Chapter 5
Sensing of Natural Soil Properties

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Abstract Site-specific sensing of varying natural soil properties is a prerequisite for an adequate control of many field operations.

Topography can be mapped rather easily as a byproduct of other farming operations by means of RTK-GPS. Information about clay, moisture and salinity of soils in a combined mode can be obtained via electric conductivity sensing. In humid areas, salinity can be left out. So here the electric conductivity is defined mainly by a combination of clay- and water content of the soil. The combined effect of these factors is well related to the yield potential of soils. Hence in humid regions, electric conductivity sensing can supply information that is needed for the control of farm operations according to yield expectations.

Electric conductivity sensing is based on soil volumes that may include the topsoil as well as the subsoil. In contrast to this, the reflectance of visible or infrared light senses only soil surfaces and thus may be less representative. Yet reflectance sensing might supply signals simultaneously about several soil properties such as texture, carbon content, cation-exchange-capacity and water content.

Keywords Capacitance • Electrical-conductivity • Permittivity • Reflectance • Surface-sensing • Topography • Volume-sensing

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5.1 Sensing of Topography

Soil properties depend to a large extent on nature, yet partly also on human activities. Both nature as well as human activities can result in spatial variations of soil properties that should be taken into account for site-specific farming. This chapter deals with properties that mainly depend on nature such as

- topography
- texture
- organic matter content
- cation-exchange-capacity
- water content
- salinity.

Soil properties that in modern farming predominantly depend on human activities, such as the supply with nutrients, are dealt with in later chapters.

Topography affects farming in many aspects. Its long-term influence on run-off of water and thus on erosion results in distinct differentiation of soil qualities between uphill- and downhill locations. Short-term effects come from the fact that the inclination of fields to the sun influences the temperature of the soil. The less oblique the solar radiation hits the soil surface, the more energy is transferred per unit area and hence the higher the soil temperature is. This explains why generally fields with slope aspects that are oriented to the South are preferred in most areas of the Northern latitudes of the sphere. It is *vice versa* in areas of the Southern latitudes, here fields that are oriented to the North are more valuable in most cases.

The resulting effect of **slope orientation** on crop growth can be vast. In some areas of the Northern hemisphere, wine is only grown on slopes that are oriented to the South. Even with small cereals, the effect of slope orientation on yield can be significant. Studies of Geary (2003) with a CERES wheat model show a loss in grain yield of 1 t/ha on a slope of 10 % oriented to the North in England.

Implications for precision farming come from the influence of topography on soil qualities, on water run-off and on yield potential. When the yield potential of a field changes as a result of varying field inclinations as well as of slope orientations, both the economy and the environment ask for adapting the input of agrochemicals to this. Site-specific operations in fertilizing and crop-protection can provide for that. Variations in soil qualities, in water run-off and thus on the prerequisites for erosion within a field call for site-specific responses in cultivation intensities. Details to respective responses are dealt with in Sect 7.2.

Yet reliable site-specific data about the relief of fields are prerequisites for any responses to topography. Traditionally, these data for relief- or contour maps have been obtained via conventional manual techniques by using theodolites and level surveying. Modern techniques for sensing and recording of topography are widely automated and include sensing methods such as

- **radar interferometry** (comparing phases as well as amplitudes of outgoing- and reflected satellite radar radiation)

- **laser light** of the ultraviolet, visible or infrared range from satellites or from aerial platforms and its reflection (transit-time)
- **inertial georeferencing** by recording linear- and rotational accelerations on a moving vehicle (see Sect. 4.4.1)
- **real-time kinematic georeferencing** via Global Navigation Satellite Systems (RTK-GPS).

With adequate processing, all methods can record modules that are used in **digital elevation models** (DEM) in order to provide for contour- or topographic maps. These can then be used to control farm operations. Such maps can be obtained in some countries or areas from geological institutions. However, often the maps from geological institutions do not provide the resolution that site-specific farming operations require, and the layout may not correspond to the respective field sizes.

Probably the best method for most cases is to rely on topographic maps that are created via the georeferencing system that precision farming needs anyway. For many farms in the future, this will be RTK-GPS or at least differential GPS based on carrier phase signals and dual frequencies (Table 3.4), sometimes in combination with inertial georeferencing on slopes. This procedure of relying on the respective **farm-specific georeferencing method** does not require separate trips through all fields. Instead, the topographic maps can be obtained as a **byproduct** when driving through the fields for other purposes, which principally can be any field operation. However, in order to cover the site-specific situation within fields well and to obtain a good resolution, it might be reasonable to omit operations that are performed with very wide widths, *e.g.* spraying.

The precision that is obtained can be enhanced by repeated recording of georeferenced topography in the same field and **averaging** the results. This prospect is challenging and promising since with an adequate software this farm-specific georeferencing of the topography can be a process that goes on rather casually and automatically along with field operations (Westphalen et al. 2004). Results about the effect of such a repeated recording of topography on the precision are presented in Fig. 5.1. The standard deviation of the error that occurred when the elevation was recorded by RTK-GPS only once in a field operation was between 12 and 20 cm. This result was halved to between 6 and 10 cm when the records from four field operations were averaged. The respective spans in the results were due to different speeds of the operations. A halving of the standard deviation was also obtained when during one field operation, both RTK-GPS and inertial sensing were used simultaneously and the results were combined. Recording the elevation in a "stop and go" mode instead of an "on-the-go" method did not change the results much.

However, a question is how with repeated recordings of the elevation the averaging should be done. An easy and obvious approach is to use **arithmetic averages** of the elevation data per grid element within the field. The results for the repeated measurements in Fig. 5.1 are based on such a procedure. An alternative to this procedure is the use of **weighted averages** per grid element. The theoretical background for this is the concept that the data from one field operation may contain more errors than those from another run. But on which basis should such weighted averages be calculated?

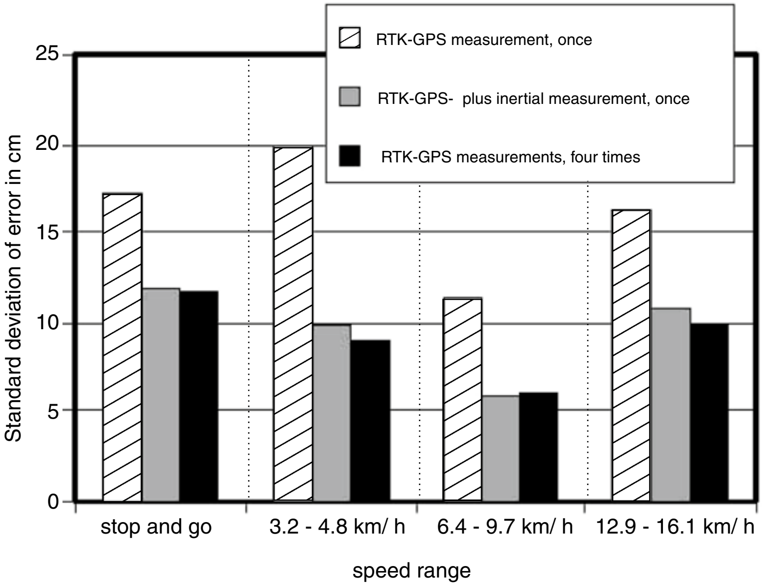

Fig. 5.1 Standard deviation of error when recording digital elevation models (From Westphalen et al. 2004, altered)

Abd Aziz et al. (2009) concluded that from each field operation the intermediate results of the subsequent krigings (see Sect. 2.4) can provide an indication for the weighing of the data. The kriging – if it occurs for blocks or grid elements – is associated with a variance of the respective data per run within each grid element. This implies that several data per block or grid element accumulate. The smaller the variance of the data within a grid element is, the better the respective elevation estimate is supported by the measured data and *vice versa*. Consequently, the averaging function weighted the elevation estimate based on the variance within the respective grid element. For details to this see Abd Aziz et al. (2009).

This processing of the data by weighted averaging instead of simple averaging reduces the errors in digital elevation models (DEMs), especially when a higher number of surveys is combined (Fig. 5.2). Since such topographic elevation maps can be generated as a byproduct, including a higher number of surveys hardly affects the costs.

Among the various methods that principally are available for generating digital elevation models or topographic maps, **RTK-GPS georeferencing** can be regarded as a favourite, possibly in combination with inertial georeferencing. This technology is needed anyway for guidance- or control purposes in precision farming. So investments on additional hardware are not needed, solely adequate software must be obtained. This procedure makes it possible to get digital elevation models and maps that precisely have the resolution and layout that fits to individual fields. These digital elevation models or maps can be used for several decades, since the topography of fields hardly changes over time.

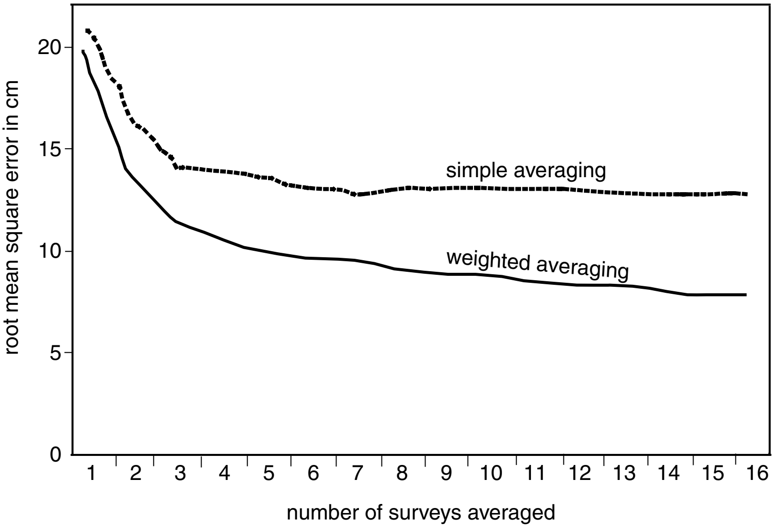

Fig. 5.2 Errors with averaging methods used for field elevation data. Effect of combining repeated elevation surveys of RTK-GPS by either simple averaging or by weighted averaging of the error data (From Abd Aziz et al. 2009, altered and simplified)

5.2 Sensing of Soil Properties on a Volume Basis

Natural soil properties such as texture, water, organic matter and salinity influence the yield potential. Georeferenced knowledge about these properties can assist in pinpointing the site-specific control of cultivation-, sowing-, fertilizing- and crop protection operations.

Spatial variations within fields are frequent for all these soil properties. Compared to this, **temporal variations** are important only for soil moisture. This has implications for mapping practices. Maps about texture and organic matter content are useful and once properly created can be up to date to assist farming for decades. But because of the varying weather, maps about the site-specific water content can be obsolete within a few days and in rain-fed areas therefore seldom are of interest except for research purposes. However, the situation for soil water is completely different when online and on-the-go control of farm operations and hence instant reaction is possible. This control can be very useful for site-specific adjustments of irrigation operations, of the depth of cultivation or the depth of sowing.

In the past, the **spatial resolutions** in the recording of the data were insufficient. The costs of manual soil sampling in the field and subsequent expensive analysing in laboratories for texture, organic matter and water did not allow for high resolutions. Often data from only one site per ha were analysed, which in most cases did not at all provide a reliable basis for precision in site-specific operations. Handheld measuring instruments can save sending the samples to laboratories, yet for high spatial resolutions still imply laborious manual sampling procedures. Either online and on-the-go procedures for proximal sensing or alternatively remote sensing methods are needed, at least for site-specific farming on large areas.

The sensing concepts that are available for this rely almost exclusively on **electromagnetic radiation** or on **electric current**. The wide spectrum of electromagnetic radiation provides for a huge variety of sensing alternatives. The interest is focussed on using visible as well as infrared light, micro- or radarwaves and finally also on electric current as indicators for soil properties. It is important to realize that in all cases no direct indications of soil properties are possible. The indications always are indirect phenomena. The respective soil properties can at best influence details of the radiation or current such as amplitude, frequency, speed of propagation *etc*. Via changes in these details it is possible to make deductions or inferences for soil properties. In short, the estimations of the soil properties are based on correlations to physical details of electromagnetic radiation or electric current. These correlations allow to use intermediates that can easily be sensed or recorded online and hence applied for a control.

It is very important to realize for which part of the soil the sensing should take place. Should the information about the respective property be obtained on a soil **volume basis** or on a soil **area basis**? The interest in most cases is focussed on a soil volume basis. The crops rely on texture, organic matter and water for a soil depth that approximately equals the vertical root length. Hence the respective properties in the topsoil as well as in an adjacent part of the subsoil count. So if the maximal vertical root length is about 1 m, it might be appropriate to get site-specific signal averages that are related to this soil layer.

But there are exceptions for which such averaging procedures do not comply to the needs. A special case for which such coarse averaging does not fit is when sensing **water in the seedbed zone** solely is required. In this special situation it might be reasonable to sense at which depth a dry topsoil zone ends and a subjacent moist zone precisely begins, where then the seeds should be placed. Hence in this special case the objective would be more a method of water sensing on a two dimensional basis. Or if the sensor scans along a **vertical cross section** within the soil, it could be defined as **sensing for a water line**. In addition, there may be reasons for controlling the application of soil-herbicides according to the organic matter content of the soil just at its surface, hence also for sensing this soil property on an area basis. There may be additional cases where sensing on an area basis or on a line basis conform to the needs.

If sensing properties on a volume basis is the objective, getting the signals from the surface would suffice only if the soil constituents were uniformly distributed within the volume. This usually is the case for the topsoil that is cultivated and thus mixed. But this does not hold for the subsoil. So if information about soil properties is needed within the layer that the roots of the crops penetrate, signals that are obtained from the soil surface alone do not suffice. One- or two dimensional sensing of soil water or soil organic matter can be reasonable for the special cases of controlling the sowing depth or the application of soil herbicides as explained above. This does not alter the general need for sensing texture, organic matter and water on a three-dimensional or on a volume basis.

Table 5.1 Methods of sensing soil properties on volume bases via electricity or via radiation

Frequencies	Wavelengths[a]	Sensing objectives	On-the-go use
Electrical conductivity, contact methods			
0–1 kHz	Infinite – 300 km	Texture, water, salinity, soil-layers	State of the art
Electrical conductivity, electromagnetic induction methods			
0.4–40 kHz	750–7.5 km	Texture, water, salinity, soil-layers	State of the art
Electrical capacitance			
40–175 MHz	790–200 cm	Water	Possible
Time domain reflectometry			
50–5,000 MHz	600–6 cm	Water	Not yet possible
Soil penetrating radar, surface reflection mode			
0.5–30 GHz	0.60–1 cm	Water	Possible
Micro- or radarwaves, mainly satellite based sensing			
0.3–30 GHz	100–1 cm	Water, roughness of soil surface	Does not apply

Compiled from data by Allred et al. (2008); Corwin (2008); Lesch et al. (2005) and Lueck et al. (2009)

[a] From higher range- to lower range limits, thus corresponding to frequencies

This distinction between volume sensing on the one hand and surface- or area sensing on the other hand is necessary since not all electromagnetic waves are able to penetrate the soil. Especially visible and infrared light only provide signals that are based on the soil surface that was hit. The situation is different for microwaves, radar waves as well as for electric currents and its electromagnetic waves. Some criteria that refer to **volume sensing techniques** are presented in Table 5.1.

Among the alternatives listed there are two techniques that can operate online as well as on-the-go and already have been introduced widely into practical farming: **electrical conductivity**- and **electromagnetic induction** sensing. These methods operate either with direct current or with alternating current on the lowest frequency end and consequently with long waves. The soil properties that can be derived from the signals of these methods are not without ambiguity. This will be dealt with later. **Electrical capacitance** sensing operates in medium ranges of frequencies and wavelengths (Table 5.1) and depends on the soil water content. This method can be used online and on-the-go as well, but up to now seldom is state of the art in practical farming. **Time domain reflectometry** is based on radar- or radio frequency signals that are guided along a transmission line or cable that is embedded in the soil. Therefore the denotion often is "cable radar". The velocity of wave propagation depends on dielectric soil properties and thus can indicate the soil water content, but not yet for on-the-go operations. The situation is different if **soil penetrating radar** is used in a surface reflection mode for water sensing. This method in principle is suited for on-the-go sensing, but despite this up to now hardly is used in farming. The same applies to soil water sensing by **micro- or radarwaves from satellites**, a method that at present can be excluded for online and on-the-go control of farm operations, but might become very useful for tactical inspections of wide areas.

