


UNIVERSIDADE DE SÃO PAULO
Escola Superior de Agricultura "Luiz de Queiroz"
Departamento de Ciência do Solo

RECUPERAÇÃO DE ÁREAS DEGRADADAS PELA MINERAÇÃO

Prof. Dr. TIAGO OSÓRIO FERREIRA

Piracicaba
2015



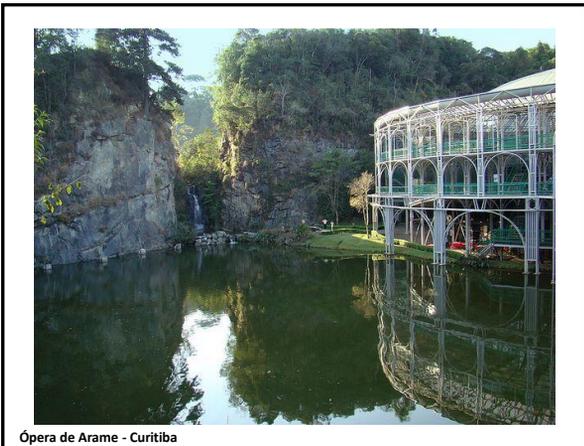

Recuperação: objetivos gerais

Recuperar...

- ✓ A fertilidade do ecossistema,
- ✓ Seus valores ecológicos,
- ✓ Econômicos e
- ✓ Estéticos

≠ de "Restaurar"



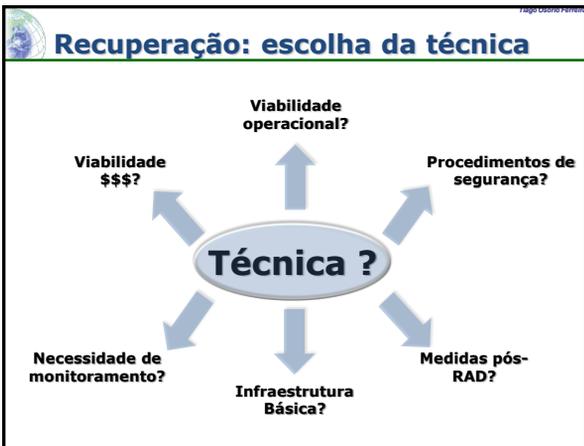


Recuperação: objetivos gerais



Recuperação: objetivos específicos

- ✓ Remoção de instalações e estruturas que ameacem a **saúde humana**;
- ✓ Re-vegetação e **estabilização de resíduos**;
- ✓ Reduzir o potencial de **drenagem ácida** ou **contaminação**;
- ✓ Desenvolvimento de **espaços públicos** para fins de recreação, construção, históricos ou de **conservação**

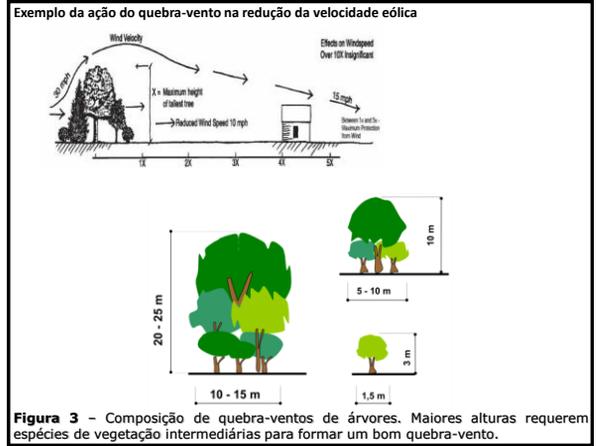


Recuperação: escolha da técnica



Recuperação: escolha da técnica





Técnicas de recuperação

Tabela 1. Utilidades adicionais de algumas espécies usadas como quebra-vento.

ESPÉCIES	Clima Sub-tropical	Pluviosidade (mm)		Altura (m)		Utilização	Madeira			Para Mel	
		800-1000	> 1000	9-24	> 24		Carvão	Dimensionado	Decorativa		
<i>Syncarpia glomulifera (aurifolia)</i>	1	1	1	-	1	1	1	2	1	2	-
<i>Tristania conferta</i>	1	1	2	1	-	2	1	1	1	1	1
<i>Eucalyptus acrotrichoides</i>	1	1	2	2	1	-	1	1	1	1	1
<i>Eucalyptus citreus</i>	-	2	1	1	-	1	1	2	1	x	2
<i>Eucalyptus cloeziana</i>	1	2	1	-	-	1	2	2	1	2	-
<i>Eucalyptus maculata</i>	1	1	2	1	1	-	1	2	2	1	2
<i>Eucalyptus microcorys</i>	1	1	2	1	-	1	1	2	1	1	2
<i>Eucalyptus moluccana</i>	2	1	1	-	-	1	2	2	2	2	1
<i>Eucalyptus paniculata</i>	1	1	-	1	1	-	1	2	2	1	1
<i>Eucalyptus ptilularis</i>	1	1	-	2	1	-	1	2	1	1	1
<i>Eucalyptus resinifera</i>	1	1	-	2	1	-	1	1	1	1	1
<i>Eucalyptus robusta</i>	1	1	-	2	1	-	1	1	1	1	1
<i>Eucalyptus saligna</i>	1	1	-	2	1	-	1	2	2	1	1

