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Chapter 7

DIGISOIL: An Integrated System of Data Collection Technologies for Mapping Soil Properties

G. Grandjean, O. Cerdan, G. Richard, I. Cousin, P. Lagacherie, A. Tabbagh, B. Van Wesemael, A. Stevens, S. Lambot, F. Carré, R. Maftai, T. Hermann, M. Thörnelöf, L. Chiarantini, S. Moretti, A. McBratney, and E. Ben Dor

Abstract The multidisciplinary DIGISOIL consortium intends to integrate and improve in situ proximal measurement technologies for assessing soil properties and soil degradation indicators, moving from the sensing technologies themselves to their integration and application in (digital) soil mapping (DSM). The core objective of the project is to explore and exploit new capabilities of advanced geophysical technologies for answering this societal demand. To this aim, DIGISOIL addresses four issues covering technological, soil science, and economic aspects: (i) development and validation of hydrogeophysical technologies and integrated pedogeophysical inversion techniques; (ii) the relation between geophysical parameters and soil properties; (iii) the integration of derived soil properties for mapping soil functions and soil threats; and (iv) the evaluation, standardisation, and industrialisation of the proposed methodologies, including technical and economic studies.

Keywords Soil properties · Sensing technologies · Geophysical techniques · Inference model · Water content

7.1 Introduction

The main objective of the European *FP7 Cooperation Work Program on Environment*¹ proposes to address global environmental issues in an integrated way by advancing our knowledge and capacities to develop new technologies for sustainable management of the environment and its resources. The DIGISOIL

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¹Framework Program 7.

46 project started in autumn 2008. As with the iSoil project (Chapter 8), it is defined
47 according to the FP7 work program and addresses ‘technologies for data collec-
48 tion in (digital) soil mapping’. The multidisciplinary DIGISOIL consortium aims
49 to integrate and improve in situ and proximal measurement technologies for the
50 assessing soil properties and soil degradation indicators, moving from the sens-
51 ing technologies themselves to their integration and application in (digital) soil
52 mapping (DSM).

53 In order to assess and prevent soil degradation and to benefit from the dif-
54 ferent ecological, economic, and historical functions of the soil in a sustainable
55 way, there is an obvious need for high-resolution, accurate maps of soil proper-
56 ties. The core objective of the project is to explore and exploit new capabilities of
57 advanced geophysical technologies for answering this societal demand. To this end,
58 DIGISOIL addresses four issues covering technological, soil science, and economic
AQ2 59 aspects (Fig. 7.1): (i) the validation of geophysical (in situ, proximal, and airborne)
60 technologies and integrated hydrogeophysical inversion techniques (mechanistic
61 data fusion); (ii) the relation between geophysical parameters and soil properties;
62 (iii) the integration of derived soil properties for mapping soil functions and soil
63 threats; and (iv) the evaluation, standardisation, and industrialisation of the proposed
64 methodologies, including technical and economic studies.

67 7.2 Objectives

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70 The purpose of the DIGISOIL project is to identify and bridge the technological
71 gap and develop pertinent, reliable, and cost-effective geophysical mapping solu-
72 tions. Considering the new equipment and signal processing developments offered
73 by recent scientific investigations, the problem of performing soil data collec-
74 tions at the catchment scale using geophysical sensors can be foreseen in the near
75 future, particularly for methods identified in the following tables (GPR, EMI, seis-
AQ3 76 mics, magnetics, and airborne hyperspectral) (Tables 7.1 and 7.2). Gravity-based and
77 thermal-based methods will not be incorporated in DIGISOIL because of their low
78 contribution to the characterisation of soil properties related to degradation pro-
AQ4 79 cesses. For gamma radiometrics, several investigations have already been carried
80 out to study their potential for soil properties mapping (e.g. Viscarra Rossel et al.,
81 2007). This technology has given satisfactory results and permits one to map types
82 of clay minerals in the topsoil through the analysis of U, K, and Th anomalies
83 in the gamma spectrum. We will not consider this method since it appears to be
84 already used in the soil science community (Wilford and Minty, 2006). However,
85 since the information provided by this technology has many interesting aspects, we
86 will integrate it as potential auxiliary data in our mapping strategy. This context is
87 therefore favourable for the development of DIGISOIL’s mapping tools and prod-
88 ucts in relation to DSM applications. With respect to these issues, the milestones of
89 the DIGISOIL project are
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7 DIGISOIL: An Integrated System of Data Collection Technologies

