

# Sensoriamento e sensores

(solo)

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[www.agriculturadeprecisao.org.br](http://www.agriculturadeprecisao.org.br)

# Objetivo

Abordar as técnicas relacionadas ao uso de sensores de alvos agrícolas, especialmente solo e plantas, para a obtenção de dados e diagnóstico da variabilidade espacial, visando tratamento localizado via mapas ou em tempo real.

# Sensores & sensoriamento

Função: produzir diagnósticos detalhado das lavouras, de forma indireta, porém em alta densidade

- Os alvos?
  - Solo
  - Plantas
  - Produto (quantidade e qualidade)

- Formas (~~nomenclatura usual~~)?

- ~~Sensoriamento remoto~~

- Sem contato com o alvo

- ~~Sensoriamento direto~~

- Contato físico com o alvo

} terminologia recente:  
**sensores proximais**  
("proximal sensors")

“Proximal soil sensing (PSS) is the use of field-based sensors to obtain signals from the soil when the sensor’s detector is in contact with or close to (within 2 m) the soil. The sensors provide soil information because the signals correspond to physical measures, which can be related to soils and their properties” (Viscarra Rossel et al., 2011)

# Sensores & sensoriamento

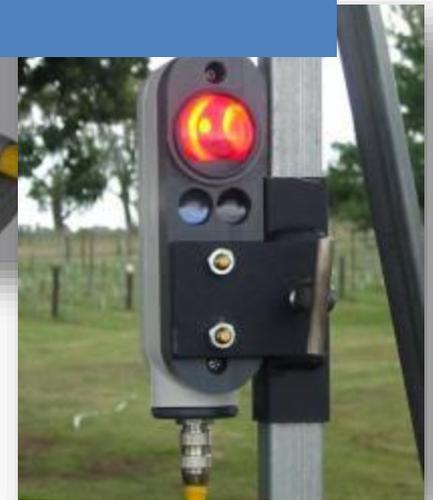
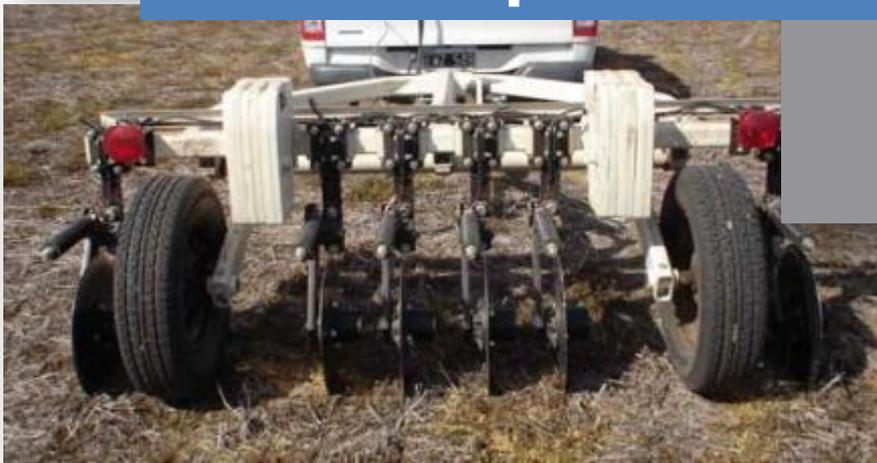
de solo



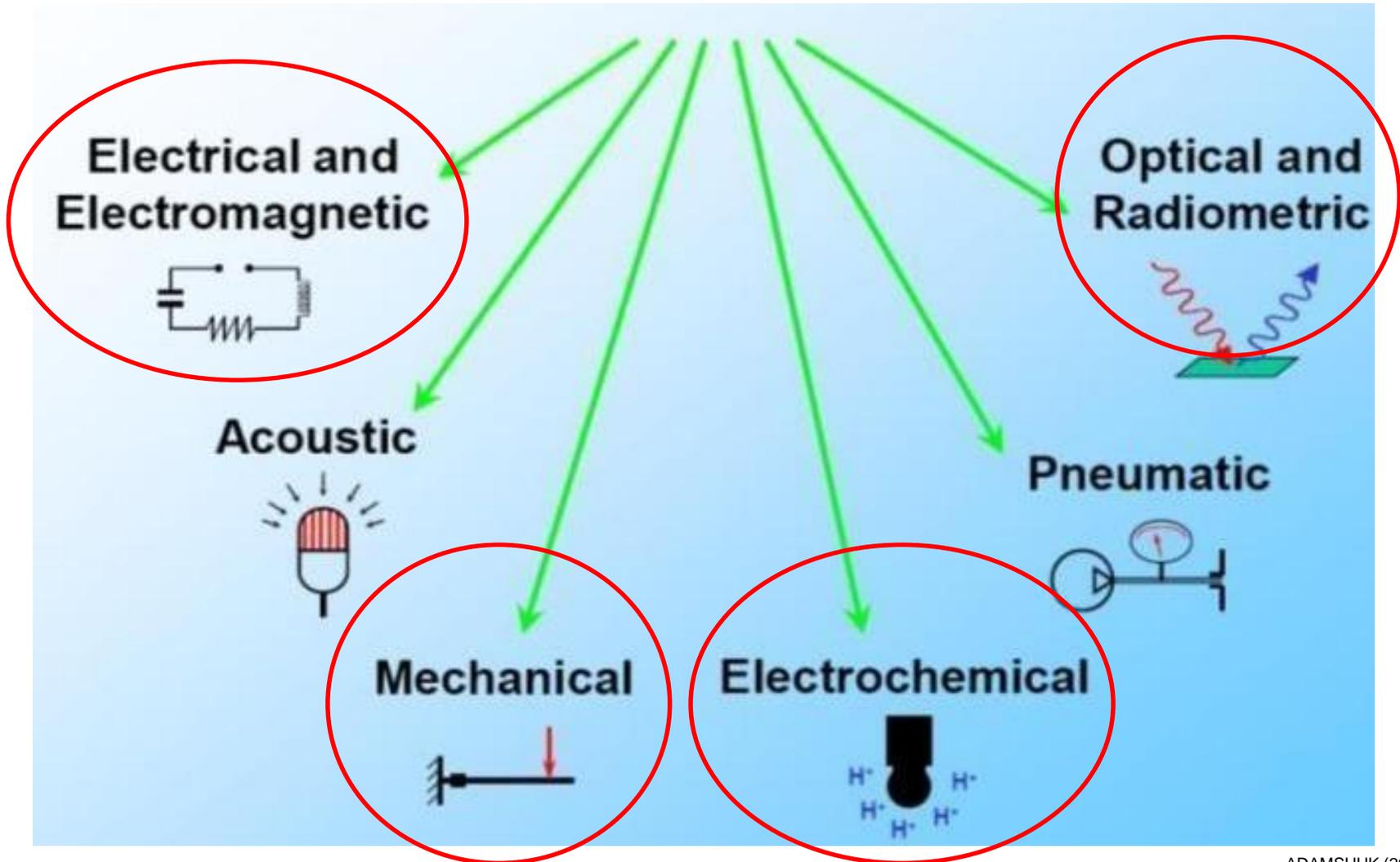
de plantas



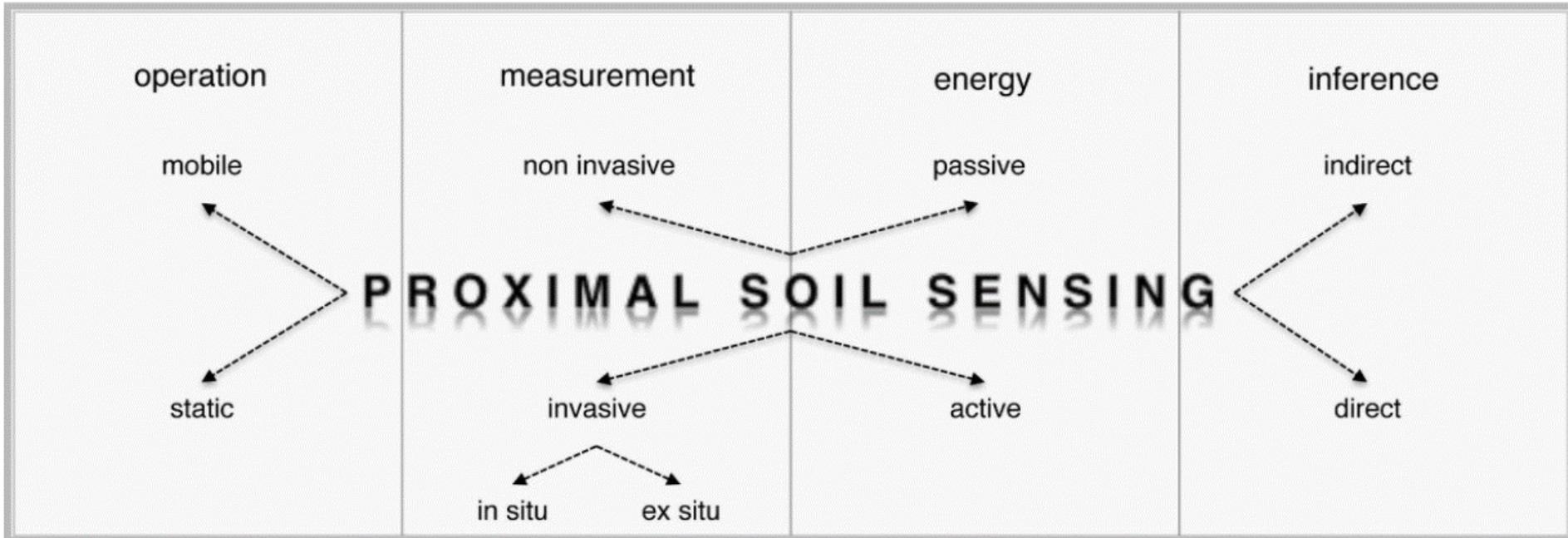
Mede-se algum parâmetro físico/químico que indiretamente relaciona-se a um parâmetro de interesse



# Sensores de solo

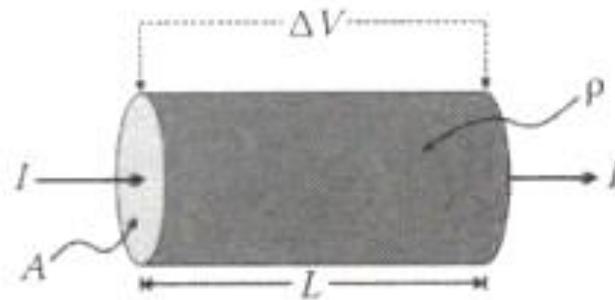


ADAMSHUK (2007)



Dhawale, N. M. (2015) - adaptado de Viscarra Rossel *et al.* (2011)

# Condutividade Elétrica do Solo



**FIGURE 5.1** Flow of electric current,  $I$ , through a cylinder composed of uniform material with resistivity,  $\rho$ , which produces a difference in an electric potential,  $\Delta V$ , from one end of the cylinder to the other.

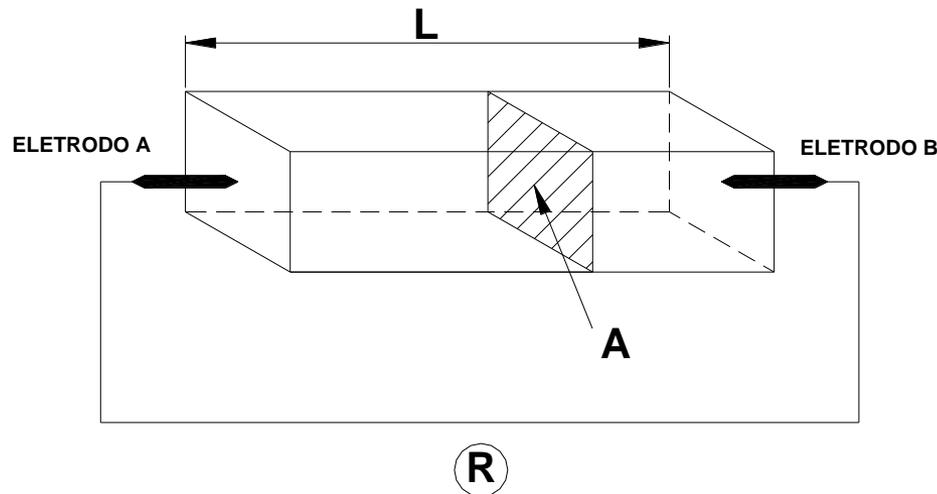
# Condutividade Elétrica

$$\sigma = \frac{1}{\rho}$$

onde:  $\sigma$  = condutividade elétrica (S m<sup>-1</sup>)  
 $\rho$  = resistividade elétrica ( $\Omega$  m)

# Resistividade Elétrica

$$\rho = R \frac{A}{L}$$



onde:  $\rho$  = resistividade elétrica ( $\Omega \cdot m$ )

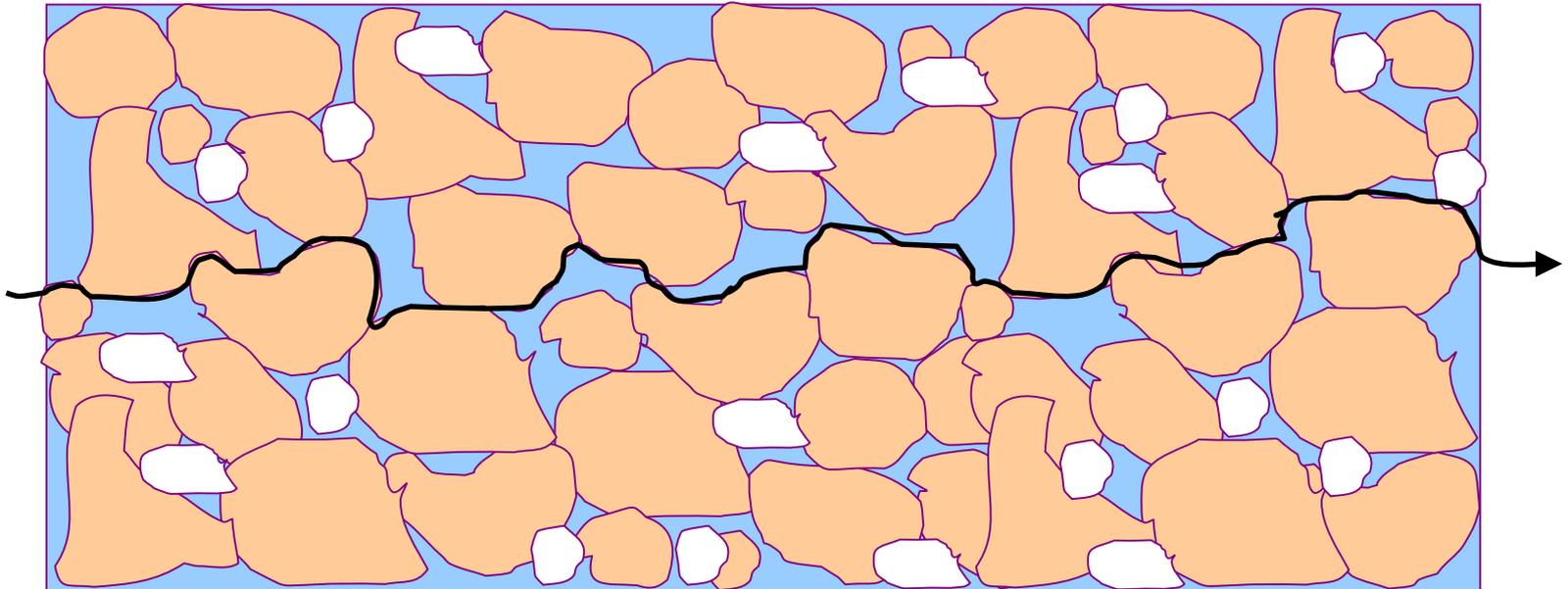
$R$  = resistência elétrica ( $\Omega$ )

$A$  = área da seção transversal ( $m^2$ )

$L$  = comprimento da amostra (m)

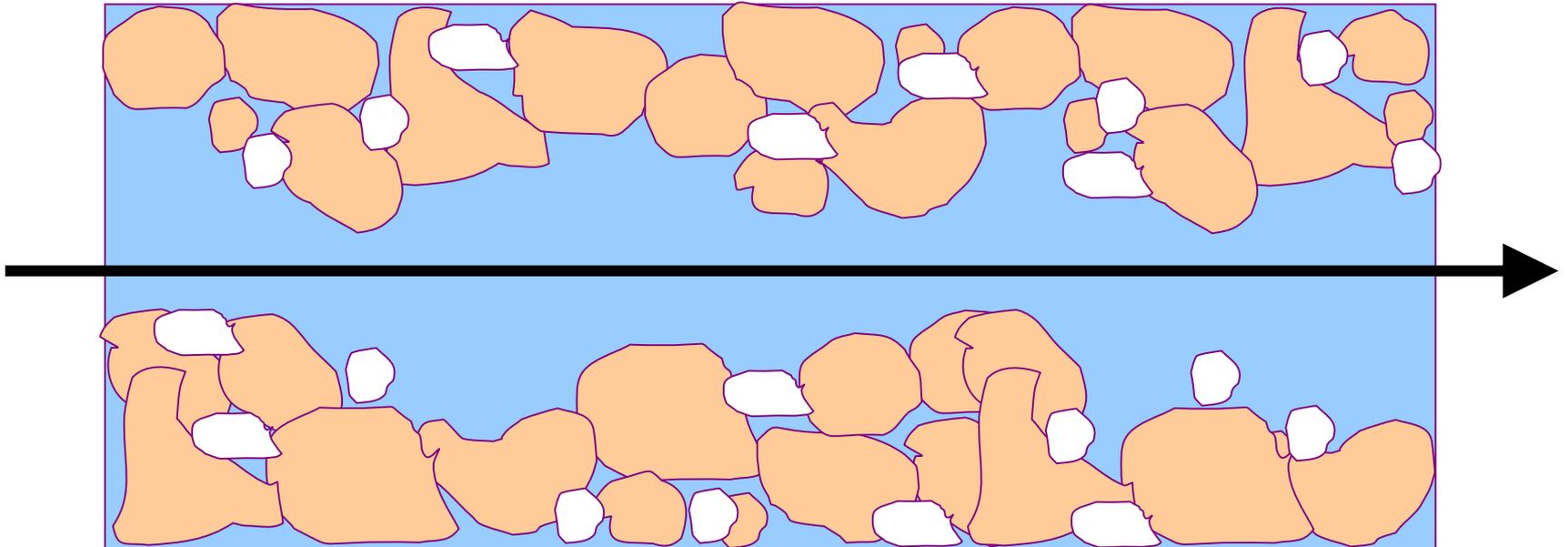
# 1ª Via

Em camadas alternantes de partículas do solo e entre os limites de suas soluções



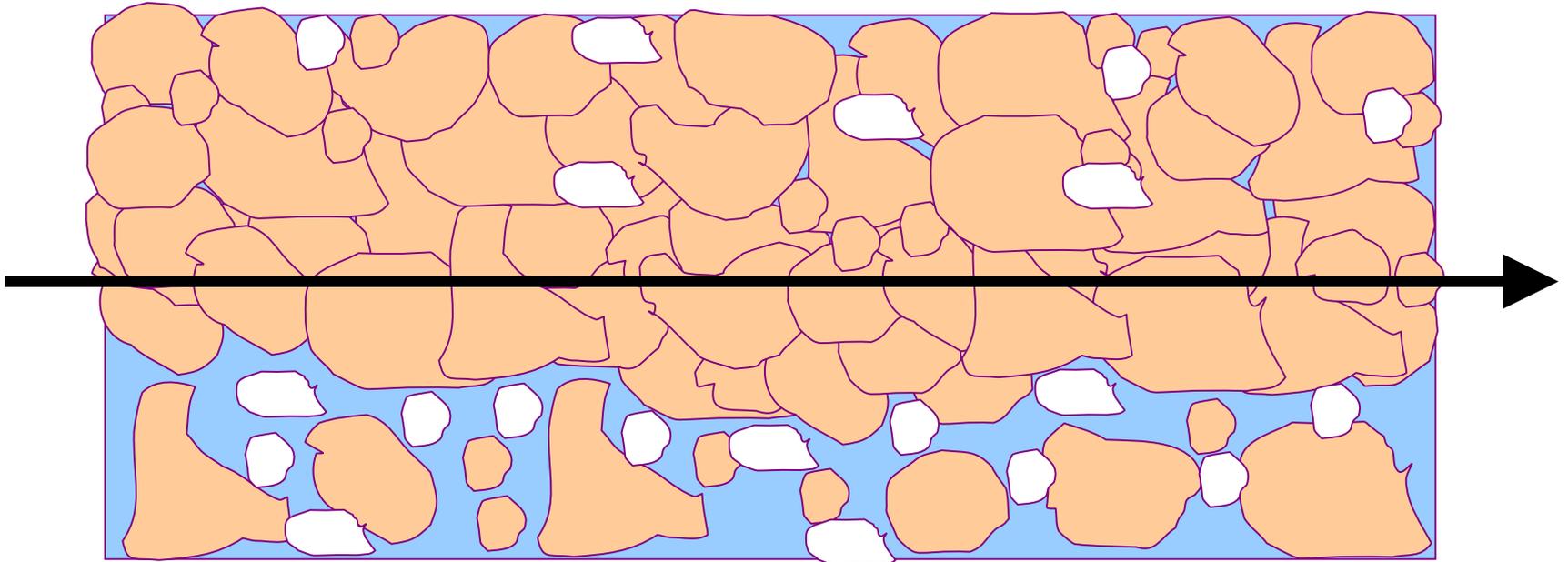
## 2ª Via

Através de soluções do solo contínuas



## 3ª Via

Através ou entre superfícies de partículas do solo em contato direto



# Condutividade elétrica aparente do Solo (CEa)

Há duas formas de se medir :

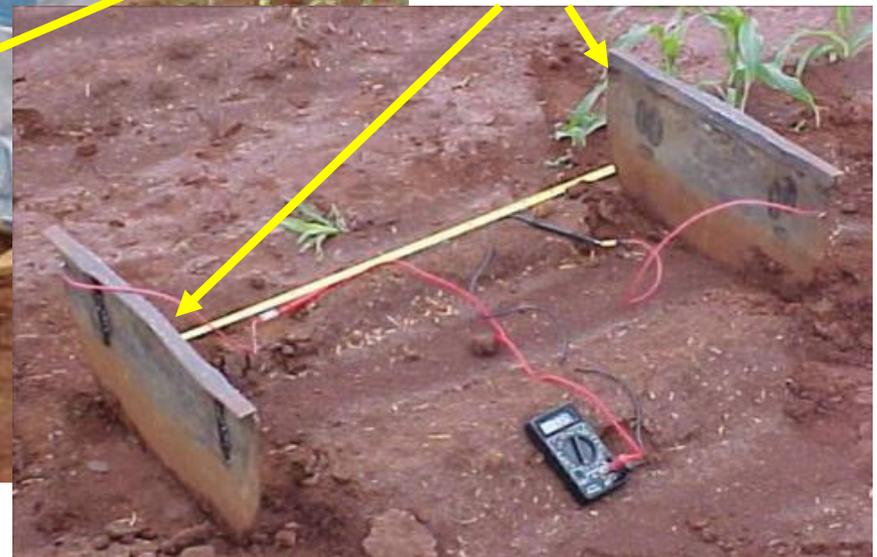
- Por contato direto
- Indução eletromagnética

# Testando a ideia



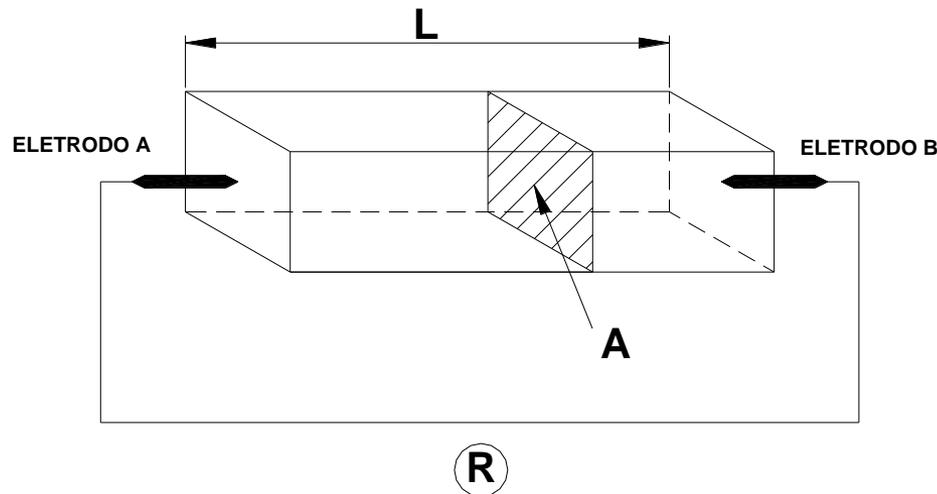
1999

Simulando discos  
de corte de  
semeadoras



# Resistividade Elétrica

$$\rho = R \frac{A}{L}$$



onde:  $\rho$  = resistividade elétrica ( $\Omega \cdot m$ )

$R$  = resistência elétrica ( $\Omega$ )

$A$  = área da seção transversal ( $m^2$ )

$L$  = comprimento da amostra (m)

# Resistividade Elétrica

$$\rho = \frac{A}{I} \frac{dV}{dx}$$

onde:

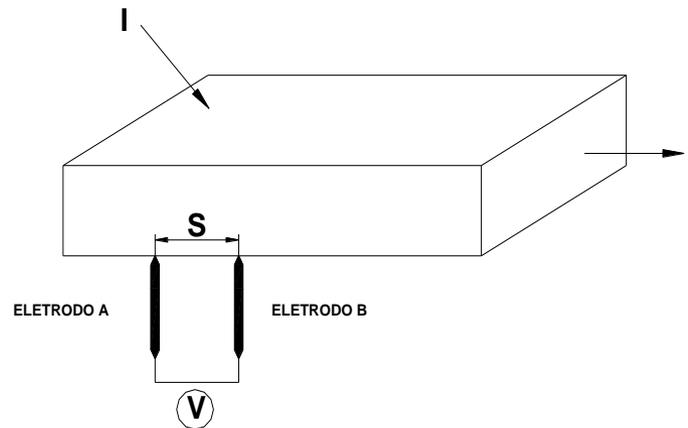
$\rho$  = resistividade elétrica ( $\Omega \cdot m$ )

$I$  = corrente elétrica (A)

$A$  = área da seção transversal ( $m^2$ )

$dV/dx$  = relação entre a voltagem e a distância entre os eletrodos

Para dois eletrodos sem área – apenas a distância ( $S$ ) entre eles



$$\rho = 2\pi S \frac{V}{I}$$

onde:

$\rho$  = resistividade elétrica ( $\Omega \cdot m$ )

$V$  = potencial elétrico (v)

$I$  = corrente elétrica (A)

$S$  = distância entre os eletrodos (m)

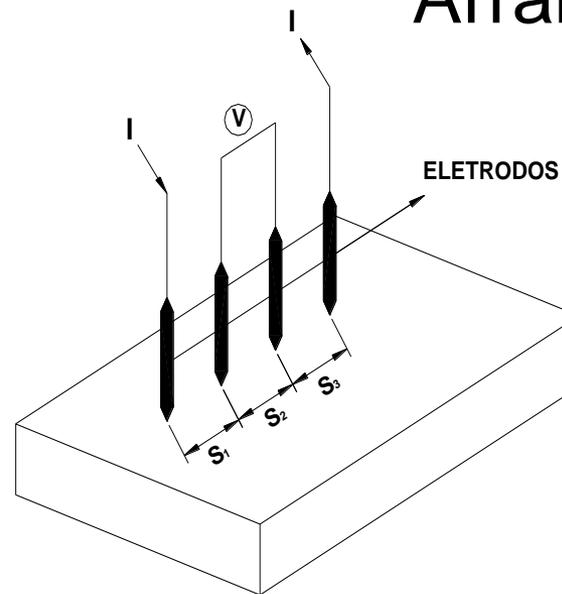
Runyan, 1975

# Resistividade Elétrica

$$\rho = 2\pi S \frac{V}{I}$$

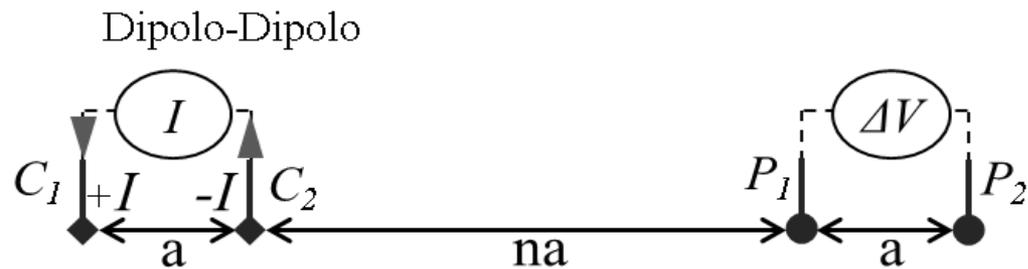
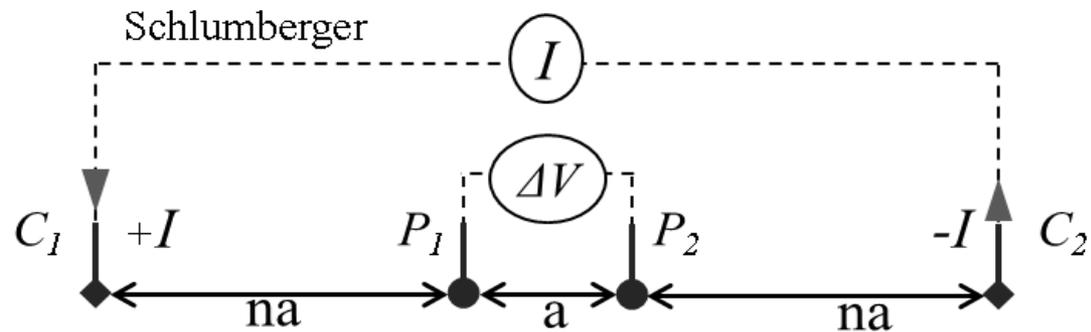
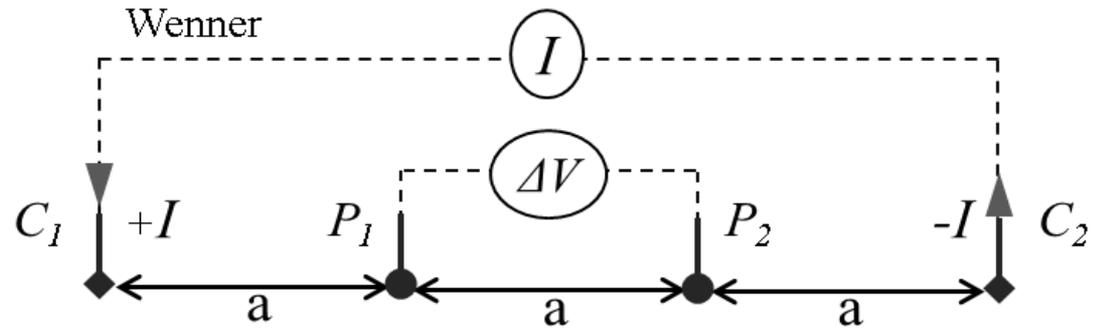
## Arranjo de Wenner