1 – Própria para a categoria indicada na coluna.
 2 – Menos própria para a categoria indicada do que a classificada com 1;
 x – Não deve ser utilizada na categoria indicada na coluna.
 Fonte: (Bátle & Souza, 1997).

Técnicas de recuperação

Table 5. Useful plant species useful for controlling air pollution

Special properties	Name of species
Pubescence on leaves to entrap and hold dust particles	<i>Guazama, Putranjiva, Nyctanthes, Trema, Holoptelea, Terminalia</i>
Leaves and branches to slow wind	<i>Albizzia, Samania, Peltophorum, Tamarindus, Dalbergia</i>
Blossoms and foliage that provide pleasant smell to mask odour	<i>Morinda, Cestrum, Annona, Michelia, Jasminum, Citrus, Plumeria, Magnolia</i>
Leaves and branches to slow the action of rain	<i>Azadirachta, Melia, Acacia auriculiformis, Delonix, Cassia</i>
Plants that absorb SO ₂	<i>Lichens, Fagus, Acer</i>

Técnicas de recuperação

Frago Osório Ferreira

Table 4. Trees tolerant to air pollutants

Dust pollution	Sulphur dioxide
<i>Alstonia scholaris</i>	<i>Albizia lebbek</i>
<i>Cassia siamea</i>	<i>Ailanthus excelsa</i>
<i>Dalbergia sissoo</i>	<i>Alstonia scholaris</i>
<i>Ficus benghalensis</i>	<i>Azadirachta indica</i>
<i>F. infectoria</i>	<i>Ficus religiosa</i>
<i>Mangifera indica</i>	<i>Lagerstroemia</i>
<i>Peltophorum ferrugineum</i>	<i>Mimusops elangi</i>
<i>Polyalthia lognifolia</i>	<i>Polyalthia longifolia</i>
<i>Shorea robusta</i>	<i>Terminalia arjuna</i>
<i>Syzygium cumini</i>	<i>Acer platanoides</i>
<i>Tectona grandis</i>	<i>Quercus palustris</i>
<i>Alnus viridis</i>	<i>Q. rubra</i>
Ozone	Oxides of nitrogen
<i>Acer negundo</i>	<i>Gagus orientalis</i>
<i>Acer plantanoides</i>	<i>Quercus rubra</i>
<i>Quercus palustris</i>	<i>Robinia pseudocacia</i>
	<i>Sambucus nigra</i>
Peroxyacetyl nitrate	Lead
<i>Acer platanoides</i>	<i>Cassia siamea</i>
<i>A. negundo</i>	<i>Zizyphus mauritiana</i>
<i>Quercus palustris</i>	



Técnicas de recuperação

Frago Osório Ferreira

FONTE: Drummond et al., 2011

Mineração Caraíba, Jaguarari, BA

Figura 1. Vista geral da área de deposição de rejeitos finos da mineração de cobre oriundos do processo de tratamento do minério: a) deposição de rejeitos finos; b e c) vista geral da bacia de rejeitos; d) perfil da área de deposição de rejeitos finos. Área total de aproximadamente 700 ha. (Fotos: Marcos Antônio Drummond).

Técnicas de recuperação

Frago Osório Ferreira

FONTE: Drummond et al., 2011

Mineração Caraíba, Jaguarari, BA

Figura 2. Primeiros estágios de revegetação com *Eucalyptus camaldulensis* na bacia de rejeitos finos da mineração de cobre: a) *E. camaldulensis* ao primeiro plantio; b) *E. camaldulensis* aos 2 anos de idade; c) *E. camaldulensis* aos 3 anos de idade; d) *E. camaldulensis* aos 4 anos de idade, já contribuindo para a fixação de capim-buffet. (Fotos: Marcos Antônio Drummond).

Técnicas de recuperação

FONTE: Drummond et al., 2011

Figura 7. Quebra-vento com tamarix aos 18 anos de idade, eficiente na contenção do efeito dunas na bacia de rejeitos finos da mineração de cobre. a) Antes do quebra vento com tamarix; b) depois do quebra-vento com tamarix. (Fotos: Marcos Antônio Drummond).