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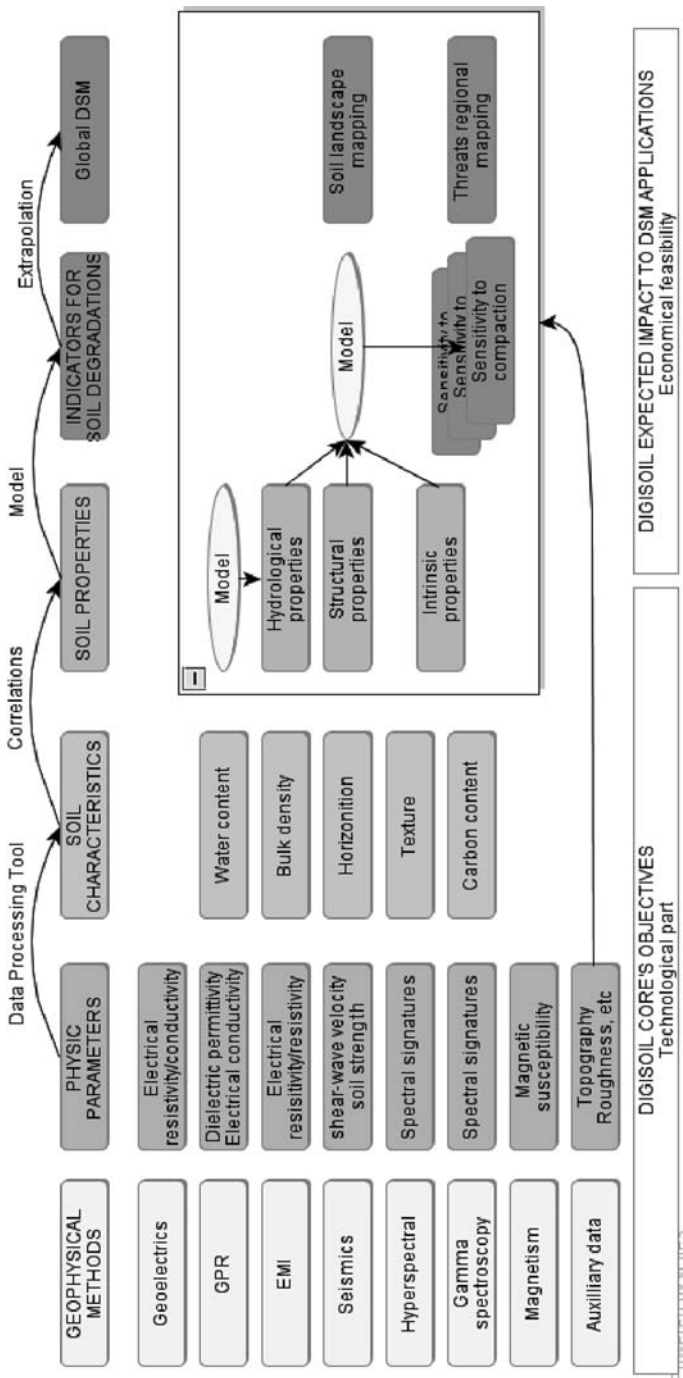


Fig. 7.1 DIGISOIL concept

Table 7.1 Common elements for the identification of risk areas

136					
137	Soil threats				
138	<hr/>				
139	Soil erosion	OM decline	Compaction	Salinisation	Landslide
140	<hr/>				
141	<i>Soil properties</i>				
142	Soil texture	Soil texture/clay content	Soil texture	Soil texture	
143					
144	Soil density		Soil density		
145	Soil hydraulic properties		Soil hydraulic properties	Soil hydraulic properties	
146		Soil organic carbon	Soil organic matter		
147					
148					
149	<i>Soil-related parameters</i>				
150	Topography	Topography	Topography		Topography
151	Land cover	Land cover	Land cover		Land cover
152	Land use	Land use	Land use	Irrigation areas	Land use
153				Climate	
154	Climate	Climate	Climate	Climate	Climate
155	Hydrological conditions				
156	Agro-ecological zone				
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158					
159					Occurrence/density of existing landslides
160					
161				Groundwater information	
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163					Bedrock
164					Seismic risk
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1. To develop, test, and validate the most relevant geophysical technologies for mapping soil properties: geoelectric, seismic, GPR/EMI, magnetic, and airborne hyperspectral.
2. To establish correlations between the measured geophysical measurements and the soil properties involved in soil functions/threats (erosion, compaction, organic matter decline, salinisation, and shallow landslides) by using innovative data processing (inversion) and correlation protocols.
3. To evaluate the societal impact of the developed techniques by investigating their relevance to end-user needs, their technical feasibility, and their cost-effectiveness.
4. To produce an exploitation plan including the standardisation of the processes and the technical specifications of the developed methodologies describing the system components in terms of equipment (sensors, acquisition system,