5.2.1 Methods for Sensing of Electrical Conductivities

Electrical conductivity is a measure of the ease with which an electric current flows through a substance, in this case through soil. It is indicated in units of Siemens per m (S/m). Occasionally the electrical resistivity – the reciprocal value – is used instead of the conductivity.

The electric current is introduced into the soil either by direct **galvanic contact** or by **electromagnetic induction** between the measuring instrument and the ground. Hence the sensing occurs either in an intrusive or in a non-intrusive way. In both cases the reactions of soils to electricity are sensed.

Soil is a very heterogeneous matter for an electric current since it consists of solids, gases and liquids. All these components can vary immensely. The solids include both mineral- and organic matter. If rocks and unbound organic matter are excluded, they can be broken down by particle diameters into sand (2.00–0.05 mm), silt (0.05–0.002 mm) and clay (less than 0.002 mm). Sand is primarily quartz and – if dry – can be considered as an electrical insulator. The clay size fraction is made up not only of clay minerals, but in addition of organic matter that is bonded to the minerals. These clay-humus bonds contribute considerably to current flow in soils, especially under wet conditions. Silt has an intermediate position. While the air in the soil too is a good insulator, the liquids can be regarded as an electrolytic aqueous solution with ions that are dissolved in it. The ions in the liquids as well as on the surface of clay-humus bonds are mainly responsible for current flows in soils.

5.2.1.1 Methods Based on Galvanic Contact with the Soil

Theoretically, either direct current or alternating current up to a frequency of 1 kHz can be used (Table 5.1). *Ceteris paribus*, direct current senses deeper. But the electrodes that introduce the direct current into the soil can get polarized by ions and thus can loose electrical contact. This problem is alleviated by employing low frequency alternating current (Allred et al. 2008), which some geologists still denote as direct current. The present commercial implements mostly run on alternating current with frequencies between 150 and 220 Hz (Lueck et al. 2009).

The sensing process is a rather simple procedure. The current flow occurs between a rolling coulter at the left and right side of the machine (Fig. 5.3). The conductivity of the soil is sensed by one or more pairs of voltage coulters that roll between the current coulters.

A principally still simpler procedure would be to use only two electrodes for sensing both the current flow and the voltage between them. Although this configuration can be used, it is more unstable (Corwin 2008). The method of using an outer pair of current electrodes and at least one pair of separate voltage electrodes between them that provides the data about the soil properties goes back to Wenner (1915). It is consequently denoted as a "**Wenner array**". This array has proven to supply more reliable results.

The sensing implement can be pulled by a vehicle with speeds up to 15 km/ h. The distance between measurement passes should be adapted to local soil variations, it usually ranges from 6 to 20 m. Consequently between 60 and 200 ha can be

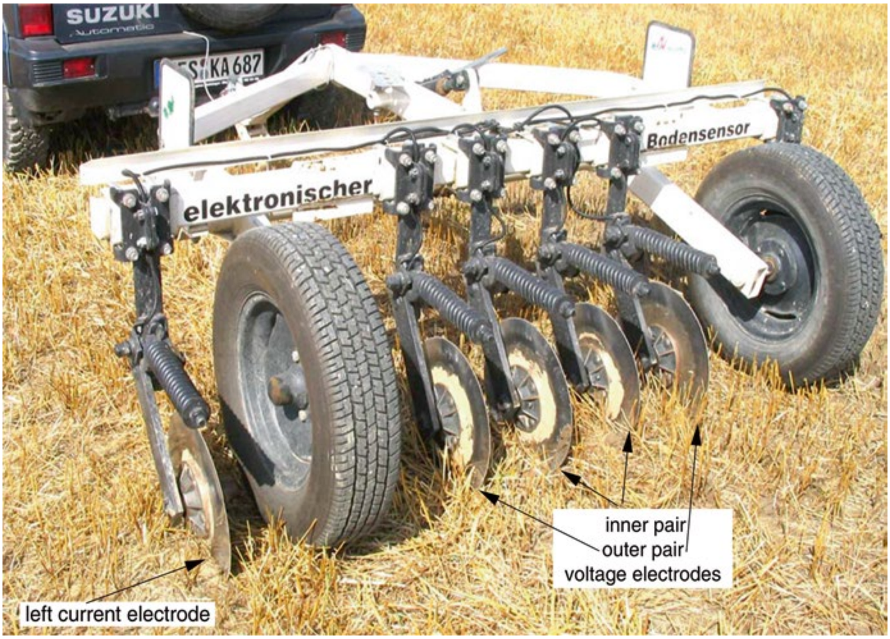

Fig. 5.3 Online and on-the-go sensing of soil electrical conductivity by a contact method, System Veris. The right current electrode is concealed by the wheel (Photo from Lorenz, Lufa Nord-West, Oldenburg, Germany, altered and supplemented)

sensed, georeferenced, logged and mapped per day. About 120 readings are obtained per ha, so the spatial resolution is very much better than with conventional soil testing methods. Yet soils that are frozen, very dry, stony or covered with much residues can prevent the application.

The volume of soil that is sensed with the Wenner array can be adjusted. It includes all the soil between the respective pair of voltage electrodes from the soil surface to a depth that equals approximately the horizontal distance between the voltage electrodes. Thus, taking the signals from the outer pair of electrodes instead of the inner pair (Fig. 5.3) allows increasing the depth of sensing.

5.2.1.2 Methods Based on Electromagnetic Induction

Electromagnetic induction occurs when a magnetic field crosses a conductor or *vice versa*. In this case, the soil is the conductor. The implement that generates the primary magnetic field just is moved at a defined distance above the soil. Travel speed and area capacity can be about the same as with contact methods (see previous section).

However, whereas the contact methods might use current that can be quasi or almost direct current (see above), electromagnetic induction methods rely on alternating current with a frequency well in the kilohertz range (Table 5.1). This is because the induction process needs alternating current.

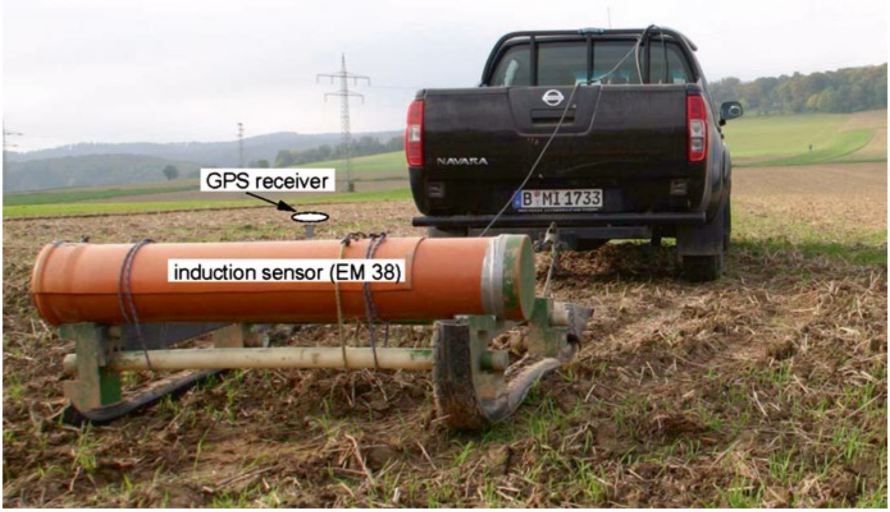

Fig. 5.4 Online and on-the-go sensing of soil electrical conductivity by electromagnetic induction. The sensing instrument (EM 38 of Geonics LTD, Canada) can be moved on a sled, on a cart or even be carried by hand. In order to prevent interference from metal, some distance to the vehicle is needed (Photo from Agri Con GmbH, Jahna, Germany, altered)

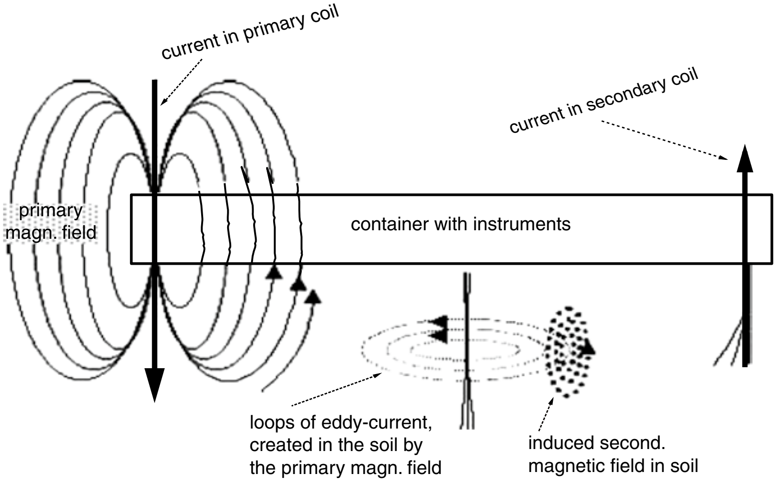

Fig. 5.5 Operating principle of soil sensing by electromagnetic induction (From Lesch et al. 2005, altered and supplemented)

The sensing implement (Figs. 5.4 and 5.5) has two wire coils, a primary- or transmitter coil plus a secondary- or receiver coil. The current that flows through the transmitter coil produces a magnetic field around it. This magnetic field also extends into the soil and thus produces there a **primary magnetic field**. While the implement moves, this primary magnetic field induces an eddy current within the soil. This eddy current in turn causes a **secondary magnetic field**. Finally, both magnetic fields induce currents in the second wire coil. This current varies with the soil properties. The measurement units are the same as with conductivity methods that rely on direct contact, namely Siemens per m (S/m). So actually, conductivity units are sensed, but the conductivity is created by electromagnetic induction.

Because of the indirect measuring approach, the induction sensing is more difficult to calibrate than contact methods that intrude the soil. The respective adjustments in the field need more time (Sudduth et al. 2003). On the other hand, the soil penetrating methods rely on good electrical contact between the coulters and the soil, which can be a problem on dry or stony soils. This problem does not exist with induction methods.

5.2.1.3 Depth of Sensing and Soil Layers

The sensing depth should fit to the maximal vertical soil penetration by the roots. For many crops, this vertical penetration by the roots is in the range of 70–150 cm. The penetration of the conductivity sensing can in a simplification be perceived as a vertical cross section that starts at the soil surface. It is not precisely known whether this ***vertical cross section*** perpendicular to the direction of travel should be oriented at a rectangle – whose vertical side equals the root penetration depth – or whether such a schematic approach is too fussy. Since the root density with many crops decreases beyond a medium depth, it might be reasonable to aim for a sensing density that too gradually tapers off with depth. The present sensing methods actually follow this approach.

Principally, several possibilities exist for increasing the depth of sensing. For a contact method (Fig. 5.3) this can be done by

- extending the distance between the voltage electrodes (Sect. 5.2.1.1)
- using lower frequencies.

With electromagnetic induction, an increase in sensing depth can be obtained by

- changing the coil orientation from a horizontal mode to a vertical mode
- lowering the height of the sensing implement above the soil
- increasing the lateral distance between the coils
- using lower frequencies.

Most sensing implements that are used commercially at present allow only for one or two of these adjustments. The contact sensing method of Fig. 5.3 is presently widely applied in the USA. It permits only to choose or alternate between two different distances of the voltage electrodes. The electromagnetic induction method of Fig. 5.4 is dominating in Europe and Canada. It allows for changing the coil orientations and for adjusting the height of the implement above the soil.

The measured reading for a soil layer of a given conductivity depends on the distance from this layer to the instrument. An important point is how in detail the vertical distances to the soil affect the results. **Response curves** that compare the presently used techniques under *ceteris paribus* conditions show the depth effects (Fig. 5.6).

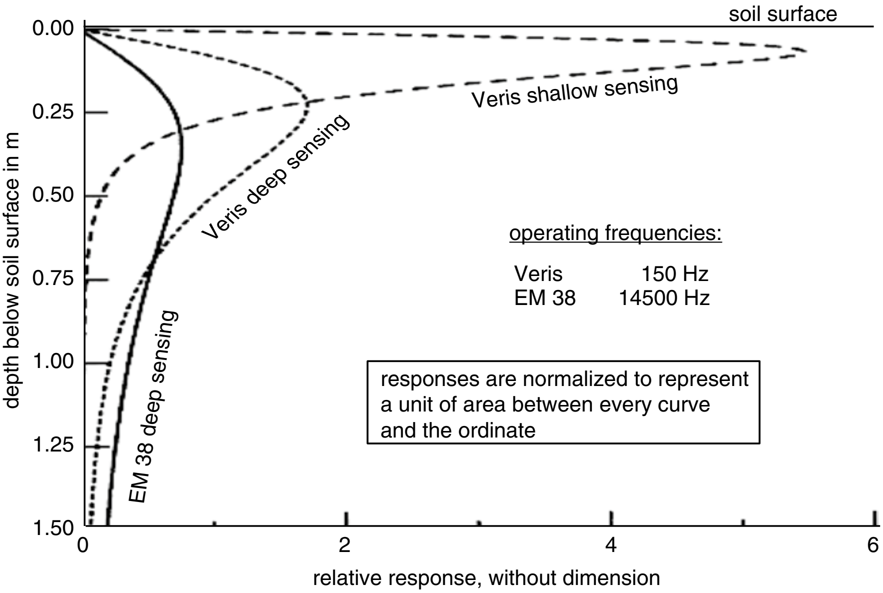

Fig. 5.6 Relative response of conductivity sensors as a function of depth. For details to the implements Veris and EM 38 see Figs. 5.3 and 5.4 (From Sudduth et al. 2005, altered)

The objective should be to have a depth weighted sensed area that approximately incorporates the maximal root expansion during the growing season of all crops within a rotation. Since principally several possibilities exist for adjusting the sensed depth, it should at least roughly be tried to get the sensed vertical cross-section adapted to this. However, going beyond the maximal root depth probably is less disadvantageous than falling behind it, since during dry periods some water is sucked from deeper horizons to the roots.

Important is also that sensing along a defined response curve pretends a uniform soil electrical conductivity within the respective vertical cross section for the whole field because the sensed signals are **integrals**. A soil with uniform properties within the vertical cross section on the one hand and another one that is composed of different layers within the sensed section on the other hand can result in the same integrated signal.

So sensing along a single defined response curve is a sensible and target-oriented procedure only with soils that have uniform properties within the rooted depth. This method can be misleading with **layered soils** since no depth resolution is delivered. And there are many soils that have special layers or horizons within the subsoil. One the one hand, these layers may prevent the drainage of water when they consist of dense claypans or similar gleysolic, hydromorphic horizons. On the other hand, there may exist layers that let seep the water too fast and hence do not store enough of it because they are made up from coarse sand and gravel. And all layers may not be positioned parallel to the soil surface. So in a three-dimensional analysis, there can be a variety of different soil conditions.

