The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1867-16

College of Soil Physics

22 October - 9 November, 2007

A soil mechanics approach to study soil compaction

Moacir S.Dias Junior
ICTP Senior Associate, Univ. Federal Lavras
Brazil

Universidade Federal de Lavras

The Abdus Salam International Centre for Theoretical Physics

College on Soil Physics - 2007

A soil mechanics approach to study soil compaction

Moacir de Souza Dias Junior, Ph.D

Department of Soil Science
Federal University of Lavras

Senior Associate - International Center for Theoretical Physics – Trieste- Italy
msouzadj@ufla.br

- The sustained use of the soil is related to the preservation of the soil structure.
- The main degradation process of the soil structure is soil compaction.
- The extent of compacted soil is estimated worldwide at 68 million hectares of land from vehicular traffic alone (Oldeman et al., 1991). 33 million ha in Europe (Akker & Canarache, 2001).
- Recover of the soil structure???
  - ⇨10-20 years ⇨shallow compaction (Dickerson, 1976; Jakolbsen, 1991).
  - ⇨ 50-100 years ⇨ subsoil compaction (Greacen & Sands, 1991).

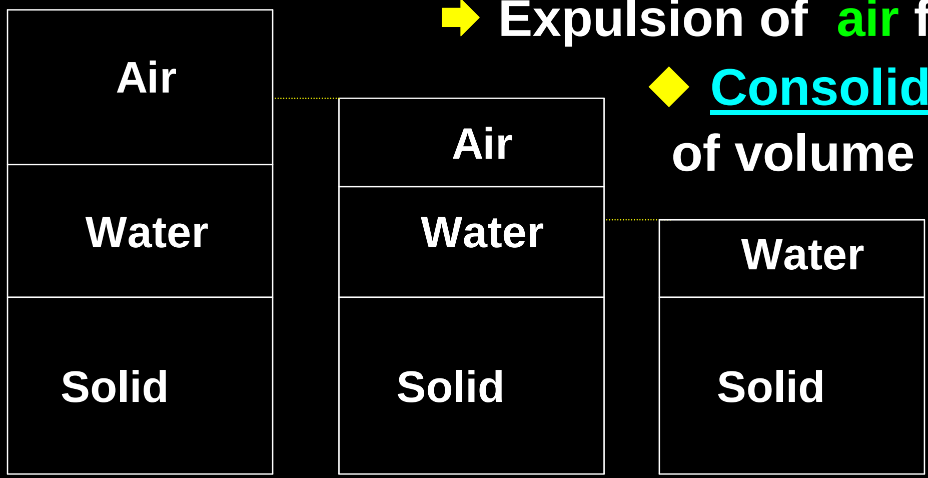
Soil before compaction

◆ Compaction of soil ➡ reduction of volume ➡ Expulsion of air from soil pores.

◆ Consolidation ➡ reduction of volume ➡ expulsion of water from soil pores

⬇

Inadequate management



◆ Consolidation ➡ reduction of volume ➡ pedogenetic processes

(Dias Junior, 2000)

Soil compaction could be caused by the use of different types of machines and vehicles in farm operations

Which might apply pressure larger than the load support capacity of the soil

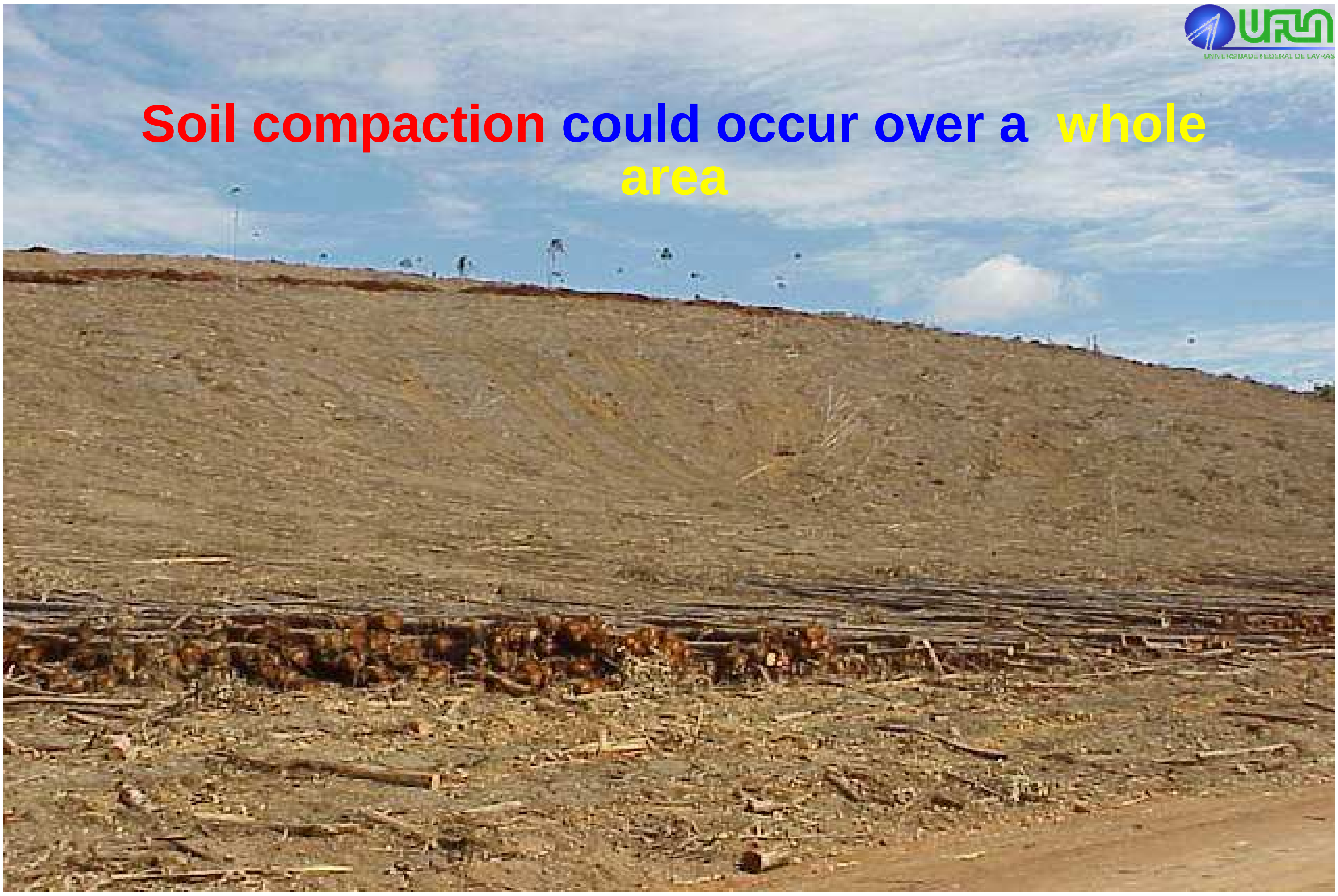
Magnitude of pressures

- **Tractor**
  64 to 380 kPa (Allmaras et al., 1988)
- **Tillage equipment**
  100 kPa (Hillel, 1982)
- **Subsoiler**
  550 kPa (Hillel, 1982)
- **Trampling**
  Human: 190 kPa (Lull, 1959)
  Cattle: 330 kPa (Lull, 1959)

Magnitude of pressure exerted by agricultural machines

Machine/Equipment	Contact pressure/pneu-tack			
	Front		Back	
	Kgf/cm^2	kPa	Kgf/cm^2	kPa
Massey Fergusson Tractor 275 4x2 TDA	2.582	253	2.761	271
Massey Fergusson Tractor 292 4x2 TDA	1.977	194	2.787	273
Massey Fergusson Tractor 299 4x2 TDA	2.723	267	2.787	273
John Deere Tractor 6405 4x2 TDA	2.582	253	2.336	229
John Deere Tractor 7500 4x2 TDA	1.977	194	2.206	216
New Holland Tractor TM 150 4x2 TDA	3.155	309	3.699	363
Automaticlly Propelled Pulverizer Max Sistem Plat. 290 4x2 TDA	3.247	318	3.391	332
Automatically Propelled Max Sistem Plat. 6600 4x2 TDA	3.236	317	2.766	271
Automaticlly Propelled Pulverizer UNIPORT Jacto 4x2	4.127	405	4.606	452
Combine Harvester for Cereals Massey Fergusson 5650 4x2	3.386	332	3.218	316
Combine Harvester for Cereals John Deere 1175 4x2	3.695	362	2.879	282
Combine Harvestr for Cotton John Deere 9935 4x2	3.484	342	3.041	298

Source: Cardoso, 2007


Soil compaction could occur over a whole area
UFLA
UNIVERSIDADE FEDERAL DE LAVRAS


UFLA
UNIVERSIDADE FEDERAL DE LAVRAS
Compaction in specific places / location
Photo: S.R. Silva


UFLA
UNIVERSIDADE FEDERAL DE LAVRAS
Compaction in specific location
Photo: S.R. Silva


UFLA
Compaction in specific locations
Photo: S.R. Silva

Depth of furrrow in the soil following farm operation with a Forwarder with Tires or Track

Soil Class		Number of passes of Forwarder		
		8	16	40
		Depth of Furrow (cm)		
PAd2	Tires	11	14	18
	Tracks	11	13	15
PAd3	Tires	14	18	26
	Tracks	12	15	20

Depth of furrrow in the soil following farm operation with a Forwarder with Tires or Track

Soil Class		Number of passes of Forwarder		
		8	16	40
		Depth of Furrow (cm)		
PAd2	Tires	11	14	18
	Tracks	11	13	15
PAd3	Tires	14	18	26
	Tracks	12	15	20

Grigal (2000)

Light disturbance – shallow depression

Moderate disturbance – furrows with depth from 5 to 8 cm

Heavy disturbance – furrows with depth from 10 to 15 cm

Due to that

Soil compaction has been identified as the main process causing soil degradation

(Canillas & Salokhe, 2002, Horn et al., 2003).

Reducing soil produtivity

Therefore , it is important to avoid the harmful effect of soil compaction

Negative effects of soil compaction

➔ Increases bulk density (Arvidson, 2001; Ishaq et al., 2001)

Project	BD Before traffic	F+S 30	F+S 66	H+F	M+F	F+C	M+M	Proc. Area
	$Mg\ m^{-3}$	Dry Season (% of increase)						
Buriti	1.02	1	0	7	-	-	-	-
Dourado	0.92	5	5	8	-	-	-	-
S. Leonardo	1.04	8	4	8	-	-	-	-
		Rainy Season (% of increase)						
Imbaúbas	1.01	22	-	21	11	-	-	34
Água Suja	1.13	13	-	-	21	6	1	26
Cajá Ba.	1.29	15	-	-	22	18	7	26

F+S 30 = Feller Büncher and Skidder narrow tires; F + S 66 = Feller Büncher and Skidder wide tires; H+F = Harvester and Forwarder; M+F = Manual and Forwarder; F+C = Feller Büncher and Clambunk; M+M = Motorized saw + Manual ; Proc. Area = Processing Area

Negative effects of soil compaction

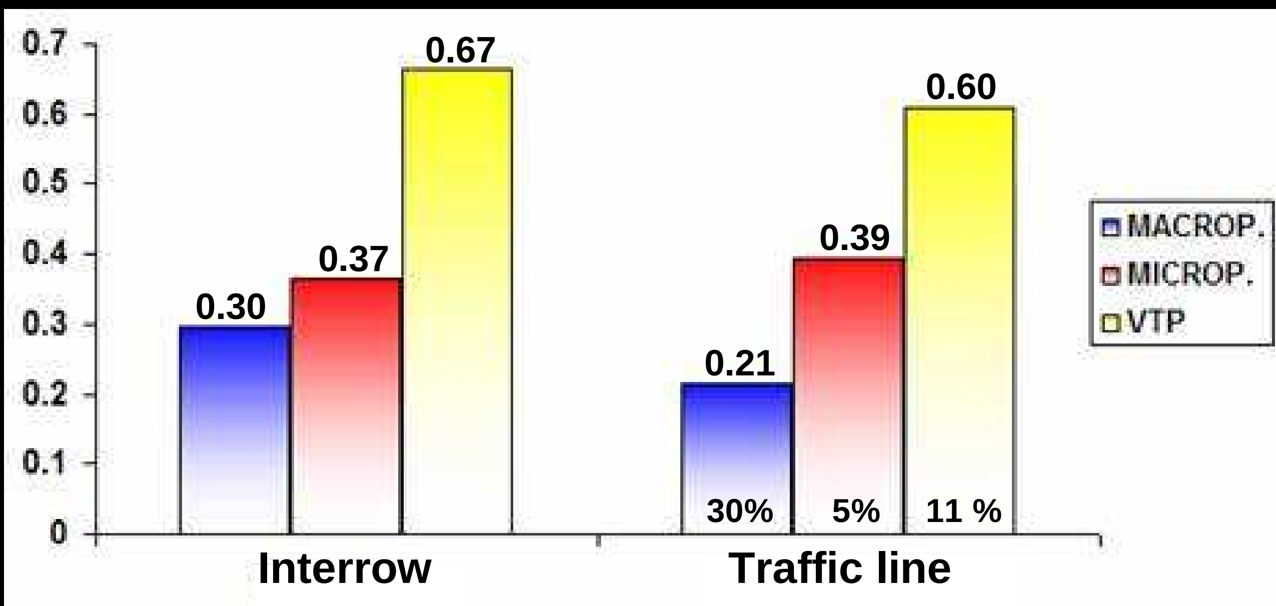
➔ Decreases total porosity, size and continuity of the pores (Servadio et al., 2001)

Project	TP Before traffic (%)	F+S 30	F+S 66	H+F	M+F	F+C	M+M	Proc. Area
		Dry Season (% of decrease)						
Buriti	61	0	0	3	-	-	-	-
Dourado	64	3	3	5	-	-	-	-
S. Leonardo	58	7	3	7	-	-	-	-
		Rainy Season (% of decrease)						
Imbaúbas	58	16	-	16	9	-	-	24
Água Suja	56	11	-	-	18	5	0	20
Cajá	51	16	-	-	28	18	8	25

F+S 30 = Feller Büncher and Skidder narrow tires; F + S 66 = Feller Büncher and Skidder wide tires; H+F = Harvester and Forwarder; M+F = Manual and Forwarder; F+C = Feller Büncher and Clambunk; M+M = Motorized saw + Manual ; Proc. Area = Processing Area

Negative effects of soil compaction

▶ Decreases total porosity and macroporosity

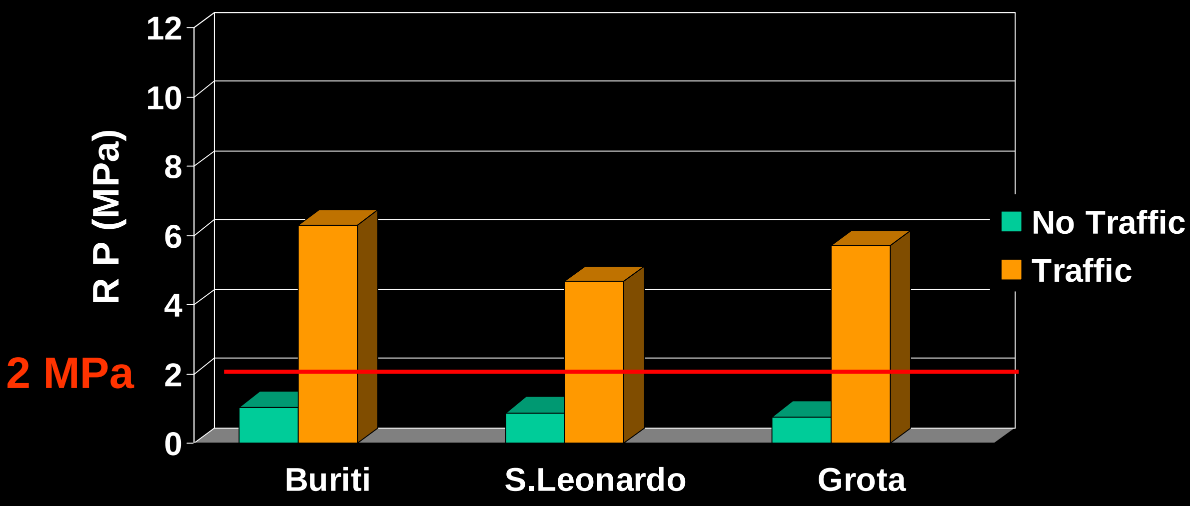


Valmet 785

(Gontijo, 2007)

