Departamento de Ciência do Solo

Laboratório de Microbiologia do Solo

Transformações do **fósforo** e do **enxofre** no solo

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Plano de Aula

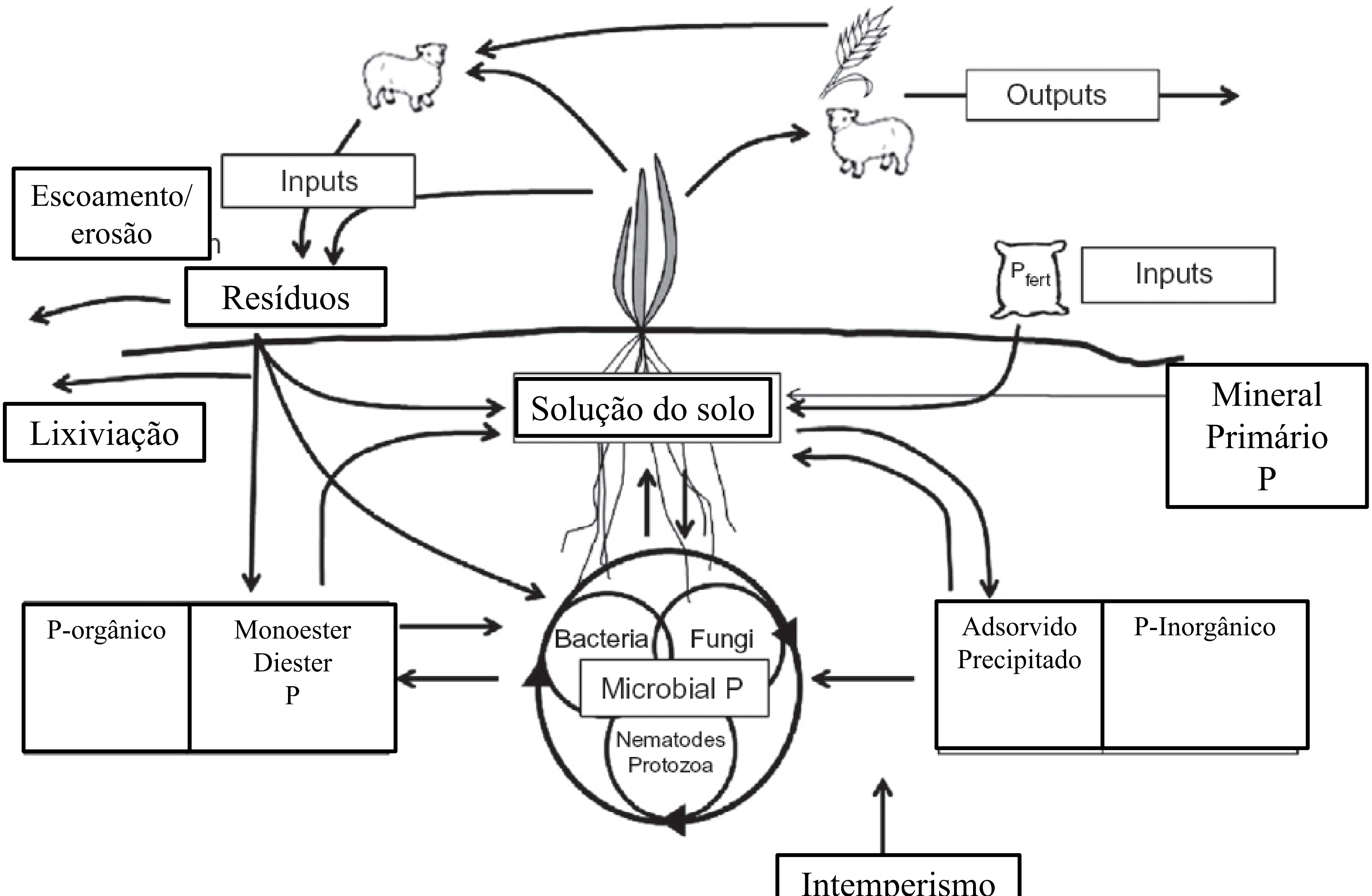
- Transformações do fósforo
  - Ciclo Biogeoquímico
  - Formas de P
  - Transformações microbianas
  - Manejo
- Transformações do Enxofre
  - Ciclo Biogeoquímico
  - Reservas de S
  - Formas de Enxofre
  - Transformações microbianas

Competências e Habilidades

- Conhecer os ciclos do Fósforo e do Enxofre;
- Reconhecer a importância dos micro-organismos do solo para a ciclagem do fósforo e do enxofre;
- Entender os processos microbiológicos envolvidos nas transformações dos elementos estudados;
- Reconhecer a importância dos micro-organismos para o manejo de fósforo e enxofre nas práticas agrícolas

Transformações do Fósforo

Ciclo Biogeoquímico do Fósforo



Reservas de Fósforo

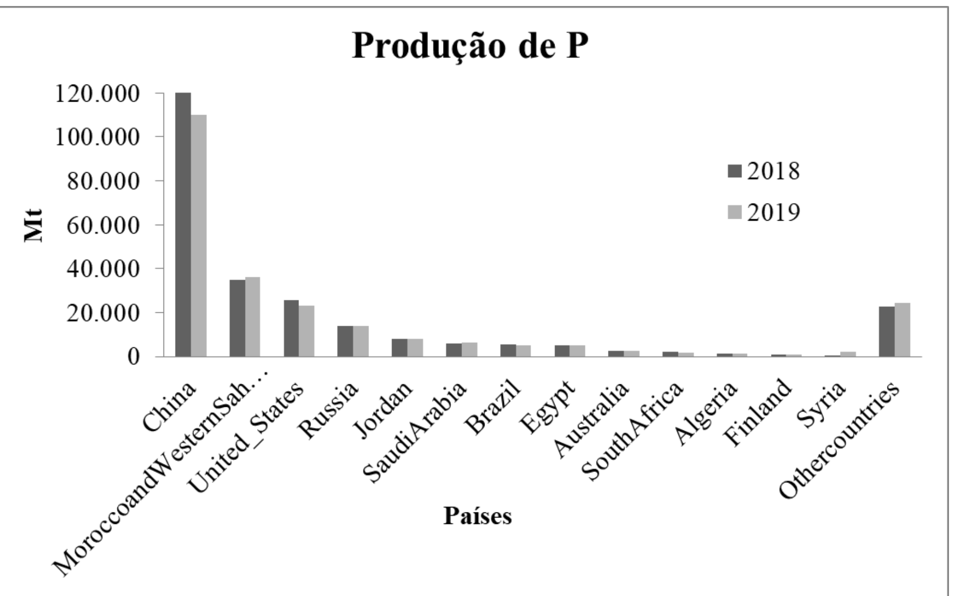
Tabela 10.1 - Reservatórios naturais de fósforo na biosfera (Stevenson, 1994)

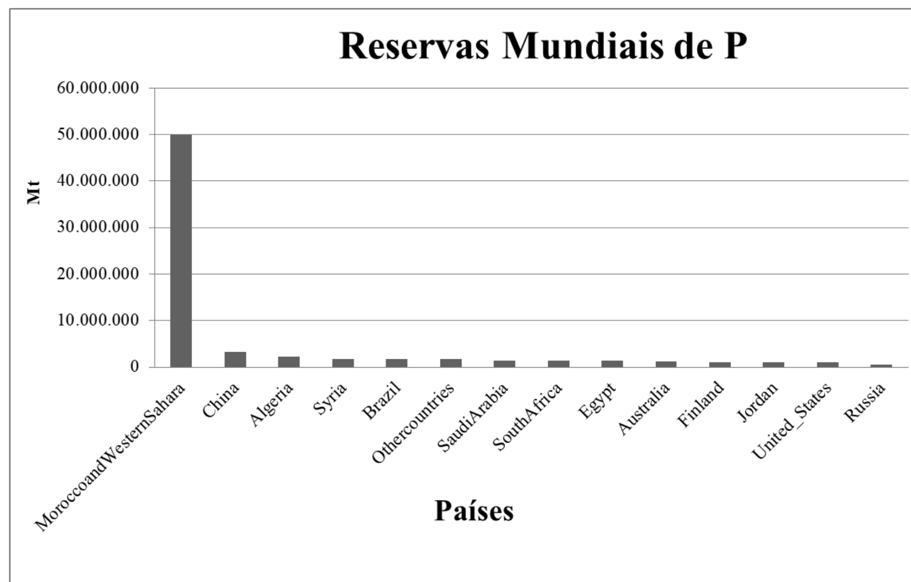
Reservatórios de P	P total x 10^{12} (kg)
-------- Oceanos --------	
Sedimentos	840.000
Dissolvido (Pi)	80
Profundeza (detritos)	0,65
Biota	0,050-0,12
-------- Terrestre --------	
Solo	96-160
Rochas fosfáticas	19
Biota	2,6
Água doce	0,09

Reserva Mundial : 69 bilhões de toneladas

https://geobancodedados.wordpress.com/2014/05/29/fosfato/

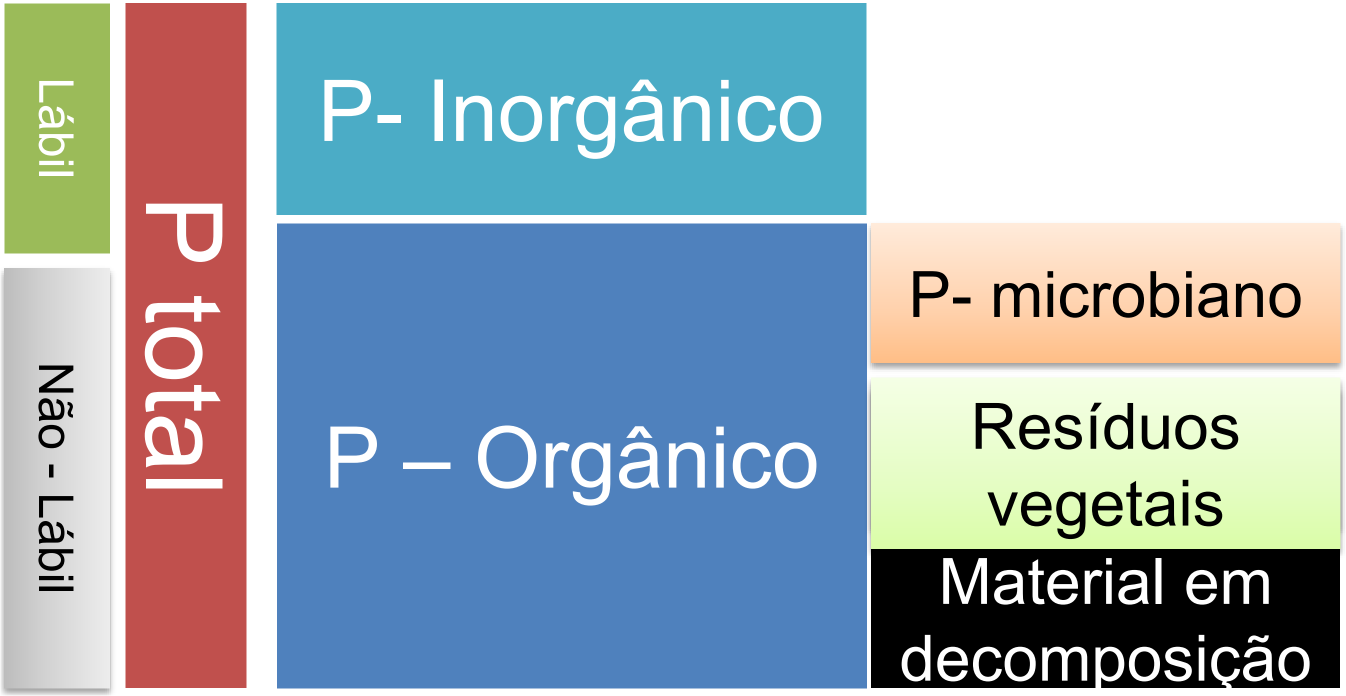
Exploração do fosfato em Bu Craa, cidade do Saara Ocidental, dominado pelo Marrocos





https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

Formas de P no Solo



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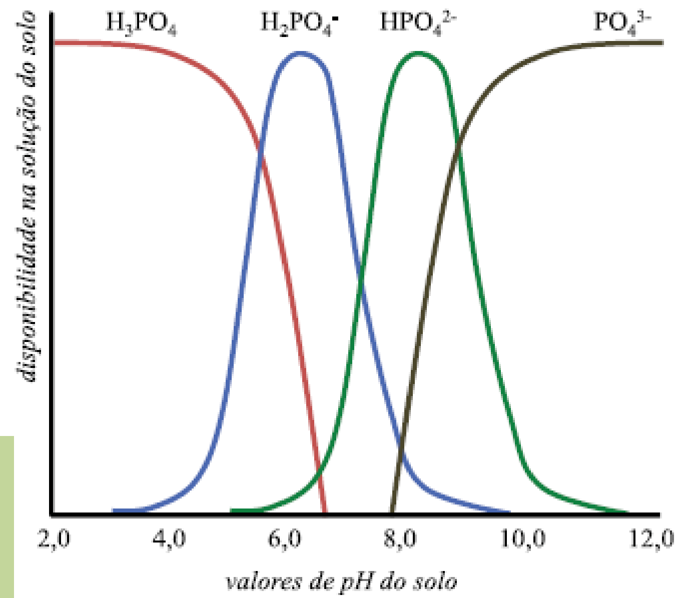