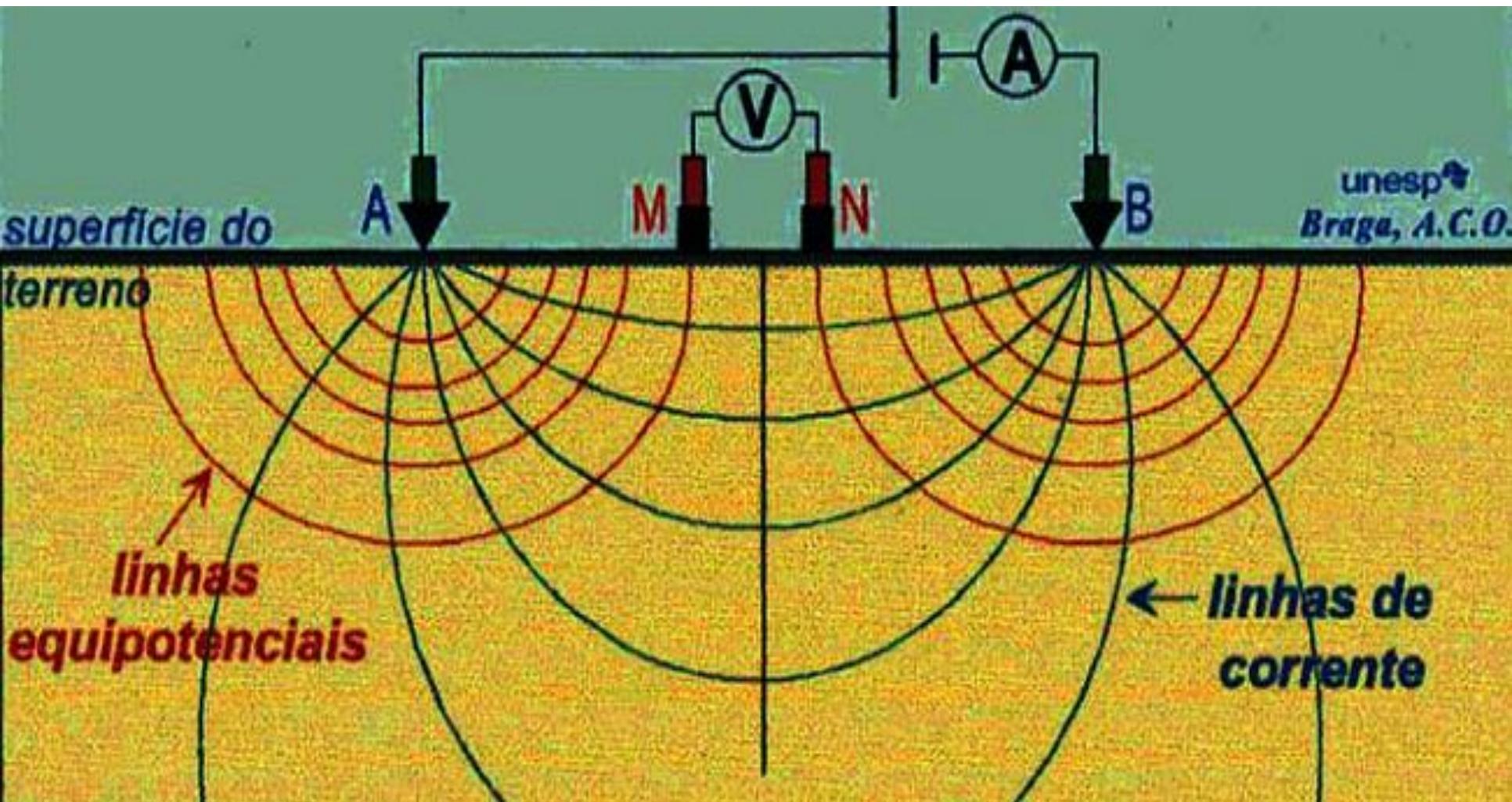
Para quatro eletrodos sem área – apenas a distância ( $S_i$ ) entre eles



Runyan, 1975

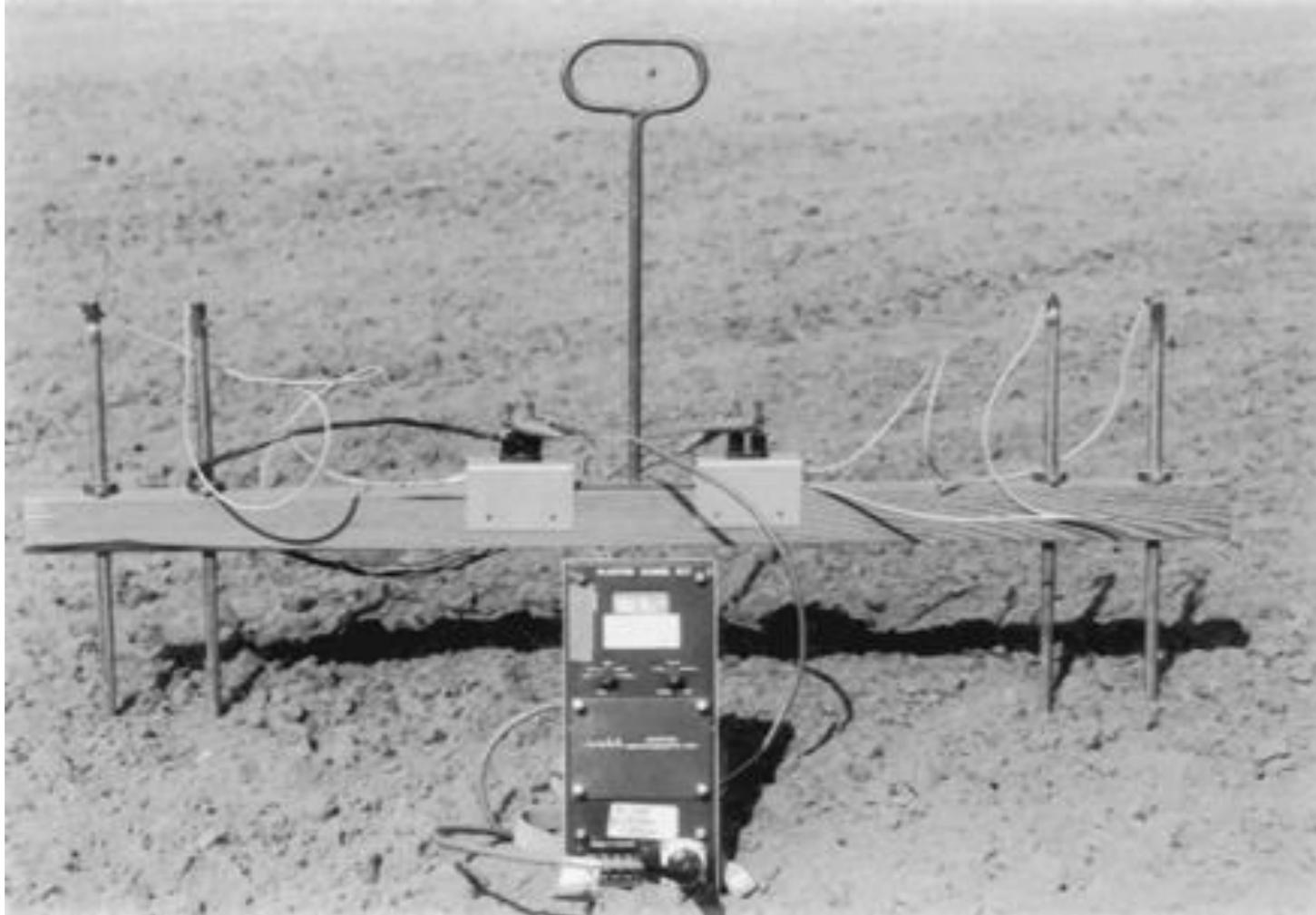
# Arranjos de eletrodos:





Braga (2002)

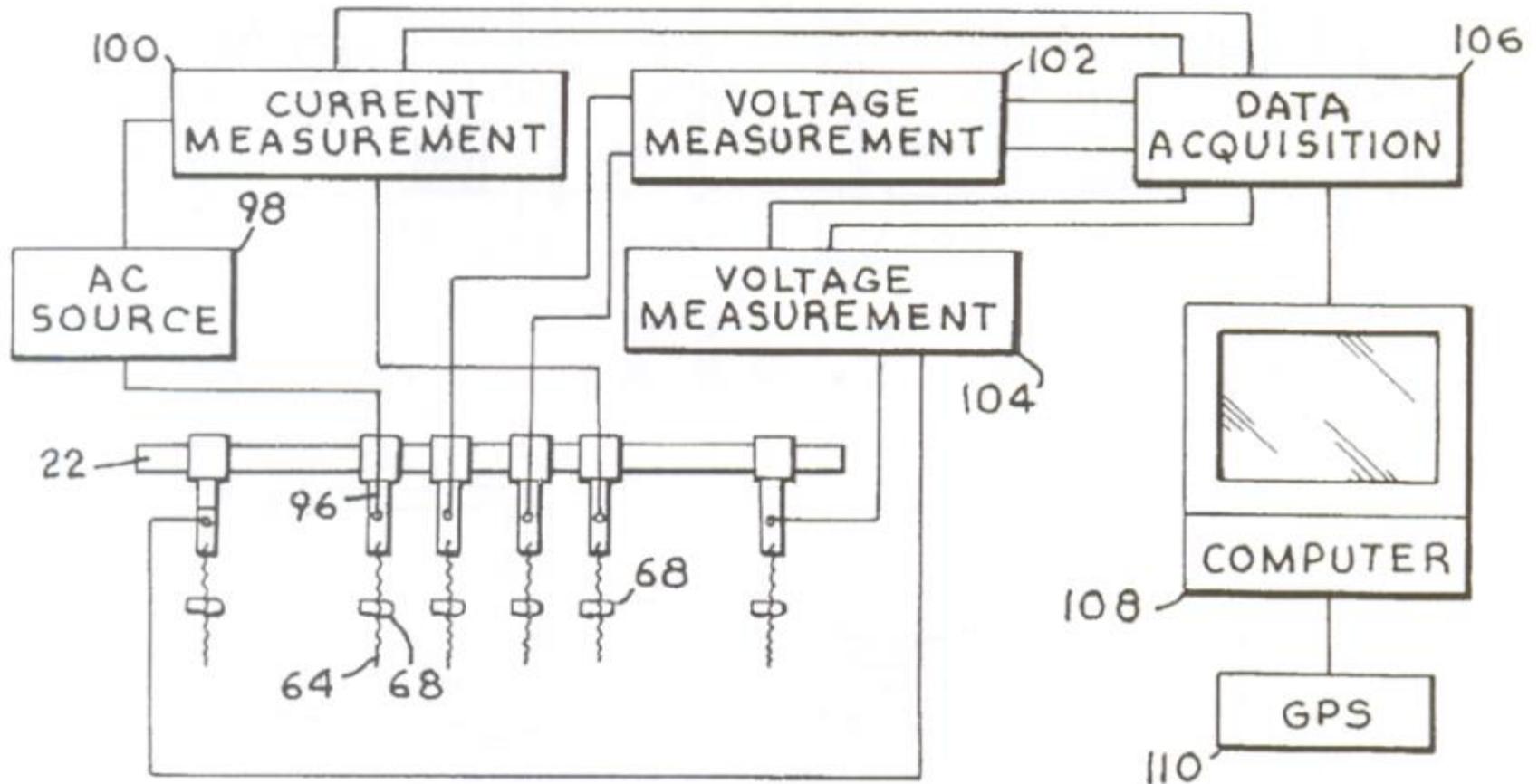
Fixed electrode soil electrical conductivity measuring was first developed in the 1920's by Conrad Schlumberger in France and Frank Wenner in the United States for deep geophysical investigations.



Jim Rhoades at the US Salinity Laboratory in California first used the technology in 1977 to investigate near-surface agricultural features.

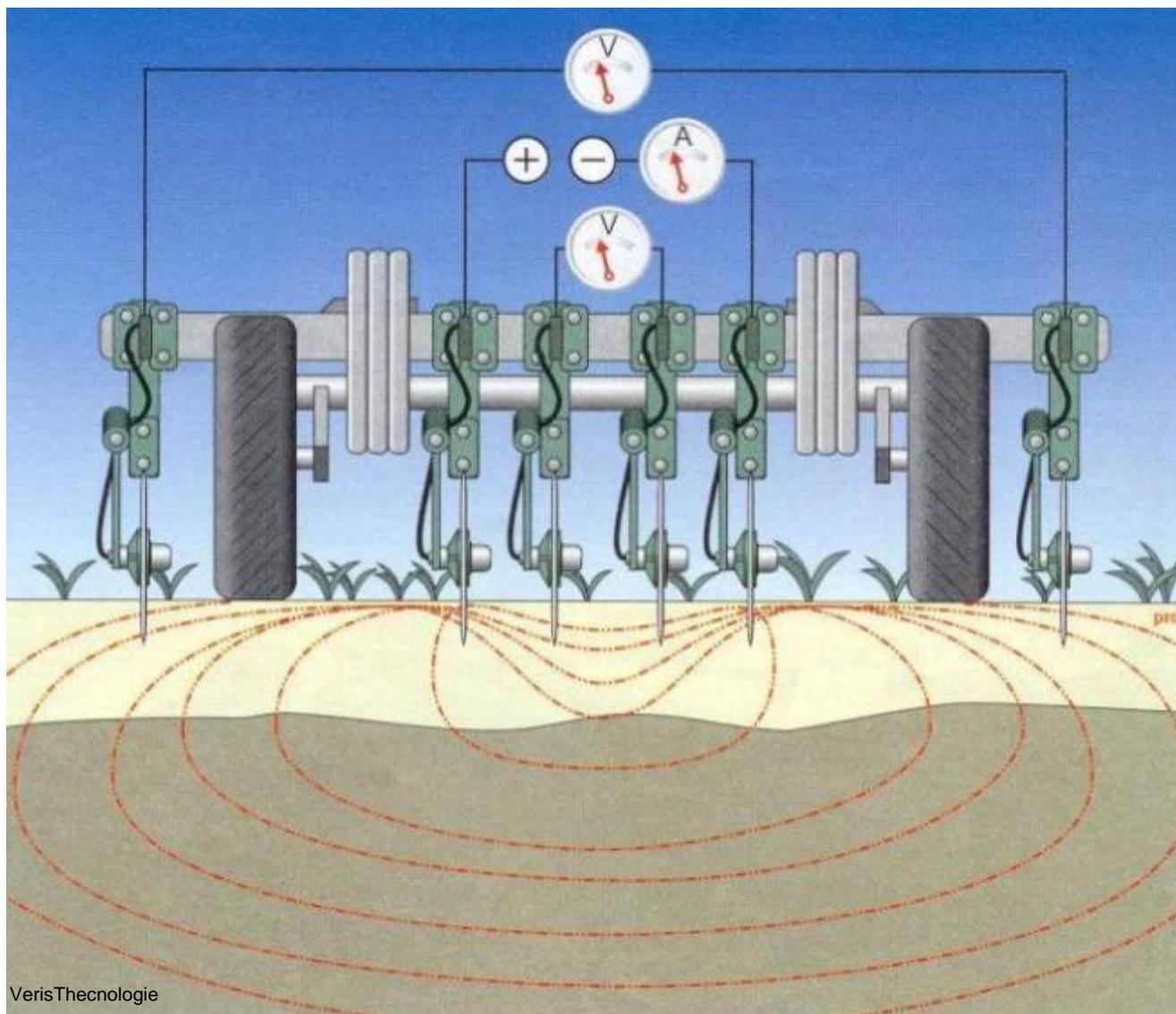
Lund, 2006

# Sistema sensor por contato



Christy & Lund, USA Patent No. 5,841,282, nov. 1998

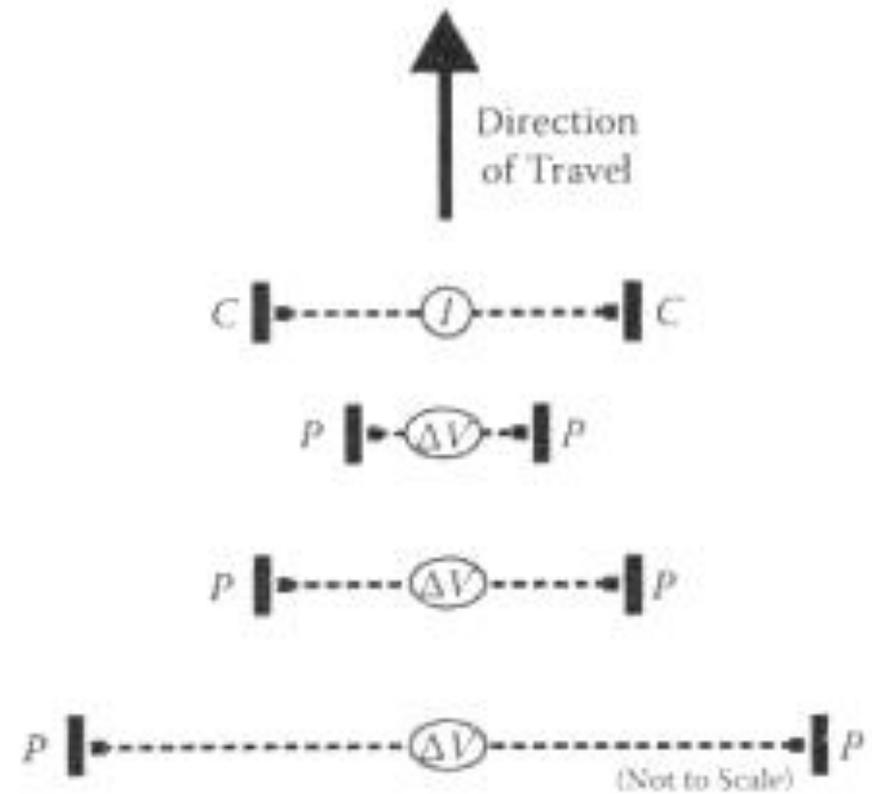
# Sistema sensor de condutividade elétrica do solo por contato







# Método por contato direto



ALLRED, B et al., (2008)



# MuCEP© (MULTi Depth Continuous Electrical Profiling) Resistividade elétrica ( $\Omega m$ ) Geocarta (França)



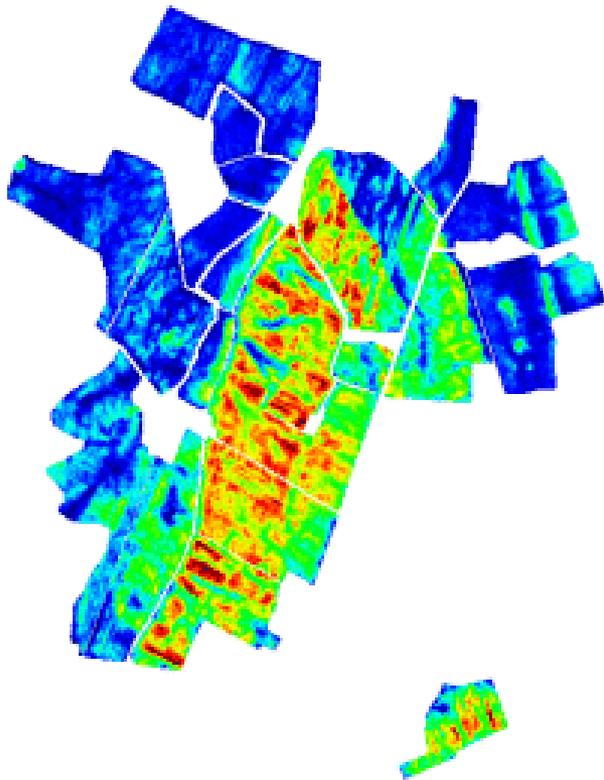
AMP© (Automatic Magnetic Profiling)



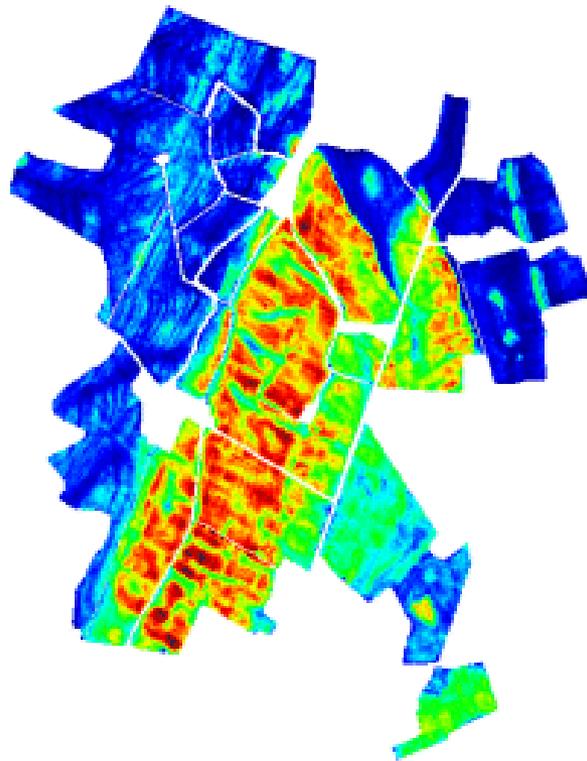
# Sistema Geocarta de resistividade elétrica aparente do solo



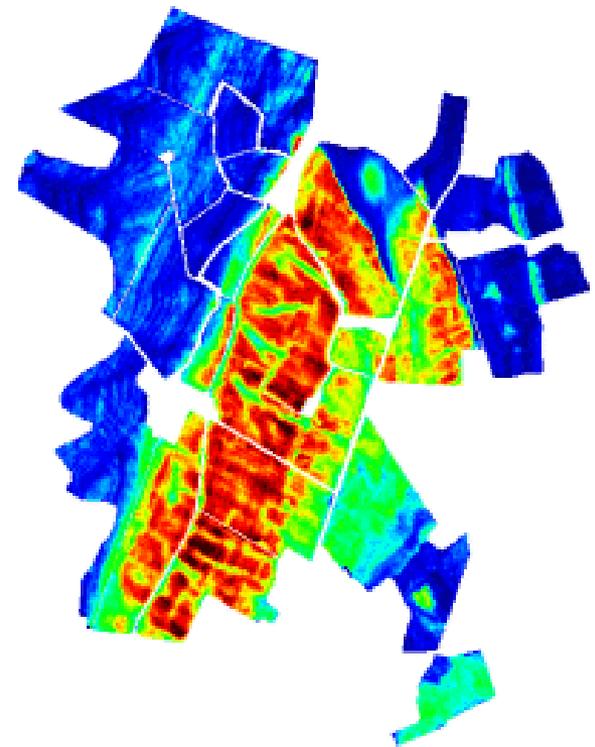
# Resistividade elétrica Geocarta (França)



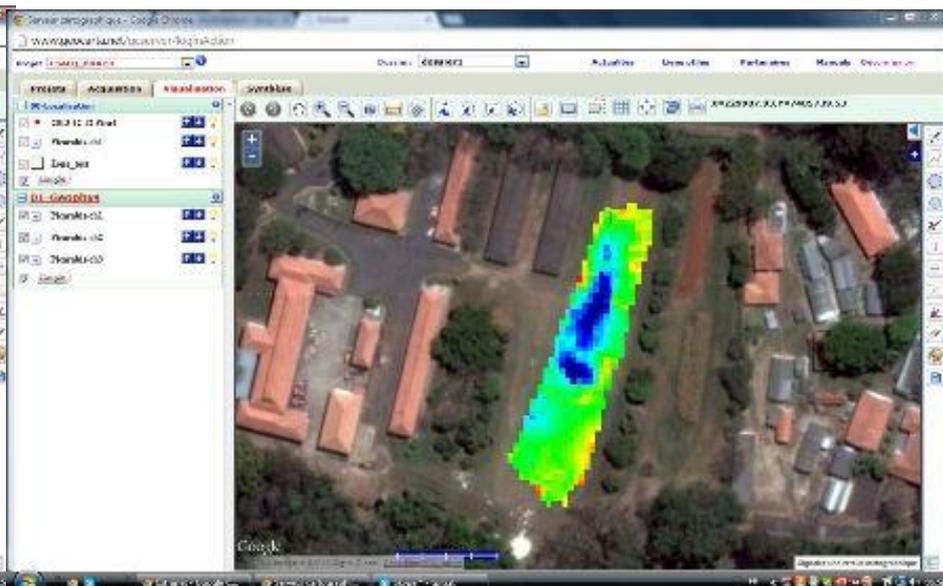
profundidade 0-0,5 m



profundidade 0 -1 m

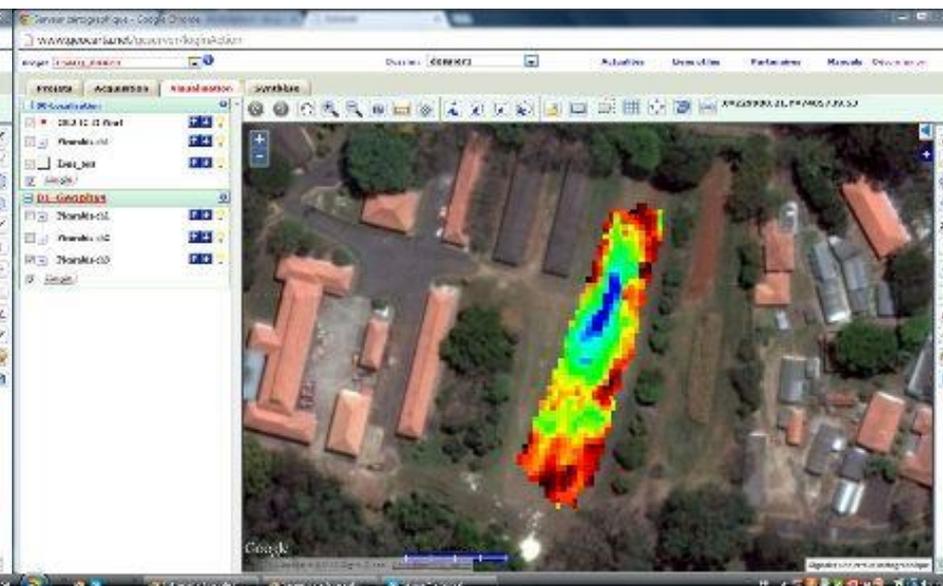
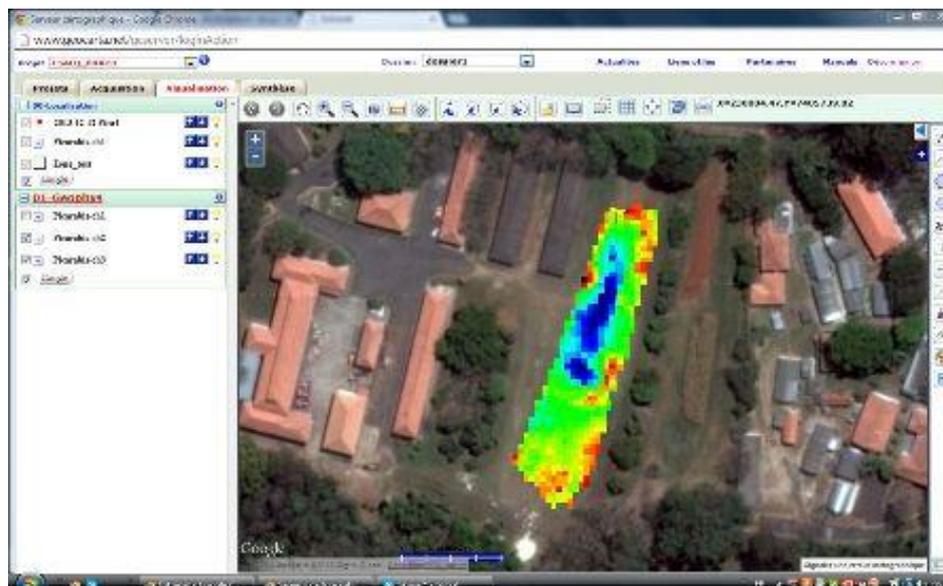


profundidade 0 – 2 m



Medições

50 cm



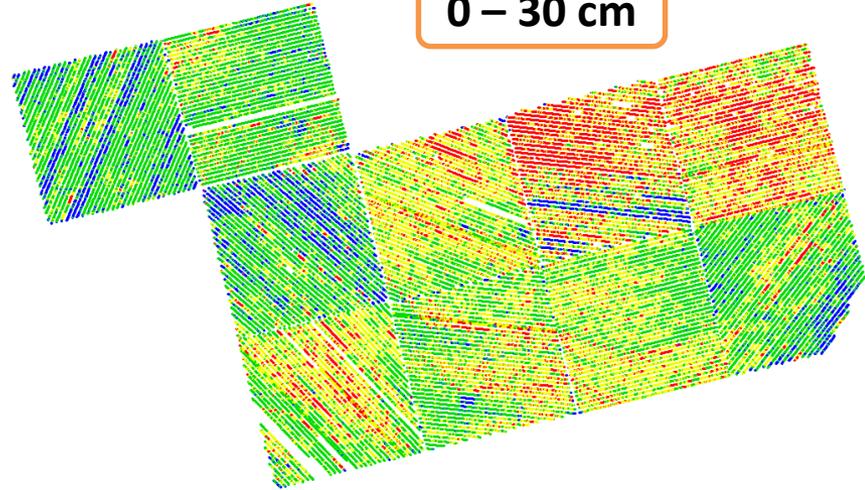
100 cm

200 cm Prof. J. P. Molin

## Veris



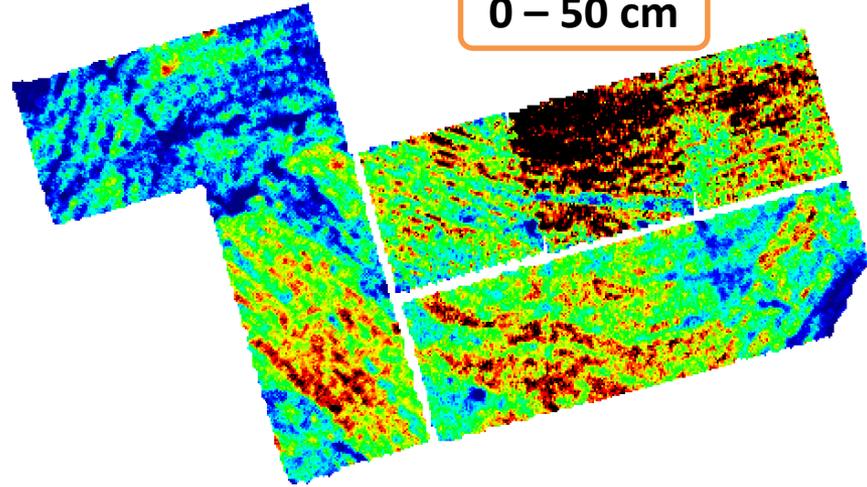
0 – 30 cm



## Geocarta



0 – 50 cm



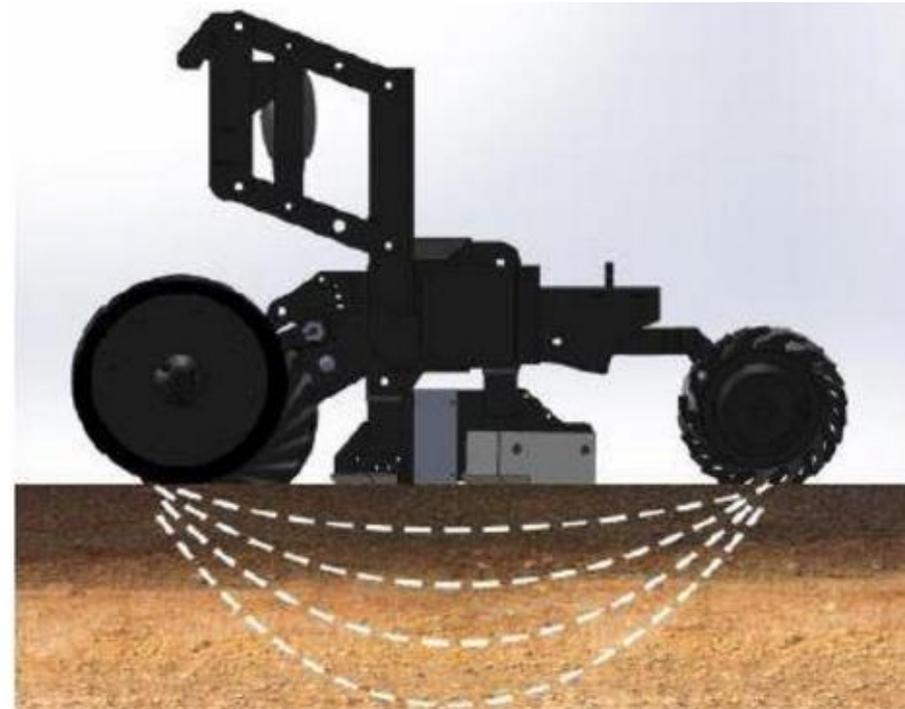
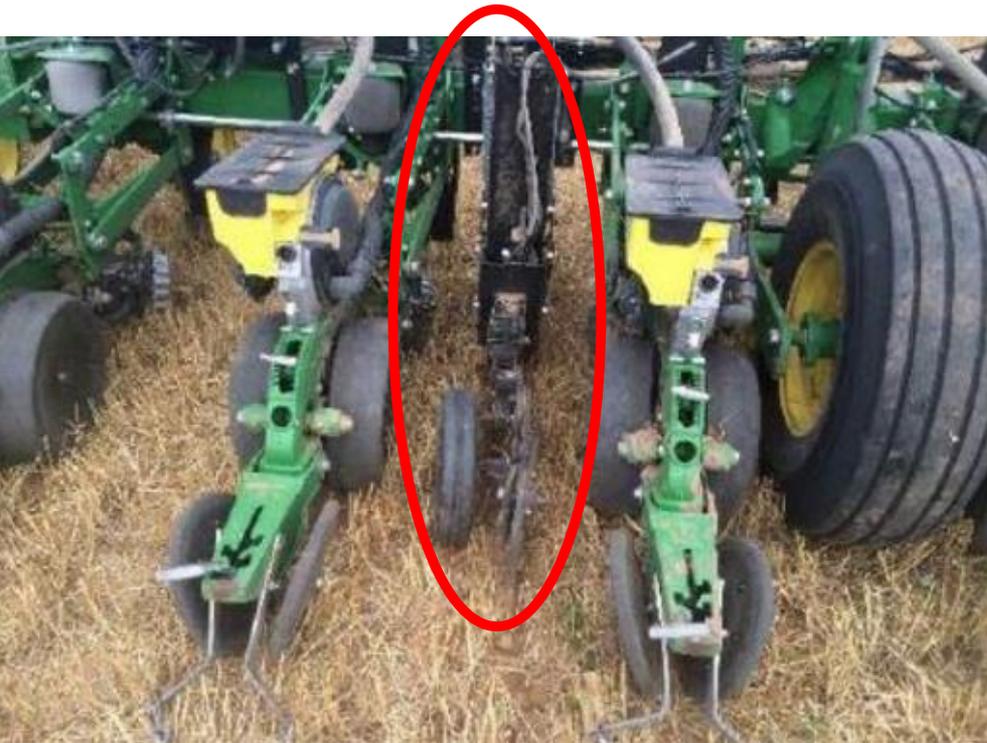