Nagative effects of soil compaction

➔ **Increase the penetration resistance of soils (Arvidson, 2001; Ishaq et al.,2001).**



Negative effects of soil compaction

➔ **Reduction in soil aeration (Gysi, 2001)**

Negative effects of soil compaction

➔ Increase in required energy for soil preparation (Stone, 1987)

Negative effects of soil compaction

➔ Alteration of soil structure and the place where roots develop

Negative effects of soil compaction

➔ Reduces water **infiltration** (Defossez & Richard, 2002)

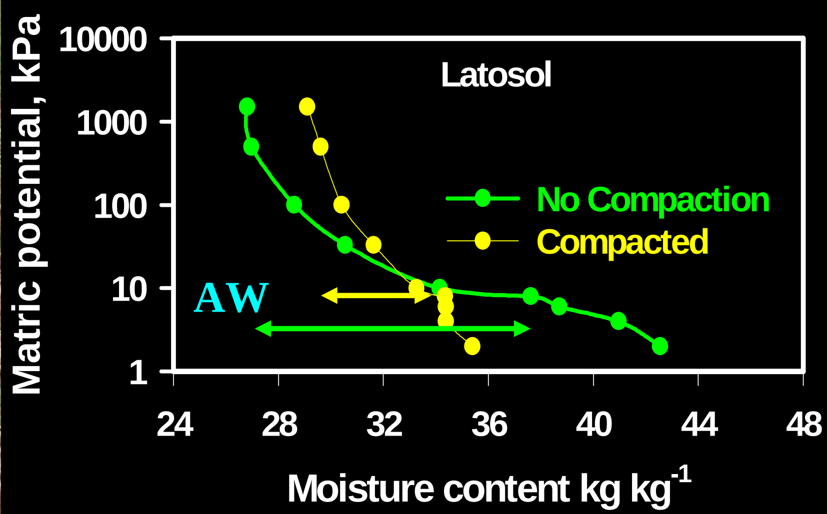
Project	IR Before traffic (mm/hr)	F+S	H+F	M+F
			% of reduction	
Buriti	148	80	86	77
Dourado	105	86	84	-
S. Leonardo	103	80	86	76
Imbaúbas	155	100	100	100
Aeroporto	180	90	91	90

F+S = Feller Büncher and Skidder narrow tires; H+F = Harvester and Forwarder; M+F = Manual and Forwarder.

Negative effects of soil compaction

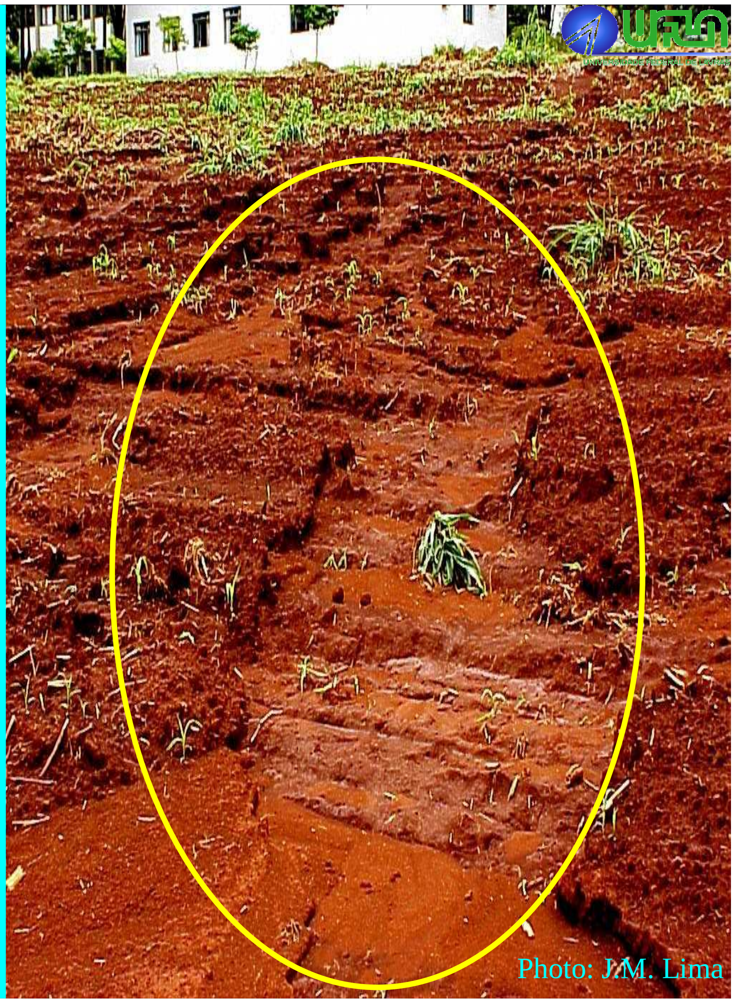
➔ Reduction of **internal drainage** and the **redistribution of soil water** (Hillel, 1982)

➔ Reduction of **available water** (Ishaq et al., 2001)



Negative effects of soil compaction

➔ Increase in surface runoff (Defossez & Richard, 2002); and the risk of erosion (Dias Junior, 2000).

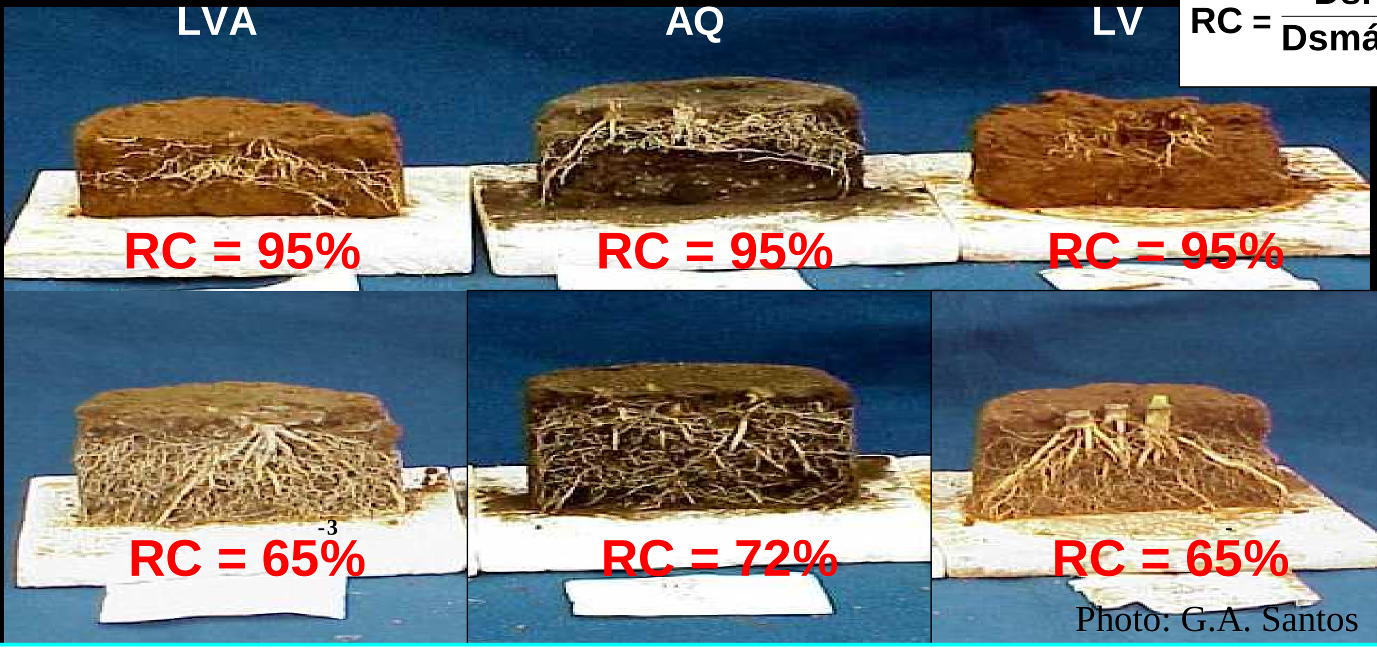


Negative effects of soil compaction

➔ Restriction of root development /penetration due to:

✶ The pressure of root growth is insufficient to overcome the mechanical resistance of the soil (Veen, 1982)

$$RC = \frac{Dsi}{Dsmáx}$$



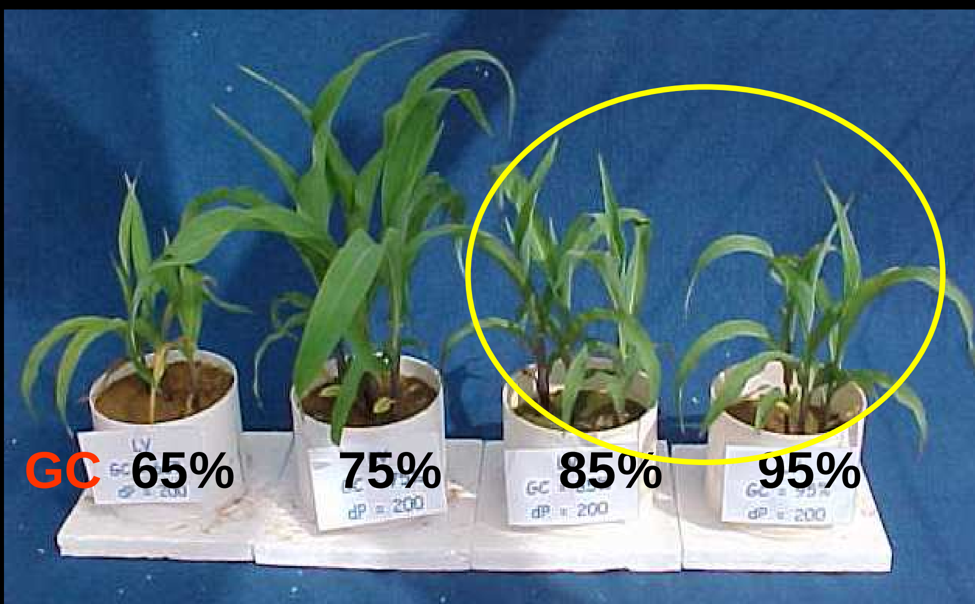
Negative effects of soil compaction

Negative effects of soil compaction

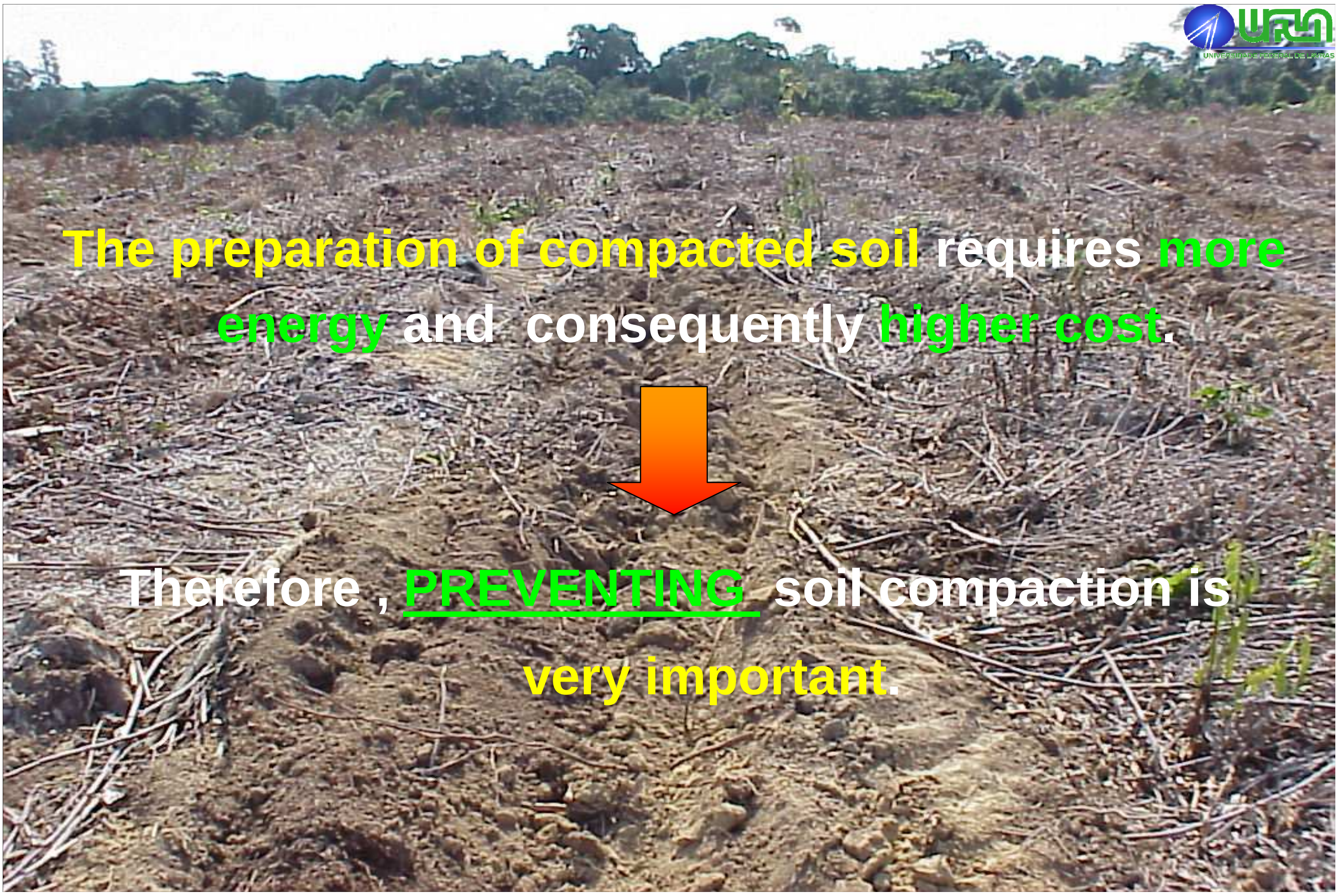
✶ High water content in the soil and its associated insufficient avaialable oxygen for respiration by the roots (Lemon & Wiegand, 1962).