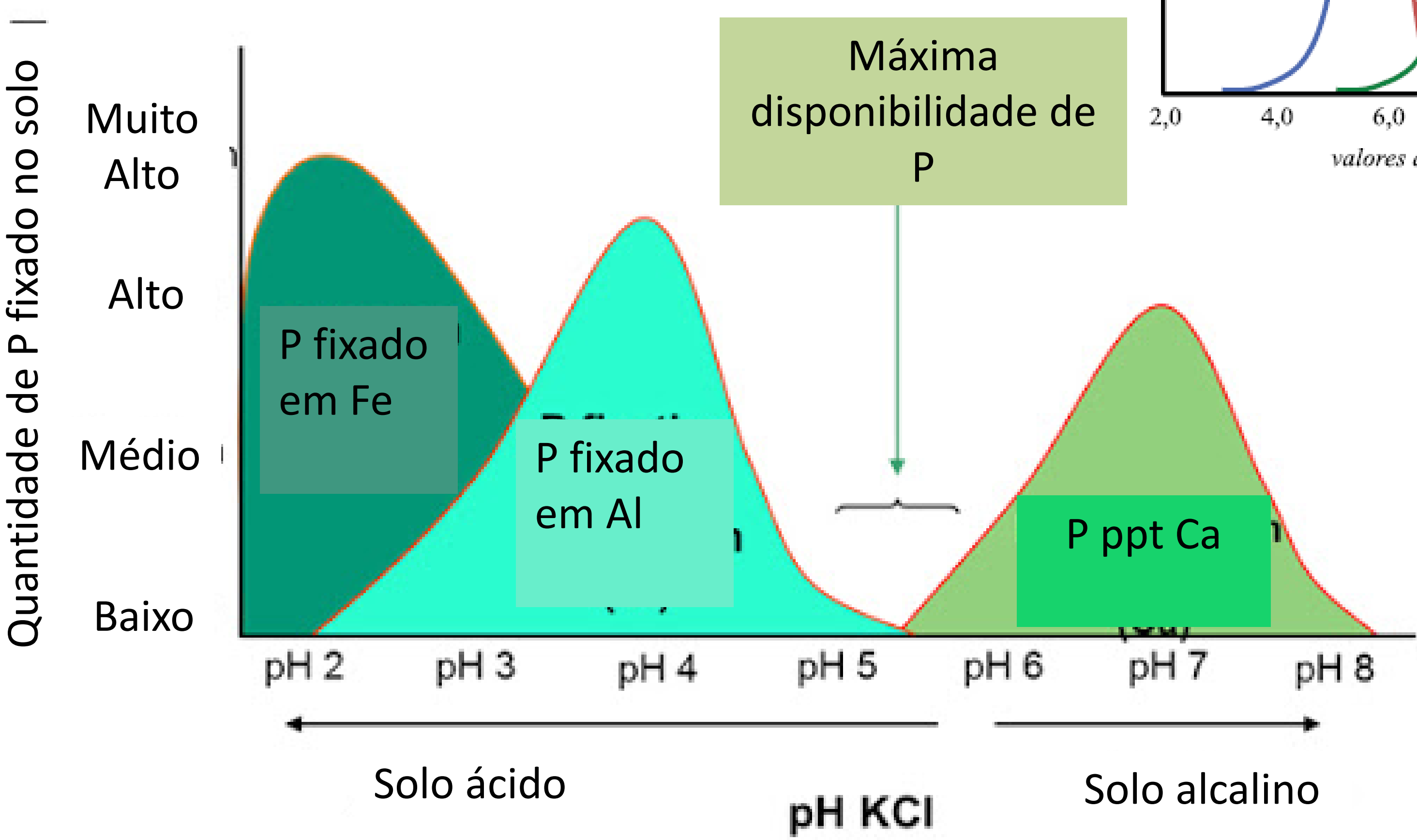

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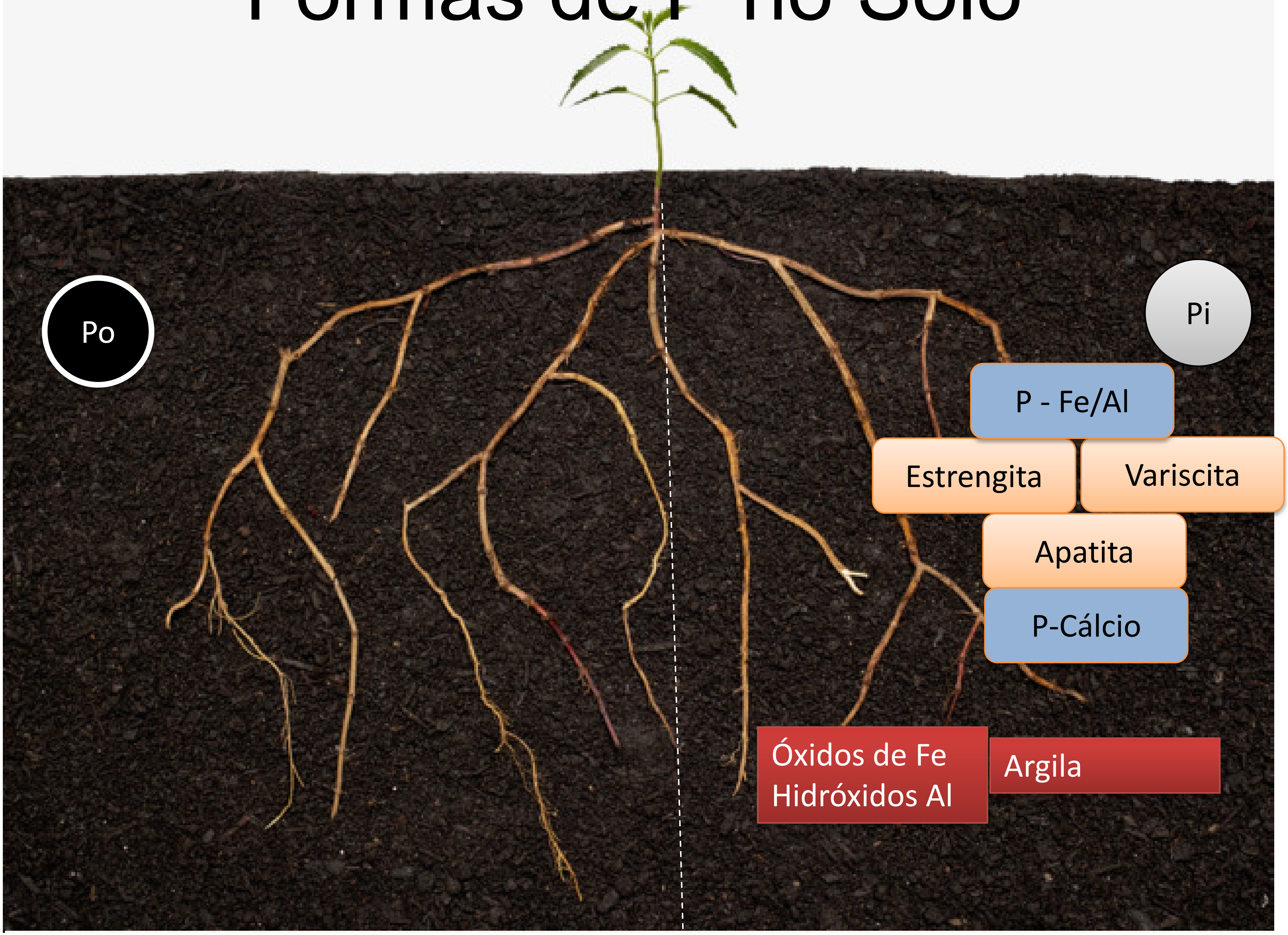
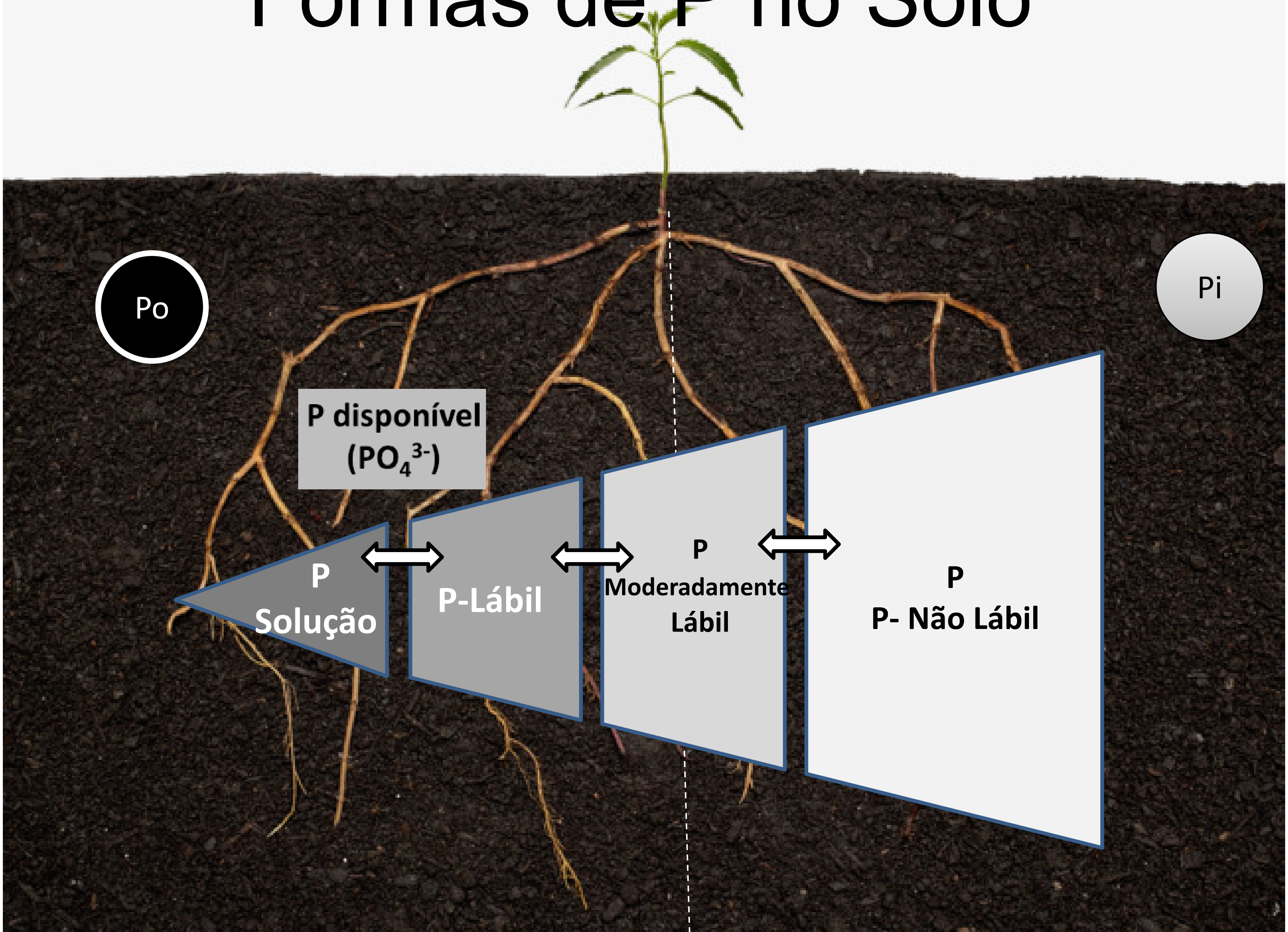
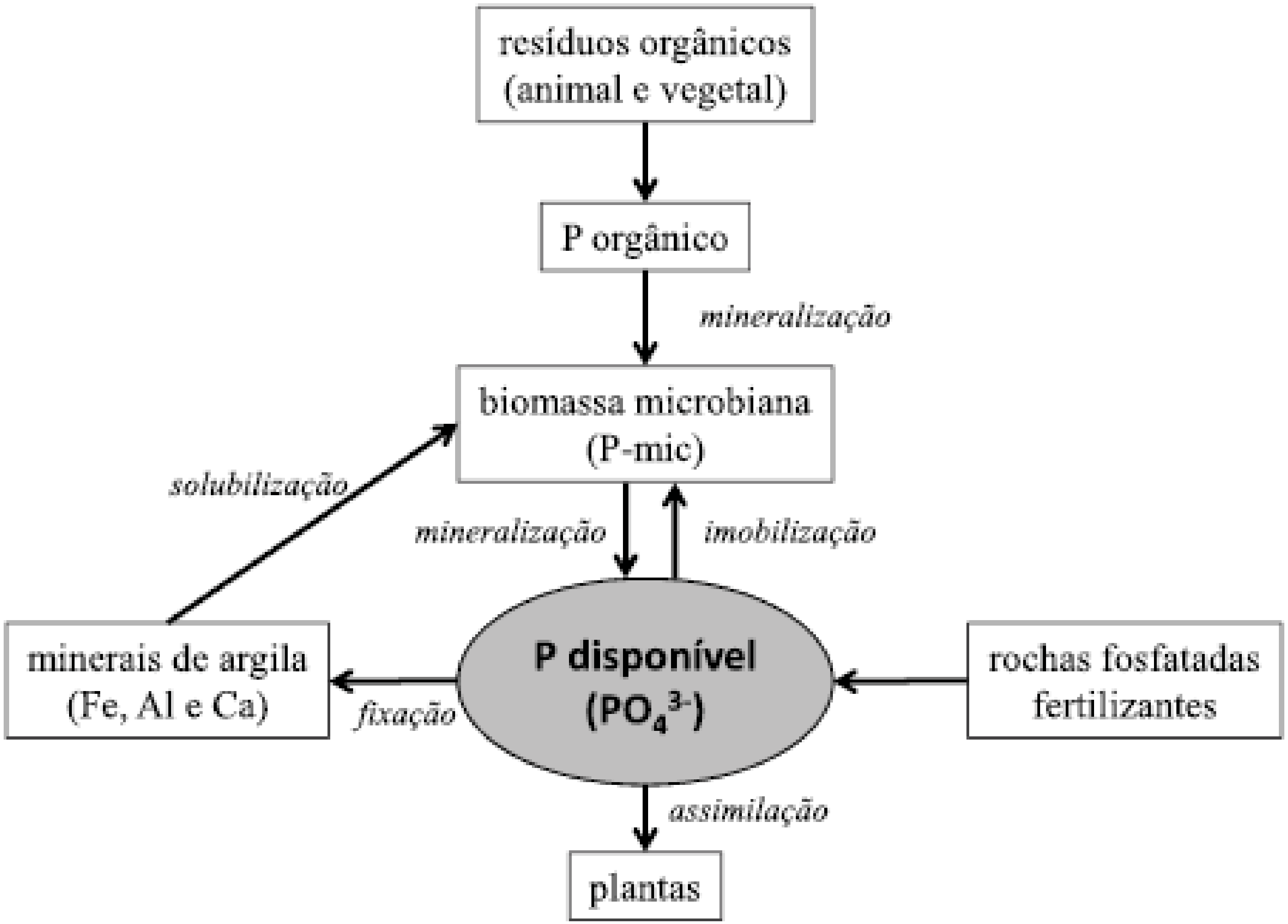


