Chapter 7
Site-Specific Soil Cultivation

Hermann J. Heege

Abstract Site-specific soil cultivation has several objectives. In primary cultivation, the main objective is the control of the working depth. Signals for this control can be derived from the clay content, the organic matter content, the hydromorphic properties and the slope of the soil. An algorithm can combine these signals to control the working depth. The soil resistance to penetration is a suitable control signal for sensing hardpans below the topsoil, but not for the working depth within the topsoil, since it depends mostly on the water content.

In secondary cultivation, clod size reduction is an important objective. The site-specific control signals for this can be obtained from the forces acting on a sensing tine of a cultivator. The standard deviations of the forces can provide for suitable control parameters.

In stubble- or fallow cultivations either fast- or slow decomposition of the residues should be aimed at depending on rotations, climate and risk of soil erosion.

The introduction of controlled traffic farming or of unmanned farm machinery will promote crop production without tillage well beyond the present use.

Keywords Controlled-traffic • Depth-control • Fractionated seedbed • Impact-sensing • Moisture-line • Tilth-control

7.1 Basic Needs

The need for soil cultivation mainly results from crop- or plant successions in modern agriculture. In case of perennial vegetation without any abrupt crop- or plant succession as *e.g.* with permanent grassland, no one thinks about cultivation. Human

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needs for specific and uniform plant products necessitate annual monoplant fields and thus soil cultivation, either as **primary cultivation** (ca.10–30 cm deep), **secondary cultivation** or **seedbed preparation** (less than 10 cm deep) and in some cases also postharvest **stubble- or fallow cultivation**.

Precision in soil cultivation should be focussed at

- creating the bulk density needed for efficient plant growth
- providing the soil aggregate sizes that guarantee a high emergence of seeds
- weed control
- crop residue management
- water management.

All these efforts can be queried. In fact, some farmers plant crops without any previous cultivation. A soil, which is high in organic matter content may – without any cultivation – provide the bulk density as well as the soil aggregates needed. Weed control can be taken care of completely by herbicides. And if crop residues just are left on the soil surface, they can efficiently reduce soil erosion. So why worry to get them buried?

Yet again, there are also serious limits to these options. Not all soils have a sufficiently high organic matter content. Very often soils get compacted by heavy harvesting machinery as well as by post-harvest rain, hence necessitating cultivation. Weed control solely by herbicides can be costly. And last but not least, crop residues in the seedbed can seriously impair the emergence of seeds. This applies especially to narrowly spaced crops such as the widely used small grains in high yielding areas and when short time spans between harvesting and sowing prevail.

In short, despite the advances in zero- and minimum tillage practices, the majority of the farmers still has to cultivate. For these farmers, cultivation might take between 30 and 50 % of the energy needed for all field operations. Yet more precision in cultivation is urgently needed and might help to reduce the present controversies about soil cultivation techniques.

7.2 Primary Cultivation

Two effects deserve attention:

- the soil inversion and
- the depth of cultivation.

It is generally known that only the **mouldboard plough** can provide for an effective soil inversion and thus for a rather complete burial of weeds as well as of crop residues. All other implements just mix the soil and therefore leave some weeds and residues on the surface. The result is that the plough is the most effective tool for mechanical weed control and does away with all problems arising from residues in sowing operations.

Yet on the other hand, the plough is a very energy- plus labour consuming tool. And the bare surface left by the plough induces soil erosion. This holds true especially for sloped fields with silty soils in continental climate.

The steady advances in **chemical weed control** induce farmers more and more to rely on herbicides instead of the plough. From an environmental point of view, the herbicides as well as the plough can be questioned. Yet the future looks brighter for weed control by herbicides than for weed control by the plough. The advances which have been made for efficient and environmentally safe herbicides as well as for crops made resistant to herbicides by genetic progress are remarkable. It will hardly be possible to offset these advances by better ploughs.

There still may be negative effects of residues from the previous crop on the emergence of seeds. They mainly result from a less accurate seed placement in the soil by the openers of the sowing machines because of the residues. Yet this obstacle to cultivation without soil inversion by a plough too is losing its impact. Several means of eliminating negative effects of **crop residues** on or in the seedbed on the emergence have been developed. Examples are openers, which hardly are affected in their seed placement by residues or raking devices which operate ahead of the coulters and move the residues in the area between the rows (row cleaners). At least with widely spaced crops such as maize, soybeans and beets, these row cleaners can be used successfully. Modern harvesting machines too substantially can alleviate the problem by leaving finely chopped- and uniformly distributed residues on the field. In short, crop residue management also less and less requires ploughing.

The subsequent text therefore deals primarily with problems and solutions for precision cultivation with tined implements.

7.2.1 Factors for the Depth of Primary Cultivation

The bulk density needed for efficient plant growth is mainly regulated by the depth of the primary cultivation. The deeper the primary cultivation tools operate, the more the soil is elevated above the original surface, thus the more the bulk density is lowered. Methods for recording the bulk density in the laboratory are state of the art. However, sensing techniques capable of recording the bulk density in a continuous manner online on-the-go are not available. But a feasible approach is to adjust and to control the depth of the primary cultivation according to surrogates such as

- water supply
- texture
- organic matter
- slope
- resistance to penetration.

7.2.1.1 Water Supply

Precipitation increases bulk density of soils. This holds especially for bare soils. But when it comes to adapting cultural practices to precipitation, it is helpful to differentiate between climate and weather. **Climate** acts on large, contiguous areas and is

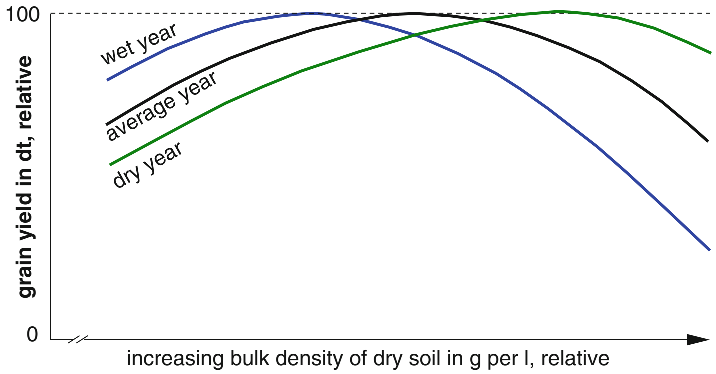

Fig. 7.1 Principal relation between soil bulk density and grain yield (From Hakansson et al. 1974, altered)

defined on a longterm basis, *i.e.* for decades and centuries. **Weather** is a matter of smaller areas and shorter time spans. Very important is the forecasting. The climate of an area is fairly constant. Forecasting therefore hardly is a problem. Yet forecasting the weather for more than a few days still is a problem in large parts of the world.

Therefore, adapting the soil cultivation to the respective climate has been state of the art for a long time. A global traveller attentive to farming operations will notice that in humid regions the primary cultivation is done deeper than in regions with low rainfall. This is, because in humid areas the water supply of the crop seldom is a problem, but the soil aeration often is. In areas with low rainfall, the situation is *vice versa*, consequently here the cultivation is either very shallow or even left out completely.

But what about the adaptation of the **cultivation depth** to short term weather expectations? Ideally the farmers would have to provide for a high bulk density in a dry growing season and *vice versa* in a wet year (Fig. 7.1).

Despite the fact that many weather satellites now operate in combination with modern computers programs, the **weather forecasts** still are not reliable beyond a few days. Much better adapted cultivation could be realized, if in the future the forecasts were accurate for at least some weeks.

An alternative approach would be adapting the depth of cultivation not to the precipitation expected in the next days but instead to the respective **water content** in the soil. This would be a response to the rainfall and the evaporation of some days of the past. Sensing techniques for recording the water content in the soil are available (Chap. 5). The problem is that the depth of primary cultivation is expected to have its effect over the whole growing season of the crop. Hence the incidental water content just at the time of cultivation may not always be a reliable indicator for the best depth of cultivation. Increasing the depth of cultivation with the water content of the soil might even be completely wrong, if the tools do not break up any more but instead of this deform and compact the wet plastic soil. Cultivating deep in regions with a humid climate still might be reasonable, but this should preferably be done during dry spells in order to prevent damage to the soil.