Técnicas de recuperação

Figure 3.2 Distance of established eucalypt plantations from Hazelwood mine³⁴

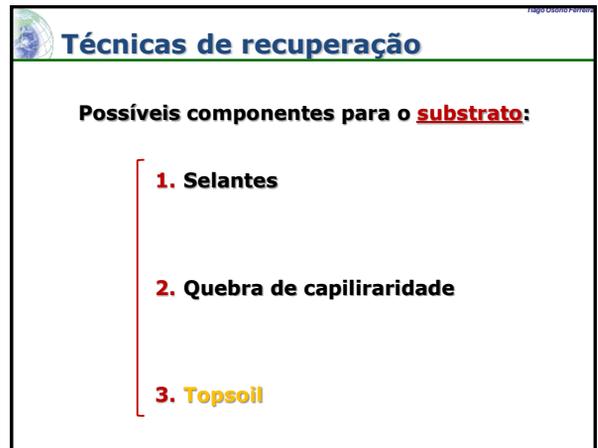
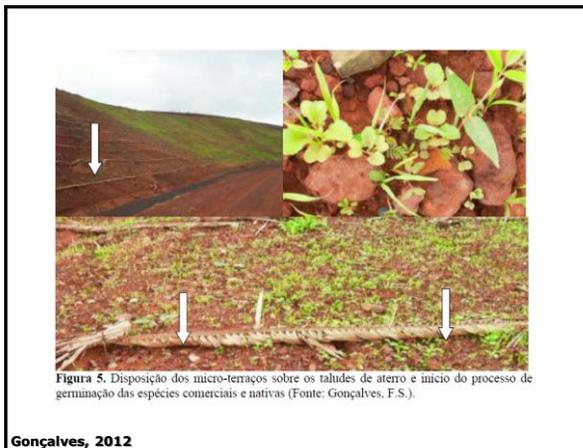
AUSTRALIA

Fevereiro, 2014



Técnicas de recuperação

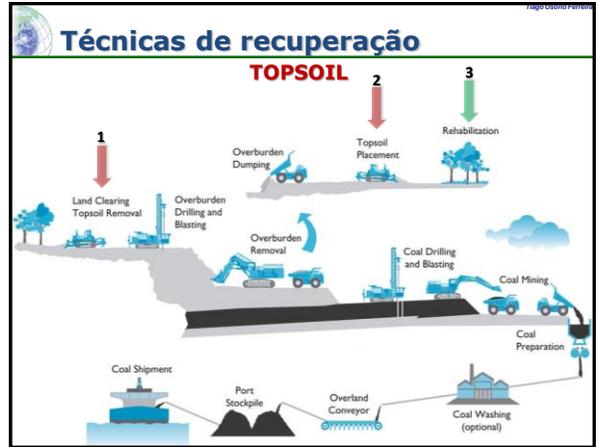
Figure 2: 'Mega-dump' of reprocessed gold tailings, south-east of Springs, Gauteng Province. Heavy rains in February 2008 led to landslides that denuded large parts of the previously vegetated slope.



Técnicas de recuperação

SELANTE
QUEBRA CAPILARIDADE
RESÍDUOS

Fonte: Luiz E. Dias UFV/DPS





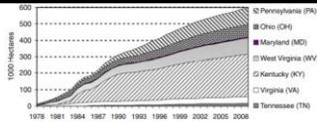


Fig. 2 Cumulative Appalachian area reclaimed and released from SMCRA regulation in seven states, 1978–2009. Eastern Kentucky areas are estimated from Kentucky totals in proportion to annual coal production. At the end of 2009 for the seven states, an additional 50,000 ha is reported as partially reclaimed but not released from SMCRA regulation. Data from US Office of Surface Mining



Fig. 3 The Appalachian coalfield of eastern USA, as it occurs in these states and further Appalachian hardwood forest vegetation



Fig. 4 Native hardwood regeneration on a Tennessee mine site reclaimed in 1978 by planting early successional tree species on lower spots, without the smooth grading and aggressive grasses that have been used commonly under SMCRA (Franklin and Ponce 2007)



Figura 1A. Uma paisagem de mina de carvão desativada e destinada a pastagem (Virginia, USA)



Figura 1B. Uma paisagem de mina de carvão desativada e destinada a pastagem (Virginia, USA)

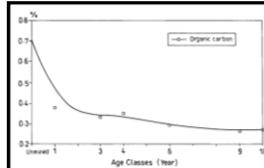


Fig. 2 Variation of organic carbon in differently aged soil dumps and unmined soil

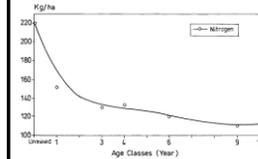


Fig. 3 Variation of available nitrogen in differently aged soil dumps and unmined soil

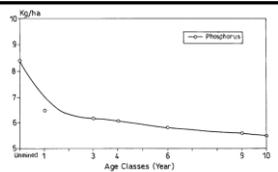


Fig. 4 Variation of available phosphorus in differently aged soil dumps and unmined soil

