A soil mechanical resistance sensor for on-line application in precision agriculture: soil strength mapping and correlation with soil physical properties.

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ABSTRACT

Knowledge of local soil strength variation may permit variation of tillage parameters to produce a more optimal soil structure for root growth and plant development. Soil strength mapping can provide another layer of information in precision agriculture. The aim of this research is to develop a sensor able to measure on-line the local soil strength variations. This sensor is designed as follows: a thin blade penetrates the soil to a specified depth while the machine is moving, a beams transfers the soil-blade forces to a transducer fixed on the machine. This transducer measures then the horizontal and vertical forces and the moment. This paper describes a field experiment performed in 2 ha field of silt soil (Hesbaye, Belgium). The first objective of this research is to establish a map of soil strength variability of the field. For this purpose, the sensor is pulled through the soil in parallel traverses at 5m separation by a tractor equipped with a DGPS receiver. The second objective of the experiment is to study the relation between the measured forces and several measured soil physical parameters. Ten homogeneous plots were identified on the sensor track in order to cover as completely as possible the diversity of soil physical conditions encountered. On the median line of each of those plots, 10 Cone Index penetrometry profiles were measured with a mobile automated penetrometer recorder, soil water content was measured in 5 points, and soil samples were taken in the center of the plot to determine the following parameters: cohesion and internal friction angle, simple compression resistance, Atterberg limits, granulometry and pF curves. This experiment allowed the first identification of different soil strength areas in the field investigated.

1. Soil strength.

Direct measurement of soil strength is destructive and implies disturbing the investigated volume of soil. External application of stress to a soil can induce compaction (for instance, due to passage of vehicles) or rupture (for instance, due to the action of soil working tools), according to its internal characteristics and to the intensity of the applied forces. A high soil mechanical resistance can be a favorable or unfavorable property depending on the objectives. It is favorable to trafficability because it raises the soil carrying capacity but is unfavorable to soil tillage because it increases the traction strength, making more difficult the creation of an optimal soil structure, disturbs seeds germination and root growth.
Several estimation methods of soil strength have been developed. Two of them are classically used. On one hand, a laboratory method based on triaxial tests of undisturbed soil samples allows the estimation of cohesion and internal friction angle. On the other hand, measuring penetration resistance by pushing a cone into the soil is a field semi-empirical method, quicker to operate but releasing a more global information. Many penetrometer applications are described in the literature, notably to evaluate the effects of vehicle passages (Jorajuria *et al,* 1997), determine compaction effects on roots development (Varsa *et al,* 1997), measure superficial crusts resistance (Martino et Shaykewich, 1994), analyze the spatial variability of soil resistance (Perfect *et al,* 1990), etc. However, the discontinuous character of those methods make them difficult to use for cartography purposes.
The objective of this research is to build a sensor able to measure on-line local soil strength variations in order to consider a localized soil tillage.

2. Dynamometer sensor.

2.1. Description and principle.

The sensor is inspired from the principle used when instrumenting soil tillage tools to determine the required traction forces (Hamza et Destain, 1998). It is made up of a slightly inclined blade moving horizontally in the soil (Fig. 1). This blade undergoes solicitations which can be reduced to horizontal (Fx) and vertical forces (Fz). The sensitive part of the sensor is an octagonal ring transducer. It is fixed, out of the soil, between the tractor and the beam supporting the blade. This ring undergoes Fx and Fz and the moment My. The detection system is constituted of strain gauges, correctly positioned and connected to constitute three Wheatstone bridges measuring Fx, Fz and My without interference.

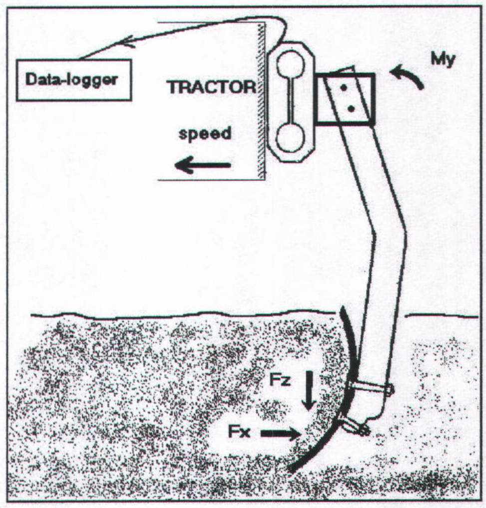

Figure 1 – General schema of the soil resistance sensor.

Fx, Fz and My are function of the soil physical state but also of the blade geometry, depth and traction speed. Those three last parameters have to be kept constant in order to detect soil strength variations.