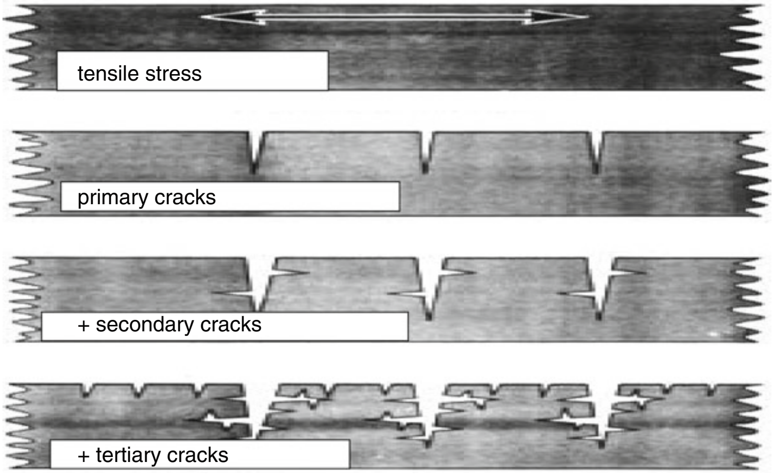

Fig. 7.2 Gradual formation of cracks in a drying clay soil (From Dexter 1988, altered)

Dry periods are especially important when it comes to **hydromorphic soils**. These soils are associated with temporal water saturation in the lower part of the topsoil, *e. g.* in most parts of the world during the winter period. Most commonly this waterlogging occurs due to a concentrated water flow into topographic depressions that are not well drained. Thus in rolling areas there may be just some spots of hydromorphic soil within a field. This hydromorphic soil can easily be recognized when breaking it up with a spade by its blue-grey colour. When the field is prepared under dry conditions, these areas need deep cultivation. Further details are dealt with below.

7.2.1.2 Texture

It is well known that the sequence freezing-thawing can substantially reduce the strength of soils and thereby promote **break-up** of clods. A similar effect can be obtained free of charge by weather sequences that cause wetting followed by drying. However, this effect depends very much on soil texture and its interaction with water. The question is, how wetting or drying of a soil affects its volume. With sandy soils, the water content hardly changes the volume. On the other hand, clay soils swell during wetting and conversely shrink while drying. These processes induce tensile stresses within the soil, and this in turn causes cracking of the dry soil (Fig. 7.2).

Therefore, if the texture within a field is not uniform, it can be reasonable to adjust the site-specific depth of cultivation for a promotion of soil break-up to this. Below it is shown how such a control can be realized (Sect. 7.2.2.1).

7.2.1.3 Organic Matter

Organic matter in a soil generally counteracts any compaction. Therefore, soils that are low in organic matter content need more cultivation. The primary cultivation tools must go deeper. The problem is that with the intensity of cultivation the **decomposition** of the organic matter too increases. Hence farmers might get into a vicious circle: a low organic matter content induces to cultivate deeper, but this in turn and in the long run might reduce the organic matter content even more.

The way out of this dilemma is not necessarily less cultivation, if this means lower yields. Because lower yields might in turn mean less incorporation of organic residues. The best solution probably is precise adaptation of cultivation needs to the respective situation, thus preventing any superfluous cultivation without any sacrifice in yield combined with care for organic matter in the soil by suitable residue management. In essence, this means precise soil and crop management. Since many fields do not have a uniform organic matter content and sensing the respective organic matter situation is possible, the control of the depth of primary cultivation via this soil property seems reasonable.

7.2.1.4 Slope

On slopes, the runoff of water deserves attention. The result of this runoff and its effect on soil erosion is accumulation of finely textured soil with much organic matter in depressions to the disadvantage of hills. Hence from the outset, sloped fields do not have uniform soils and need site-specific attention.

Site specific cultivation can

- either provide for improved adaptation to results of erosion that occurred in the past or
- be targeted at reducing erosion in the future.

The improved adaptation to erosion from the past is possible by controlling the depth of cultivation according to the respective texture and organic matter content on hills, slopes and in depressions of the fields.

And reducing erosion in the future can be obtained by improving the infiltration of water and thus decreasing the runoff. Several practices can contribute to this such as keeping the soil surface vegetated as much as possible, leaving crop-residues at the soil surface and finally – if bare soil cannot be avoided – increasing the depth of cultivation. So whenever feasible, vegetation or its residues should be used to improve infiltration and to prevent erosion. Deep cultivation of bare soil as a means for this should be regarded as an exceptional matter.

There are cases where improving the infiltration still cannot prevent that a substantial portion of the precipitation runs off. This inevitable runoff should occur without much soil erosion. For this, the water should be slowly channelled downwards via broad, saucer shaped, grassed waterways into ditches. These grassed waterways can act as perennial runoff strips.

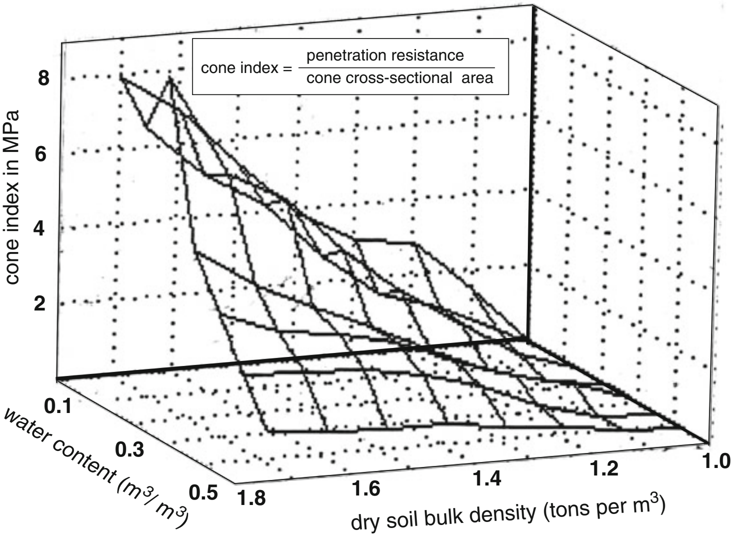

Fig. 7.3 The effect of bulk density and water content on the cone index (From Sun et al. 2003, altered)

7.2.1.5 Resistance to Penetration

Soil resistance to penetration has for a long time been an object of investigations, *e.g.* in search of a **substitute** for bulk density. Traditionally, probes with a sensing cone on the tip are pushed **vertically** into the soil. Yet this mode of operation hardly is suitable for on-the-go sensing. Therefore, the interest has shifted to probes, which move in a **horizontal** direction through the soil and can easily be drawn by a tractor (Lüth 1993). So continuous- instead of punctual signals are recorded. Adamchuk et al. (2008) placed several horizontally oriented sensing cones that were staggered along a vertical blade for simultaneous recording of the horizontal resistance at several depths below the soil surface.

The signals obtained from penetrometers are strongly influenced by the **water content** of the soil regardless of the sensing direction. The results shown in Fig. 7.3 are based on a cone index, which is penetration resistance divided by cone cross sectional area. The effect of the water content of the soil on the cone index is several times higher than the influence of the bulk density.

This explains why it is attempted to sense resistance to penetration and water content simultaneously. The objective in doing this is to correct the cone index data for the influence of the water content (Sun et al. 2003; Hartung and Drücker 2009). Without such corrections, the resistance to penetration cannot provide reliable signals to control the cultivation depth, since the water content of a soil can vary considerably on a temporal- as well as on a spatial basis.

