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A GUIDE TO SUCCESSFUL SUBSOILING

CÉGEP DE VICTORIAVILLE

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A guide to Successful Subsoiling
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INTRODUCTION

Soil compaction is one of the main problems for crop production in the province of Quebec and is closely linked to the intensification of production. Although it can sometimes be difficult to visually observe an effect on the crop, compaction decreases yields, inhibits soil drainage and increases the risk of crop diseases and nutrient deficiencies (Raghavan et al., 1990). It is essential to implement strategies to prevent soil compaction, but this guide will only focus on the remediation of compaction through subsoiling. When properly done, subsoiling loosens the soil allowing roots to penetrate deeper into the profile, increasing water infiltration, and improving conditions conducive to biological activity. It is therefore the starting point for the alleviation of compacted soils. However, subsoiling is a complex and expensive operation which must be well planned and executed in order to achieve the desired results. Problems caused by improperly executed subsoiling may outweigh the benefits. In order for this operation to be successful it is important to understand both the optimal field conditions for subsoiling and the basic mechanics involved.

1. PRELIMINARY DIAGNOSIS

It is important to know the soil characteristics of a given field in order to choose the optimal degree of loosening, the timing and depth of work, and the direction of subsoiling with respect to both the slope of the surface and the orientation of subsurface drains, if applicable.

DESIRED OUTCOME

In many situations complete soil loosening is sought because it allows for better root development and water infiltration, which in turn improves soil structure and biological activity. However, in some cases it may be preferable to perform only a partial subsoiling rather than a complete loosening.

For example, even though a soil may not be highly compacted, there may still be a plow pan present at a depth of 20-25 cm (8-10”), which can delay soil drying. A partial subsoiling with widely spaced narrow tines, having been carried out under good conditions during the previous season, may be enough to allow for adequate soil drying.

Another example is when the soil has a low natural permeability. The subsoiled layer can store more water after loosening. If the water infiltration is slowed down by the less permeable underlying layer, the soil will be slow to dry, bearing capacity will be decreased, and field entry delayed. A partial loosening with more widely spaced tines would reduce the risk of these potential problems developing.

Another reason for partial subsoiling is that in some situations the presence of a compacted layer such as a plow pan can help protect the subsoil from compaction by offering a firm surface at depth to absorb and distribute the pressure applied by machinery tires. Spoor *et al* (2003), recommend breaking up the pan only to a limited extent in order to allow water infiltration and root development beyond the compacted layer, while maintaining some support and protection against compaction of the underlying soil. In this situation the compact layer should only be cracked or fissured rather than being completely disrupted.

FIELD CHARACTERISTICS

In order to properly evaluate field characteristics a number of soil profiles must be examined, with an emphasis on evaluating the depth of compaction (Weill, 2009; Ball, 2007). A penetrometer can assist in this evaluation, complementing the information given by the soil profiles, by providing data on the depth of compaction over a much more extensive area of the field. However, this measurement cannot replace the soil profile evaluation because the penetrometers readings vary with soil moisture content. The field drainage map and surface topography should also be studied.

Soil texture and moisture content

Soil texture has a major influence on soil vulnerability to compaction. In addition, soil texture influences the role that soil moisture content plays on the effectiveness of subsoiling.

Light soils

Light soils may be structureless and compact, especially when the percentages of fine sand or silt particles are high. Sand or silt particles can pack very tightly, resulting in drastically reduced porosity and very poor root penetration and water infiltration. Light soils are easily compacted, especially when they are wet and also, but to a lesser extent, when they are dry. This is due to their low percentage of clay which results in a weak structure that cannot resist the forces of compression. For this reason, it can sometimes be preferable to subsoil just before seedbed preparation or even seeding in order to limit the number of passes after subsoiling (Spoor et al., 2003). This is currently being practiced by some producers in Quebec. The use of GPS technology facilitates this operation by ensuring that the loosening can, if necessary, be done very close to seeding rows. Since light sandy soils are not cohesive the moisture level during subsoiling is not as important as it is for clay soils. This is why subsoiling can be carried out in the spring in some of these soils.

Heavy soils

Heavy soils are more resistant to compaction than light soils when both are dry due to their usually strong structure, comprised of more solid aggregates. However, they are sensitive to compaction when wet. Consequently, subsoiling in clay soils must always be done when the soil is in a dry condition. Spring is never a good period for subsoiling a clay soil in Quebec because these soils are always too wet at that time of the year. Another reason for subsoiling in late summer/early fall are that the following winter freeze-thaw cycles also help to break up the large clods which sometimes result from subsoiling. It would otherwise be very difficult to prepare a good seedbed for spring-sown crops

Heavy soils, even when compacted, are often fissured thus allowing some root and water to reach the sub-soil. In such situations, subsoiling may be unnecessary. Considering how difficult and expensive it is to subsoil successfully, it is important to evaluate the situation prior to taking action.

Glacial tills

In Quebec, some soils in mountainous regions (Appalachian and Laurentian Mountains and foothills) originate from glacial tills. These loamy and often rocky soils are frequently massive down to considerable depths.

Roots are often blocked at the bottom of the tillage layer. In these soils the main objective of subsoiling is often to increase rooting depth. Adequate surface drainage is required, otherwise water can accumulate in the loosened layer.

Speed of drainage

Considering the huge impact that water content has on a soil's vulnerability to compaction, particularly in heavy soils, it is essential to ensure good drainage. This implies that surface and sub-surface drainage are checked prior to planning a subsoiling operation. When drainage is slow, field operations may have to be carried out under wet soil conditions, and will lead to further compaction. In addition, when drainage is slow, the soil remains too wet for any subsoiling operations to take place. Even if the soil can be successfully loosened it risks being re-compacted rapidly because the soil will often remain too wet following its loosening.

Depth of compaction

It is very important to consider the depth of compaction for subsoiling. When compaction is deep, it is not always possible to subsoil the entire depth of compacted layer.

Shallow compacted layer (usually less than 40 cm)

When the compacted layer is shallow enough for treatment, the entire depth of the compacted layer must be loosened. Such an operation allows water and roots to penetrate deep into the profile.

Loosening only the upper part of a shallow compacted layer can result in serious waterlogging problems. The upper part of the compacted layer can store more water after loosening. The remaining lower part of the compacted layer blocks this increased volume of absorbed water, thus increasing drying time. This can delay field entry and compromise the entire production season.

In addition, when water becomes ponded in the profile due to downward percolation being restricted by a compacted and rather impervious layer, the soil becomes anaerobic and natural soil restructuring cannot occur.