Formas de P no Solo

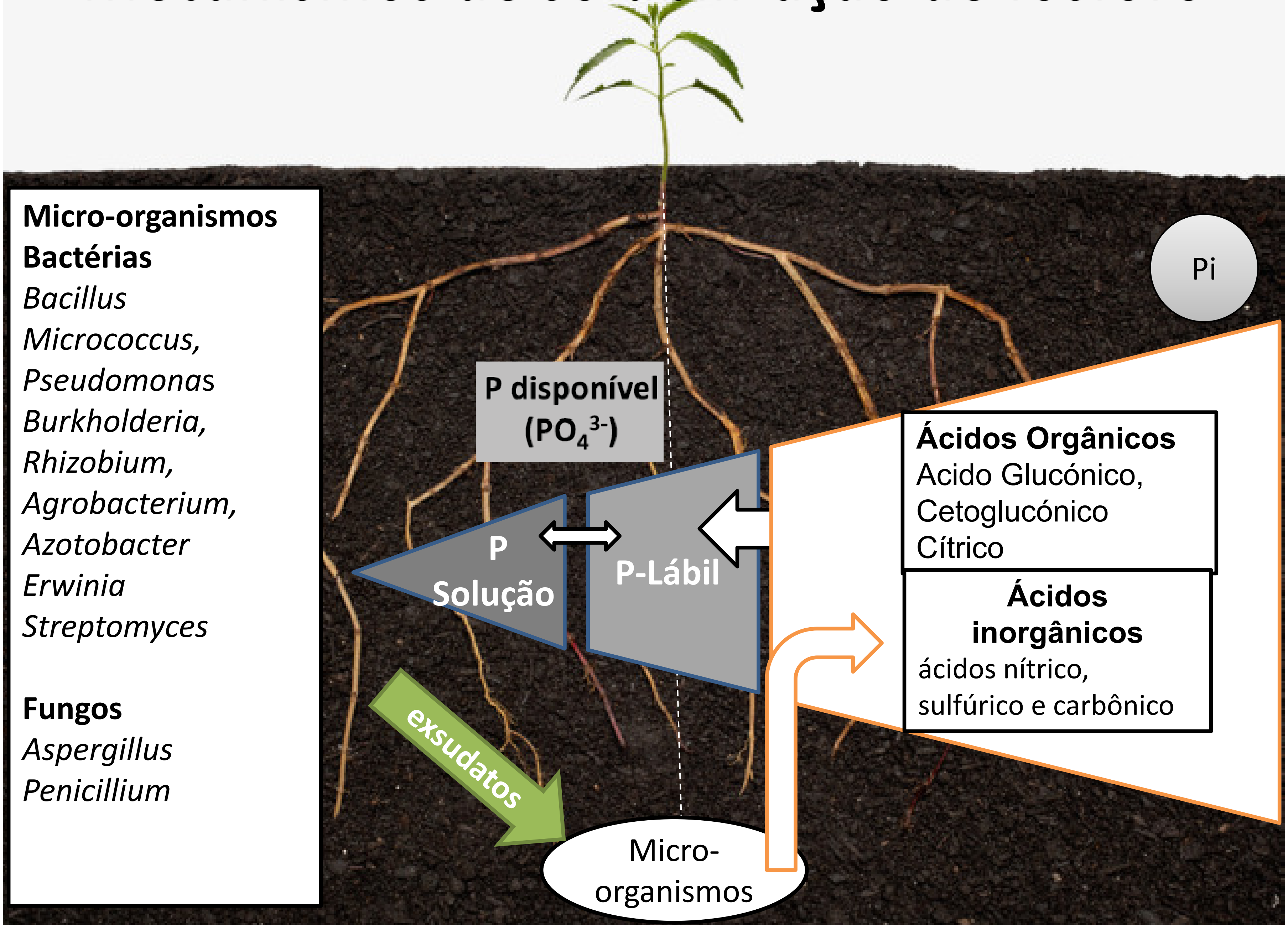
Formas de P no Solo



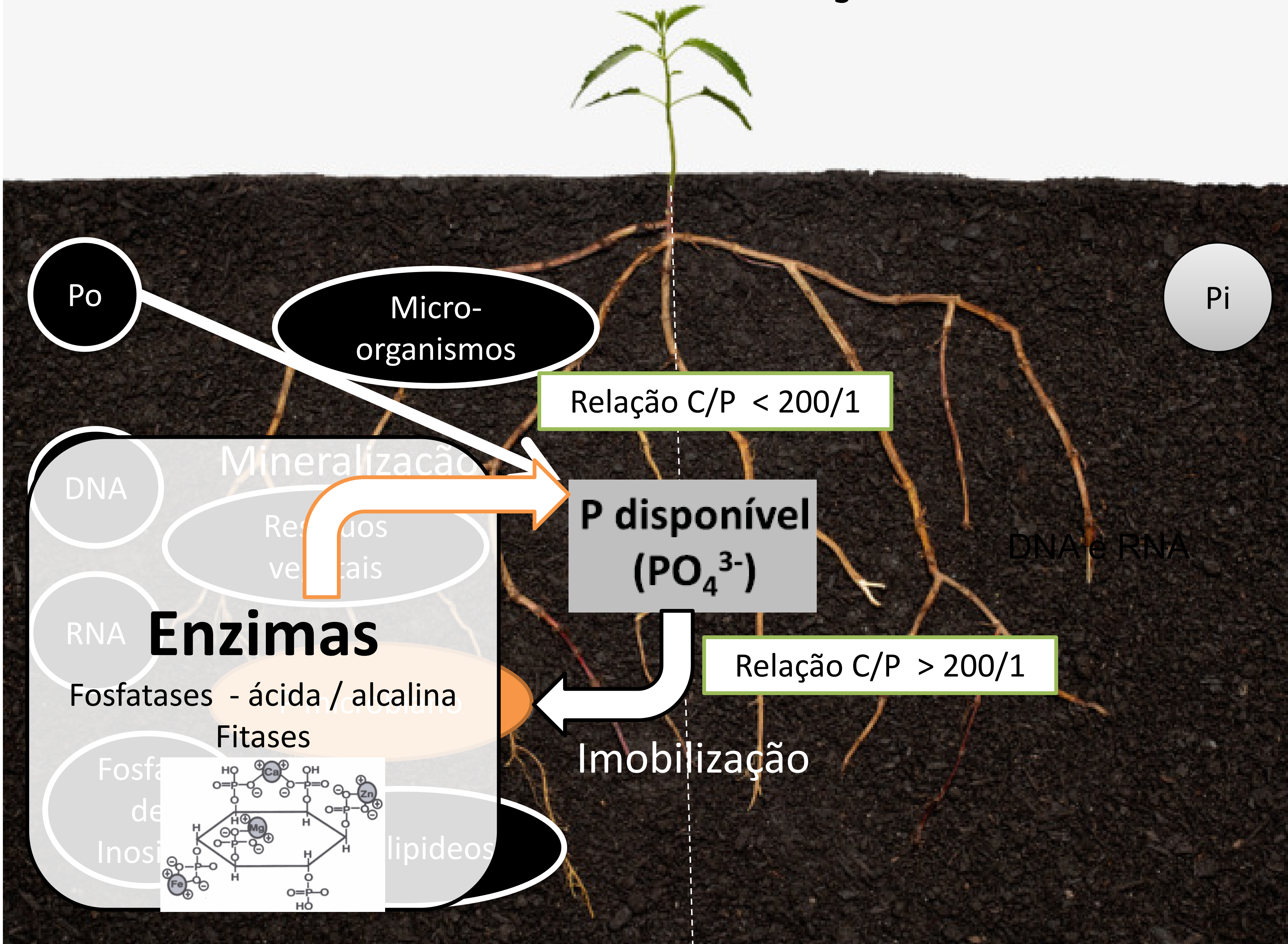
Ciclagem de P no Solo



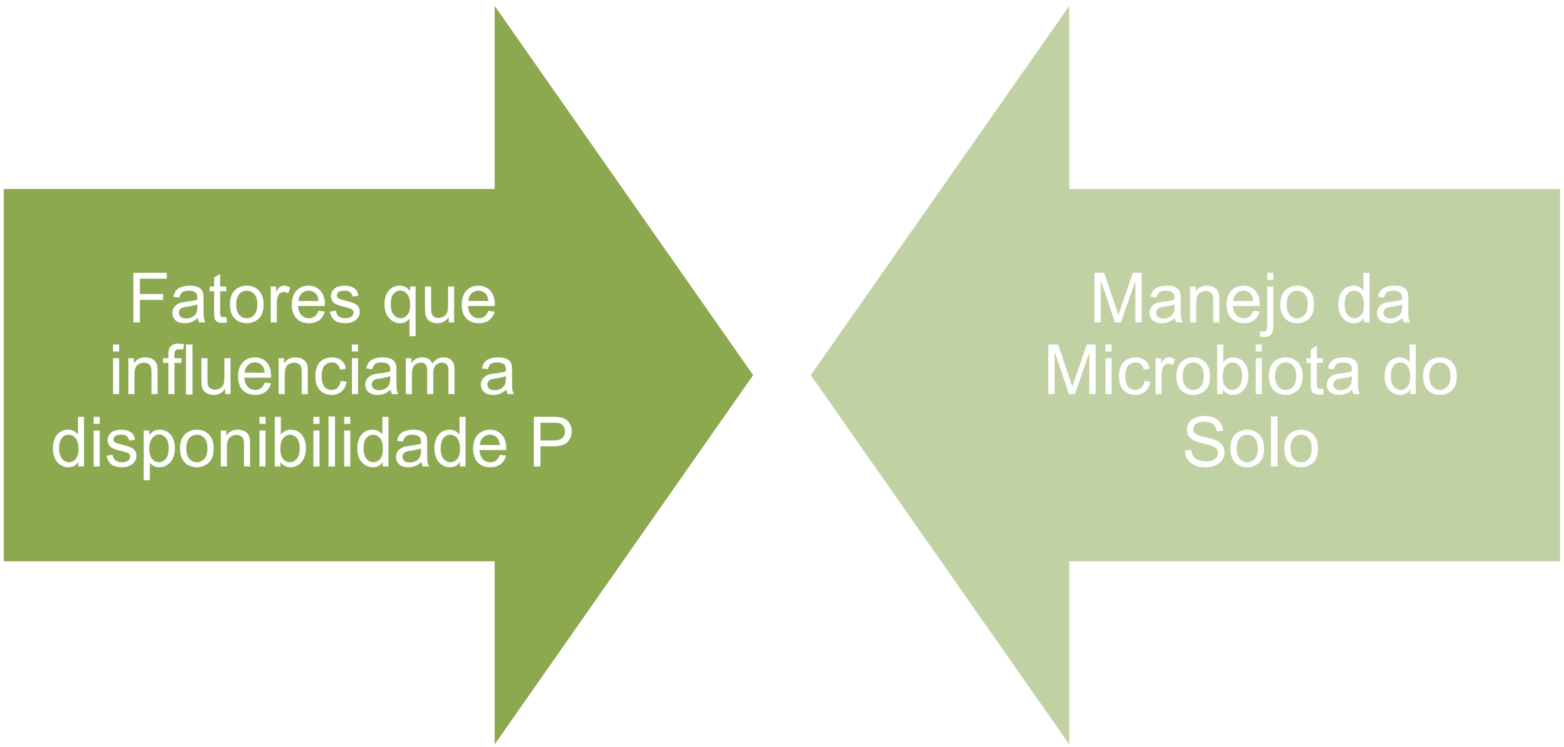
Mecanismos de solubilização de fósforo



Mecanismos de mineralização de fósforo



Manejo do P do solo



Manejo do P do solo

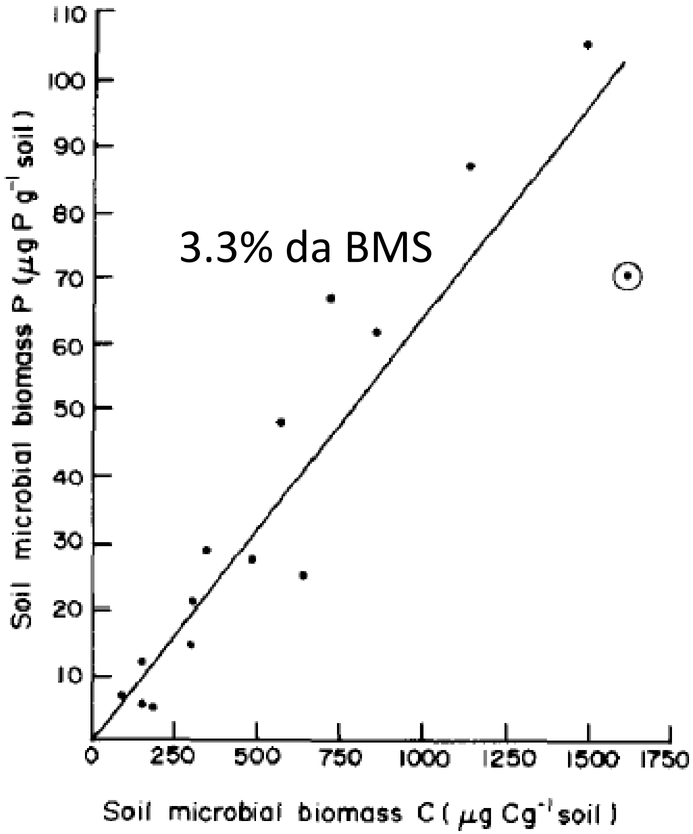


Fig. 1. Relationship between phosphorus and carbon in the soil microbial biomass. Encircled value—see text.

% P na BM - 1.4 a 4.7% (C/P = **10.6-35.9**)

Brookes et al 1984 ***Soil Biol. Biochem.*** Vol. ***16, No. 2, pp. 169-175, 1984***

Manejo do P do solo

Table 3. Soil biomass P expressed as a percentage of total soil organic P

Soil No.	Agricultural history	Total soil organic P ($\mu g\ P\ g^{-1}$ soil)	Biomass P ($\mu g\ P\ g^{-1}$ soil)	Biomass P as % of total soil organic P	
1.	Arable	180	6.0	3.3	$3.0^a \pm 0.2$
2.	Arable	210	5.3	2.5	
11.	Arable	242	7.0	2.9	
15.	Arable/grass	810	27.5	3.4	
7.	Arable out of grass	270	21.0	7.8	
5.	Grassland	330	72.3	21.9	$13.7^a \pm 3.5$
8.	Grassland	352	61.7	17.5	
10.	Grass/clover ley	190	15.0	7.9	
12.	Grassland	210	12.0	5.7	
13.	Grassland	500	24.8	5.0	
14.	Grassland	200	48.6	24.3	
4.	Deciduous woodland	350	67.2	19.2	

[a]Mean and standard error.

Brookes et al 1984 ***Soil Biol. Biochem.*** Vol. ***16, No. 2, pp. 169-175, 1984***

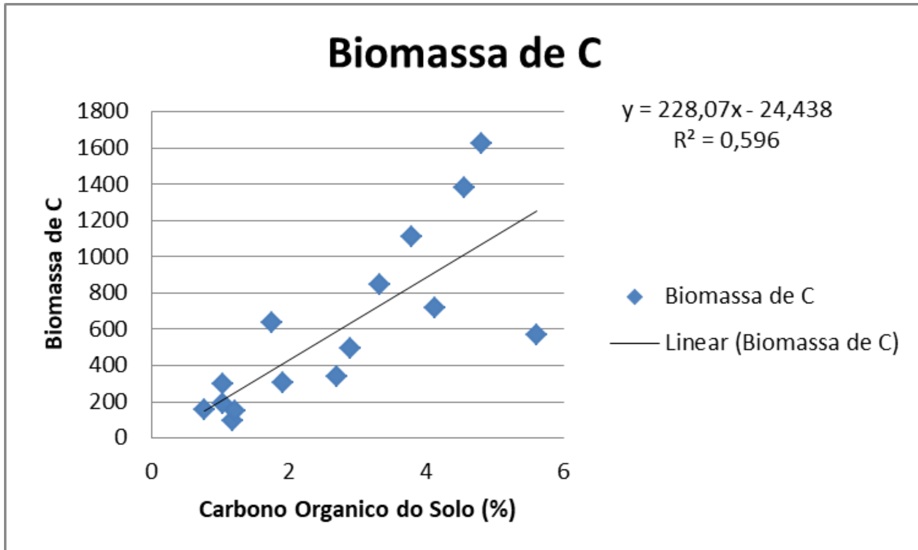
Soil No.	Site and cropping history	Total N (%)	Organic C (%)	Total P (%)	P extracted by 0.5 M $NaHCO_3$ from non-fumigated soil (μg P g^{-1} soil) P_i	P_o	P_t
1.	Broadbalk Plot 03 (Continuous wheat)	0.108	0.77	0.053	4.3	1.6	5.9
2.	Broadbalk Plot 08 (Continuous wheat)	0.108	1.04	0.105	76.0	5.9	81.9
