et al., 2000 Broadhurst et al., 2013 Chaney et al., 2005, 2010 Lasat et al., 2001 McGrath et al., 2000 Reeves, 2006 Rouhi, 1997 Saison et al., 2004 Salt et al., 1995 Schwartz et al., 2006 Simmons et al., 2013, 2014
Thlaspi capaeifolium ssp. *Rotundifolium*	Pennycress	Zn	Herbaceous	Baker and Brooks, 1989 Rascio, 1977 Reeves, 2006
Viola caliminaria	Viola	Cd, Zn	Herbaceous	Baker and Brooks, 1989 Reeves, 2006

Not - Hyperaccumulators

Latin	Common	Targeted TEs	Vegetation Type	Reference
Amaranthus hypochondriacus	Amaranth	Cd	Herbaceous	Li et al., 2013
Brassica juncea	Indian Mustard	Cd, Zn	Herbaceous	Bauddh and Singh, 2012 Blaylock et al., 1997 Bluskov et al., 2005 Lai et al., 2008
Brassica napus	Rapeseed	Cd, Zn	Herbaceous	Thewys et al., 2010 Van Slycken et al., 2013 Witters et al., 2012
Helianthus annuus	Sunflower	Cd, Zn	Herbaceous	Adesodun et al., 2010 Cutright et al., 2010 Nehnevajova et al., 2005 Nehnevajova et al., 2007 Padmavathiamma and Li, 2009 Stritsis et al., 2014
Populus spp.	Hybrid poplar	Cd, Zn	Tree	Hu et al., 2013 Ruttens et al., 2011 Van Slycken et al., 2013 Thewys et al., 2010 Hinchman et al., 1997
Salix spp.	Willow	Cd, Zn	Shrub	Algreen et al., 2013 Evangelou et al., 2012 Ruttens et al., 2011 Thewys et al., 2010 Van Slycken et al., 2012 Witters et al., 2012
Sedum alfredii	Sedum	Cd, Zn	Herbaceous	Li et al., 2011 Lu et al., 2013 Wang et al., 2012 Xiaomei et al., 2005 Xing et al., 2013 Zhuang et al., 2007

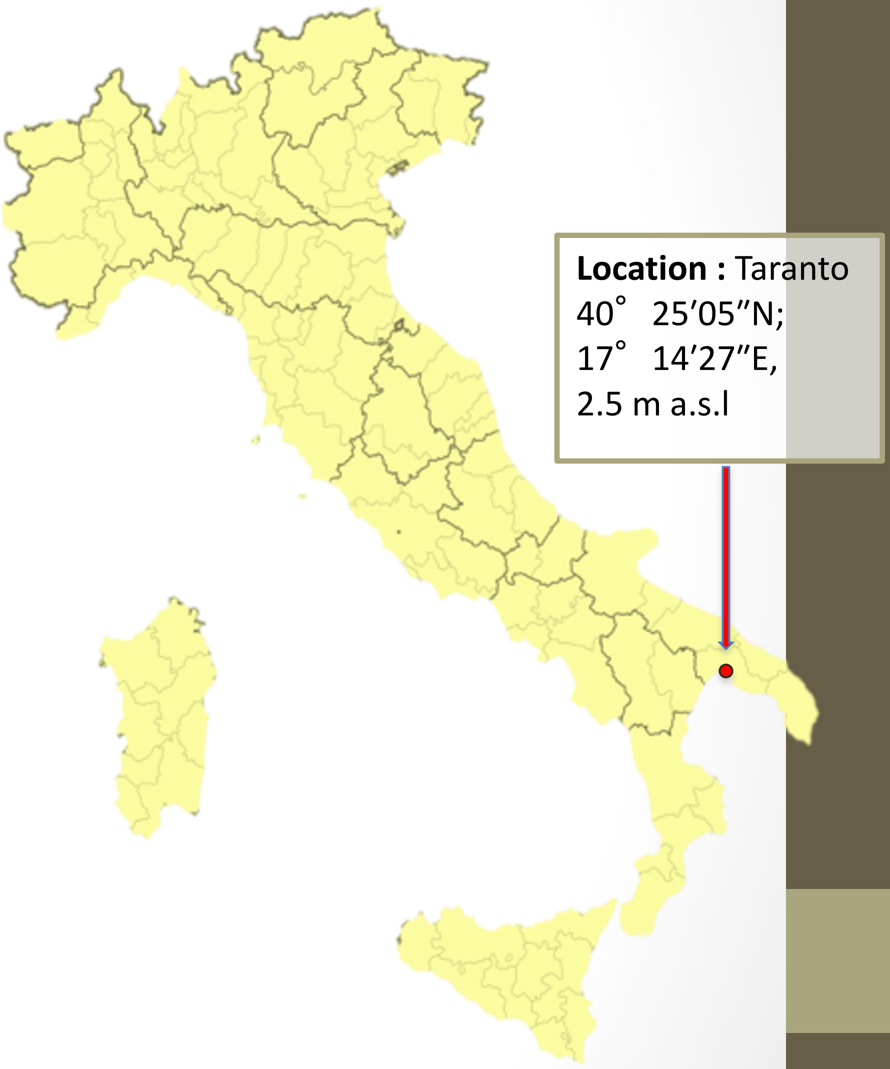
Phytoextraction of trace elements by different species under Mediterranean conditions

INORGANIC

Site description

- Military site formerly used for the disposal of metal waste

- Soil with scattered, moderate mixed-contamination TEs (Cd, Cu, Ni, Pb, Zn)