Notwithstanding the influence of the water content, penetrometers are well suitable to detect **hardpans** in soils, *e.g.* those that might exist below the topsoil as a

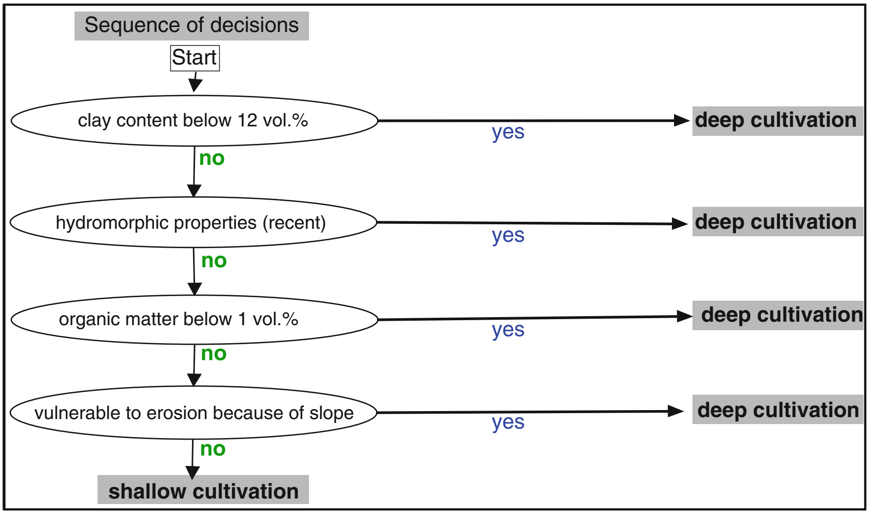

Fig. 7.4 Sequence of decisions for the control of the primary cultivation depth (From Sommer and Vosshenrich 2004, altered)

result of geological deposits or might develop from longterm plowing at the same depth (Gorucu et al. 2006). The density of usual hardpans differs very substantially from that within the topsoil. Any differences within the topsoil are smaller, hence more difficult to sense.

7.2.2 Site-Specific Control of the Primary Cultivation Depth

7.2.2.1 Algorithm for the Control

Sommer and Vosshenrich (2004) developed a control system for the cultivation depth. It is based on several soil properties and a control algorithm (Fig. 7.4).

Whenever the **clay content** is below 12 % by volume, **hydromorphic properties** exist, the **organic matter content** is below 1 % by volume or **slope induced erosion** might occur, deep cultivation is practiced. It should be noted that with this control system every one of the four indications alone – or in a combination – brings about deep operation. Whenever none of these situations exists, the control system goes to shallow cultivation. All of these indications are not short timed and therefore lend themselves for control via maps and their overlay (Fig. 7.5). Particularly regarding the clay- and the organic matter content, the maps prepared for this overlay control system might be used for many consecutive years, since these soil properties are rather constant over a very long time.

The hydromorphic situation might change when the drainage has been improved. And the precautions necessary to prevent erosion depend not only on the respective

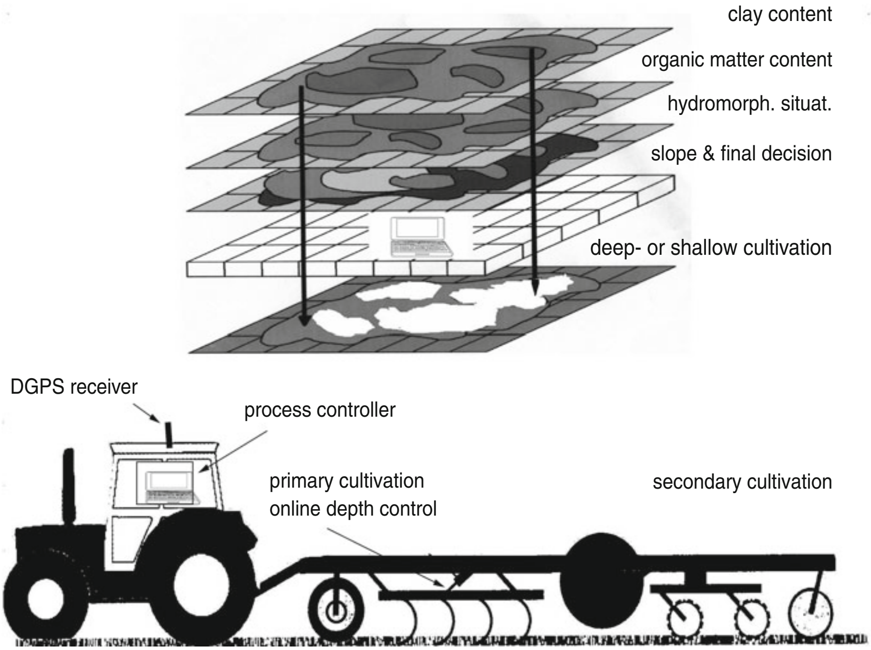

Fig. 7.5 Map overlay for a site-specific depth-control of primary cultivation (Vosshenrich and Sommer 2005a, altered and supplemented)

slope, but on crop residues left near the soil surface as well. So for these two factors the situation might vary over time.

There are fields where neither hydromorphic soil nor prevention of erosion need attention, and only a varying clay- and organic matter content remain as control factors. Both factors can be recorded online and on-the-go. So principally a control in real-time would be possible (Vosshenrich and Sommer 2005b). However, for most cases it seems reasonable to control by **georeferenced maps** instead of employing a real-time system. Because a dual-map overlay control system – once created – can be used for many years.

But what means deep- or shallow cultivation in absolute terms? Vosshenrich and Sommer (2005a) defined 20 cm for deep- and 10 cm for shallow cultivation. These absolute depths refer to Northern German conditions. As outlined above, the respective climate should be considered when the local adjustment for deep- and shallow operation is defined in absolute terms.

An **interaction** of the factors clay- and organic matter content concerning the needed depth of cultivation can be expected. The higher the organic matter content is, the lower the clay content probably can be, and *vice versa*. This is, because both factors inherently promote soil break-up without any cultivation. Vosshenrich and Sommer (2005a) state that with an organic matter content of 1.5 % or more a clay content of 8–10 % would be sufficient for shallow cultivation. However, until now this interaction is not included in a control algorithm that is state of the art.

It is generally recommended to use this site-specific cultivation system only with soils that do not have compacted zones. The advice therefore is to start with this system after a first deep cultivation of the whole field under dry conditions.

In principle, such a system is feasible with many different cultivation tools. Differentiating between primary- and secondary cultivation in this respect might make sense in humid climates. Yet this distinction hardly helps under dry conditions, where the depth of cultivation might not substantially go below the level of the seedbed.

7.2.2.2 Economics

Provided the soil is not uniform within a field, which is the rule, the savings from site-specific cultivation in a humid climate can justify the additional investment needed for the depth control. This is the result of a study by Hartung and Druecker (2009) as well as by Isensee and Reckleben (2009) undertaken in Northern Germany on rolling fields and soils of glacial origin.

The site-specific cultivation was done with the technology and the equipment as explained in Figs. 7.4 and 7.5. The depth of the primary cultivation was mostly either 20 or 10 cm, since for a more gradual control system no information existed. The result of the depth control system was that on the average approximately half the area was cultivated shallow.

The **benefits** realized from the site-specific primary cultivation were 6 € per ha in fuel costs and 2 € per ha from the increased work-rate, thus a sum of 8 € per ha. At first sight this sum of benefits may seem trivial. However, the total charge including labor cost for primary cultivation by tined implements according to contractor rates is about 25 € per ha. Hence the benefits in fuel costs and from the increased work-rate amount to about 32 % of the usual contractor expenses. In the long term, these benefits can easily cover the additional costs for the control needed.

There were no significant effects of this site-specific primary cultivation on the **yields** of small grains (Sommer and Vosshenrich 2004; Isensee and Reckleben 2009).

It can be expected that this cultivation method reduces the decomposition of the soil organic matter because of less aeration at locations where deep work is not needed. However, this benefit of site-specific operation is difficult to evaluate.