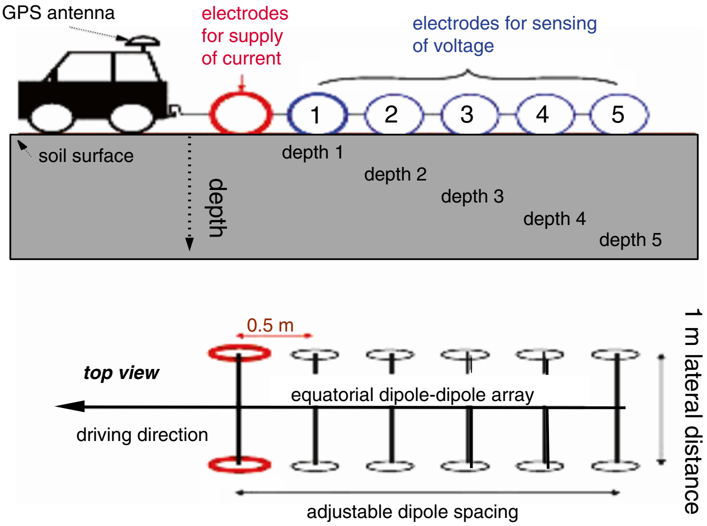

Fig. 5.7 Sensing electrical conductivity in a contact mode by the Geophylus electricus via rolling electrodes that are spaced in the direction of travel (From Lueck et al. 2009, altered)

A response to this problem for layered soils is successive or simultaneous sensing along response curves that have different **gradients with depth**. It has been shown (Mertens et al. 2008; Saey et al. 2009; Sudduth et al. 2010) that special software and differences existing in the response curves of the present sensing implements allow for a rough delineation of soil layers. In case the soil within a field consists of only two layers with distinct differences in electrical conductivities, this vertical horizon sensing can be quite successful.

A special data processing technique has been developed – called **inversion of electrical conductivity** measurements – that aims at mapping special layers or horizons. This technique is not simple since the sensed volumes of different response curves (Fig. 5.6) overlap and because it must be prevented that different combinations of layers with their respective conductivities generate the same final result (Gebbers et al. 2007; Sudduth et al. 2013). It is obvious that the precision in the detection of soil layers can be enhanced if signals from more than two response curves within the respective soil depth can be obtained.

The "**Geophilus electricus**" – a development of the University of Potsdam and the Technical University of Berlin – delivers signals along five response curves or even more simultaneously on-the-go (Lueck et al. 2009; Lueck and Ruehlmann 2013; Radic 2008). The implement is based on rolling electrodes, so it operates in the contact mode as the instrument in Fig. 5.3. The rolling electrodes are spiked at the circumference. However, the current electrodes on the one hand and the voltage electrodes on the other hand are not arranged on one axis perpendicular to the direction of travel (Fig. 5.3), but instead they run in pairs that are separated in the direction of travel (Fig. 5.7). Five voltage electrode pairs – spaced at successive distances in the direction of travel behind the current electrode pair – independently sense electrical conductivity. With increasing distance between the current pair of electrodes and a respective voltage pair, signals from deeper soil are delivered. The increased number of response curves allows a more accurate resolution of depth signals. Hence principally the prerequisites for precise three-dimensional recording and mapping of electrical conductivities via inversed signals are better.

Further enhancing of the depth resolution is possible by varying **electrical frequencies** within the range of 1 mHz to 1 kHz and thus increasing the depth of sensing by lower frequencies or *vice versa*. Four different frequencies can be sensed simultaneously, which multiplied with five voltage electrode spacings allow to record 20 response curves almost simultaneously on-the-go. And when operating at the higher frequency ranges even more than 20 response curves can be obtained. This is because current with higher frequencies is at least partly transferred by induction via its magnetic field and not solely via conduction. And the transfer via induction instead of conduction causes phase shifts in alternating current. Since these phase shifts diminish the power that is transmitted, they too can be recorded and allow to obtain additional response curves.

Operating modes such as travel speed, field capacity and number of local readings per ha come up to those mentioned in the latter part of Sect. 5.2.1.1.

This method is not yet used commercially and more experimental experience might be necessary (Lueck et al. 2009). And more response curves alone do not alter the fact that there still is overlapping for all response curves near the soil surface. This is because all response curves – even if these successively go deeper and hence differ in shape – still originate at the soil surface similar to the gradients shown in Fig. 5.6 from other sensing instruments. By elaborate post-processing that involves **inversion** of all electrical conductivity measurements, mapping of rather thin layers or horizons might be possible – as mentioned above (Gebbers et al. 2007). In the future, powerful computers might even allow to do this on-the-go.

Another approach for a more detailed depth resolution and hence better sensing of soil horizons is based on **varying the coil orientation** of the electromagnetic induction system (Figs. 5.4 and 5.5) continuously on-the-go between the vertical and the horizontal position (Adamchuk et al. 2011). Hence the vertical horizon is scanned in modes that alternate between deep and shallow readings. This concept allows to sense in varying depths with a very compact implement. Postprocessing of the response curves via inversion procedures here too is necessary.

The prospects of thus sensing soils in three dimensions with a high resolution deserve attention. It is not the layers or horizons of soils alone that are of interest. Equally important is what happens to the water that is moving through the soil. The water travels through the soil to water tables on top of the saturated soil zone and from there into rivers and might carry nutrients from mineral- or organic fertilizers as well as even pesticides with it (Schepers 2008). Hence there is increasing concern about the **preferential water flow** routes that bypass most of the soil and can be regarded as traffic lanes for an unwanted transport of these components into the environment. Soil electrical conductivity is related to the water content and thus principally also to preferential water flow routes. However, there exist substantial

Table 5.2 Soil types and electrical conductivities

Soil texture class or influence of salt	Electrical conductivity in mS/m
Sand	0.1–1.0
Loamy sand	1.0–5.0
Loam	5.0–12.5
Silt	12.5–25.0
Clay	25.0–100
Saline soil	>100

From Bevan (1998), simplified and altered

temporal differences for the situation of soil layers on the one hand and water flow on the other hand. The soil layers hardly change over time, but the water flow does. Hence sensing the preferential water flow will depend on **change detection** by means of repeated recordings over time. And reliable signals probably will need specific electrical frequencies as well.

Future experience will have to show, how much vertical **horizon sensing** is needed and for which cases simpler procedures of uniform **volume sensing** with a depth that approximates the maximal vertical root length is sufficient.

5.2.2 Electrical Conductivities, Soil Properties and Yields

The sensing results in units of electrical conductivity partly depend on the temperature of the soil and of the measuring devices. To eliminate this effect, an adjustment according to the prevailing temperature is necessary. This applies especially when conductivity is sensed via electrical induction. Provided the implements are well calibrated, properly adjusted and are sensing the same soil depths, the results for the common systems – the contact method (Fig. 5.3) as well as the induction method (Fig. 5.4) – are very similar (Sudduth et al. 2003, 2005). Therefore, the results will be dealt with *in cumulo*.

The sensed soil properties can be divided up on the one hand in fairly **static properties** such as texture and organic matter content and on the other hand in **dynamic properties** that vary in time as *e.g.* water content. Generally, soil texture can be regarded as the most static property. Its influence on the electrical conductivity is listed in Table 5.2.

Within the texture classes, **clay** exerts a dominating influence. Contrary to this, the effect of sand theoretically is close to zero. But in reality it is not since an autocorrelation exists between the contents of sand and clay in a soil. Because the higher the content of sand is, the lower the shares of clay and other soil constituents become.

The pre-eminent influence of clay results from several facts. Firstly, the clay fraction has the highest ion exchange capacity of all texture classes. In the absence of electrical conductors like metallic materials with movable electrons, the exchangeable ions are the carriers of electricity. But secondly, the ions need a moist medium – sufficient water – to fulfill this function. The clay also supplies this prerequisite. This is obvious when the **field capacity**, which is the moisture held in soil after excess water has drained away and the downward movement has stopped, is compared. At field capacity, a pure sandy soil would have about 15 % volumetric water, whereas the content for a clay soil can go up to 50 % (Lueck and Eisenreich 2000). And a third factor contributes to the electrical conductivity of clay soils. In most cases, the soil content of organic matter increases with its clay content. This can be the long-term result of the higher water content of these soils, since this decreases the decomposition of the organic matter. In addition, many clay constituents can form special bonds with decomposed products from organic matter. The clay-humus bonds that thus are created still further enhance the water holding capacity of soils. So in essence, a positive interaction between clay, water and organic matter can further enhance the high electrical conductivity of the clay fraction. The clay constituents – left alone – cause only part of this effect. And the interaction between clay and water means that on a temporary basis neither static properties nor dynamic properties completely dominate (see above). Yet this situation exists in reality for all texture classes as a result of varying moisture in the soil.

Excessive electrical conductivities exist in **saline soils** (Table 5.2). These soils are found in dry, arid regions when hardly water moves downward in soils, but instead water is sucked to the surface where it evaporates. This water transports **dissolvable salts** towards the surface plus topsoil and leaves them there. The resulting salinity limits water uptake by plants because it reduces the osmotic potential for this.

The dominating effect of salinity explains why historically the sensing of soil conductivities started in arid regions (Corwin 2008) and from there later spread out into humid areas as well. And it must be mentioned that Table 5.2 conceals the fact that the electrical conductivity always is defined by interactions of several factors. If the influence of temperature on the signals is eliminated by means of careful calibrations, adjustments or post-processing, there remain three important factors or parameters in **arid regions**, namely the concentration of salt ions in the soil water, soil texture and water content. In more **humid areas** where no accumulation of salts near the soil surface has taken place, the dominating factors that affect the conductivities are just texture and water content of the soil. Less important factors such as the bulk density of soil here can be left out.

5.2.2.1 Electric Conductivities and Soil Properties in Humid Areas

Figure 5.8 shows an example of the influence of texture classes on electrical soil conductivity for humid conditions. The sensing was done in two fields in an EM 38 vertical mode, thus with a depth up to about 1.5 m (Fig. 5.6).

For both fields, the effects of clay were in the same direction and similar, therefore, the signals were pooled. So the data from both fields appear on the same regression, but they stand for different ranges of clay content.

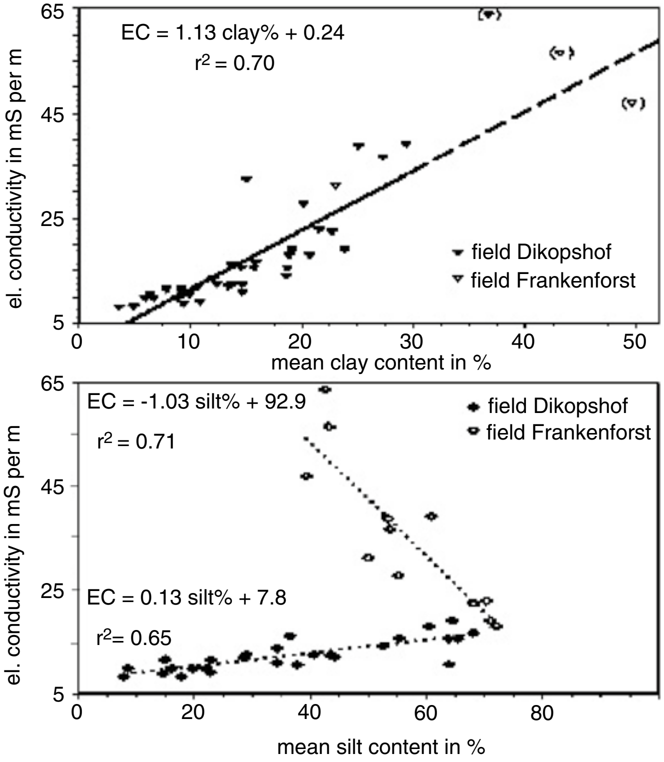

Fig. 5.8 Electrical conductivities depending on the clay- and the silt contents of two soils near Bonn, Germany. For both soils, the effects of the clay on the conductivities were similar. Therefore, the results are presented in a common regression (*top*). Data points in *brackets* were excluded from the calculation. The effects of the silt were quite different (*bottom*). A comment to this is in the text (From Mertens et al. 2008, altered)

However, the sensing method does not provide for signals about different layers within the depth response curves, it supplies averaged data for the whole sensed depth. The topsoils of both fields are mainly loams that originated from loess with varying thicknesses between some cm and 1.5 m. The subsoil of both fields is quite different, for the field Dikopshof it is sandy and for the field Frankenforst it is clayey. These differences in the subsoil mainly cause the shifting of the clay points for Frankenforst to a much higher range. So the textures of both soils were different not only horizontally but especially in vertical directions.

Theoretically, the silt content should have only a small- and the sand content almost no influence, since the conductivity is mainly defined by ions of the soil constituents. However, **autocorrelation** with the clay content must be considered. Sand content is defined when clay- and silt content are known since these three texture classes add up to about 100 %. And apart from sand, even the silt content alone can depend on the clay content. When the clay content is very high, there is less space left for silt. So if total autocorrelation for the sand content holds when

Table 5.3 Correlation between soil properties and electrical conductivities

Soil properties	Corr. coeff. squared (r^2) to surface-layer soil	Corr. coeff. squared (r^2) to soil profile-averages
Soil moisture	0.50	0.24
Clay	0.66	0.72
Silt	0.30	0.28
Cation-exch. cap.	0.70	0.70

The horizontal surface-layers and the vertical soil profiles denote the places where the reference samples were taken (averages for 12 fields in the North-Central USA, extracted from Sudduth et al. 2005)

clay- and silt content are defined, at least partial autocorrelation for the silt still applies, when the effect of a high clay content is known.

It is this partial autocorrelation to the effect of clay that probably explains the contradictory results about the influence of the silt content on the electrical conductivities (Fig. 5.8, bottom). The depth weighted clay contents in the field Frankenforst are much higher than those in the field Dikopshof. The misleading effect of autocorrelation thus probably was much higher in Frankenforst than in Dikopshof. In short, the results shown in Fig. 5.8, bottom, might be uncertain.

An important question is the respective impact of clay on tbe one hand and water on the other hand on electrical conductivities. Table 5.3 shows summarized results of extensive sensing with the presently dominating systems either by contact methods (Fig. 5.3) or by induction (Fig. 5.4). The depth of sensing corresponded to the **deep response curves** in Fig. 5.6. Since with well adjusted implements the records for the contact- or induction methods are similar if the depth that is sensed is about the same, such results were pooled. Effects of salinities on the signals probably can be ruled out, since these are based on areas with humid climates. The results are presented separately for reference samples taken from surface-layers (topsoils) and for samples that came from vertical soil profiles that include the effects of respective subsoils.

For both cases, the influence of the soil moisture on the electrical conductivity is lower than the effect of the clay content (Table 5.3). The influence of the silt too is rather low. The correlation to the site-specific cation-exchange capacity (CEC) is on a similar level with the clay content. This is in line with basic expectations since it is the clay particles in combination with organic matter bonded to them that mainly provide the cation-exchange capacity. Moreover, the ions are the carriers of the conductivity.

Yet the **ions need water** to function as carriers. Whereas the texture and organic matter in the soil might vary spatially but remain temporally constant, the soil moisture changes on a time basis as well. Hence the question arises, should the sensing be done when the moisture is at a low-, at a medium- or at a high level. Whereas a low level might reduce the temporary variations of the signals since it decreases the influence of a transient factor, a high level principally promotes the current flow.

The electrical conductivities in Fig. 5.9 are based on sensing of several loamy soils in a vertical induction mode, thus with a depth of approximately 1.5 m (Fig. 5.6).