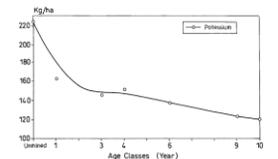
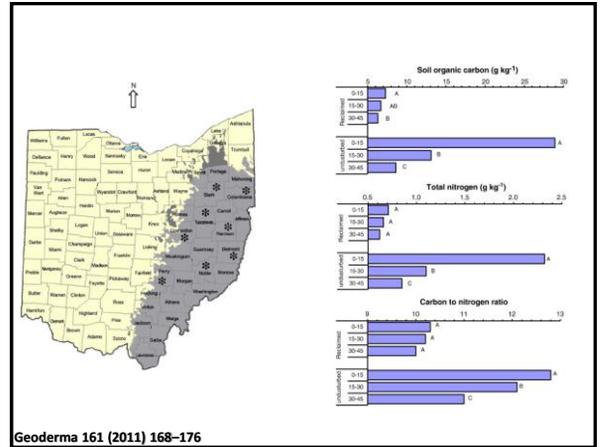
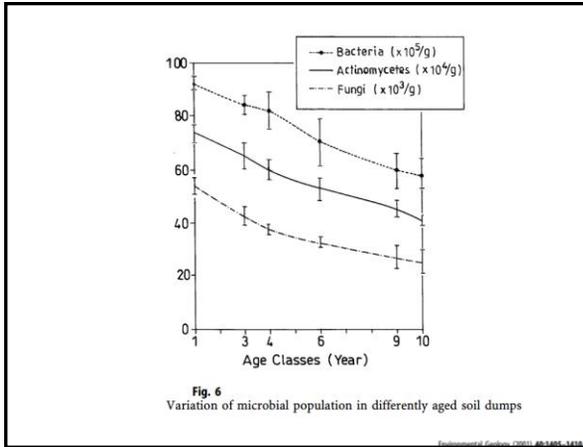


Fig. 5 Variation of available potassium in differently aged dumps and unmined soil

Environmental Management (2011) 47:755–761



Topsoil: estocagem

Altura

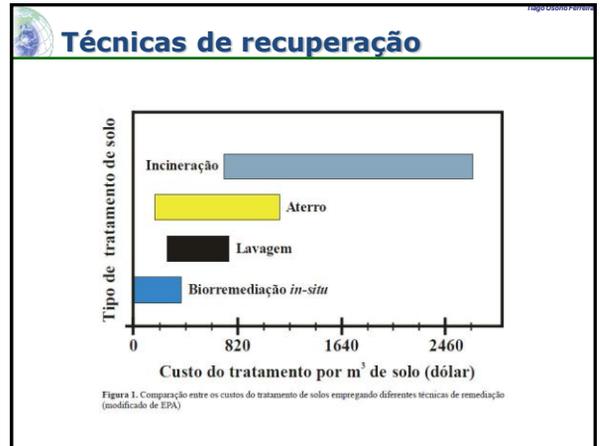
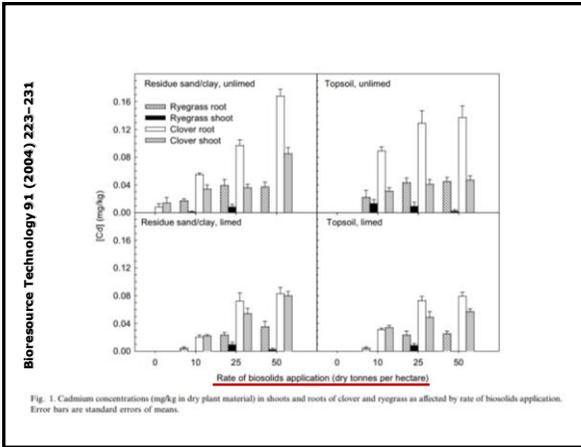
- ✓ 5 metros (max) arenosos
- ✓ 2-3 metros text. média
- ✓ 1 metro argilosos

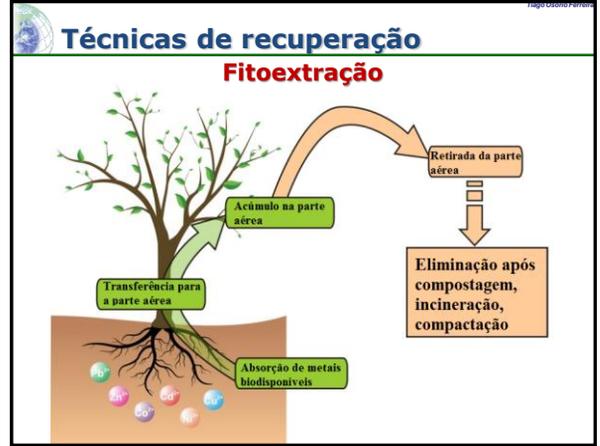
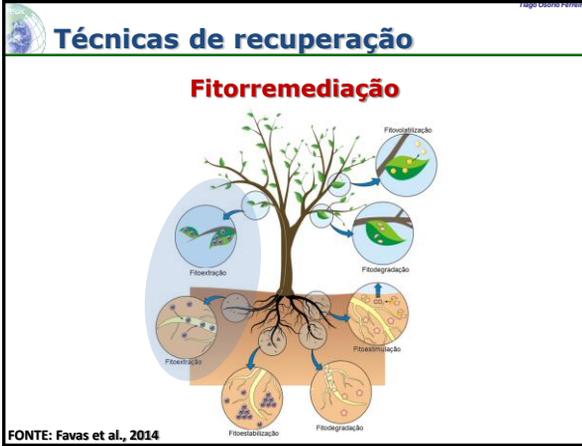
Técnicas de recuperação