3.	Broadbalk Plot 022 (Continuous wheat)	0.250	2.69	0.130	84.8	0.5	85.3
4.	Broadbalk Wilderness (Deciduous woodland)	0.371	4.13	0.081	10.8	6.3	17.1
5.	Park Grass Plot 3a (Unmanured permanent grass	0.453	4.81	0.061	3.1	3.4	6.5
6.	Park Grass Plot 4/1a (Permanent grass)	0.423	4.55	0.192	38.3	2.5	140.8
7.	Highfield Permanent Arable (Arable rotation)	0.186	1.91	0.095	53.2	9.1	62.3
8.	Highfield Permanent Grass (Permanent grass)	0.322	3.32	0.078	10.0	14.9	24.9
9.	Non-experimental Permanent Grassland (Highfield)	0.357	3.78	0.092	12.4	12.3	24.7
10.	Woburn Long Term Phospha (Nil Plot) (grass/clover ley)	0.120	1.04	0.066	6.5	8.6	15.1
11.	Woburn Permanent Arable (Arable rotation)	0.119	1.19	0.092	41.1	12.2	53.3
12.	Woburn Permanent Grass (8 yr grass ley)	0.115	1.21	0.074	28.6	5.0	33.6
13.	Saxmundham Rotation I (Bonemeal Plot) (grass ley)	0.194	1.76	0.082	6.5	3.1	9.6
14.	Counteswells (Permanent grass)	0.390	5.61	0.092	7.2	23.9	31.1
15.	Tarves (Barley/grass-clover/roots rotation)	0.332	2.90	0.202	67.4	34.4	101.8

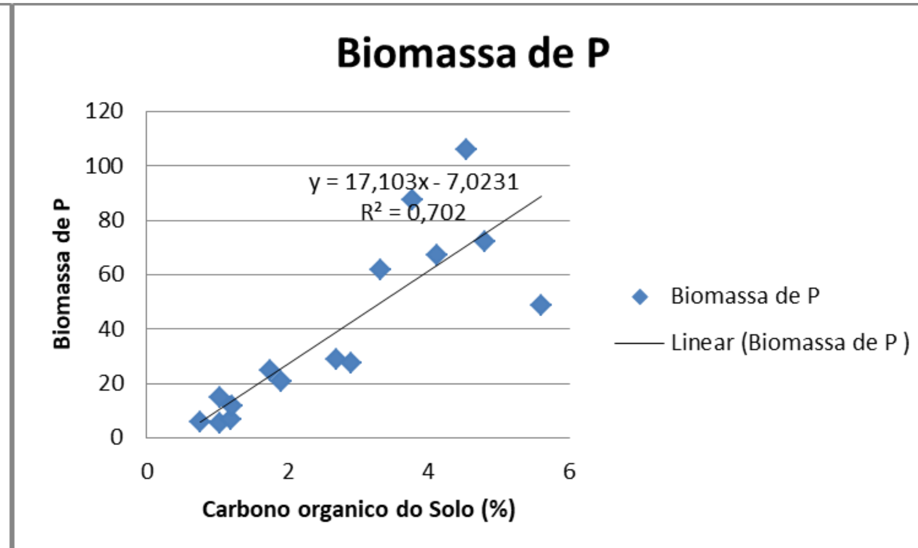
and P_t

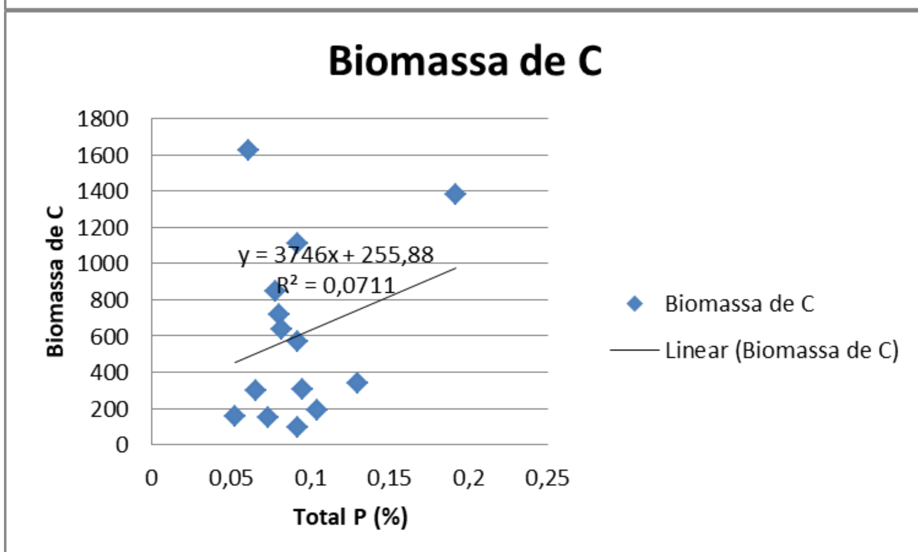
Soil No.	Biomass C (μg g^{-1} soil)	Biomass P (μg g^{-1} soil)	% P in biomass[a]
1.	158	6.0	1.9
2.	190	5.3	1.4
3.	342	28.9	4.2
4.	715	67.2	4.7
5.	1627	72.3	2.2
6.	1379	106.0	3.8
7.	305	21.0	3.4
8.	847	61.7	3.6
9.	1112	87.6	3.9
10.	300	15.0	2.5
11.	99	7.0	3.5
12.	148	12.0	4.1
13.	635	24.8	2.0
14.	569	48.6	4.3
15.	492	27.5	2.8
Mean and standard error			—
Slope of regression line			$3.25^{b} \pm 0.25^{c}$

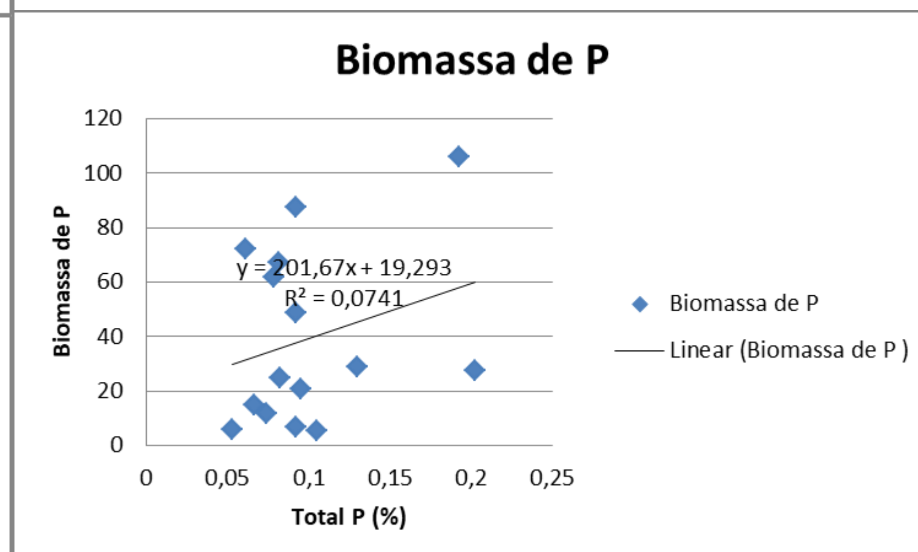
Brookes et al 1984 ***Soil Biol. Biochem.*** Vol. ***16, No. 2, pp. 169-175, 1984***

Qual a relação do Carbono e Fósforo do solo com a biomassa microbiana de C e P?