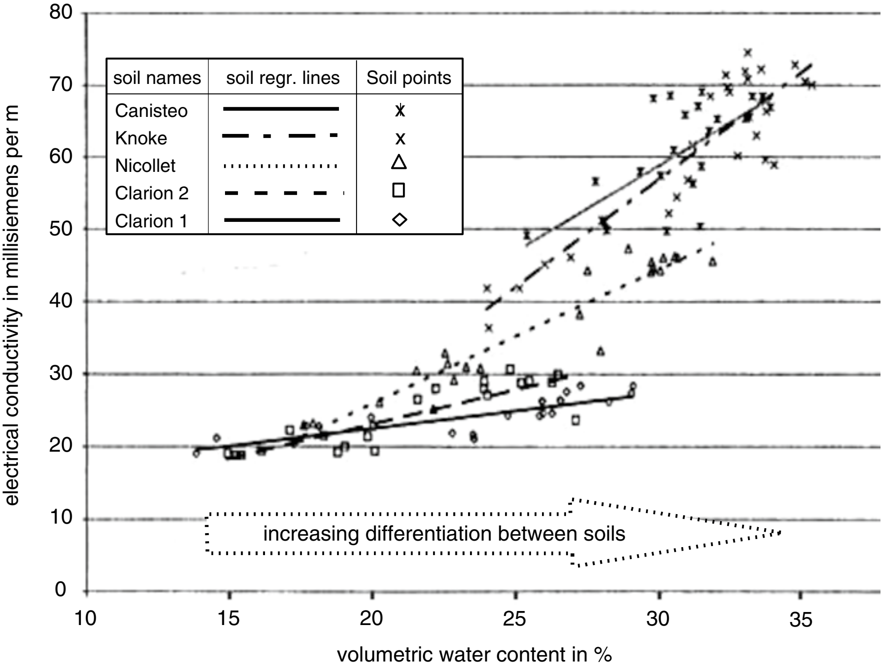

Fig. 5.9 Electric conductivity depending on the volumetric water content for loamy soils in Iowa, USA (From Brevik et al. 2006, altered)

The varying site-specific effects of texture and organic matter have been eliminated completely by the design of the experiments, namely by sensing at exactly the same locations at different times, and hence when the water content was not the same. So the regressions represent only **temporal variations** that were caused by the respective soil water content.

The results indicate that electrical conductivity has the greatest potential to differentiate between soils when these are moist (Fig. 5.9). Hence obtaining reliable signals about **soil texture** is more difficult in areas where low soil moistures prevail – *e.g.* in dryland regions without irrigation. But instead of this, the perspectives of getting suitable information about **soil moisture** from conductivity data improve in these areas. This is in line with results that were obtained by McCutcheon et al. (2006), Neudecker et al. (2001) as well as Padhi and Misra (2011).

However, it can be questioned whether conductivity signals are the best choice for sensing water. Methods that rely on electrical capacitance, on reflectance or on radar waves might be better suited. For details on this see later chapters.

5.2.2.2 Electric Conductivities and Soil Properties in Arid Areas

In arid areas, **soil salinity** deserves attention. Its negative effects can be diminished or even disposed of by site-specific, georeferenced melioration or reclamation, *e.g.* by removing the salinity through site-specific irrigation and leaching out of salts in combination with adequate drainage. In case the salinity is mainly based on high levels of exchangeable **sodium**, it is not only crop growth that is impaired, since in this case soil tilth deteriorates as well. This is because sodium ions induce the soil particles to deflocculate or disperse and thus promote soil crusts. The aim is to replace the sodium with calcium and then to leach the sodium out. This can be enhanced by applying calcium-sulfate, sulfur or sulfuric acid. The latter two chemicals help if free lime is present in the soil, which then reacts with sulfuric acid to calcium-sulfate.

Irrespective of the particular situation, the first step is sensing the salinity in general. The traditional method for this has been to measure the electrical conductivity of a current, which passes through a **soil solution** that was extracted from a saturated soil sample. This method is precise since it focuses on salinity and eliminates or neutralizes the effects of texture or moisture within the soil. It is still used as a reference method. Yet up to now this method cannot be applied in an on-the-go manner, it is just used for soil samples in the laboratory. Hence for practical farming, this method can be ruled out when it comes to site-specific sensing with a high spatial resolution on larger fields.

However, it has been shown at several places (Hendrickx et al. 1992; Lesch et al. 2005; McKenzie et al. 1997; Rhoades et al. 1997) that for practical purposes the sensing of electrical conductivities of soil volumes is a suitable surrogate of solution sensing in laboratories. This volume sensing can be done either by methods that use contact electrodes (Sect. 5.2.1.1) or via systems that employ electromagnetic induction (Sect. 5.2.1.2). These techniques allow for on-the-go sensing with high spatial resolutions. Correlations with varying texture and with changing moisture of soils exist, but for many situations these do not alter much the indicated results in terms of general salinity (Hendrickx et al. 1992). This is because in most cases the salinity has an overriding influence on the respective electrical conductivity (Table 5.2).

Whether crops suffer from soil salinity depends on the respective species. The yields of most crops are not much affected when salt levels in terms of electrical conductivities are below 200 mS/m. Levels above 400 mS/m hurt many crops and above 800 mS/m all but the very tolerant plants are affected (Cardon et al. 2010). This means that the field shown in Fig 5.10 presents serious problems of salinity for most crops, although the distinct local differences call for site-specific ameliorations.

It must be expected that differentiating between the effects of salinity, texture and water content on electrical conductivity gets more difficult with low salinity levels. And even with higher salinity levels the signals needed for site-specific ameliorations might be more precise if **separating the effects** of soil constituents were possible. A concept in this direction has been developed by Zhang et al. (2004) as well as by Lee et al. (2007) and Lee and Zhang (2007). It is based on the fact that the amount of total current flowing in a soil can depend on conductive- as well as on capacitative behaviours of the soil. The methods of sensing by electrical conductivity as used hitherto use either direct current or alternating current with frequencies well below 40 kHz. Electric current with these properties ensures that the conductive behaviour of soils dominates.

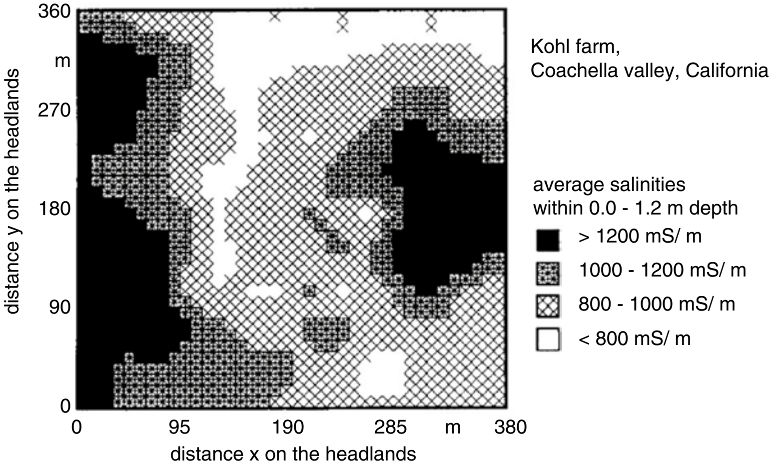

Fig. 5.10 Map of soil salinity based on electrical conductivities in the rootzone of a field in California, USA (From Rhoades et al. 1997, altered)

The situation is quite different if alternating current with frequencies in the MHz range is used. Under these circumstances, the capacitative behaviour of soils becomes more prominent. Hence, if the sensing is done successively by different frequencies within a sufficiently wide range, signals of both the conductive- and the capacitative characteristics of soils can be obtained. The electric conductivity primarily provides signals about the salinity, whereas the capacitative behavior of soils predominantly depends on the respective water content. Thus principally differentiating between salinity and moisture of soils is possible. For further details about soil moisture sensing see Sect. 5.2.3.

5.2.2.3 Electric Conductivities and Crop Yields in Humid Areas

The economics of farming depend largely on crop yields. These can be regarded in a retrospective or in a perspective. Site-specific techniques for retrospective views on yields are dealt with in Chap. 12. Both views have to deal with a multitude of factors that influence the yields, such as the weather in various stages of crop development, soil and crop properties as well as techniques and practices used for irrigation, cultivation, sowing, crop protection and harvesting. This itemization shows that the indication of crop yields by soil electrical conductivities can – at most – be a partial one. But since maps about soil conductivities are becoming standard facilities for site-specific farming, their usefulness for predicting yield potentials should be known. After all, the local yield potential – if it can be derived *a priori* – can help to define the adequate site-specific input of seeds, irrigation water and agrochemicals.

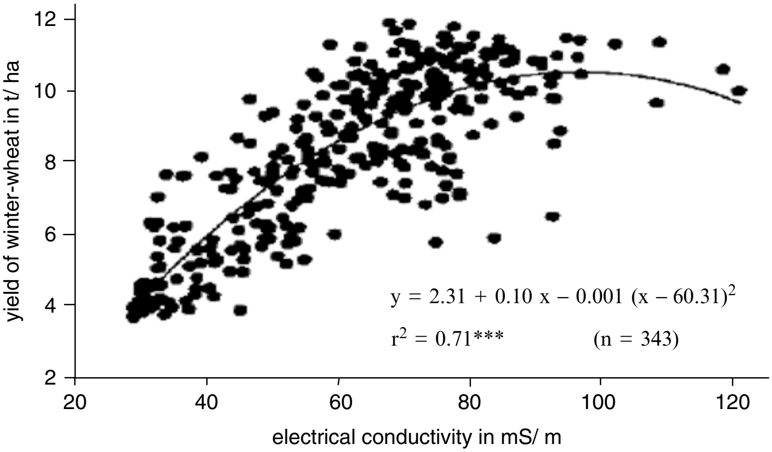

Fig. 5.11 Electrical conductivity sensed in an induction mode with a depth of about 1.5 m and yields of wheat in Germany (From Neudecker et al. 2001, altered)

Traditionally, the yield potential of soils is attributed to its texture, particularly to its clay content. This holds especially for the topsoil. The clay and its bonds with organic matter affect the water holding capacity as well as the hydraulic properties and provide for the cation-exchange-capacity that is needed to store plant minerals. However, there are limits to the **agronomic benefits of clay**. Very high clay contents can be detrimental because this can reduce water permeability, inhibit deep drainage and consequently lead to waterlogged soil conditions. This applies in general for the whole soil depth that the plants roots penetrate and even some depth below this. Yet this holds particularly for the subsoil, since the latter hardly is cultivated and in addition is less penetrated and thus not loosened by the roots of crops.

It should be realized that sensing of the water situation in soils by means of electrical conductivity is done in a twofold manner, *i.e.* directly since water is a carrier of ions and indirectly via the effect of clay on the water regime.

When yields and electrical conductivities are compared on a site-specific basis, rather unambiguous results can be expected provided the conductivity varies distinctly within the field and the sensed subsoil has no hydromorphic layers or claypans.

Figure 5.11 shows the situation for a field, in which the electrical conductivities vary along a rather wide range. The diagram shows two typical criteria for the relation between site-specific electrical conductivites and yields: firstly a rather wide spread of the data and secondly on the average a change from a positive- to a negative influence on the yield at a high level of conductivity. The first criterion is the result of the many factors that affect yields. And the second characteristic can be explained by the fact that beyond a certain clay level in the soil, its effect on the yield is reversed (see above).

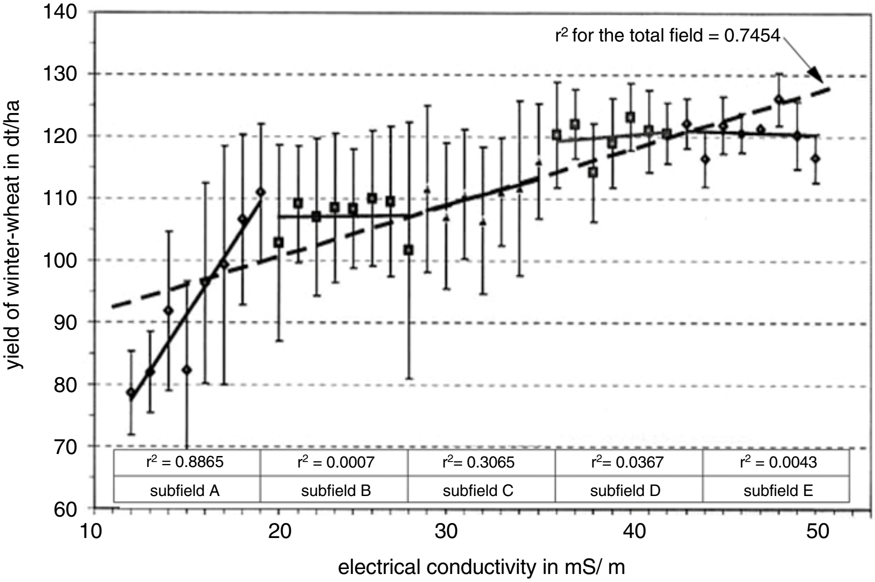

Fig. 5.12 Effects of electrical conductivities on yields of winter-wheat in Schleswig-Holstein, Germany for a field and its subfields. Regressions are shown for the total field as well as for its subfields. The regression for subfield C is on the same line as the main regression for the whole field and hence is difficult to depict. The *vertical lines* represent the respective standard deviations (From Reckleben 2004 and Schwark and Reckleben 2006, altered)

The change from a positive- to a negative effect on yield occurs in Fig. 5.11 at a rather high level of conductivity, namely about 80 mS/m. It is reasonable to suspect that the transition from rising to declining yields depends on the water supply during the growing season.

In humid areas, the transition from a positive to a negative effect can already be attained with an electrical conductivity of 40 mS/m or less (Domsch et al. 2003; Lueck et al. 2002). And where a rather uniform soil prevails, the effects of its properties on site-specific yields may fail to appear at all.

The regressions in Fig. 5.12 indicate how different the relation between electrical conductivities and site-specific yields within a single field can be. The regression for the total field suggests a distinct positive effect of conductivities in the range from 12 to 49 mS/m on wheat yields. However, the division into subfields shows that this is largely due to the increasing yields between 12 and 19 mS/m and much less to rising yields above this level. There are ranges above this level where no increases occur. In this case, the decrease of yields probably starts somewhere between 44 and 49 mS/m. The standard deviations of the site-specific yields decrease with high yield levels (Reckleben 2004).

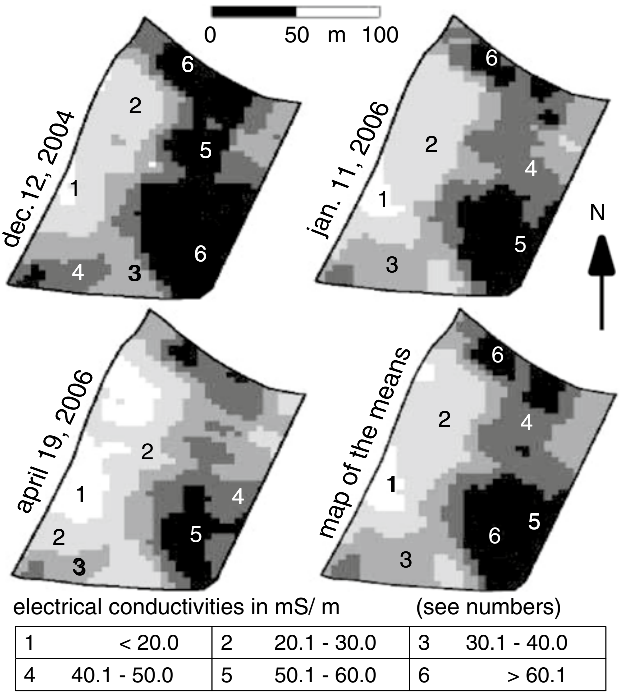

Fig. 5.13 Maps of three repeated recordings and of the mean signals that were obtained from these (From Mertens et al. 2008, altered)

5.2.2.4 Perspectives for the Use of Electrical Conductivities

For **humid regions**, clay- and water content of the soil are the main factors that define the site-specific electrical conductivities. Whereas the clay content is constant on a time basis, the moisture changes steadily. The temporally varying site-specific signals hence are mainly the result of the changes in water content. An effective method to even out these temporal variations resulting from the transient water factor is to record signals online and on-the-go at different dates and then to create maps that rely on mean data per cell. A prerequisite for this method is precise georeferencing that provides accurate spatial matching of the signals.

The original maps in Fig. 5.13 were taken from the same area (field Frankenforst in Fig. 5.8) at different times. They show distinct similarities. But they reveal also some differences, which probably are mainly due to temporal variations in the soil moisture. The **map of the means** neutralizes the temporal water effect at least partly. This procedure of averaging the results from repeated mappings must not be expensive. A single map causes an investment of about 6 Euros per ha on a contractor basis. So the contracting expenses for three maps add up to 12 Euros per ha. The expenditures for processing to maps of the means hardly count and hence can be ignored. Yet relevant is that the maps can be used for many years. If the use is

10 years, the costs per year resulting from the contracting expenses would only be between 1 and 2 Euros per ha.