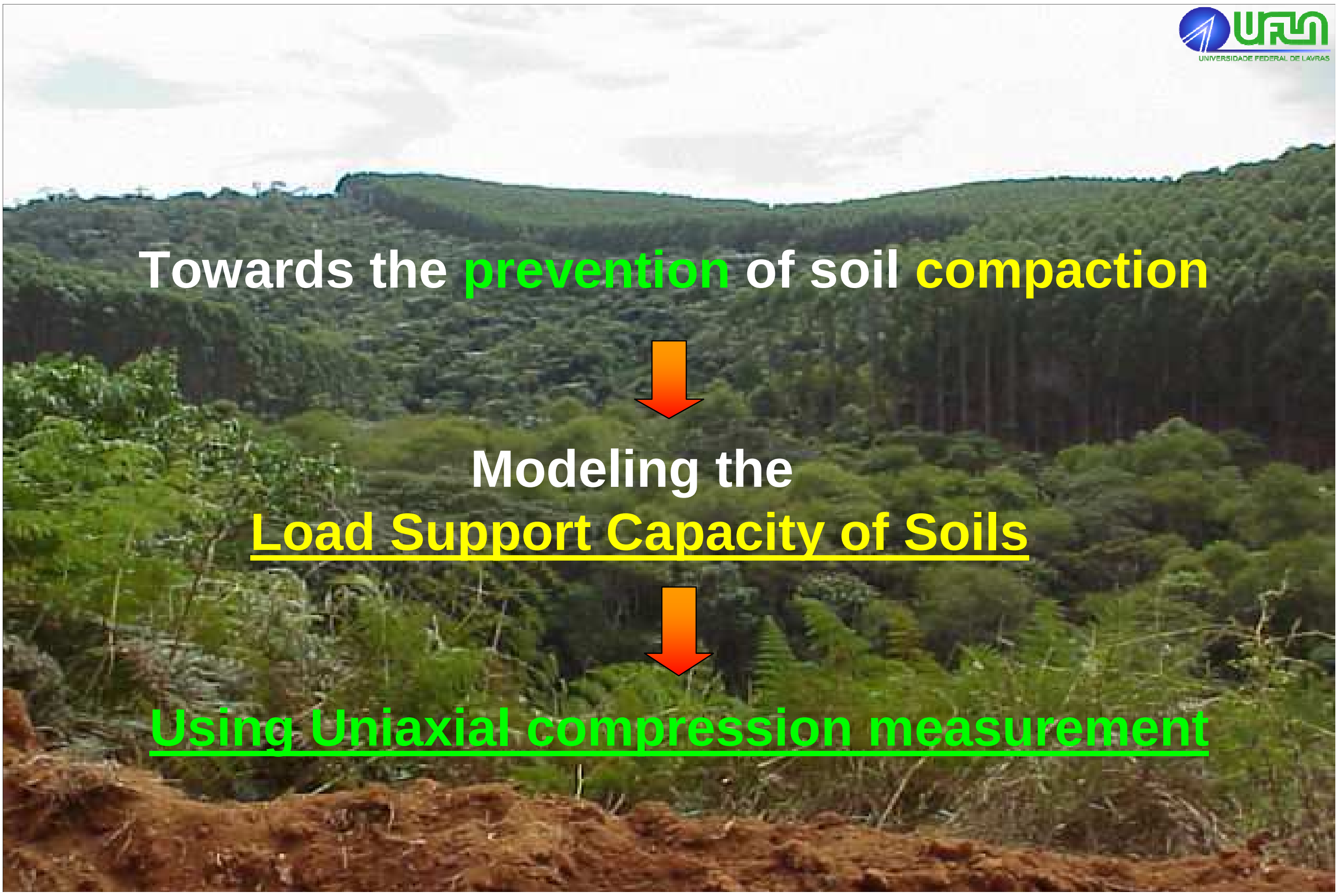
Negative effects of soil compaction

➔ the restriction of root growth could lead to reduction in productivity due to limitation in water uptake and absorption of necessary nutrients (Santos, 2001)



➔ **Therefore** , when soil compaction happens, it is necessray **to break the compacted layer,** softening the soil, for **improved** growth of plants. This could be achieved by **tillage** and **subsoiling**.





Methodology Development

Collection of undisturbed samples:
- Uhland Sampler
- Cylindrical ring


Foto: C. F. Araujo Junior & B. S. Pires

Methodology Development

Fotos: C. F. Araujo Junior & B. S. Pires

Methodology Development

Methodology Development

- ✓ **Trim the excess soil sample to ring size;**
- ✓ **The volume of soil corresponds to the volume of the ring;**
- ✓ **Record the information of the samples, this include: Project description, sample number and other details about the sample;**

Methodology Development

Saturate the samples by capillary by placing them in water in a bowl (about 2/3 of the ring height) for 24 h;

Methodology Development

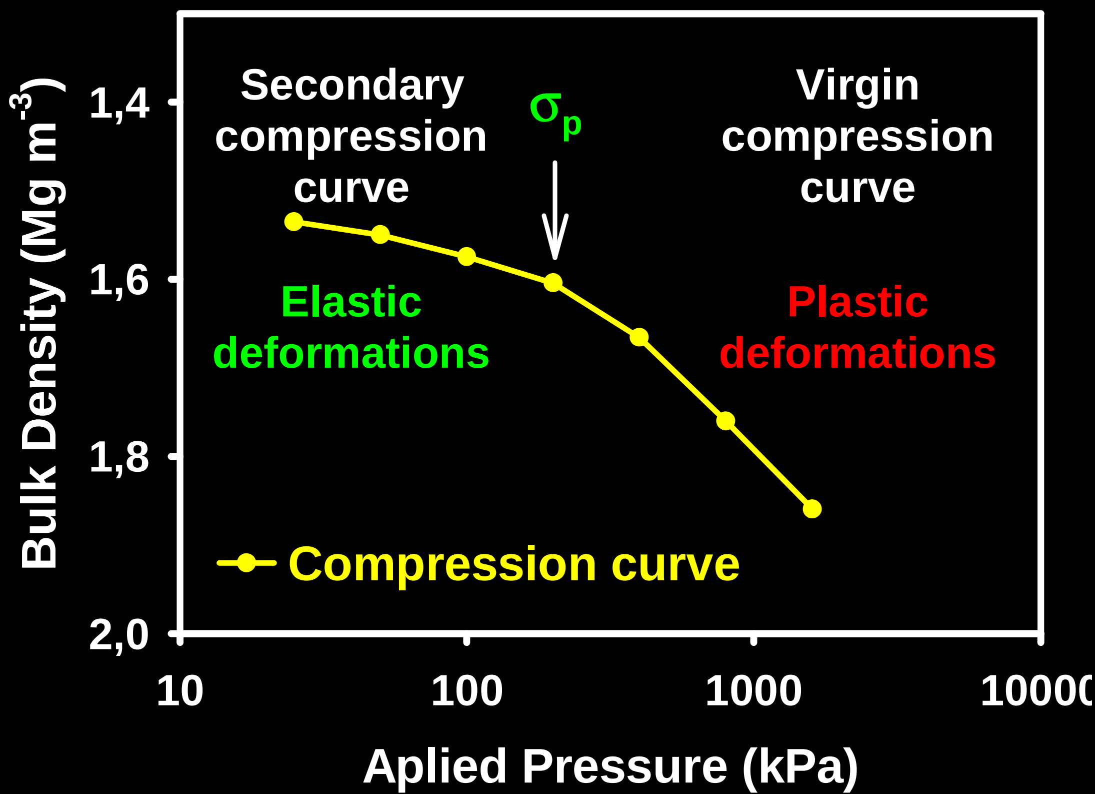
Air-dry the samples in the laboratory until the desired moisture content is obtained

Methodology Development

- **Before the uniaxial compression test, take note of the mass of the sample + ring;**
- **Submit the undisturbed soil samples equilibrated to different moisture contents or matric potentials to uniaxial compression (Bowles, 1986);**

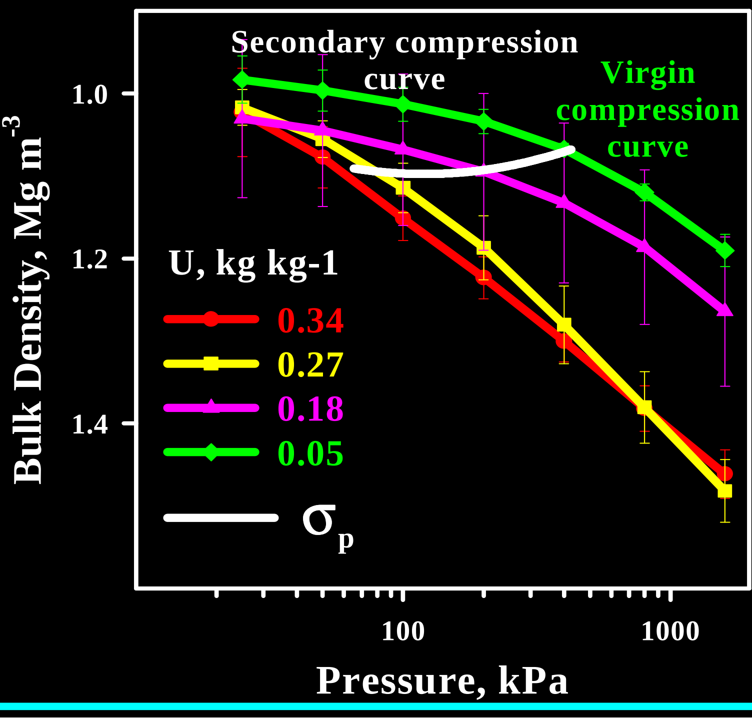
Uniaxial Compression Test

- Consolidometer (Boart Longyear).
- Undisturbed soil samples.
- Applied pressures :
  - ⇨ 25, 50, 100, 200, 400, 800 e 1.600 kPa.
- Samples partially saturated.
- Pressure applied until 90% of maximum deformation is achieved (Taylor, 1948).



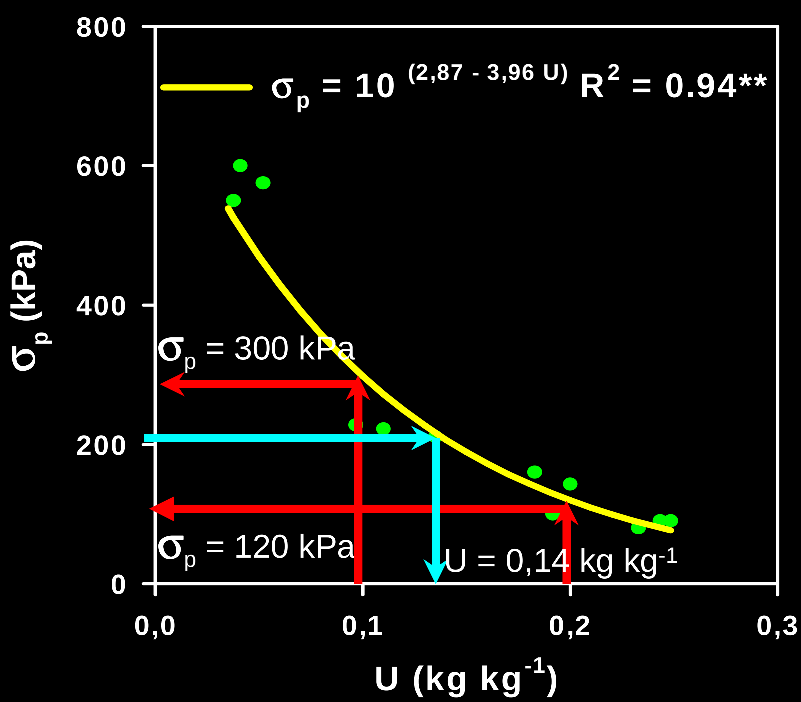
Soil compression curves were used to evaluate soil compressibility

- Preconsolidation pressure - estimation of the Load Support Capacity.
- Dry soils have ↑ σ_p - compaction is not important;
- Wet soils have ↓ σ_p - soil is vulnerable to soil compaction.



Bearing Capacity Model

It is used to determine the load support capacity of the soil as a function of the moisture content.

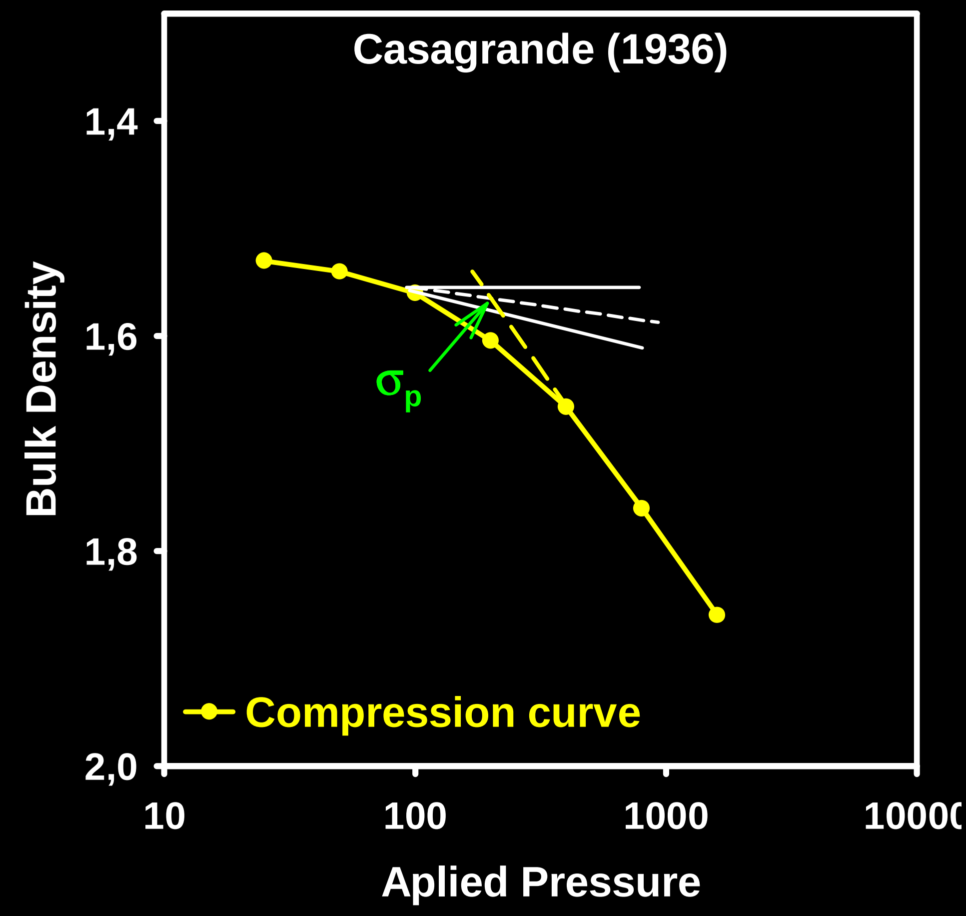


General Considerations

- For a specific soil condition, the proposed Bearing Capacity model accounts for soil management history in terms of preconsolidation pressure as a function of moisture content.
- Preconsolidation pressure ⇨ estimation of the Load Support Capacity of unsaturated soils.

Problem

- ➔ How to determine in a fast way the preconsolidation pressure?
- ➔ Most used method in soil mechanics:
  - ◆ Casagrande (1936) - graphical procedure.