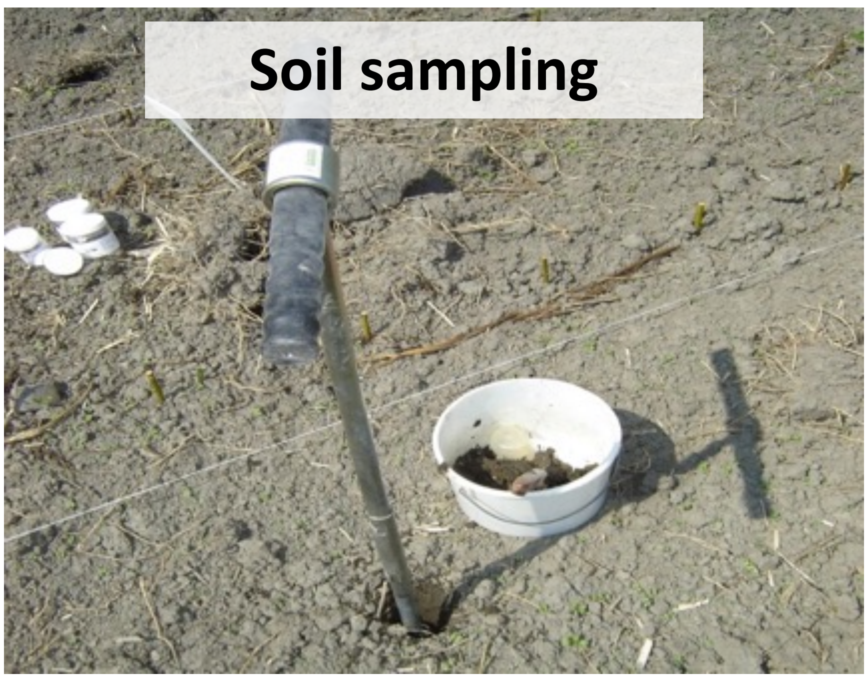

Before planting


Ploughing

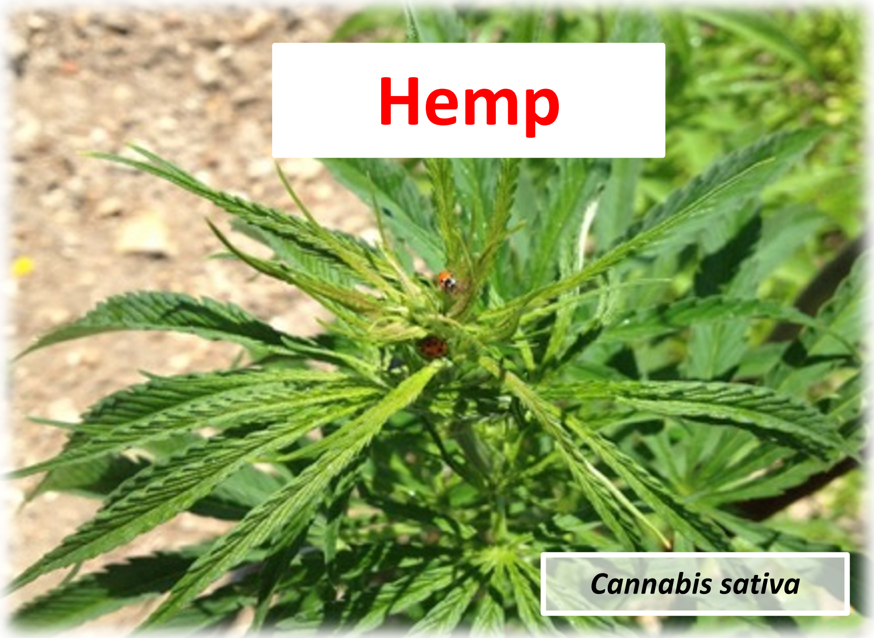

Removal of waste
materials

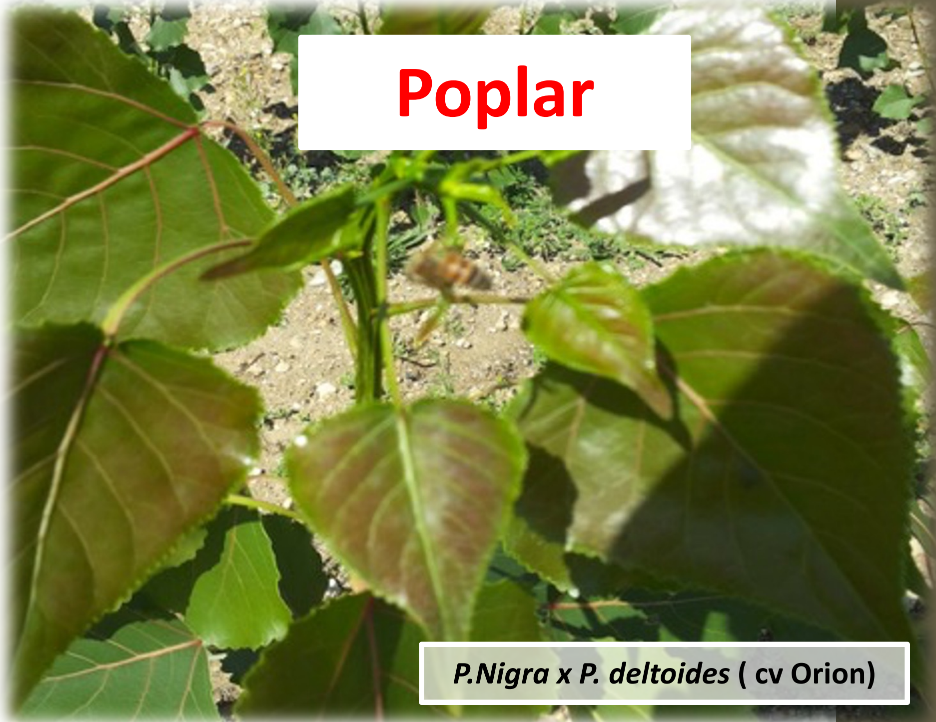

Irrigation system
set-up


Bed preparation


Soil sampling


Bed preparation


Hemp
Cannabis sativa


Poplar
P.Nigra x P. deltoides (cv Orion)


Willow
S. matsudana x alba
(cv Levante)

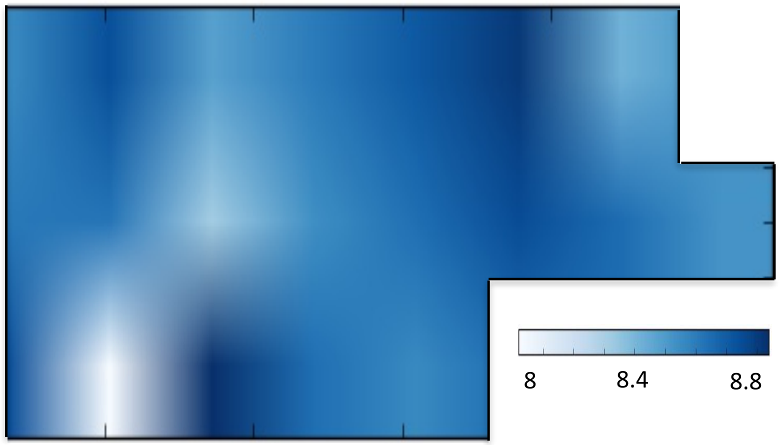

Alfalfa
Medicago sativa

Some characteristics

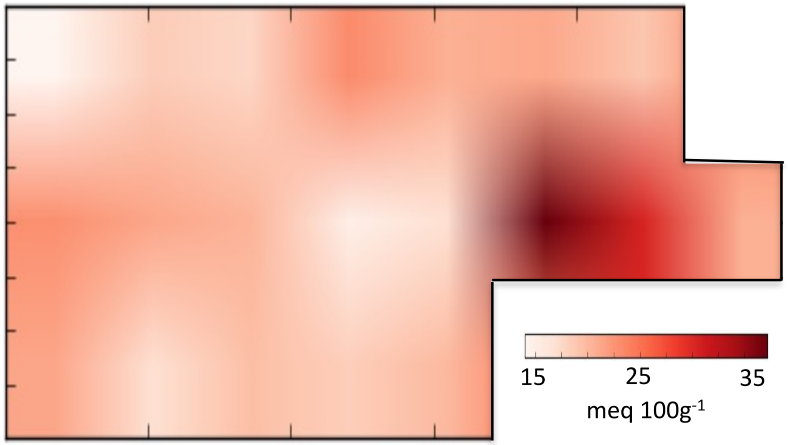
- Planting density (willow and poplar): 0.4 m x1.2 m (20,880 plants ha^{-1})
- Sowing density:20 kg ha^{-1} (alfalfa); 250 seeds m^{-2} (hemp)
- Mechanical weed control (twice each year)
- Fertilization Super Phosphate 300 kg ha^{-1} at planting, 180 kg ha^{-1} of ammonium nitrate each spring
- Sprinkler irrigation (adjusted on actual crop ET)
- Woody crops cut back after year 1, hemp sown on year 2
- Unplanted plots (4)
- Twenty plots grouped in a randomized-block design