Topsoil: manejo

1. Acidez
2. Salinidade
3. Sodicidade
4. Inoculação
5. Adubação (macro e micro)
6. Características físicas (água, raízes)

Qualidade





Técnicas de recuperação

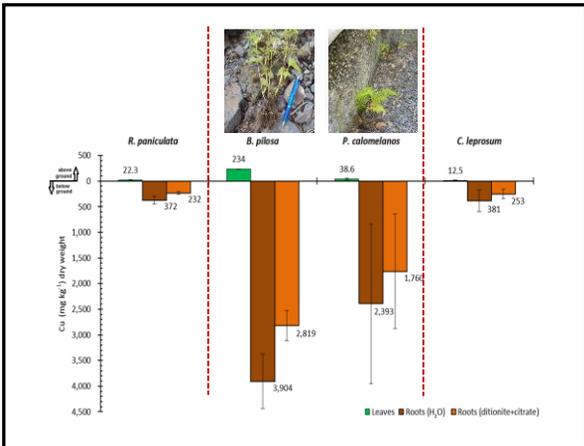
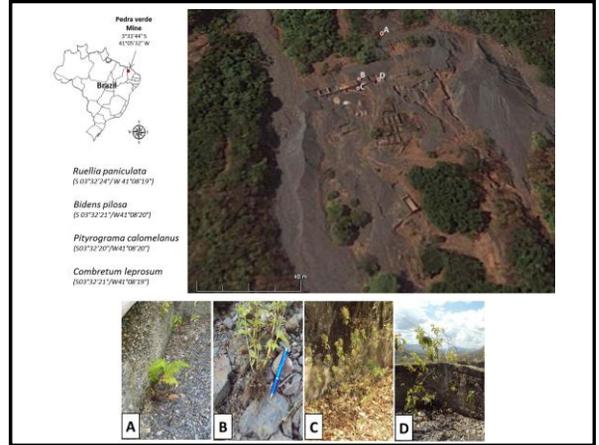
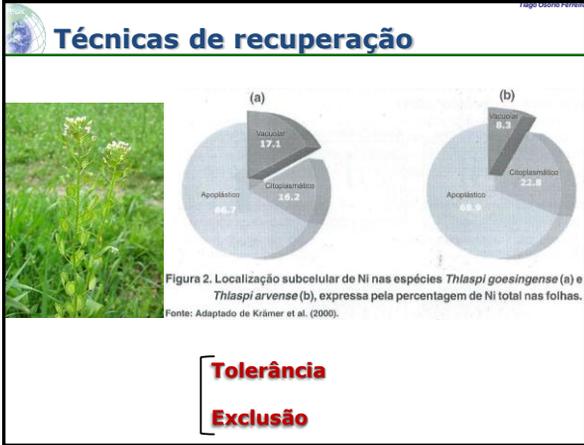
Quadro 1. Faixa normal, valores mínimos de teor de metais pesados para acumuladora e hiperacumuladora e número de espécies hiperacumuladoras

Elemento	Faixa normal	Limiar acumuladora	Limiar hiperacumuladora	Número de hiperacumuladoras
----- mg kg ⁻¹ (matéria seca) -----				
As	-	-	1.000	8
Cd	0,1-3	20	100	3
Co	0,03-2	20	100	28
Cr	0,2-5	50	100	Desconhecido
Cu	5-25	100	1.000	37
Mn	20-400	2.000	10.000	9
Ni	1-10	100	1.000	317
Pb	0,1-5	100	1.000	14
Se	0,05-1	10	1.000	20
Zn	20-400	2.000	10.000	15

Fonte: Boyd (2007).