Dias Junior & Pierce (1995)

Pressão	Log Pressão	Ds	Ds R Virgem	Ds regressão
25	1.3979	1.3905	1.2897	1.3845
50	1.6990	1.4444	1.3825	1.4502
100	2.0000	1.5097	1.5160	1.5160
200	2.3010	1.5878	1.5681	1.5817
400	2.6021	1.6712	1.6609	1.6474
800	2.9031	1.7537	1.7537	1.7131
1600	3.2041	1.8465	1.8465	

Method 1 (Suction <= 100 kPa)

σ_p = 151 kPa

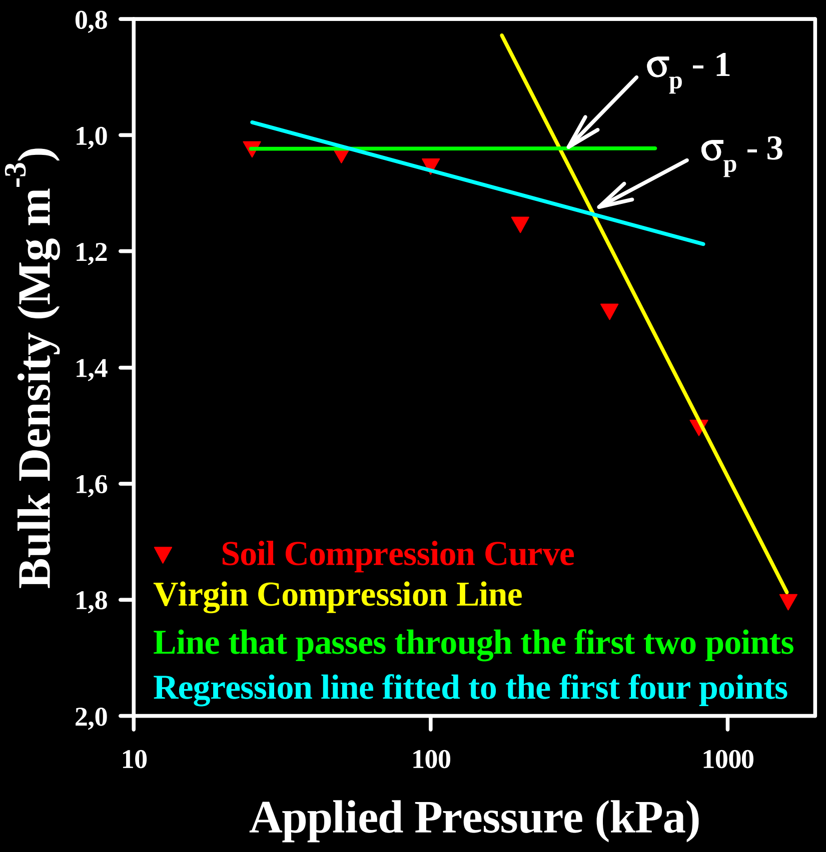
Ds = 1.53 Mg m^{-3}

Method 3 (Suction > 100 kPa)

σ_p = 238 kPa

Ds = 1.61 Mg m^{-3}

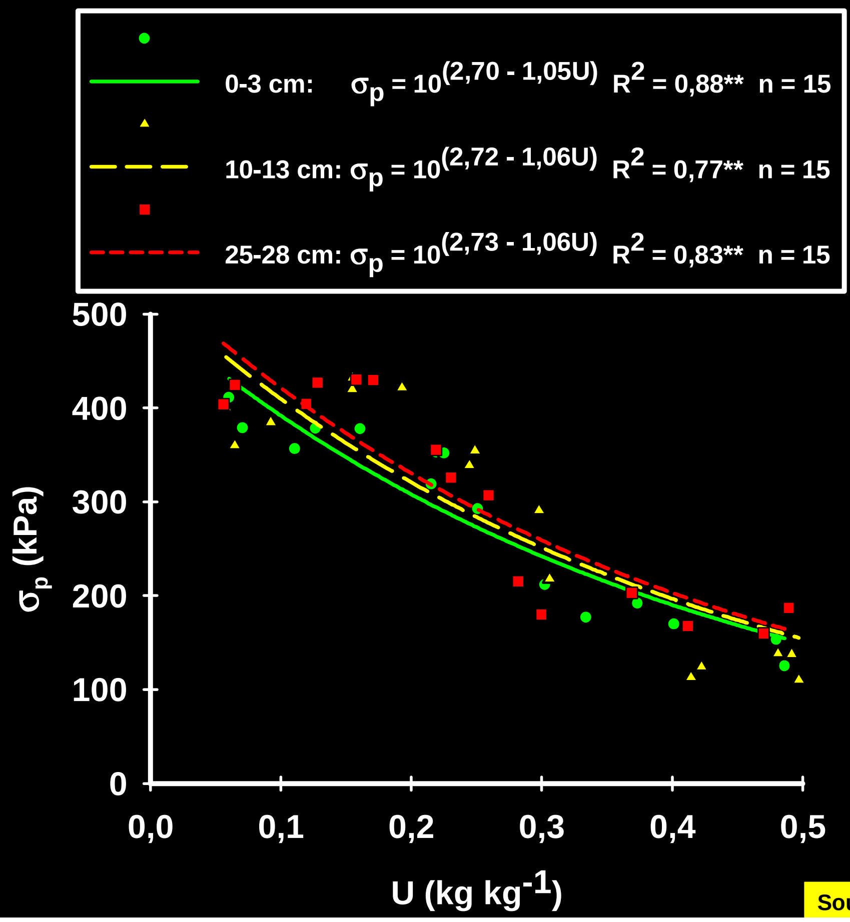
Computer Screen



Statistical Method

Snedecor & Cohran (1989)

Load support capacity model of a soil at 3 depths



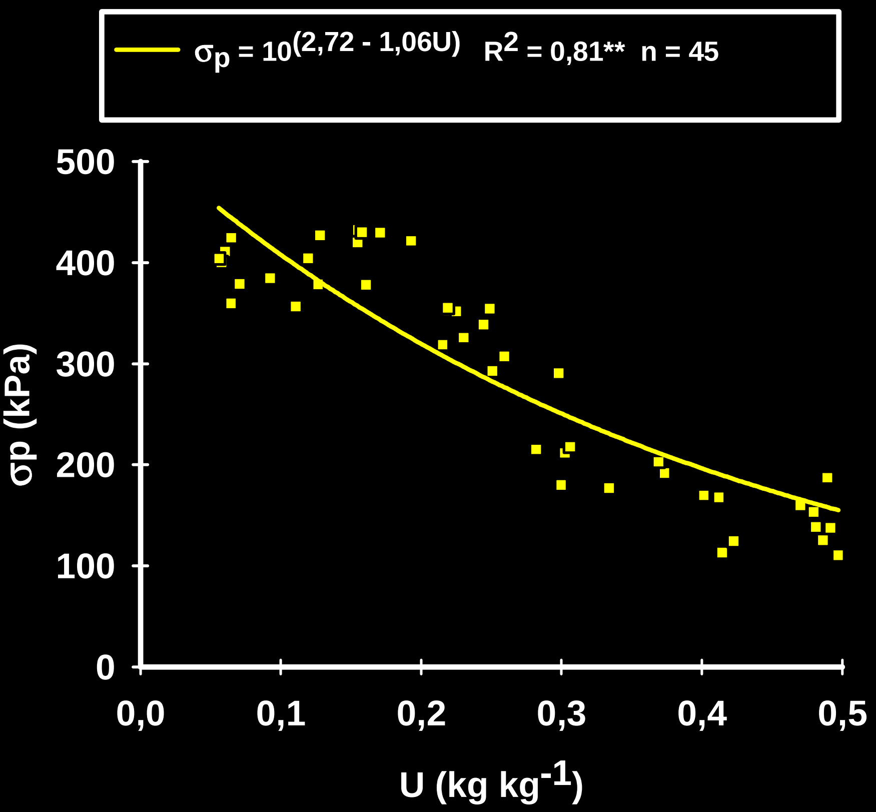
Source: C.F. *Araujo Junior, 2007*"

Homogeneity test as described by Snedecor & Cochran (1989)

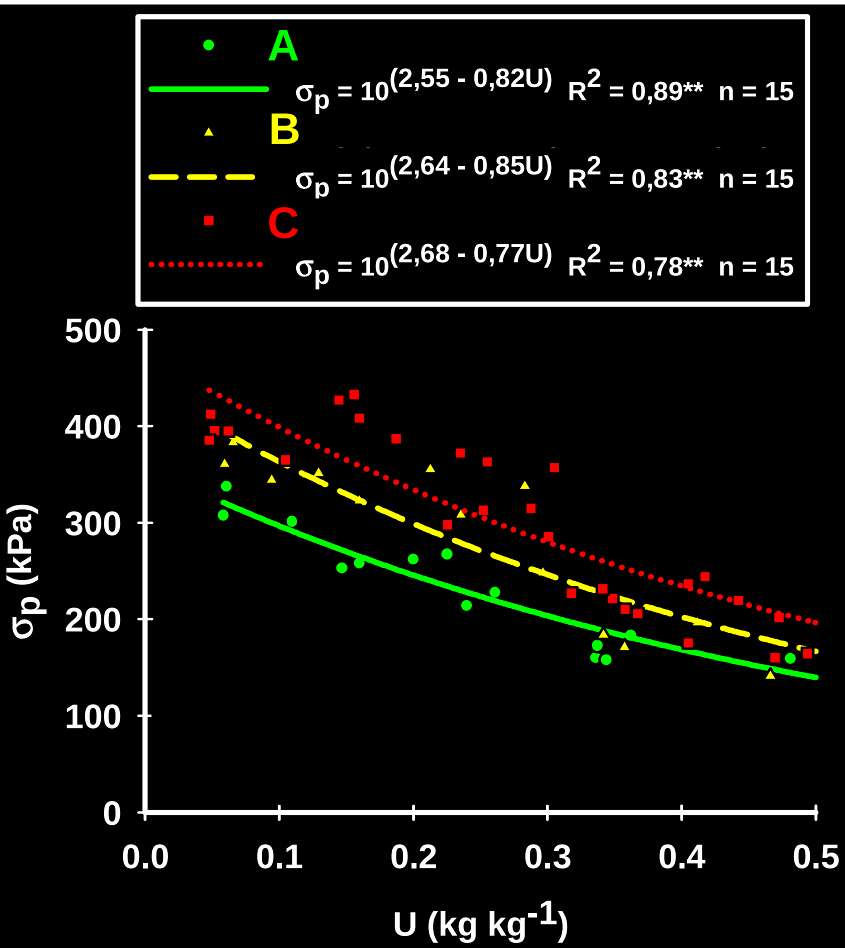
Management	Depth (cm)	F	F: Angular Coefficient, b	F: Linear Coefficient, a
A	0 a 3 vs 10 a 13	H	ns	ns
A	0 a 3 e 10 a 13 vs 25 a 28	H	ns	ns

Source: C.F. *Araujo Junior, 2007*"

Load support capacity model of the soil



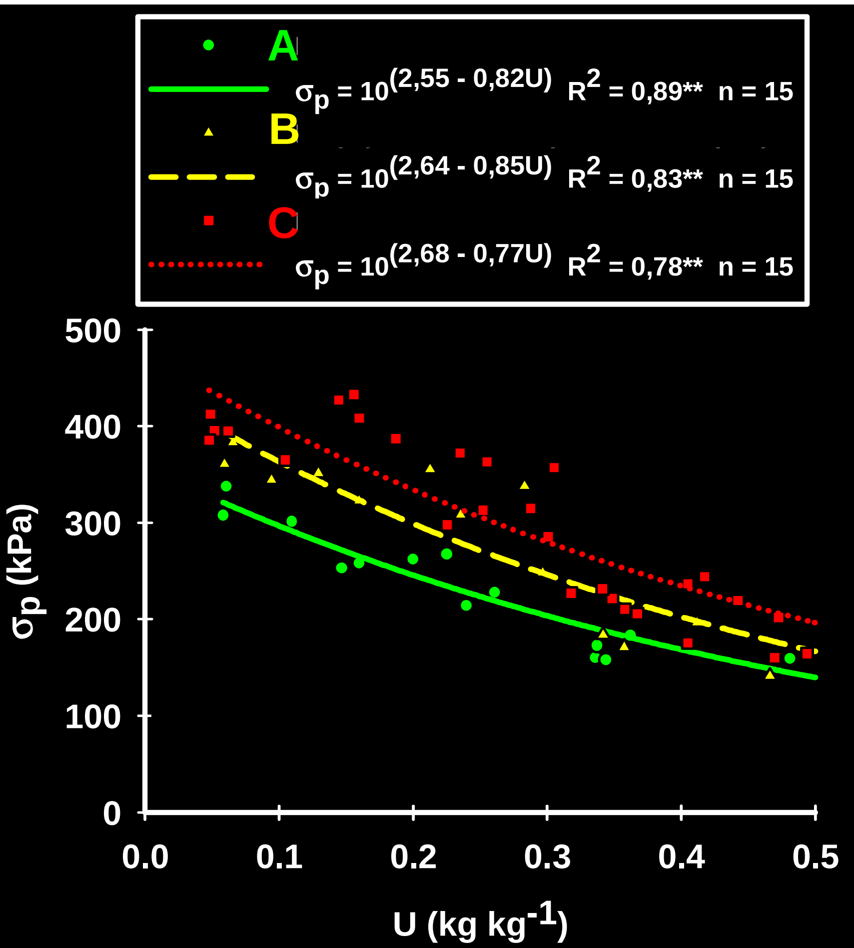
Source: C.F. *Araujo Junior, 2007*"



Source: C.F. *Araujo Junior, 2007*"

Homogeneity test as described by Snedecor & Cochran (1989)

Management	F	F	
		Angular coefficient, b	Linear coefficient, a
A vs B	H	**	ns
A vs C	H	ns	**
B vs C	H	ns	**



Source: C.F. *Araujo Junior, 2007*"

Application of the Load Support Capacity model in practical environmental problems

To evaluate the efficiency of the subsoiling operations

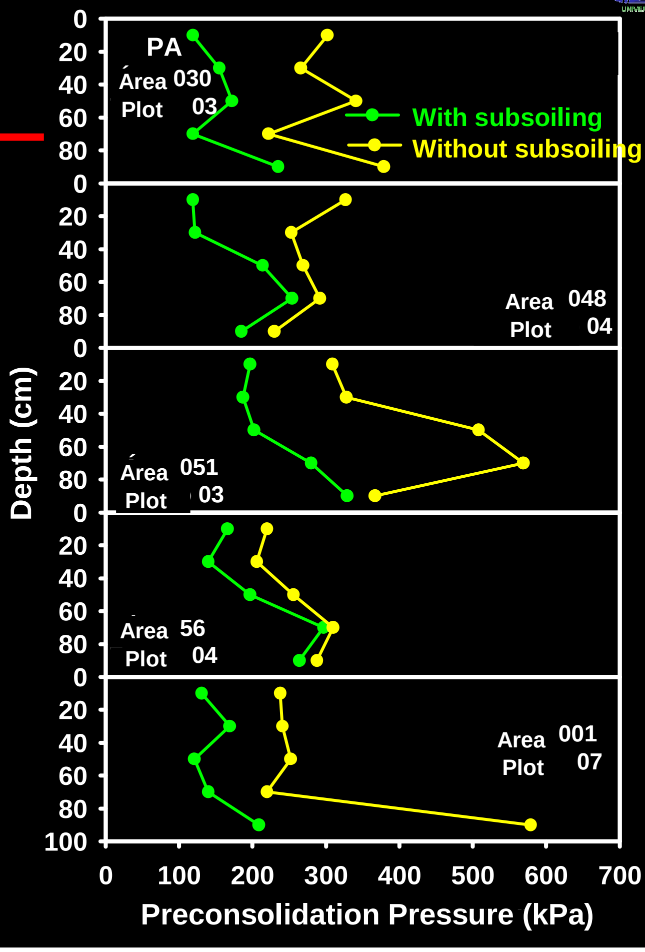
Römkens & Miller (1971)