Deep compact layer (usually more than 40 cm deep)

When the compacted layer extends to a considerable depth it is often not possible to loosen the entire compacted zone. In such situations, subsoiling can cause serious waterlogging problems similar to those resulting from loosening only the upper part of a shallow compacted layer. In clay soils, mole drainage (which creates drainage channels underground) may be more appropriate than subsoiling. However, if the subsoil is not completely impervious and allows some downward water movement, subsoiling the upper part of a compacted layer can be beneficial by increasing the rooting depth.

Field topography

The direction of subsoiling must be planned as a function of both the direction of subsurface drains, if present, and field topography. Since water moves along the channel created by subsoiling, it is important to choose a subsoiling orientation that will optimize the removal of this water. To achieve this, it is recommended to aim for an oblique angle with respect to subsurface drains (Figure 1). It is also important not to direct the water towards lower areas in the field.

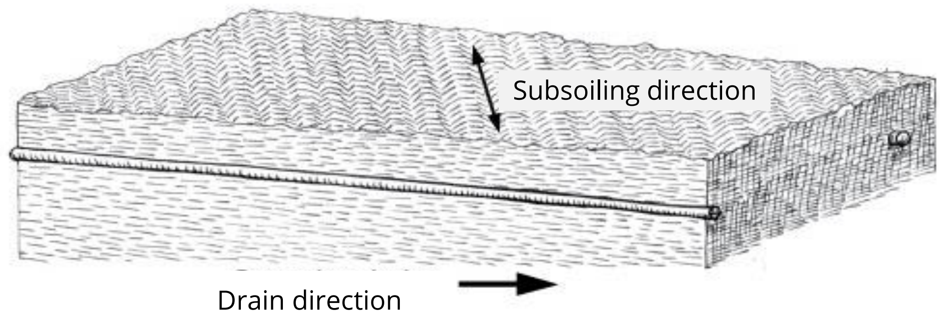


Figure 1. Subsoiling direction at an angle with the drains ©.

2. SUBSOILER TYPES

In choosing the type of subsoiler, account must be taken of the objectives of the operation and of the field characteristics. The following criteria must be considered:

- the degree of soil surface disturbance that can be tolerated: in some cases, the soil surface should be disturbed as little as possible (no-till systems, pastures, established green manures, or crops established prior to subsoiling);
- the desired degree of soil loosening within the profile: in some situations, the entire profile should be loosened while in others, where the goal is only to let water percolate deeper, minimal cracking may be more appropriate;
- the severity of compaction and the depth of the compacted zone.

The three main components of a subsoiler are the toolframe, the legs, and the points (CPVQ, 2000). A tine (also known as a shank) is made up of a leg and a point. Some subsoilers also have discs fitted in front of the tines and a compacting roller behind. The spacing between the tines is variable and can be adjusted on most toolframes to provide the desired geometry (see section 3). In Quebec, a spacing of 75 cm (30") is most commonly used.

THE TOOLFRAME

The subsoiler's toolframe can either be V-shaped or straight. V-shaped toolframes may only be fitted with a single row of tines, while straight toolframes may be fitted with either one or two rows (Figure 2). The power required to pull either a V-shaped toolframe or a two row straight toolframe, where the tines are staggered alternately, can be less than that for a single row straight toolframe where the tines are all in line. This is because the following tines pass through soil where the resistance has been reduced to some degree by the passage of the leading tines.

V toolframe (Photo : D. La France).

Straigh toolframe with one row of shanks.

Figure 2. V-shaped and straigh toolframes.

THE LEGS

There are three main types of legs for subsoilers: straight, curved, and slanted (Figure 3 and Figure 4). Since most of the soil loosening is initiated by the point, the shape of the leg has little influence on the overall mode of loosening because it passes through soil that has already been loosened by the point. However, the wider the leg the more it will contribute to local soil disturbance, particularly when the depth of work is greater than the critical depth (see section below for critical depth).

Straight legs

Straight vertical legs (rake angle of 90^0; Figure 3a) minimise soil disturbance ahead of their passage, since there is little tendency to lift the soil upwards. These legs have been found to require more power than the other types (curved or slanted), but when leaned slightly backward (rake angle less than 90^0- see Figure 3) there is little difference in the power requirement (Raper, 2005).

Curved legs

The lower part of curved legs (Figure 3b) has a rake angle less than 90^0, forcing the soil to move the soil upwards. The upper part of these legs may be vertical or lean forward (rake angle greater than 90^0). Tines with the upper part of their leg leaning forward (Figure 3c) are designed for work only down to a predetermined depth. If they work below that depth (Figure 4) the upper part of the leg pushes the soil downwards, which increases the power requirement and tends to re-compact the soil locally (Raper and Bergtold, 2006).

Slanted legs (Paraplow)

Slanted tines (Figure 3d), where the legs are inclined sideways, minimise soil surface disturbance whilst also requiring slightly less power than the other two types of legs. The proportion of soil that is loosened is also greater with this type of subsoiler (Raper, 2006, 2007). This type of leg is more popular in Europe than in Quebec.

Points

Points vary in width, wing lift height, rake angle, and length. Soil loosening is very dependent on the point's geometry.

Point width and wing lift height

Points are either narrow or winged (Figure 5a and b). Winged points have wings attached either directly to the point or to the leg. The width of narrow points can vary between 2.5 and 12.5 cm (1 and 5") and that of winged points, between 15 and 30 cm (6 and 12").

When compared with narrow points, winged points have several advantages. They:

- loosen a much greater volume of soil;
- reduce the power required per unit of loosened soil;
- increase the depth of efficient work (see below in Section 3 for an explanation of the critical depth).

Even though an individual winged point results in an increased power requirement of 10 - 20% per tine, this increase is more than compensated for by an approximate 90% increase in the volume of soil loosened. This increase in loosened soil volume allows for the spacing between the tines to be increased by about 30% for a similar overall disturbance. Thus, the number of tines needed to disturb a given width of soil is reduced, improving overall efficiency (Spoor and Godwin, 1978).

The degree of soil lifting is influenced by the wing lift height (Figure 6). This is the vertical distance between the bottom (front) of the wing and the top (back) of the wing. This distance varies between 2.5 and 10 cm (1 and 4"). Increasing wing lift height results in greater soil disturbance as the soil slides up and over the wings.