Terram/Falker



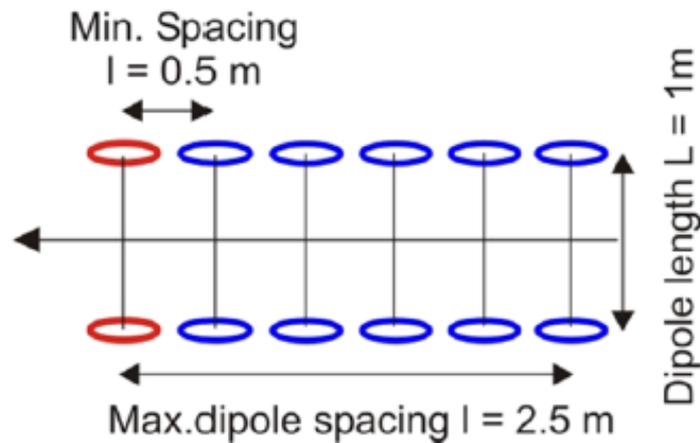
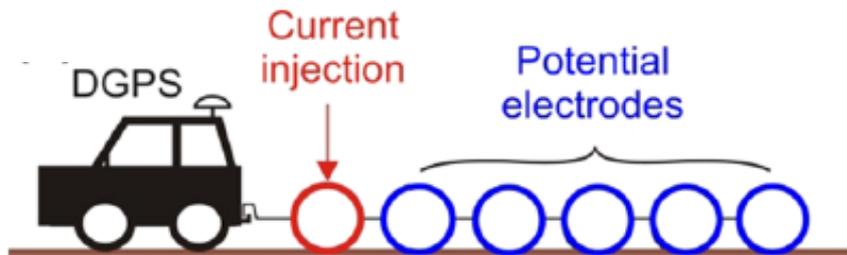
# iScan

Sensor óptico (duas bandas) para estimativa de matéria orgânica, mais sensor de condutividade elétrica



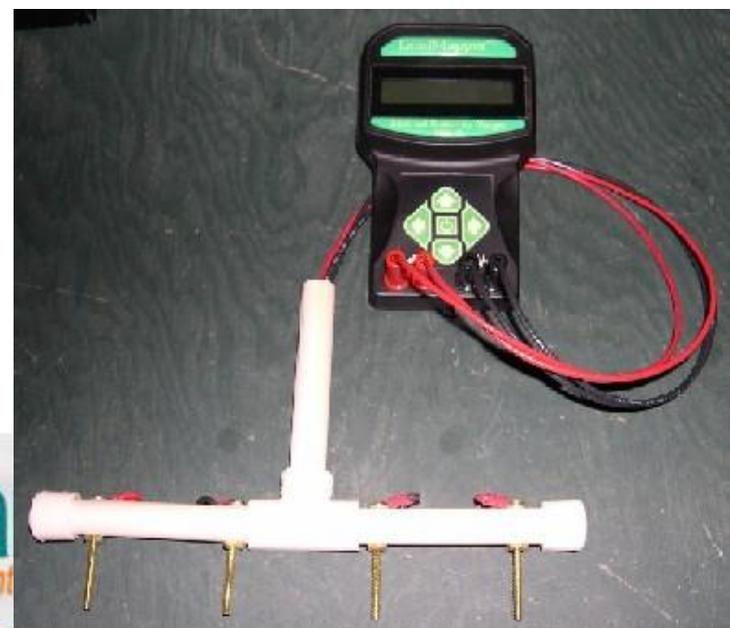
Veris Technologies

# Sistema Geophilus



A distância entre os pares de eletrôdos define a profundidade de investigação

# Sistema medidor de CE por contacto (manual)



**LANDMAPPER®** La  
Enlight

**FIELD EC METER WITH LAB ACCURACY**

- Fast
- Portable
- Versatile
- Affordable
- in-depth  $\Omega \cdot m/S \cdot m^{-1}/mV$

LandMapper  
ERM-02  
Electrical Resistance Meter

AB MN

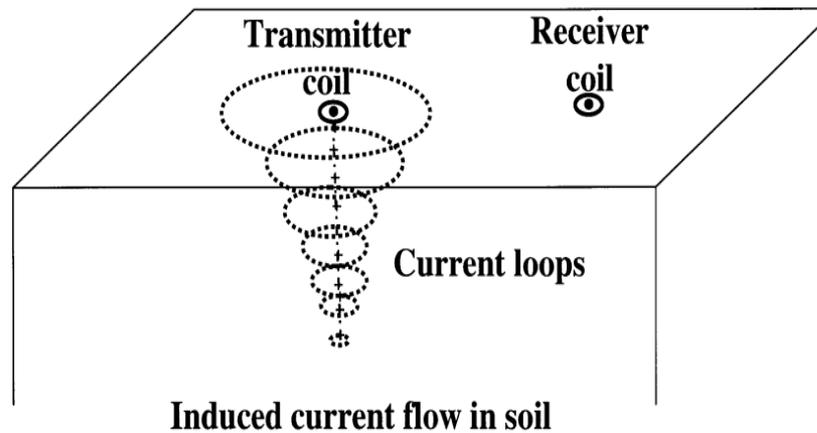
A3 M3 A2 M2 A1 M1 N1 B1 N2 B2 N3 B3

A farmer in a field using the LandMapper ERM-02 handheld EC meter to measure soil electrical conductivity.

LandMapper ERM-02

<http://www.landviser.net/content/landmapper-erm-02-new-handheld-ecersp-meter>

# Mensuração por indução eletromagnética



CORWIN; LESCH, 2003

# Sensor por indução



FABC, Castro, PR, 2001

Vertical - até 0,30m



Horizontal - até 1,20m





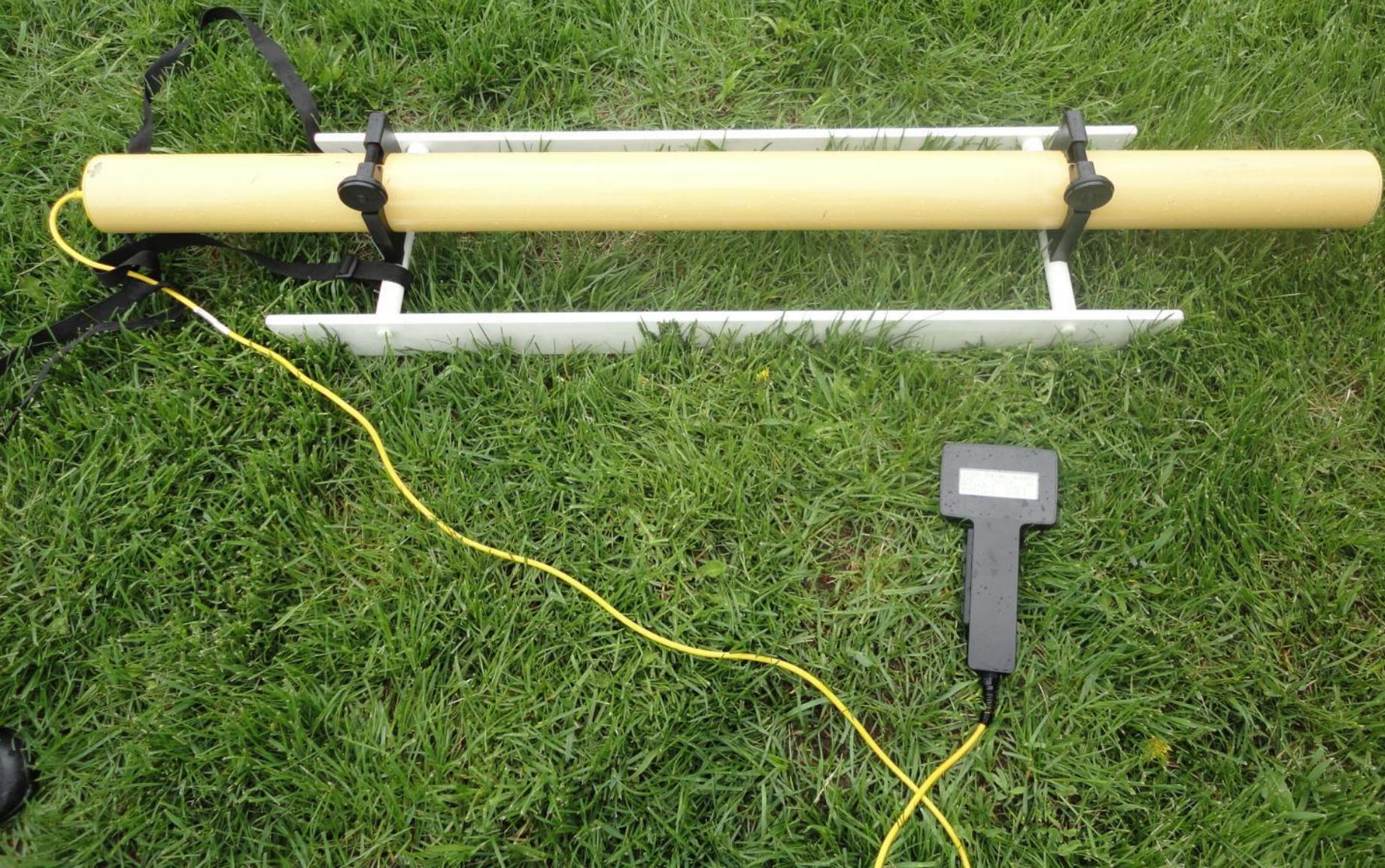
## Desafios relacionados à interferência de metais





Detectores de metais... e de profundidades de impedimento (solo)

Dualem.com





[Geoplanta.com.br](http://Geoplanta.com.br)



<http://www.geophysical.com/profiler.htm>

Profiler EMP 400



F Araujo, 2019

## Topsoil Mapper (TSM)



[www.geoprospectors.com](http://www.geoprospectors.com)

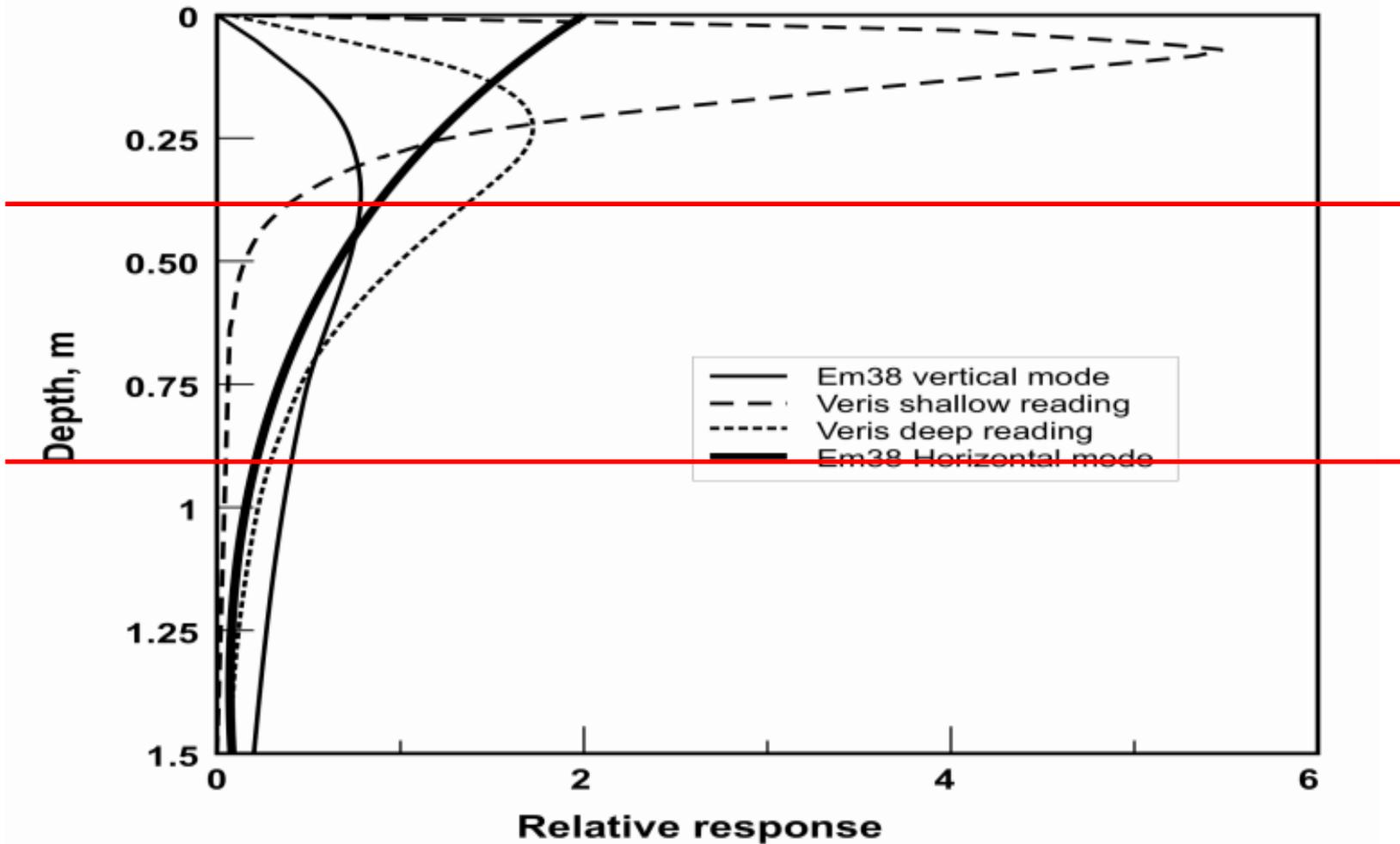




<http://geometrics.com/geometrics-products/geometrics-electro-magnetic-products/>

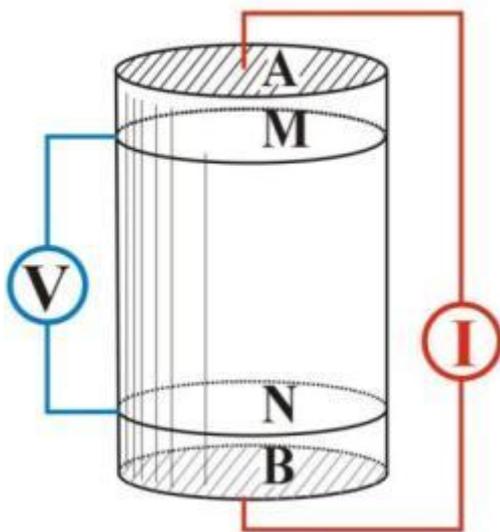
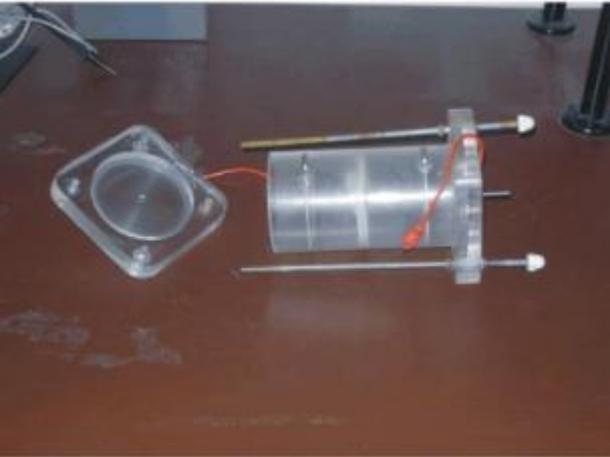






Relative response of ECa sensors as a function of depth. Responses are normalized to yield a unit area under each curve (McNeill, 1992 and 1980).

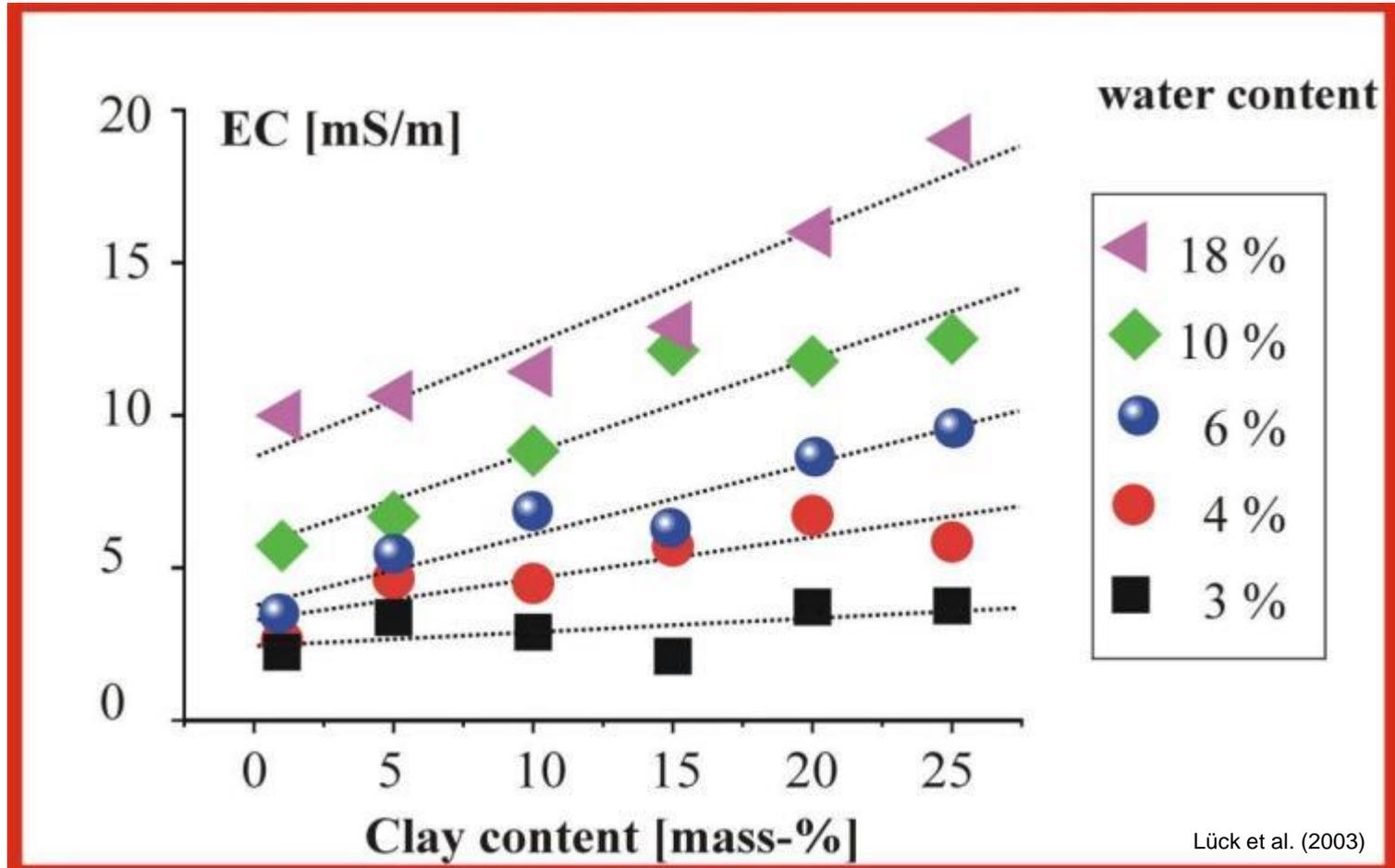
# Experimentos de laboratório



Misturas  
homogêneas

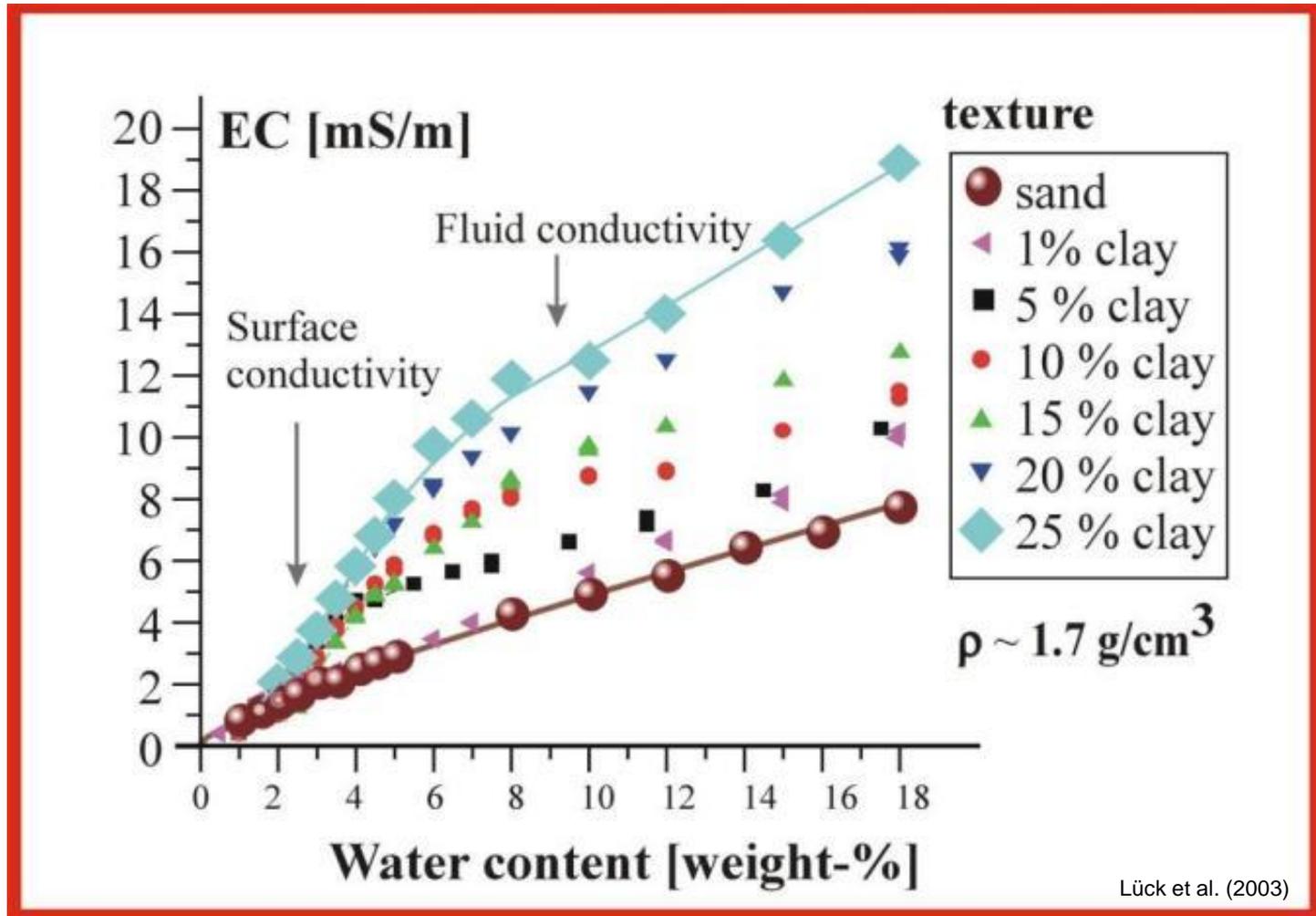
Lück et al. (2003)

# CE e textura



Misturas homogêneas

# CE e umidade



# Uses of EC Maps

Use	Soil Properties Estimated
Delineation of management zones	Soil texture, organic matter, CEC, drainage conditions: Soil factors that most influence yield, particularly plant-available water content
Directed soil sampling within more accurate soil boundaries	Soil texture, organic matter, CEC, drainage conditions
Variable rate seeding	Topsoil, CEC: Soil factors that most influence yield, particularly plant-available water content
Variable rate nutrient application based on soil productivity	Depth to claypan subsoil or parent material, soil texture
Variable rate herbicide application	Soil texture, organic matter, CEC
Interpretation of yield map	Soil factors that most influence yield, particularly plant-available water content
Fine-tuning of NRCS soil maps by refining soil type boundaries and identifying unmapped inclusions	All soil factors
Guidance for placement and interpretation of on-farm tests	All soil factors
Soil salinity diagnosis	Electrolytes in soil solution
Drainage remediation planning and placement of iron (FE)-tolerant varieties	Water holding capacity, subsoil properties, water content, salinity

Grisso et al, Virginia Tech

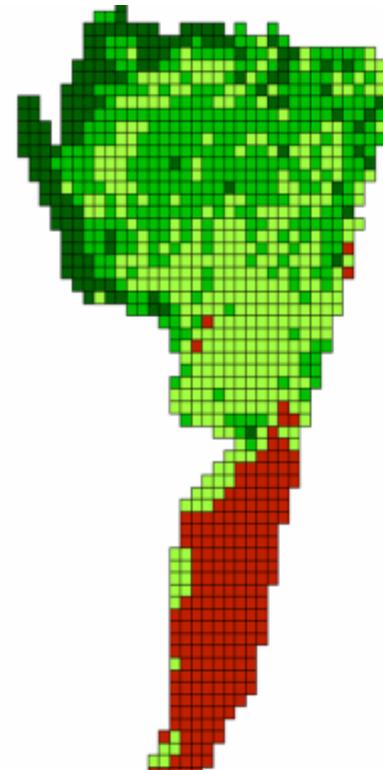
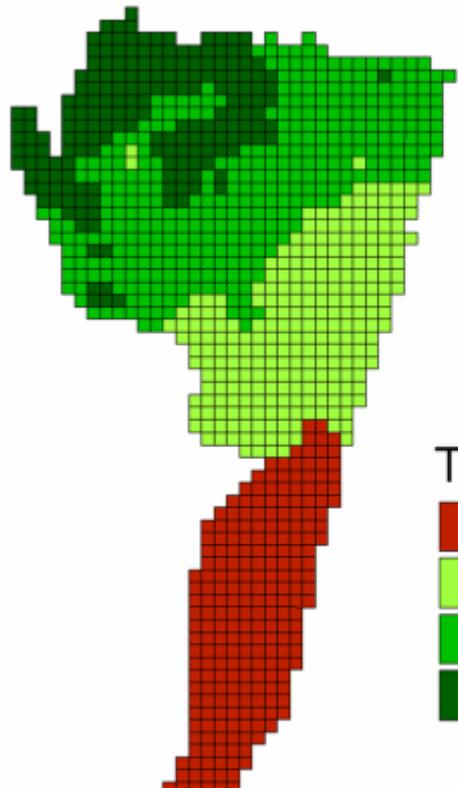


Prof. J. P. Molin

# Alguns resultados de investigações feitas no Brasil

# Condutividade elétrica do solo por contato

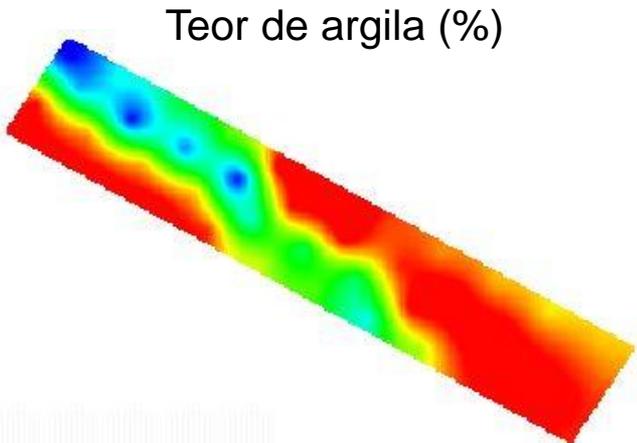
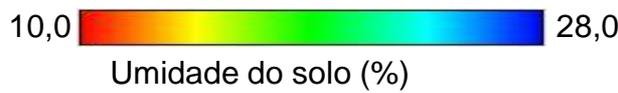
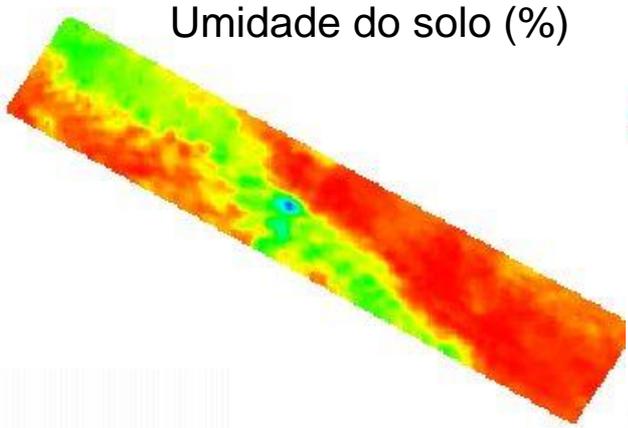
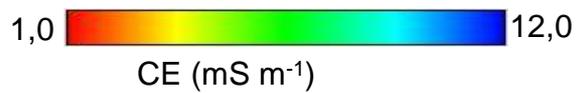
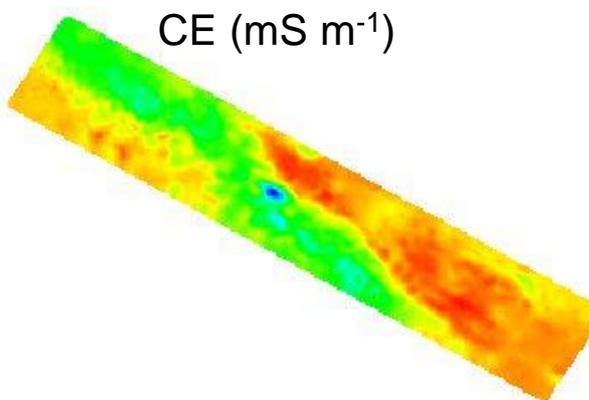
Trabalho realizado em 2002 no Paraná