⬇

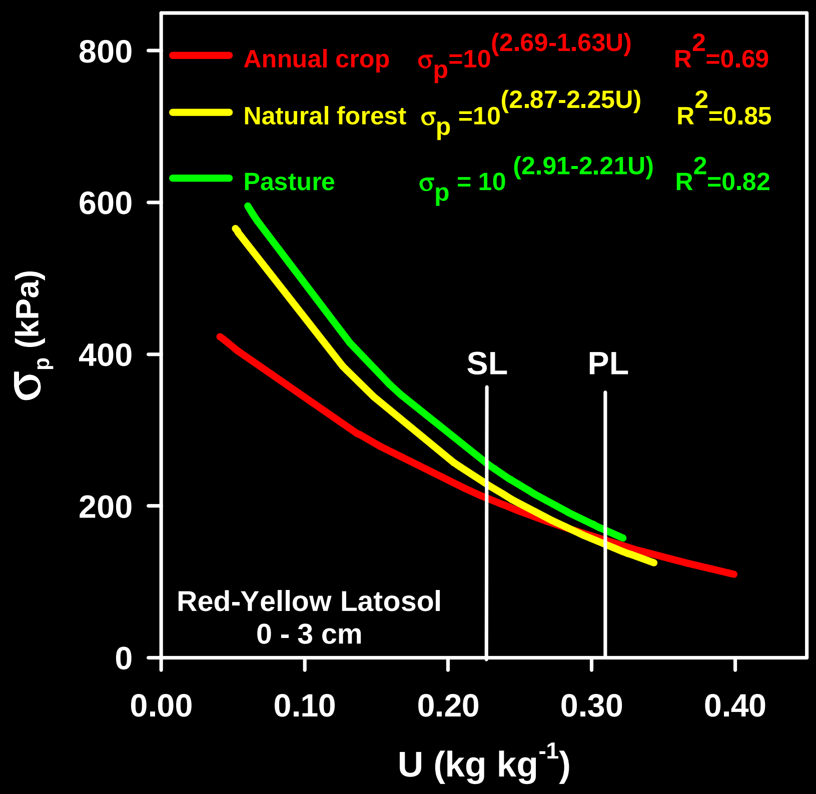
Preconsolidation Pressure

⬇

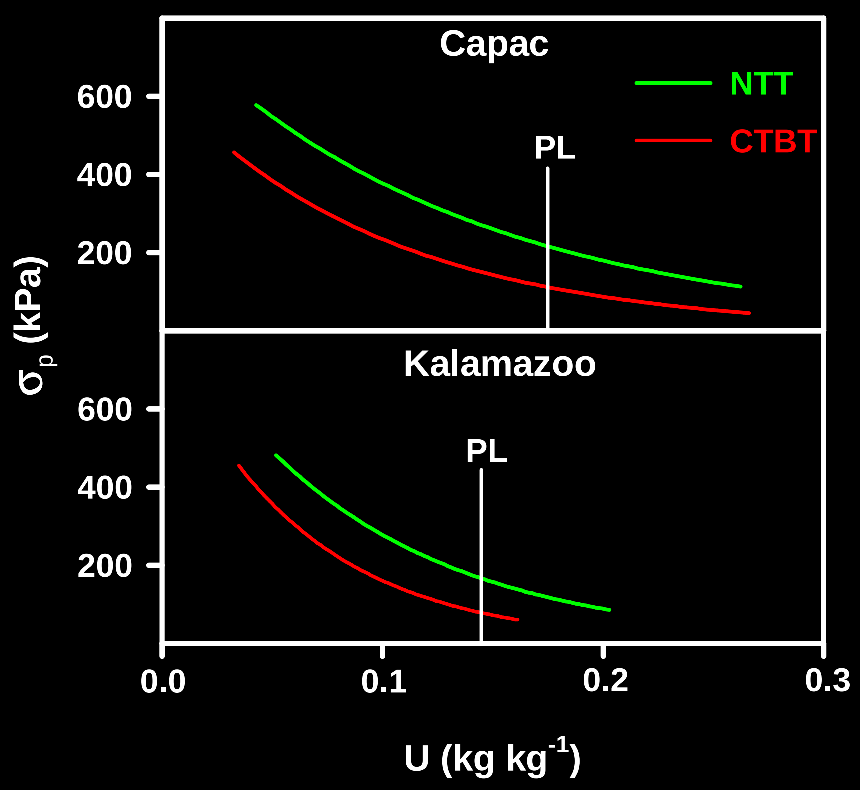
Estimation of the resistance of soil to the growth and elongation of roots



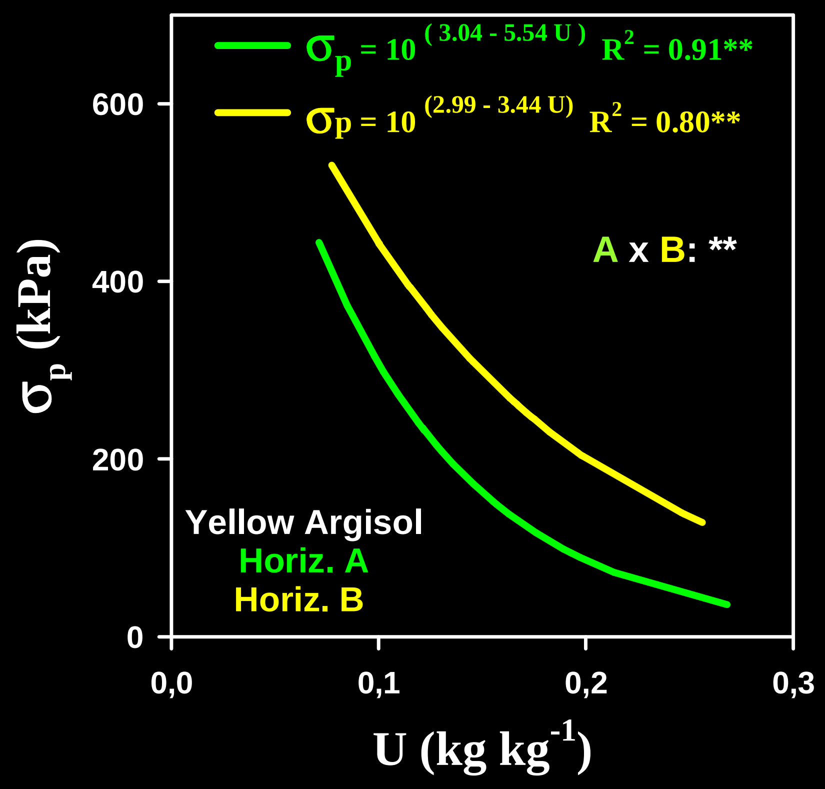
Identification of the management more susceptible and resistant to soil compaction



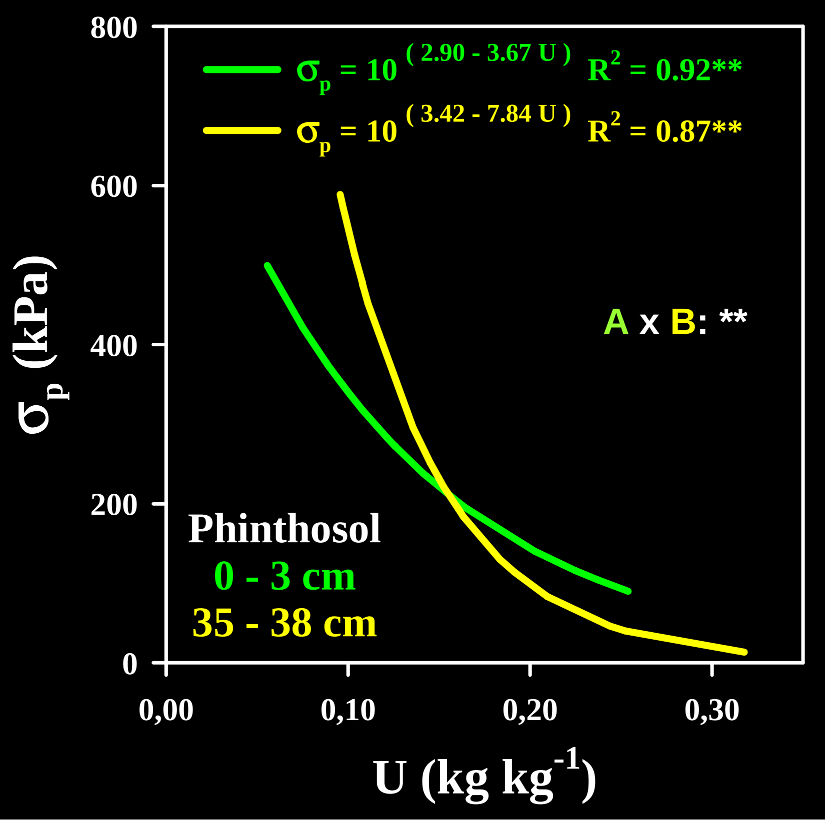
Identification of the management more susceptible and resistant to soil compaction



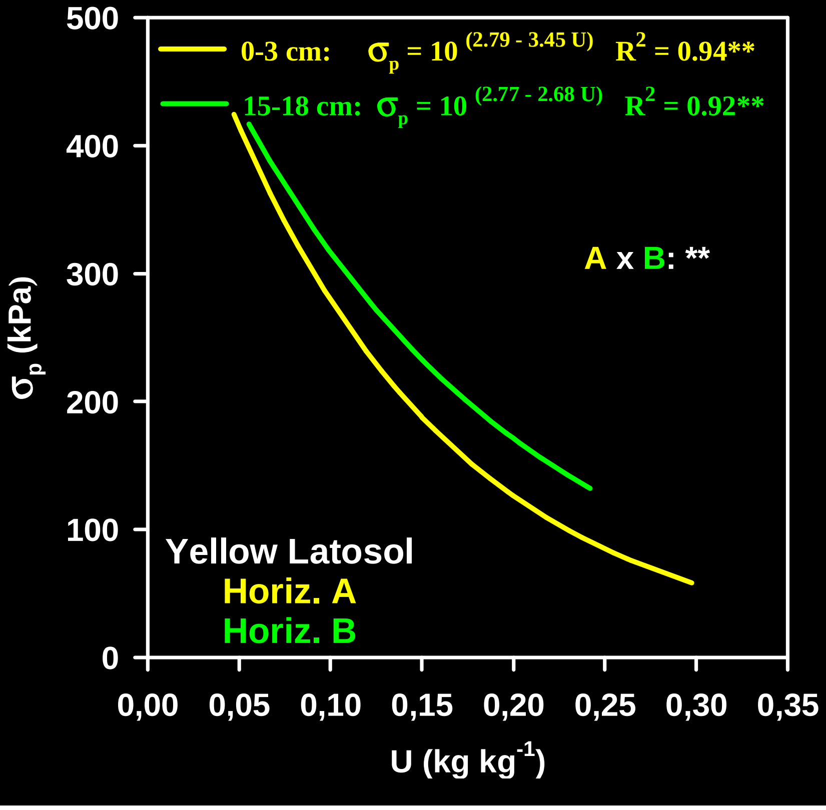
Identification of the soil horizon that may limit root growth



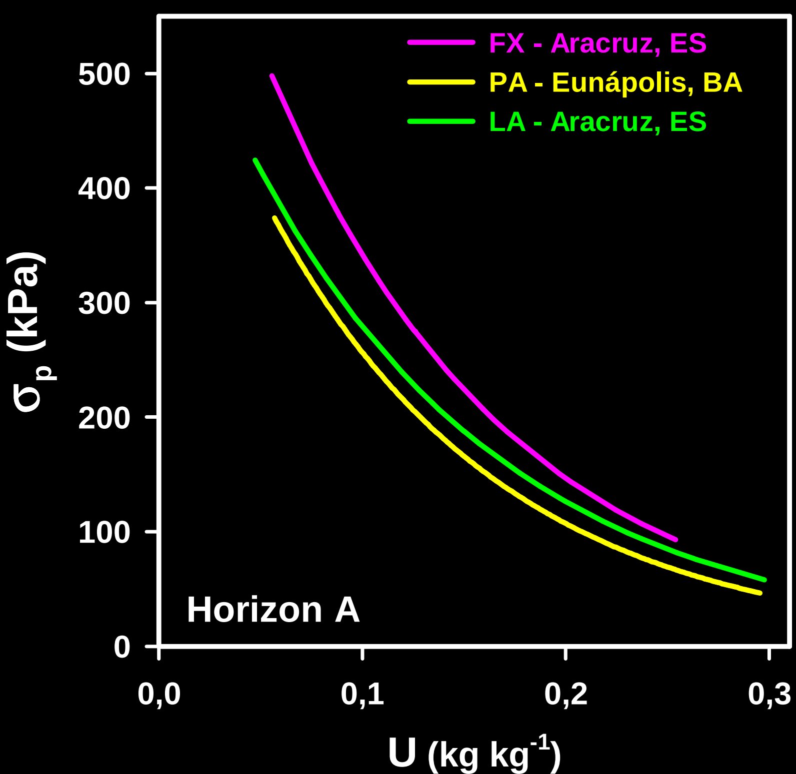
Identification of the soil horizon that may limit root growth



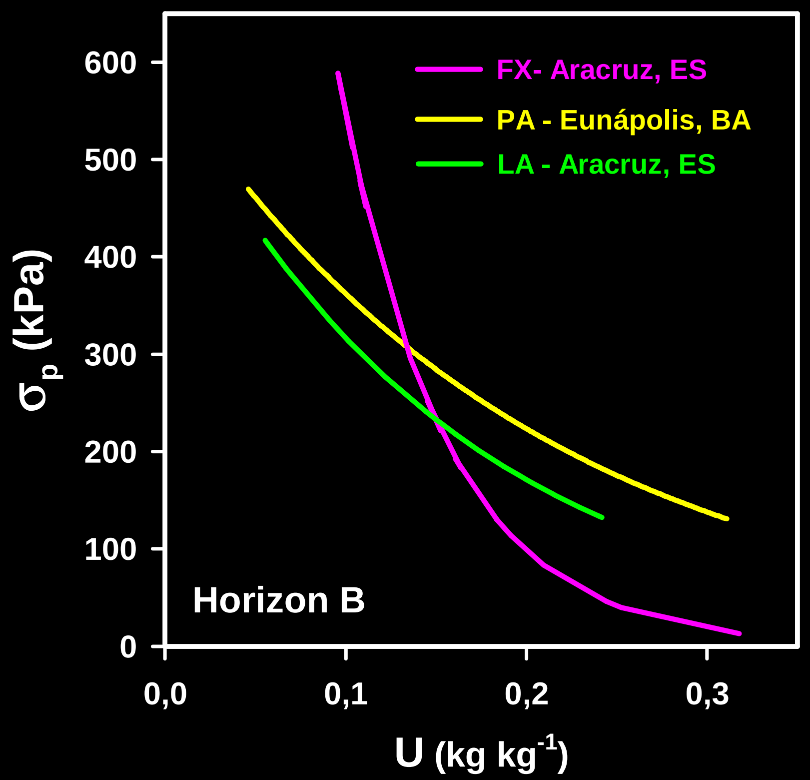
Identification of the soil horizon that may limit root growth



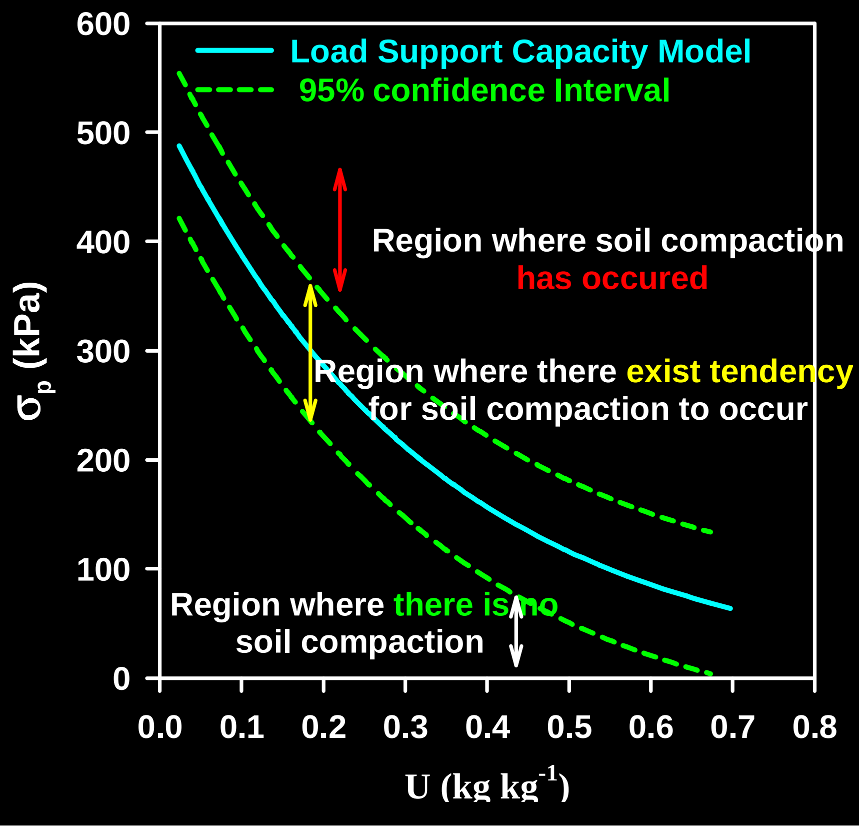
Identification of the soil class more susceptible and resistant to soil compaction