7 DIGISOIL: An Integrated System of Data Collection Technologies

Table 7.2 Potential influence of soil threats on functions of soils

Function of soil/soil threat	Biomass production	Storing, filtering and transformation	Bio diversity pools	Physical and cultural media	Raw material	Carbon pool	Geological and archaeological heritage
Erosion	x	x	x	x	x	x	x
Decline in organic matter	x	x	x	–	x	x	–
Contamination	x	x	x	x	x	x	x
Sealing	x	x	x	x	x	x	x
Compaction	x	x	x	x	–	x	x
Decline in soil biodiversity	x	x	x	–	–	x	–
Salinisation	x	x	x	–	–	x	–
Floods and landslides	x	x	x	x	x	x	x

x potential influence; – no influence

mobile vector), techniques (signal processing, inversion or fusion processes, specialisation), and operational protocols.

7.3 Strategy and Workplan

The DIGISOIL architecture is structured according to five items in relation to the above-cited objectives of the project:

1. *Identification of pertinent sensor technologies:* the capabilities of the different geophysical techniques will be investigated and technically adapted so as to characterise highly complex soil properties (spatial and temporal heterogeneities, low variations of properties, context-dependant, etc.). Two series of experiments will be carried out with a two-step feedback approach in order to analyse sequentially, and on different sites, the quality of the results and the efficiency of each technology.
2. *The data integration for estimating soil properties:* the conversion of geophysical parameters into soil properties and the derivation of soil threats are not straightforward. Most of the time, several indicators are necessary to reduce the uncertainty of the estimation. Studying the different correlation between indicators and possible soil properties should finally lead to an innovative methodology of fusion, guaranteeing a final assessment in terms of soil diagnostics (soil properties, threats, and soil functions).
3. *Testing and validation on selected sites:* the Commission policies have to deal with various European environments. For that reason, the sensor technologies will be tested on two series of sites: (i) second-order test sites for a specific

226 technique adaptation and (ii) first-order sites for testing the validity domain of
 227 different sensors at the same location. The latter have been selected in order
 228 to ensure a maximal geographical representativeness within Europe. For this
 229 validation task, classical in situ invasive sensors will be used.

230 4. *Evaluation of the proposed methodologies*: as the intent is oriented towards serv-
 231 ing DSM applications, the results should be evaluated in terms of technical
 232 feasibility, maturity, and economical costs.

233 5. *Exploitation of the proposed methodology*: with respect to the Work Program’s
 234 objectives, which stipulate that technologies developed in the Collaboration
 235 Program have to be finally exploited as European services, an exploitation
 236 plan, including technical specifications of the developed methodologies, will be
 237 presented.

241 **7.4 From Soil Threats to Geophysical Properties**

242
 243 The DIGISOIL project can be seen as the setting up of operational techniques useful
 244 for implementing existing and emerging EU environmental legislation and policy –
 245 like the European Soil Thematic Strategy, which aims to protect soil functions and
 246 prevent soil degradation. Table 7.3 represents the main soil and soil-related param-
 247 eters to be considered by member states for delineating risk areas. Since soil texture,
 248 soil water content, soil hydraulic properties, bulk density, and soil organic matter
 249 are involved in many soil functions, these properties have to be considered the first
 250 priority. Soils under threat cannot continue to perform all their environmental, eco-
 251 nomic, social, and cultural functions in the same way after being degraded (e.g.
 252 biomass production is not possible on sealed soils). The gradual loss of performance
 253 of soil functions depends on the severity of a threat, which can be gauged in terms
 254
 255

256 **Table 7.3** Main ground-based and airborne geophysical methods and related physical parameters.
 257 Italics indicate methods that will not be integrated into the DIGISOIL tool