Soil characteristics

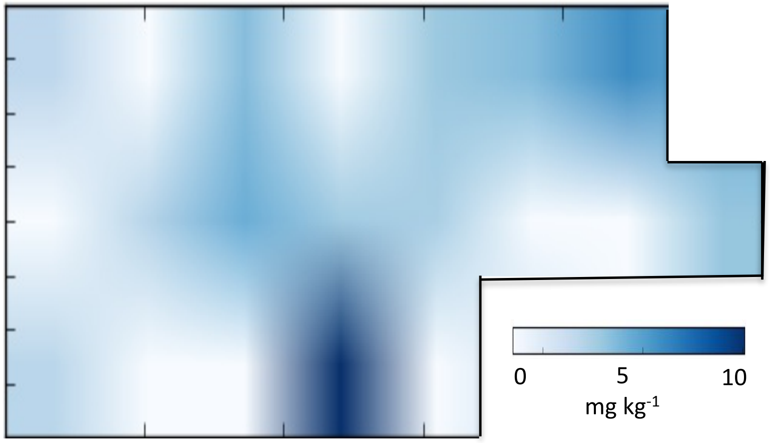
pH



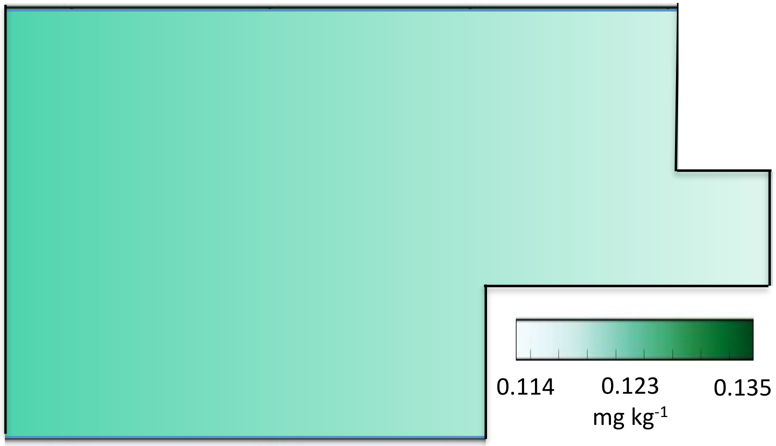
Cation-Exchange Capaciity



Total Cd

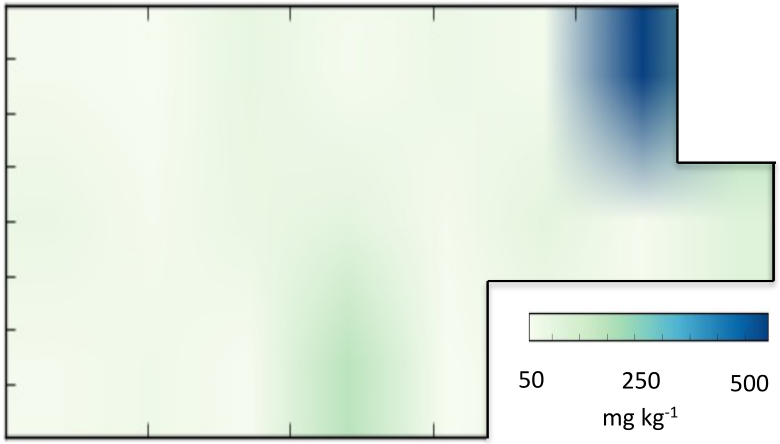


Extractable (DTPA) Cd

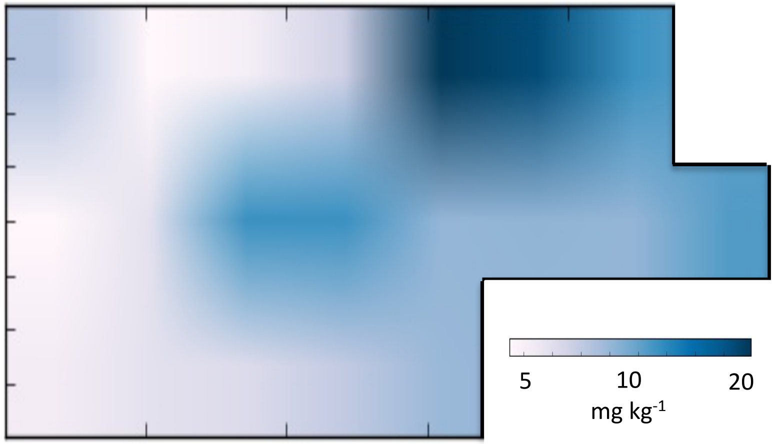


Soil characteristics

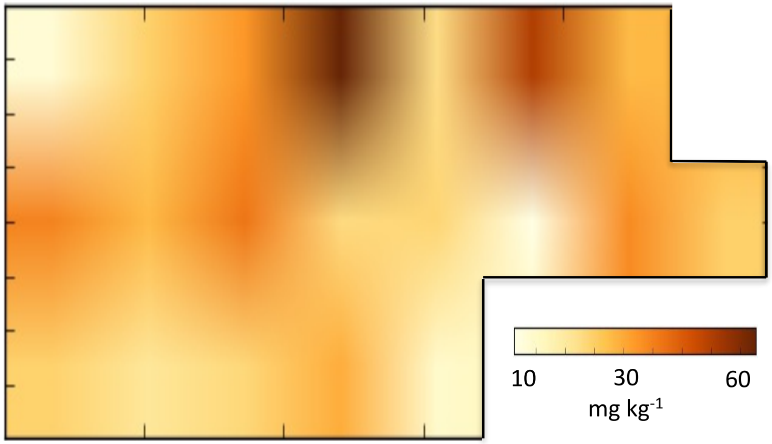
Total Cu



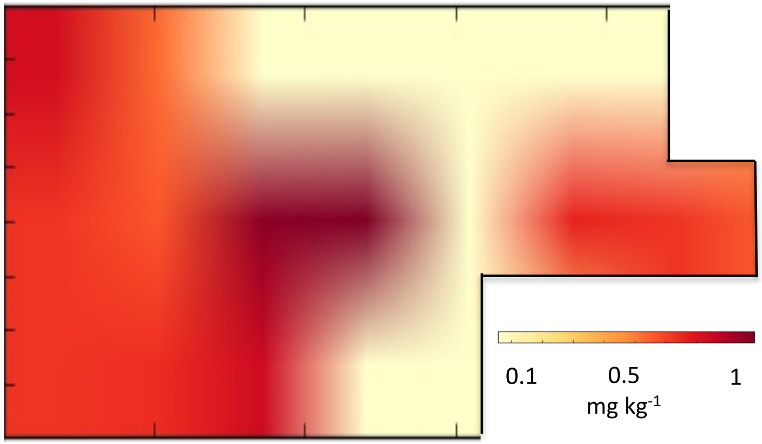
Extractable (DTPA) Cu



Total Ni

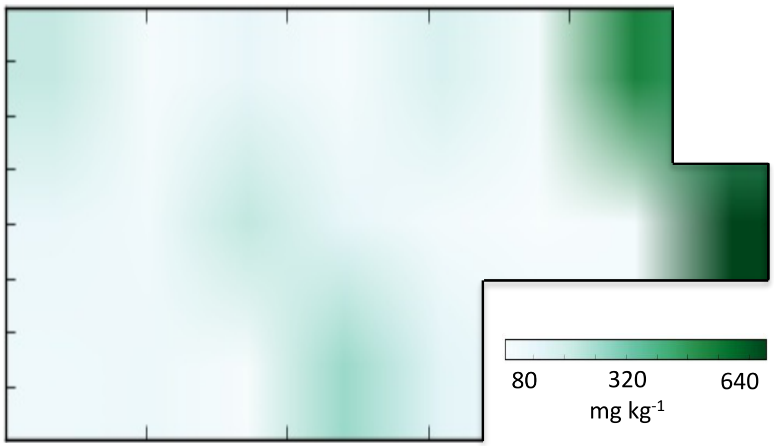


Extractable (DTPA) Ni