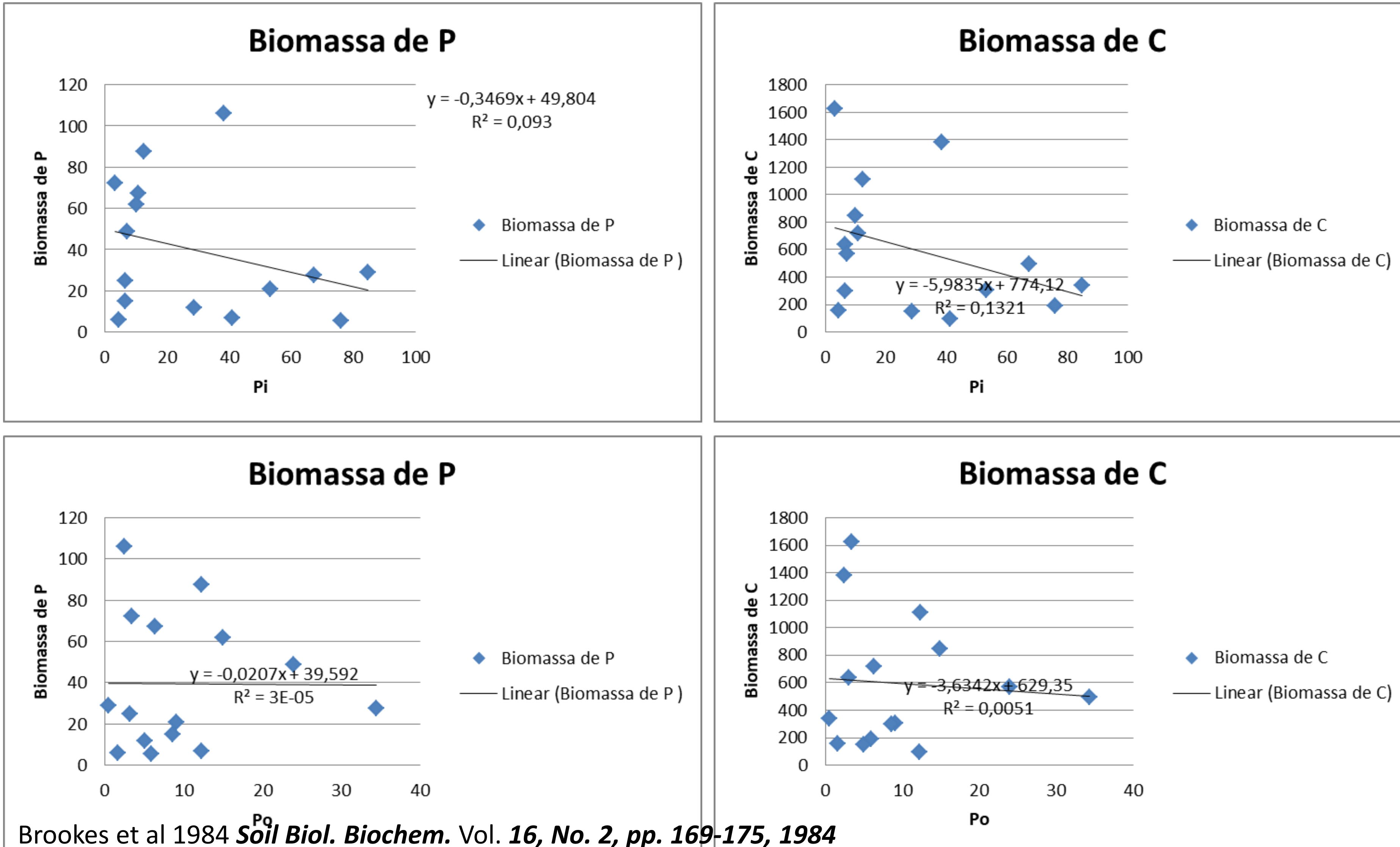






Brookes et al 1984 ***Soil Biol. Biochem.*** Vol. ***16, No. 2, pp. 169-175, 1984***

Qual a relação do Fósforo Orgânico e Inorgânico do solo com a biomassa microbiana de C e P?



Brookes et al 1984 ***Soil Biol. Biochem.*** Vol. ***16, No. 2, pp. 169-175, 1984***

Fluxo anual de P

Table 4. The soil biomass phosphorus contents and calculated annual P flux through the biomass in the 0–10 cm soil layer. Crop P removals given where available

Soil No.	Agricultural history	Soil weight (t ha^{-1} < 6.24 mm in a 10 cm soil depth)[b]	Biomass P (kg P ha^{-1})	Annual biomass P flux (kg P ha^{-1} yr^{-1})[a]		P removed in crop (kg P ha^{-1} yr^{-1})
1	Arable	1135	6.8	2.7	6.8[d] ± 1.7	9.3
2	Arable	1048	5.6	2.2		22.8
3	Arable	948	27.4	11.0		28.8
7[c]	Arable out of grass	1200	25.2	10.1		ND
11[c]	Arable	1620	11.3	4.5		ND
15	Arable/grass	940	25.9	10.4		ND
5	Grassland	952	68.8	27.5	22.7[d] ± 4.3	8.0
6	Grassland	952	100.9	40.4		12.0
8[c]	Grassland	1050	64.8	25.9		ND
9	Grassland	1050	92.0	36.8		ND
10	Grassland	1500	22.5	9.0		9.0
12[c]	Grassland	1500	18.0	7.2		ND
13	Grassland	1522	37.8	15.1		17.8
14	Grassland	1018	49.5	19.8		ND
4	Woodland	808	54.3	21.7		NA

Brookes et al 1984 ***Soil Biol. Biochem.*** Vol. ***16, No. 2, pp. 169-175, 1984***

Qual o impacto do plantio convencional e rotação de cultura sobre o P da biomassa?

Table 2 Microbial biomass C, N, P and S as affected by different tillage and crop rotation systems

Crop rotation	Microbial biomass							
	C		N		P		S	
	CT	NT	CT	NT_plus	CT	NT	CT	NT
	$\mu g\ g^{-1}$ soil							
0- to 5-cm depth								
S/W[a]	223 b[b]A[c]	369 aA	23.4 bA	33.6 aA	10.8 aA	12.1 aB	17.0 aA	8.9bB
M/W	181 bA	389 aA	17.5 bA	27.6 aA	9.0 bB	12.1 aB	16.8 aA	12.7aA
C/W	145 bA	372 aA	17.2 bA	28.3 aA	10.7 bA	18.3 aA	12.2 aA	12.0aAB
5- to 10-cm depth								
S/W	105 aB	154 aB	14.1 bB	23.7 aA	5.6 aB	5.6 aB	14.8 aB	16.5aA
M/W	195 aA	185 aAB	19.9 aA	19.3 aA	9.0 aA	8.2 aAB	19.7 aA	14.5bAB
C/W	105 bB	268 aA	8.4 bC	22.4 aA	8.6 aA	10.0 aA	16.3 aAB	10.1bB
10- to 20-cm depth								
S/W	220 aA	269 aA	25.4 aA	24.4 aA	8.8 aB	8.4 aA	9.5 bB	14.2aA
M/W	225 aA	195 aA	22.0 aA	16.7 aA	12.0 aA	7.3 bA	14.0 aA	13.1aA
C/W	111 bA	195 aA	11.5 aB	15.5 aA	8.0 aB	8.4 aA	7.2 aB	13.2aA

[a] *S* Soybean, *W* wheat, *M* maize, *C* cotton
[b] Values followed by the *same lower case letter* comparing tillage within crop rotation are not significantly different at $P \leq 0.05$
[c] Values followed by the *same upper case letter* comparing crop rotations within tillage regime are not significantly different at $P \leq 0.05$

Balota et al 2003 Biol Fertil Soils (2003) 38:15–20

Enzimas do P

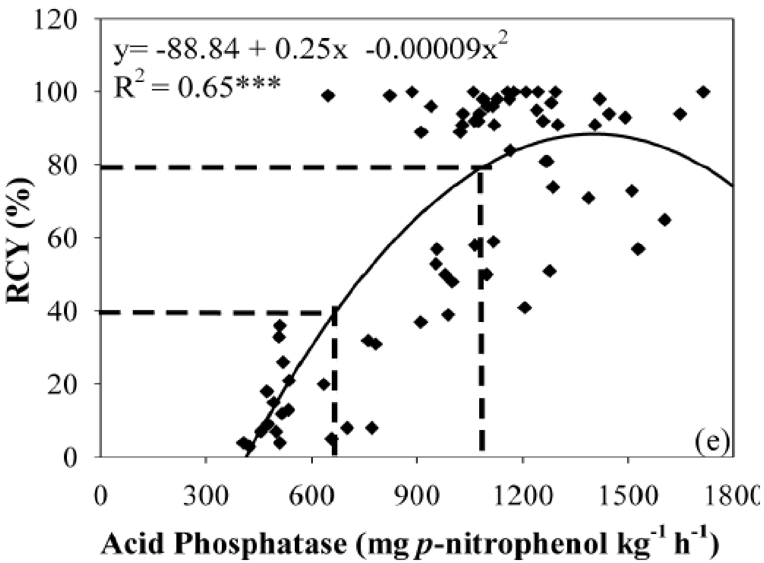
Table 2. Enzyme activities in soils under different tillage and crop rotations systems.

Crop Rotation[1]	Amylase		Cellulase		Arylsulfatase		Acid Phosphatase		Alkaline Phosphatase	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
	mg GLU $g^{-1} d^{-1}$						mg PNP $g^{-1} h^{-1}$			
					0 – 5 cm					
S / W	461 b[2]A[3]	670 aA	118 aA	150 aA	8.9 bA	18.7 aB	621 bA	792 aA	147 bA	186 aA
M / W	451 bA	750 aA	94 bA	193 aA	8.4 bA	32.7 aA	572 bAB	832 aA	127 bA	207 aA
C / W	490 bA	929 aA	86 bA	220 aA	7.6 bA	28.0 aAB	508 bB	852 aA	86 bB	187 aA
					5 – 10 cm					
S / W	392 bB	648 aA	67 aB	96 aA	8.0 bB	20.4 aA	482 bB	633 aA	103 bB	160 aA
M / W	730 aA	595 bA	139 aA	144 aA	12.5 bA	27.1 aA	608 aA	658 aA	133 aA	159 aA
C / W	350 bB	615 aA	87 aB	98 aA	4.1 bC	26.3 aA	495 bB	711 aA	75 bB	161 aA
					10 – 20 cm					
S / W	496 bAB	601 aA	92 aA	105 aA	6.1 bA	20.7 aB	615 aA	688 aA	134 aA	152 aA
M / W	546 bA	587 aA	105 aA	118 aA	6.7 bA	25.9 aA	625 bA	777 aA	142 bA	191 aA
C / W	446 bB	573 aA	82 aA	90 aA	4.2 bA	19.2 aB	458 bB	685 aA	100 aB	139 aA

[1] S: Soybean; W: Wheat; M: Maize; C: Cotton; [2] Values within a row of the same depth followed by same lower case letter comparing tillage are not significantly different at $P \leq 0.05$; [3] Values within a column of the same depth followed by same upper case letter comparing crop rotation are not significantly different at $P \leq 0.05$.