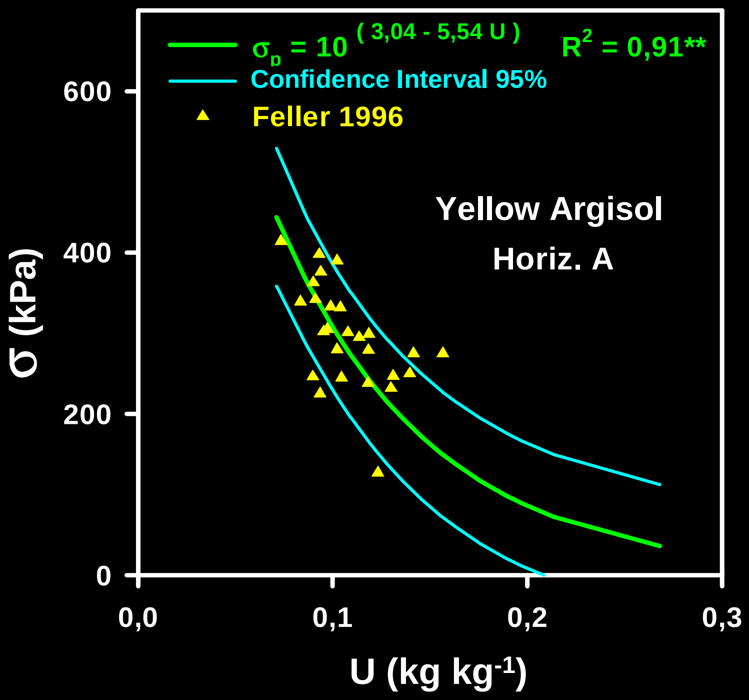
Identification of the soil class more susceptible and resistant to soil compaction



Identification of mechanical operation that causes soil compaction

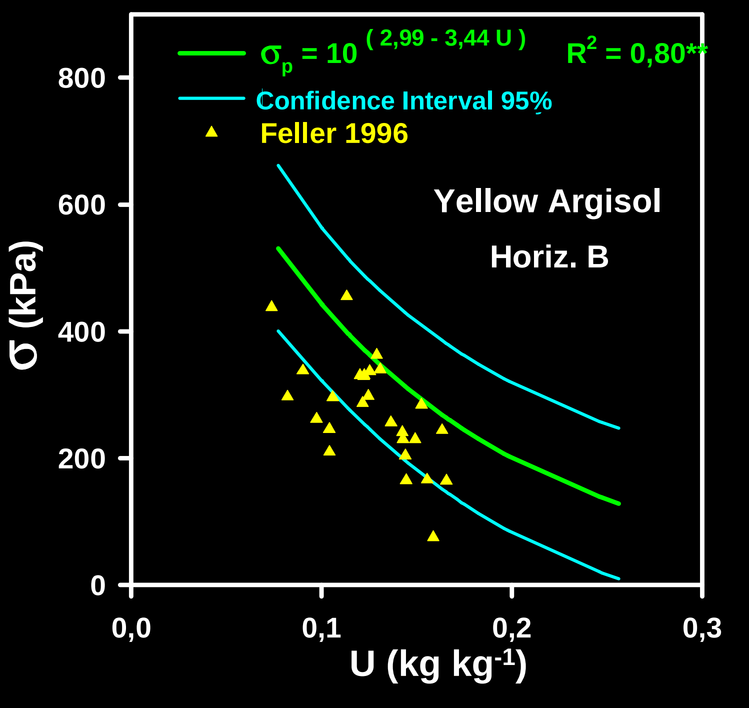


Identification of mechanical operation that causes soil compaction



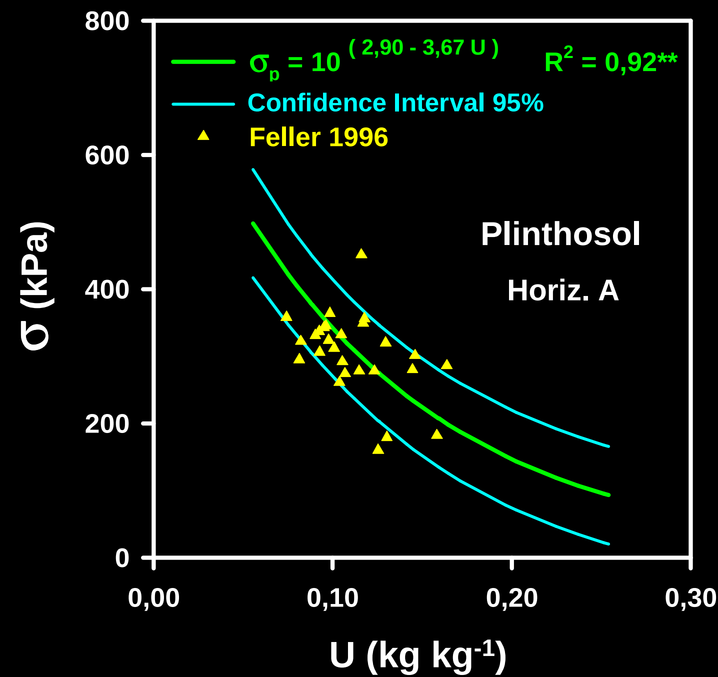
UNIVERSIDADE FEDERAL DE LAVRAS

Identification of mechanical operation that causes soil compaction

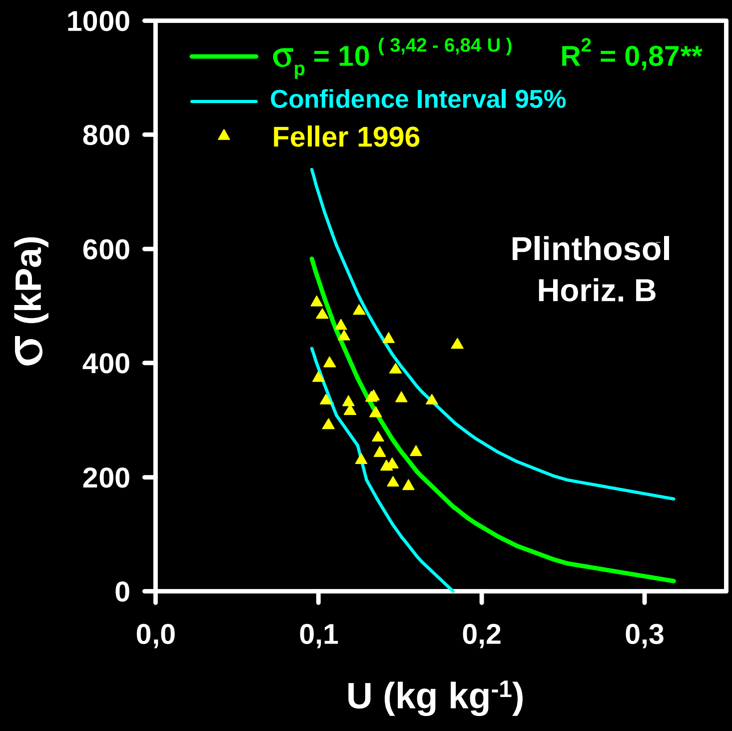


UNIVERSIDADE FEDERAL DE LAVRAS

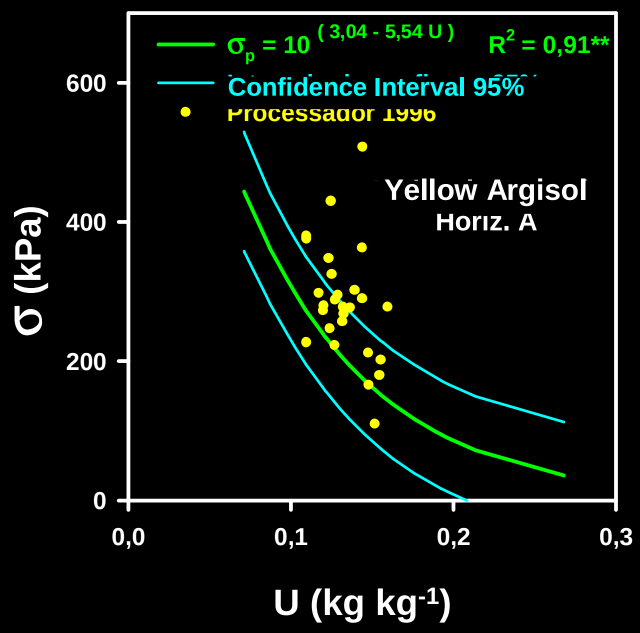
Identification of mechanical operation that causes soil compaction



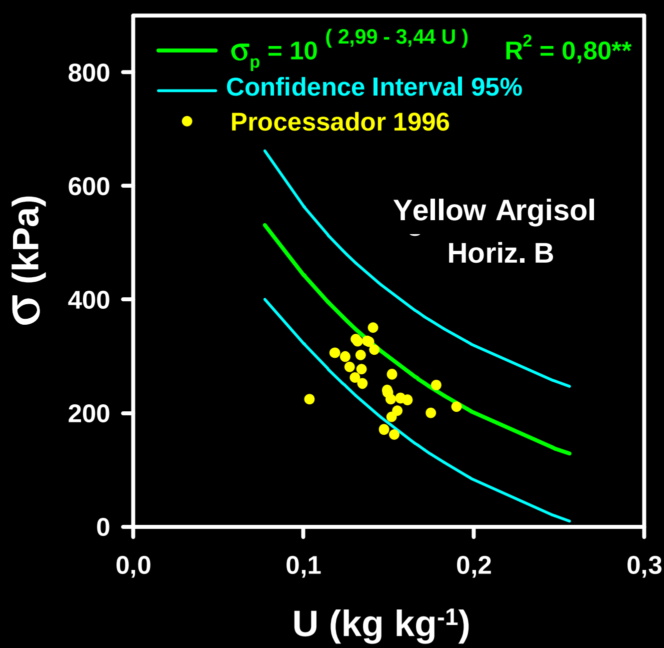
Identification of mechanical operation that causes soil compaction



Identification of mechanical operation that causes soil compaction

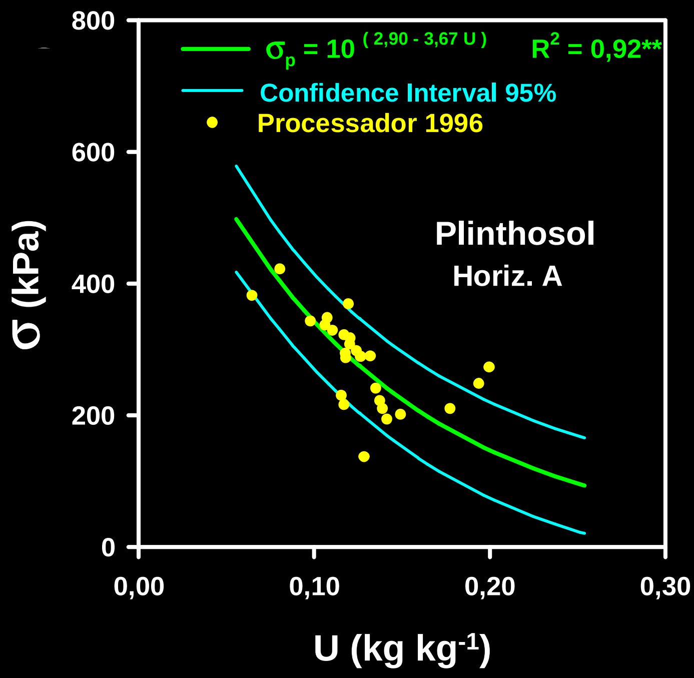


Identification of mechanical operation that causes soil compaction

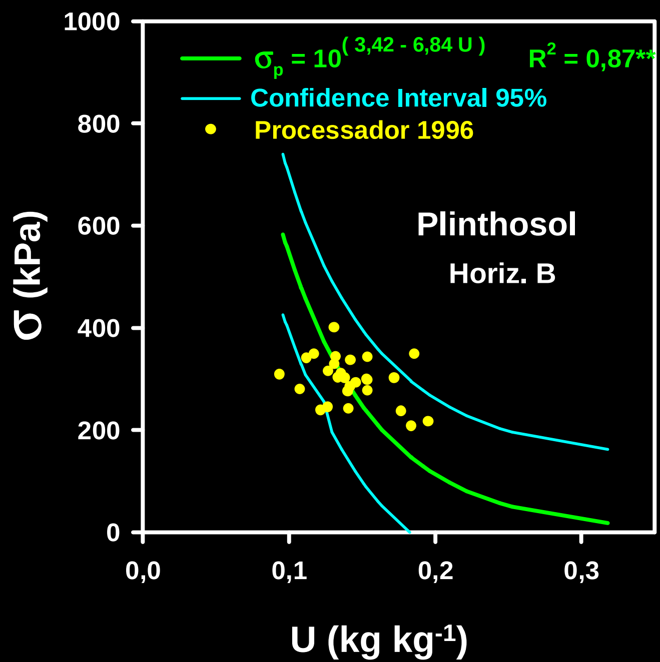


UFLA UNIVERSIDADE FEDERAL DE LAVRAS

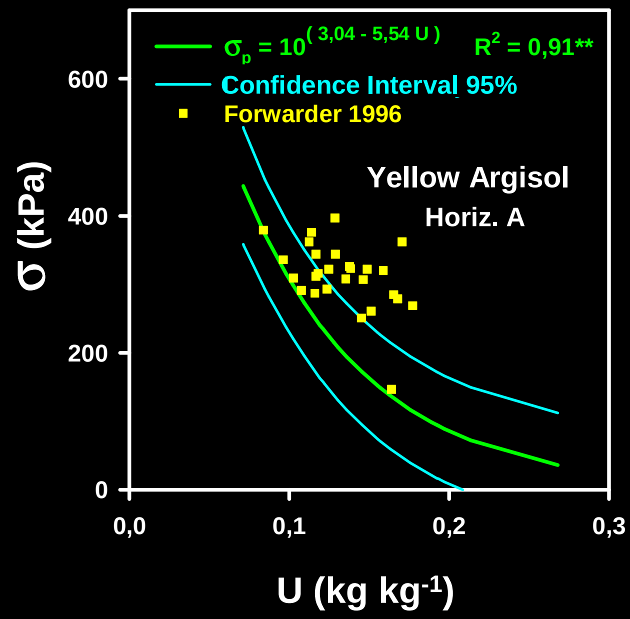
Identification of mechanical operation that causes soil compaction



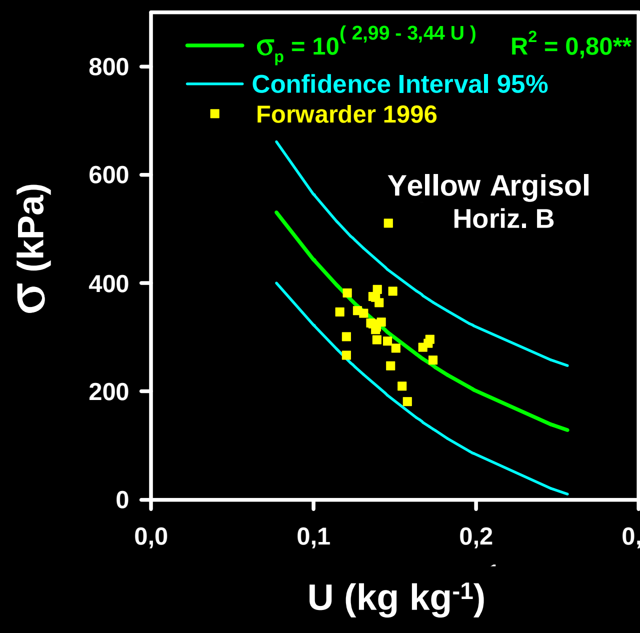
Identification of mechanical operation that causes soil compaction