Geometry was chosen to require only low traction power (blade length: 27 cm and width: 4.5 cm). It is placed with a 10° angle to the vertical to facilitate its soil penetration. Preliminary tests showed good sensitivity, which means a high ratio between measured forces and cone index values observed with conventional penetrometer.

Depth is kept constant by using the three points position control system of the tractor. The sensor is fixed on a supporting structure pulled by the three points fixation system. The whole structure is adjusted for a 30 cm blade depth to collect information from the most superficial soil layer.

Traction speed is kept at a constant value of 5 km/h by a precise engine speed adjustment. This advancement speed is classical for many cultivation works and the sensor will then be studied in normal working conditions.

2.2. Sensor design.

The octagonal ring dynamometer design is based on the works of Godwin R.J., 1975, and Hamza and Destain, 1998, and uses the formula of Cook et Rabinowicz, 1963. The calculation takes into account the maximal moment My that has to be transmitted by the ring. This moment was estimated by the fundamental equation of earthmooving mechanics (Reece A.R., 1965). The whole system was carried out in the Agricultural Engineering Department of the Agricultural University of Gembloux - FUSAGx, Belgium. A laboratory calibration of the sensor showed good linear relations ($r^2 > 0.9999$) between applied solicitations and the output electrical tensions of the Wheatstone bridges.

3. Measurement chain and data acquisition.

A complete measurement chain was developed in order to acquire simultaneously the signals provided by the soil strength sensor and those of a DGPS system. The measurement chain consists of an industrial laptop, an analog acquisition card and a signal conditioner supplying stabilized tension to the gauges bridges. The soil sensor signal acquisition had to be characterized by (1) a possibility of geocoding for cartography and (2) a high measurement rate high enough to allow a frequency analysis of the traction forces, suited to deliver information about soil breaking patterns. Such an acquisition has been performed with the “Labview” software (National Instruments). A high frequency Labview application was modified to allow signal acquisition at a 500 Hz rate as well as time recording which will serve to post-processing geocoding. One DGPS position per second was recorded by using the "Geographic Tracker" software of Mapinfo Corporation.

4. Field experiment.

4.1. Objectives and experimental schema.

An experiment was carried out in October 99 in the Hesbaye region (Belgium). The experimental plot is located in the silty soil area and covers 2 ha. It presents two slight undulations of a few meters high (3-4 meters) over a length of 600 meters. The soil is classified as Aba, silt soil with a textural B horizon (Baeyens, L. 1960). The wheat cultivated on this plot was harvested in August 99. The soil was not modified until the experiment. The first objective of the experiment was to establish a cartography of the sensor signals to obtain an image of the soil resistance natural variability at this field scale. The second objective was to study the relations between traction forces and several soil physical parameters measured in 10 test-plots, spread over the field (Fig. 2). Those parameters are for one part penetrometer profiles, providing quick but global characterization of soil strength and for the other part, humidity, pF curves, density, granulometry, Atterberg limits, triaxial and simple compression tests which will allow a more fundamental approach of the problem. The ten plots were identified on the sensor track in order to cover as completely as possible the diversity of soil physical conditions encountered by the sensor. The plots are treated as homogeneous soil units, but they were chosen long enough (20 meters) to obtain representative mean solicitations for each plot. This dimension corresponds also to the resolution which could practically be considered for a localized soil tillage approach.