Balota et al 2004 Braz. J. Microbiol. vol.35 no.4 São Paulo Oct./Dec. 2004

Enzimas do P



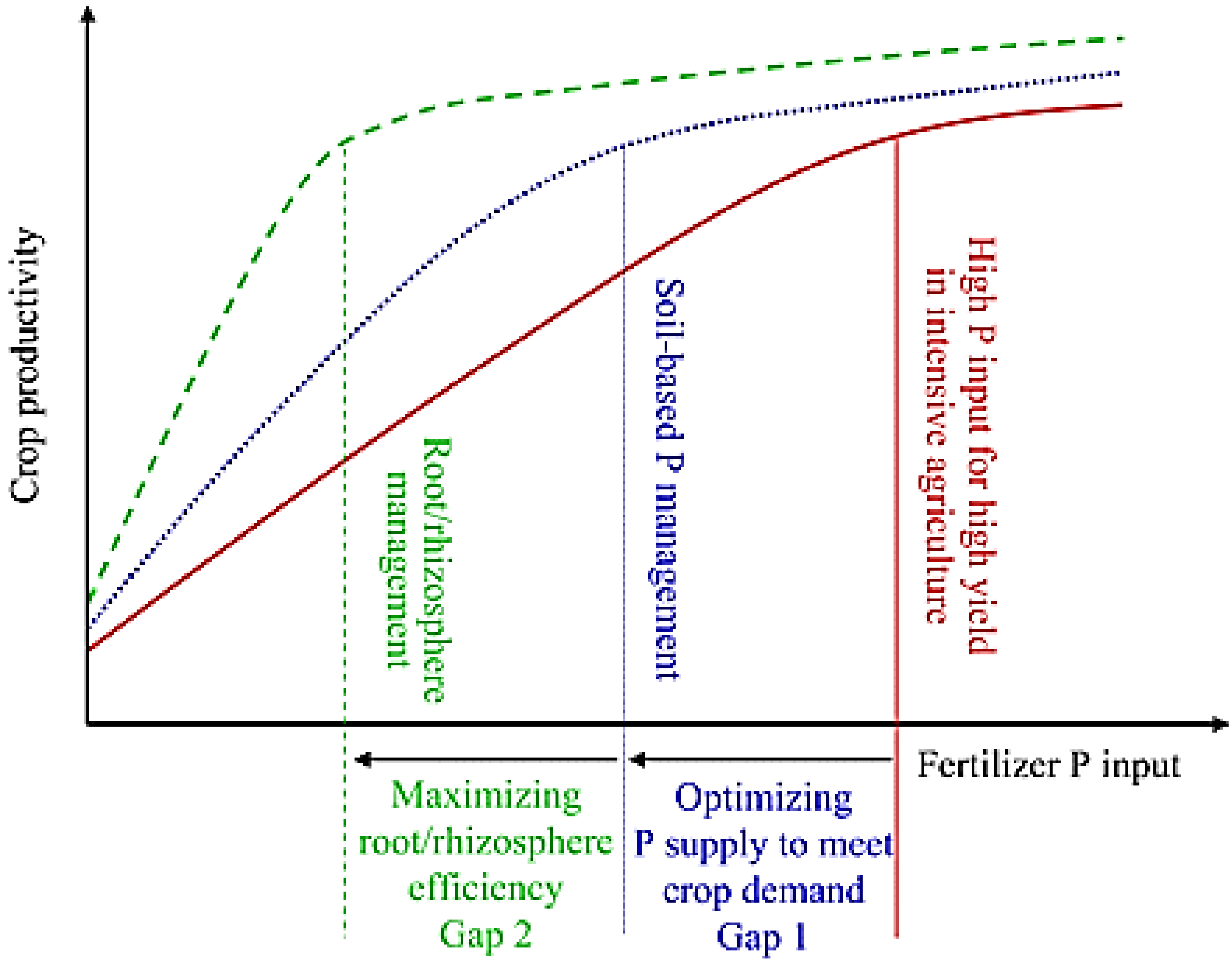
4. Relationships among relative cumulative yield (RCY) and (a) microbial biomass C (MBC), (b) basal respiration, (c) cellulase, d) b-glucosidase, (e) acid phosphatase, and (f) arylsulfatase. The data points represent the three field replicates of the 24 selected treatments. Dashed lines represent the limits of the interpretative classes: £40% RCY: low, 41 to 80% RCY: moderate and > 80% RCY: adequate. ***Significant at *P* < 0.001.

Table 4. Interpretative classes for microbial indicators in a clayey Red Latosol of the Cerrado region (0–10-cm depth) as a function of the relative cumulative yield (RCY).

Microbial indicator	Interpretative class as a function of RCY†		
	Low	Moderate	Adequate
Microbial biomass C, mg C kg^{-1} soil	≤215	216–375	>375
Basal respiration, mg C kg^{-1} soil	≤40	41–90	>90
Acid phosphatase, mg *p*-nitrophenol kg^{-1} soil h^{-1}	≤680	681–1160	>1160

† Interpretative classes are: ≤40% RCY: low; 41–80% RCY: moderate; and >80% RCY: adequate.

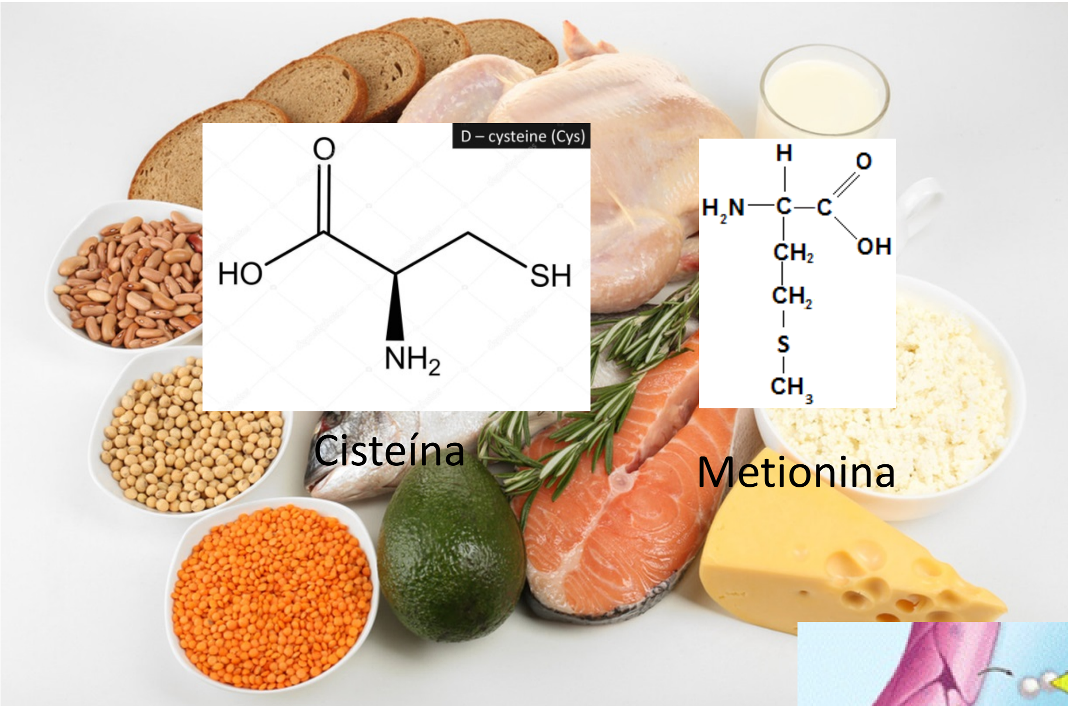
Lopes et al 2013 Soil Sci. Soc. Am. J. 77:461–472