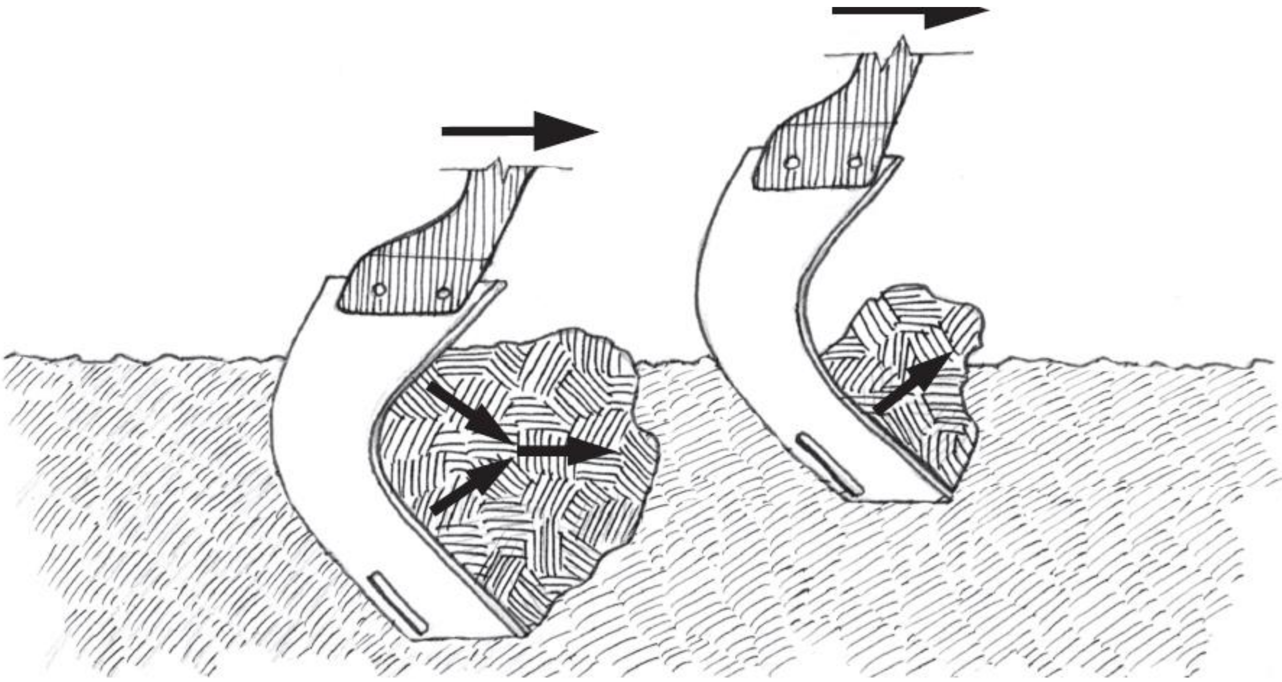
Straight leg (a).

Curved leg (b).

Leg with the upper part leaning forward (c).

Slanted leg (d).

Figure 3. Straight and curved legs



Subsoiling too deeply, increasing forces and causing some local compaction.

Subsoiling at adequate depth.

Figure 4. Subsoiler working depth adjustment when the upper part of a curved tine leans forward. Adapted from Raper (2006) and Gill and Vanden Verg (1966) ©.

Narrow point (a).

Point with wings (b).

Figure 5. Narrow and winged points.

Figure 6. Wing lift height and rake angle.

Point length and rake angle.

The point rake angle is the angle between the upward face of the point and the horizontal (Figure 6). The smaller it is, the easier the point can penetrate the soil and the lower its draft resistance The rake angle can be decreased by increasing the length of the point while maintaining a constant lift height.

When the rake angle is too great (which is generally not the case for commercially manufactured subsoilers), the soil is pushed forward rather than being lifted upwards, which compacts the soil ahead instead of loosening it, and increases the draft resistance (Figure 7).

(a)

(b)

(c)

Figure 7. Subsoiler with point and wings too vertical (a and b). The soil is pushed ahead of the tine and compacted (c) instead of being lifted.

3. EFFECT OF SUBSOILING ON THE SOIL

Depending on the degree of soil compaction, soil moisture content and working depth, subsoiling can either loosen the soil by forcing it upwards or compact it by compressing it around the point. It is therefore important to understand what conditions are conducive to loosening rather than compacting the soil.

LOOSENING OF THE SOIL

Loosening can be achieved through brittle disturbance or tensile disturbance. In the first case, the soil is fractured and the resulting units slide upwards allowing the soil mass to expand and hence be loosened. The units are rearranged with reference to each other as they are lifted and fall back down (Figure 8). In the second case, the entire mass of soil is lifted upwards and, if wings are fitted, this mass is cracked as it bends over the top of the wing before falling back down (Figure 9). It is frequent to see the entire soil surface being lifted between the tines during subsoiling (Figure 9).

For soil loosening to occur in a brittle manner, the soil must be sufficiently dry to move and fracture in response to the influence of the upward force of the point. The resistance to this upward movement of the soil is referred to by a variety of terms: confining force, confining pressure and confining resistance. In this guide the term 'confining resistance' will be used.

Generally, the degree of loosening is greater if the soil experiences brittle rather than tensile disturbance. However, it is possible to cause a tensile type of disturbance at a higher moisture content than that for a brittle disturbance.

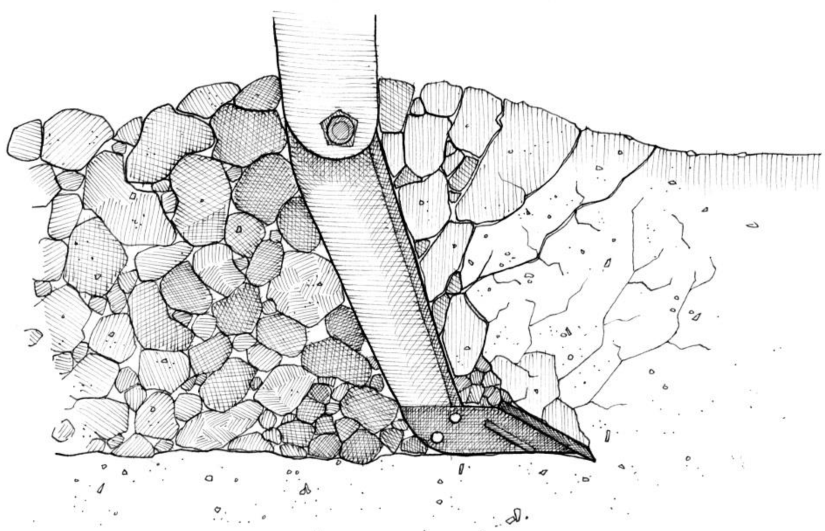
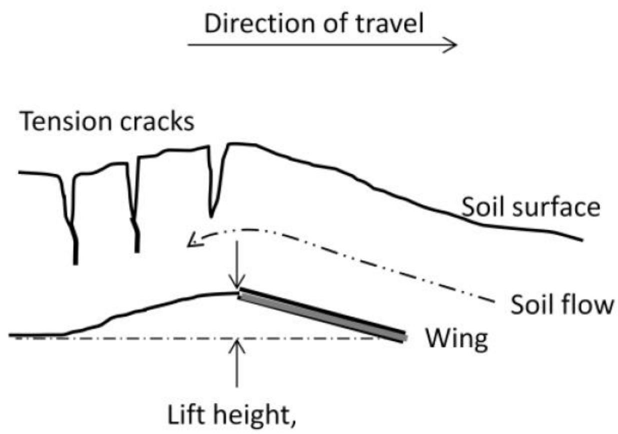


Figure 8. Loosening of the soil achieved though brittle disturbance ©.