7.3 Secondary Cultivation

Except for sandy fields or for soils high in organic matter content, usually some **clod break-up** by secondary cultivation is needed for a good crop emergence. In a cloddy soil, the seeds do not get close contact with the soil water, hence the germination is reduced. Figure 7.6 shows the emergence of small cereals depending on the mean

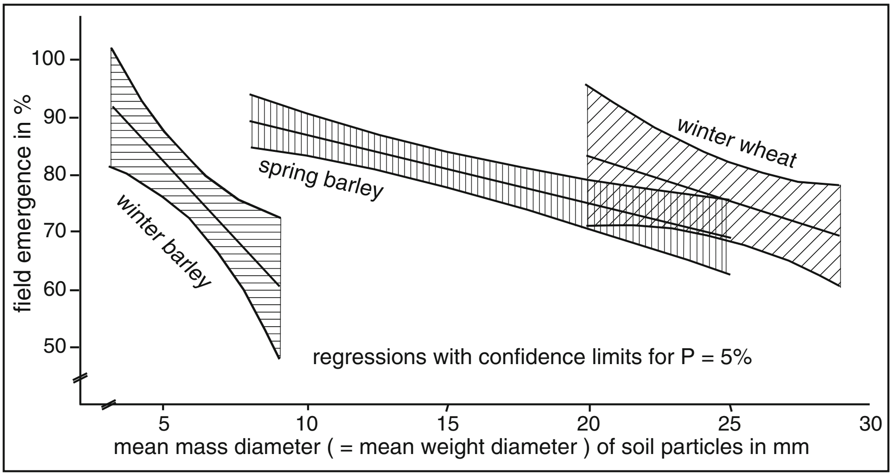

Fig. 7.6 Soil clod size reduction and field emergence (Heege and Vosshenrich 2000)

mass diameter of soil clods from experiments in Germany. This parameter of soil tilth is often denoted as mean weight diameter (MWD). It is determined by a sieving process and by weighing the fractions.

The wide span from 3 to 20 mm mean diameter that can provide for a high emergence may be surprising. Yet the balance between the water- and air supply in the seedbed is important. In Germany, winter barley is sown substantially earlier in autumn than winter wheat at a time, when the soil still is rather dry. Therefore, for a good balance of water to air, winter barley needs a finer seedbed than winter wheat, which gets enough water anyway because of the rather wet soil in late autumn or early winter.

There are exceptions from the general rule that the field emergence increases with the soil break-up. These exceptions apply to soils with a high silt content in a climate, where heavy showers instead of drizzling rains show up. Under these conditions, the surface of a fine seedbed can get puddled by showers and in subsequent dry weather it can become crusted. The result is a cut off in aeration and thus poor emergence. However, these exceptions do not invalidate the general rule.

7.3.1 Sensing Soil Tilth

Since the soils in many fields are not uniform in texture or organic matter content and compaction by the harvesting machines is irregular too, the tilth differs within a field. The knowledge that the farmer has about the site-specific clod sizes in the seedbed depends on his visual impression and therefore is fragmental. There is a need for real-time sensing of the site-specific clod sizes produced during seedbed preparation.

Table 7.1 Approaches to sense soil tilth

Sensing techniques	Authors
Non contact sensing techniques	
Gamma-ray attenuation	Oliveira et al. (1998)
Image analysis and -processing	Bogrekci and Godwin (2007a)
	Stafford and Ambler (1990)
Laser relief metering	Bertuzzi and Stengel (1988)
	Destain and Verbrugge (1987)
	Harral and Cowe (1982)
Reflectance of visible-and/or infrared radiation	Bowers and Hanks (1965)
	Orlov (1966)
	Zuo et al. (2000)
Ultrasonic relief metering	Scarlett et al. (1997)
Contact sensing techniques	
Horizontal mini penetrometer	Olsen (1992)
Strain gage on spring tine	Bogrecki and Godwin (2007b)

This would allow to adjust the **cultivating intensity** on-the-go or alternatively to adapt the site-specific **seed-rate** in order to compensate for coarser seedbeds.

The traditional method to examine the clod size distribution is mechanical sieving of soil samples. This method is laborious and probably completely unsuited for on-the-go sensing in real-time. However, it is still used as the standard reference method in research for the assessment of tilth. Many attempts to realize a sensing of the clod size distribution in a more convenient way have been made (Table 7.1).

The methods can be classified into non contact- and contact techniques, depending on the physical principles employed. Up to now, none of these methods is used in practical farming. And on-the-go sensing in real-time has been realized only with either relief sensing by ultrasonics or with a strain gage on a spring tine of a cultivator. The latter principle is dealt with below in detail.

7.3.1.1 Principle of Tilth Sensing via Impact Forces Acting on a Tine

The basis of this method are the **impact forces** that act on a spring type tine during secondary cultivation. These forces result from the collision of the tine with soil clods. They can be recorded by measuring the distance, for which the tine is deflected because of the soil's resistance.

A rather simple method to sense the deflection of the tine is the use of a strain gage. The deformation of the tine is measured by bonding a small electrical conductor to this machine part. Since this electrical conductor is stretched, distorted or compressed together with the tine, its current output changes. From this – after careful calibration – the forces can be obtained.

There is a fundamental difference in the objectives of sensing the soil forces that act on a tine or a cone depending on whether the control of either primary- or secondary cultivation is aimed at.

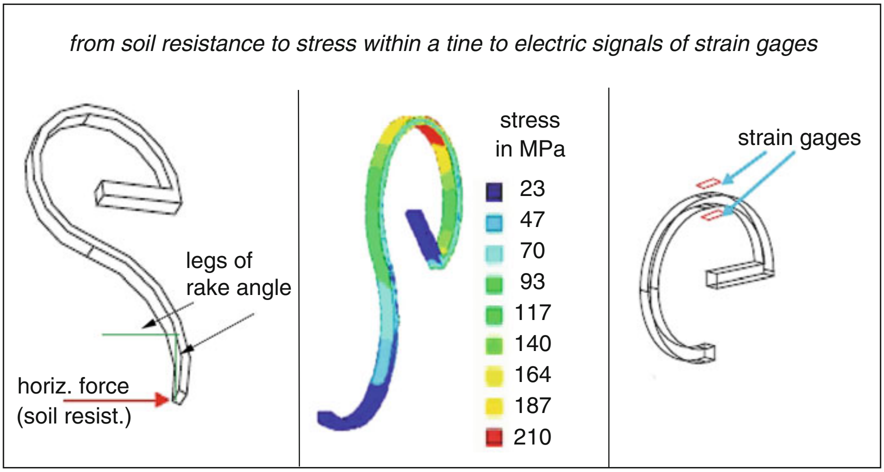

Fig. 7.7 Sensing instrumentation for recording the soil break-up in a seedbed (From Bogrekci and Godwin 2007b, redrawn and altered)

With primary cultivation the main question is the **depth of operation**. The concept is that the higher the soil resistance to a tine or a cone moving in the soil is, the more the soil density should be reduced and the deeper the primary cultivator should operate. Yet up to now the realization of this idea has not been successful. This might be explained by the fact that for most soils the resistance to a tine or a cone is predominantly influenced by the water content and much less by the soil density (Fig. 7.3). And since the water content of a soil can change fast in a spatial- as well as in a temporal mode, the sensing objectives for the soil density hardly are met.

With secondary cultivation the situation is different: the main objective is not the density, it is the **tilth** or break-up of the soil. The emergence of crops mainly depends on the soil break-up within the seedbed as shown in Fig. 7.6 whenever zero tillage methods are excluded and tillage is needed.

Bogrekci and Godwin (2007b) have shown that a **strain gage** located at a suitable location on a spring tine of a cultivator can provide a reliable and an inexpensive source of signals about the soil break-up in a seedbed. Figure 7.7 shows, at which location of the spring tine the strain gage should be bonded. It is the highest point of the tine and the position, where the soil resistance causes the maximum load or stress on the tine.

7.3.1.2 Results with Tilth Sensing via Impact Forces

The general situation under *ceteris paribus* conditions is that the finer the soil structure is, the lower the mean horizontal force on the tine is. This results from the fact that for the finer soil particles it is easier to flow backwards around the tine. Therefore they exert less horizontal resistance. But despite this it must be asked, whether the **mean** horizontal force is the most suitable parameter for sensing the break-up of the soil.