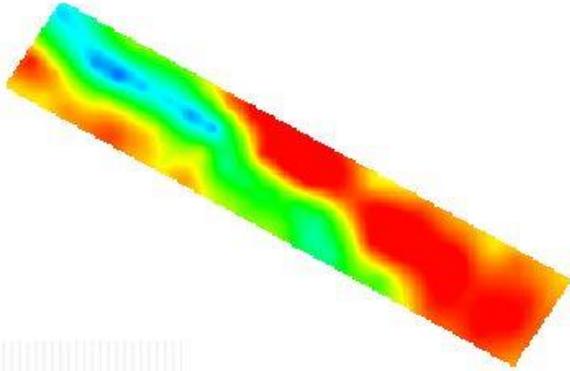
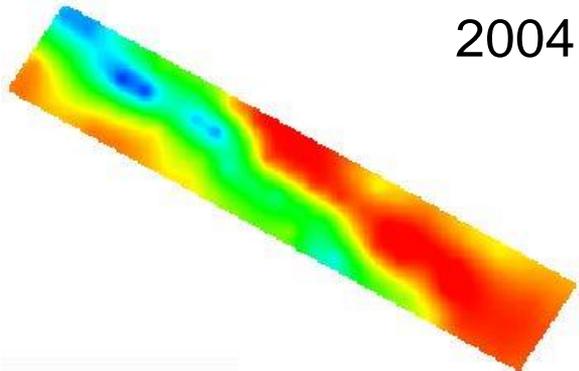
# CE do solo por contato e relação com água do solo, textura e variabilidade temporal - Trabalho realizado em SP e PR, em 2003 e 2004

(0 a 0.3 m)

## 2003



## 2004



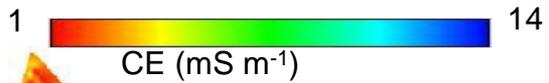
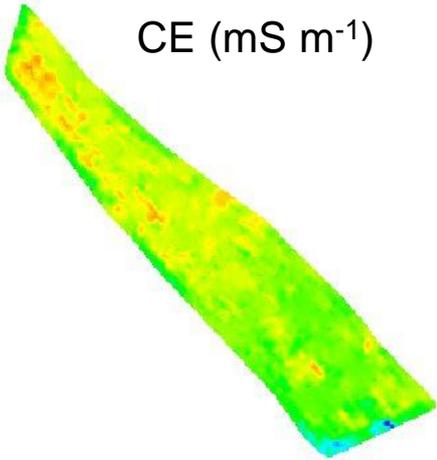
# área 1

MOLIN & FAULIN, 2011

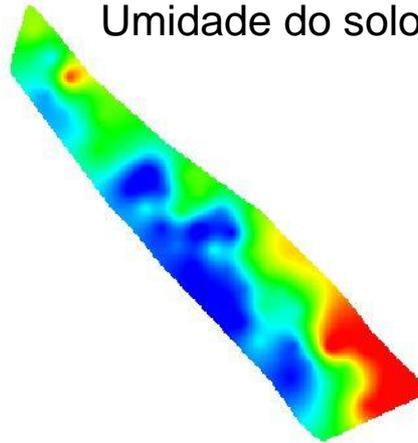
(0 a 0.3 m)

2003

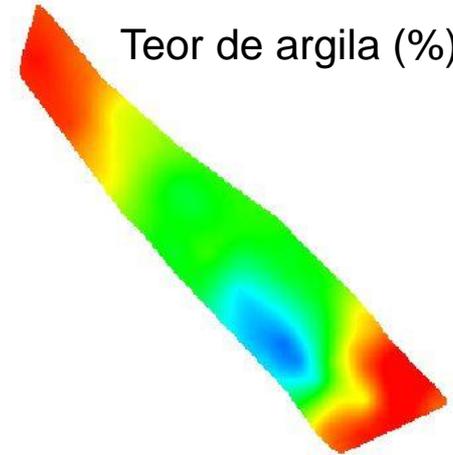
CE (mS m<sup>-1</sup>)



Umidade do solo (%)

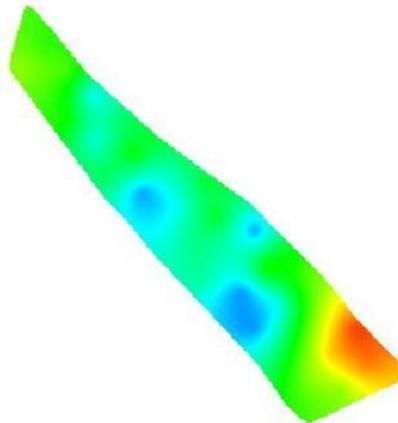
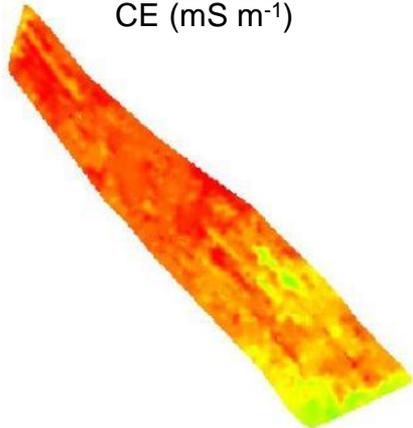


Teor de argila (%)



2004

CE (mSm<sup>-1</sup>)



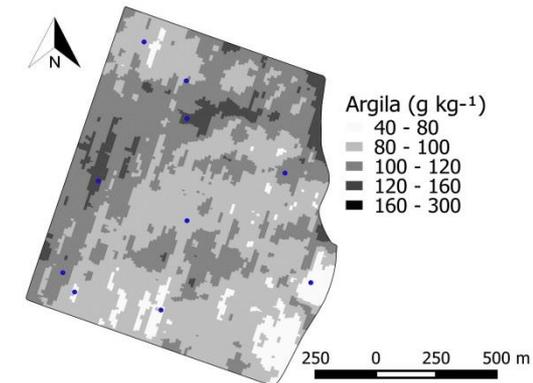
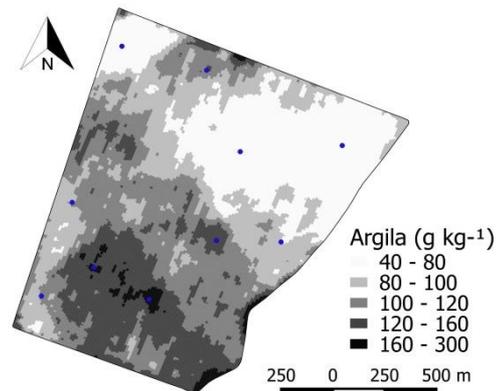
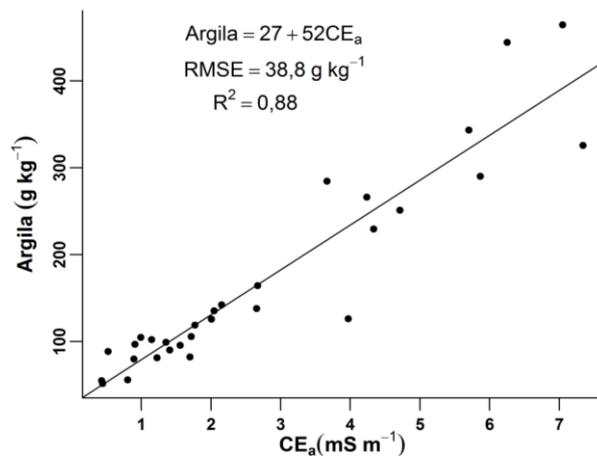
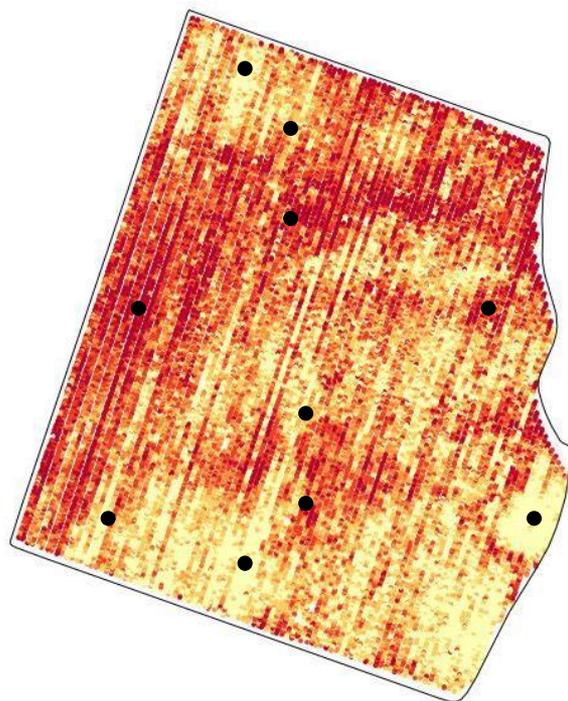
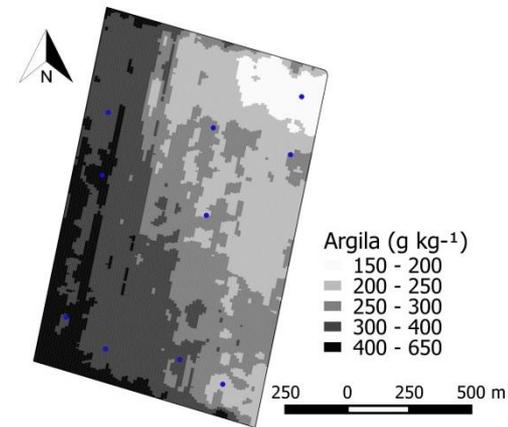
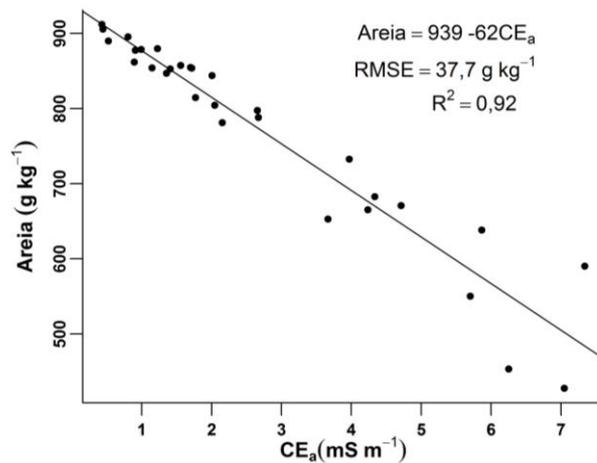
área 2

MOLIN & FAULIN, 2011

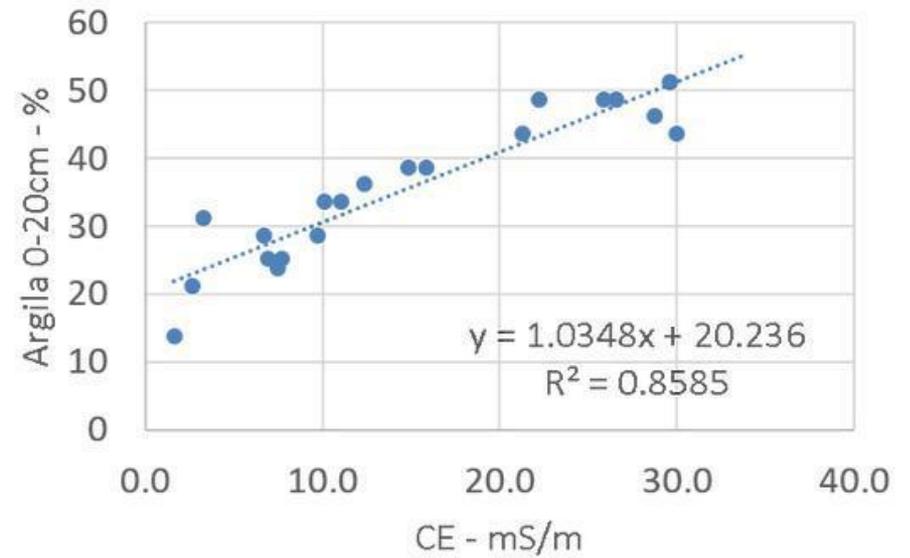
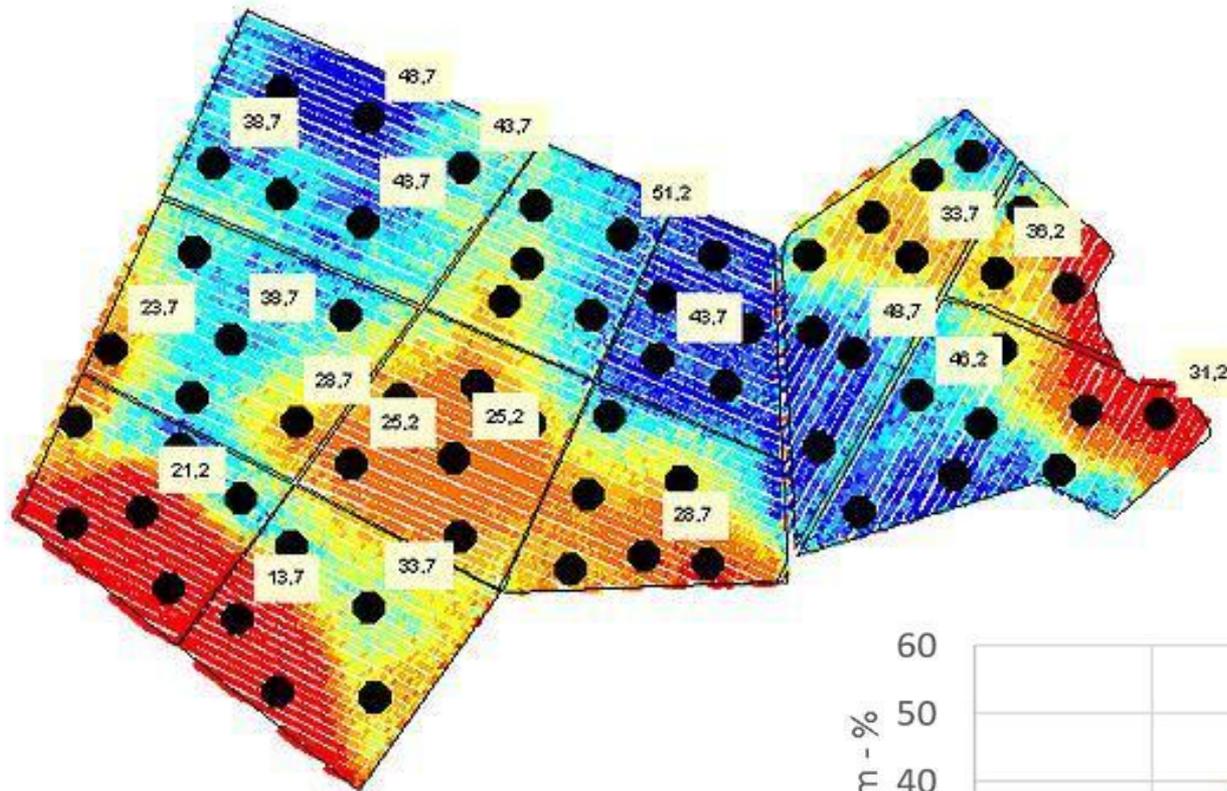
## Regression analyses between EC and soil moisture and clay levels

	Field	Year	Moisture level		Clay level	
			r <sup>2</sup>	F	r <sup>2</sup>	F
EC	1	2003	0.77	*	0.73	*
		2004	0.74	*	0.72	*
	2	2003	0.04	*	0.00	*
		2004	0.09	*	0.00	ns

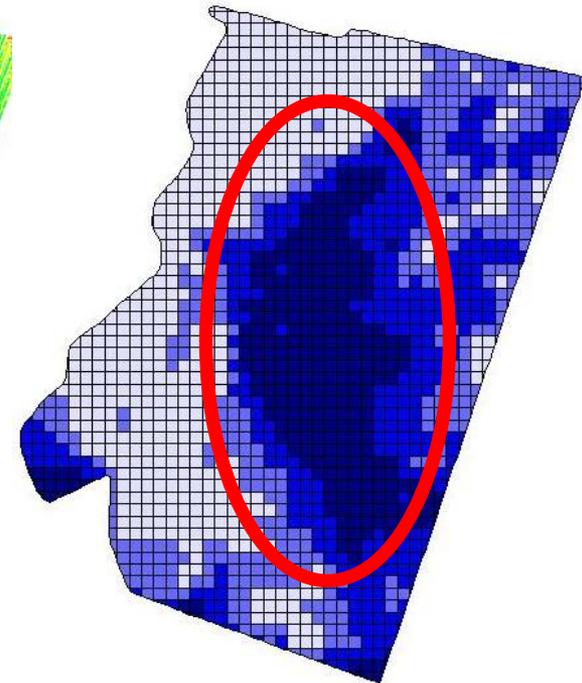
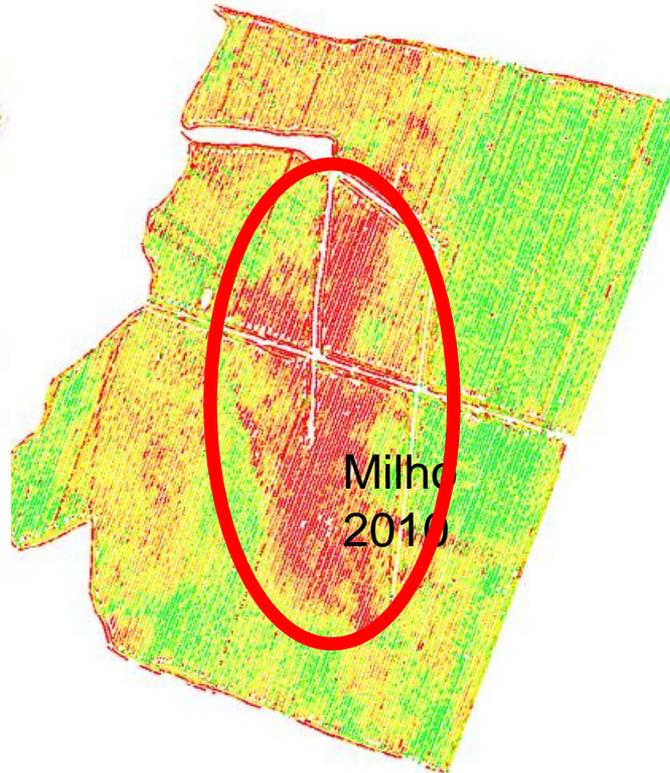
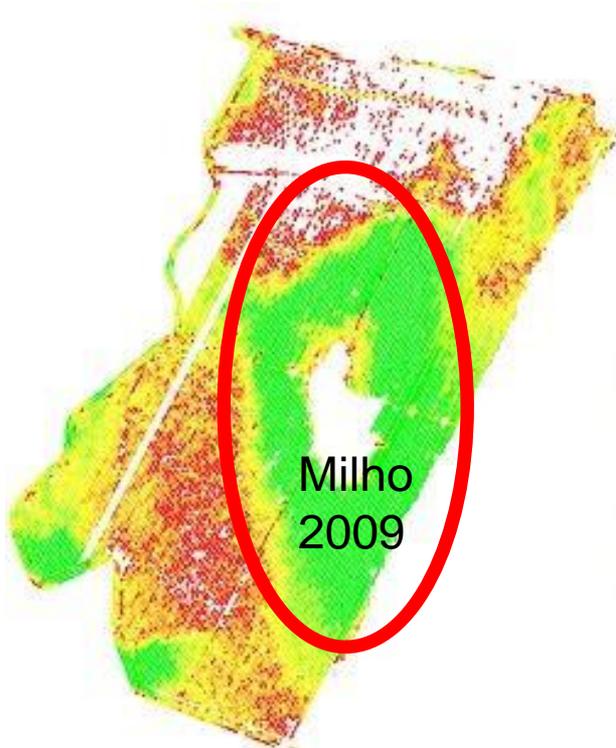
\* F test, significant at  $p < 0.01$ ; ns = F test, non-significant ( $p > 0.01$ )



Borba et al., 2015



# CE e a água no solo



Produção de massa (seca)  
(tonne/ha)

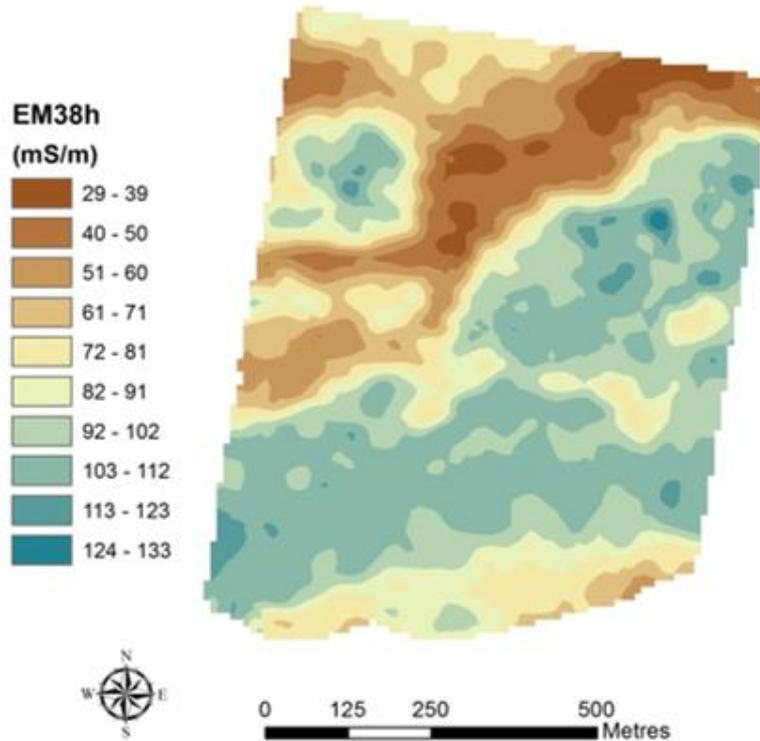
3.53 - 21.74	(27.38 ha)
2.34 - 3.53	(36.42 ha)
1.66 - 2.34	(35.85 ha)
1.20 - 1.66	(35.84 ha)
0.87 - 1.20	(36.61 ha)
0.61 - 0.87	(37.01 ha)
0.31 - 0.61	(37.65 ha)

6,19 - 11,14	(20,66 ha)
5,68 - 6,19	(21,96 ha)
5,20 - 5,68	(22,04 ha)
4,68 - 5,20	(22,10 ha)
4,08 - 4,68	(22,19 ha)
3,15 - 4,08	(21,79 ha)
0,01 - 3,15	(20,00 ha)

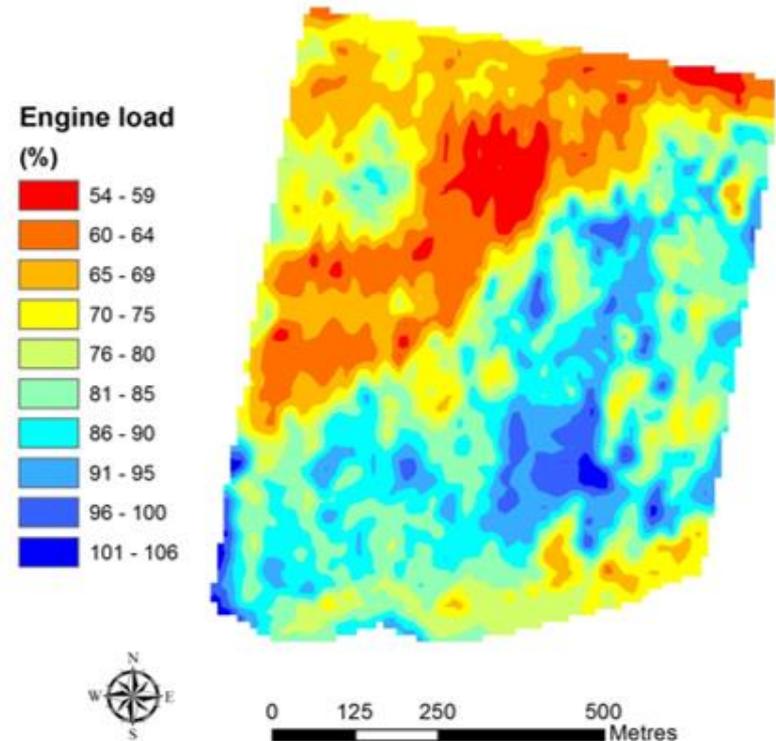
Condutividade

1.2 - 1.9
1.9 - 2.3
2.3 - 2.9
2.9 - 4.2

# Vehicle engine load during sowing



**Soil ECa measured using EM38h**

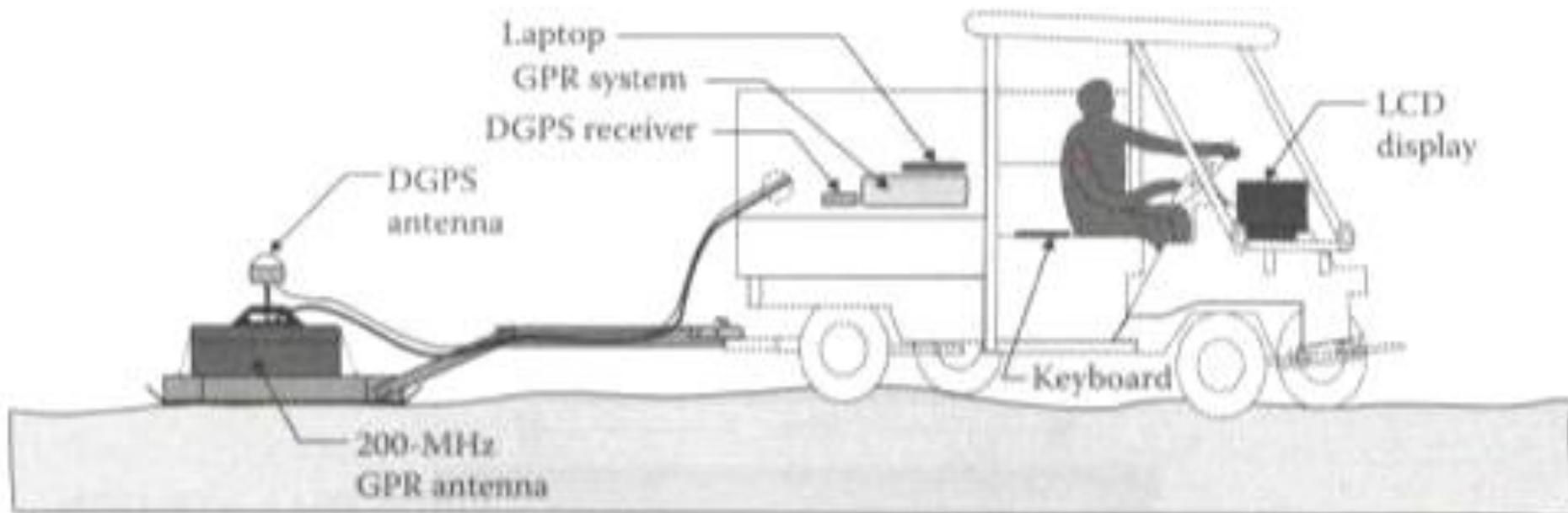


**Engine load (% of total power rating)**

Data supplied by Rupert McLaren, McLaren Farms 'Glenmore', Barmedman, NSW



# Radar de penetração no solo (GPR)



ALLRED, B et al., (2008)

# Radar de penetração no solo (GPR)



# Sensores para quantificar o estado de compactação do solo



# Penetrômetros



# Penetrômetro de Impacto



# Penetrógrafos



# Penetrômetro hidráulico-eletrônico

POTÊNCIOMETRO LINEAR

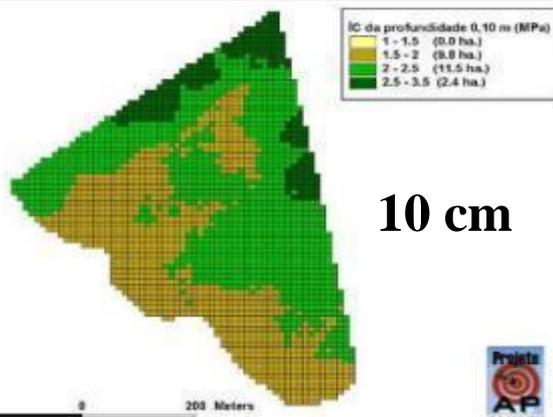


CÉLULA DE CARGA-500Kgf

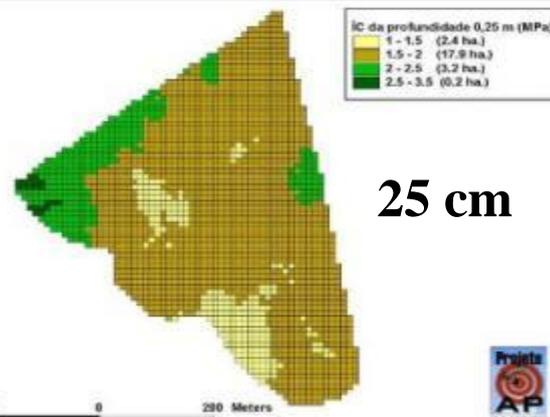


HASTE E PONTEIRA

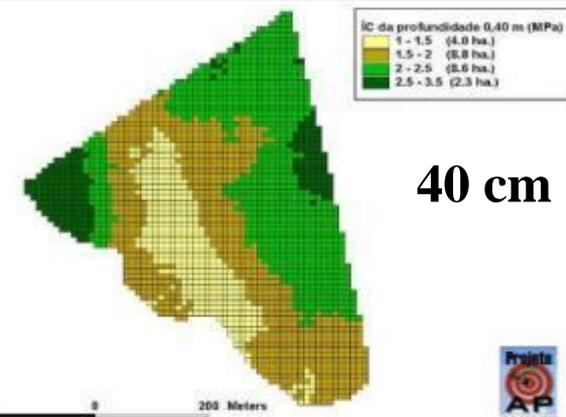




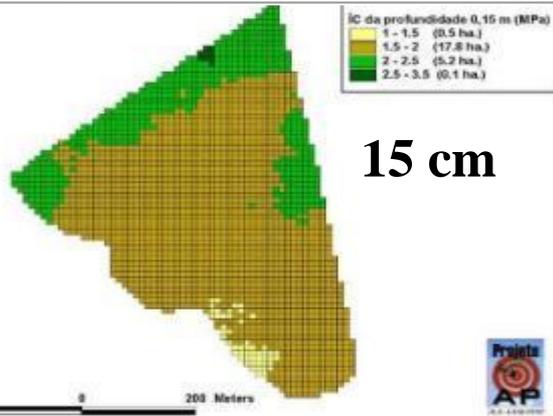
10 cm



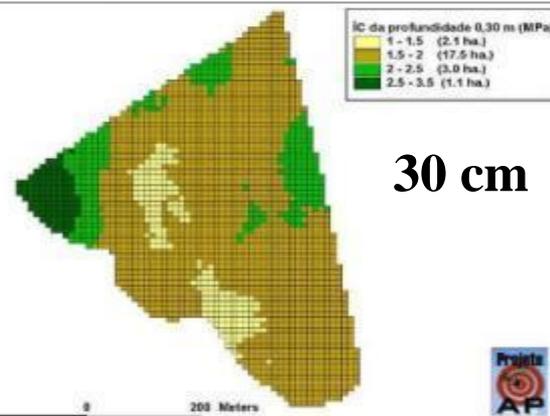
25 cm



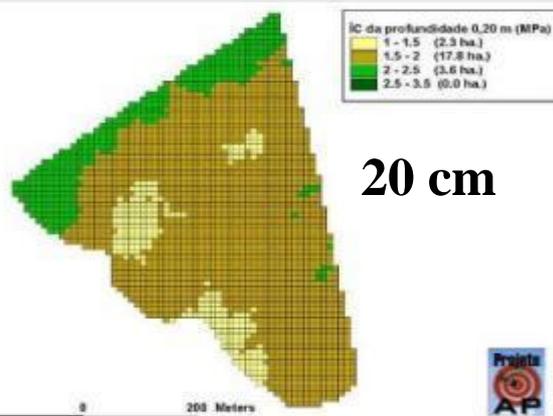
40 cm



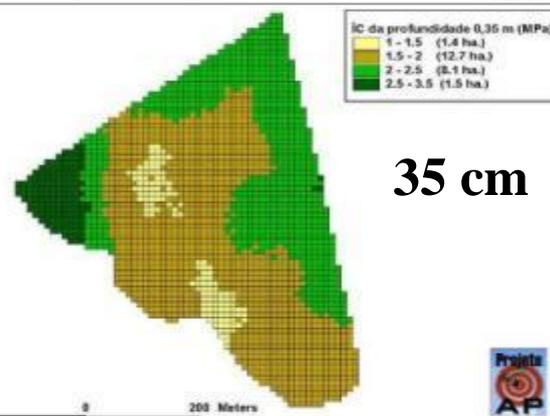
15 cm



30 cm



20 cm



35 cm

Evolução da compactação no perfil

## Campeões de Produtividade – SOJA



### Principais Características Comuns:

Fancelli (2016)

- a) Correta **Distribuição de Plantas** (ponto de honra);
- b) **Adubação equilibrada** e de acordo com a expectativa de produção (excesso não implica em altas produtividades);
- c) **Ausência de compactação** ( $<1,5 \text{ MPa/dm}^3$ ; adequado =  $1,0 \text{ MPa/dm}^3$ );
- d) Na camada de solo (0-20 cm):  $V\% > 65\%$  e  $CTC > 7 \text{ cmol}_c/\text{dm}^3$
- e) Na camada de solo abaixo de 35-40cm:
  - (i) saturação por bases ( $V\%$ ) acima de 30%;
  - (ii) saturação de cálcio acima de 20% na CTC efetiva;
  - (iii) valores absolutos de cálcio acima de  $0,8 \text{ cmol}_c/\text{dm}^3$  e
  - (iv)  $pH$ , em  $\text{CaCl}_2$  superior a 5,0
- f) Uso de **bioreguladores** ou **bioestimulantes** foliares.
- g) **Sementes grandes** (6,5 ou 7,0) e com alto vigor ( $>85$ ).
- h) Aplicação de **Fungicidas na etapa Vegetativa** (V5/V6).