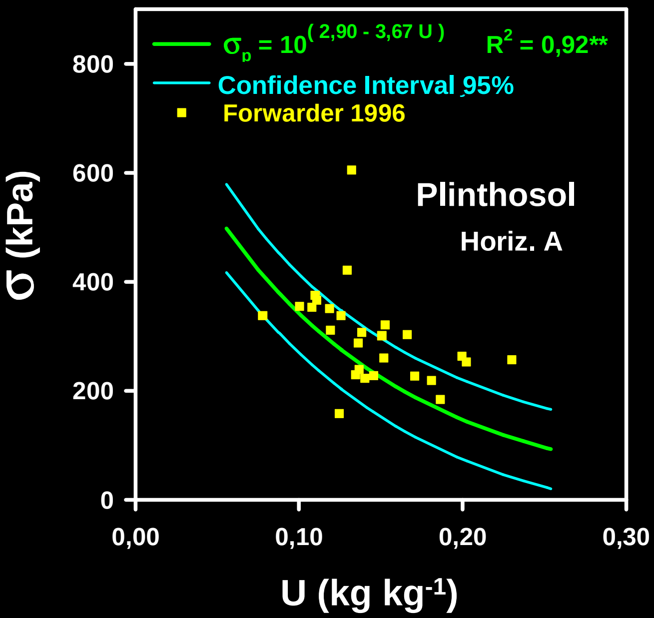
Identification of mechanical operation that causes soil compaction



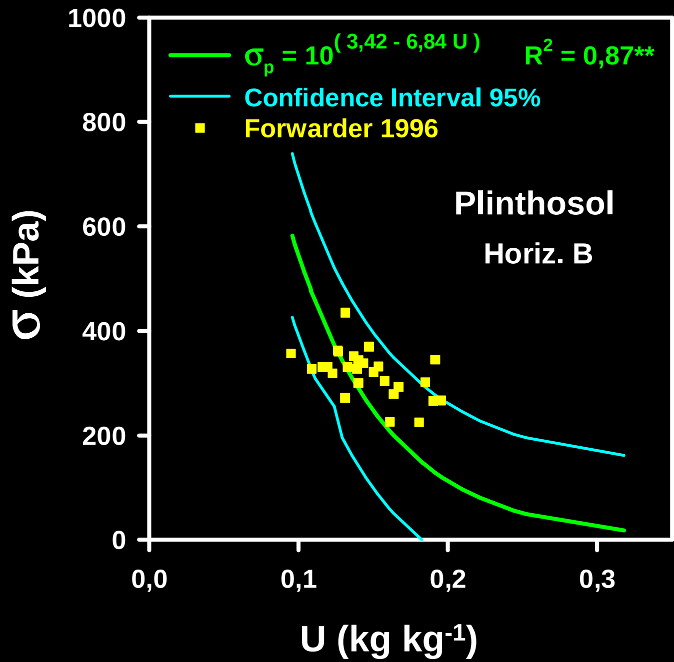
Identification of mechanical operation that causes soil compaction



Identification of mechanical operation that causes soil compaction



Identification of mechanical operation that causes soil compaction

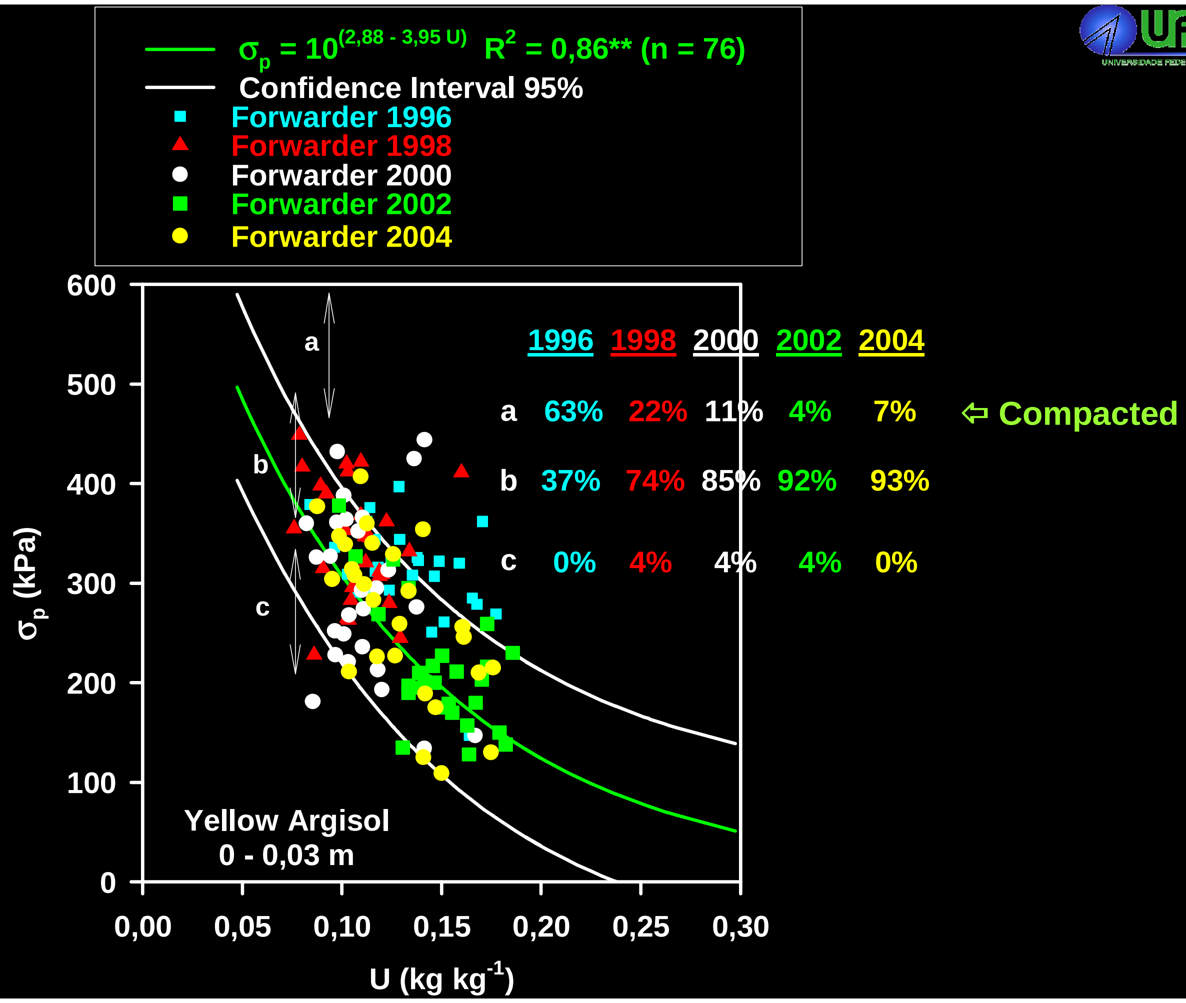


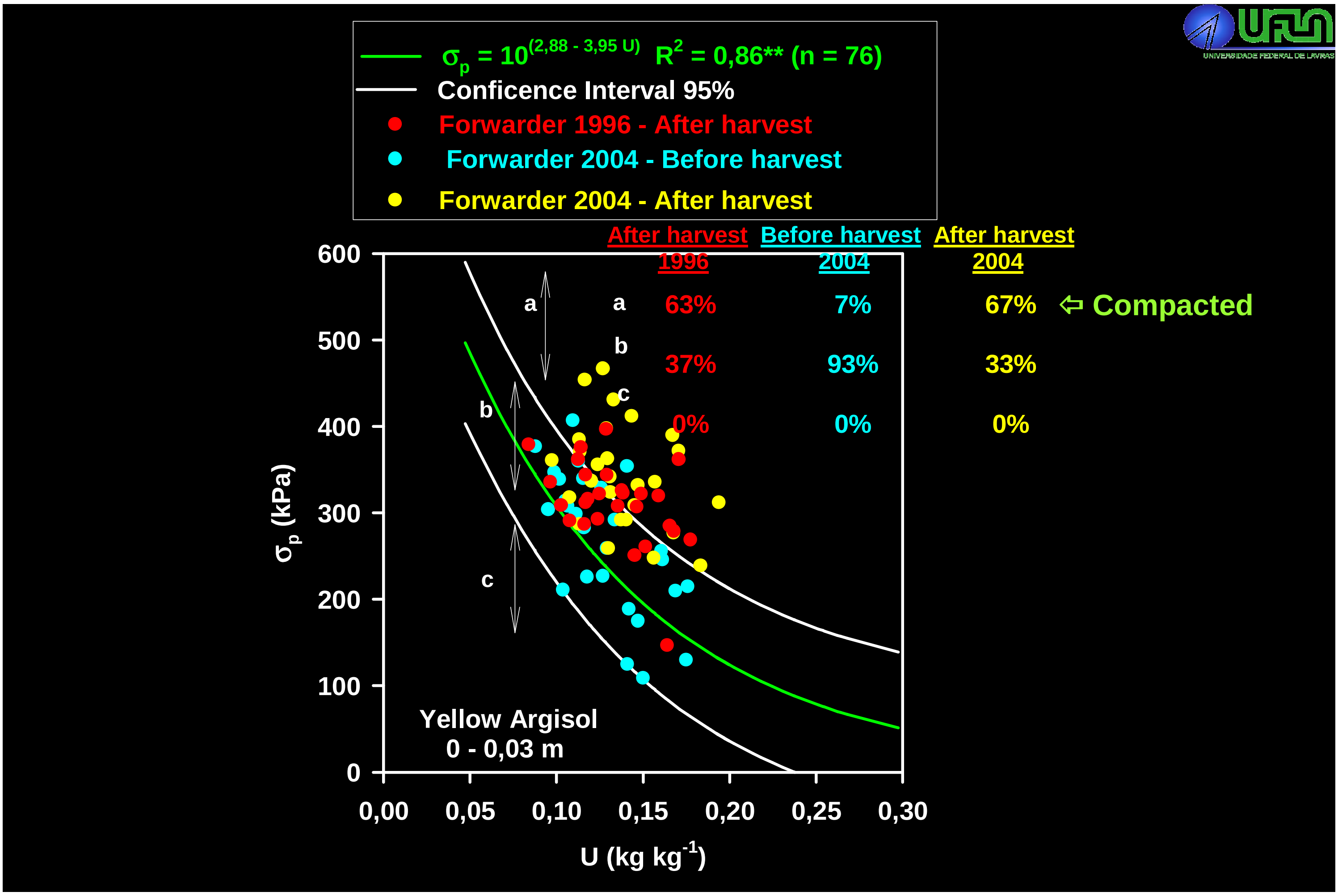
The critical operations in the harvest of eucaliptus

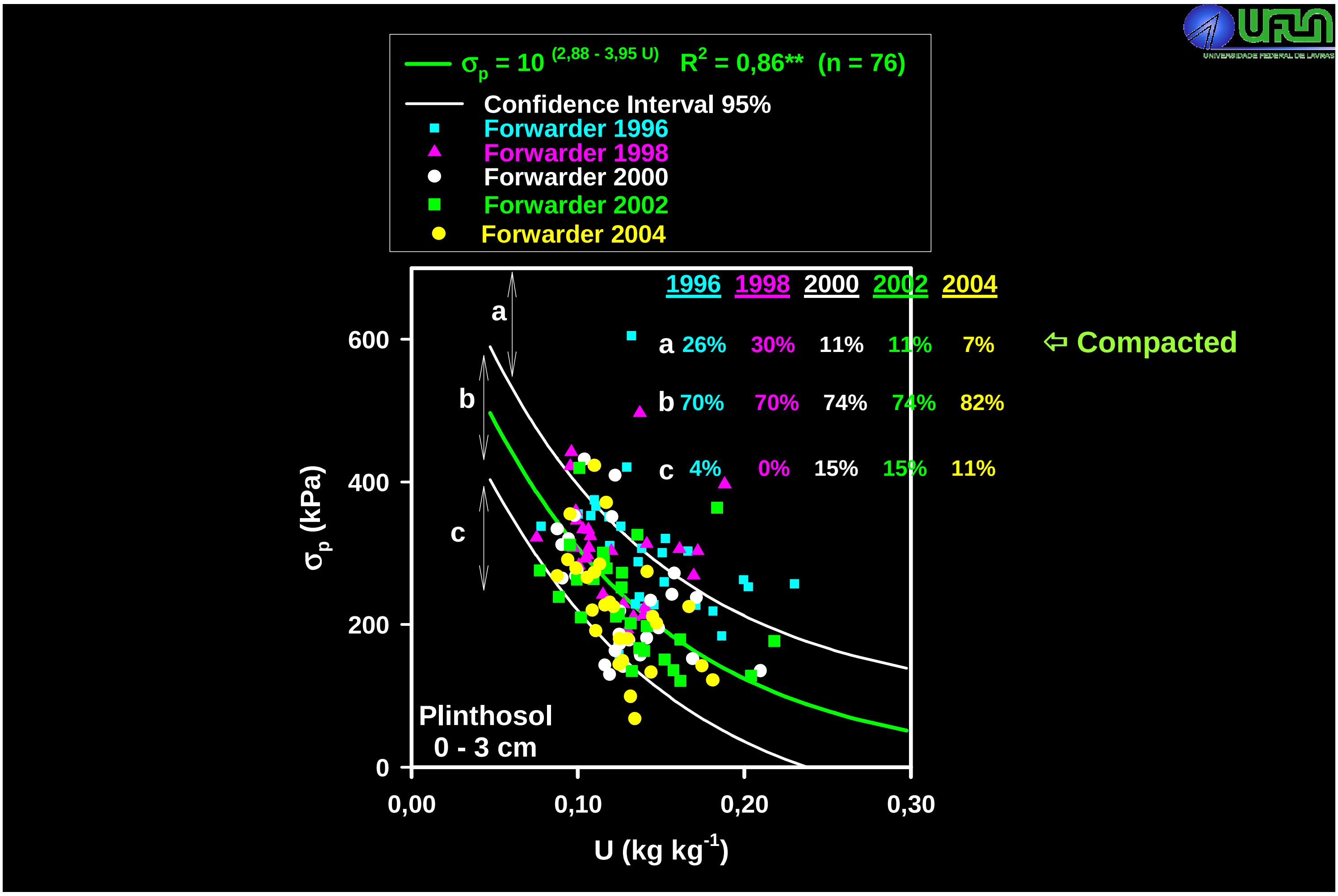
FORWARDER

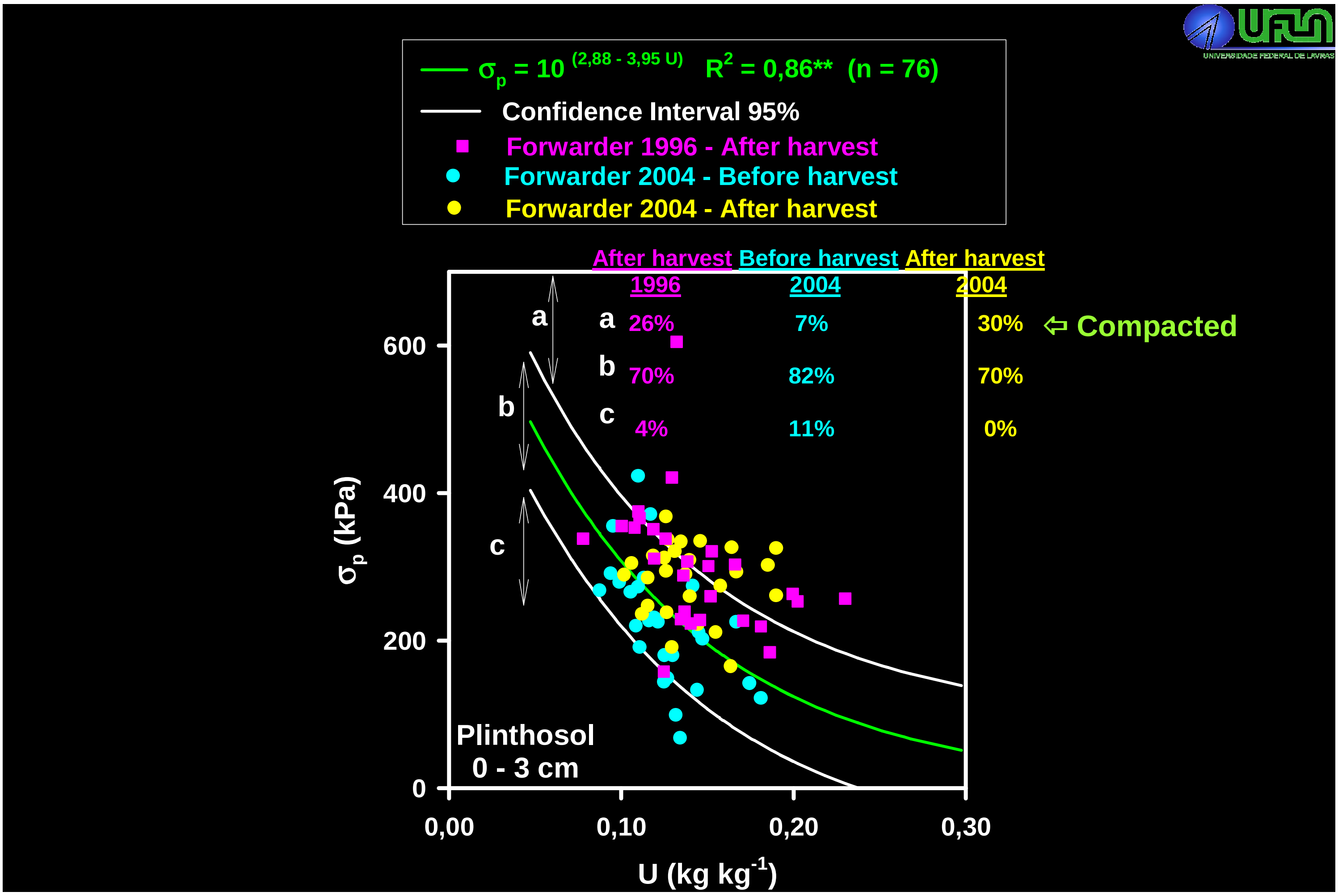
To measure the preconsolidation pressure during a production cycle of eucaliptus