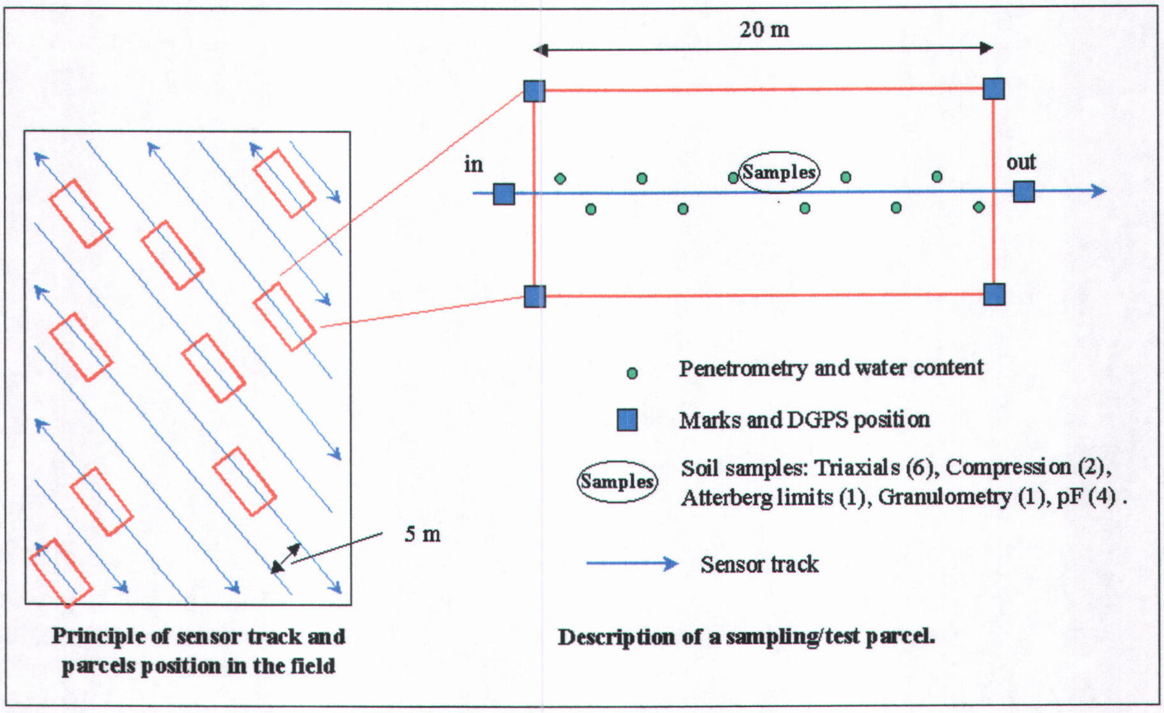

Figure 2 - Experimental plan (Hannut, 10/99).

4.2. Signal processing.

A program written in C++ converts in post-processing the tension delivered by the sensor to the values Fx, Fz and My by using the calibration equations established in laboratory and taking into account the own weight of the sensor. It also calculates the recording time of each measurement from the first recording time, the measurement rate and the delay between the local time of the computer and the DGPS UTM time. The program generates two additional types of files. The first type contains only the data related to the test-plots, extracted according to the state of a binary switch indicating the passage of the sensor in a plot. Those files will be used for studying the relations between measured soil physical state and recorded traction solicitations. The information contained in the file extracted for plot 1 is presented in figure 3. The second type of file contains the mean value of each solicitation computed for each second of measurement. They are destined to the cartography of Fx, Fz and My over the whole field.

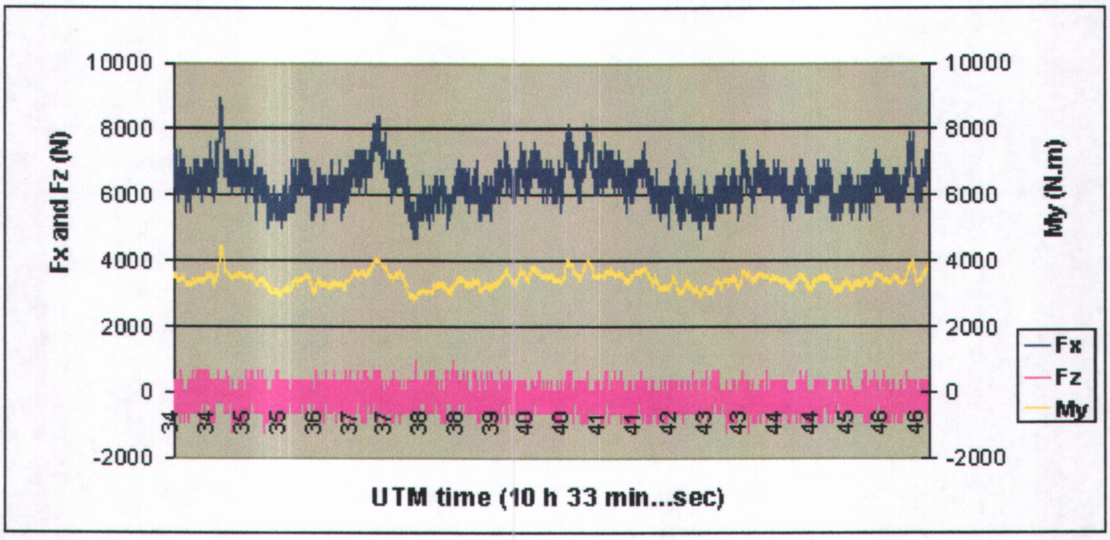

Figure 3 – Forces measured in plot n°1.