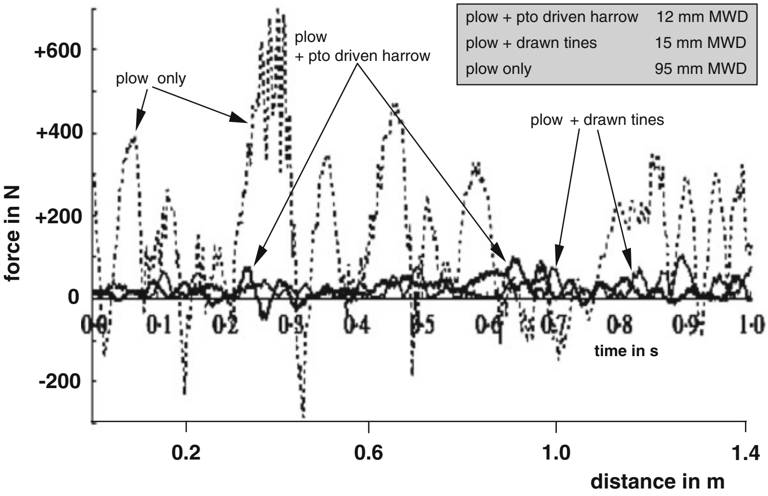

Fig. 7.8 Signals on the sensing tine for three different tilths of a clay soil (From Bogrekci and Godwin 2007b, supplemented and altered). *MWD* mean mass diameter of soil clods

In principle, soil clod sensing is **impact sensing**. Almost every clod in a seedbed is a unique case in terms of size, mass and shape. Therefore, the impacts delivered by the clods on the recording tine must vary constantly. The sensitivity of the sensing instruments including the cultivator tine must allow for indicating this. An investigation of several spring tine types in this respect showed that the tine type as shown in Fig. 7.7 gave the best results.

An important factor of cultivator tines is the **rake angle**, which is the angle between the tine part operating in the soil and the undisturbed soil surface, seen perpendicular to the direction of travel. The lower the rake angle is, the smaller the soil resistance is in most cases. However, the larger the rake angle is, the more the soil is broken up. This is, because with a larger rake angle it is more difficult for the clods to pass the tine, hence the soil resistance as well as the break-up are higher.

The tine in Fig. 7.7 left has a rake angle of approximately 90°, which is a common angle in implements for secondary cultivation. Bogrekci and Godwin (2007b) have shown that using a 90° rake angle enables the soil break-up to be distinguished more effectively than when using smaller angles. This as well probably is due to the fact, that the clods cannot go around the tine as easy as with smaller angles, and this improves their recording.

In Fig. 7.8, the forces recorded by the sensing tine are shown for a soil, which was either only ploughed or secondary cultivated as well. The secondary cultivation was either by a drawn tined harrow or by a harrow that was operated via the power-take-off (pto). All curves show a **high resolution** on a time basis. They hold for a travel speed of 5 km/h. Since the duration is 1 s, the length of travel represented by the abscissa in Fig. 7.8 is about 1.4 m. Within this distance, all curves of the three different methods of soil cultivation show more than ten amplitudes. Therefore, the impact of each clod on the sensing tine seems to be well recorded.

Along all curves there are short instances, within which the forces become negative. This is the result of vibrations of the spring tine. The differences in the forces before and after secondary cultivation are evident; however, those between the seedbed preparation by the drawn harrow tines on the one hand and the power- take-off driven harrow on the other hand are not. Some evidence of a finer seedbed after secondary cultivation by means of the power-take-off drive is given by the comparison of the respective mean weight diameters (see insert of Fig. 7.8).

However, when the erratic course of the curves is taken into account, it cannot be expected that the mean force is the best benchmark for the site-specific tilth sensing. A mean criterion can hide many details of the data from which it was obtained. A close observation of the course of the curves suggests that concentrating the analysis on the respective amplitudes, frequencies or standard deviations of the forces might be reasonable. In a statistical analysis by Bogrekci and Godwin (2007b), which was focussed on an indicator for the soil tilth, the best results were supplied by the **standard deviation of the forces**.

It should be noted, that this analysis had the mean weight diameter (MWD) of the soil aggregates as an indicator of the soil tilth. There are several factors that might influence the signals of the soil break-up that are obtained via the standard deviation of the forces. Such factors can be the driving speed, the depth of cultivation, the soil type and the direction of cultivation compared to the direction used in the previous primary cultivation.

The influence of the **driving speed** as well as of the **soil type** seem to be rather small. As to soil type this might be expected, since – provided the clod sizes do not differ – its effect on the mass of soil aggregates is rather small. At least this holds, when peat soils are excluded. As to the driving speed, this might be surprising, since the driving speed must have a considerable influence on the impact forces. But with all implements that use drawn tines for soil cultivation, the driving speed also significantly affects soil break-up. Higher driving speeds increase the break-up as a result of the higher impact forces. So if the tilth after cultivation is compared, the effects of the driving speed on the soil break-up as well as on the forces exerted on the sensing tine go in the same direction and therefore probably even out.

The results shown in Fig. 7.9 are based on pooled data for driving speeds ranging from 5 to 15 km/h and for two soil types. Despite this, the root mean square error is only 3.5 mm for the mean weight diameter of the soil aggregates.

But the **sensing-depth** of the tine is important. In most cases, forces on tines increase more than proportional with the depth of operation in the soil. So if the cultivation implement does not provide a constant depth, a special depth control device for the sensing tine is necessary.

It seems reasonable to compare the soil tilth that this tine sensor indicates with results obtained by the standard sieving procedure. A correlation based on the respective mean weight diameters that were recorded after careful calibration is shown in Fig. 7.10. The result is a rather simple linear relation, as might be expected

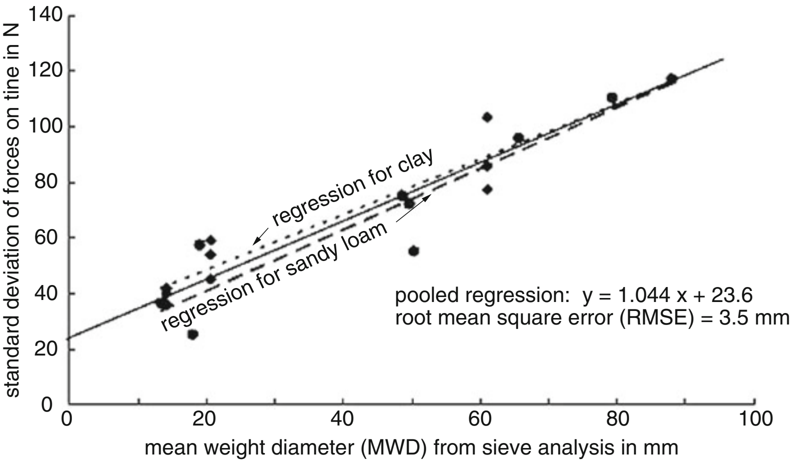

Fig. 7.9 Sensing of soil tilth by the standard deviation of the forces acting on a sensing tine (From Bogrekci and Godwin 2007b, altered)

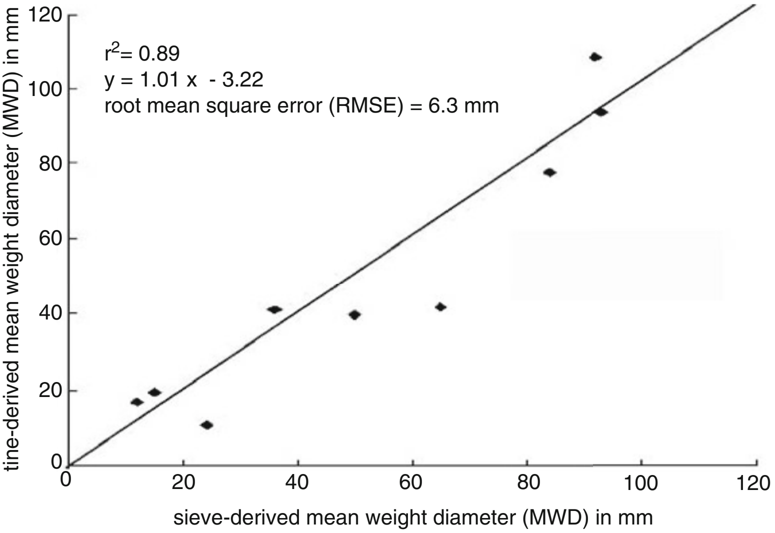

Fig. 7.10 Soil tilth recorded either by the standard sieving method or by the tine sensor (From Bogrekci and Godwin 2007b, altered)

from the data in Fig. 7.9. The root mean square error of recording the soil break-up via the tine sensor instead of the standard sieving method is 6.3 mm of the mean weight diameter. Taking into account the reactions of the crops on the mean weight diameter (Fig. 7.6), this error seems acceptable.