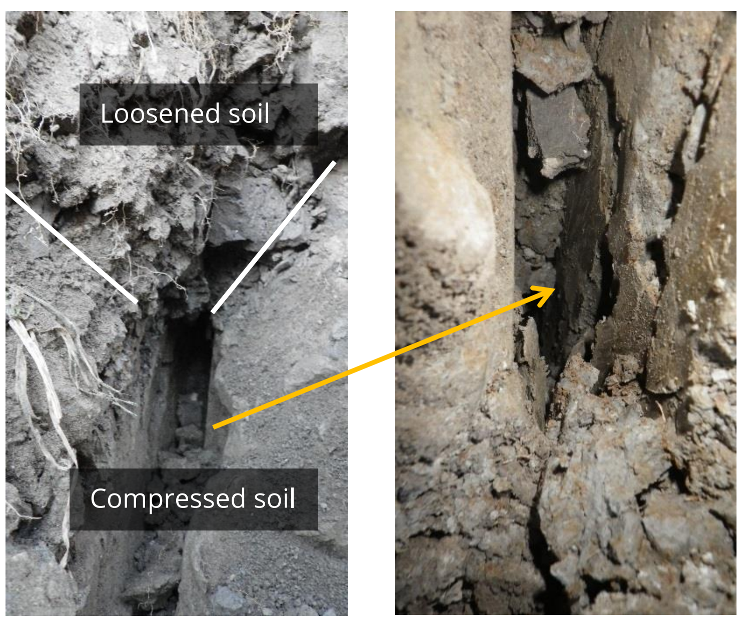
Tension cracks formed during subsoiling (a) (Godwin and Spoor (2015) after Spoor (2006)). Reproduced with the kind permission of the authors and CABI.

Soil lifting causing tension cracks (b).

Figure 9. Loosening of the soil achieved though tensile disturbance.

SOIL COMPRESSION AROUND THE POINT AND THE LOWER PORTION OF THE TINE

As subsoiling depth increases the resistance to upward soil movement also increases. At and below a certain depth, the critical depth, it becomes easier for the soil to move laterally around the point rather than upwards, compressing the soil at the sides of the point and the lower section of the leg (Figure 10).



Soil loosened above 35 cm (14”) depth and compressed below that depth (a).

Compressed area (b).

Figure 10. Effect of subsoiling at a depth of 40 cm (17") in a very compact soil, moderately humid at depth.

CRITICAL DEPTH

The critical depth is the maximum working depth at which the soil can be cracked and lifted upwards rather than being laterally compressed. Below this depth, the subsoiler's points compact the soil and smearing often occurs along the channels created by the points (Figures 11 and 12).

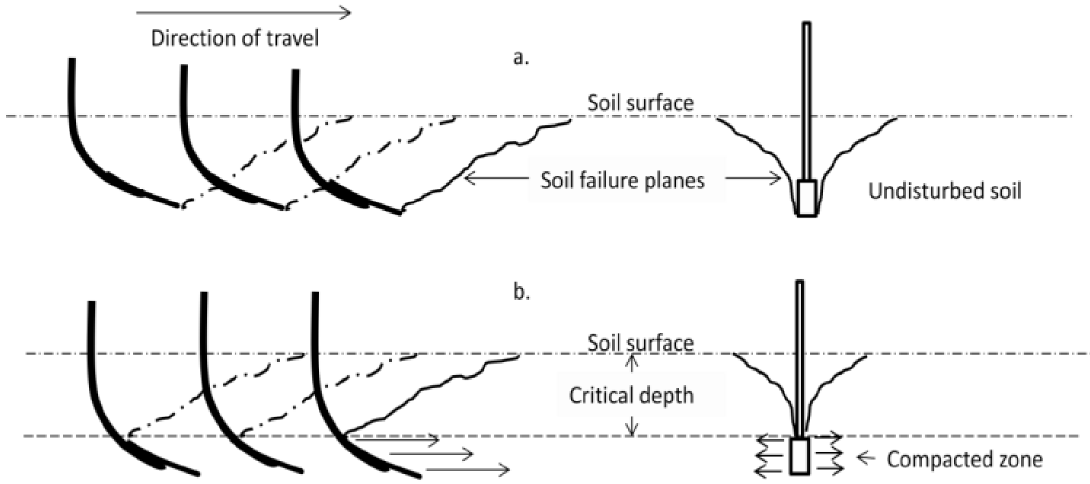


Figure 11. Side elevation (left) and cross-section (right) of a narrow tine showing the effects of operating depth on soil disturbance above (a) and below (b) the critical depth. After Godwin and Spoor (1977), redrawn from Spoor (2006); reproduced with the kind permission of the authors and CABI.

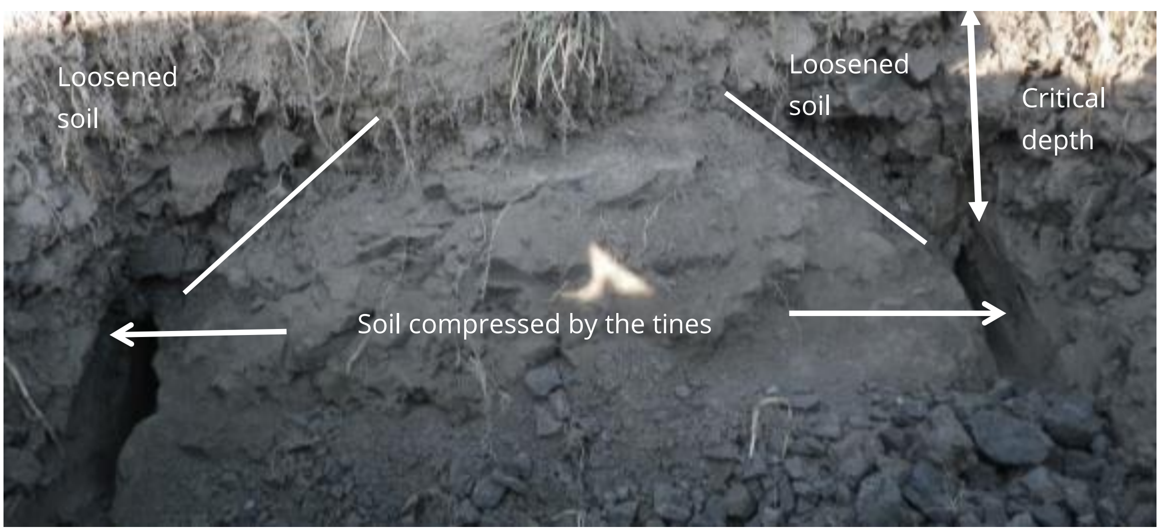


Figure 12. Brittle loosening above the critical depth and compression below it for a very compacted and moderately humid clay soil. The soil was fractured between 0 and 35 cm (14") depth and further compacted below that depth.