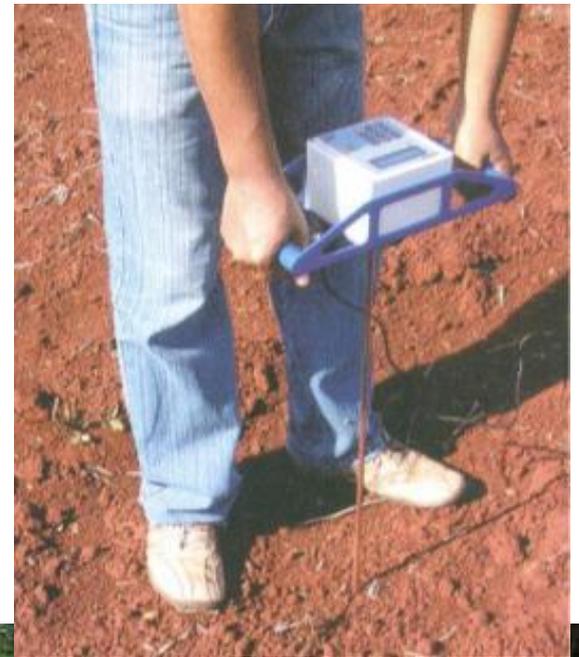
Tais **constatações** confirmam as condições decisivas para o desempenho satisfatório das plantas, representado pelo aprofundamento e adequado funcionamento das raízes, além da maior tolerância a condições de estresse e manifestação de alta produtividade.

Fancelli (2016)

fancelli@usp.br

Fonte: **Banco de Dados CESB (2016)**

# Penetrômetros de coleta eletrônica de dados



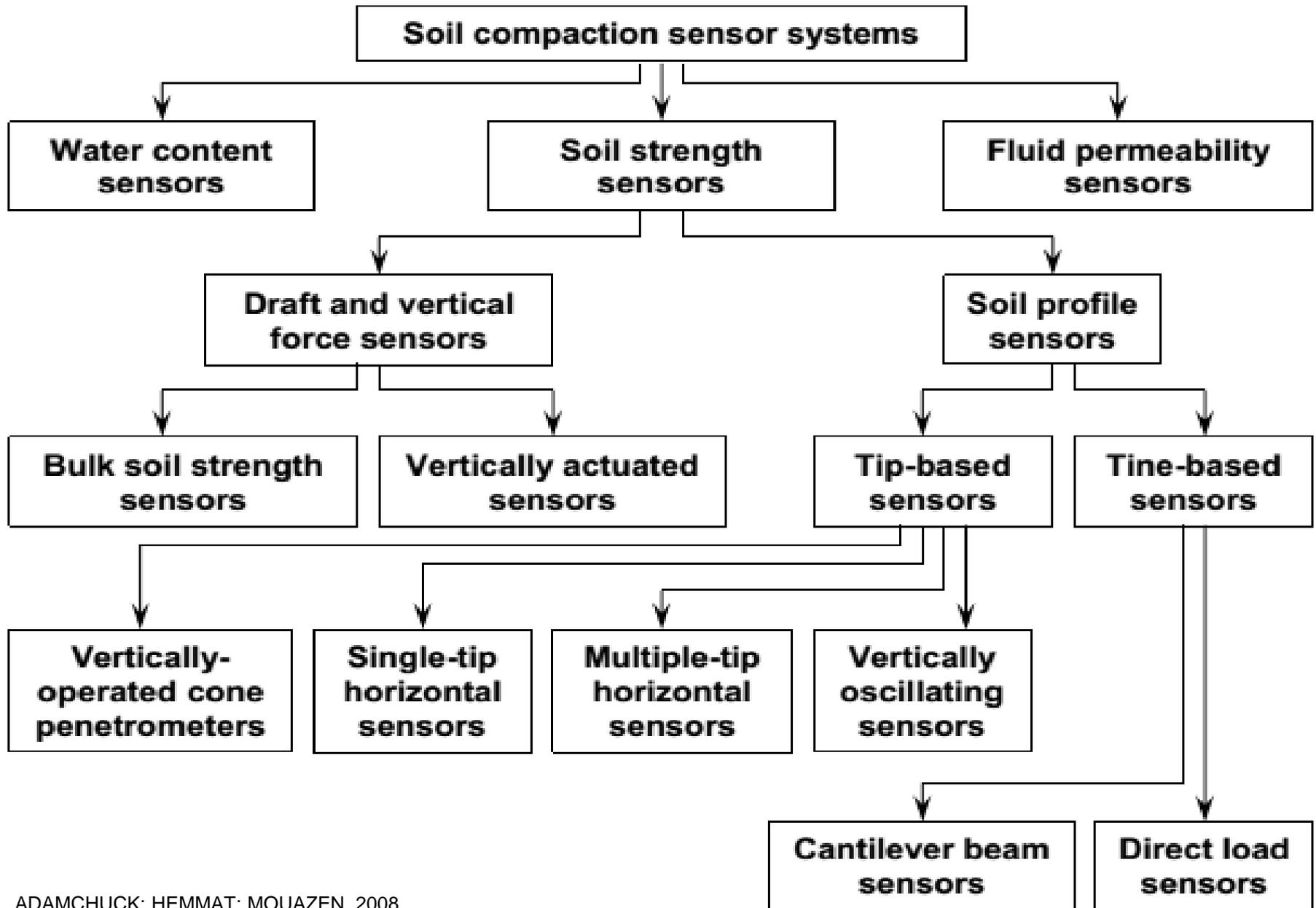


Falker, Show Rural 2011



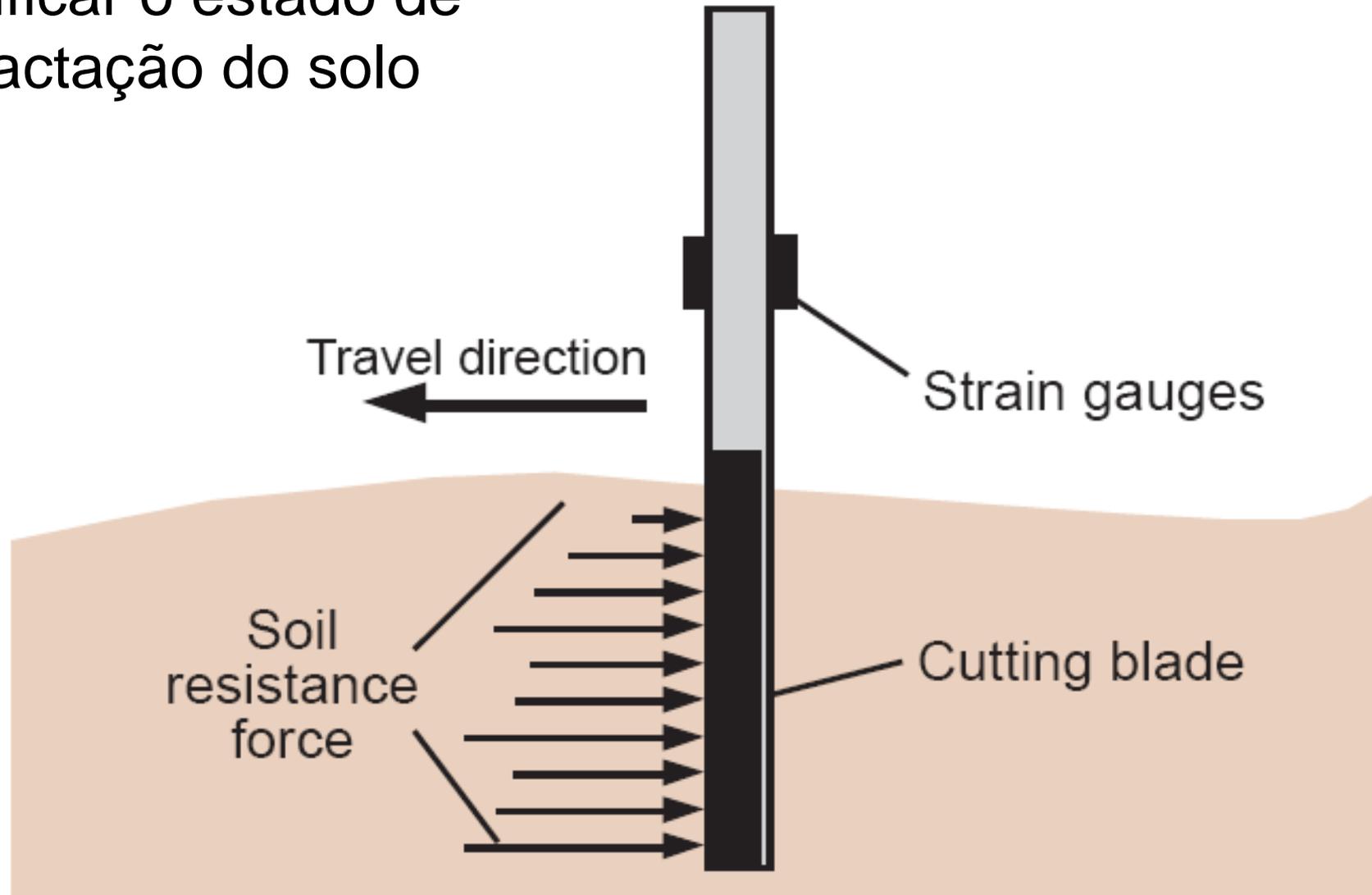
Tekeste et al. (2006)





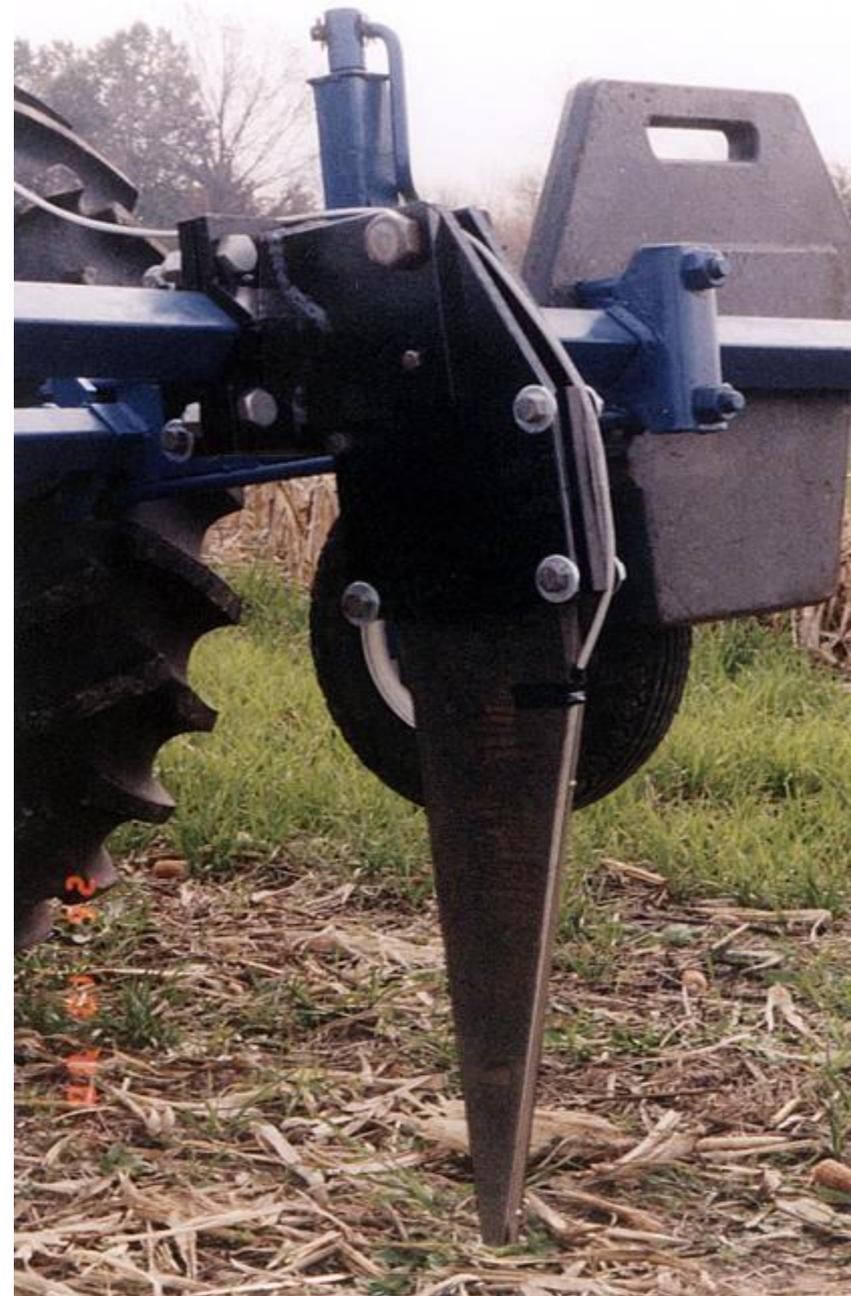
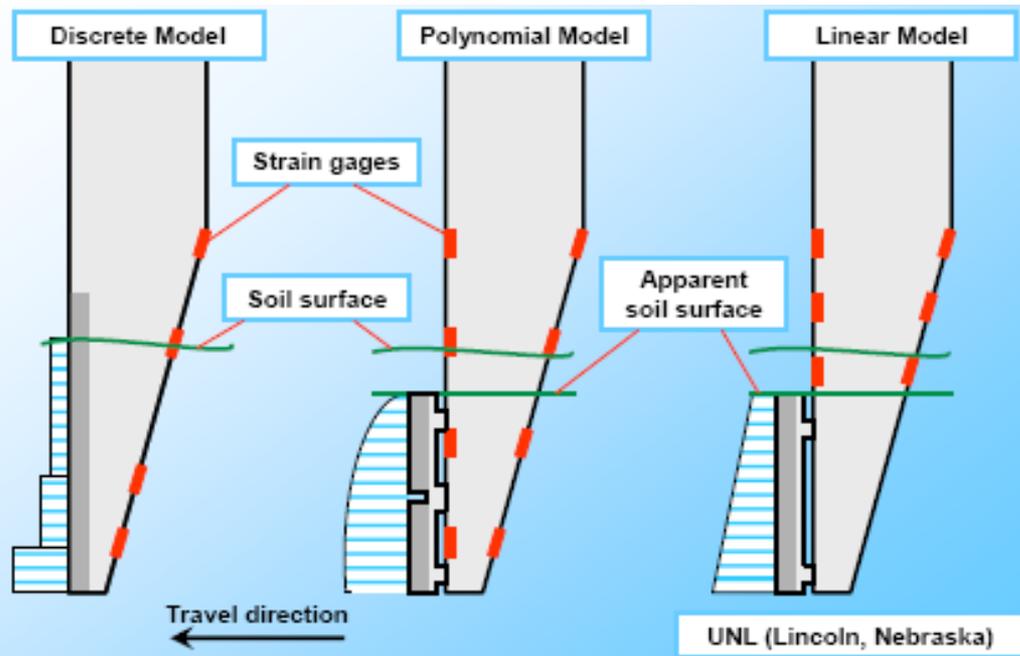
ADAMCHUCK; HEMMAT; MOUAZEN, 2008

# Evoluções na forma de se quantificar o estado de compactação do solo



ADAMSHUK, 2002

Un. de Nebraska, EUA

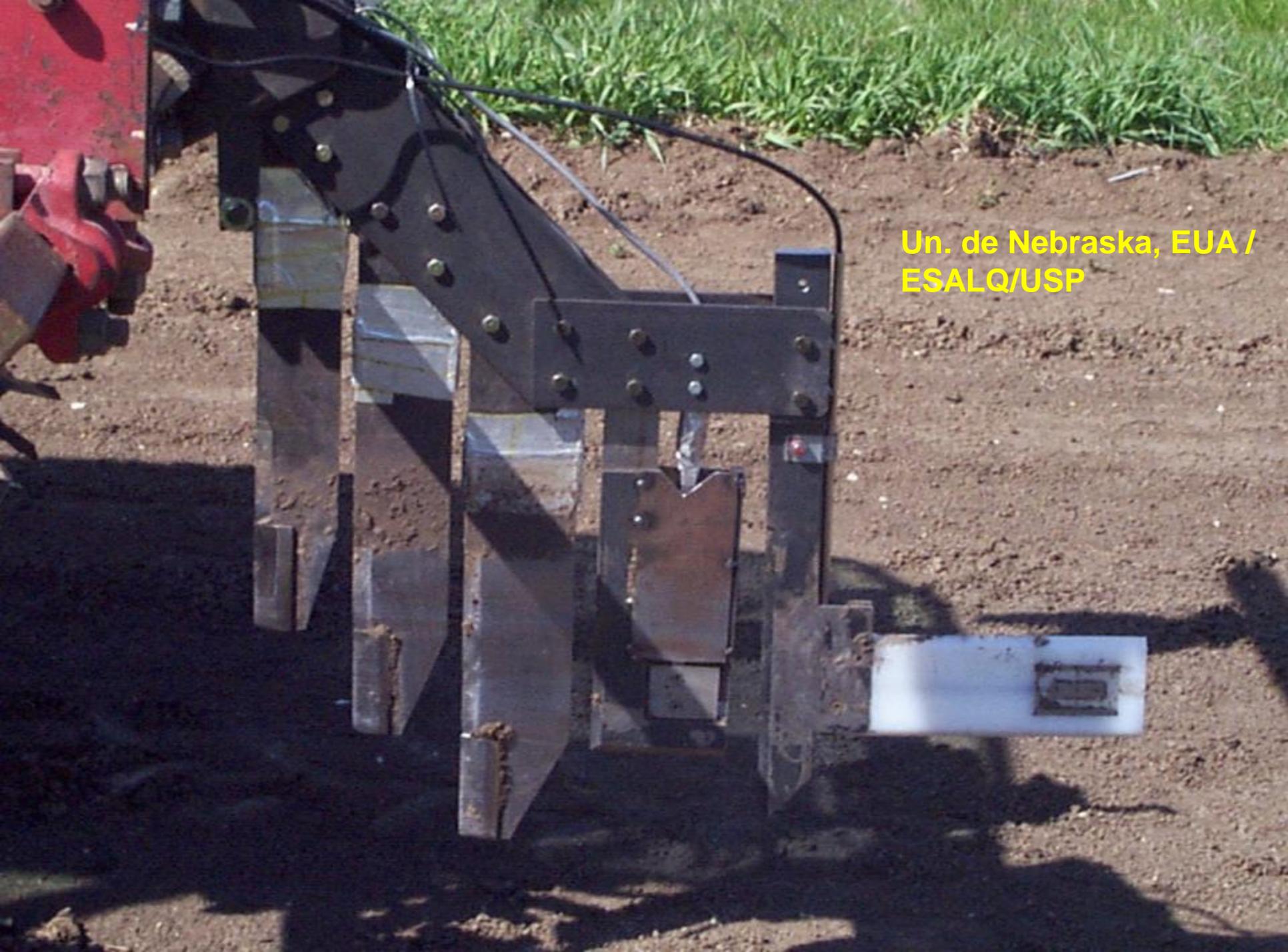


Silsoe College, UK

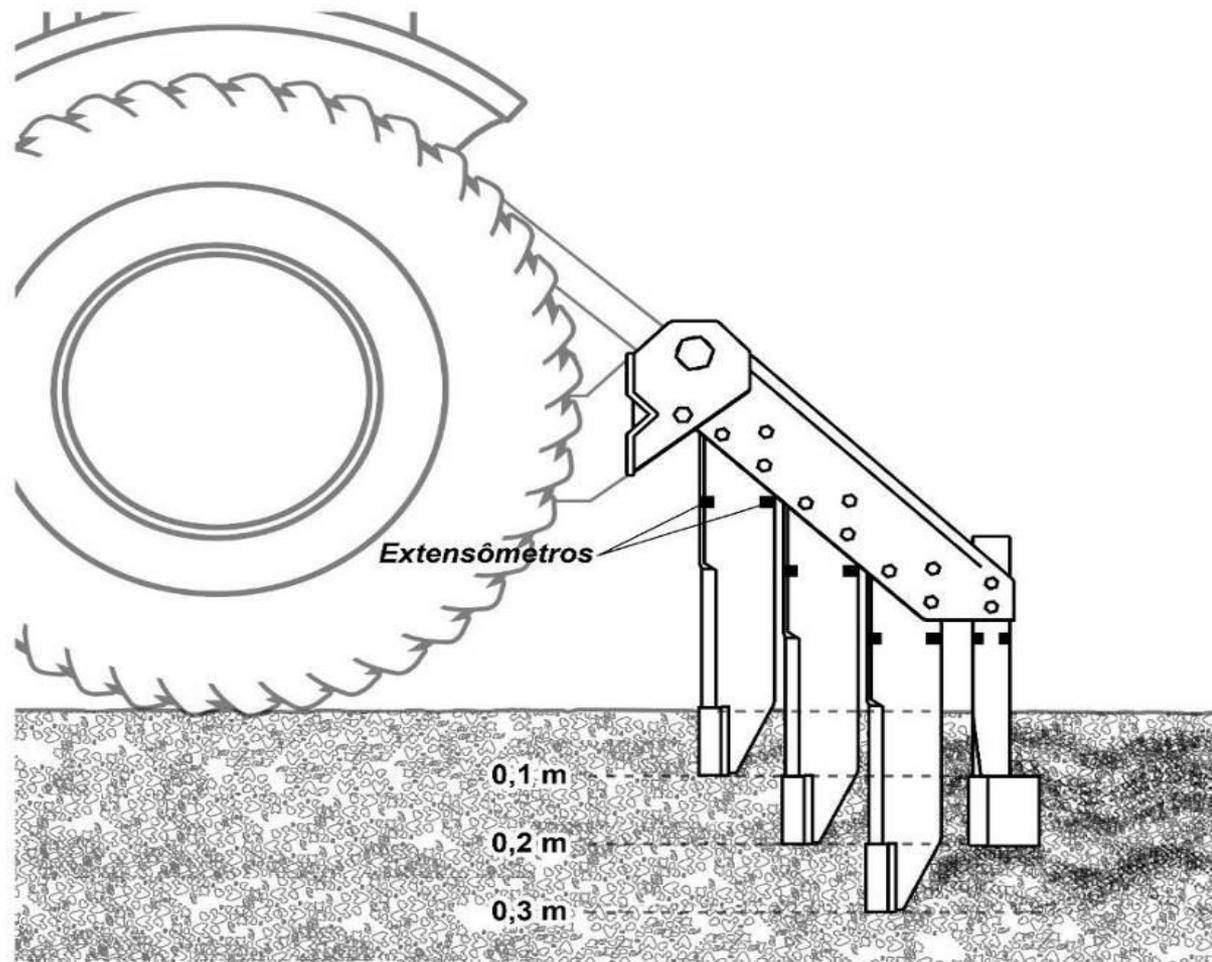
Uppsala, Suécia



Un. de Nebraska, EUA /  
ESALQ/USP



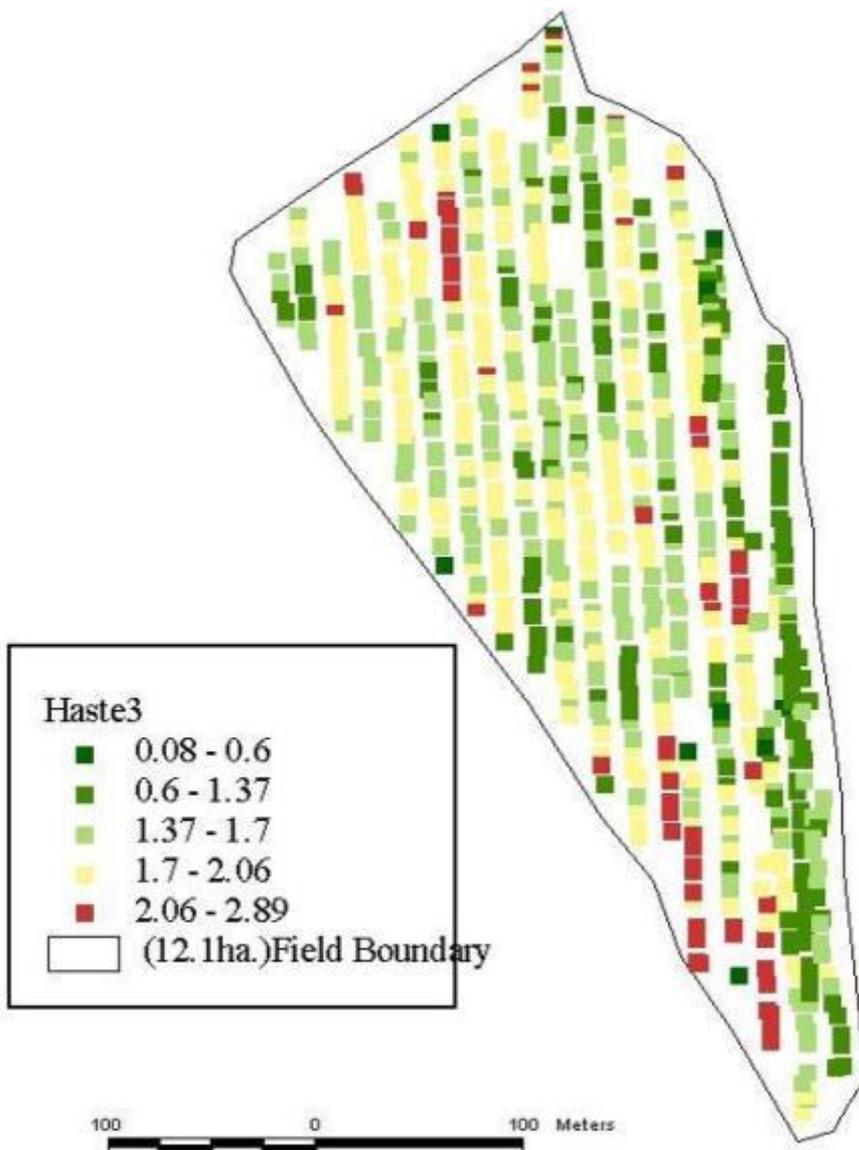
# Hastes instrumentadas



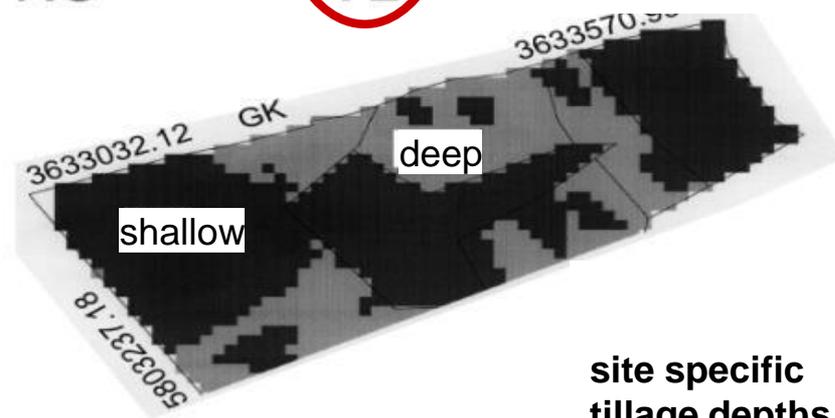
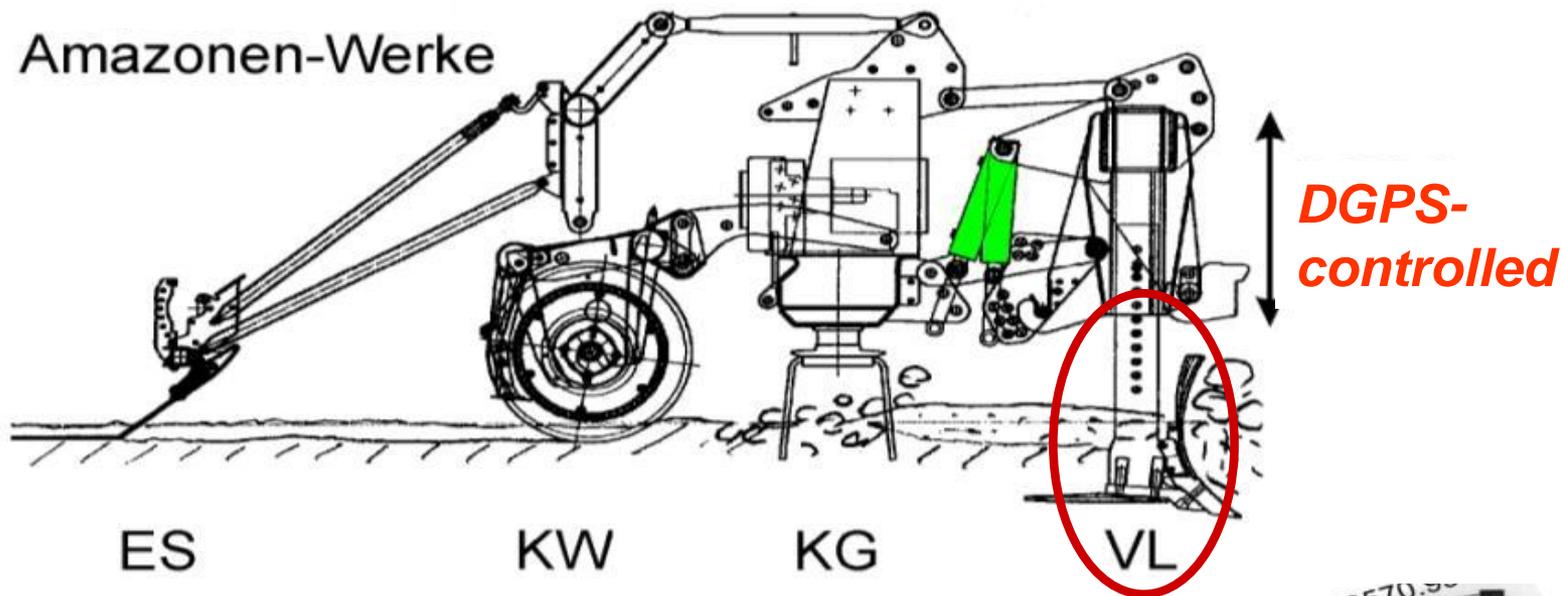
Molin, Amaral & Colaço, 2015