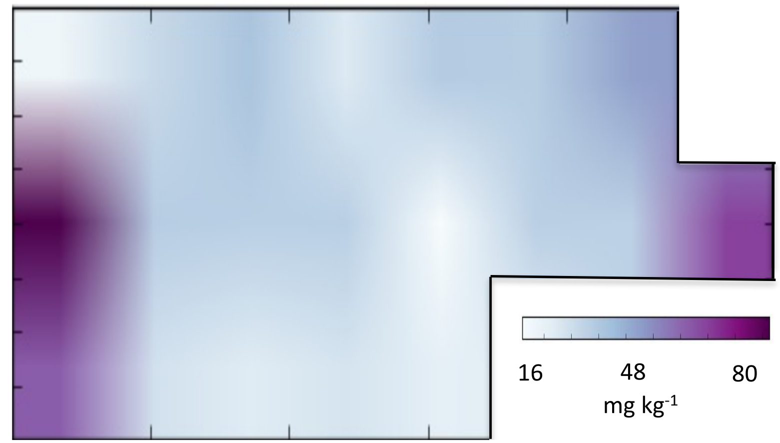


Soil characteristics

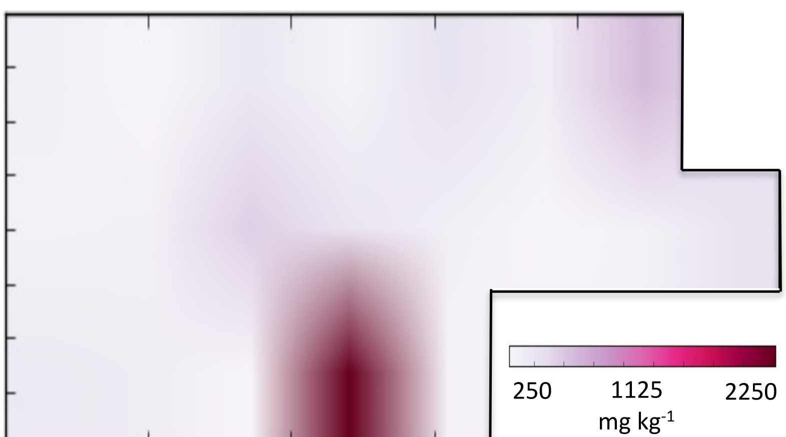
Total Pb



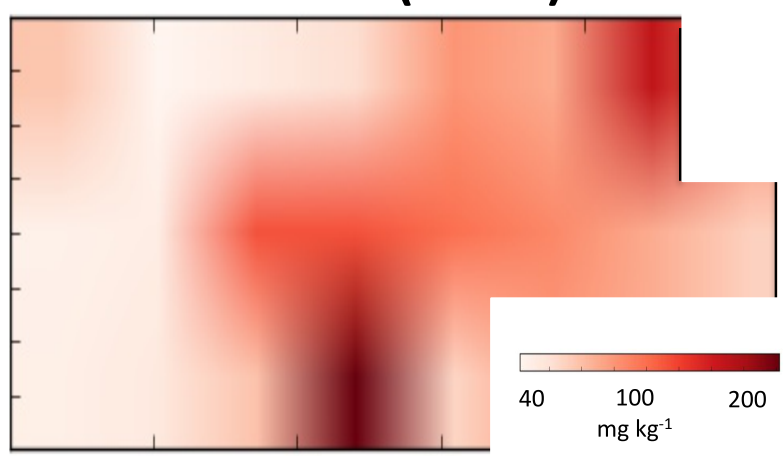
Extractable (DTPA) Pb



Total Zn



Extractable (DTPA) Zn



Measurements

1 - Biomass yield

2 - TE concentration in the biomass

3 - TE accumulation

4 - Soil TE assessment

5 – Water use

1 - Biomass yield assessment

Willow and Poplar: 5 plants/plot - Aboveground biomass (stem+leaf)
3 plant/plot - Root biomass