Quadro 2. Plantas hiperacumuladoras de metais pesados

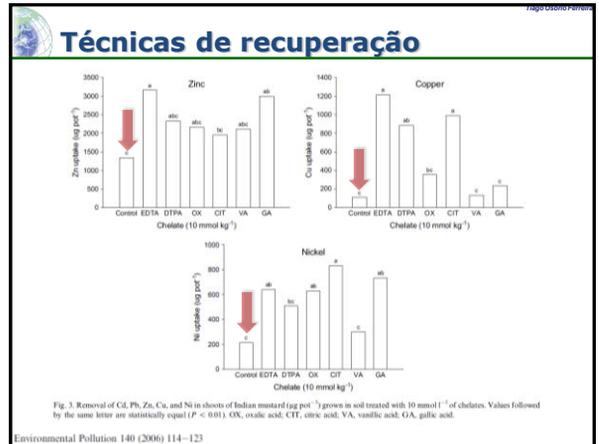
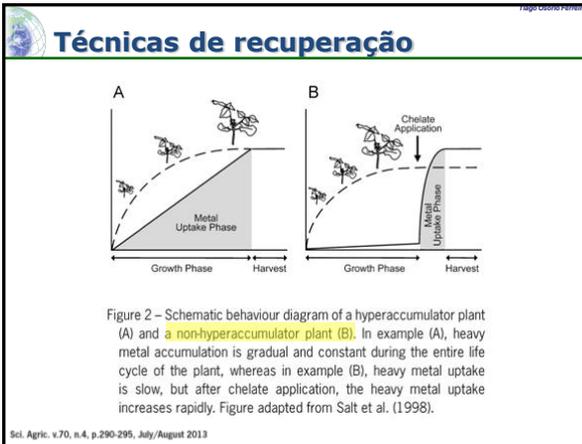
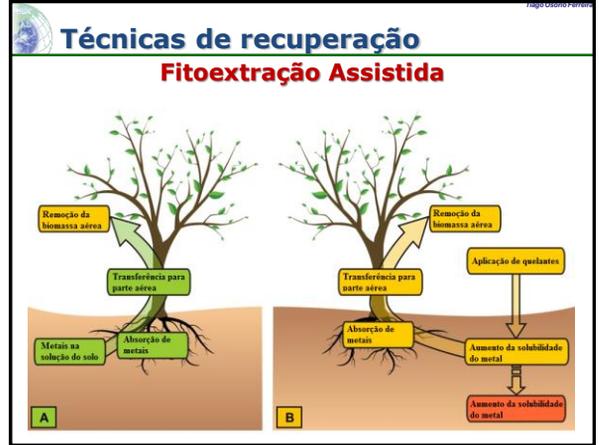
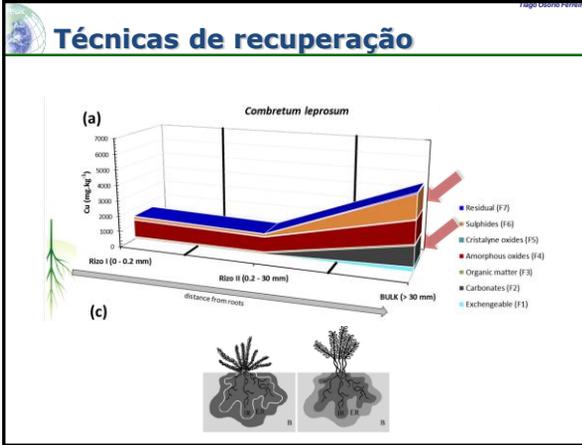
Metá	Espécie de planta	Referência
As	<i>Pteris vittata</i>	Mi et al. (2001)
As	<i>Pteris obscura</i>	Srivastava et al. (2006)
As	<i>Pteris quadriaurita</i>	Srivastava et al. (2006)
As	<i>Pteris rijkuyensis</i>	Srivastava et al. (2006)
As	<i>Phytolacca carolinensis</i>	McGrath & Zhao (2003)
As	<i>Pteris caesia</i>	McGrath & Zhao (2003)
As	<i>Pteris longifolia</i>	McGrath & Zhao (2003)
As	<i>Pteris umbrosa</i>	McGrath & Zhao (2003)
Cd	<i>Thlaspi caerulescens</i>	Baker & Walker (1989)
Co	<i>Alyssum murale</i>	Tappero et al. (2007)
Co	<i>Heuermannium robertii</i>	Brooks (1998)
Cr	<i>Salsola kali</i>	Gardner-Torresdy et al. (2005)
Cu	<i>Ipomea alpaia</i>	Baker & Walker (1989)
Cu	<i>Acaclitua biflorifolia</i>	Chaney et al. (2007)
Mn	<i>Physalis adnata</i>	Xu et al. (2004)
Mn	<i>Alysic rubicaulis</i>	Chaney et al. (2007)
Ni	<i>Alyssum murale</i>	Tappero et al. (2007)
Ni	<i>Siberia acuminata</i>	Jaffre et al. (1976)
Ni	<i>Berhoya zoodii</i>	Rubinson et al. (1997)
Ni	<i>Alyssum botanoides</i>	Morrison et al. (1985)
Ni	<i>Thlaspi goettingense</i>	Barceló & Poschenrieder (2003)
Ni	<i>Alyssum pinodasikvae</i>	Barceló & Poschenrieder (2003)
Ni	<i>Raychonia douarri</i>	Barceló & Poschenrieder (2003)
Ni	<i>Physalis senegalensis</i>	Chaney et al. (2007)
Pb	<i>Thlaspi rotundifolium</i>	Reeves & Brooks (1983)
Pb	<i>Minuartia verna</i>	Barceló & Poschenrieder (2003)
Se	<i>Astragalus racemosus</i>	Beath et al. (1937)
Se	<i>Astragalus juncea</i>	Qian et al. (1999)
Tl	<i>Arenaria intermedia</i>	Leblanc et al. (1999)
Zn	<i>Sesuvium alfredii</i>	McGrath & Zhao (2003)
Zn	<i>Arabidopsis halleri</i>	Barceló & Poschenrieder (2003)
Zn	<i>Thlaspi caerulescens</i>	Reeves & Brooks (1983)