# Preparo localizado do solo - Escarificador de movimento vertical



site specific  
tillage depths

# Preparo localizado do solo - Escarificador de movimento vertical

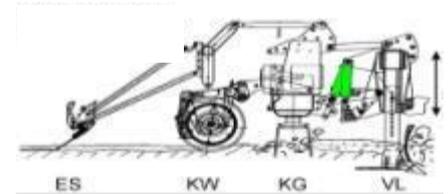


Amazone Centaur

WERNER, A. (2008)

# Saving of diesel-fuel with site specific soil tillage

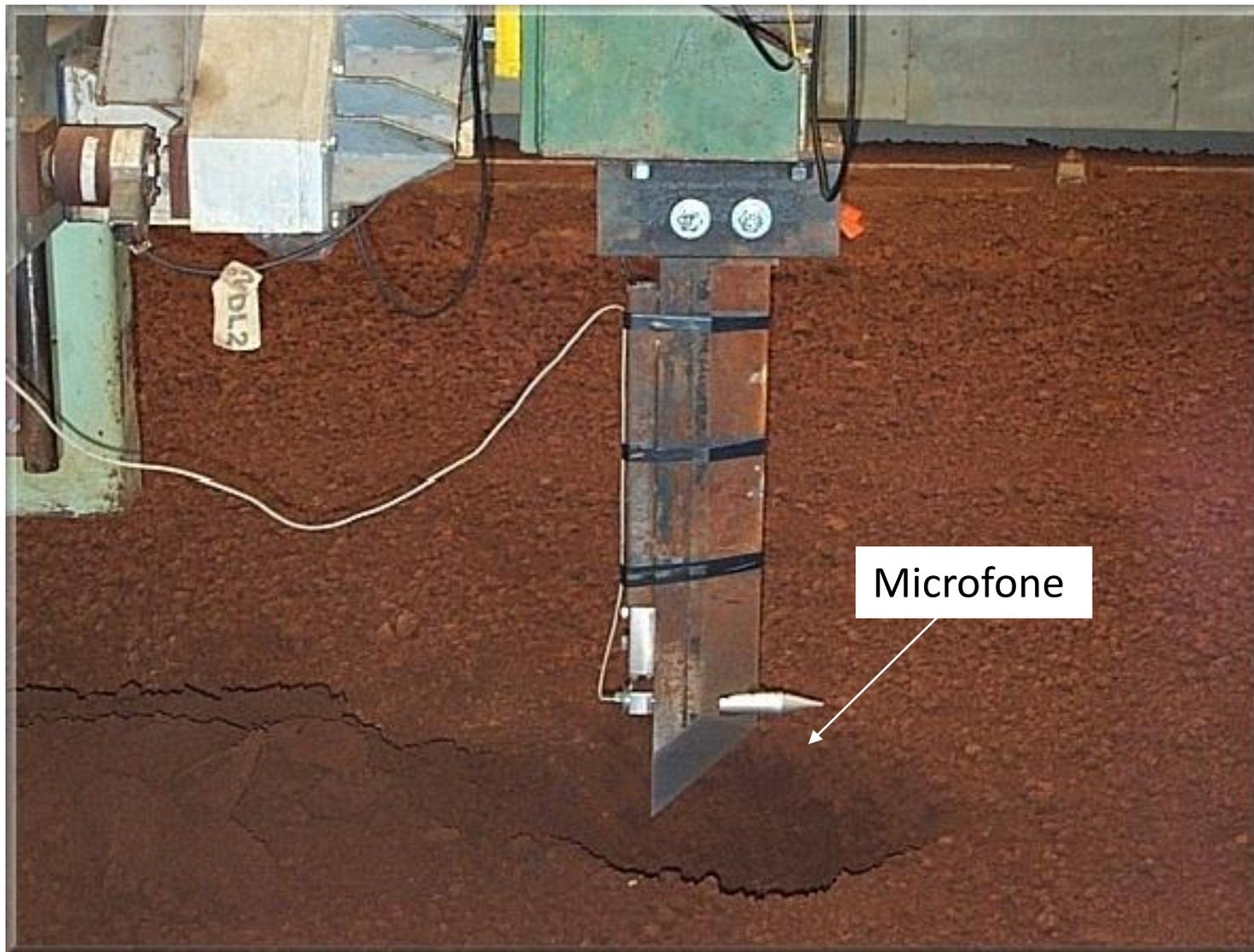
- chisel plough – (in Twülpstedt)



	deep (run 1)	shallow (run 2)	deep (run 3)	shallow (run 4)
Length of runs (m)	422,3	416,5	420,1	424,4
Fuel consumption (l)	3,18	1,50	3,02	1,35
Fuel consumption (l/ha)	25,1	12,0	24,0	10,6

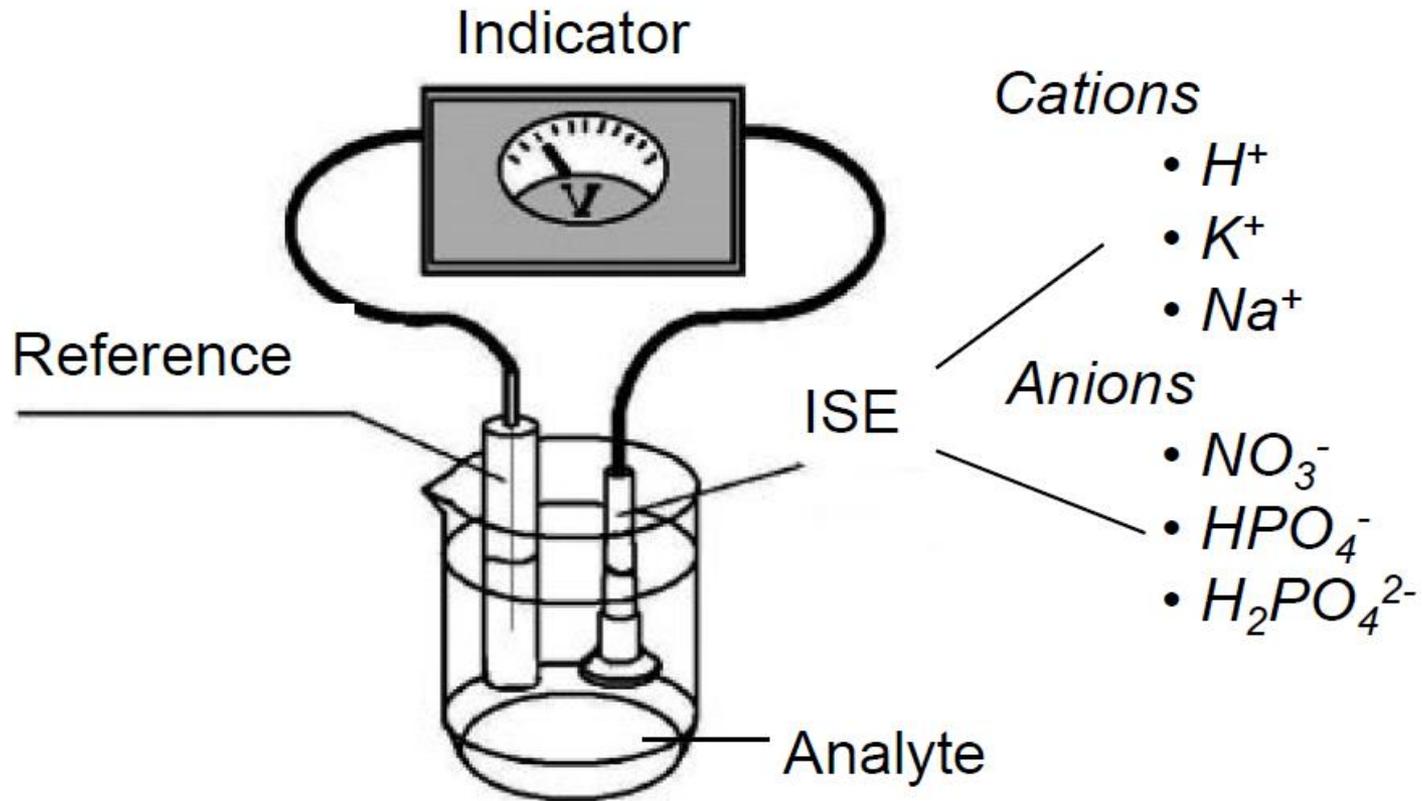
= 52% reduction

# Sensor acústico para detecção de camada compactada



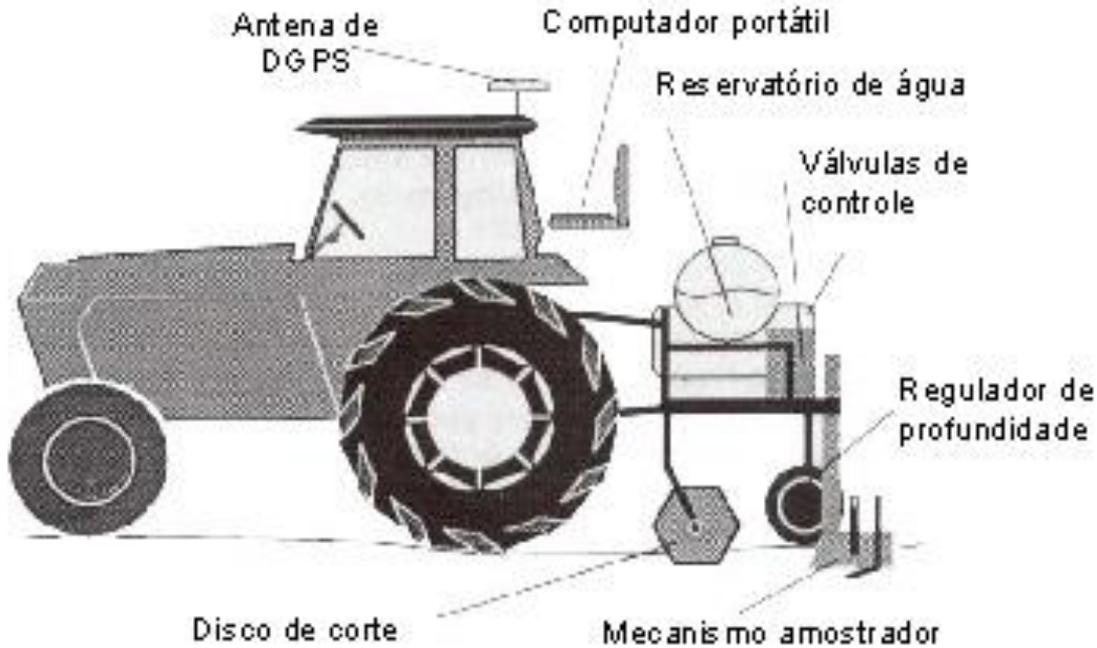
Un. of Illinois

# Eletróquímicos



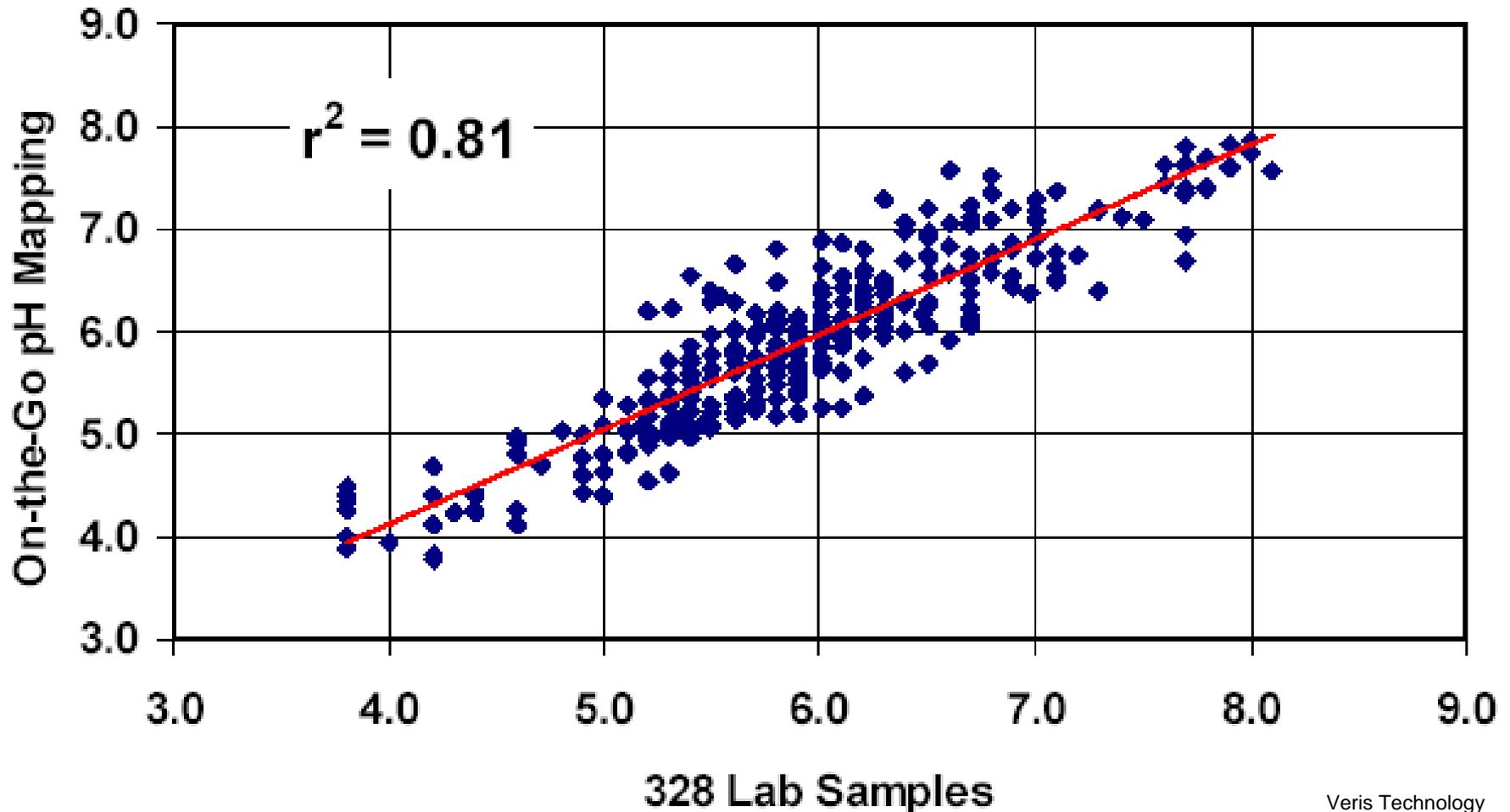
Ion-selective electrode setup

# Protótipo de um sistema sensor de pH (eletroquímico)



ADAMSHUK, 2000

# Dados de testes em 15 talhões (328 amostras), entre 2002 e 2004



Veris Technology

# Sistema sensor de pH

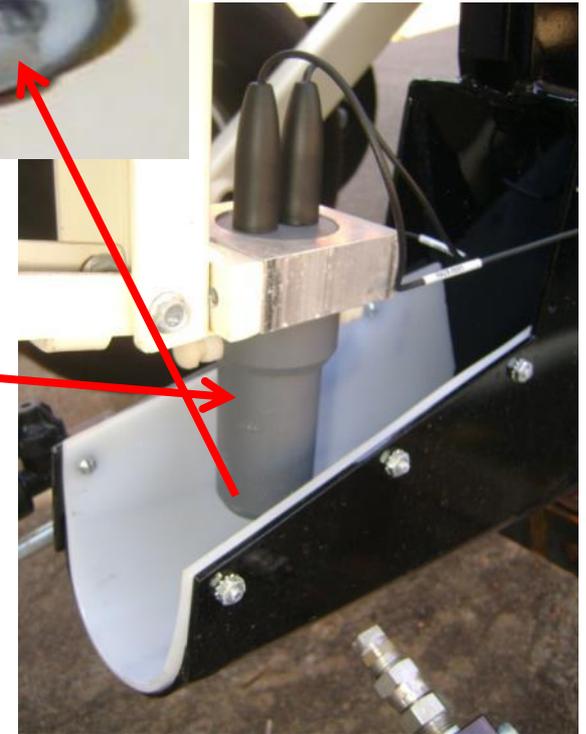


...é o mais próximo do conceito  
de laboratório no campo

# Sensores eletroquímicos



O amostrador desce até o solo

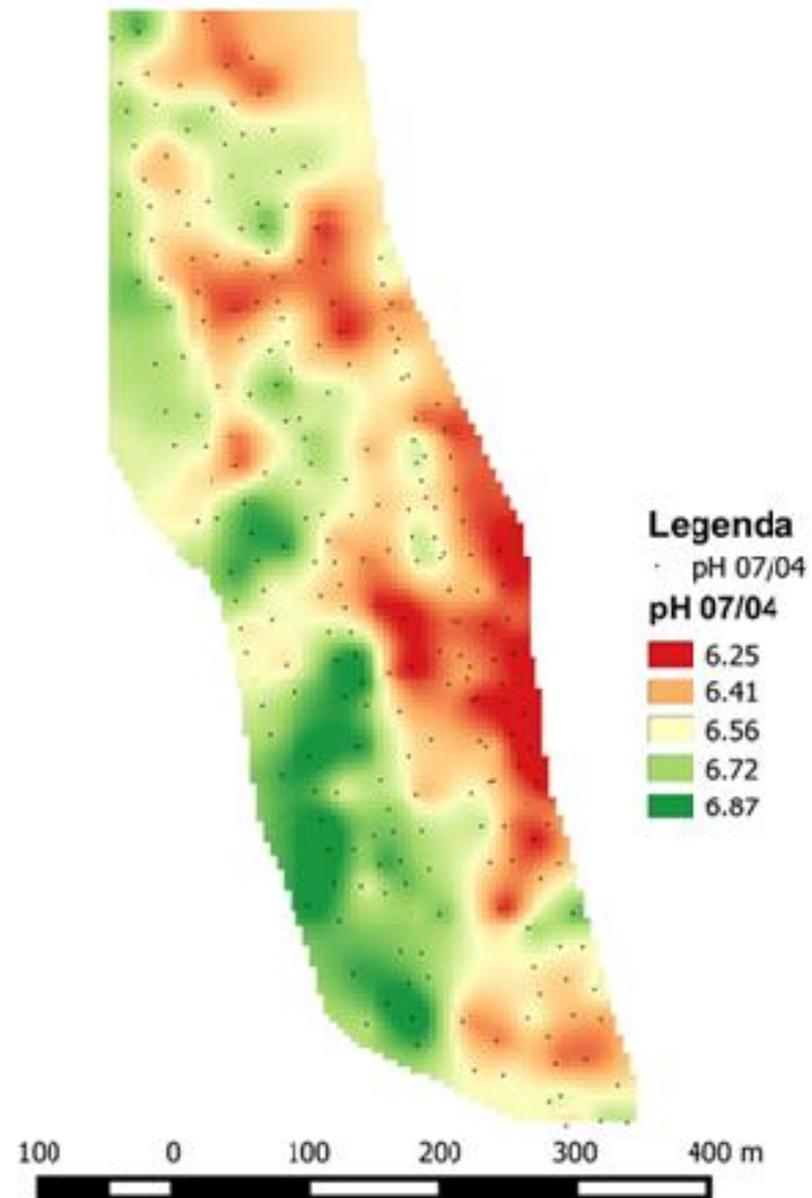
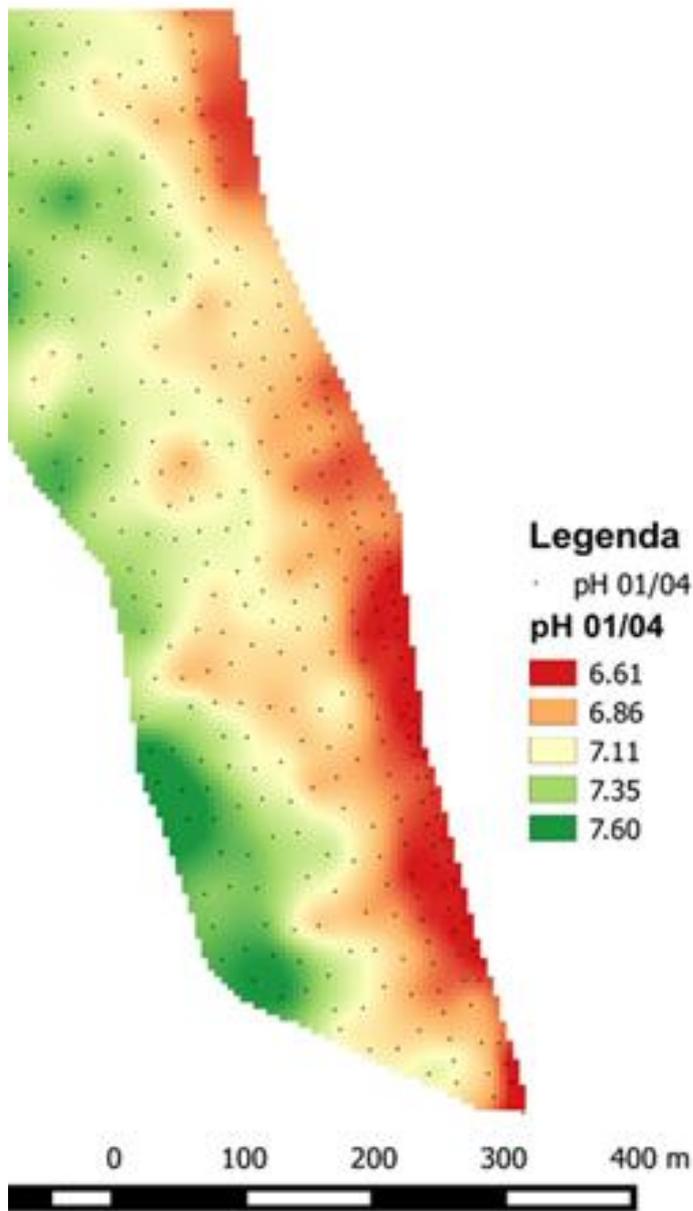


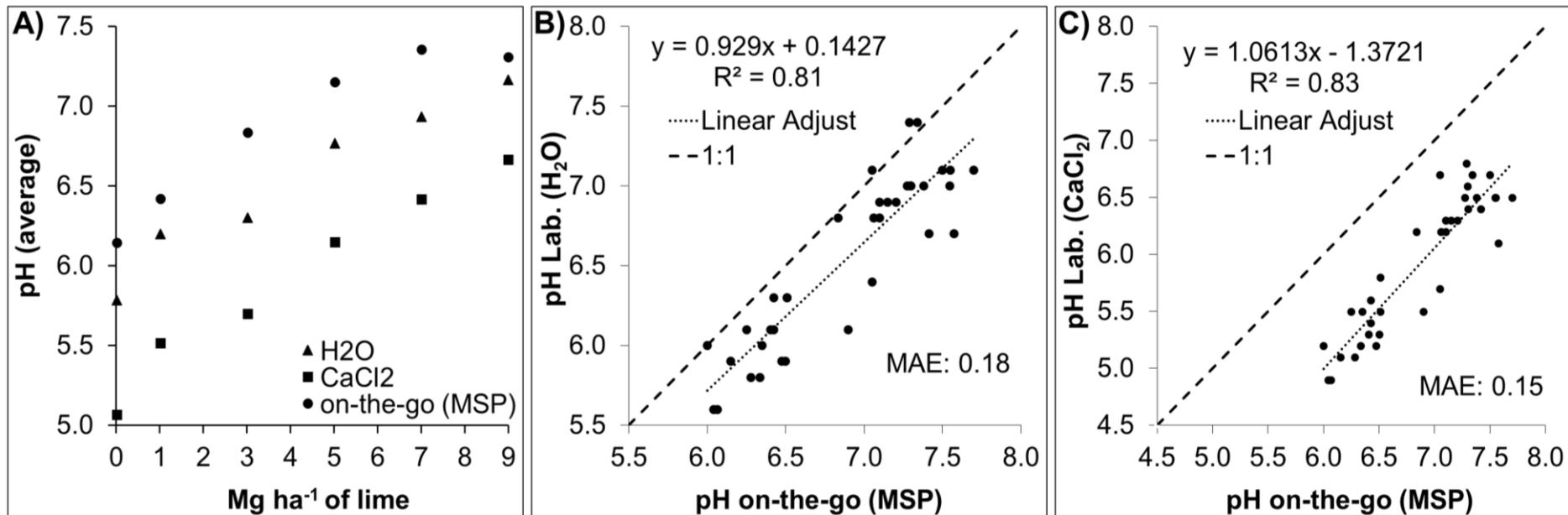
A amostra é empurrada contra dois eletrodos de pH que fazem a leitura











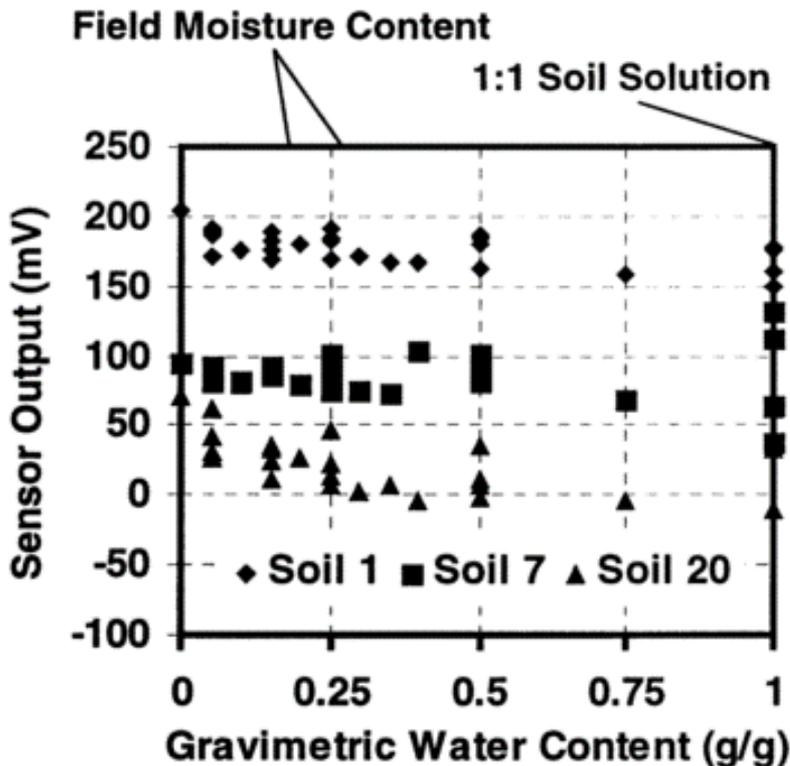
Relationships between applied limestone and pH determined on-the-go and in-lab using H<sub>2</sub>O and CaCl<sub>2</sub> methods

Eitelwein et al. (2016)

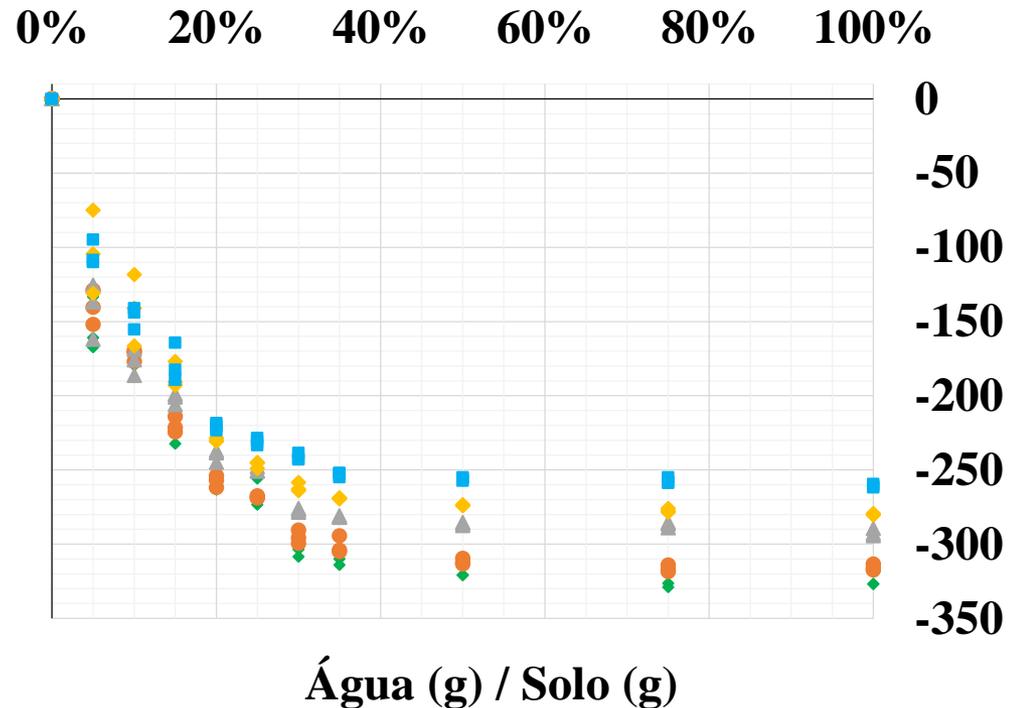
# Influência da umidade em Íon Seletivos (ISE)

Se a umidade do solo é um fator que influencia a resposta do ISE, é necessário conhecer o teor de umidade para calibração de modelos.