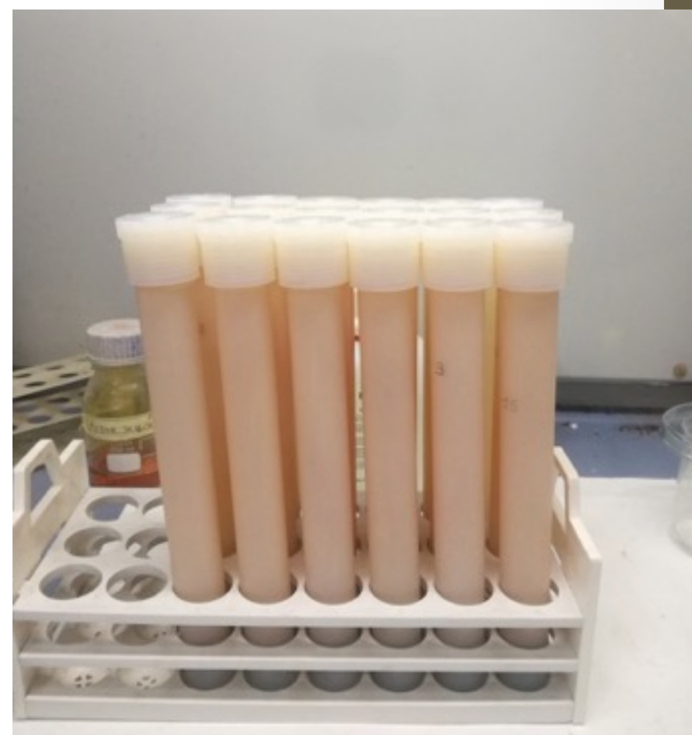
Hemp and Alfalfa: $1m^{-2}$/plot

All data expressed as **Mg ha^{-1} yr^{-1} (DW)**

2 - TE concentration in the biomass

Mineralization and ICP-AES spectroscopy

Data expressed as **mg (TE) /kg biomass (DW)**



3 - Total TE accumulation

TE_x accumulation (g ha^{-1} yr^{-1})=$[TE_x]$*Biomass yield

4 - Soil TE assessment

%=$[TE_i]$-$[TE_f]$/$[TE_i]$

Te_i initial soil TE concentration
TE_f final soil TE concentration

→ Total

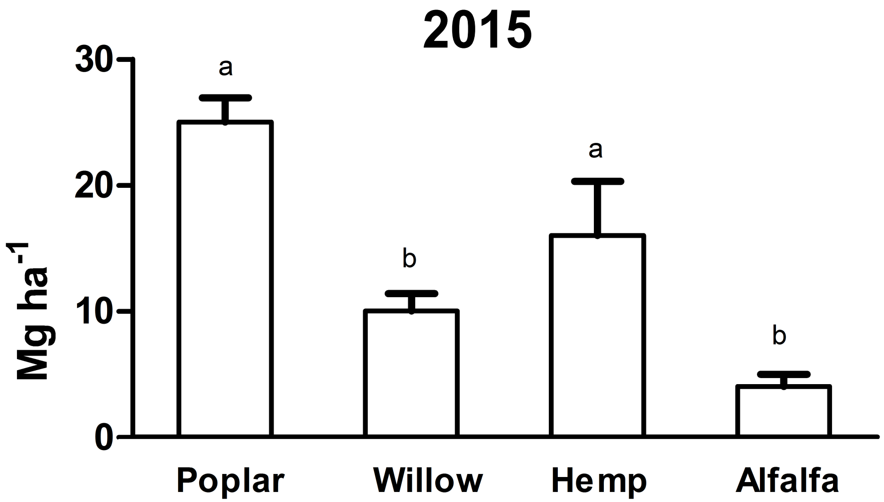
→ DTPA-extractable

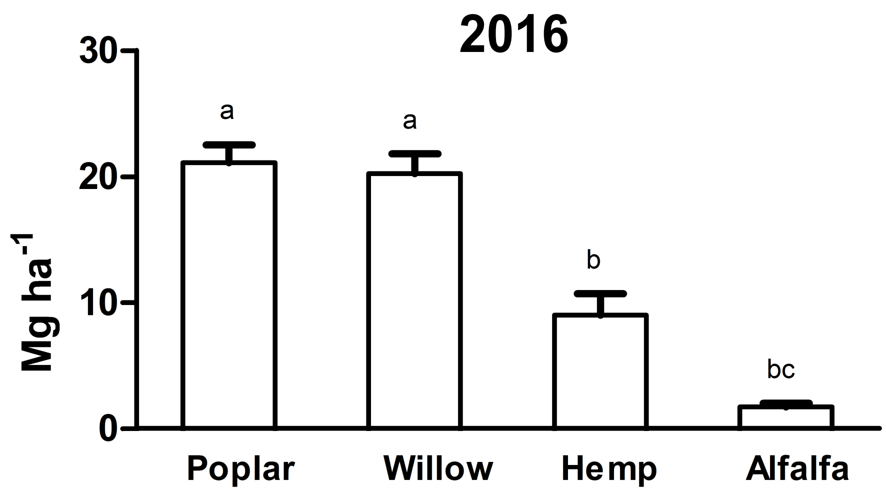
5 – Water use of different crops

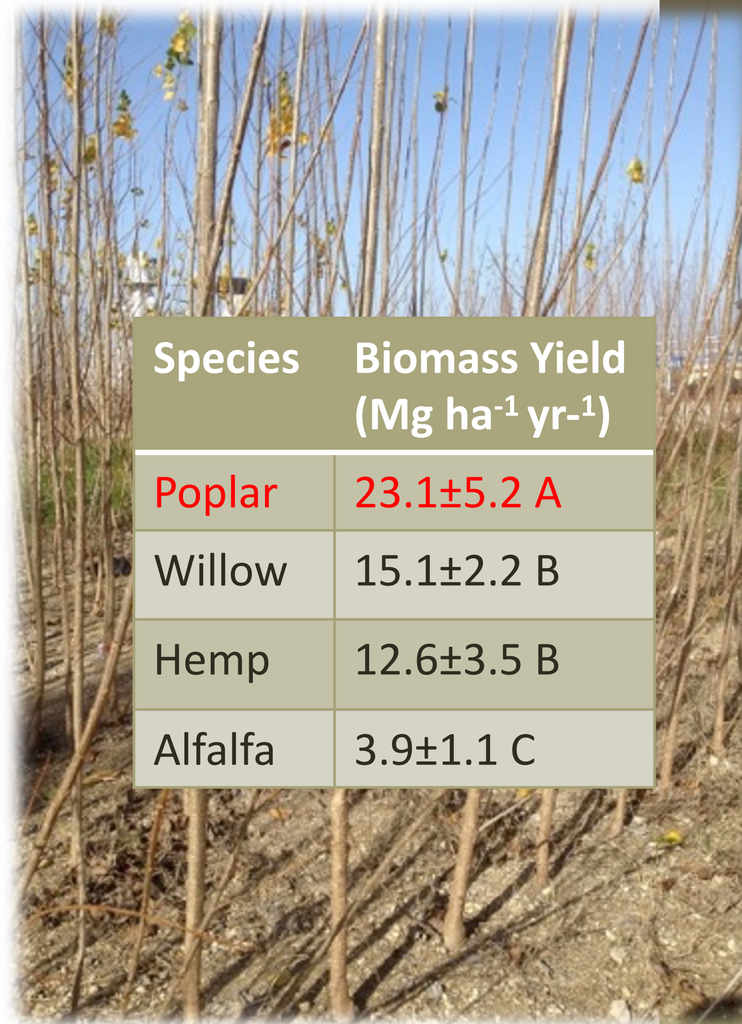
Water use ($m^3\ t^{-1}$)= Irrigation amount (m^3)/Aboveground biomass (t)

Results

Aboveground Biomass yield

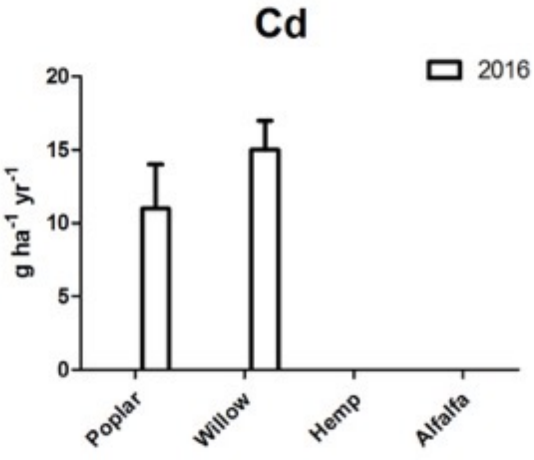


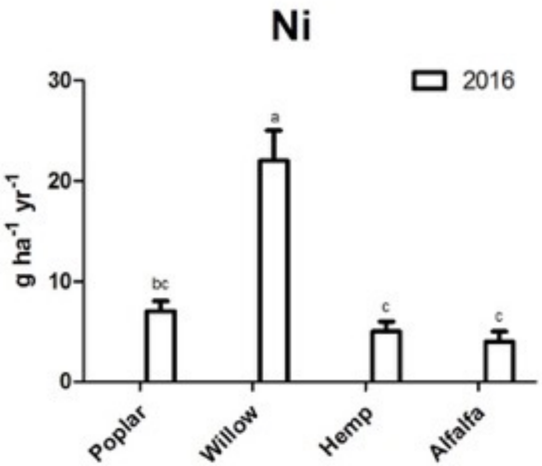




Species	Biomass Yield ($Mg\ ha^{-1}\ yr^{-1}$)
Poplar	23.1±5.2 A
Willow	15.1±2.2 B
Hemp	12.6±3.5 B
Alfalfa	3.9±1.1 C