An interesting perspective would be the creation of conductivity maps from repeated readings as a **byproduct** of other farm operations. With the increasing use of GNSS- or GPS based precision guidance, it might become feasible to record signals about soil conductivities as well as about topography while moving across the fields for other farming purposes. Hence more reliable maps for yield predictions could be obtained by averaging of signals from the same spot (Figs. 5.1 and 5.2).

It is general experience that the soil's potential for high yields depends largely on its ability to store and provide water for plant growth. The objective of averaging conductivity signals would be not to eliminate the water effect, but instead to remove the influence of its variation. The water tension in soils differs greatly, depending on whether the water is absorbed by soil particles, is in soil capillaries or moves freely. Apart from the weather or irrigation, it is the soil texture that determines the amount of water that is absorbed, stored and available for plant growth. So in short, it is an **interaction between soil and water** that defines largely the development of crops – aside from the application of agrochemicals.

Sensing of electrical conductivities in humid areas relies to a large extent on this interaction between soil texture and water. The conductivity signals quasi integrate the effects of clay and moisture. And fortunately, the effects of increasing clay- and water content on electrical conductivities on the one hand and on yields on the other hand point in the same direction, if soils with very high clay contents are excluded. Consequently, if by mapping of the means the temporally varying water effect can be removed, the signals obtained from conductivity sensing principally might be better suited for estimating yield potentials than the traditional analyses of only soil textures in laboratories. Hence maps of the mean electrical conductivity might become **yield-predicting-maps**. And traditional maps about soil texture instead probably will only serve as supplementing references in the future.

So sensing of electrical conductivities instead of the traditional analyzing of textures has distinct advantages:

- The signals are easily mapped online and on-the go instead of taking samples in the field and analyzing them in laboratories. Thus data from hundreds of sites per ha instead of one or two sites per ha can be afforded, which is a prerequisite for subsequent site-specific operations.
- The sensing criterion is not only texture, but in addition the water situation in soils. In principle, this complies with agronomic needs.

However, any attempt to derive site-specific yield potentials from electrical conductivities must take into consideration that – without being aware of this – sensing of **soil layers** may be included. In case soil layers in the subsoil are sensed that exist as pans, restrict the drainage of water and are not penetrated by the roots, the results can be very misleading. This is because the response curves of the presently dominating conductivity sensing systems (Figs. 5.3, 5.4, 5.5, and 5.6) pretend uniform soil properties within the vertical area that is sensed. Generally, an increasing clay content of soils increases the yield potentials – within limits. But this advantage can turn into the opposite if the clay sensed is concentrated in a dense pan that restricts drainage as well as root development. More sensing and processing techniques for precise site-specific mapping of such layers and pans within the rooted soil volume should be developed. This could help to precisely evaluate the agronomic effects of uneven texture and water situations within the sensed soil volumes in a vertical direction.

In **arid regions**, the interpretion of the signals that are obtained is somewhat simpler as a result of the overriding influence of salinity (Table 5.2). And because of this, maps of the means might not be necessary. Yet the benefits from salinity mapping in arid regions can be huge, since this is the starting basis for precise site-specific soil reclamation and soil fertility.

Presently less evident are the perspectives for electrical conductivity sensing in **dryland regions** without irrigation, where effects of salinity and of soil water are difficult to assess (McCutcheon et al. 2006). Yet the perspectives for the use in these regions might get better when precise separating of the effects that these soil constituents exert on the signals becomes state of the art (see Sect. 5.2.2.2, bottom).

5.2.3 Water Sensing Based on Permittivity and Capacitance

5.2.3.1 Basics

Soil sensing via electrical conductivity presently is mainly used for getting site-specific information in an integrated and summarizing way about the factors texture, organic matter and water. This integrated and summarizing information helps to assess the yield potential *a priori*. But there exist situations when information about the site-specific situation for a single factor alone – water – is needed.

The water content can be regarded as the most transient soil property. It can increase drastically within a few hours because of rain and decrease again within some days during dry spells. From this follows that a map about the respective water situation might help to explain the yield of a crop *ex post*, but the use of the same map for site-specific control of farming operations hardly ever can be extended over long time periods. Yet there can be occasions where a more precise knowledge about the temporal soil water content can help substantially, *e.g.*

- when **cultivations** must be scheduled since the breakup of clods that is needed as well as the prevention of compaction due to the weight of farm machines for many soils can depend on the water content.
- for **sowing- and planting** in the defining of the best time and in the control of the site-specific depth since the seeds need water for emergence.
- in the scheduling and site-specific control of **irrigation**. Agricultural crops extract most – but not all – of their water requirements from the top 30 cm soil

> layer (Sharma and Gupta 2010). Irrigation water that ends up in deeper soil layers remains largely unconsumed by crops and might simply seep down, taking with it dissolved agrochemicals that pollute underground water. Consequently, a continuous monitoring of moisture in the top soil layer combined with controlled irrigation can save water and avoid unwanted leaching of minerals and pesticides.

Presently feasible methods for site-specific and on-the-go sensing of the water situation in bare fields rely either on electrical capacitance, on electrical permittivity or on infrared radiation. The latter method is based on **soil surface** sensing whereas electrical capacitance and -permittivity are measured within **soil volumes**. These volumes may be restricted, yet principally provide information from three dimensions instead of only from the two dimensions of surfaces. Capacitance methods use signals obtained from electric current flow, hence from electrons. And permittivity methods rely on recording of electromagnetic radiation – thus photons – from microwaves or radar waves.

Principally, **electrical capacitance** is the ability of a body to hold an electric charge It is a measure of the amount of electrical energy stored or separated for a given electric potential, *e.g.* in a parallel-plate capacitor or in a given soil volume. Since electrical charges are expressed in units of coulombs and electric potentials in units of volts, the capacitance has the SI unit of a coulomb per volt, which is defined as a unit of farad (F).

In contrast to capacitance, the **electrical permittivity** is the ability to resist the formation of an electromagnetic field, in this case in the soil. In other words, it is a measure of how an electromagnetic field affects the surrounding – and is affected by it. Thus permittivity relates to the ability of a material to “permit” an electromagnetic field. Important is that the permittivity ε is the sum of a real part and an imaginary part.

The **real part of the permittivity** is associated with storage of electrical energy and thus with the capacitance of a material when an alternating electrical field is applied. In fact, the real part of the permittivity can be obtained from the capacitance in farad by dividing it by the overlap area of the capacitor plates and by multiplying it by the separating distance of these plates. Consequently, from the dimensions involved, it follows that permittivity is expressed in farad per m. However, this is the absolute permittivity of a material. In most cases, this absolute permittivity is replaced by the relative permittivity. This relative permittivity represents the absolute permittivity divided by the permittivity of a vacuum or of air, which equals 1 (one). This means that the numerical values for the absolute- and relative permittivities are identical. The difference is that the relative permittivity is dimensionless and because of this, it often is denoted as the **dielectric constant,** although it is not a real “constant”.

The **imaginary part of the permittivity** is associated with energy dissipation, it is therefore often denoted as dielectric loss. There are applications where this energy dissipation is the main objective, *e.g.* when foods are heated in a microwave oven.

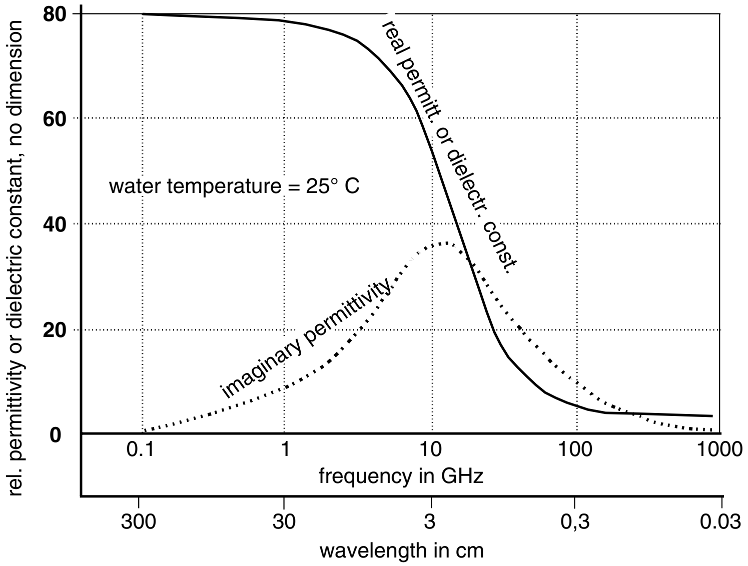

Fig. 5.14 Permittivities of water with a temperature of 25 °C as depending on frequencies or lengths of microwaves (Compiled from data by Komarov et al. 2005)

For sensing of soil moisture, it is the real part of the relative permittivity or the dielectric constant that is used. Because regarding this physical criterion, water has outstanding properties. Within a wide range of frequencies, the real part of the relative permittivity or the dielectric constant is

- around 80 for free water
- between 3 and 7 for dry soil minerals (sand, clay *etc.*)
- between 2 and 5 for dry organic constituents of soils
- around 1 for air or for a vacuum.

Hence in principle, both the **dielectric constant** and the **capacitance** – that depends on it – offer good prerequisites for differentiating between water and other soil constituents. Yet there are still some important details to consider.

Both the real part and the imaginary part of the permittivity of moist materials depend strongly on the frequency of an electromagnetic field. This can be explained by interactions with water molecules. Because of its dipole structure, the water molecules get polarized in an electromagnetic field. And the alternating electromagnetic field causes the polarized water molecules to vibrate. As a result of inertial forces, these vibrations can get out of line with the respective frequency of the electromagnetic field.

The courses of the permittivity curves – as shown in Fig. 5.14 over frequencies and corresponding wavelengths – probably are mainly due to such effects on molecular vibrations. Regarding signals from the real part of the permittivity or the dielectric constants, the frequencies used for water sensing usually are below 10 GHz. Hence the respective wavelengths are above 3 cm.

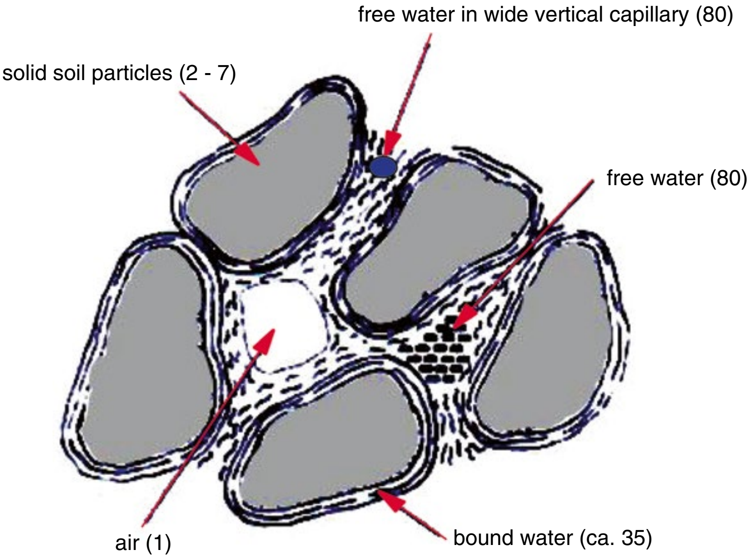

Fig. 5.15 Constituents of a soil in a horizontal cross-section and – *in brackets* – its real relative permittivities (From Scheuermann et al. 2002, altered)

Water is held in soils either as "**free water**" or as "**bound water**". Free water drains readily and is easily available for uptake by crops. Contrary to this, bound water molecules are attached to soil particles by means of capillary- or colloidal forces. The finer the soil particles are and thus the higher the clay content is, the more water is bound. And since at least some of the bound water might not be available for uptake by crops, agronomists preferably use the tension that is needed to extract water from the soil as a criterion for the supply of plants. This tension can be expressed in units of Pascal or in mm of water column.

The problem is that for direct sensing of the **water tension**, presently no on-the-go methods are available or in sight, neither for operating from farm vehicles, nor from aerial platforms or from satellites. However, in an indirect way it is possible to sense whether moisture can be drawn from the soil, namely during the growing season by means of site-specific signals about the water-transpiration of crops. This will be dealt with in Sect. 6.5.2.

Yet fortunately the sensing of soil moisture by way of real permittivity too takes into account mainly free water and leaves out bound water – at least approximately. This is because bound water has lower permittivities than free water as a result of surface tensions that act on it (Fig. 5.15). However, a standard method for defining the bound water by means of permittivities does not exist. In a laboratory, bound water can be determined by first removing it in a drying oven using a temperature of 105 °C and 24 h time. After this, the soil is subjected to air with 50–60 % relative humidity. It takes up moisture from this air because of its hygroscopic properties. The bound water is equivalent to this hygrocopic equilibrium moisture that can easily be recorded by weighing before and after uptake (Robinson et al. 2002).

After having sensed the real relative permittivity or dielectric constant, the soil water content excluding bound water can be estimated using **Topp's equation** (Topp et al. 1980):

$$\text{Volumetric soil water content} = -0.053 + 0.029\,\varepsilon - 0.00055\,\varepsilon^2 + 0.0000043\,\varepsilon^3$$

ε is the real relative permittivity or dielectric constant.

This equation provides for reliable results (Stoffregen et al. 2002) under the premise that ε was sensed precisely for the respective soil.

Sensing of permittivity is possible either on the basis of velocities or of reflections of waves. For wave velocities, time signals are recorded. Thus the sensing occurs in the time domain. A well established method of this kind is the **time domain reflectometry (TDR)**. Electromagnetic waves are guided along transmission lines or cables within the soil. The time that is needed depends on the permittivity of the soil and thus indicates its water content. This method provides for rather reliable results and therefore often is used as a reference. Topp's equation was obtained using this method.

But unfortunately, methods that sense on a time domain up to now are not yet suited for on-the-go site-specific operations. These methods therefore are left out here. Instead, methods that rely on signals from **reflected radiation** will be dealt with. These methods operate either from satellites or on-the-go from terrestrial vehicles. Yet it will be shown that using reflected radiation can make it difficult to obtain accurate dielectric constants of soils.

5.2.3.2 Water Sensing from Satellites by Permittivity

Water sensing from satellites is used extensively for observing the earth's atmosphere with the objective of weather forecasting within large areas. But contrary to this, sensing of soil moisture from satellites within single fields and thus for site-specific farming still is not state of the art. In the past, neither the spatial- nor the temporal resolutions did correspond to the needs.

Yet both drawbacks are slowly disappearing. The spatial resolution for data from some modern **radar satellites** that operate in an **active mode** now even is going down to 1–100 m^2, which is sufficient. In addition, providing for information on a daily basis may become feasible because of more satellites. And the capability of micro- or radar waves to penetrate the space between the satellites and the earth never has been a problem. These waves have almost **all weather capabilities** – contrary to those from the visible- and infrared range (Sect. 3.3). An exception from this all weather capabilitiy may hold solely at times of heavy rainfall. Hence some general perspectives for signals about soil moisture from satellites by means of micro- or radar waves are encouraging.