**Solos de regiões temperadas**



**Solos de regiões tropicais**





# Espectrometria de raios Gama

Os sensores de raios gama medem as concentrações de  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{137}\text{Cs}$ . O equipamento mede algo como 800 pontos/ha

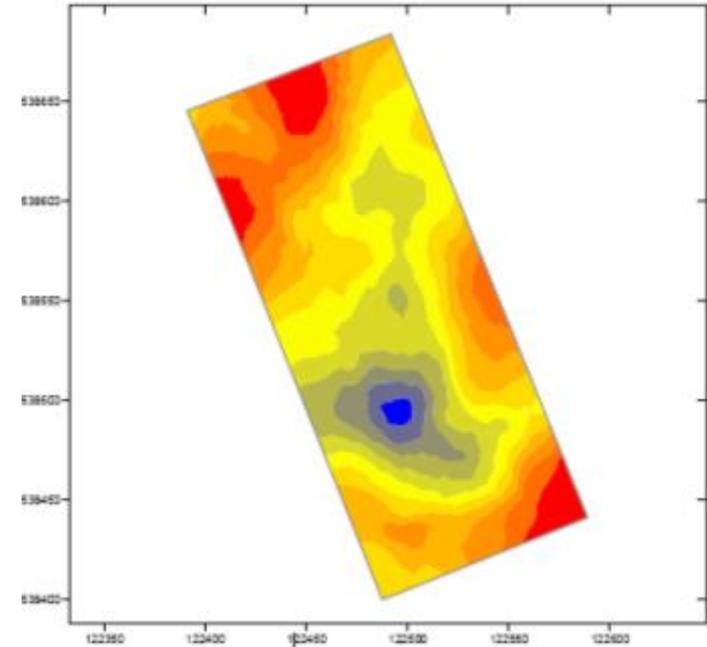
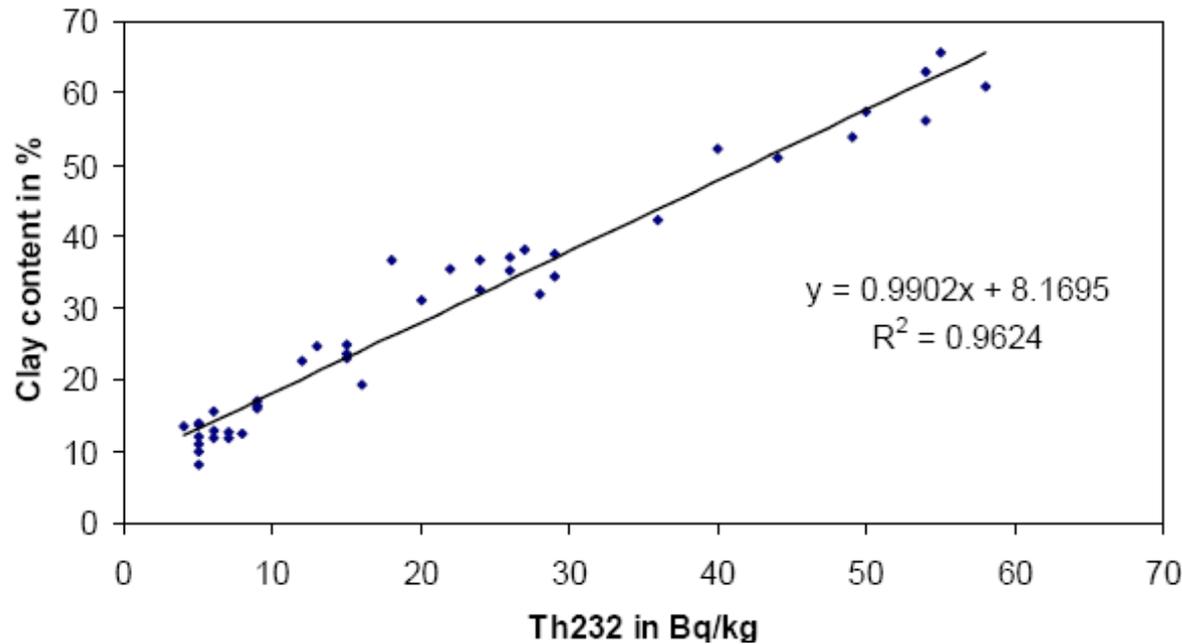


THE MOLE  
[www.soilcompany.com](http://www.soilcompany.com)

LOONSTRA, E, 2008



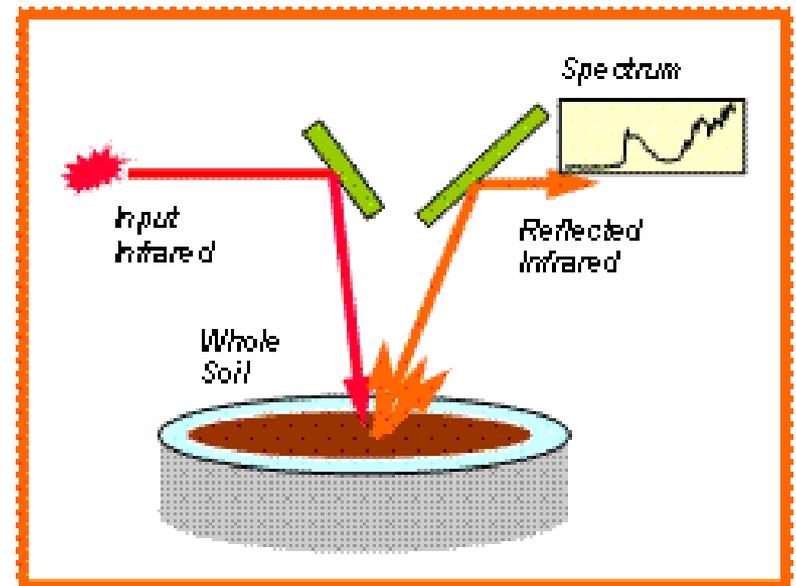
# Espectrometria com raios Gama



Correlation between  $^{232}\text{Th}$  and clay in Sweden

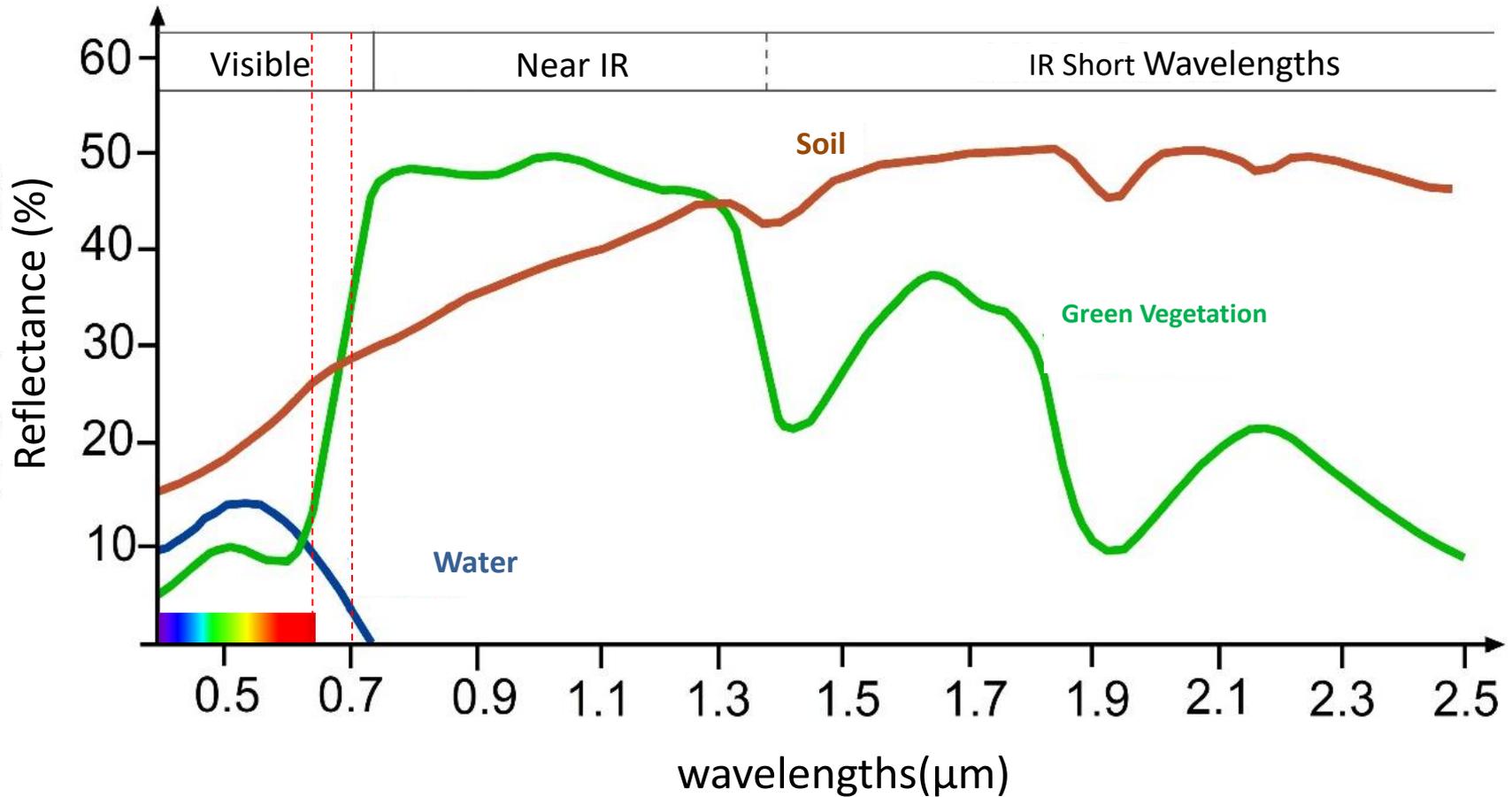
LOONSTRA, E, 2008

# Óptica aplicada a sensores de solo



<http://www.clw.csiro.au/services/mir/what.html>

# Distribuição do comprimento de ondas eletromagnéticas



# Algumas das técnicas

vis – região do visível

NIR – infravermelho próximo

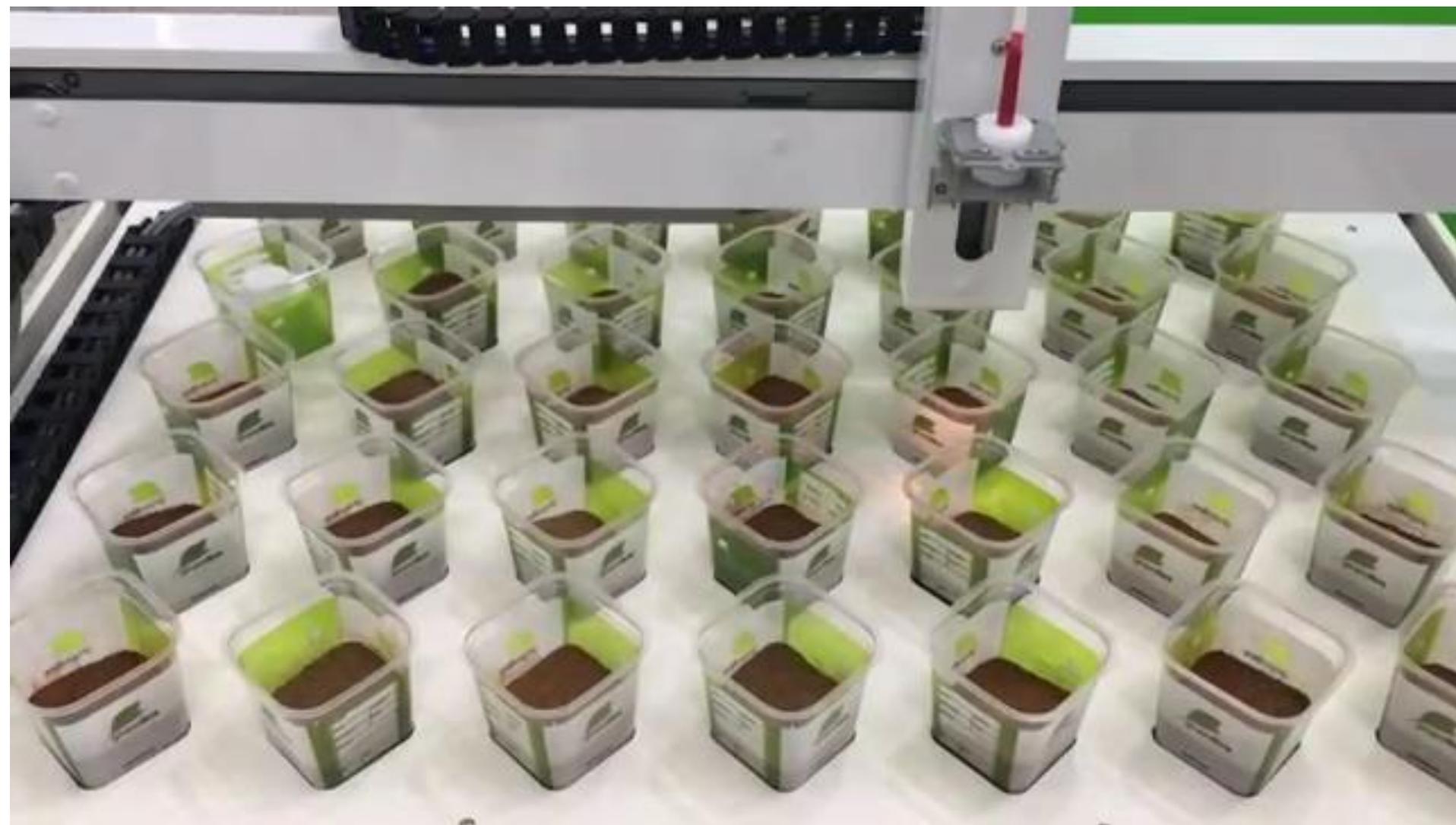
MIR – infravermelho médio

LIBS – laser induced breakdown spectroscopy

Raios X

INS – inelasting neutron scattering

ITU - TeraHertz

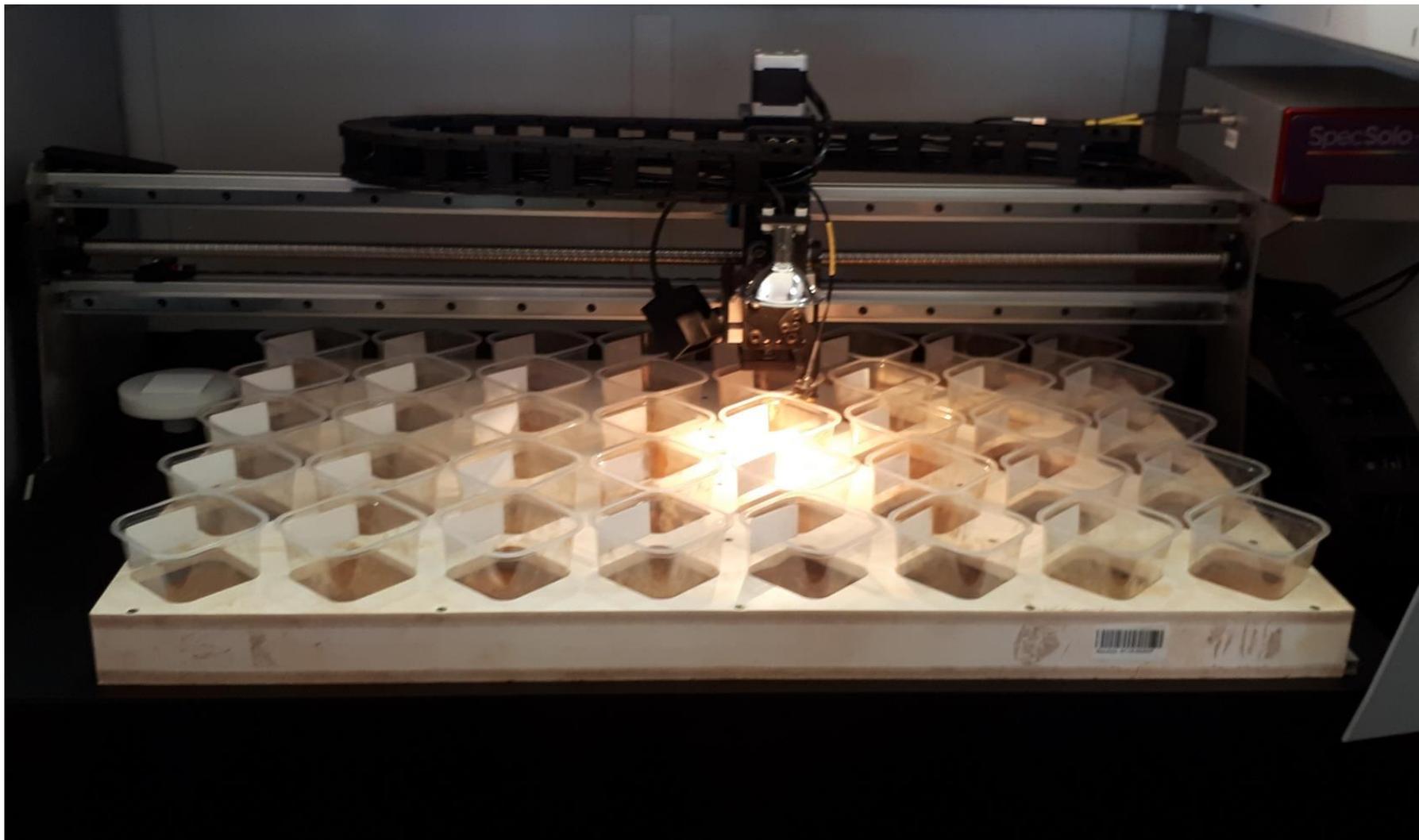


ConBAP 2016



**LAP**  
Laboratório de Agricultura de Precisão

Prof. J. P. Molin



IBRA Agrishow 2018





**Eletrodos de CE**

**Condutividade elétrica**



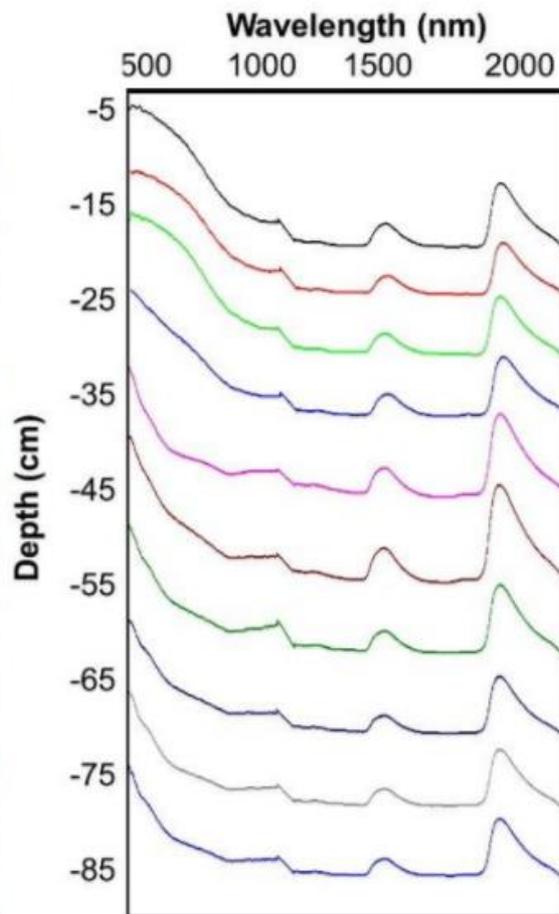
**Janela de VIS-NIR**

**Espectrorradiometria**

Soil core collection



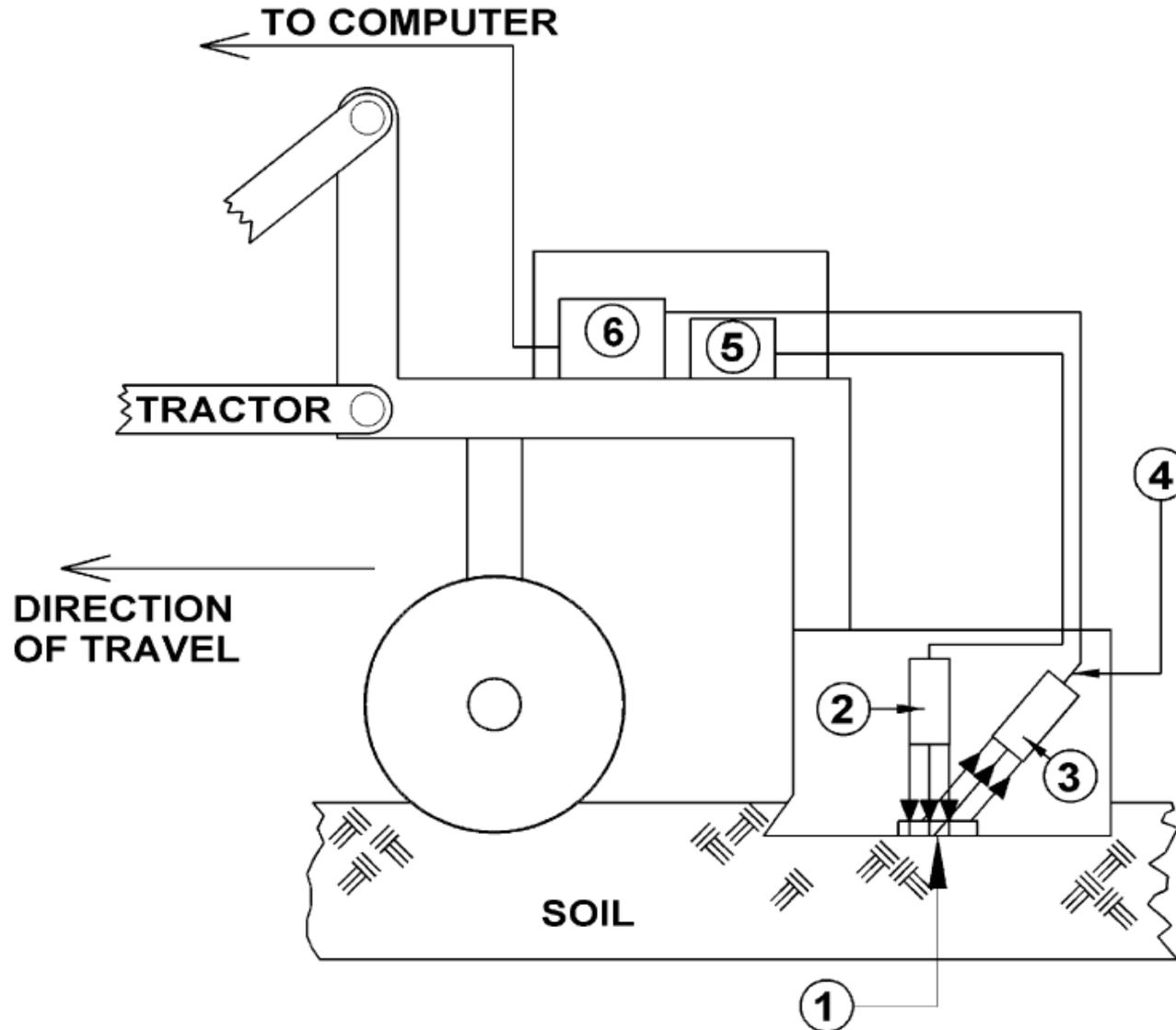
Soil core



In-situ spectra collection



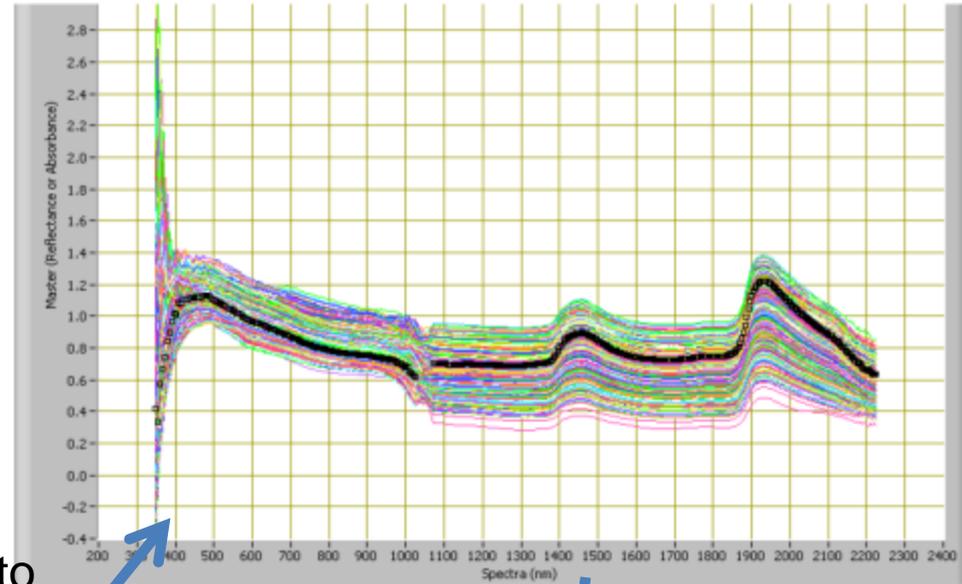
# Espectrorradiometria de campo



CHRISTY, 2007

# Espectrorradiometria de campo

VIS-NIR - 2007



Equipamento

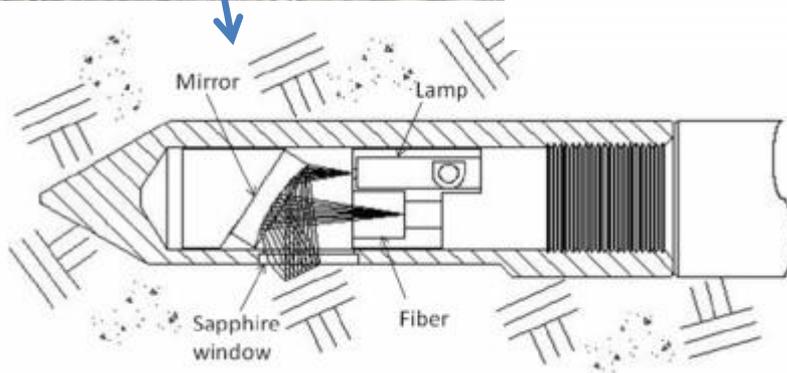
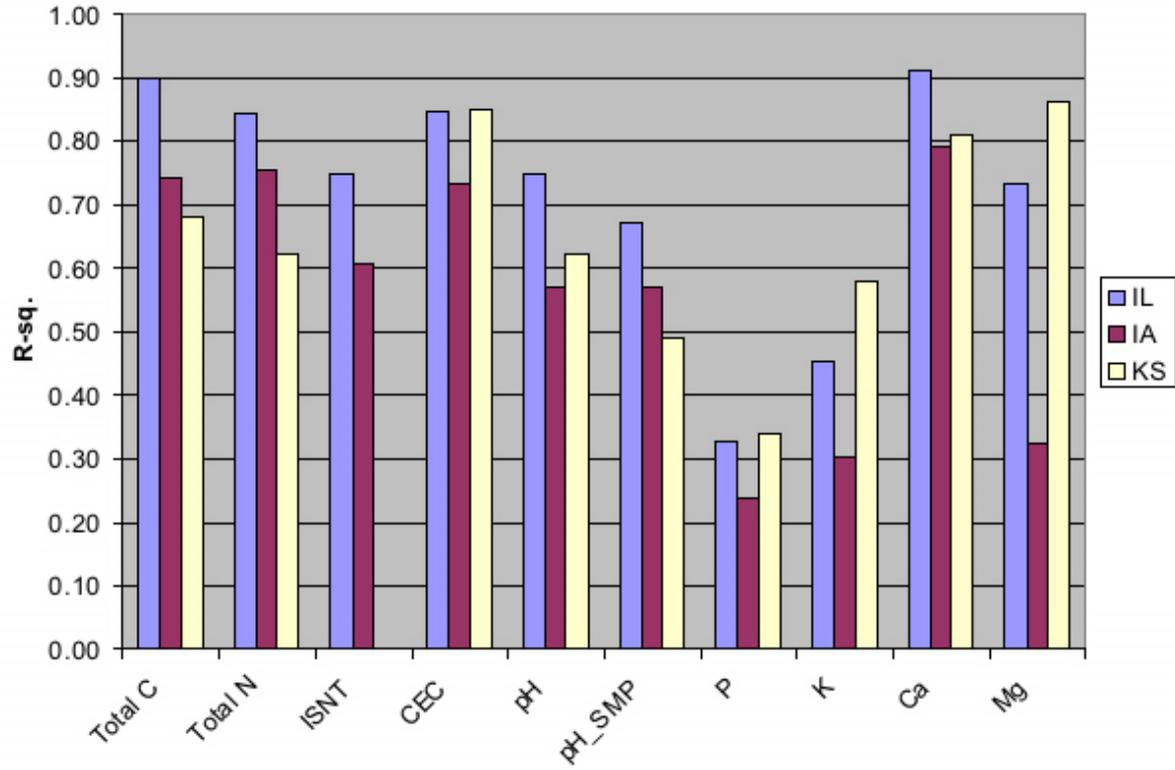


sensor



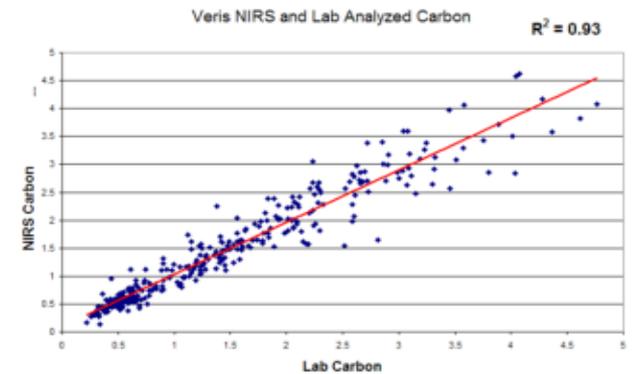
Ferramentas de análise dos dados:

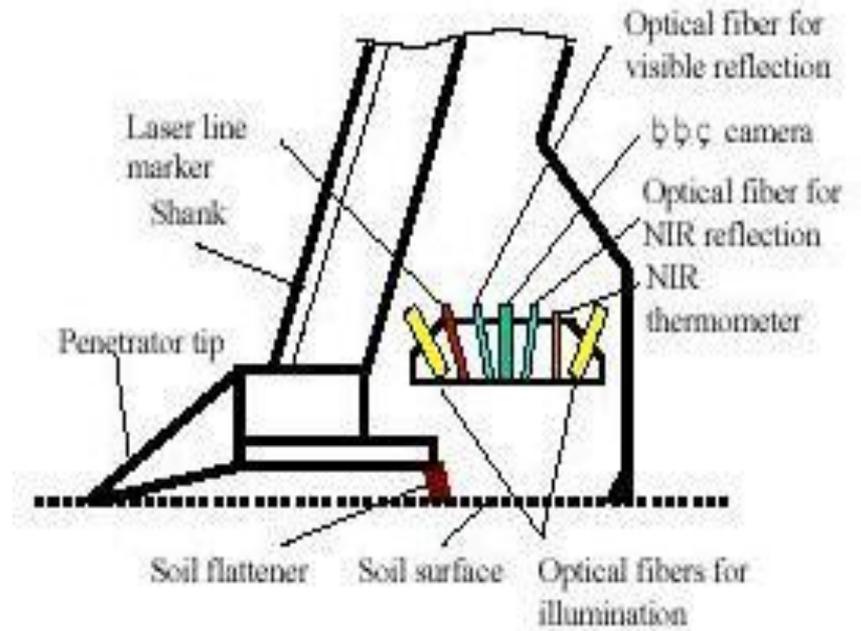
- Análise de componentes principais
- Agrupamento com lógica fuzzy
- calibração para a propriedade específica
  - limpeza de dados
  - regressões parciais
  - validação cruzada