258 Geophysical methods	259 Physical parameters
260 Ground-penetrating radar (GPR)	261 Dielectric permittivity, electric conductivity, 262 magnetic permeability, frequency dependence of 263 these electromagnetic properties
264 Seismic reflection and refraction	265 Volume and shear-wave velocities
266 Electromagnetic induction (EMI)	267 Electrical resistivity (electric conductivity and 268 frequency dependence)
269 Electrical resistivity (geoelectric)	270 Electrical resistivity (almost zero-frequency)
<i>Gravity</i>	<i>Density</i>
<i>Magnetics</i>	<i>Magnetic susceptibility and viscosity</i>
<i>Airborne thermic</i>	<i>Surface temperature</i>
<i>Airborne hyperspectral</i>	<i>Spectral reflectance</i>
<i>Gammametry</i>	<i>Gamma spectrum (U, K, Th)</i>

7 DIGISOIL: An Integrated System of Data Collection Technologies

Table 7.4 PLS regression output statistics of the best model for each dataset

Data	Calibration			Validation			
	N	RMSEC ^a g C kg ⁻¹	RMSEC/SD	N	RMSEP ^b g C kg ⁻¹	RPD ^c	R ²
ASD	108	2.8	0.45	37	3.3	1.79	0.82
ASD ^d	77	1.7	0.25	24	2.4	2.33	0.90
CASI (Ortho)	94	3.0	0.93	32	4.4	1.08	0.44
CASI (Attert)	75	3.4	0.51	24	3.8	1.97	0.87
Casi+SASI	73	2.9	0.60	26	1.9	2.50	0.92

^aRoot mean square error of calibration

^bRoot mean square error of prediction

^cRatio of performance to deviation (RMSEP/SD)

^dOnly including the dataset of dry soil surfaces

of its intensity and duration. Depending on the type of threat, different soil functions may be affected (Table 7.4). In some cases more than one threat occur on a certain piece of land.

The combination of threats sometimes worsens their effect on soil functions. As illustrated in Fig. 7.1, which summarises the DIGISOIL concept, the core objectives of the program are focused on determining the most relevant soil properties, which in a second phase (and through the use of pedo- and hydro-models, as well as auxiliary data) will allow us to map soil threats and functions (Tables 7.3 and 7.4). In the last decades, geophysical prospecting applied to subsurface characterisation has been of an increasing interest, particularly in soil science. Major advances in this technological domain can be attributed to the development of integrated measuring systems, increasing computing power, equipment portability, and hardware/software diffusion. In this context, two kinds of technological platforms can be involved: ground-based and proximal technologies, working from the surface and from the air. Ground-based geophysical instruments are now equipped with digital signal processing and recording capabilities previously restricted to large corporate computing centres. This improved computational capacity has provided investigators with near real-time results that, in turn, drive improvements in instrument sensors and processing algorithms. In a similar way, recent airborne geophysics has sparked strong interest due to the possibilities of civil airplanes equipped with optical, thermal, or hyperspectral sensors. The most common methods that take advantage of these enhancements, and their related parameters, are listed in Table 7.5.

Measuring the electrical resistivity of soil was proposed in the DIGISOIL project because it is closely related to several soil parameters and can be performed over areas of several hectares with high resolution (Panissod et al., 1997; Chapter 26, this volume). Up to now, the interpreting electrical measurements have remained difficult because the different influences soil parameters have on electrical resistivity are still hard to discriminate. There are numerous relationships between electrical resistivity and any one soil physical or chemical parameter. For example, there are

linear (or more complex) correlations between electrical resistivity and soil temperature (Keller and Frischknecht, 1966), soil water content and salinity (Sen et al., 1988), soil cationic exchange capacity (Shainberg et al., 1980), soil texture (i.e. clay content), and soil porosity (Friedman, 2005). Other studies have demonstrated the influence of soil structure on electrical resistivity, such as the impact of bulk density or the effect of cracks (Samouëlian et al., 2003).

Spatial electrical investigations therefore enable us to describe soil structural heterogeneity, with the aim of delineating specific zones for use in precision agriculture or to map soil texture (Tabbagh et al., 2000) or salinity (Corwin et al., 2006). Nevertheless, despite these known relationships, it remains difficult to describe the effect of ancillary parameters on electrical resistivity, especially the effect of the soil structure (which changes quickly under the influence of water content and temperature). To address these issues, specific experiments will be conducted in the DIGISOIL project, such as taking measurements that should help describe the evolution of at least one or two parameters (assuming the others remain constant). As an example, Fig. 7.2 shows three electrical resistivity maps recorded at three dates when only the soil water content was supposed to vary (Besson et al., 2008).