When the points are working below the critical depth, the upper part of the legs can still loosen the soil (Figure 12). The disturbance that occurs, however, is shallower than the working depth of the tine and is less extensive because the leg is narrower than the point.

The critical depth depends upon the type of implement being used, how it is adjusted and operated, and the prevailing soil conditions. Soil moisture content and density are particularly important in affecting the confining resistance. The greater the confining resistance, the shallower the critical depth. In situations where the critical depth is shallower than the desired working depth the following implement and operational modifications can be made to increase the critical depth (Spoor, 2006):

Implement modifications:

- increase the width of the point;
- add wings, thus increasing the effective width of the point;
- increase the lift height of the wings;
- decrease the rake angle

Operational modifications:

- place shallower tines ahead of deeper tines (refer to part 4 and 5) in order to reduce the confining resistance;
- carry out a preliminary subsoiling or cultivation pass shallower than the intended working depth in order to reduce the confining resistance (refer to part 4 and 5).

Adjusting tine spacing may also help decrease the confining pressure (Figure 13).

Figure 13. Slanted tine subsoiler with tine spacing of 50 cm (20") and working to a depth of 40 cm (16") in a clay soil. The small spacing between tines reduces the mass of soil that must be lifted by each individual tine, thus reducing the confining resistance.

Soil moisture content can have varying effects on the critical depth. On the one hand, as the soil moisture content increases soil plasticity also increases and the soil is more easily deformed and compressed around the point, hence the critical depth becomes shallower. On the other hand, when a compacted soil is very dry, the confining resistance is great which could affect adversely critical depth.

However, the critical depth in very dry compacted soils depends on the relative moisture content throughout the profile. If the surface soil is dry and soil at depth is also dry and hard, and therefore difficult to compress, the critical depth will increase despite the increase in confining resistance. When, however, the surface layers are dry and hard with a high confining resistance, but the soil at depth is moister and more compressible, the subsoiler point will compress the moister soil and critical depth will be effectively reduced. Hence, it is important to select an appropriate moisture content for subsoiling, ideally in the friable moisture range, but this is often hard to obtain.

Unfortunately, it is not possible to predict the critical depth prior to subsoiling, so it must be observed and monitored during the work. Observing soil profiles during subsoiling operations are therefore critical in order to verify whether the desired disturbance is being achieved at the desired depth. A good operational procedure is to run the subsoiler for 10 - 20 m in a representative part of the field and then open up a trench perpendicular to the direction of work, to a depth greater than the subsoiling depth. Then, facing counter to the direction of work, manually pull the soil away from the disturbed zone into the deeper trench (this makes the task easier) to expose the actual disturbance pattern. Adjustments, if necessary, can then be made to the implement and/or the working depth, and the work is monitored again. This process is repeated until the desired disturbance pattern and appropriate working depth are achieved. Once all the necessary adjustments have been made, and when surface observations indicate that the work being achieved looks satisfactory, a final profile check needs to be made for confirmation. After that, subsequent checks for working depth can be made rapidly by pushing a stick into the disturbed zone to determine working depth, thus avoiding the need to open up another profile.

Although critical depth cannot be predicted accurately, the following simple rule of thumb provides some rough guidance as to its likely depth. For many single tines working in friable soils (not too wet, not too dry) the critical depth will be at approximately 6 times the point width. Hence, for a 75 mm (3") wide point the critical depth would be at approximately 45 cm (18").

There are a number of negative effects that may arise from subsoiling below the critical depth. These include:

- Required power much greater;
- Smaller volume of loosened soil;
- Loosening objective not achieved;
- Compaction at depth.

In addition, multiple passages with the subsoiler below critical depth could create compaction at depth.

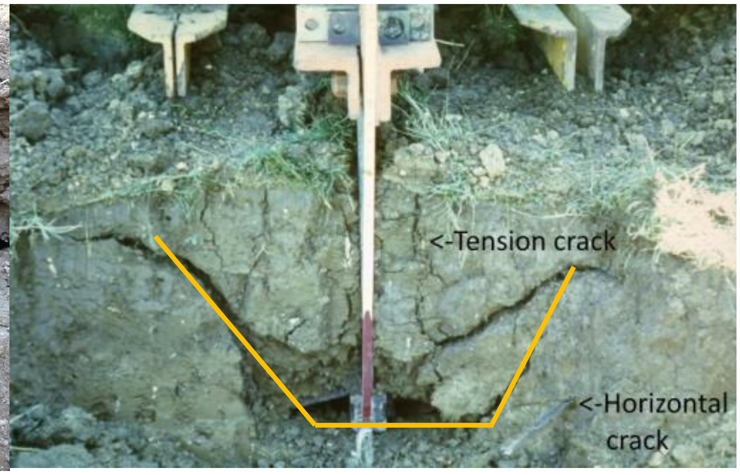
GEOMETRY OF THE LOOSENED ZONE AS A FUNCTION OF THE SOIL TEXTURE AND LEVEL OF COMPACTION

A soil will always deform along its planes of least resistance. The geometry of the actual loosened zone and how the fractures run will vary depending on the type of soil and the degree of compaction.

Situation 1: Light soils or slightly compacted clay soils

In these soils, the planes of least resistance are situated between the small structural units (sand grains, silt particles or small aggregates). These units slide easily over one another and the geometry of the loosened zone has a V (a) or 'open U' shape (b) depending on the point being used (Figure 14).

Narrow point: V shape of the loosened soil (a).



Wide point: Open U shape of the loosened soil (b) (Godwin and Spoor (2015) after Spoor (2006). Reproduced with the kind permission of the authors and CABI.

Figure 14. Geometry of the loosened zone with a narrow point (a) and a winged point (b).

Situation 2: Compact clay soils with defined planes of low resistance

When the soil is a compacted clay, the structural units and large hardened clods are often attached together through weak bonds. This can give the false impression in the undisturbed state that it is a continuous, uniform mass. In this case, subsoiling breaks the soil along the planes of lowest resistance, between the large clods and structural units. As a consequence, these big clods get separated one from another and the failure pattern at the edges is more irregular than a clear V or U. In such situations subsoiling can result in a fairly rough soil with big clods of soil on the surface (Figure 15).

Figure 15. Large 30 to 60 cm (12 to 24") clods resulting from subsoiling a heavy clay with curved tines. In this situation the points worked just below the compacted layer.