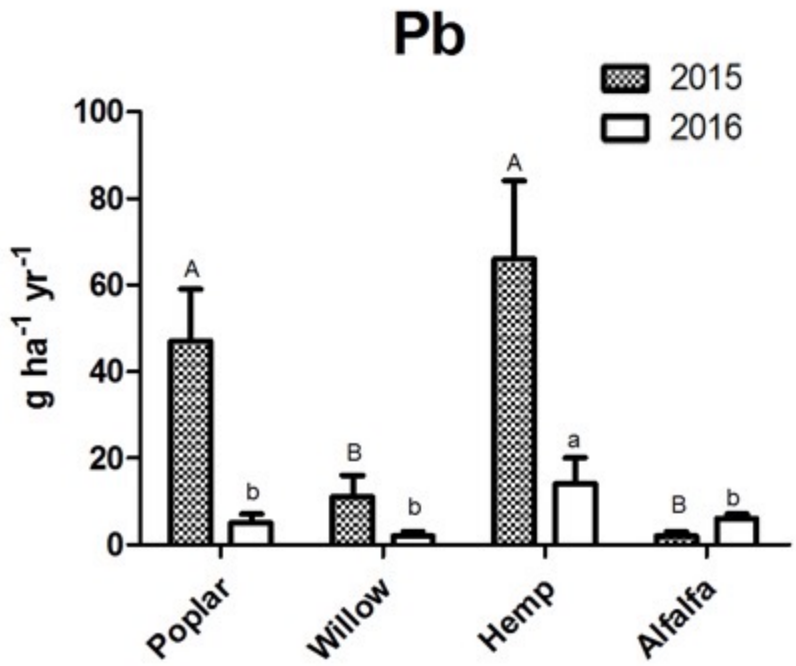
TE accumulation in aboveground biomass





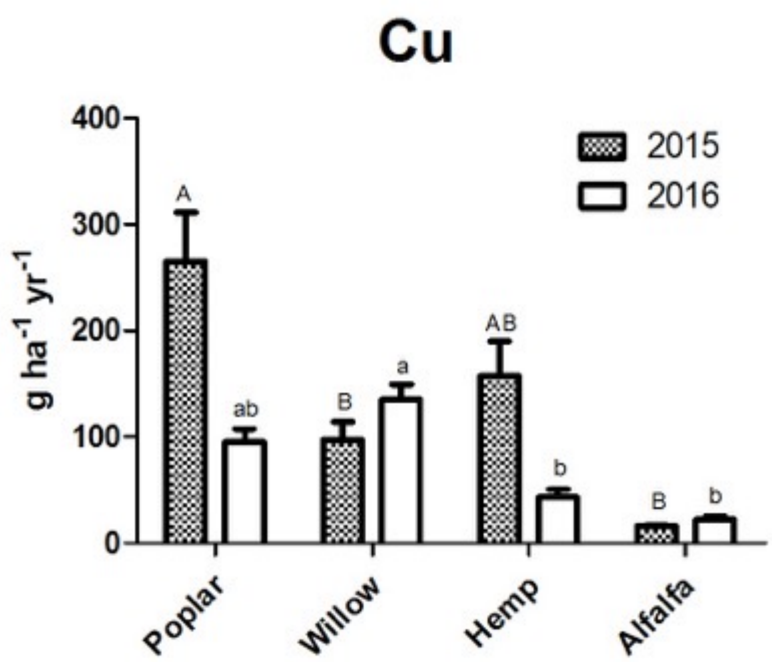
- Only found in the 2nd year
- Cd only in poplar and willow
- Ni mainly in willow
- Few grams per ha

TE accumulation in aboveground biomass



- Poplar, willow and hemp: 1st year>2nd year
- Alfalfa: 1st year<2nd year
- Best performing: **Hemp** (≈35 g ha^{-1} yr^{-1})

TE accumulation in aboveground biomass



- Poplar and hemp: 1st year>2nd year

  Willow and alfalfa: 1st year<2nd year

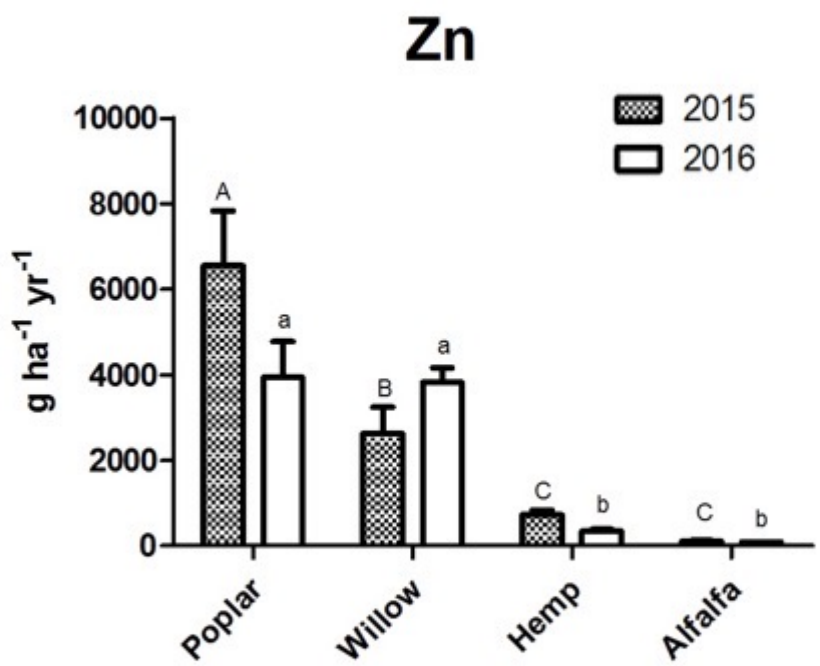
  Best performing

  Poplar (≈190 g ha^{-1} yr^{-1})

  Willow (≈115 g ha^{-1} yr^{-1})

  Hemp (≈90 g ha^{-1} yr^{-1})

TE accumulation in aboveground biomass



Poplar, and hemp: 1st year>2nd year

Willow and alfalfa: 1st year<2nd year

Best performing:

Poplar (≈5,200 g ha^{-1} yr^{-1})

Willow (≈3,200 g ha^{-1} yr^{-1})