Técnicas de recuperação

Limitações

- Limited to shallow soils or where contamination is localized to the surface (< 5 m)
- Still under development and therefore not accepted by many regulatory agencies
- There is little knowledge of farming, genetics, reproduction and diseases of phytoremediating plants
- Metal concentrations in the soil can be toxic and lethal to plants
- Generally, plants are selective in metal remediation
- Treatment slower than the traditional physico-chemical techniques
- Contamination may spread through the food chain if accumulator plants are ingested by animals
- Efficient phytoremediating plants may not adapt to climatic and environmental conditions at contaminated sites
- If the plants release compounds to increase the mobility of the metals, these can be leached into groundwater
- The area to be decontaminated must be large enough to allow application of cultivation techniques
- Toxicity and bioavailability of degradation products remain largely unknown



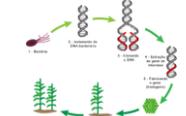
Técnicas de recuperação

Quadro 3. Espécies de plantas com elevada produção de biomassa e potencial de uso na fitoextração

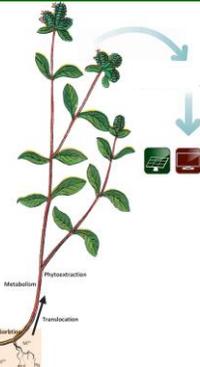
Espécie	Contaminante/substrato	Referência
<i>Salix</i>	Metais pesados/solo	Greger & Landberg (1999)
<i>Populus</i>	Ni/solo, água, água subterrânea	Barceló & Poschenrieder (2003)
<i>Brassica napus</i> , <i>B. juncea</i> , <i>B. nigra</i>	Metais pesados, Solo/solo	Brown (1996); Bañuelos et al. (1997)
<i>Cannabis sativa</i>	Cd/solo	Ostwald (2000)
<i>Helianthus</i>	Pb, Cd/solo	EPA (2000); Elkatib et al. (2001)
<i>Phragmites australis</i>	Metais pesados/rejeitos	Massacci et al. (2001)
<i>Glyceria fluitans</i>	Metais pesados/rejeitos	McCabe & Otte (2000)

Técnicas de recuperação

Perspectivas

1. Domesticção 
2. Plantas com potencial + quelantes 
3. Transgênicas 

Técnicas de recuperação

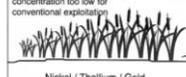


FITOMINERAÇÃO
"colheita" / recuperação de metais



Técnicas de recuperação

THE PHYTOMINING OPERATION

1. Crop grown on soil containing metal concentration too low for conventional exploitation.


Nickel / Thallium / Gold

Complexing agents may be added to enhance metal uptake of crop.
2. Possible production of electricity.


Plant material burnt
3. Small volume of plant ash (bio-ore) containing high concentration of target metal.


Smelt bio-ore to yield metal

Journal of Geochemical Exploration 61 (1999) 407–415

Fig. 4. Model of a proposed system for phytomining for metals.

Técnicas de recuperação

S. A. NEERAJANTYAM, Soil Science Soc. China 16(2005)

Fig.1 Morphological features of microcrystalline bacteria: (a) *Acetivibrio fermentans* (b) *Leptothrix amara*; (c) Black sulfur precipitates due to growth of SRB; (d) *Desulfotubaria* spp.; (e) *Desulfotomaculum* sp.; (f) *Thiomargarita* spp.

Técnicas de recuperação

Fig. 2 Scanning electron micrographs of precipitates containing sulphate-reducing bacteria SRB-GJ.

$$\text{Organic matter (C, H, O)} + \text{SO}_4^{2-} \xrightarrow{\text{SRB}} \text{HS}^- + \text{HCO}_3^-$$

$$\text{Me}^{2+} + \text{HS}^- \rightarrow \text{MeS}(\downarrow) + \text{H}^+ (\text{Me}^{2+} \text{---the metal cation})$$

Técnicas de recuperação

Fig. 1. Precipitation of Cu^{2+} by sulphate-reducing bacteria. K- abiotic control, (G)-sulphate-reducing bacteria from the potable mineral water (spring Cudjovka), VSZ-sulphate-reducing bacteria from the industrial waste water (the metallurgical plant).