Situation 3: Clay soils without well defined planes of least resistance

When the soil is so massive and compact as to be effectively uniform with no or few clearly defined cracks, it may be forced to fail along small particles (sand, silt or small aggregates), or into massive irregular lumps, and the geometry of the loosened zone may resemble that of either situation 1 (Figure 16) or situation 2.

Figure 16. A very compacted clay soil which could not be broken into large clods; only a small portion was loosened with a V shape geometry.

Observations made in trials done by the CÉTAB+

During the CETAB+'s subsoiling trials all three situations were observed. It was also observed that the working depth of the subsoiler sometimes had an important effect on the geometry of the loosened zone.

Table 1. Geometry of the loosened area as a function of soil type, degree of compaction and subsoiling depth

Soil type	Degree of compaction	Structural units	Working depth of the subsoiler	Geometry of the loosened soil (as described above)
Light (including till)	Low to high	Sand grains, silt or small aggregates	variable	Situation 1
Heavy	Slightly compacted	Small aggregates	variable	Situation 1
Heavy[1]	Very compacted	Large lumps joined together or completely massive	Slightly greater than that of the compacted layer	Situation 2
			Within the compacted layer	Situation 3

[1] In soils that are sufficiently dry with a critical depth greater than the working depth.

VOLUME OF LOOSENED SOIL

The main factors affecting the volume of loosened soils are tine spacing, point width, working depth, and the addition of leading tines working at a shallower depth.

Tine spacing and point width

In Quebec it is commonly observed that only a relatively small proportion of the soil is loosened during the subsoiling operation (Figure 17). This is because most of the time the spacing between tines is too wide (75 cm; 30”) and the depth of work is too shallow.

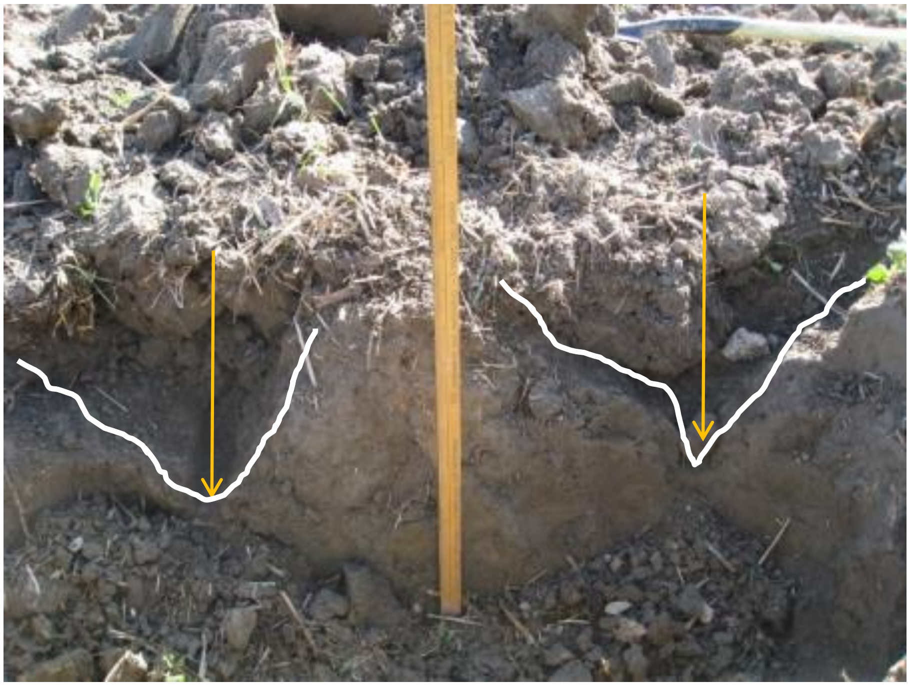


Figure 17. Partial soil loosening because of an insufficient working depth. In this case, the Vs do not overlap and only a small proportion of the soil has been loosened. The orange arrows indicate where the tines have passed.

The influence of tine spacing on the uniformity of soil loosening can be clearly seen in Figure 18. At wide tine spacings, each tine works individually leaving large undisturbed soil zones between them (Figure 18 top). As tine spacing is progressively reduced, a spacing is eventually reached where the disturbance zones of the individual tines interact with each other and complete soil breakout between the tines occurs (Figure 18 bottom). The actual tine spacing required for complete breakout is dependent upon the prevailing soil conditions.

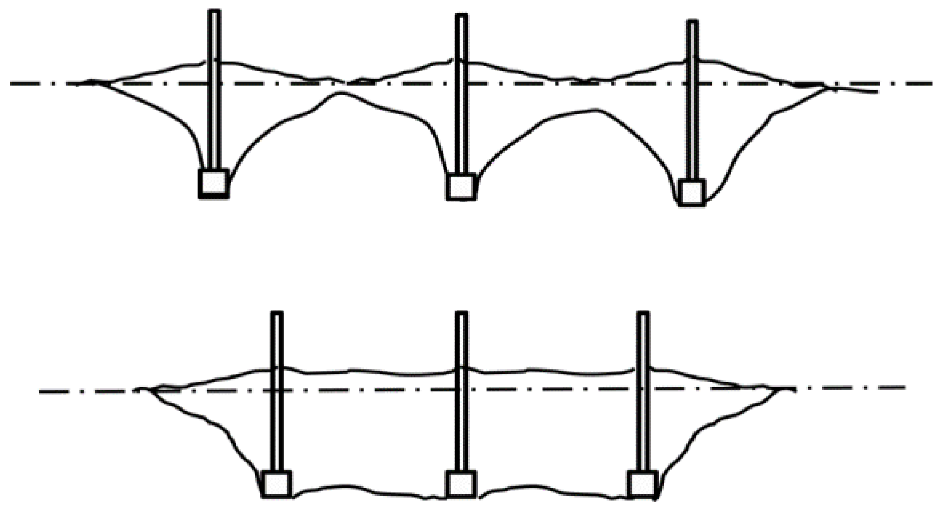


Figure 18. Influence of tine spacing on the uniformity of soil loosening surface shape (leveling). Top: too wide. Bottom: optimum. Godwin and Spoor (2015) after Spoor and Godwin (1992). Reproduced with the kind permission of the authors and CABI.

As shown in Figure 14 , increasing the width of the points by adding wings increases the volume of loosened soil.

Working depth

For an individual tine, as long as the critical depth is not reached, the deeper the working depth the greater the volume of soil which is loosened (Figure 19).