Decrease in soil TE concentration

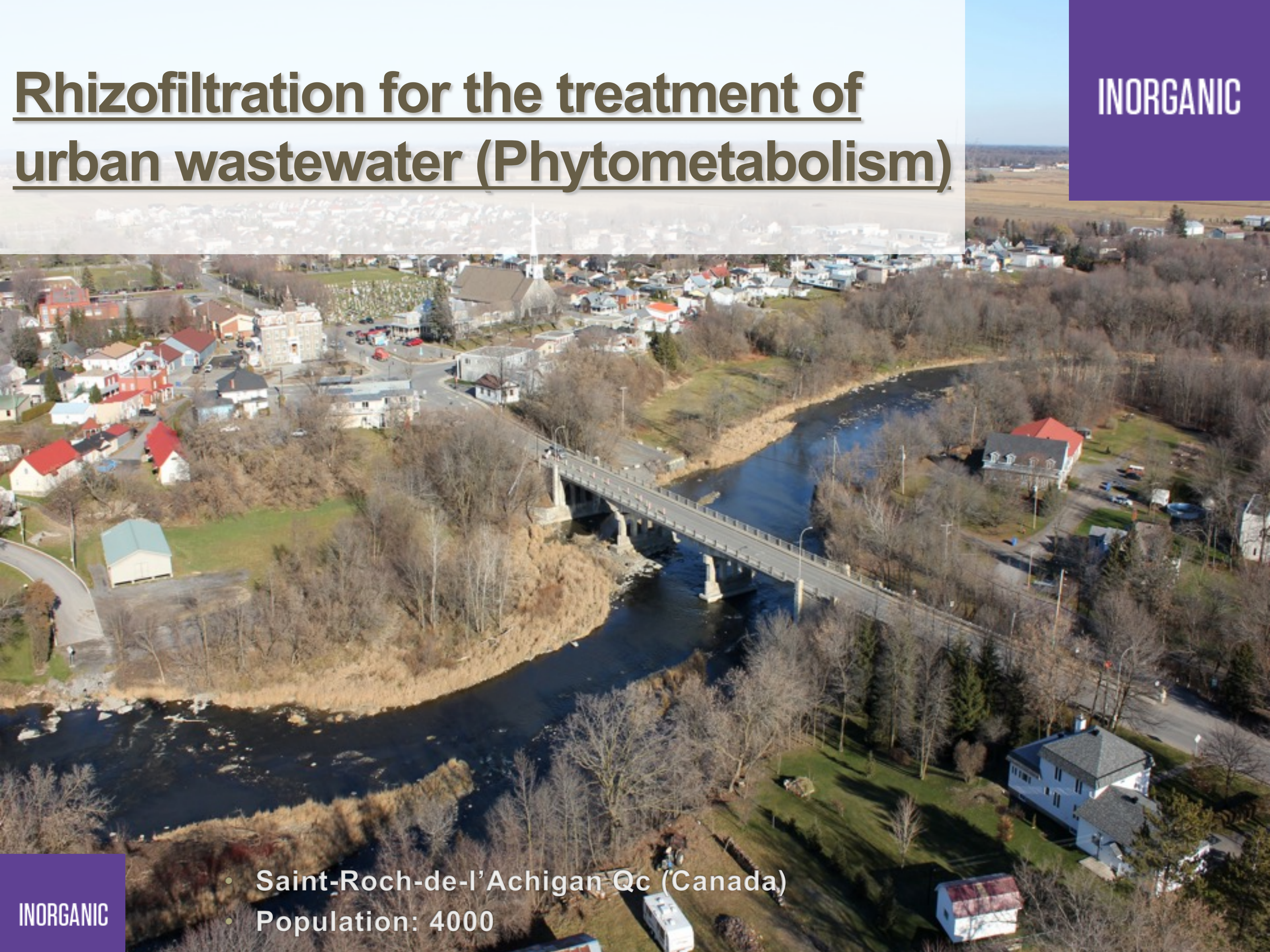
	Cadmium		Copper		Nickel		Lead		Zinc	
	Tot	DTPA-Ex	Tot	DTPA-Ex	Tot	DTPA-Ex	Tot	DTPA-Ex	Tot	DTPA-Ex
Willow	6.6	**59.9**	11.4	16.0	12.4	22.0	13.6	24.1	19.6	**72.9**
Poplar	5.2	**37.0**	10.0	19.5	9.1	**49.4**	8.4	46.0	25.3	**63.4**
Hemp	2.1	30.4	9.4	5.9	11.8	41.1	14.7	**46.5**	18.4	11.7
Alfalfa	3.9	26.9	11.1	15.7	4.6	**60.6**	4.1	3.0	15.6	46.4
Unplanted	1.4	21.6	6.4	4.3	2.7	2.2	0.8	9.0	7.5	6.8

The effect is presented as variation (%) between the initial and the final value. Values in bold denote a significant ($p \leq 0.05$) effect

- **Only** the **DTPA-Extractable** soil fraction significantly affected
- Soil under willow: Cd (60%) and Zn (73%)
- Soil under poplar: Cd (37%), Ni (50%) and Zn (63%)
- Soil under hemp: Pb (47%)
- Soil under alfalfa: Ni (60%)

Rhizofiltration for the treatment of urban wastewater (Phytometabolism)