Natural recovery of soil structure

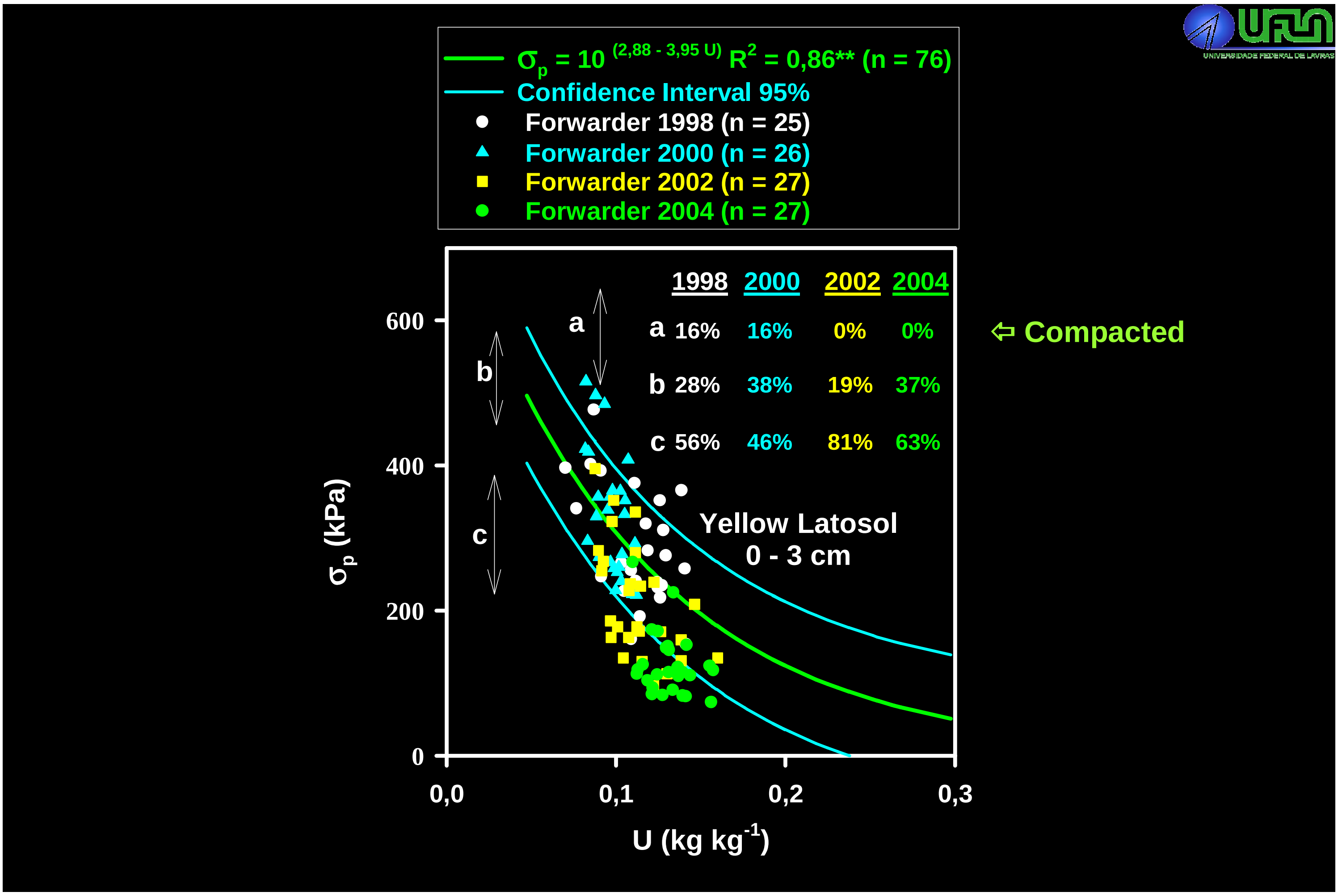



σp = 10^(2,88 - 3,95 U) R2 = 0,86** (n = 76)
Conficence Interval 95%
Forwarder 1996 - After harvest
Forwarder 2004 - Before harvest
Forwarder 2004 - After harvest
After harvest 1996
Before harvest 2004
After harvest 2004
a 63% 7% 67% ⇦ Compacted
b 37% 93% 33%
c 0% 0% 0%
σp (kPa)
U (kg kg-1)
Yellow Argisol
0 - 0,03 m
0 100 200 300 400 500 600
0,00 0,05 0,10 0,15 0,20 0,25 0,30
UFLA UNIVERSIDADE FEDERAL DE LAVRAS

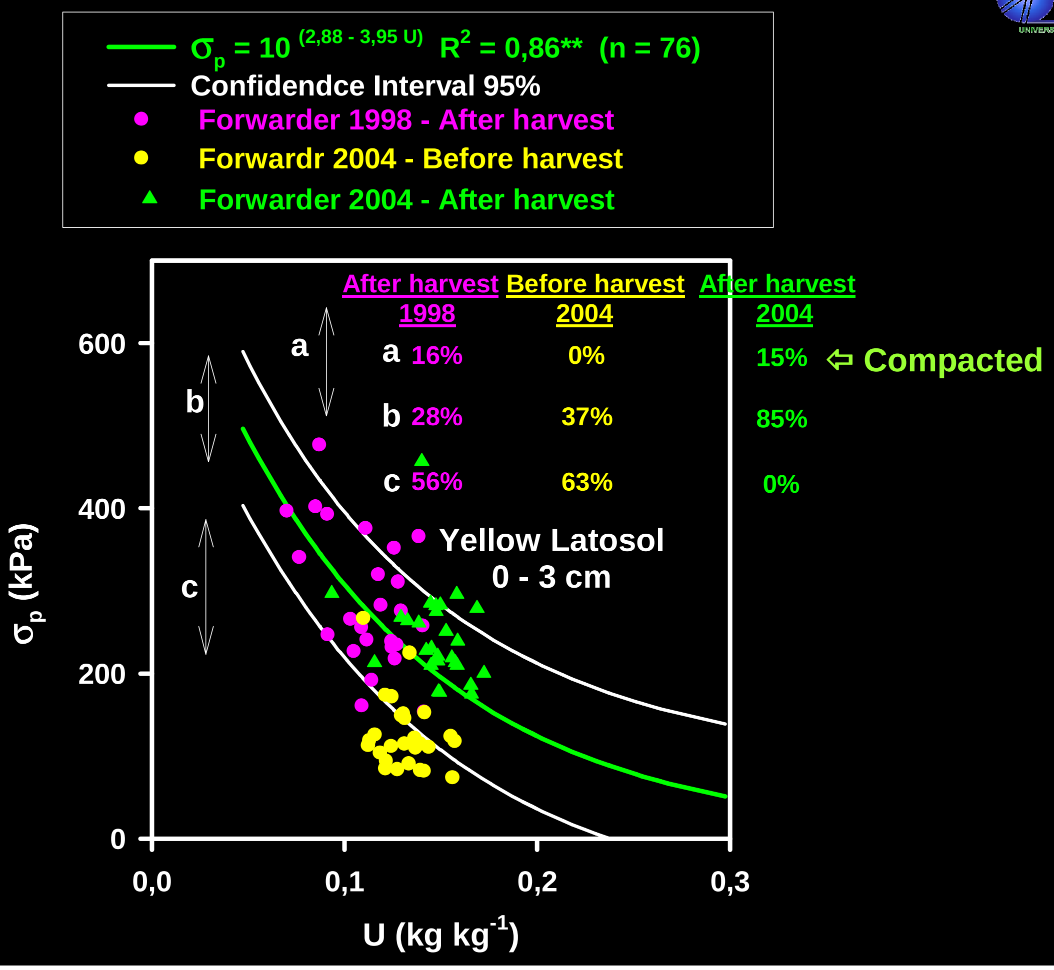

σp = 10 (2,88 - 3,95 U) R2 = 0,86** (n = 76)
Confidence Interval 95%
Forwarder 1996
Forwarder 1998
Forwarder 2000
Forwarder 2002
Forwarder 2004
1996 1998 2000 2002 2004
a 26% 30% 11% 11% 7% ⇦ Compacted
b 70% 70% 74% 74% 82%
c 4% 0% 15% 15% 11%
σp (kPa)
U (kg kg-1)
Plinthosol
0 - 3 cm
0 200 400 600
0,00 0,10 0,20 0,30
UFLA UNIVERSIDADE FEDERAL DE LAVRAS



UFLA
UNIVERSIDADE FEDERAL DE LAVRAS
σp = 10 (2,88 - 3,95 U) R2 = 0,86** (n = 76)
Confidence Interval 95%
Forwarder 1996 - After harvest
Forwarder 2004 - Before harvest
Forwarder 2004 - After harvest
After harvest 1996
Before harvest 2004
After harvest 2004
a 26% 7% 30%
b 70% 82% 70%
c 4% 11% 0%
⇦ Compacted
Plinthosol
0 - 3 cm
σp (kPa)
U (kg kg-1)
0
200
400
600
0,00
0,10
0,20
0,30
a
b
c



UFLA
UNIVERSIDADE FEDERAL DE LAVRAS
σp = 10 (2,88 - 3,95 U) R2 = 0,86** (n = 76)
Confidence Interval 95%
Forwarder 1998 (n = 25)
Forwarder 2000 (n = 26)
Forwarder 2002 (n = 27)
Forwarder 2004 (n = 27)
1998 2000 2002 2004
a 16% 16% 0% 0%
b 28% 38% 19% 37%
c 56% 46% 81% 63%
⇦ Compacted
Yellow Latosol
0 - 3 cm
σp (kPa)
U (kg kg-1)
0
200
400
600
0,0
0,1
0,2
0,3
a
b
c



Identification of mechanical operation that causes soil compaction

Photo: F.P. Leite

	$\sigma_{pt}^{1} > \sigma_{pmáxest}^{2}$ State	
	Dry	Wet
	--------------- (%) -----------------	
Feller and Skidder[3]	5	15
Harvester and Forwarder[4]	8	31

1 – Preconsolidation pressure determined after traffic, 2 – Preconsolidation pressure etimated with equation within the 95% confidence interval, 3 - Feller Büncher (model 2618 with track) and Skidder (model 460 with tyres 30.5L.32), 4 – Harvester (model 1270 with tyres 700x26.5) and Forwarder (model 1710 with tyres (750x26.5).

UFLA UNIVERSIDADE FEDERAL DE LAVRAS

UFLA UNIVERSIDADE FEDERAL DE LAVRAS

Identification of critical number of passes

Yellow Argisol - Eunápolis - BA

Horizon	Forwarder	Traffic Intensity		
		8	16	40
		% of compacted soil samples		
A	Tires	58	57	84
	Tracks	63	46	77
B	Tires	21	32	42
	Tracks	13	25	39

Photo: S.R.Silva

Identification of critical applied load

Yellow-Read Latosol
Santa Maria de Itabira - MG

	Load of a Forwarder with tires (4 passadas)		
	1/3 (3 m^3)	2/3 (6 m^3)	3/3 (9 m^3)
Depth	**% of compacted soil samples**		
0–3 cm	60	80	90
10–13 cm	70	80	90

(Silva et al., 2007)

Identification of the residue effect (Without residue)

2 passes

8 passes

Photo: A.R. Silva

Identification of the residue effect (Brushwood)

2 passes 8 passes

Photo: A.R. Silva

Identification of the residue effect (Brushwood and bark)

2 passes 8 passes

Photo: A.R. Silva

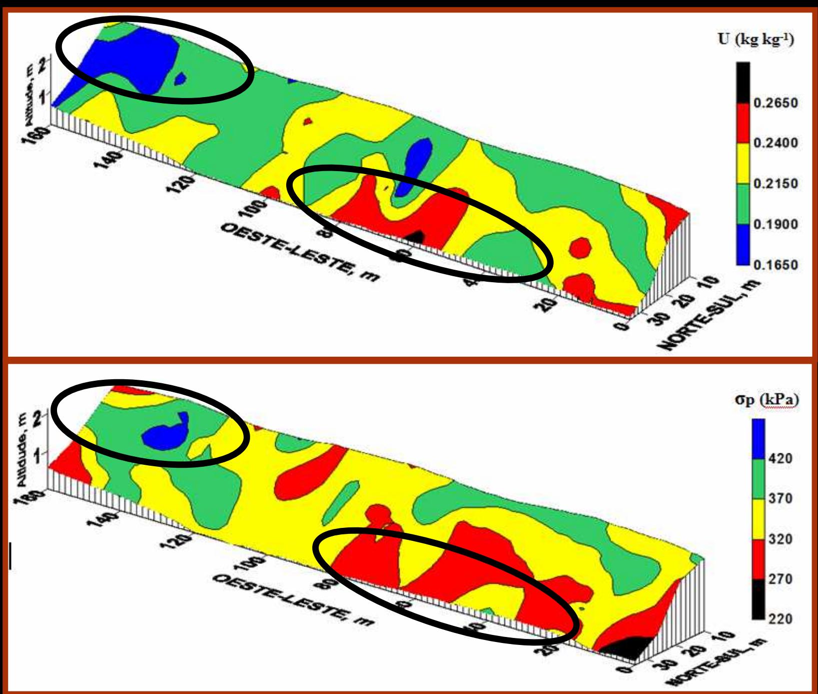
Identification of the residue effect

Yellow Latosol - Guanhães - MG

	Residue		
	Brushwood and bark	Brushwood	Without residue
Depth	% of compacted soil samples		
	2 passes of a Forwarder with tires		
10–13 cm	0	0	30
	8 passes of a Forwarder with tires		
	0	10	50

(Silva et al., 2007)

Trafficability maps



Use to estimate:

① The load support capacity

② The susceptibility to compaction

③ The resistence to tillage operations

(Gontijo, 2007)

Final Considerations

- The proposed methodology shows promising potentials to:

➔ Determine of the load support capacity of soils, which can be used as an auxiliary criterion for planning and managing mechanical operations;

➔ Quantify the effect of traffic on soil structure;

➔ Identify the presence / occurence of compaction layer