Other studies will evaluate the possibility of using field spectroscopy (Chapter 11) to estimate carbon content (Stevens et al., 2006). Visible and near-infrared (VNIR) spectral analysis and diffuse reflectance analysis are techniques that can rapidly quantify various soil characteristics simultaneously (Ben-Dor and Banin, 1995; Viscarra Rossel et al., 2006). There are three types of VNIR techniques (Chapter 13), which operate at different spatial scales and in different environments: (1) laboratory spectroscopy (LS); (2) portable field spectroscopy (PS); and (3) imaging spectroscopy (IS). LS and PS rely on ground-based sensors (such as the Fieldspec Pro FR from Analytical Spectral Devices covering 350–2,500 nm). IS uses air- or space-borne sensors such as the Compact Airborne Spectrographic Imager or CASI (covering 405–950 nm) and the Shortwave Infrared Airborne Spectrographic Imager (SASI), covering 900–2,500 nm). Two different test sites in southern Belgium were monitored within the framework of the Belgian airborne imaging spectroscopy campaigns under the PRODEX program. The aim was to explore the capabilities of VNIR spectroscopy in the context of soil organic carbon (SOC) inventories and monitoring. The sites, Ortho in the Ardennes (50°8' N, 5°36' E) and Attert (49°45' N, 5°44' E), were overflown with a CASI sensor in October 2003 when cereal fields had been ploughed, harrowed, and reseeded.

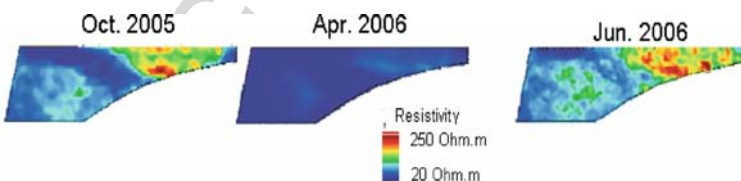


Fig. 7.2 Resistivity maps for three dates showing the impact of water saturation in soils on electrical resistivity (Besson et al., 2008)

7 DIGISOIL: An Integrated System of Data Collection Technologies

Exactly 120 soil spectra from 13 bare fields were taken at Ortho and 40 from 10 bare fields at Attert using the Fieldspec Pro (ASD). At the same sites, topsoil (0–5 cm) samples were taken and analysed for moisture content and organic carbon content (the latter by wet oxidation). Furthermore, three bulk density samples were taken in each field in order to calculate the SOC stock in the ploughed layer (mean thickness 22 cm). Another dataset from a previous IS campaign near Attert, using both CASI and SASI sensors, was also analysed. We used both stepwise and partial least square (PLS) regression analysis to relate spectral measurements to SOC content. Root mean square error of prediction (RMSEP) for the ASD ranged from 2.4 to 3.3 g C kg⁻¹ depending on soil moisture content of the surface layer (Table 7.4). Imaging spectroscopy performed poorly, mainly due to the narrow spectral range of the CASI. Tests using both the CASI and the SASI performed better. The variation in soil texture and soil moisture content degrades the spectral response to SOC contents. Currently, RMSEP allows us to detect an SOC stock change of 1.9–4.4 g C kg⁻¹ or 4.2–9.9 Mg C ha⁻¹ in the upper 22 cm of the soil and is therefore still somewhat high, at least in comparison with changes in SOC stocks resulting from management or land conversion reported in the literature (0.3–1.9 Mg C ha⁻¹ yr⁻¹; Freibauer et al., 2004). A detailed SOC map produced by IS reflected the patterns in SOC content due to the site's recent conversion from grassland to cropland (Fig. 7.3).