INORGANIC



- Saint-Roch-de-l'Achigan Qc (Canada)
- Population: 4000

INORGANIC

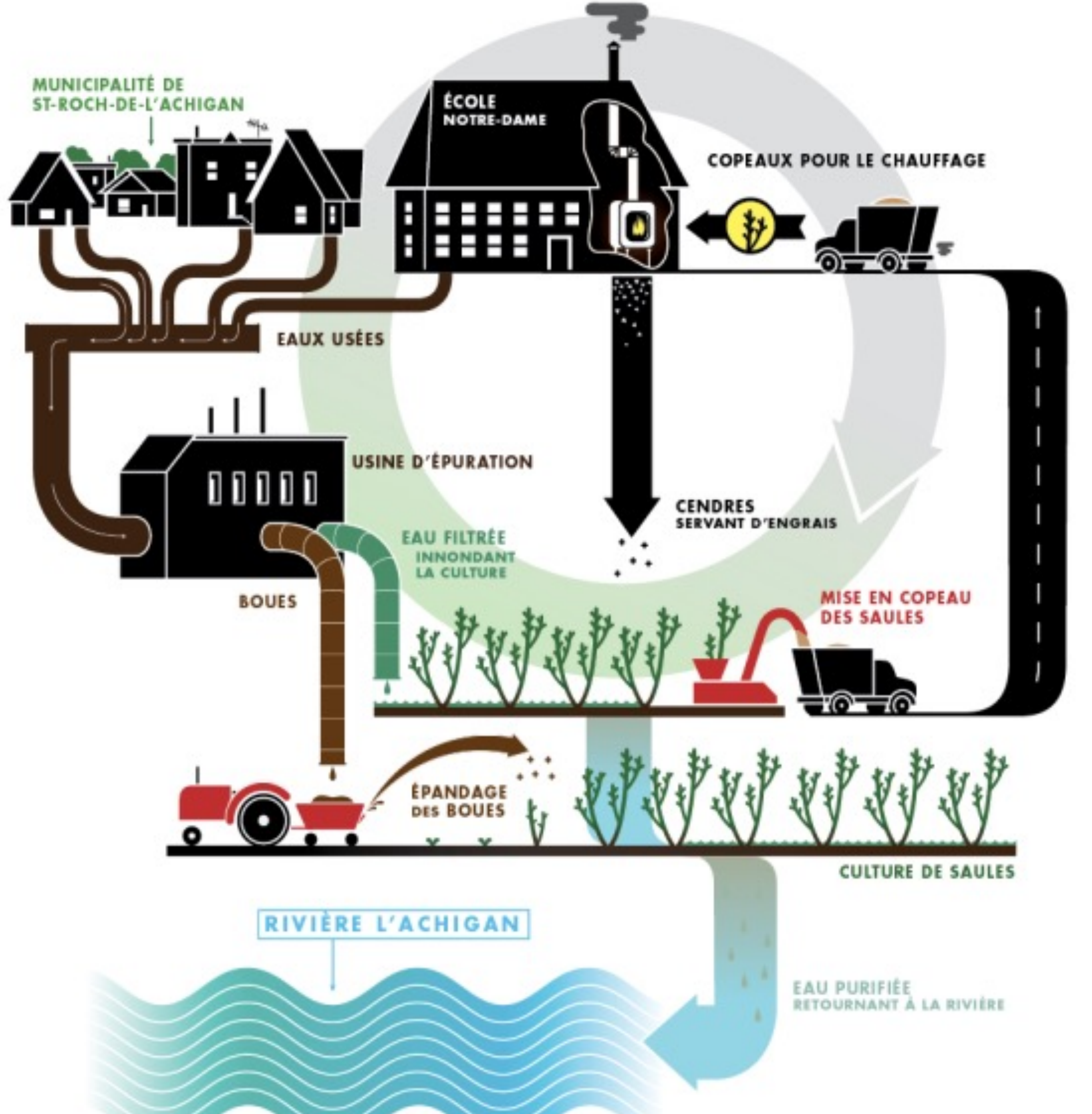
Overview

- Municipal pre-treated effluents often contain large amounts of nutrients, **nitrogen** and **phosphorus** in particular
- Such elements are **pollutants** for the environment (eutrophication) but at the same time represent a source of **nutrients** for the plant
- Some plants can be used to attenuate problem

The best suited plant/crop…

- High ET
- Fast growth
- Easy establishment
- Large root system
- Long lasting
- No food/no fodder destination…


STATION D'ÉPURATION
ST-ROCH E L'ACHIGAN

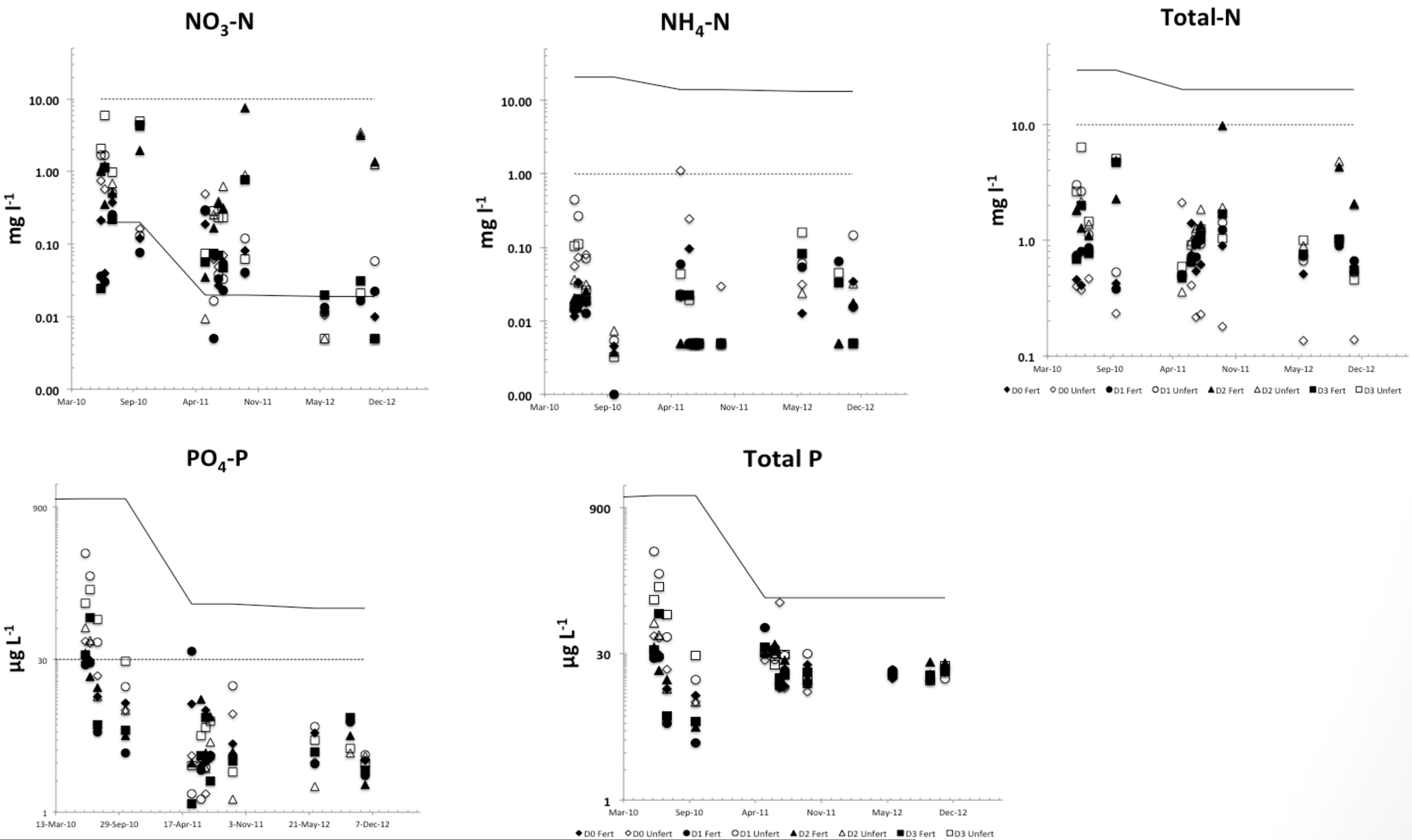

MUNICIPALITÉ DE
ST-ROCH-DE-L'ACHIGAN
ÉCOLE
NOTRE-DAME
COPEAUX POUR LE CHAUFFAGE
EAUX USÉES
USINE D'ÉPURATION
CENDRES
SERVANT D'ENGRAIS
EAU FILTRÉE
INNONDANT
LA CULTURE
BOUES
MISE EN COPEAU
DES SAULES
ÉPANDAGE
DES BOUES
CULTURE DE SAULES
RIVIÈRE L'ACHIGAN
EAU PURIFIÉE
RETOURNANT À LA RIVIÈRE

Main characteristics

•Filter surface: 7.200m^2
•Species: *Salix miyabeana*
•Planting density: about 16.000 plants ha^{-1}
•Planting date: June 2008
•Rotation cycles: 2 years
•Wastewater supply:
First rotation: first year 0 (min) - 580 mm (Max)
second year 0 (min) - 780 mm (Max)
Second rotation: first year 0 (min) – 650 mm (Max)
second year 0 (min) - 950 mm (Max)
•Working period: 135 days (May- September)

Decontamination efficiency

In most cases, the pollutant concentration in drainage water was low enough to meet the legislative limit values in Quebec (Canada)



Guidi Nissim et al. 2015. Ecological Engineering 81:395–404