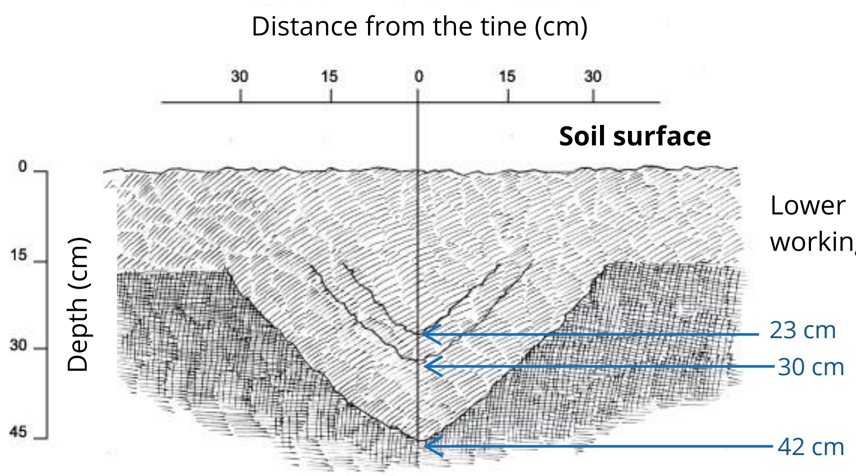


Figure 19. Influence of working depth on the volume of loosened soil for three working depth (23, 30 and 43 cm; 9, 12, 18"); (CETAB+, unpublished) ©.

In situations where a compacted soil layer overlies a weaker non-compacted layer, if the subsoiler's points works more than about 5 cm (2") below the compact layer, there is a high risk that the soil around the points will deform locally and the compact layer will not be broken, apart from slits created by the subsoiler's legs (Figure 20).

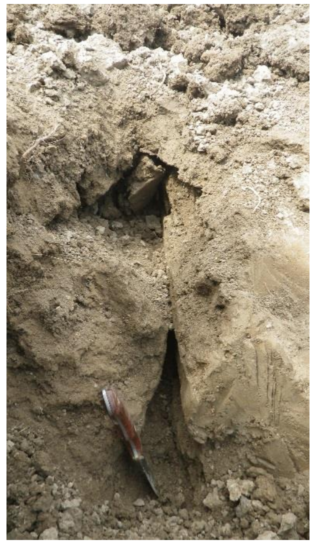


Figure 20. Slit created by a tine because the subsoiler's point worked more than about 5 cm (2") below the compacted layer.

Addition of shallow leading tines

The addition of shallower working leading tines ahead of the subsoiler's deeper tines allows for an increase in the extent of loosened soil without increasing the power required to pull the tool. This is because the shallow tine soil disturbance significantly reduces the confining resistance on the deeper tines which allows the spacing between the deeper tines to be increased by about 25%. The optimum depth for the leading tines is at about 60% of the working depth of the deeper tines (Spoor and Godwin, 1978). In terms of lateral spacing, the leading tines should be positioned between the deeper tines and work in an area of soil that would not be loosened by the deeper tines if they worked alone (Figure 21, Figure 22 and 23). The addition of shallower working leading tines also increases the critical depth of the deeper tines allowing, where required, an increase in effective subsoiling depth.

Figure 21. Subsoiler with shallow leading tines ahead of the deeper tines (photo by Dick Godwin).

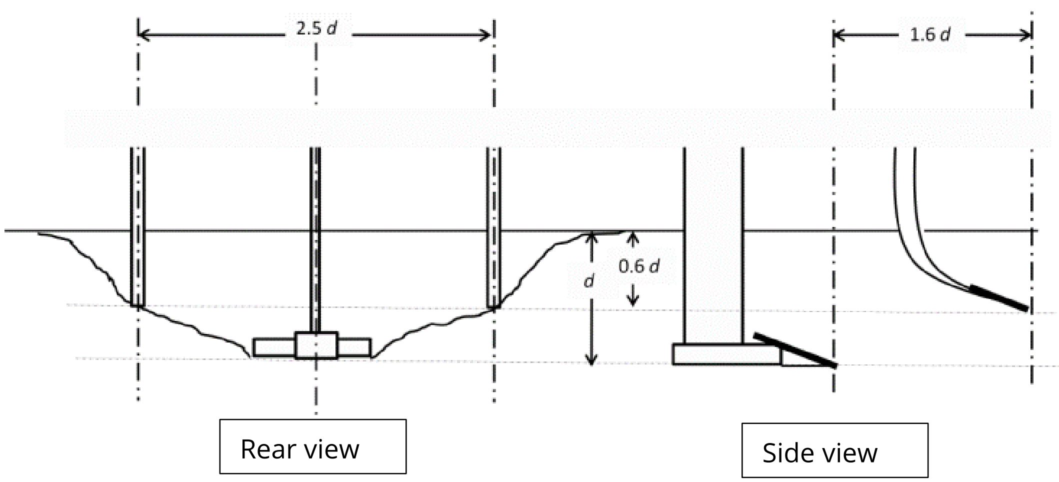


Figure 22. Optimal position of leading shallow tines, showing the soil disturbance pattern (left). Godwin and Spoor (2015) after Spoor and Godwin (1978). Reproduced with the kind permission of the authors and CABI.

Figure 23. Soil disturbance from a winged tine only (top) and winged + shallow leading tines (bottom). Godwin and Spoor (2015) after Spoor and Godwin (1978). Reproduced with the kind permission of the authors and CABI.

General rules for complete soil loosening as a function of the subsoiler type.

The required tine spacing to achieve complete soil loosening is given in Table 2 (Godwin and Spoor, 2015). In the example given in Table 3 the required spacing, as a function of working depth, has been calculated for a standard narrow point subsoiler with points approximately 7.5 cm (3") wide.

Table 2. Recommended tine spacing as a function of the depth of work (Godwin and Spoor, 2015)

Point configuration	Recommended tine spacing as a function of depth of work (d)
Narrow points (7.5 cm, 3")	1.0 – 1.5 times the working depth
Wide points (with wings; 30 cm, 12")	1.5 – 2.0 times the working depth
Wide points (with wings), and leading tines	2.0 – 2.5 times the working depth

Table 3. Examples of recommended tine spacing as a function of the depth of work for a subsoiler with narrow points.

Working depth (cm (inches))	Recommended tine spacing as a function of the depth of work (1 to 1.5 times the working depth)
30 cm (12")	30-45 cm (12-18")
40 cm (16")	40-60 cm (16-24")
50 cm (18")	50-75cm (24-30")

4. SUCCESSFUL SUBSOILING

In addition to the factors linked to implement geometry, soil loosening is also influenced by tractor speed and the tine's capacity to work at proper depth. These factors depend on tractor power and tine protection mechanism strength. A few different strategies are available in order to optimize subsoiling with the tools available on the farm.

SPEED AND POWER REQUIREMENT

In general, it is recommended to subsoil at a speed of about 5 to 6 km/h in order to sufficiently break the soil. The degree of disturbance achieved tends to increase with increasing speed when working under dry conditions.