Accuracy of the spectral techniques is lower than that of most routine laboratory SOC analyses. However, the large number of samples that can be analysed by hyperspectral techniques outweighs the slight loss of precision compared to

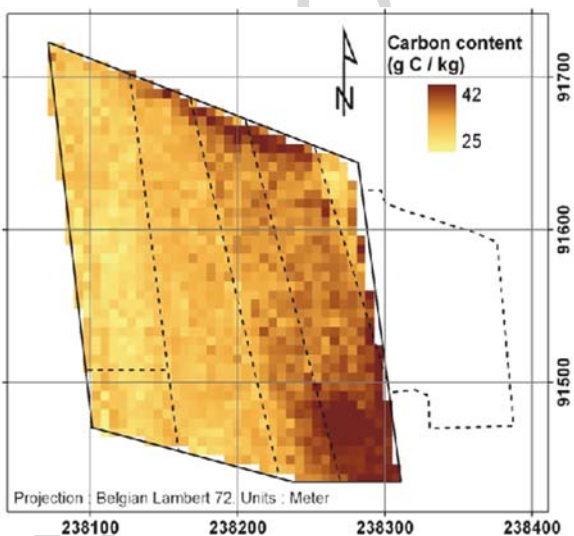
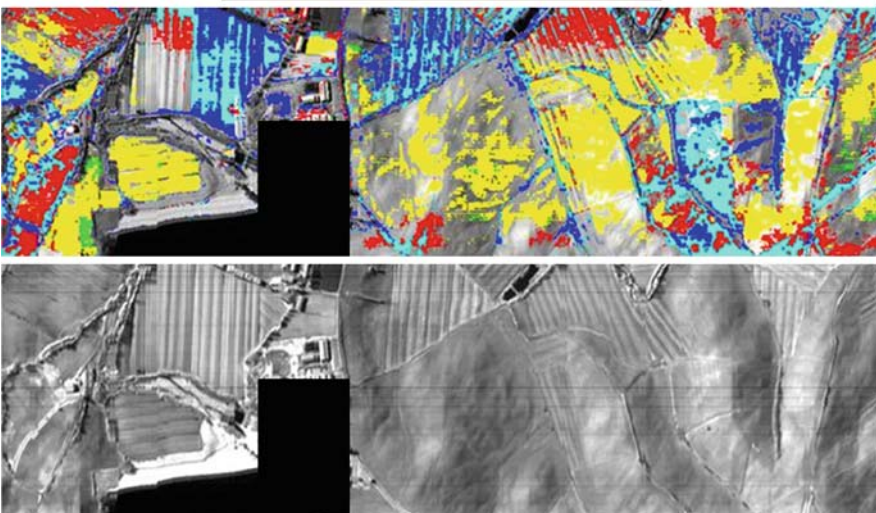


Fig. 7.3 Map of soil organic carbon content in a freshly ploughed field after land consolidation. The borders of the original fields that were joined are indicated with *dashed lines* (Stevens et al., 2006)

406 traditional chemical analyses. The greatest potential lies in airborne applications
 407 because imaging spectroscopy can cover a wide region almost instantaneously and
 408 produce thousands of samples. Relatively poor detection levels are attributed to sen-
 409 sor characteristics (artefacts, noise, and limited spectral range) and factors affecting
 410 the soil spectral response (limited variability in SOC content, disturbing factors).
 411 The problem of disturbing factors will be addressed in the DIGISOIL project,
 412 through an experimental study of the effect of soil moisture, soil texture, and soil
 413 roughness on reflectance. Experiments on soil texture recovery, particularly well-
 414 suited for distinguishing between calcite and clayed minerals and using ULM's
 415 onboard sensors, have already begun (Fig. 7.4). Furthermore, specifications for air-
 416 borne sensors as well as the optimal strategy for calibration and validation will be
 417 documented.

418 Ground-penetrating radar (GPR) is an increasingly used non-invasive and
 419 proximal electromagnetic (EM) sensing technology that can image the subsurface
 420



447
448 **Fig. 7.4** ULM facility and resulting images: one based on Spectral Angle Mapper (SAM) classifica-
 449 tion; the second based on SWIR data where absorption bands of mineral clays ($2.0\text{--}2.4\ \mu\text{m}$)
 450 are present (Univ. Firenze). *Red*: calcite, *green*: chlorite, *yellow*: illite, *blue*: illite-smectite, *cyan*:
 smectite