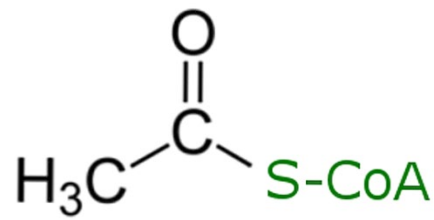


Shen et al 2011 Plant Physiology DOI: https://doi.org/10.1104/pp.111.175232

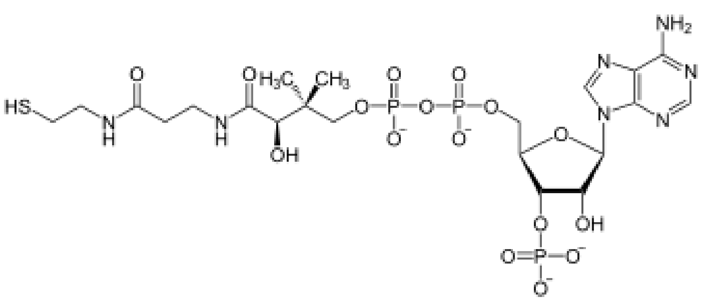
TRANSFORMAÇÕES DO ENXOFRE

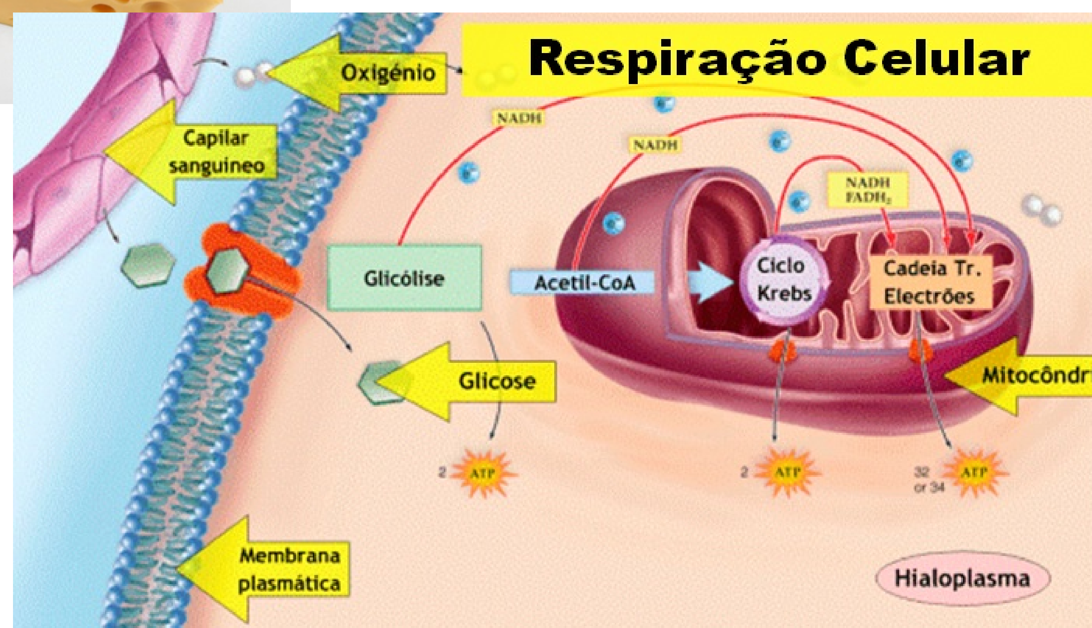
Importância do Enxofre



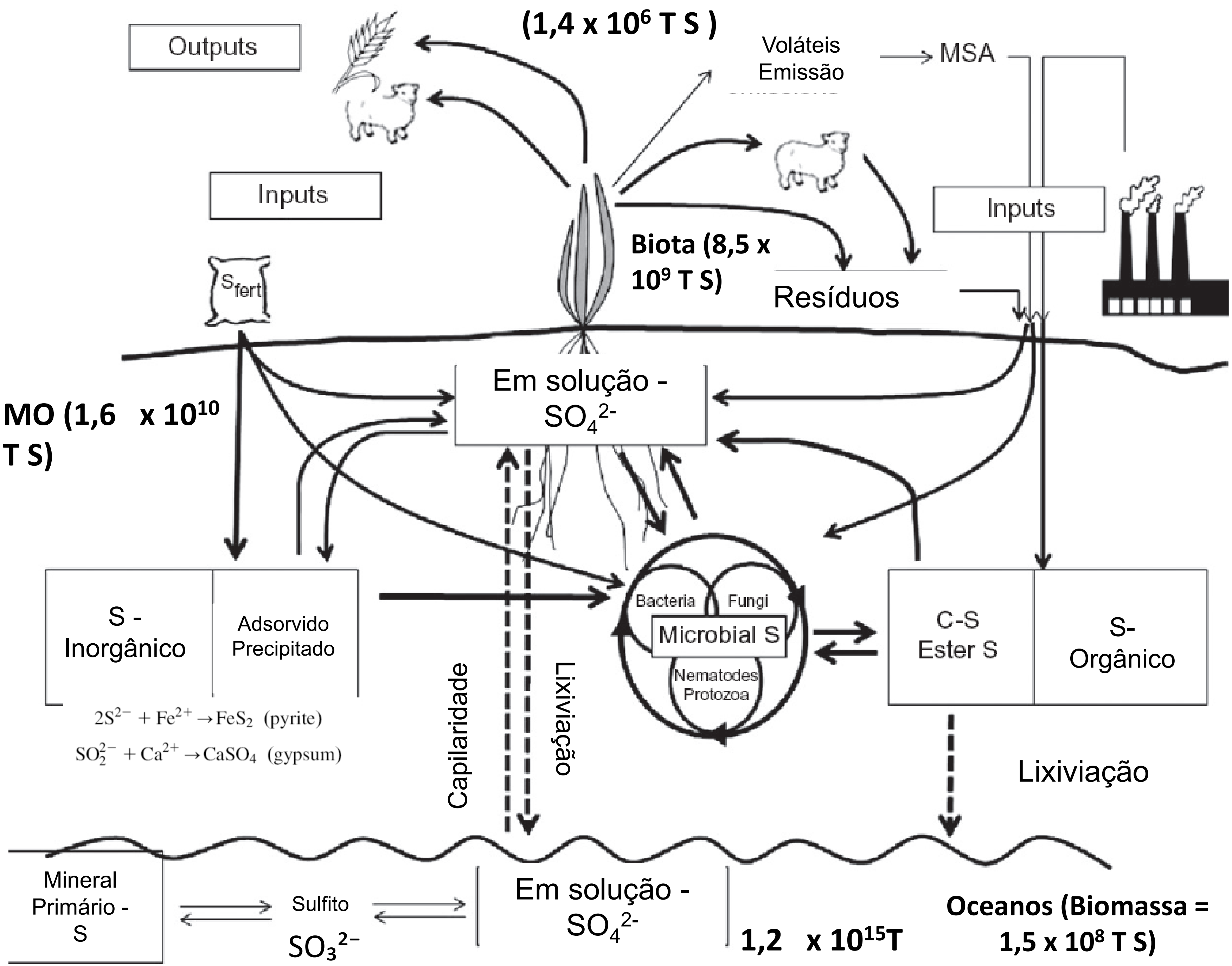


Acetil-Coenzima A





Coenzimas: tiamina, biotina e **coenzima** A



(1,4 x 10^6 T S)
Outputs
Voláteis
Emissão
MSA
Inputs
Inputs
Biota (8,5 x 10^9 T S)
Resíduos
S fert
MO (1,6 x 10^10 T S)
Em solução - SO_4^{2-}
S - Inorgânico
Adsorvido
Precipitado
$2S^{2-} + Fe^{2+} \rightarrow FeS_2$ (pyrite)
$SO_2^{2-} + Ca^{2+} \rightarrow CaSO_4$ (gypsum)
Capilaridade
Lixiviação
Bacteria
Fungi
Microbial S
Nematodes
Protozoa
C-S
Ester S
S-
Orgânico
Lixiviação
Mineral
Primário -
S
Sulfito
SO_3^{2-}
Em solução - SO_4^{2-}
1,2 x 10^15T
Oceanos (Biomassa = 1,5 x 10^8 T S)

Microbiota do Solo - S

- *Acidothiobacillus*
- *Sulfobacillus,*
- *Thiomicrospira*
- *Achromatium*
- *Beggiatoa*
- *Thermothrix*

Quimioautotróficos obrigatórios ou facultativos

$$S^0 + 1.5O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+$$

$$H_2S + 1/2O_2 \rightarrow S^0 + H_2O$$

- *Chlorobium*
- *Chromatium*
- *Ectothiorhodospira*
- *Thiopedia*
- *Rhodopseudomonas*

Fototróficos anaeróbicos

$$CO_2 + H_2S \rightarrow S^0 + \text{fixed carbon}$$

- *Desulfobacter*
- *Desulfobulbus*
- *Desulfococcus*
- *Desulfonema*
- *Desulfosarcina*
  Desulfotomaculum
- *Desulfovibrio*

Quimiheterotróficos anaeróbicos

$$\underset{\text{acetate}}{CH_3COOH} + 2H_2O + 4S^0 \rightarrow 2CO_2 + 4S^{2-} + 8H^+$$

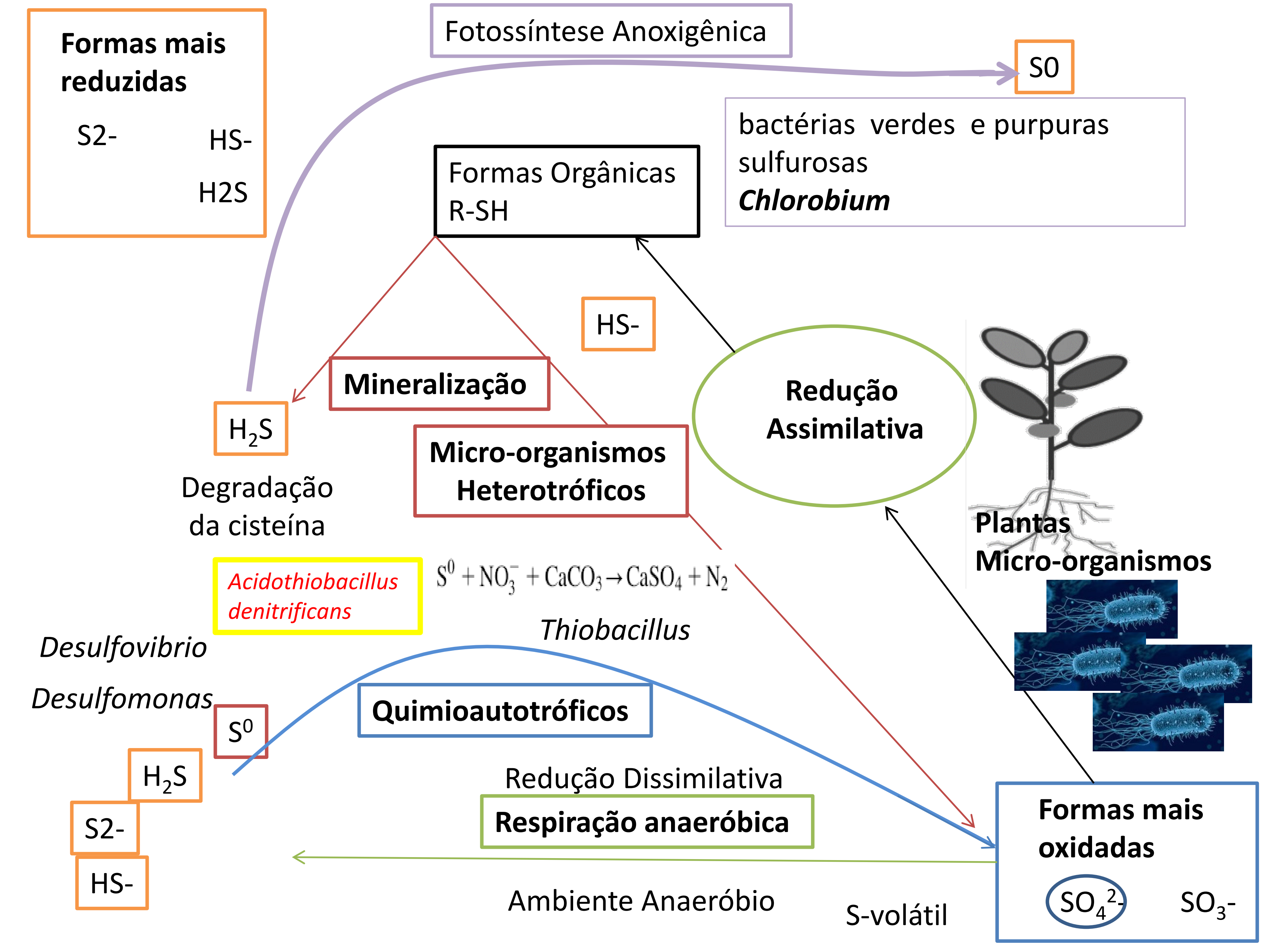
$$4H_2 + SO_4^{2-} \rightarrow S^{2-} + 4H_2O$$

$$\underset{\text{methanol}}{4CH_3OH} + 3SO_4^{-2} \rightarrow 4CO_2 + 3S^{2-} + 8H_2O$$

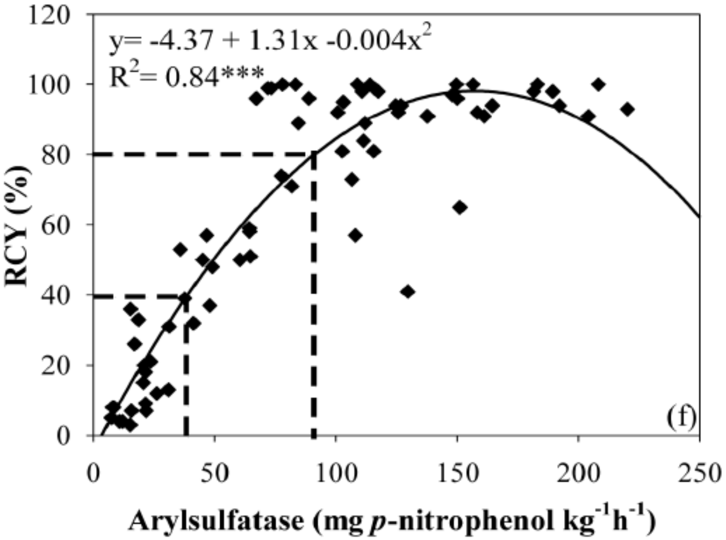
Estado de oxidação do Enxofre

Estado de oxidação	Espécie
+6	H_2SO_4, XSO_4
	↑
+4	SO_2
	↑
+2	SO
	↑
+1	HSO
	↑
0	S
	↑
-1	SH
	↑
-2	H_2S, COS, CS_2

Martins, Cláudia Rocha, & Andrade, Jailson Bittencourt de. (2002). Química atmosférica do enxofre (IV): emissões, reações em fase aquosa e impacto ambiental. *Química Nova*, *25*(2), 259-272. https://dx.doi.org/10.1590/S0100-40422002000200015


Formas mais reduzidas
S2-
HS-
H2S
Fotossíntese Anoxigênica
S0
bactérias verdes e purpuras sulfurosas
Chlorobium
Formas Orgânicas
R-SH
HS-
Mineralização
H2S
Micro-organismos Heterotróficos
Redução Assimilativa
Plantas
Micro-organismos
Degradação da cisteína
Acidothiobacillus denitrificans
S0 + NO3- + CaCO3 → CaSO4 + N2
Thiobacillus
Desulfovibrio
Desulfomonas
S0
Quimioautotróficos
H2S
S2-
HS-
Redução Dissimilativa
Respiração anaeróbica
Formas mais oxidadas
SO42-
SO3-
Ambiente Anaeróbio
S-volátil

Enzimas do S



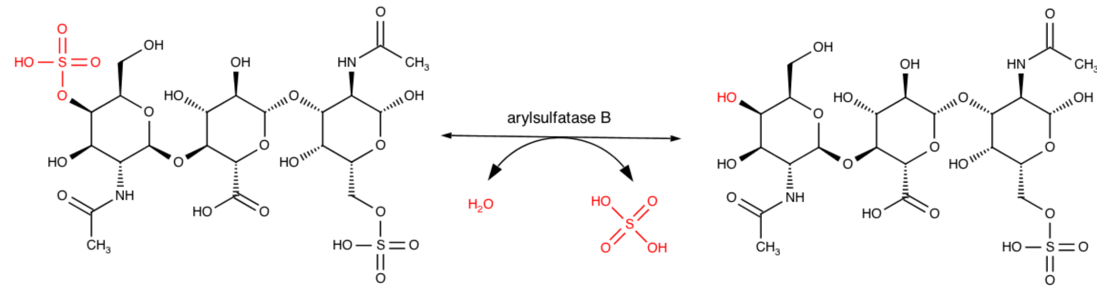


Table 4. Interpretative classes for microbial indicators in a clayey Red Latosol of the Cerrado region (0–10-cm depth) as a function of the relative cumulative yield (RCY).

Microbial indicator	Interpretative class as a function of RCY†		
	Low	Moderate	Adequate
Microbial biomass C, mg C kg^{-1} soil	≤215	216–375	>375
Basal respiration, mg C kg^{-1} soil	≤40	41–90	>90
Arylsulfatase, mg *p*-nitrophenol kg^{-1} soil h^{-1}	≤40	41–90	>90

† Interpretative classes are: ≤40% RCY: low; 41–80% RCY: moderate; and >80% RCY: adequate.