7.3.1.3 Implications for Soil Tilth Sensing

The important prospect is that a tine sensor instead of a sieving method can deliver signals about soil tilth online and on-the-go. Thus it is possible to react on the respective site-specific situation in real-time. The object of control would be either the soil **break-up** by the secondary cultivation or the **seed-rate**, assuming that a higher seed-rate might be needed with a coarser seedbed and *vice versa*. However, the concept of adjusting the seed-rate to the respective soil break-up is like repairing a symptom and leaving its cause unaltered. The better approach for most crops probably is to avoid local deficiencies in the relative emergence as much as possible. Hence, controlling the soil break-up on the basis of the tilth sensed is the more logical procedure.

Where should the sensing-tine take the signals during the cultivation procedures? It would be possible to take the signals after primary cultivation by placing the sensing-tine **ahead** of the secondary cultivation implement. With suitable implements, this would allow to set up a control system for the secondary cultivation on the basis of the soil break-up by the primary tool. However, in order to get the desired seedbed, it still would be necessary to know the final soil break-up by the secondary implement in advance. This knowledge – on a soil specific basis – is hardly available. A simpler and more logical control system ensues if the sensing tine is placed **behind** the secondary cultivation implement. Thus the effect of the respective primary- and secondary implement is included in the final control. However, this position of the sensing-tine would need very fast control results in order to prevent too late adjustments since the sensing occurs afterwards. A compromise between these positions ahead or behind would be to place the sensing tine within the secondary cultivation tools, *e.g.* within the last row of tines.

The emergence of the seeds depends largely on the water transferred to them from the soil, therefore on the clod break-up as well as on the water content in the soil. But knowing the water content at the time of secondary cultivation and sowing alone is not sufficient. The short-term water supply in the first days **after** sowing is the most important criterion for emergence. Because this is so, there is still a huge lack of certainty when the question of the soil break-up needed for high emergence comes up. With much rain in the first days after sowing a coarse seedbed suffices and might be even beneficial, and with dry days after sowing it is *vice versa*.

But the short-term weather forecasts still are not reliable in most parts of the world. The expectations for reliable rain-forecasts, which were raised since the introduction of **weather satellites** and of new meteorological techniques, have not been met. The situation is that the existing uncertainties about short-term weather prospects bring about one of the biggest problems with many precision farming operations in rainfed areas. This applies especially to secondary cultivation and sowing operations. The objectives with the use of a soil tilth tine sensor could be defined much more precisely, if the rainfall in the next few days were known, because then the soil break-up needed could be defined more accurately.

Mapping the results of a tine-sensor would be possible. However, this would be reasonable only if additional soil properties, which were sensed too, were important. Such a property could be the site-specific water content of the soil instead of the rain expected. The lower the water content of the soil, the finer the seedbed should be. So if recent data about the water content were mapped, both the water situation as well as the soil break-up data could be combined in a new control map for subsequent cultivation- or sowing operations. Yet experience with such a concept up to now is not available.

The ideal concept of site-specific secondary cultivation would be a system of real-time on-the-go control for soil tilth, possibly obtained in one operation based on a tine sensor. Up to now such a concept can only be realized with power-take-off driven implements. These allow adjusting the soil break-up by altering the speed of the tines as well as their cuts per unit of travel distance on-the-go. Modern drives for the **power-take-off** and for the travel speeds of tractors provide the means for such on-the-go adjustments.

However, **drawn tools** on secondary cultivation implements are dominating in most parts of the world. And with solely drawn tools it hardly is possible to adjust the soil break-up on-the-go during one pass.

In short, sensing the soil break-up during cultivation in real time is feasible, but the possibilities of using the signals are limited. The restrictions in use on the one hand come from present deficiencies in the precision of the weather forecasts, and on the other hand are caused by present limits in the adjustment of drawn secondary cultivation implements. But these conditions can change. Hopefully, in the future the meteorological advances will provide for more precise weather forecasts, and more cultivation implements will be at hand, which allow for adjusting the soil break-up while operating. So the long-term outlook for site-specific secondary cultivation still might be good.

With primary cultivation, the situation is completely different. The main objective of the control is not precise clod break-up, but the decrease of soil bulk density via depth of operation. The latter can rather easily be adjusted on almost all implements. And furthermore, the short-term weather in the next days hardly is important with primary cultivation. Instead of this, the depth of the primary cultivation must be adjusted to long-term precipitation effects and to soil inherent properties. The knowledge about these factors is available or can rather easily be obtained. Therefore, as compared to secondary cultivation, the control of site-specific primary cultivation is a matter of present day realization.

7.3.2 Precision in the Vertical Direction Within the Seedbed

A uniform soil tilth in the vertical direction within the seedbed might be adequate with soils that do not tend to surface crusting after heavy rain and subsequent dry weather as well as with crops that emerge rather easily. But soils with a high silt- and low organic matter content can get crusted under the weather conditions described above. And the seeds of some crops – *e.g.* sugar beets, spring sown small cereals and some oil crops – emerge better if the seedbed created by secondary

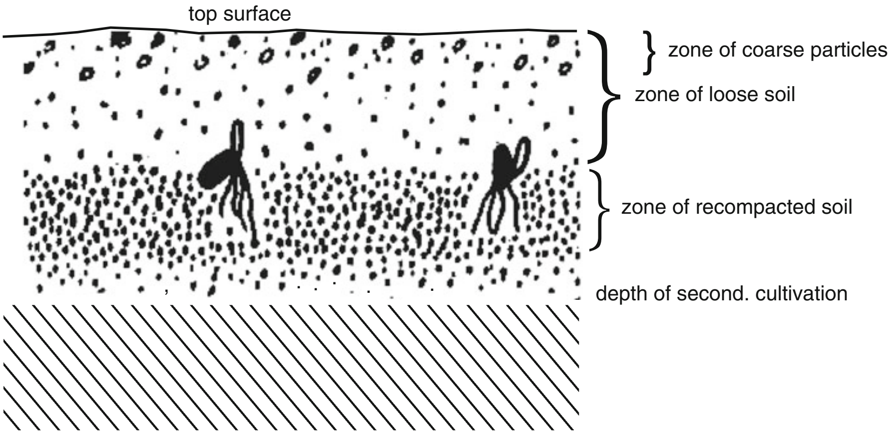

Fig. 7.11 Fractionated seedbed for the prevention of crust formation on the top surface by some coarse soil particles (vertical cross-section)

cultivation is not uniform in the vertical direction. So for these cases, soil size reduction within the seedbed should be controlled not only in the horizontal direction, but in the vertical direction as well.

The soil particles that have direct contact with the seeds always should be fine in order to ensure water transfer. Possibly immediately underneath the seeds, the soil should be denser than above them. This helps to draw some water from below in a dry spell. Loose soil above the seeds provides for the aeration needed. And if surface crusting might develop, there should be coarser soil particles on or near the surface to prevent this. So a **fractionated seedbed** (Fig. 7.11) would be needed (Heege and Vosshenrich 1998, 2000; Heinonen 1985; Hakansson et al. 2002; Satkus and Velykis 2008).

Up to now, no farm machines are available that allow precisely to adjust the degree of fractionation. But at least the seedbed could tend to be structured as outlined above. To a small extent, the more dense soil immediately underneath the seeds is created by the pressure of the seed openers. And some vertical fractionation of soil particles can be obtained by segregating small soil particles from larger ones during secondary cultivation. While the soil is stirred, small particles have a better chance than the larger ones to sift downwards in voids, *e.g.* behind tines. As a result, more large aggregates remain near the surface.

This **segregation by sifting** needs rather slow moving tools, such as the tines of drawn implements. With fast moving tines, such as those of power-take-off driven implements, no segregation occurred (Heege and Vosshenrich 2000). Probably this can be explained by the time that is needed for small particles to sift downwards in voids behind tines. With fast moving tines, this time is too short for a remarkable segregation to take place.

The fractionation depends on the **rake angle** of the tines (Fig. 7.7, left). A low rake angle and therefore tines pointed forward in the direction of travel improve the segregation. This is, because these tines tend to lift more coarse clods to the surface and hence to create larger voids for the small particles to sift downwards in.

Many secondary cultivation implements have tools that operate with rather low speeds. Examples for these tools – in addition to drawn cultivator tines – are drawn discs and rollers or power-take-off driven rod weeders (Fig. 7.12). These tools hence can leave a partially fractionated seedbed (Winkelblech and Johnson 1964; Maze and Redel 2006).