4.3. Forces cartography.

Geocoding forces data with their DGPS position was performed by matching the UTM time from both files. The cartography was performed with MapInfo software, it gave a control of the plot's localization whereas a thematic analysis (6 classes of same population) gave a first general idea of the forces variability (Figure 4). The limits of the classes are indicated in the legend, as well as the populations, between brackets. The observation of those maps already allows the identification of diverse soil resistance zones. Some parts of track-lines of the sensor showed superior forces to their two adjoining lines. This may be due to the fact that the sensor was passing in an ancient compacted wheel track, or to a variation of blade depth (for instance, when the tractor is driving inside previously compacted wheel tracks). Another explanation is that the graphical representation shows as adjacent lines that are actually distant of 5 meters: intermediate measurements would have probably shown more progressive soil resistance variations. The correct choice and use of adapted geostatistical solutions (spatial filtering, kriging interpolations, ..) during the next cartography step should solve these indeterminations.

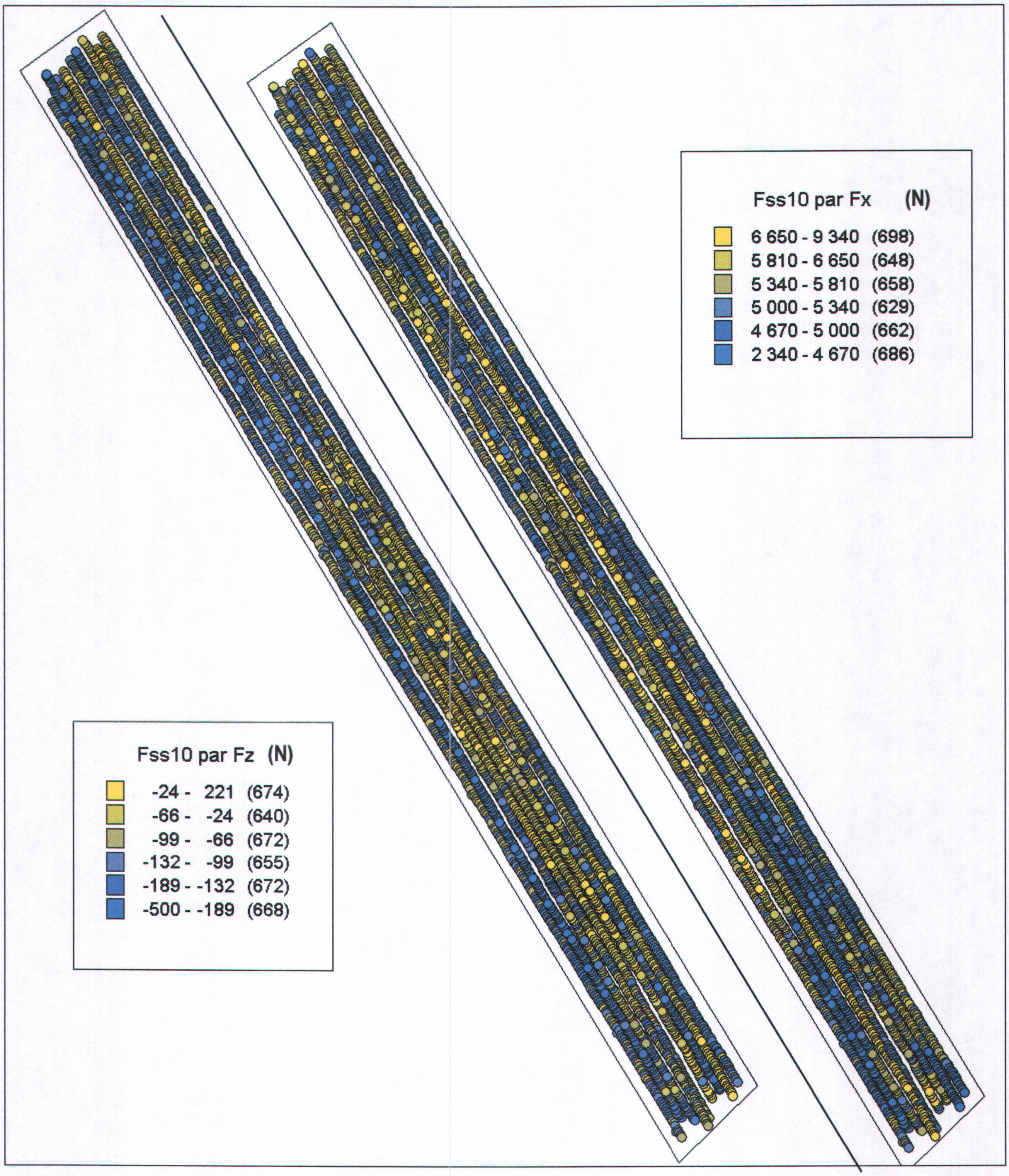

Figure 4 – Cartography of horizontal (Fx) and vertical (Fz) forces recorded in Hannut (October 99).