Fig. 3. EDS qualitative analysis of precipitates originated from the model solution by using one reactor (the simultaneous running of the hydrogen sulphide bacterial production and the copper precipitation by the bacterial produced hydrogen sulphide).

$$\text{Organic matter (C, H, O)} + \text{SO}_4^{2-} \xrightarrow{\text{SRB}} \text{HS}^- + \text{HCO}_3^-$$

$$\text{Me}^{2+} + \text{HS}^- \rightarrow \text{MeS}(\downarrow) + \text{H}^+ (\text{Me}^{2+} \text{---the metal cation})$$

Técnicas de recuperação

World reference base for soil resources 2014
International soil classification system for naming soils and creating legends for soil maps

TABLE 1
Simplified guide to the WRB Reference Soil Groups (RSG) with suggested codes
Note – this table is not to be used as a key. For full definitions, please refer to Chapter 3 and the Key (Chapter 4).

RSG	Code
1. Soils with thick organic layers:	
Mitsooks	HS
2. Soils with strong human influence -	
Soils with long and intensive agricultural use:	
Anthrocks	AT
Soils containing significant amounts of artefacts:	
Technosols	TC
3. Soils with limitations to root growth -	
Permafrost-affected soils:	
Cryosols	CR
This soils or soils with many coarse fragments:	
Leprosols	LP
Soils with a high content of exchangeable Na:	
Solonetz	SN
Alternating wet-dry conditions, shrink-swell clays:	
Vertisols	VR
High concentration of soluble salts:	
Solonchaks	SC
4. Soils distinguished by FeAl chemistry -	
Groundwater-affected soils, underwater soils and soils in tidal areas:	
Gleysols	GL
Allophanes or Al-humus complexes:	
Andosols	AN
Subsoil accumulation of humus and/or oxides:	
Podzols	PZ
Accumulation and redistribution of Fe:	
Plinthosols	PT
Low activity clay-B horizon, many Fe oxides, strongly structured:	
Nitisols	NT
Dominance of kaolinite and oxides:	
Ferralsols	FR
Stagnating water, abrupt textural difference:	
Planosols	PL
Stagnating water, structural difference and/or moderate textural difference:	
Stagnosols	ST

Técnicas de recuperação

(Reddy et al. 1986)

Reação	ΔG° (kcal/mol)
1.- $C_6H_{12}O_6 + 6 O_2 \rightarrow 6CO_2 + H_2O$	-686.4
2.- $5C_6H_{12}O_6 + 24NO_3^- + 24 H^+ \rightarrow 30CO_2 + 12N_2 + 42 H_2O$	-646.0
3.- $C_6H_{12}O_6 + 12 MnO_2 + 24 H^+ \rightarrow 6 CO_2 + 12 Mn^{2+} + 12 H_2O$	-457.8
4.- $C_6H_{12}O_6 + 24 Fe(OH)_3 + 48 H^+ \rightarrow 6CO_2 + 24Fe^{2+} + 66 H_2O$	-100.0
5.- $C_6H_{12}O_6 + 3 SO_4^{2-} \rightarrow 6 CO_2 + 3S^{2-} + 6 H_2O$	-91.0

(Fe, Me) + S²⁻ → (Me Fe) S₂

Técnicas de recuperação

Fonte: F. M. Vazquez (USC)

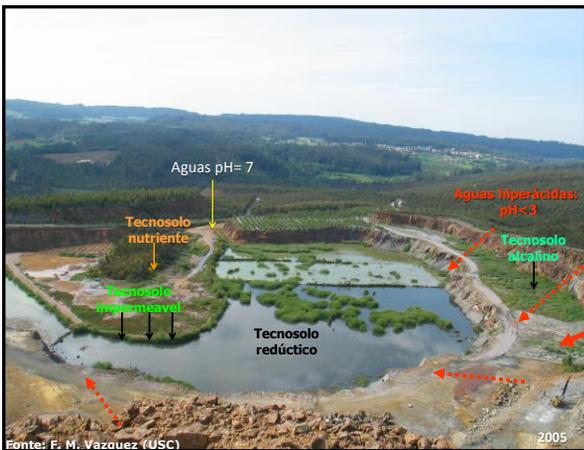
Técnicas de recuperação

Fig 22 - Zonificação biogeoquímica em um humedal de *Thypha latifolia*

Fonte: F. M. Vazquez (USC)

Técnicas de recuperação

Fonte: F. M. Vazquez (USC)





 **Técnicas de recuperação**



Controladores de temperatura para a eliminação de patógenos