But what about the ability of micro- or radar waves to provide sufficiently accurate signals about soil water? The relations between soil moisture and real

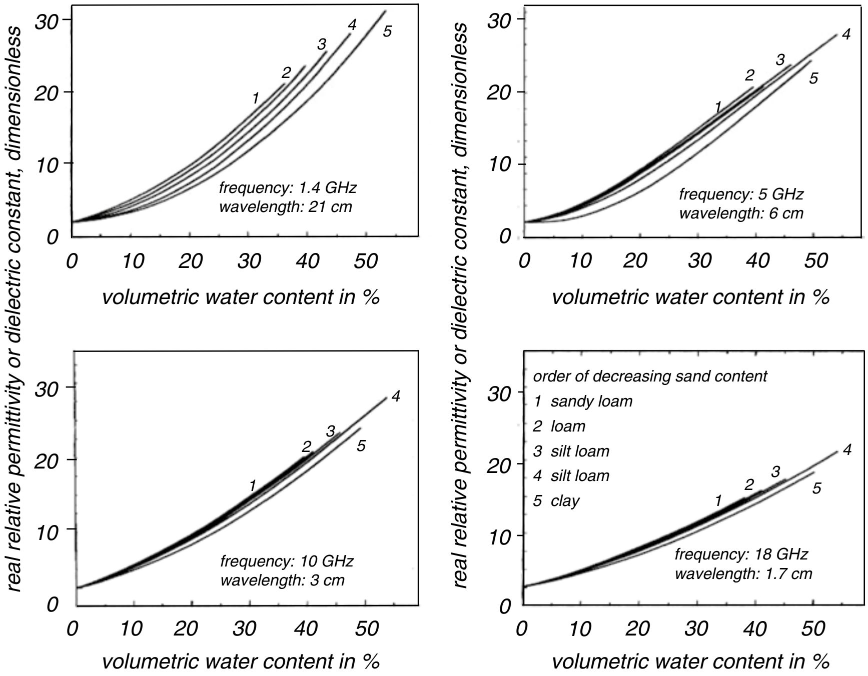

Fig. 5.16 Real permittivites or dielectric constants of five soils sensed with different frequencies (Compiled from Hallikainen et al. 1985)

permittivities presented in Fig. 5.16 are based on experiments in a laboratory and hence refer to well controlled conditions. The respective volumetric water contents were obtained by adding water to soils that had been completely dehydrated in a drying oven before. This means that the moistures indicated include also bound water. And since bound water has lower real permittivities or dielectric constants than free water (Fig. 5.15), this should show up when soils that differ in their texture and thus in the sand- or clay content are compared.

This assumption is supported by the curves for the soils with different textures. For all frequencies and wavelengths that were used, it shows that the sandy soils had the highest real permittivities and the clay soils the lowest (Fig. 5.16).

However, the effect of soil texture depends on the micowave properties. The differences between the soil types are quite apparent when low frequencies of 1.4 GHz and correspondingly long waves were used, but get stepwise smaller with higher frequencies and hence shorter waves. So in order to account for the bound water – which is not available to plants – long microwaves are needed.

Very important is the **depth of sensing**. In case the signals are reflected only from the soil surface, which is the case with visible- and NIR radiation, a few raindrops or even dew can cause misleading results. Fortunately, microwaves do

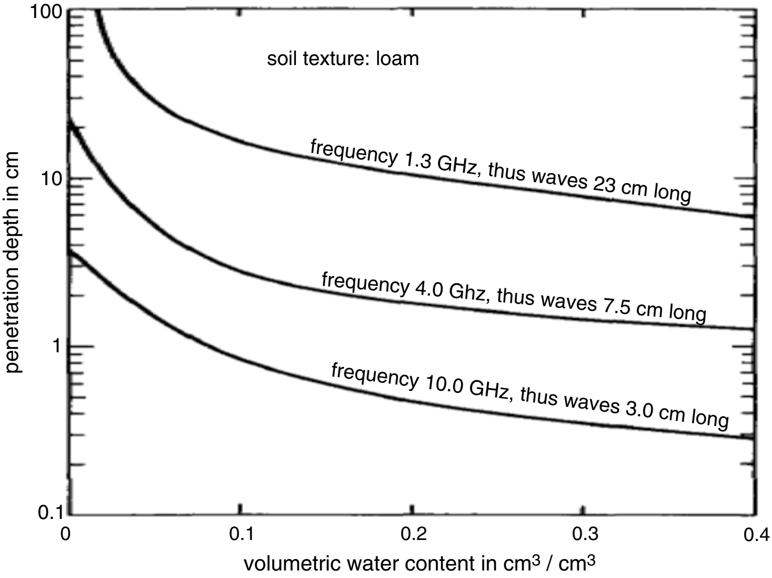

Fig. 5.17 Depths of sensing by microwaves and soil moisture. The y axis has a logarithmic scale (From Ulaby et al. 1996, altered)

penetrate into soil. However, the depth depends on wavelength and on soil moisture (Fig. 5.17). The longer the waves and the lower the soil water content, the deeper can be sensed.

Yet the farmer does not know exactly *a priori* about the soil moisture content, especially not on a site-specific basis. This is, what he wants to know. A general rule – which disregards the actual water content and relies on average situations – is that the depth of moisture sensing is one fifth of the wavelength (Paul and Speckmann 2004).

Hence the depth of sensing

- for a frequency of 30 GHz and a wavelength of 1 cm is only 0.2 cm
- for a frequency of 10 GHz and a wavelength of 3 cm is about 0.6 cm
- for a frequency of 1 GHz and a wavelength of 30 cm is about 6 cm
- for a frequency of 0.5 GHz and a wavelength of 60 cm goes up to 12 cm.

The latter depth is about the maximum which can be achieved with present day technology operating on a surface reflection mode. This maximum depth suffices for controlling the sowing depth of crops on a site specific basis. It does not quite suffice, if for irrigation purposes, information about the water available for a growing crop is needed. The roots of most crops take up water far beyond this maximum depth. In short, regarding the depth of sensing there are limits for radar waves that operate in the surface reflection mode.

However, there are additional limits for water sensing by active radar waves. This method relies on reflection of radiation and this depends not only on the frequencies and the real permittivities or dielectric constants of the respective soils. Equally important are factors that have to do with the site-specific **surface** that is hit by the radiation such as

- the slope of the soil relative to the incident radar wave
- the roughness of the soil surface at scales relative to the wavelength
- the structure of any vegetation.

The last factor will be dealt with in Chap. 6 since it is important for sensing of crops by means of radar waves. When it comes to water sensing in bare fields, only the first two factors apply (Fig. 3.5). But the effect of these factors on the signals that are obtained with active radar sensing can be equal of even greater than the effects of soil moisture (Engman and Chauhan 1995). So methods are needed that make it possible to eliminate these disturbing effects.

Two approaches to cope with these problems seem to be feasible. The first approach is based on the fact that the error or noise caused by varying slopes or by changing roughness of the soil surface depends largely on the **incidence angle** with which the radiation coming from the satellite hits the earth. This angle varies between satellites and can often be adjusted. By systematically using different incidence angles, the effects of varying slopes as well as different surface roughnesses can be detected and be taken care of while the sensed data are processed (Baghdadi et al. 2008 and Srivastava et al. 2003). However, up to now neither signals nor maps that are corrected in such a way are available commercially.

The second approach relies on "**change detection**". Its theoretical background is that the factors which define the permittivity change differently on a **time basis**. The soil moisture varies almost constantly and sometimes even rather fast. Contrary to this, the slope of the soil always is about the same. And the roughness of the soil surface as well as the structure of the vegetation do change, however, in most cases much more slowly than the soil water content does. Hence repeated sensing within defined time spans combined with sophisticated processing of the signals allows to separate the effects of soil water from those of site-specific variations in slope, surface roughness and even vegetation (Moran et al. 2000; Kim and van Zyl 2009). But this method of "change detection by means of multi-temporal sensing" too is not yet state of the art. So the future will have to show whether using several incidence angles or change detection will provide a breakthrough for more precision in the sensing of soil moisture.

However, if bare areas are flat and have smooth surfaces, it is even possible to do without these special sensing and processing techniques as shown in Fig. 5.18 for fields from a farming region in Western Turkey.

Summing up the outlook for soil water sensing by radar satellites: the perspectives are encouraging, especially when taking into consideration that in the future operating with various incidence angles and change detection might remove still existing obstacles. **Low frequencies** and hence **long waves** will be needed in order to obtain sufficient sensing depth. Perhaps it might be feasible in the future to provide farm machinery that is operating in fields in an online and on-the-go manner with signals or maps about the respective site-specific soil water situation in a

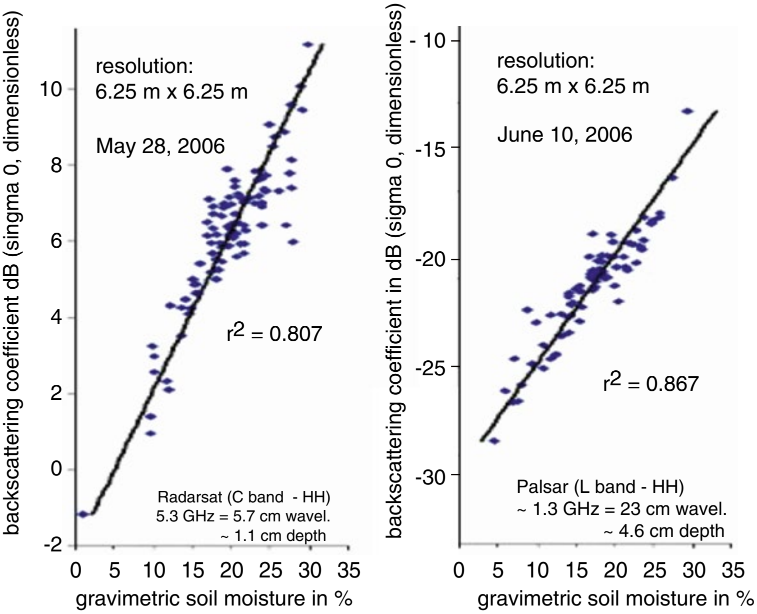

Fig. 5.18 Reflection of radar microwaves back to the emitting satellites depending on the moisture content of bare soils. The backscattering coefficient on the y axis indicates the ratio between the wave power that is backscattered to the satellite and the incident wave power. This ratio of wave power is usually expressed in decibel (dB). The latter is ten times the common logarithm of this power ratio. Any negative values result from common logarithms below 1 (From Balik Sanli et al. 2008, altered)

similar way as georeferencing from satellites today is state of the art. However, such continuous signal transfer from the satellites to farm machines is not yet possible. Since radar satellites are not operating in a geostationary mode but instead orbit in a polar mode, this would require the availability of many more satellites in order to provide a continuous signal transfer. Furthermore, a network that links satellites, processing and farmers would be a prerequisite.

5.2.3.3 Water Sensing from Field Vehicles by Permittivity

This mode of water sensing would be attractive in precision farming if it could occur during usual farming operations and thus be used for simultaneous on-the-go control. Such a procedure is not yet state of the art, however, not beyond feasibility.

The emitting and sensing of radar reflectance from a land vehicle – as shown in Fig. 5.19 – is based on a frequency of 500 MHz. This frequency is below the usual range that is used by satellites. The lower frequencies and hence longer waves result in deeper sensing. A sensing depth of about 12 cm can be obtained (see Sect. 5.2.3.2).

Fig. 5.19 Sensing surface reflectance of ground penetrating radar (From Redman et al. 2003, altered)

This is probably the deepest sensing that can be realized in the radar surface reflectance mode presently. Some farming operations and irrigation methods might benefit from control procedures that were based on such a depth. However, the equipment that is used for this mode of land based on-the-go surface reflectance sensing still is rather clumsy and not available commercially.

Principally there is no reason why sensing of radar reflectance – if it occurs from land vehicles instead of from satellites – should not have to cope with the influence of soil surface roughness on the signals. However, a general experience is that the effect of **surface roughness** on the signals decreases when the wavelength increases (Paul and Speckmann 2004). This would imply that as a result of the longer wavelengths that are used, the land based sensing as outlined above should have less to deal with surface roughness.

Yet results that have been obtained so long do not indicate that this problem therefore has gone. The raw signals that were recorded via Topp's equation (Sect. 5.2.3.1, last part) when operating in a grassy field and silt loam soil reveal more variability than would be expected from the water situation (Fig. 5.20). It is suspected that despite the longer wavelengths, at least part of this excessive variability is due to surface scattering of the reflected radiation. In order to make up for this, means of ten adjacent signals respectively were generated by applying a simple moving averaging filter. The thus obtained curve of the means seems to provide reasonable estimates although the question of biased results arises.

The black points represent results from time domain reflectometry. The estimates obtained with this method are generally presumed to be accurate and can hardly be influenced by surface roughness, which is also suggested by their course (Fig. 5.20).

5.2.3.4 Water Sensing from Farm Machinery by Capacitance

This method needs galvanic contact with the soil, similar to the electrical conductivity method in Fig. 5.3. But contrary to this conductivity sensing method, the positive and negative electrode are positioned very close to each other, *e.g.* within the same cultivator tine.

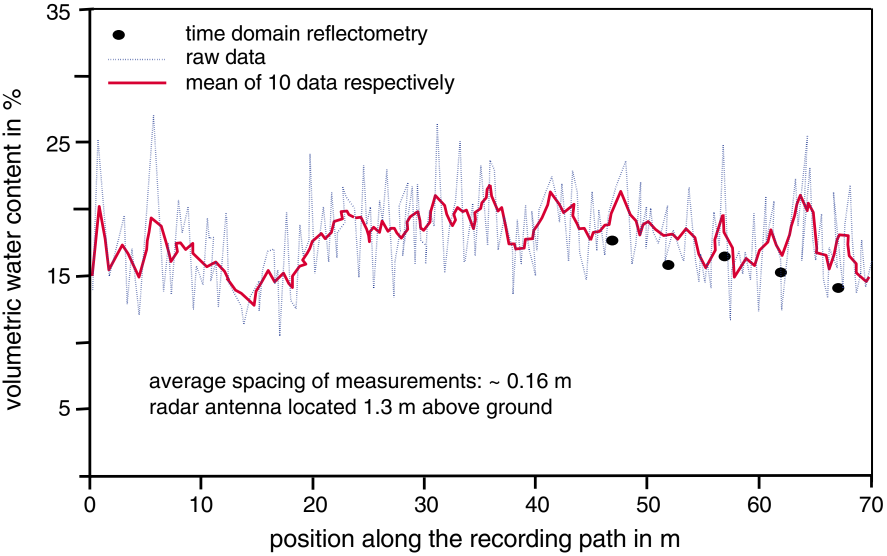

Fig. 5.20 Soil water content sensed from a land-based vehicle by means of ground penetrating radar signals that were obtained via surface reflectance. The data were processed by applying Topp's equation to the signals (From Redman et al. 2003, altered)

The two electrodes – a brass cone and a metallic ring – make up the tip of a cultivator tine. They are separated by an insulator (Fig. 5.21). The soil that surrounds the tine is part of the capacitor. The sensing is done by measuring the "impedance" that exists for the current flow. This electro-physical criterion defines – in a rather simplified description – the resistance to current flow within a capacitor. The design of the sensor allows simultaneous recording of soil moisture via impedance as well as of penetration resistance, which depends heavily on soil water. Of course, this does not prevent the system to be used solely for moisture sensing.

An important factor is the **electrical frequency**. The present implements operate with frequencies between 40 and 175 MHz. Low frequencies make it difficult to sense precisely. This is because with low electrical frequencies, the signals that are obtained depend not only on the real permittivity or the dielectric constant, but on electrical conductivity as well (see Table 5.1 and Sect. 5.2.2.2 last part). The effect is that texture and perhaps also the ion concentration in the soil water influence the sensor output and thus the moisture that is indicated. On the other hand, higher frequencies increase the expenses for the electronic devices (Kizito et al. 2008).