Lopes et al 2013 Soil Sci. Soc. Am. J. 77:461–472

Qual impacto do manejo sobre a atividade da enzima Arylsulfatase

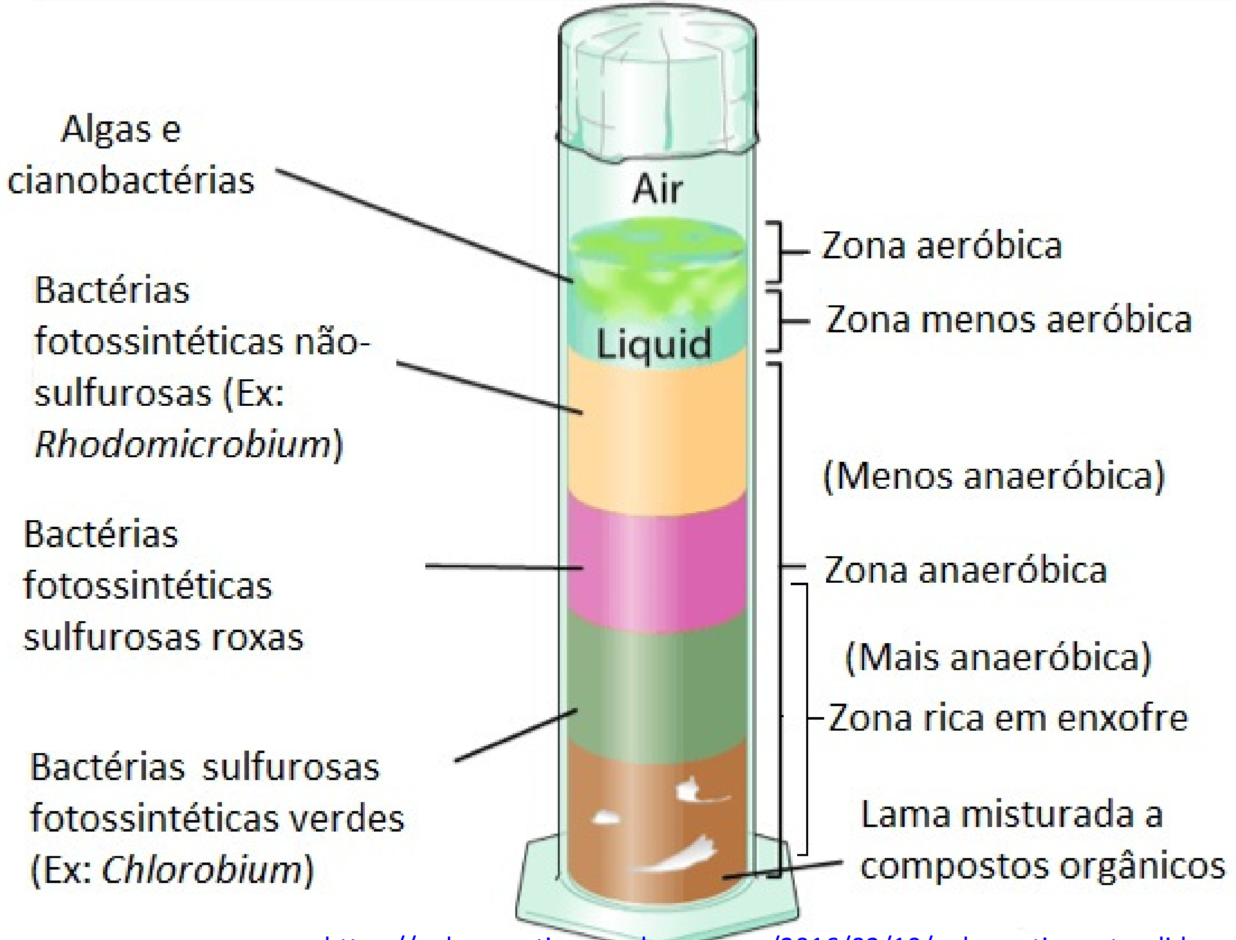
Table 6
Microbial biomass-C and enzymatic activity in soils under different managements in Brazil.

Vegetation type	MB-C μg g^{-1}	Carbon cycle		Nitrogen cycle		Phosphorus cycle		Sulfur cycle	Reference
		β-glucosidase (EC 3.2.1.21) μg PN g^{-1} h^{-1}	Cellulase (EC 3.2.1.4) μg GL g^{-1} d^{-1}	Urease (EC 3.5.1.5) μg N g^{-1} h^{-1}	Amidase (EC 3.5.1.4) μg GL g^{-1} d^{-1}	Aci. phosphatase (EC 3.1.3.2) μg PN g^{-1} h^{-1}	Alk. phosphatase (EC 3.1.3.1) μg PN g^{-1} h^{-1}	Arylsulfatase (EC 3.1.6.1) μg PN g^{-1} h^{-1}	
Caatinga	102	64	nd	nd	nd	335	166	nd	Wick et al. (2000)
Buffel grass	79	42	nd	nd	nd	264	124	nd	
Joazeiro	159	187	nd	nd	nd	389	384	nd	
Umbuzeiro	124	136	nd	nd	nd	403	199	nd	
Cerrados	402	47	nd	nd	nd	383	nd	99	Matsuoka et al. (2003)
Vineyard	153	41	nd	nd	nd	291	nd	34	
NT	99	52	nd	nd	nd	281	nd	17	
Cerrados	444	26	nd	nd	nd	868	nd	73	Mendes et al. (2003)
NT	214	52	nd	nd	nd	499	nd	48	
CT	125	24	nd	nd	nd	257	nd	16	
CT 1	146	nd	118	nd	461	621	147	9	Balota et al. (2004b)
CT 2	153	nd	94	nd	451	572	127	8	
CT 3	170	nd	86	nd	490	508	86	8	
NT 1	286	nd	150	nd	670	792	186	19	
NT 2	303	nd	193	nd	750	832	207	33	
NT 3	269	nd	220	nd	929	852	187	28	
NT	432	783	nd	384	nd	601	nd	nd	Trannin et al. (2007)
Pasture	329	863	nd	154	nd	692	nd	nd	
Cerrados	480	322	nd	nd	nd	374	191	nd	Jakelaitis et al. (2008)
Pasture	133	127	nd	nd	nd	317	33	nd	
NT	126	145	nd	nd	nd	354	148	nd	

nd = not determined in the study; PN = p-nitrophenol; GL = glucose; N = N-NH_4^+; Aci. = acid; Alk. = alkaline; NT, no-tillage; CT, conventional tillage. 1,2 and 3 are different crop rotations, whose plant species were not informed. Plant species: Joazeiro (*Ziziphus joazeiro* Mart.); Umbuzeiro (*Spondias tuberosa* Arr. Com.), Buffel grass (*Cenchrus ciliaris* L.); Vineyard (within lines) (*Vitis vinifera* L.); Eucaliptus (*Eucaliptus* spp); Pasture (*Brachiaria* spp.).

Kaschuk et al 2010 - Soil Biology & Biochemistry 42 (2010) 1–13

Coluna de **Winogradsky**



https://aulanapratica.wordpress.com/2016/02/10/aula-pratica-estendida-montando-uma-coluna-de-winogradsky/

Exercícios

1. Como os micro-organismos agem sobre o fósforo do solo e qual importância (econômica e ambiental) desses para o manejo de P no solo?

2. Como manejar a microbiota do solo quanto ao P?

Exercícios

1. O enxofre elementar deve ou não deve ser utilizado como fertilizante? Por que?

2. Como a arilsulfatase pode ser utilizada em estudos de solo? O que ela representa?

Table 3 Microbial biomass ratio (C:N:S:P) and C_{mic}/C_{org} percentage as affected by different tillage and crop rotations systems[a]

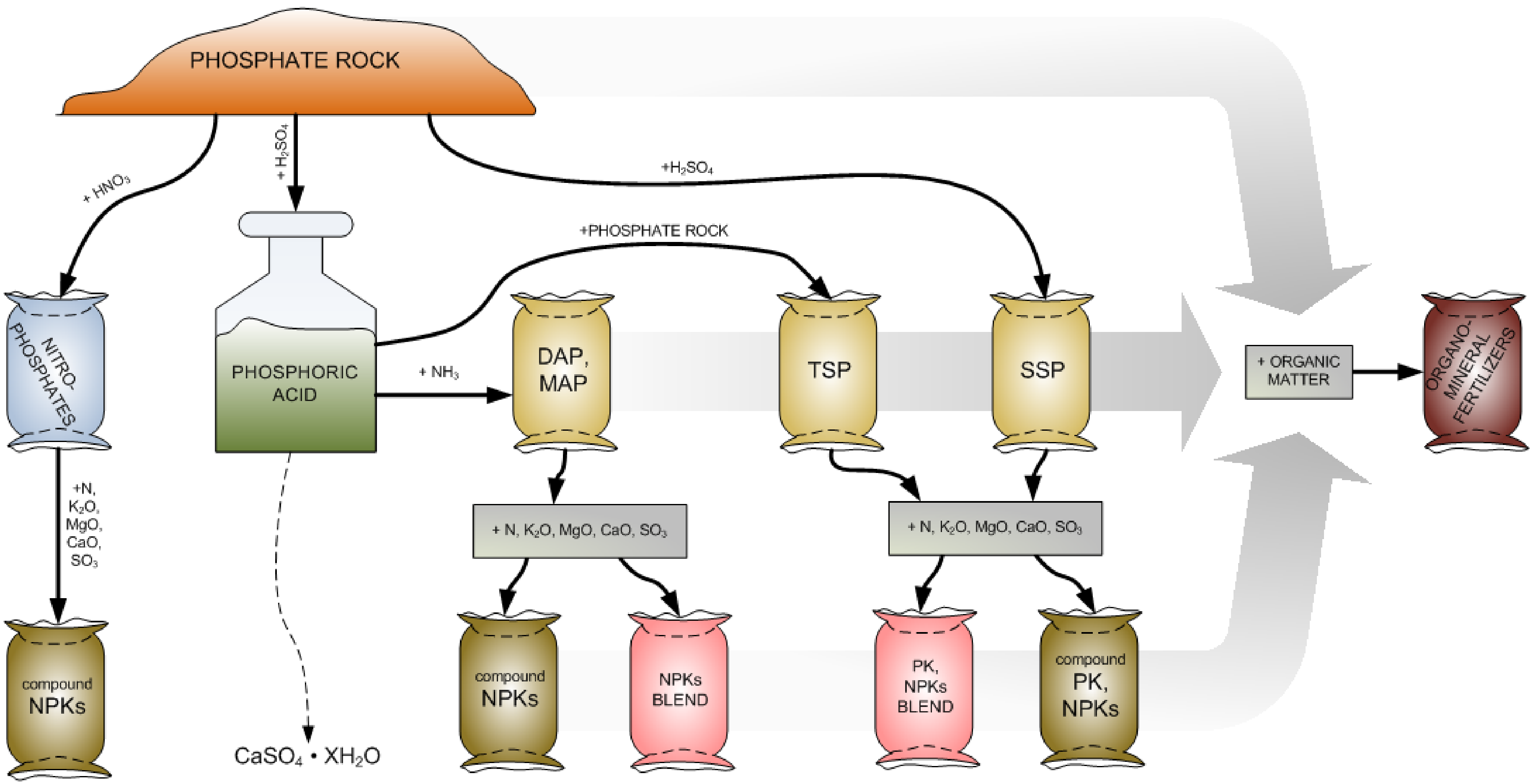
Crop rotation	C:N:S:P Ratios		C_{mic}/C_{org}	
	CT	NT	CT	NT
			%	
0–5 cm				
S/W	21:2:2:1	30:3:1:1	1.5 a[b]A[c]	1.8 aA
M/W	20:2:2:1	32:2:1:1	1.2 bA	1.7 aA
C/W	14:2:1:1	22:2:1:1	1.0 bA	1.8 aA
5–10 cm				
S/W	19:3:3:1	27:4:3:1	0.8 aB	0.9 aA
M/W	22:2:2:1	22:2:2:1	1.3 aA	1.0 aA
C/W	12:1:2:1	27:2:1:1	0.8 bB	1.4 aA
10–20 cm				
S/W	25:3:1:1	32:3:2:1	1.5 aA	1.7 aA
M/W	19:2:1:1	27:2:2:1	1.4 aA	1.1 aB
C/W	14:1:1:1	23:2:2:1	0.8 aA	1.2 aAB

[a] *S* Soybean, *W* wheat, *M* maize, *C* cotton
[b] Values followed by the *same lower case letter* comparing tillage within crop rotation are not significantly different at $P \leq 0.05$
[c] Values followed by the *same upper case letter* comparing crop rotations within tillage regime are not significantly different at $P \leq 0.05$

Qual o impacto do plantio convencional e rotação de cultura sobre o P da biomassa?

Balota et al 2003 Biol Fertil Soils (2003) 38:15–20

Processo de produção de P fert



http://aeep.eu/phosphate-fertilizers/production/