Recording the fractionation of the seedbed may be possible on the basis of the soil resistance or of the impact forces exerted on horizontal sensing tips that are mounted at suitable depths of a vertical tine (Adamchuk et al. 2008). As with sensing of the general soil break-up (Fig. 7.7), the best results probably will be obtained by using the standard deviations of the impact forces (Figs. 7.9 and 7.10). Clods on top of a fractionated seedbed can be expected to deliver higher standard deviations than the fine particles in the zone provided for seed placement.

Yet the problem is not the sensing method. It is the lack of cultivation tools, which allow for precisely adjusting the **intensity of fractionation**. The development of cultivation tools suitable for such an adjustment is an important prerequisite for more precision in the vertical direction of the seedbed. There is an urgent need for advances in this direction.

7.4 Stubble- and Fallow Cultivation

Stubble- and fallow cultivations are “interim” operations between two successive crops. When a crop is sown a few days after harvesting of the preceding crop, they may be left out completely. Often planting occurs some weeks or a few months after harvesting. Then only one operation may be necessary, which after small grains is called stubble cultivation. But when a complete fallow year (summer-fallow) is practised before another crop is established, several passes of fallow cultivation may be needed. So the length of the fallow period after harvesting is an important criterion.

Generally, humid, high yielding areas have short fallow periods, since the water supply for the crops hardly is a problem. In dry-land regions the situation can be *vice versa*. Here there may be plenty of land, but not enough water. Therefore, a long fallow time can be reasonable in order to accumulate and store precipitation in the soil, which then later can be useful to get a better crop yield. The rationale of summer-fallow is to use the precipitation of 2 years for a crop growing season of 1 year.

The objectives of stubble- or fallow cultivation are **weed control, residue management**, sometimes **erosion control** and **conservation of soil moisture**.

Weed control as an objective of cultivation has lost in importance as a result of modern possibilities with efficient herbicides (chemical fallow), which can easily be realized in a site-specific mode (see Sect. 6.2).

The objectives in **residue management** depend on the climate. In humid, high yielding areas with short fallow periods, the main objective is to get fast decomposition of the large amounts of residues in order to avoid interference with seed openers. The decomposition of the residues depends on its contact with the soil, therefore on its incorporation by cultivation. A rule for small cereals in Germany is a depth of incorporation or a soil layer of 1–2 cm per every 10 dt of straw per ha (Taeger-Farny 2003). Since high yielding small cereals can leave about 90 dt of straw per ha, this would mean a depth between 9 and 18 cm.

The grain yield within a field can vary considerably, and the same holds true for the residues. Consequently, the depth of incorporation should not be uniform, instead it should be adapted to the site-specific amount of residues. Pforte and Hensel (2006) as well as (2010) propose a control system for the **depth of incorporation** that is based on percent residue cover. Their online approach relies on vehicle based reflectance spectroscopy and wavelengths in the near-infrared range from about 800 to 1,400 nm. Within the visible- and infrared spectrum, this is the wavelength range that has the maximum difference in reflectance between straw on the one side and bare soil on the other side. This means that this near-infrared range can provide signals for an online on-the-go control of the incorporation-depth based on percent residue cover.

A varying site-specific residue load can also result from an uneven straw distribution by combines. This applies especially to high capacity combines with wide cutter heads. However, an even distribution and short chopping of the straw are technically possible and can hopefully be taken for granted in the future. It would not be reasonable to adjust the depth of straw incorporation to deficiencies of combines that can be corrected.

It might be possible to sense the site-specific residue load in other ways, namely either by converting from site-specific crop yields to amounts of residues or by remote sensing from satellites (Zheng et al. 2012). However, none of these methods has been field-tested for site-specific operations.

The objectives of residue management are quite different in regions with dry-land farming and long fallow periods. Here fast decomposition is not a topic; it might be even a disadvantage. Instead, the prevention of soil erosion – mainly via wind – is a much more important point (Schillinger and Papendick 2008). Residues left on or near the soil surface are very effective in reducing erosion by wind as well as by water. Therefore, when summer-fallowing of erosion prone soils is practiced, incorporation of the residues should be mostly avoided. The objective is having at least partly "**anchored crop residues**" on the field. These residues extend well above the soil surface, yet still are attached to the soil, *e.g.* by their roots.

Conservation of soil moisture as an objective of stubble- or fallow cultivation too is highly dependent on the respective climate. In a humid climate this objective hardly counts. Yet in dry-land regions, success in farming strongly depends on the ability to manage water.

How should in this respect fallow fields be managed? The important point here is to minimize evaporation by weeds as well as from bare soil. Based on the same area, plants always evaporate more than bare soil. The rationale of summer-fallowing rests on this. Plants with their elaborate root system just are very effective in

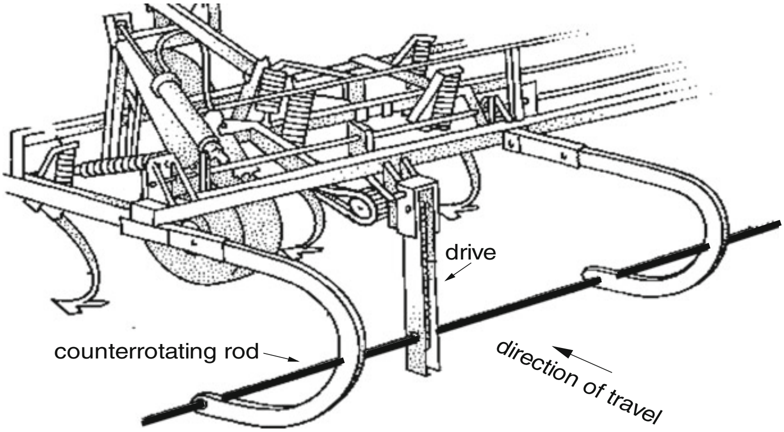

Fig. 7.12 Rod-weeder (From Gist 2002, altered)

sucking water to the surface. Therefore, weeds must be completely kept off the field, either by a site-specific application of herbicides or by cultivation. But capillaries of soils as well can suck water to the surface. This applies particularly to non-disrupted, continuous capillaries. Hence a bare, undisturbed, settled soil evaporates more water than the same field with a shallow, cultivated top layer (Wuest and Schillinger 2011). The problem is that this top layer can promote erosion. So this top layer either needs a special protection against erosion, or the disruption of the soils capillaries must occur below the surface with targeted precision. Technical solutions for both alternatives are available.

The classical instrument for shallow cultivation with at least some inherent protection against erosion is the **rod-weeder** (Fig. 7.12). Its main tool is a horizontal square rod with vertical cross-sectional side lengths of about 25 mm. This rod is oriented perpendicular to the direction of travel and is rotated against the direction of travel. Its depth of operation is between 5 and 10 cm. This implement creates stratification or fractionation within its operating depth. Due to the rotations of the rod against the direction of travel, coarse clods, weeds and residues mainly pass by overhead. Small soil particles instead are not carried upwards and therefore squeezed downwards. The result comes close to the ideal stratification and fractionation as pointed out in Fig. 7.11. This implement up to now mainly is used for dry-land farming in Northwestern areas of Canada and the USA. Its prospects in other parts of the world as a means of preventing surface crusting and erosion in combination with modern sowing techniques deserve attention.

When it comes to the disruption of the soil capillaries with targeted precision in order to prevent evaporation, farmers in dry-land areas refer to a process of "**setting a moisture line**" in the field. The rod-weeder does this quite well because of its rather shallow operation. And in addition it accumulates weeds, straw and clods on or near the surface to assist in erosion control. However, it does not leave "anchored crop residues" as well as "anchored killed weeds" on the field. The residues and weeds just are lifted and mainly deposited on the surface, they are not anchored to the soil any more.

Fig. 7.13 Setting a moisture line in a fallow field by an under-cutter. The *insert* shows the main tool. The soil surface is covered with anchored crop residues (Photo from Schillinger, altered)

Yet leaving an anchored protection is possible, if the soil is not tilled at all at the surface and weed control completely left to herbicides. Setting a moisture line still would be necessary to reduce evaporation from the fallow land (Zaikin et al. 2007). This can be achieved by an implement, which just cuts the soil well below the surface in a horizontal direction, but hardly breaks it up vertically. Such an implement is the **under-cutter** (Fig. 7.13). Its main tools are wide, horizontal blades, which cut through the soil about 10 cm below the surface. The soil surface with anchored protection against erosion is almost left undisturbed. Petrie (2009) has shown that for winter wheat after summer-fallow the combination of once undercutting in the spring followed by herbicide applications for weed control was as effective as several times rod weeding during the fallow period in terms of water conservation and grain yields.