4.4. Study of the relations between forces and soil physical parameters.

The study and general analysis of soil physical parameters will be carried out when we are in possession of the whole set of results. The relation between those parameters and the measured forces will be approached from a fundamental aspect on one hand, using modelization and frequency spectra analysis. On the other hand, empirical relations will be searched by global statistical analysis. Apart from triaxial and simple compression tests still in process, the laboratory tests determining soil physical parameters are completed. First comments related to those tests are given in the following paragraphs.

4.4.1. Granulometry.

Soil samples destined to granulometry analysis were taken through the top 0 to 30 cm soil layer. Granulometry curves confirm the good textural homogeneity of the field predicted by the pedological map (fine silt).

4.4.2. Bulk density.

The dry bulk densities obtained by gravimetric measures over several unperturbed samples are comprised between 1.4 et 1.55 gr/cm^3 according to the plots. Additional measurements will be done on the samples destined for triaxial and simple compression tests.

4.4.3. Water content.

In order to obtain enough data without accumulating a hardly operable amount of samples for a classical gravimetric determination, a water content sensor ("ThetaProbe", developed by Delta-T Devices) has been used to carry-out in-situ measurements. A specific calibration was performed for the Hannut soil. (A non disturbed soil sample was taken in each of the then test plots.) In each of these plots, soil water content was measured with the ThetaProbe in five positions along the sensor track, for the layers of depth 0-15 cm and 15-30 cm. No significant vertical or horizontal water content variations were observed inside of the test plots. The order of magnitude of soil water content was of 22%. Few percents of variations were observed between plots.

4.4.4. Atterberg Limits.

State of consistency of silty-clay soils depends mainly on their water content. Atterberg defined conventional tests for the determination of water contents delimiting the solid, plastic (wp) and liquid (wl) states of those soils. Those limits are directly function of all the physico-chemical soil parameters and constitute some synthesis parameters. The plasticity index (Ip = wl - wp) measures the range of water content in which a plastic behavior is expected for the material. The plasticity index observed in all the plots is considered as "low" (from 5 to 10 %). The consistency index (Ic = (wl – w)/ Ip), taking into account the soil water content, characterizes its consistency state. The soil state encountered during this experiment is qualified as not very consistent to consistent, according to the plots. The position of the representative point on Casagrande's diagram (couple wl, Ip) allows the identification of the dominant type of clay mineral. The point representing the Hannut soil indicates the category of the "less plastic silts" (not very consistent silts). The localization of this point shows the absence of swelling clays associated to complications in mechanical behavior.

4.4.5. pF curves.

Soil moisture tension has a significant influence on the apparent cohesion and thus on the mechanical behavior of the soil. This tension depends on the soil type and on its water content. The relation between water content and soil moisture tension (pF curves) is then useful for studying mechanical behavior of any type of soil. pF is the logarithm of suction height (negative pressure expressed by the water column which equilibrates the soil suction). A pF curve was established with two samples for each of the ten plots. The curves are globally similar for all the plots.

4.4.6. Penetrometry profiles.

Thirteen penetrometry profiles were recorded in each plot with an automatic mobile penetrometer. A C++ program was used to correct the profiles depth error due to the unevenness of the field surface. This pre-processing turns the profiles to be comparable and allows the calculation of an average profile for each plot. Mean Cone Index measured at 20 cm depth ranged from 1 to 2.5 Mpa.

4.4.7. Compression and triaxial tests.

The triaxial test determines the internal soil mechanical resistance parameters, that is to say the effective cohesion and internal friction angle. The simple compression test determines a standard compression resistance value (MPa). This last notion is more global and is influenced by soil water content at the moment of the test. These laboratory tests are still in process.

5. Conclusion.

The use of a sensor for determining on-line the soil physical state presents a double interest. Firstly, it can be mounted on moving vehicles equipped by DGPS positioning systems. Once processed, the data is mapped and can bring complementary information compared to other types of maps already available in precision agriculture. Cartography of soil physical properties will facilitate the study of their influence on plant development and yields. It is a new layer of information in precision farming. Secondly, this sensor may be used to regulate in real time the functioning parameters of soil tillage machines according to the local soil physical state encountered, in order to create a more optimal soil structure.
The first results of this experiment are promising. The dynamometer and the measurement chain built during the year 1999 seem sensitive enough and well suited to the detection of local soil strength variations.

Acknowledgements

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