A way out of this situation can be using the results from conductivity sensing for a **site-specific correction** of the signals from capacitance sensing in order to arrive at precise water mapping. Kelleners et al. (2009) indicate that such a procedure could improve the accuracy of water sensing. The instrumental solution for this could be sensing of capacitance and conductivity in one operation by employing **several frequencies** simultaneously with combined processing of the signals for the

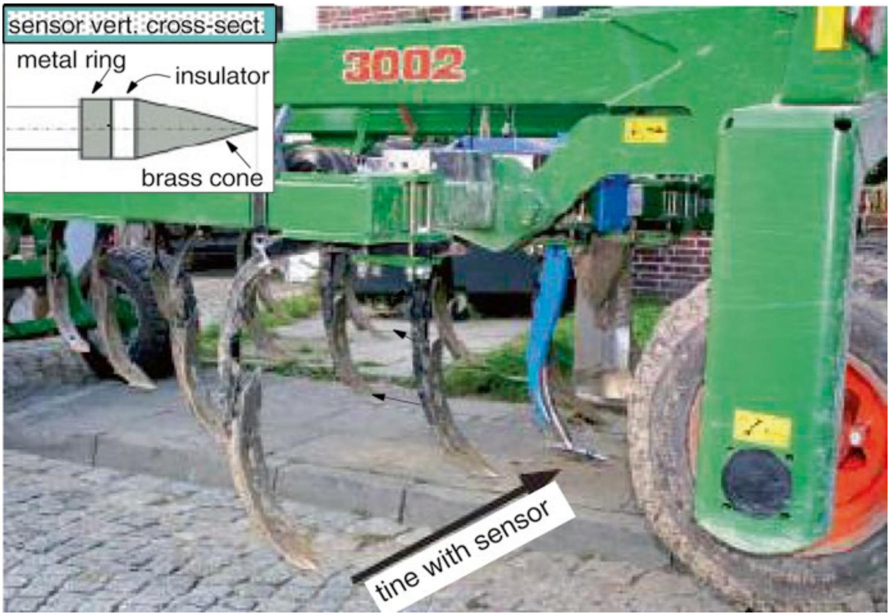

Fig. 5.21 Capacitance sensing in the tip of a cultivator-tine. The *insert – top left* – is a vertical cross-section of the sensor. The electrical frequency is 100 GHz (From Drücker et al. 2009 and Sun et al. 2004, altered)

desired output criterions. An interesting alternative to this solution would be sensing of capacitance in real-time on-the-go and converting previously made maps of the mean conductivity by the results. Not only sensing for the respective water situation, but also the generating of "yield-predicting-maps" might benefit from such procedures to enhance the precision.

However, the temporal implications of the respective sensing objectives should be considered. Sensing for water always is a **short-term matter** because of the influence of the weather. In contrast to this, sensing for soil properties mainly aims at yield indicating maps and these – if created properly – can be used for decades. This fundamental temporal difference will have consequences for the practical management.

5.3 Sensing of Soil Properties on a Surface Basis by Reflectance

When soil sensing is done by reflected visible or infrared radiation, properties of the soil's skin and not of a defined volume are indicated. The signals originate from a surface that can be part of the **top-surface** of a field or of a surface within a **vertical**

cross-section of a soil, which *e.g.* is disclosed by a cultivating tool. Whatever the situation is, an important difference to volume sensing is that the signals are based on two dimensions and not on three dimensions in distance. And this generally means that – *ceteris paribus* – the signals come from less soil and hence might be less representative.

Yet what matters really: is it the amount of soil or is it the respective geometrical place within the soil?

When it comes to **sensing of water**, the depth of the water carrying soil layer from the surface is important for crop growth. Sensing the top-surface of a field does not supply any indication about the depth where a soil stores water. Immediately after a short rain, just 2 mm of the top-surface may be wetted. Following a longterm precipitation, 100 mm down from the top-surface might store water. Yet the signals from the top-surface might be the same. So these signals hardly help.

However, the situation for water sensing can be different if instead of the horizontal top-surface a vertical cross-section within the soil is scanned. This requires some scraping or plowing aside of soil that can be done during soil cultivation or during sowing. Thus an adequate sensing perspective for the control of sowing-, cultivation- or irrigation operations might be created.

It can be relevant that the topsoil is occasionally mixed when cultivations take place. Because of this mixing, the soil constituents that respectively are at the surface will vary. The soil constituents change their position within the cultivation depth. So even if only constituents that just were at the surface were recorded during the mapping, previous mixing within the topsoil provides actually for some volume sensing. This is especially the case when the sensing of the same field is repeated several times in the course of some years and thus **maps of the means** are obtained. These maps of the means then are estimates of the situation within the volume of the cultivated topsoil although the sensing occurred in two-dimensional patterns. However, this **cultivation induced change** from top-surface dimensions to volume dimensions does not make sense with transient soil properties such as water content. This method solely is well suited for soil properties that not at all or hardly all change over time. Thus obtainable maps of the means could be reasonable for texture, organic matter content and cation-exchange-capacity.

The situation is different when site-specific signals about soil conditions for the application of pre-emergence herbicides are needed. The application rate for these herbicides should be adapted to the site-specific **organic matter** content of the soil top-surface. Because the pre-emergence herbicides are partly absorbed by the organic matter of the soil surface and this makes them ineffective. In order to make up for the growing absorbance with increasing organic matter content, it is generally recommended to adapt the rates of application to this (Fig. 5.22).

This does not necessarily imply a higher burden to the environment. Because higher organic matter contents in soils also result in faster decomposition of herbicides (Hance 1973). So if a higher herbicide rate is absorbed, it is also faster decomposed.

Because these herbicides mainly get in contact with the top-surface of the soil, on-the-go information about the organic matter within this top-layer is precisely what is needed for controlling the application.

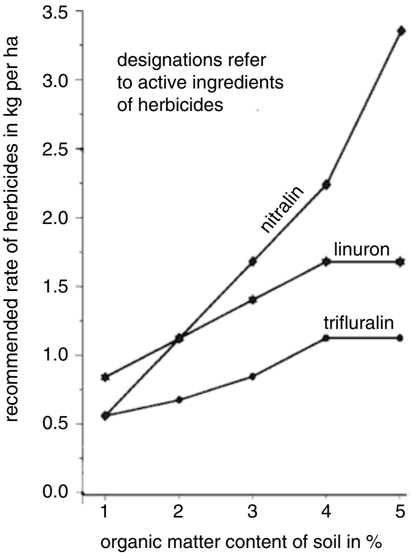

Fig. 5.22 Recommended application-rates for pre-emergence herbicides and soil organic matter content (Compiled from specifications by Krishnan et al. 1981)

A simple – though not precise – indicator of the organic matter content is the **color of soils**. This is because the black color of humus removes all other colors of soil constituents. It especially replaces the red color of oxidized iron components and the yellow colors of aluminum in soils. Hence generally, the darker a soil appears, the more organic matter it has. But this is a very rough indication, because the water content too influences the color of a soil. The dryer a soil is, the brighter it looks.

Sensing methods that rely on details of colors have been used occasionally for purposes of precision farming in the past, however, they have largely been replaced by spectroscopic methods. Since colors are caused by wavelengths, it is reasonable to avoid the detours that inherently are connected with color measurements and to sense the wavelengths directly. This is dealt with in the next section.

5.3.1 Basics of Surface Sensing

Soil surface sensing can be based on diffuse reflectance in various wavelength ranges: the **visible** region (400–700 nm), the **near-infrared** domain (700–2,500 nm) and the **mid-infrared** range (2,500–25,000 nm). Traditionally, the visible- and the near-infrared region have been used, however, results with the mid-infrared range are promising.

The sensing approach can be oriented at indicating a **single soil property** – *e.g.* solely water or organic matter – or at recording and mapping **multiple soil properties** in one operation. The single property approach might make sense for online and on-the-go control of field operations for which just one soil property is very significant. Examples for this are controlling the sowing depth according to soil moisture or the application of pre-emergence herbicides in proportion to organic matter in the soil. All first attempts of online and on-the-go controls for site-specific operations have been based on single soil property sensing concepts.

However, the better the knowledge about the agronomic effects of soil properties is and the more the technology of spectroscopic sensing advances, the more favorable the terms get for multiple soil property sensing. This concept corresponds to the notion that some field operations probably require site-specific adjustments that simultaneously are based on several factors. For example: controlling the sowing depth could be reasonable not only according to soil moisture in the vertical soil cross-section, but also proportional to texture. And for the application of pre-emergence herbicides, the control could be based not only on organic matter, but again on texture as well.

There is another point that supports the multiple soil property concept. It is the fact that several soil properties do not exist independently from each other. In many cases, the organic matter content too depends on the texture. For instance, the water content firstly depends on the weather. Yet following precipitation, what remains in the topsoil and is available to a crop depends on texture and organic matter as well. The cation-exchange-capacity relies heavily on texture and organic matter too. So there are many interdependencies among soil properties.

An important question is, on which wavelengths the sensing should be based on. There are two general approaches for this: the full spectrum approach or the discrete waveband approach.

A **full spectrum approach** means that within the spectrum chosen (*e.g.* visible and near-infrared range) practically all wavelengths are included in the sensing process by recording in steps of for instance 5 nm or even less. Modern spectroradiometers can do this within a fraction of a second. Hence at every site-specific spot, many signals are sensed. These signals are subjected to sophisticated statistical evaluation processes like partial least squares regressions or others in order to obtain information about soil properties.

Since a full spectrum can include the important ranges or wavebands of several soil characteristics with their specific “fingerprints”, this method is principally suited for **multiple soil property sensing**. Such multiple soil property sensing and mapping is close to becoming a reality for a variety of site-specific farming operations (Lee et al. 2009; Viscarra Rossel et al. 2006).

The **discrete waveband approach** dispenses with signals from a wide spectral range and just is confined to using narrow key wavelength bands. Much effort has been and still is devoted to detecting these **key narrow bands**. This sensing method can be reasonable for estimating just one soil property, *e.g.* water or organic matter. In many cases, interdependencies among soil properties are not taken into account. This might not be necessary, if *a priori* the correlations between the respective properties and the key reflectances are high, as it is the case with water and organic matter.

Experience will show, which properties can successfully be sensed via full spectrum approaches or when discrete waveband approaches are reasonable. But whatever method is used, the accurate **calibration** of the sensing equipment deserves attention. The calibration is an adjusting procedure. It aims at getting the right scale or relation between property data on the one hand and spectral signals on the other hand. The best data basis for an accurate calibration can be provided by the respective field, for which the sensing of properties is pending. But theoretically this is impossible, since it implies direct converting of output to input. Hence the input for the calibration must be supplied from another field that has a similar soil. And since worldwide a huge variety of different soils exist, this means that a reservoir for site-specific spectral calibration data is needed. Brown et al. (2006) have started to develop such spectral soil reflectance libraries.

5.3.2 Results of Surface Sensing in Laboratories

Figure 5.23 shows effects of moisture, organic matter and texture plus iron on visible and near-infrared reflectance of soils. Increasing contents of water, organic matter or clay result in decreasing reflectance. However, in the same order of soil properties, this effect becomes smaller. As for texture, this effect is ambiguous in the visible- and in the near-infrared range that is adjacent to it. The iron content of the soil may be important as well.

For a **discrete waveband approach**, the best wavelengths (fingerprints) are important. Within the visible and near-infrared range these are (Lee et al. 2009; Mouazen et al. 2007; Shonk et al. 1991; Zhu et al. 2010):

for water
970 nm; 1,200 nm; 1,400 nm; **1,450 nm**; 1,820 nm; **1,940 nm**; 2,000 nm; 2,250 nm,
for organic matter
660 nm; **1,772 nm**; **1,871 nm**; 2,070 nm; 2,177 nm; 2,246 nm; 2,351 nm; 2,483 nm,
for clay
1,877 nm; 1,904 nm; 2,177 nm; 2,192 nm; **2,201 nm**; 2,220 nm; 2,492 nm and
for cation-exchange-capacity
1,772 nm; 1,805 nm; **1,877 nm**; 2,090 nm; 2,276 nm; 2,306 nm; 2,498 nm.

Key wavelengths are indicated in **bold**.

The wavelengths belong – with one exception – to the near-infrared range, which is defined here as extending between 700 and 2,500 nm.

Coefficients of determination or squared correlation coefficients (r^2) that are based on **full spectrum** sensing of numerous soil samples via reflectance in laboratories are listed in Table 5.4. The respective full spectra were used to indicate various soil properties simultaneously. Only some of the sensed soil properties are shown. The data were processed by partial least squares regressions.

The summarized result is that the accuracy of sensing for the soil properties listed increases in the order visible-, near-infrared- and finally mid-infrared reflectance, hence with the wavelengths. In most cases, the results for organic carbon excelled those for all other properties. For the silt- and sand content, it must be taken

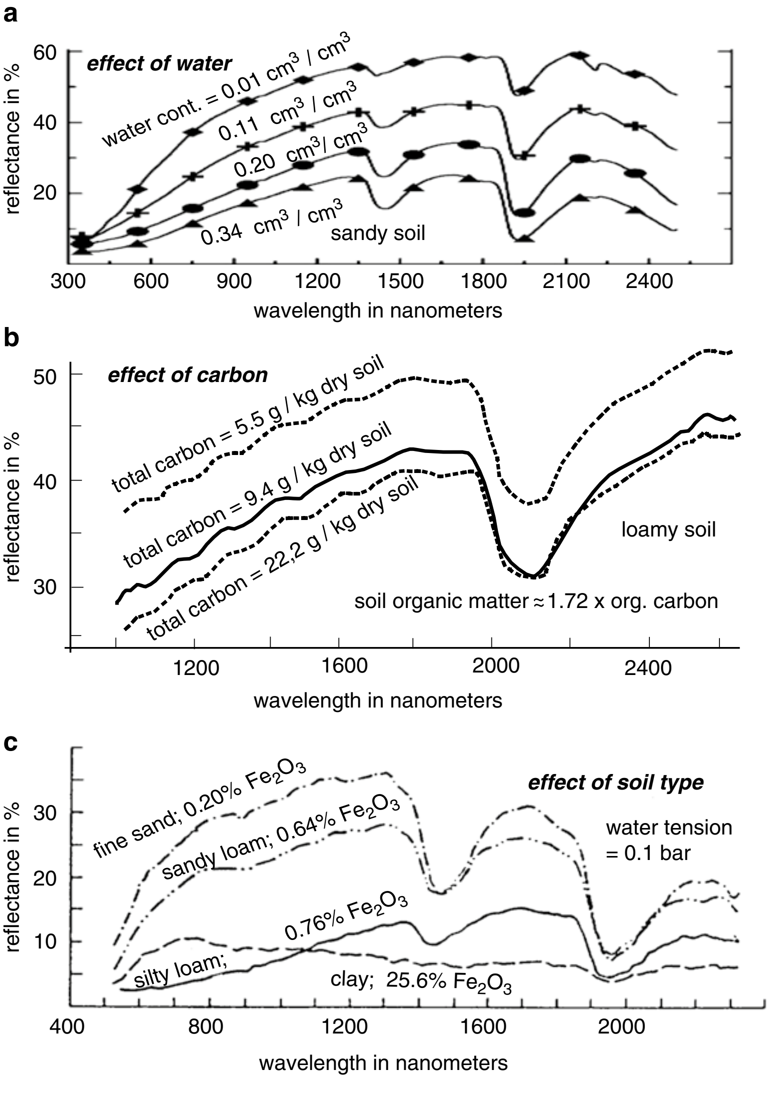

Fig. 5.23 Soil Reflectance as affected by water, carbon and texture (*top*: from Zhu et al. 2010; *center*: from Huang et al. 2007; *bottom*: from Baumgardner et al. 1986, all altered)

into account that these properties together with the clay content add up to 100 %. Therefore, autocorrelation with the clay content must exist. And finally, soil water content was not included in these investigations.

It is generally known that soil water can be sensed as precisely or even more accurately than soil organic matter by near-infrared radiation (Mouazen et al. 2007; Viscarra Rossel et al. 2006; Zhu et al. 2010; Slaughter et al. 2001). Actually, for water, the sensing process is no problem. The question is whether the sensing for

Table 5.4 Correlation between soil properties in laboratories and ranges of reflectance

	Correlation coefficients squared (r^2)		
	Range of reflectance[a]		
Soil properties	Visible	Near-infrared	Mid-infrared
From Viscarra Rossel et al. (2006), summary of extensive literature review			
Organic carbon content	0.78	0.81	0.96
Clay content	0.71 combined		0.82
Cation-exchange-capacity	0.73 combined		0.88
From experiments of Viscarra Rossel et al. (2006)			
Organic carbon content	0.60	0.60	0.73
Clay content	0.43	0.60	0.67
Silt content	0.31	0.41	0.49
Sand content	0.47	0.59	0.74
Cation-exchange-capacity	0.16	0.13	0.34
From experiments of McCarty et al. (2002)			
Organic carbon content, 1.series	–	0.82	0.94
Organic carbon content, 2.series	–	0.98	0.98

[a] The ranges are for visible reflectance 400–700 nm, for near-infrared reflectance 700–2,500 nm and for mid-infrared reflectance 2,500–25,000 nm

this soil property makes "sense" via reflectance due to the transient situation and the limitation to the soil surface. An essential point for soil water sensing is whether this is done on the top-surface or along surfaces of vertical cross-sections within the soil (see above).