Vista de baixo do sensor

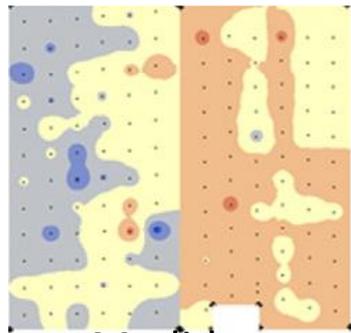
### Lab tests





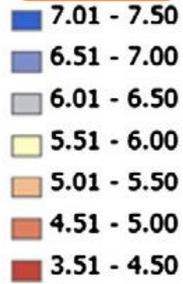
# Espectrorradiometria de campo

SHIBUSAWA, 2008

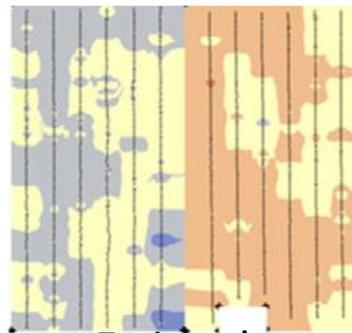


Medido

**pH**

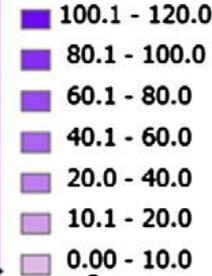


$R^2$  0,69

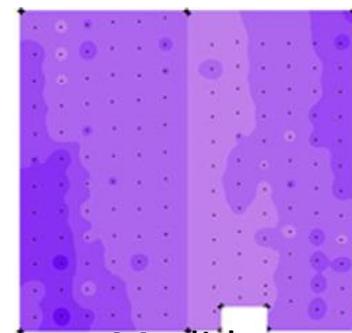


Estimado

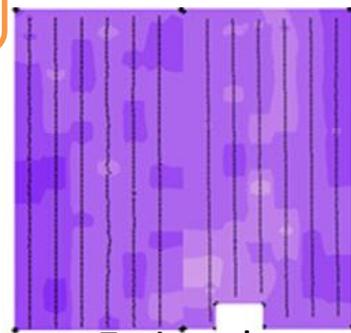
**P**



$R^2$  0,72

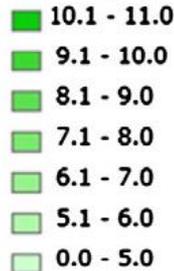


Medido

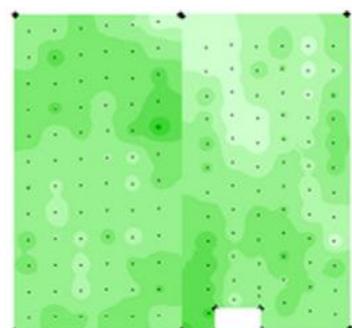


Estimado

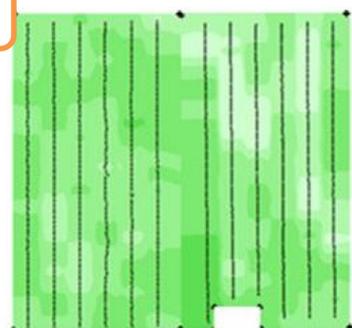
**MO**



$R^2$  0,90

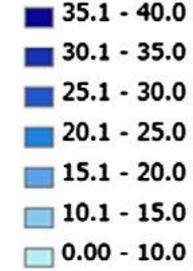


Medido

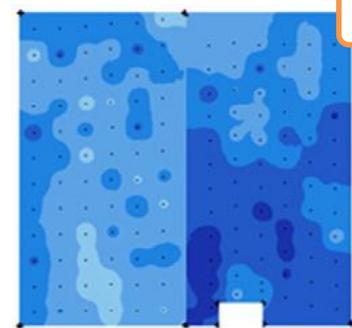


Estimado

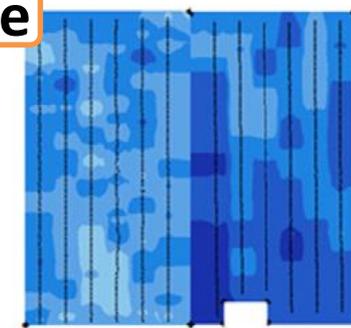
**Umidade**



$R^2$  0,93

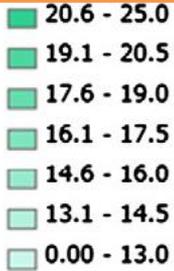


Medido

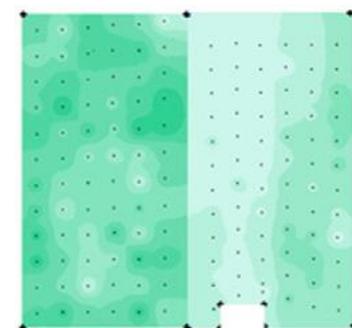


Estimado

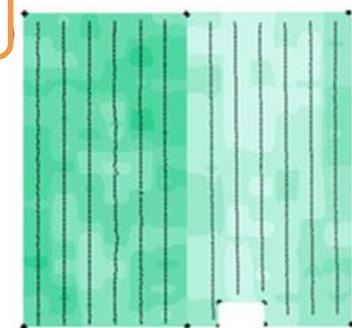
**CTC**



$R^2$  0,89

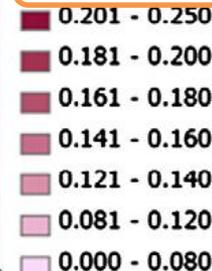


Medido

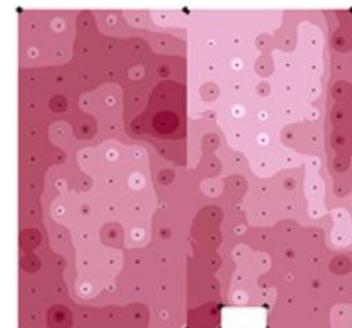


Estimado

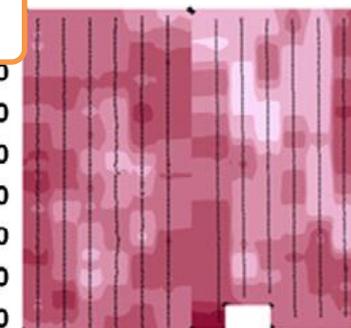
**N**



$R^2$  0,87



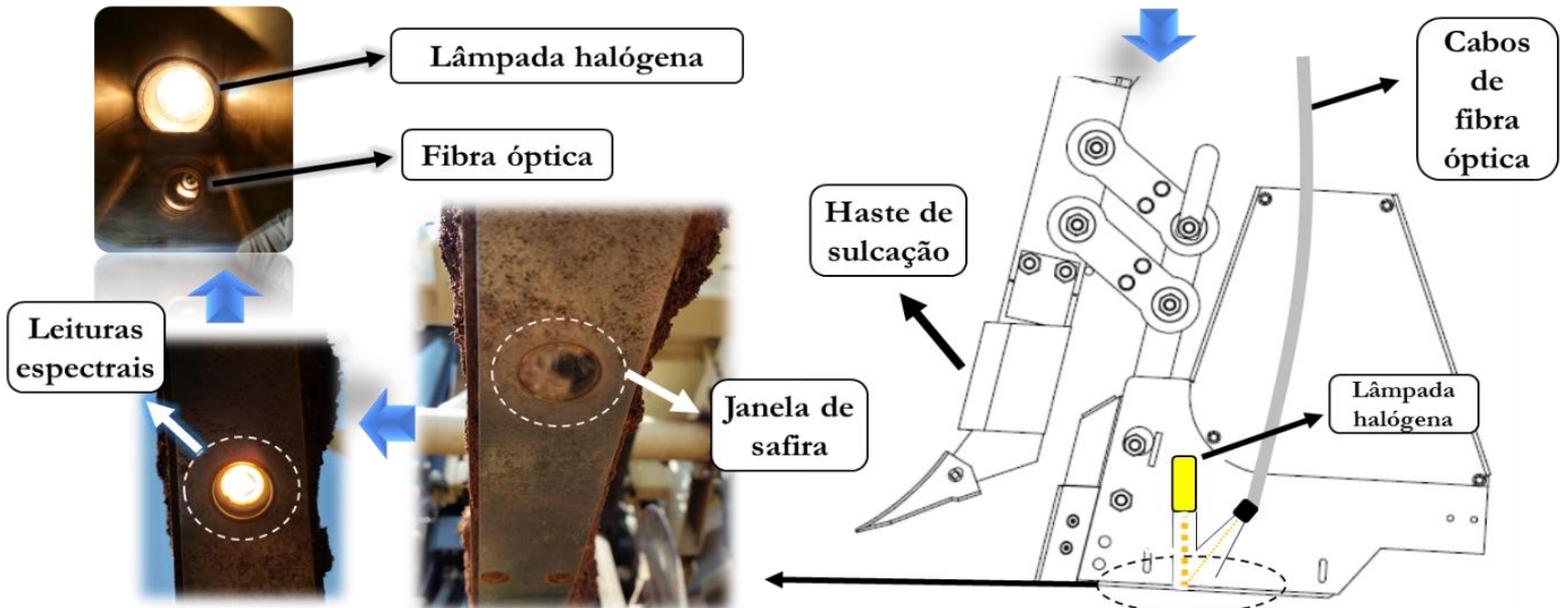
Medido



Estimado

Kodaira e Shibusawa (2013)

# Espectroscopia vis-NIR difusa



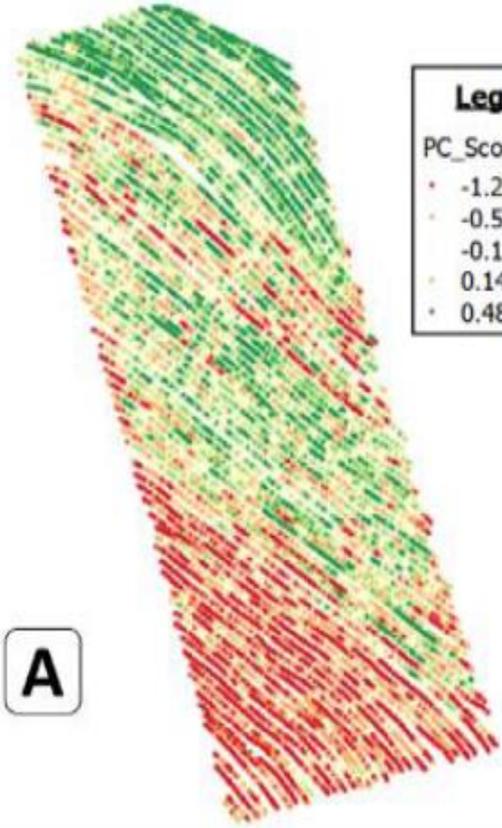


## Espectrorradiometria de campo



## Espectrorradiometria de campo

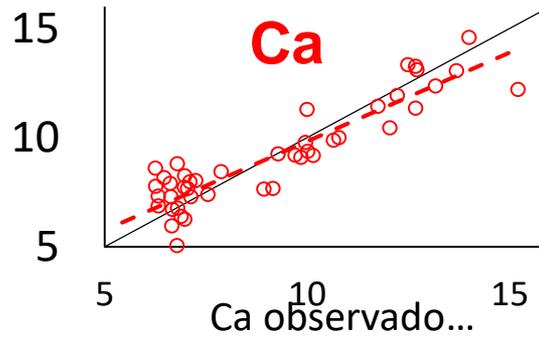
Vis-  
NIR:  
CP1



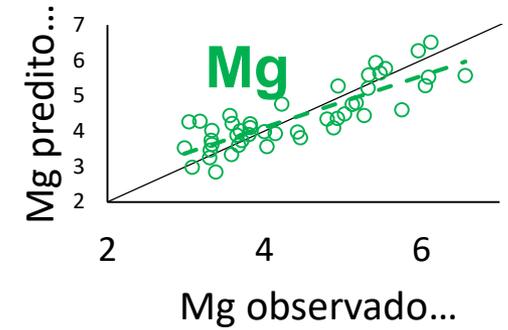
**Legenda**

PC\_Scores

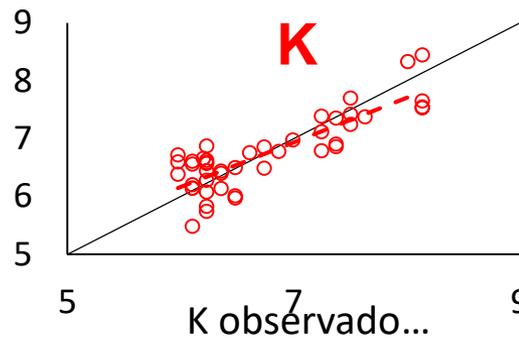
- -1.24 - -0.50
- -0.50 - -0.17
- -0.17 - 0.14
- 0.14 - 0.48
- 0.48 - 1.52



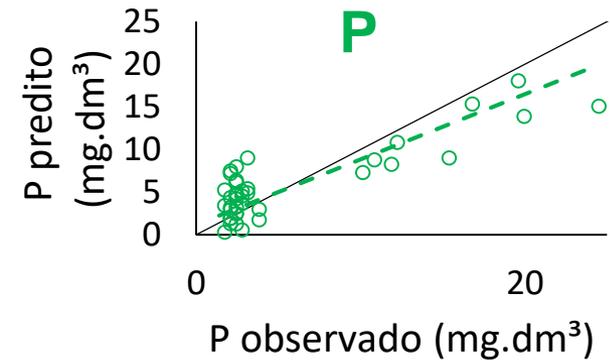
$R^2 = 0,83$   
RMSE =  
1,16



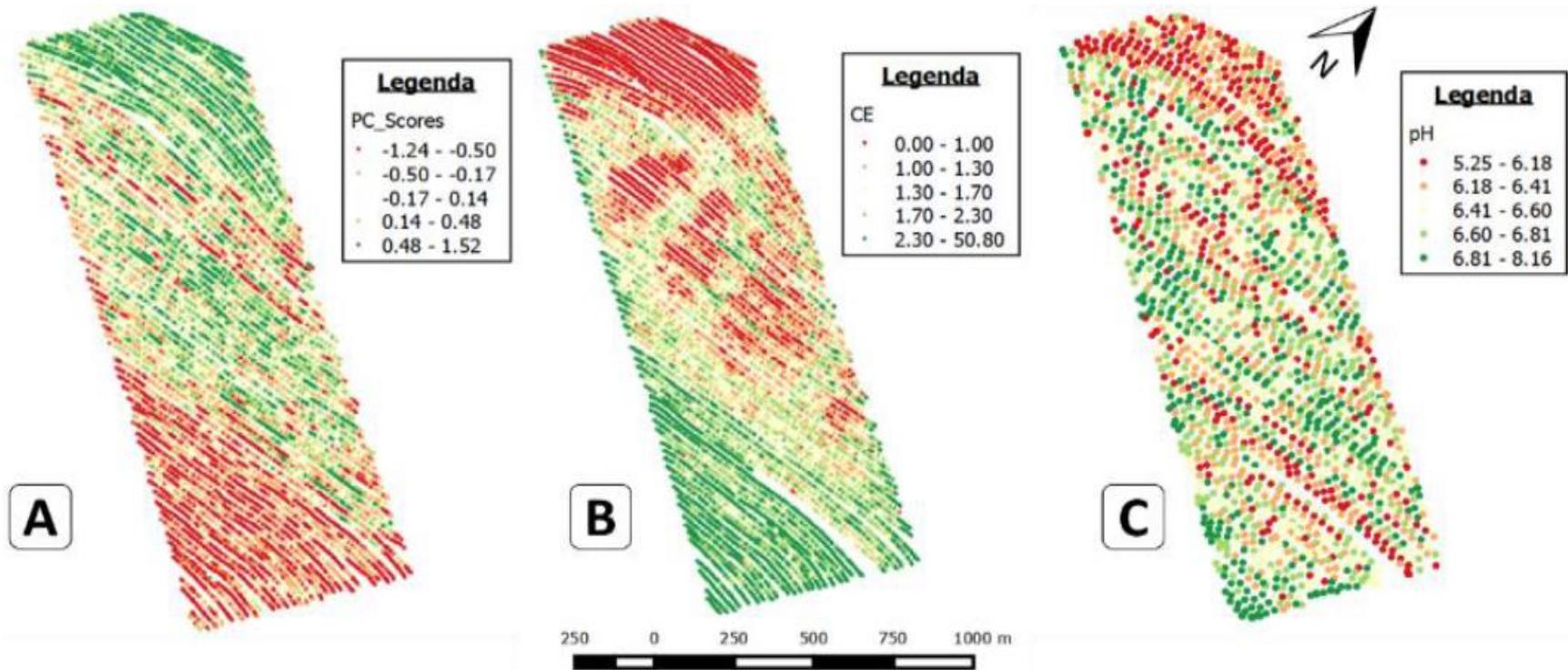
$R^2 = 0,71$   
RMSE = 0,29



$R^2 = 0,72$   
RMSE =  
0,14



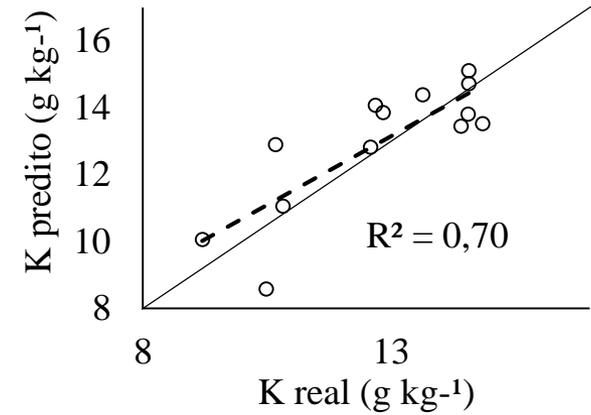
$R^2 = 0,65$   
RMSE =  
13,70



Scores do segundo componente principal das leituras espectrais (A), condutividade elétrica aparente (0 – 30 cm; B) e pH do solo (C) em uma área de 138 hectares, Campo Novo do Parecis, MT

(Adaptado de Eitelwein et al. 2016)

# Calibração: sensores x análises de referência

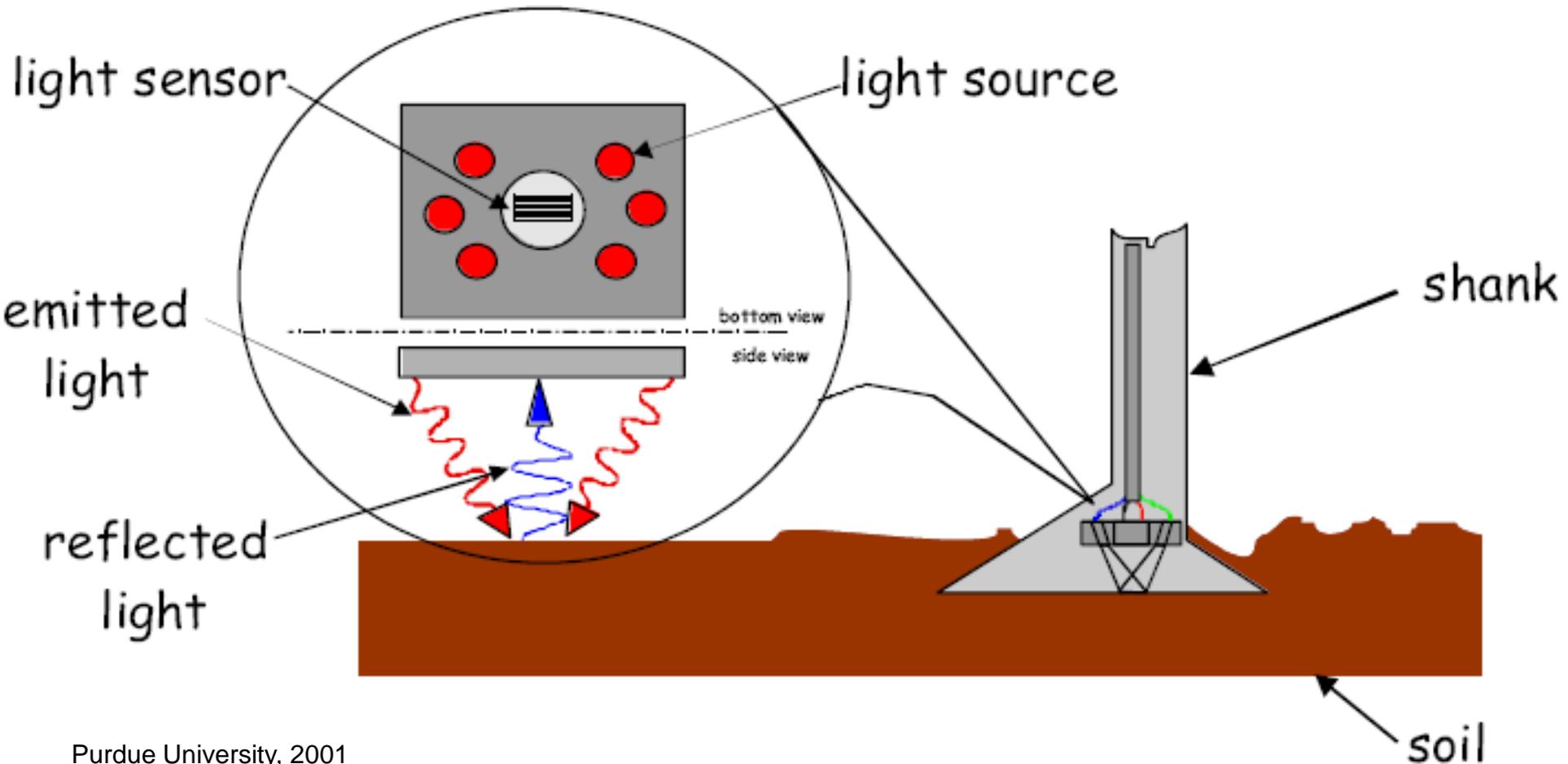


Correlação linear de Pearson entre os resultados das determinações de atributos químicos de 72 amostras de solo analisadas por quatro laboratórios distintos

	P			K			Mg			Ca		
	Lab. 3	Lab. 4	Lab. 1	Lab. 3	Lab. 4	Lab. 1	Lab. 3	Lab. 4	Lab. 1	Lab. 3	Lab. 4	Lab. 1
Lab.2	0,52	0,36	0,32	0,4	0,42	0,29	0,19	0,14	0,04	0,2	0,18	-0,07
Lab. 3		0,92	0,90		0,91	0,87		0,81	0,73		0,67	0,12
Lab. 4			0,92			0,86			0,68			0,01

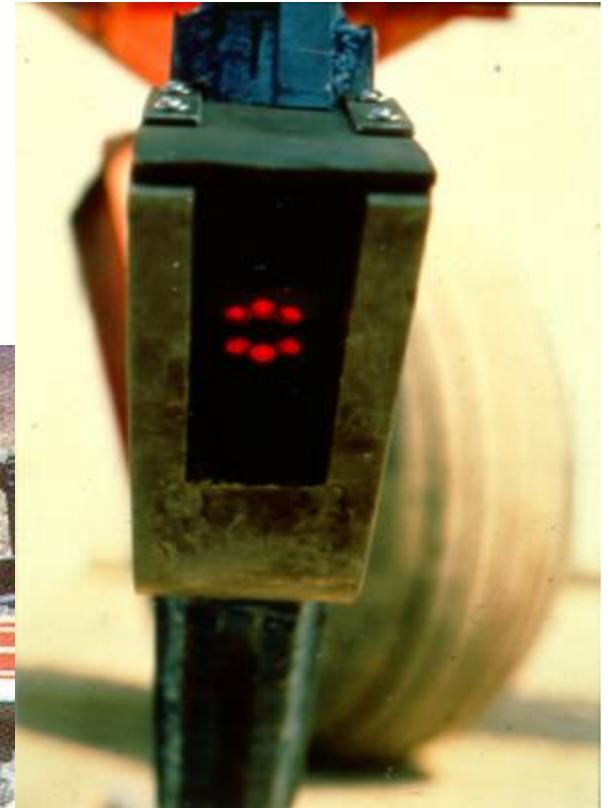
# Sensor de MO

## Cross-Section of the Sensor



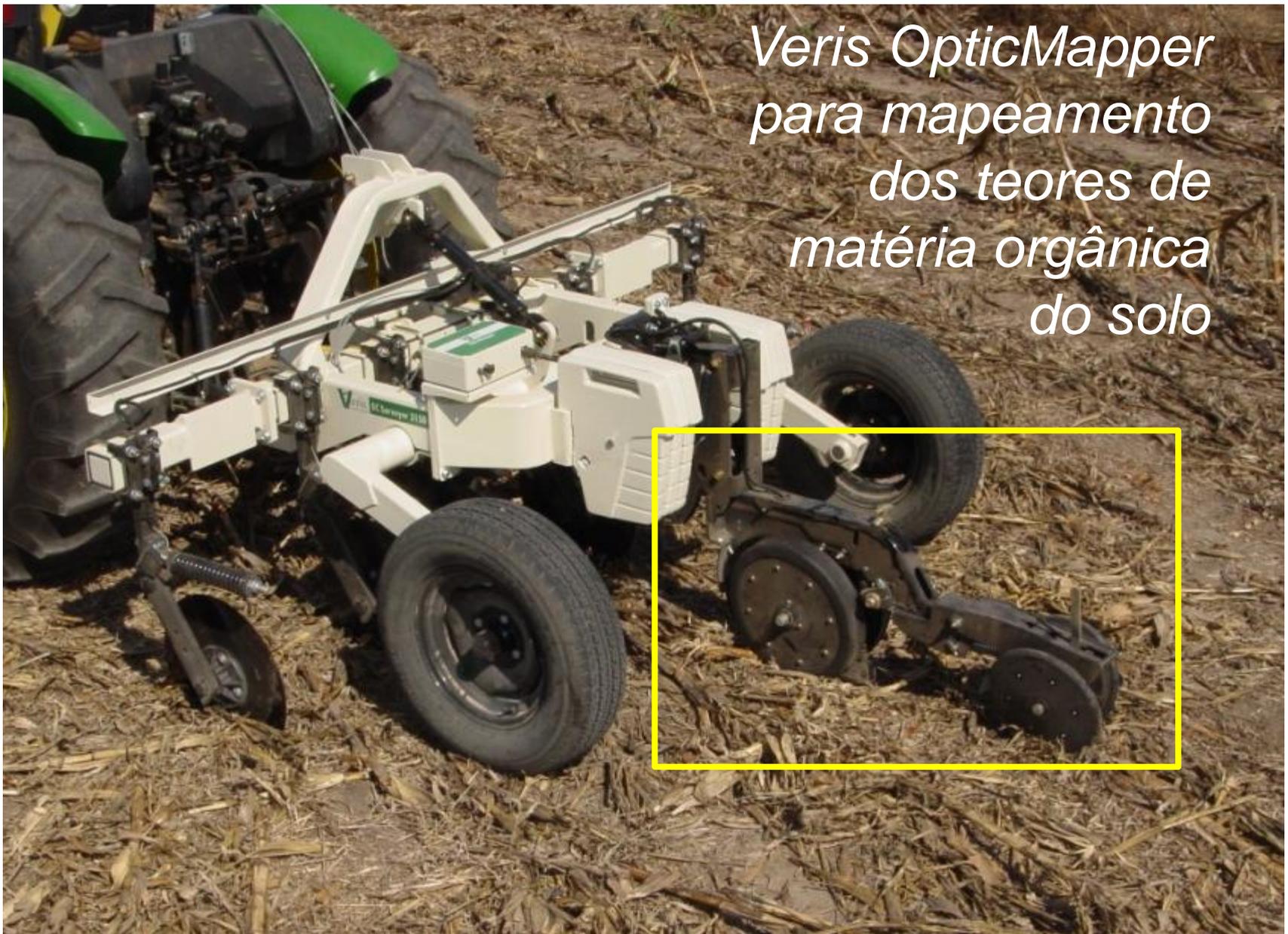
Purdue University, 2001

# Sensor de MO



Anúncios, 1996

*Veris OpticMapper  
para mapeamento  
dos teores de  
matéria orgânica  
do solo*



VerisThecnologie

Number of wavelengths: 2

- Spectral range: visible and near-infrared
  - Light source: LED
- Detector: active area 5.76 mm photodiode



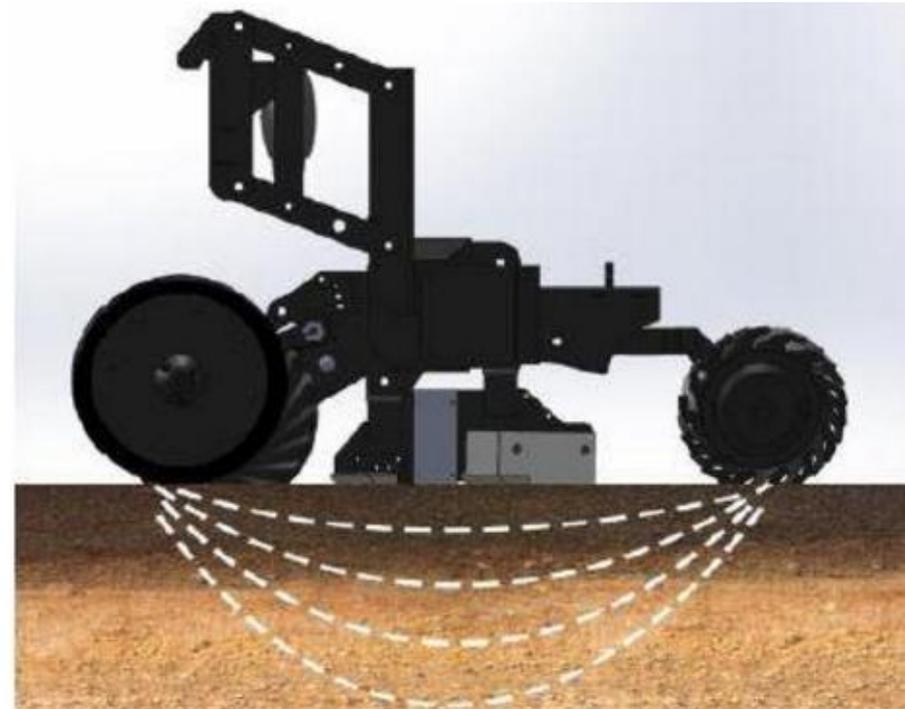
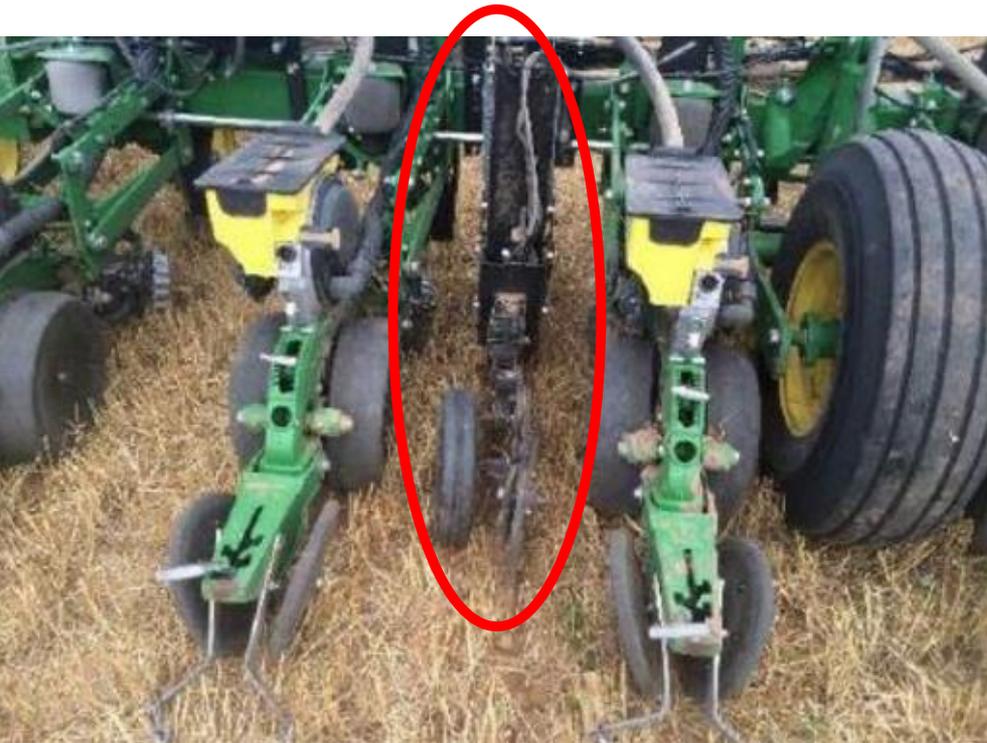
VerisThecnologie



Prof. J. P. Molin

# iScan

Sensor óptico (duas bandas) para estimativa de matéria orgânica, mais sensor de condutividade elétrica



Veris Technologies

SmartFirmer (PrecisioPlanting) - sensor optico para umidade e matéria orgânica, na linha da semeadora, para incisar condições locais e definir população ideal



Agrishow 2019

<http://www.americanagriculturist.com/equipment/hottest-planter-tech-tool-2017>

Tendências:

Raio X e LIBS (laser induced breakdown spectroscopy)

Leitura complementar:



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**REVIEW PAPER**

**SENSOR SYSTEMS FOR MAPPING SOIL FERTILITY ATTRIBUTES: CHALLENGES,  
ADVANCES, AND PERSPECTIVES IN BRAZILIAN TROPICAL SOILS**

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