7 DIGISOIL: An Integrated System of Data Collection Technologies

451 and identify its physical properties (Chapter 25). It is based on sending electromag-
452 netic radiation (ultra-wideband VHF-UHF) into the soil and recording the reflected
453 signals. In areas of agricultural and environmental engineering, GPR has been
454 used to identify soil vertical structures, locate water tables, follow wetting front
455 movement, identify soil hydraulic parameters, measure soil water content, assess
456 soil salinity, monitor contaminants, and delineate soil compaction. Nevertheless,
457 existing GPR techniques still suffer from major limitations due to simplifying
458 assumptions on which they rely, particularly about EM wave propagation. In gen-
459 eral, the radar system and antennas are not accounted for, ray approximation is
460 applied to describe GPR wave propagation, and only the propagation time to reflect-
461 tors is considered in signal processing algorithms. Reflection amplitude can also
462 be used, but this is limited to the surface reflection for airborne GPR, and requires
463 calibrations that are not practical for automated and real-time mapping. As a result,
464 only a part of the information contained in the GPR data is usually used, and signifi-
465 cant errors in the estimates are often introduced. To circumvent these shortcomings,
466 Lambot et al. (2004) have recently developed a new approach: stepped-frequency
467 continuous-wave monostatic off-ground GPR. The off-ground mode is particularly
468 appropriate for real-time mapping of shallow subsurface properties. The radar sys-
469 tem is based on ultra-wideband vector network analyser (VNA) technology. In
470 contrast to classical GPR systems, the physical quantity measured by a VNA is
471 exactly known and defined as an international standard. This permits the use of
472 advanced full-waveform forward and inverse modelling techniques to estimate soil
473 EM properties from the GPR signal, which intrinsically maximises information
474 retrieval from the recorded data. In that respect, Lambot et al. (2004) developed
475 a remarkably accurate EM model for their specific radar configuration, which
476 included internal antenna and antenna–soil interaction propagation effects; they
477 were able to exactly solve the three-dimensional Maxwell equations for wave propa-
478 gation in multilayered media. Through GPR signal inversion, the approach has been
479 successfully validated in a series of controlled hydrogeophysical experiments for
480 electromagnetic soil characterisation (which included dielectric permittivity, elec-
481 tric conductivity, and frequency dependence of these quantities). GPR data inversion
482 has been also integrated with hydrodynamic modelling to retrieve soil hydraulic
483 properties from time-lapse radar data and to monitor the dynamics of continuous
484 water content profiles (Lambot et al., 2006). In addition, the technique improves
485 shallow subsurface imaging, which represents an important asset for determining
486 high-resolution soil stratigraphy. Figure 7.5 shows an example of a field applica-
487 tion where the developed method is used for real-time mapping of the soil surface
488 dielectric permittivity and correlated water content, bridging the spatial scale gap
489 between traditional soil sampling and remote sensing in hydrology.

490 To complement the above-cited techniques, DIGISOIL aims also to explore inno-
491 vative geophysical methods for characterising specific soil properties. In particular,
492 seismic methods will be tested in order to quantify the soil's mechanical modulus, a
493 parameter closely related to soil compaction (Grandjean, 2006). Already validated
494 in geotechnics for investigating zones tens of metres in extent, the challenge will be
495 in adapting the methodology to small seismic devices, i.e. zones of several metres.

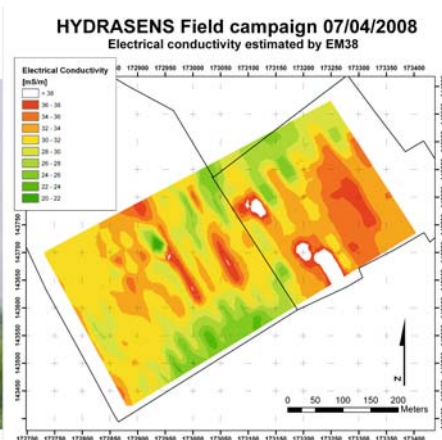


Fig.7.5 Real-time mapping of soil surface water content with advanced GPR (Lambot et al., 2006)

7.5 Conclusions

In order to assess and prevent soil degradation, and to benefit from the different ecological, economic, and historical functions of the soil in a sustainable way, there is an obvious need for high-resolution, accurate maps of soil properties. The core objective of the project is to explore and exploit new capabilities of advanced geophysical technologies for answering this societal demand. Some geophysical techniques that will be carried out in the project are based on positive experiences in the domain and promise to fulfil the objectives of the project. Electrical and GPR measurements, hyperspectral imagery, and more innovative methods like seismic methods will be tested and technically adapted to soil properties mapping. An important output of the project will concern the use of related soil properties in an application dedicated to digital soil mapping (Chapter 5).

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