So this combination of undercutting and chemical, site-specific fallowing deserves attention in dry-land regions. It protects the soil in two ways. Firstly, it prevents erosion effectively. Secondly, because this combination widely eliminates cultivation, less soil organic matter is decomposed. This weighs heavily in dry-land areas, since the effect of cultivation in reducing the soils organic matter is much more pronounced in dry and warm areas than in humid regions with lower temperatures.

7.5 No-Tillage: Prerequisites, Consequences and Prospects

The prerequisites as well as the prospects for no-tillage practices depend largely on the precision exerted in farming. An important trigger for the interest in no-till has been and still is the development of efficient and competitive herbicides. Without these, the present use of no-till practices – *e.g.* on soils with a high organic matter content – would not be possible.

But there is also an important development of the past decades, which constrains no-till. It is the increasing use of heavy farm machinery. Especially on wet soil, this machinery induces soil compaction. The use of wide, low-pressure tires alleviates the problem only partly. The situation often is that cultivation has to correct the damage that was exerted on wet soil in previous operations, *e.g.* during harvesting.

It is possible to inform the farmer via an online sensor whether his machinery is compacting the soil in an undue way. A **field-trafficability-sensor** indicates the depth of sinkage of the tires and thus can inform the operator on-the-go about the site-specific situation (Brunotte 2007). However, what are the options when a farmer realizes that his machine is damaging the soil? It is very unlikely that he will stop a harvesting operation: the soil might be even wetter after having waited a few days. The farmer is better informed about the situation, yet his options are rather limited. One option – however – generally is reasonable. In case the farmer is operating the machine with an inflation pressure of the tires, which is too high for field use and should have been adjusted before starting the work, he can correct this.

A challenging approach to solve the compaction problem with heavy machinery is the "**Controlled Traffic Farming**" concept (Chamen 1998; Chamen et al. 2003). It is based on the experience that normally plants grow better on non-trafficked soil and wheels run better in tracks. Consequently, cropping areas in the field are strictly separated from wheel lanes. This means that the same wheel tracks are used for every sowing-, fertilizing-, spraying- as well as harvesting operation, and this year after year. Since compaction by wheels in the cropping area does not occur any more, tillage can be omitted and no-till practices can be used. Despite the area lost because of the tracks, higher yields can be obtained than with conventional farming (Chamen et al. 2003; Kelly et al. 2004; Tullberg et al. 2007). Precise maneuvering is essential, yet this is easy to provide by GPS guidance systems.

The agronomical advantages of this concept are striking. However, the consequences for the machinery and its management can create problems. The running gears of all tractors and machines should be able to use the same tracks. Only small deviations in the track widths are possible as a result of differences in tire widths (Fig. 7.14, top). In case wagons or trucks are loaded on-the-go from the harvesting machines and not at special places on the headlands, their track width too must be adapted.

A precise track use is not possible with round trips in the field. Instead driving up and down is needed – preferably along the longest side of the field. This is no problem in flat areas. But this driving pattern does not fit well to rolling areas and especially not to contour farming practices. Furthermore, the system does not allow random turns within the field. So any loading vehicles irrespective of the filling level should not leave the lane before arriving at the headlands.

Adapting all implements to the same track width is not easy because of the **wide tracks** of present day high capacity grain combines. Their track width exceeds that of modern heavy tractors by about one third. Technically, enlarging the track widths of tractors and trailers is possible. Yet problems arise in densely populated countries from public road-traffic regulations for tractors and trailers on such wide tracks. It is mainly for this reason that controlled traffic farming with tractors, trailers and combines

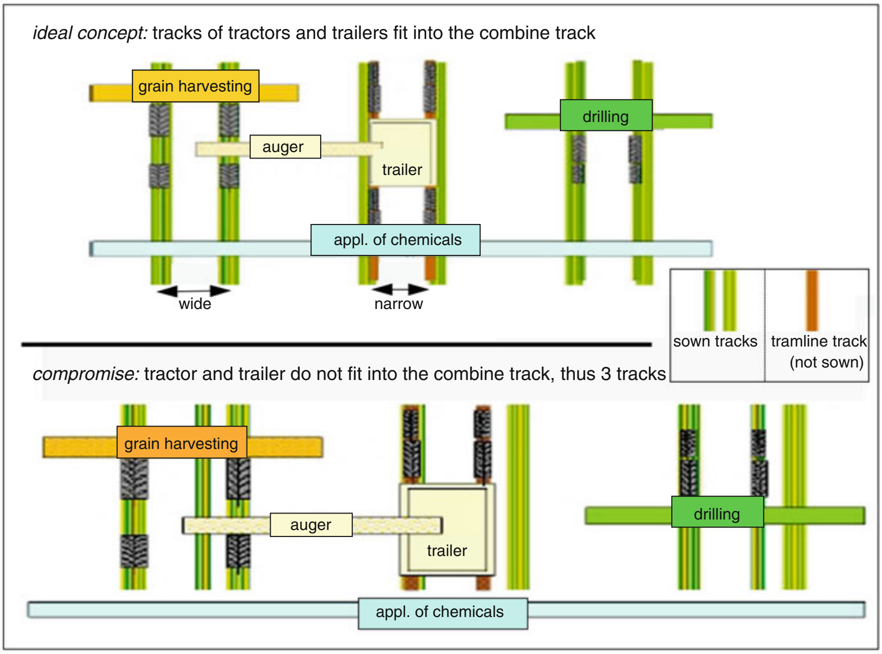

Fig. 7.14 Arranging the tracks of various farming operations for controlled traffic farming in order to avoid soil compaction in the growing area. The objective is the separation of growing area from trafficked soil (From CTF Controlled Traffic Farming 2009, altered)

running in the same tracks seldom is practised in densely populated countries. There are alternatives, *e.g.* employing two standard track widths and to let the narrower running gears use only one track of the combine (Fig. 7.14, bottom). Yet this increases the tracked area of the land.

Controlled traffic farming has gained considerably in Australia, where problems with wider tracks on tractors and trailers on public roads are less common. This makes it possible to operate there with one **standard track width** for all machines (Fig. 7.14, top). In Europe – where the concept was initiated (Chamen et al. 2003) – it is mainly used for rotations of small cereals and rape (colza). Concepts for rotations with forage- or root crops should be developed. The prospects of getting rid of technically induced soil compaction and thus to pave the way for a widespread application of no-till practices deserve attention. It should be borne in mind that all standards of present day track widths are man-made and therefore can in principle be altered.

Another approach of reducing soil compaction and by this to eliminate cultivation needs is the introduction of **unmanned farm machinery** or **robots**. The present large and heavy farm machinery results from its ability to provide for a high work-rate per time unit for the driver. But modern automatic guidance systems such as RTK- GPS and other control systems can eliminate the need for a permanent

Fig. 7.15 Unmanned tractor (Courtesy John Deere Co.)

driver. And as soon as no permanent driver or operator is needed on the machine any more, the incentive for using large and heavy equipment is gone. Having several small machines instead of a large one then does not imply higher labour costs any more. Robotic implements can operate around the clock. They can be used in a more flexible way with small and irregularly shaped fields. Because of the higher number of implements, the default risk is smaller than that of large conventional machines. But above all, the smaller robots might reduce soil compaction and therefore also help to introduce no-till practices.

However, presently robots are available only for rather simple operations such as mowing or rice transplanting. Small robots, which move up and down in fields for **scouting purposes** such as detecting of weeds, of diseases, of insects or for sampling soil are in the focus of research (Blackmore 2007). A medium sized prototype farm robot has been presented by the farm machinery industry (Fig. 7.15).

Yet there still remain many farming operations, for which until now robotic solutions do not exist. There is still much to do before soil compaction by giant machines is eliminated by swarms of small robots that move through fields and make it possible to farm generally without any tilling of the soil.

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