It is expected that for sensing in laboratories, mid-infrared radiation will replace the hitherto dominating near-infrared reflectance due to the more precise indications. The situation is different for sensing in fields in an on-the-go mode. Because when using mid-infrared radiation, the soil has to be rather dry – a prerequisite that hardly can always be met in fields. Mid-infrared radiation is absorbed very strongly by moist soil and consequently not enough of it is reflected for sensing (Christy 2008). Visible and near-infrared radiation is less absorbed by moist soils. This allows measurements from moist field samples – a prerequisite of on-the-go signals for simultaneous online control of field machinery or for mapping. An important point is also the investment for the sensing instruments. The longer the wavelengths, the more expensive the spectroscopic implements are. Yet technological progress is more and more reducing the differences in investment.

Figure 5.24 shows similar results from full spectrum sensing of multiple soil properties with processing of the data by partial least squares regression. The soil samples came from ten fields in various regions of the Midwestern United States and were either taken in a segmented manner from the pedogenic horizons along **vertical soil profiles** or from **top surfaces** at various sites within each field. From the various soil properties that were included in the investigation, only the results for the most important natural properties – organic matter and clay content – are shown. These properties provided the best correlations between the traditional analyses and the reflectance sensing in the order organic carbon, clay.

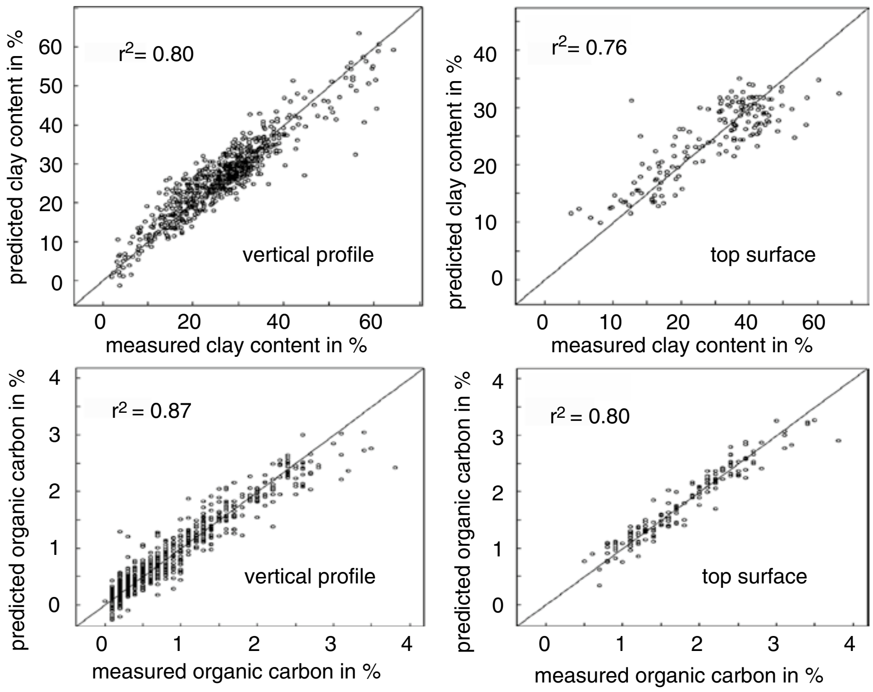

Fig. 5.24 Comparison of predicted soil properties – obtained by traditional analysis – with measured values from full spectra of visible plus near infrared reflectance sensing in laboratories. The soil samples were taken either from vertical soil profiles (1.2 m deep) or from top surfaces. For wavelength ranges see Table 5.4 (From Lee et al. 2009, altered)

Since the vertical profiles represented not only the topsoil but the subsoil as well, its properties varied more than those that were taken solely from the top surfaces. The sensing results for the samples from the vertical profiles were better than those that were based on the top surfaces (Fig. 5.24).

The wavelength range that should be used for a full spectrum approach might depend on the soil properties needed. Lee et al. (2009) found that the soil property estimates from a reduced wavelength range of 1,770–2,500 nm were of similar accuracy than those obtained from the complete visible plus near-infrared range. The most important information obviously originates from the upper part of the near-infrared range. However, Lee et al. (2009) did not include mid-infrared reflectance and soil water in their investigations. When it comes to water, near-infrared radiation below the range mentioned above can provide important information.

Yet apart from this, single- as well as multiple soil property **sensing in laboratories** is possible with remarkable accuracies and is becoming “state of the art”. For on-the-go **sensing in fields**, this stage of development largely still is a matter of the future.

For **remote sensing** from satellites or from aerial platforms, limitations that result from atmospheric barriers and from clouds must be considered. Atmospheric barriers that exist outside atmospheric windows (Fig. 3.3) can affect near- and mid-infrared radiation. In addition, clouds can block the transmission of all visible and all infrared waves. And regarding crop- or plant sensing, the unique effect of visible light on the photosynthetic process must be considered.

5.3.3 Concepts and Results for Surface Sensing in Fields

The ultimate goal is site-specific control of field operations by means of local soil properties. Proximal on-the-go sensing from farm machines lends itself for doing this either by simultaneous online control in real-time or by subsequent control via mapping. When remote sensing from satellites or from aerial platforms is used, up to now online control in real-time is not possible, so in these cases subsequent control via mapping is the choice.

Soil moisture hardly is suitable for mapping because of its transient feature. Its use for online control of the sowing depth is dealt with in Sect. 8.3.1.3. Other natural soil properties that can be recorded by reflectance such as texture, organic matter and cation-exchange-capacity are rather constant over time and hence well suited for control via mapping.

Sensing soils in fields occurs under much less controlled conditions than in laboratories, where dried and sieved samples in an accurately fixed position are subjected to the radiation. In fields, the soil moisture changes, and the soil particles vary from dust to crumbs, clods or residue pieces. Furthermore, on-the-go sensing excludes any fixed position. Hence a lower accuracy must be expected.

All concepts that have been used so far for proximal sensing by field machinery sense from a **flattened soil surface**. This allows to keep the distance to the soil rather constant. The flattened surface is obtained by sensing the soil at the bottom of a cultivator sweep (Fig. 5.25). Hence the information about the soil properties does not originate precisely from the top surface but instead from an area a few cm below this depending on the depth adjustment of the cultivator shank. This system of **sensing underneath a cultivator sweep** sometimes simply operates in the space between the upper flanks of the sweep and the soil below it (see Sect. 8.3.1.3). However, the concept that is outlined in Fig. 5.25 uses a closed bottom of the sweep. The radiation passes a sapphire window that is mounted along the bottom of the sweep. Contact between the passing soil and this window is supposed to create a self-cleaning effect and to prevent contamination of the optical path by dust or mud (Christy 2008).

Such soil property sensing by means of reflectance lends itself for combining with suitable field operations. It seems reasonable to **group the sensing** according to the time spans for which the respective soil properties can be used. Properties like *e.g.* conductivity, organic matter, clay and cation-exchange-capacity of soils are valid over a long time. Hence it is sensible to record these properties with simultaneous georeferencing in the same map or map-series and thus to combine the respective sensors into one machine (Fig. 5.26).

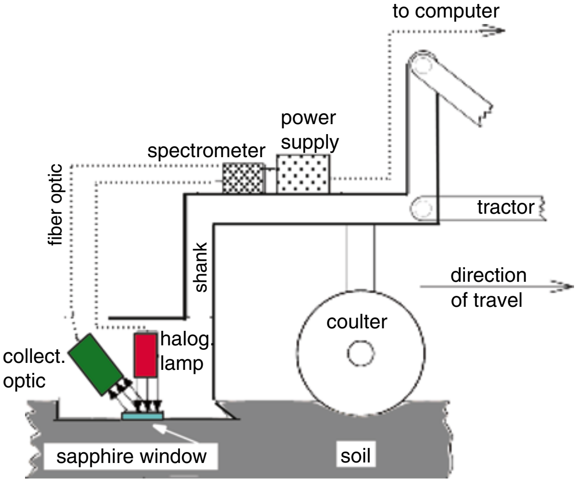

Fig. 5.25 Operating principle of on-the-go soil property sensing by near-infrared reflectance (From Christy 2008, altered and not to scale)

Fig. 5.26 Simultaneous mapping of both near-infrared reflectances underneath a cultivator sweep and electrical conductivities in the contact mode (Photo from Veris Technologies, Salina, USA, altered)

The situation is quite different for the short-timed water content. Mapping might be useless, but instead immediate control of sowing depth, cultivation depth or irrigation intensity might be needed. So for this, the combination with sowing, cultivation or irrigation would be reasonable.

But what about the **accuracy** of sensing in on-the-go field operations compared to recording in laboratories? Unfortunately, a direct and unbiased comparison of the

Table 5.5 Accuracies of on-the-go and full spectrum carbon sensing via reflectance for defined point estimations depending on the variables considered in a stepwise regression

Variable	Corr.coeff. squared (r^2), without dimension	Root mean squared error in 10 g/kg
Carbon only	0.70	0.189
Carbon + topography	0.81	0.156
Carbon + topography + water	0.83	0.144
Carbon + topography + water + clay	0.88	0.127

Extract from Huang et al. (2007)

Legend: field size = 50 ha. 85 geo-referenced and defined points for traditional soil analyses. 3,700 points for mean reflectance readings. Carbon negatively correlated to topography and positively correlated to water or clay

Range of total carbon: 5.5–28.9 g/kg. Range of elevation: 290–303 m

accuracies is not possible since this would imply the same spatial resolution for records from laboratories and from on-the-go sensing in fields. This prerequisite does not hold. The technique shown in Figs. 5.25 and 5.26 easily can provide a spectrum for every 8 cm of travel. Present practice is to use 50 readings respectively for an average spectrum. Thus for every 4 m of travel, a signal is available. And with a swath-width of 20 m, about 125 readings per ha result. Such a high resolution is completely beyond any real possibilities when the recording is based on analyses of samples in laboratories. Hence from the **spatial resolution** that can be obtained, online and on-the-go sensing inherently is much better suited for site-specific farming than analyzing in laboratories. It could have a lower **accuracy per signal** than laboratory techniques yet still provide a benefit as a result of the much better spatial coverage

But disregarding any spatial resolution, online and on-the-go reflectance sensing can be compared with traditional analysing on the basis how well for defined points within a field it supplies soil property data that agree with those that are obtained with conventional state of the art laboratory methods. Such a **defined point estimation** relies on the assumption that conventional laboratory analyses are accurate. This assumption probably is reasonable because of the long experiences with these conventional laboratory methods and the well developed procedures when using them.

Among the various natural soil properties, much interest goes to organic matter or the **carbon** content, particularly since water is a special case as a result of its transient character and clay can be roughly detected by electrical conductivity – except for arid regions. However, the natural soil properties are interdependent. A question is how much can be gained in accuracy for the **sensing of carbon** if the **dependence on other soil properties** is taken into account.

The results in Table 5.5 are based on defined point estimations of total carbon sensing by the on-the-go technique of Figs. 5.25 and 5.26 in a sandy loam of glacial origin in Michigan, USA, hence in a humid, moderate climate. The reflectance signals were recorded within a range of 900–1,700 nm with a spectral resolution of 6 nm. A multiple soil property sensing approach and a sophisticated processing of

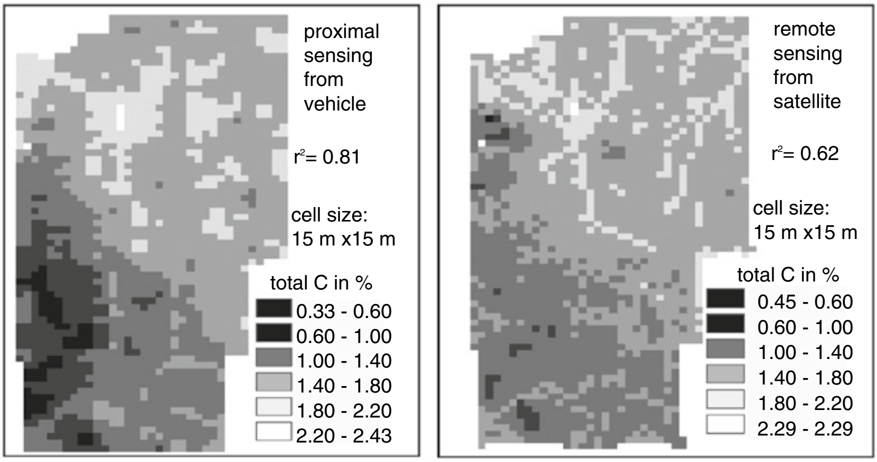

Fig. 5.27 Carbon maps obtained by reflectance sensing either from a land based vehicle or from a satellite (From Huang et al. 2007, altered)

the reflectance signals by stepwise multiple regression with principal component analysis allowed to obtain the effects of various soil properties on the prediction of carbon sensing. The processing included site-specific topographic signals that were obtained via RTK-GPS (Sect. 5.1).

For all properties or variables listed, it holds that their incorporation in the sensing and processing improved the estimation of soil carbon (Table 5.5). The most important effect on the coefficient of determination (r^2) as well as on the root mean squared error had the topography (slope and inclination).

However, this topographical effect is – at least partly – an indirect one. Because site-specific moisture and texture too depend on topography. And since topography with present day technology is easy to sense and map, it should be the first choice for improving the carbon sensing on a multiple property basis.

The carbon maps in Fig. 5.27 are based on such multiple soil property sensing. However, besides carbon only topography was taken into account by the processing program. So actually, **dual soil property sensing** with the aim of carbon recording took place. The wavelength range for the proximal sensing in the left map extended from 900 to 1,700 nm – as with the correlations in Table 5.5. For the remote sensing in the right map, the range went from 450 to 2,350 nm, however, with some interruptions in the infrared part due to transmission barriers outside the atmospheric windows. Although generally longer wavelengths allow for more precision, the results for remote sensing were less accurate than those for proximal sensing. Its coefficient of determination (r^2) – based on defined point estimations – is lower. Explanations for this may be – among others – the interruptions caused outside the atmospheric windows and the much longer sensing distances (see Sect. 3.2). Yet apart from this, the maps from proximal and remote sensing look similar.

It should be noted that the variation of the carbon content within the field was rather high (Fig. 5.27), which facilitates the sensing. On-the-go sensing with the same implement in fields with a smaller carbon variation resulted in much lower coefficients of determination and hence less useful results (Bricklemyer and Brown 2010). So far, the best results with on-the-go carbon sensing have been obtained in humid, moderate areas and with weathered soils. In arid and semiarid regions, the organic carbon content of soils is much lower and the fraction of **inorganic carbon** on the total carbon content generally is higher. This makes it much more difficult to get reliable maps about the site-specific situation of organic carbon.

5.4 Summary

Among the many concepts that basically can be used to sense soil properties, a few are about mature for on-the-go applications in site-specific farming such as:

- Sensing topography and mapping of digital elevation by means of RTK-GPS
- Sensing electric conductivities in humid areas for maps that inform about the site-specific yield potential
- Sensing salinity in arid areas by means of electric conductivities
- Sensing water via optical reflectance from horizontal and vertical soil surfaces for the control of sowing depths and irrigation
- Sensing organic matter in humid, moderate areas by means of optical reflectance.

Additional techniques for sensing soil properties are developing. These are *e.g.* techniques for sensing soil water in a separate mode via radar waves or via electric capacitance and especially techniques for sensing multiple soil properties simultaneously by means of infrared reflectance.

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