The power required to subsoil a compacted soil can be 10 times greater than when the same soil is not compacted (Godwin and Spoor, 1977). Working depth is probably the most important factor influencing the power requirement (Table 4). Even though these power requirements can vary from soil to soil, in general one can say that in compacted soils it is normal to need at least 80 hp per tine.

Table 4. Power required per tine as a function of the working depth (Spoor, 2006).

Working depth	Required power (hp/tine)
30 cm (12")	50
40 cm (16 ")	75
50 cm (18 ")	125

As already mentioned in sections 2 and 3, although it would be expected that the addition of wings or leading shallow tines would increase the required power, in practice it is actually the opposite because the spacing between the tines can be increased.

Adding wings allows an increase in tine spacing of about 30%. Adding leading tines in addition to wings allows the tine spacing to be increased by a further 25%. The leg type and the angle of leg with respect to the vertical plane also affects the required power, but much less so than the addition of wings and leading tines (Spoor and Godwin, 1978).

PROTECTION MECHANISM OF THE SUBSOILER

In most cases, subsoiler tines have a built in protection mechanism to avoid breakage when they hit an obstruction, such as a rock. These mechanisms include shear bolts, springs, or hydraulic pressure systems. The latter two systems allow the tine to rise if it hits something too hard and then automatically move back to the chosen working depth. Springs and hydraulic systems exert a force that maintains the tine in working position during normal operation. When the soil is very compacted, this force may have to be as high as 1000 kg (2200 lb), otherwise the tines are forced out their working depth (Figure 24).

Figure 24. Tines that cannot penetrate a compacted sandy soil. The tine at the extreme right is the only one working at the desired depth while the one next to it cannot enter the soil properly.

PROBLEMS OBSERVED WHEN SUBSOILING A VERY COMPACTED CLAY SOIL

In a subsoiling demonstration organized by the CETAB+ on a very compacted clay soil, 6 different subsoilers supplied by their manufacturers along with the tractors to pull them, were compared. Numerous problems arose during the demonstration, which illustrate some of the difficulties involved in carrying out such an operation successfully. These problems are listed in below (Table 5).

Table 5. Problems encountered while subsoiling a very compact clay soil. The compacted layer was from a depth of 5 cm to a depth of 45 cm (2 to 18”) [1].

Subsoiler	Tractor	Problem
V toolframe. **5 curved tines with small wings (total width: 15 cm; 6”).**	Inter 7240 200 hp 40 hp/tine	The tines could not penetrate the soil deeper than 15 cm (6”) because the springs of the protection system were not strong enough.
Straight toolframe. **One straight tine and one curved tine with small wings (total width: 15 cm; 6”)**	NH 110 110 hp 55 hp/tine	The tractor was not powerful enough to maintain an adequate speed. Weight balancing had to be adjusted by loading the front bucket with soil. However, the tines did penetrate the soil to a depth of 42 cm (17”).
V toolframe. **5 straight tines with small wings (total width: 15 cm; 6”).**	New Holland T8330 330 hp 65hp/tine	The tines could not penetrate the soil more than 20 cm (8”) because the springs of the protection system were not strong enough (730 kg; 1600 lb). The tines could not maintain their vertical position and became inclined. The wings were removed to see if this would improve penetration, but the result was the opposite. Without wings the tines could only penetrate the soil to a depth of 10 cm (4”).
A single straight tine on a modified mole drainer. **Wings, more or less vertical, had been added.**	John Deere 7340 135-150 hp/tine	The tine did penetrate the soil well, to a depth of 55 cm (22”), but it was working below the critical depth which was 37 cm (15”). The soil was therefore compacted by the tine at depths greater than 37 cm. The fairly vertical wings made the situation worse by increasing the volume of compacted soil. They pushed the soil ahead, horizontally, instead of lifting it towards the surface (Figure 7).
Straight toolframe. **4 slanted tines (parabolic subsoiler)**	New Holland T7070 200 hp 50 hp/tine	The tractor was not powerful enough or heavy enough, which limited the speed and working depth. Wheel slippage was very high. The working depth was 35 cm (14”).
Straight toolframe. **3 straight tines.** **Very narrow points** **(total width: 3.75 cm; 1.5”)**	John Deere 7340 135-150 hp 50 hp/tine	The tractor was not powerful enough which limited the speed, but in this case did not limit the working depth. It was properly balanced and the wheel slippage was normal. The tines did penetrate the soil to a depth of 42 cm (17”) but they were working below the critical depth which was 37 cm (15”). The soil was compacted by the tines at depths greater than 37 cm.

[1] Subsoiler brands are not mentioned here because most problems were not due to the subsoiler tool itself, but to the lack of power of the tractors, and their poor balancing.

The major problems encountered have therefore been either a lack of power of the tractors, poor balancing, tine protection mechanisms being too weak, or a working depth limited by the critical depth.

Such problems were also encountered many times during on-farm trials. The maximum possible working depth has always been less than 35 cm (14”) which was generally insufficient for relieving compaction. In some situations, a double pass, with the second pass going deeper, solved this problem (see section below).

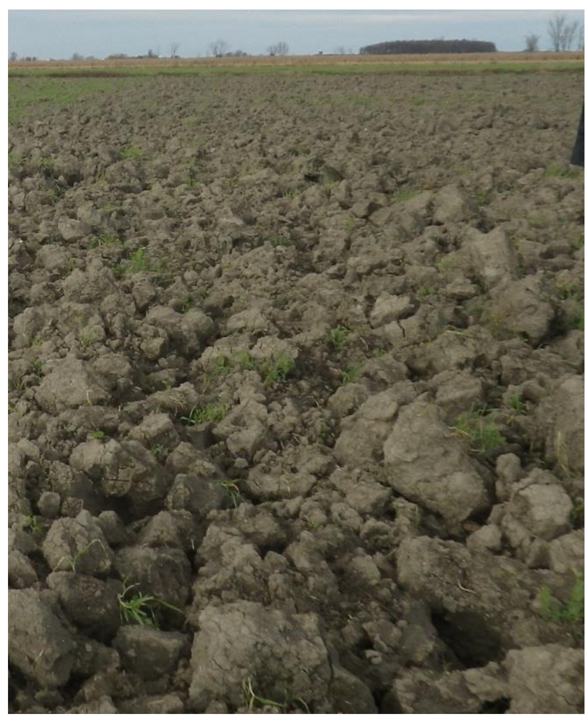
SUBSOILING STRATEGIES FOR ACHIEVING COMPLETE SOIL LOOSENING

Depending on the power available to pull the tools and the type of soil, different strategies can be used in the field to achieve complete soil loosening; these are listed in Table 6. The use of a cover crop to stabilise the soil after subsoiling and improve soil structure should always be considered.

Reminder: In many situations, the compacted layer overlies a weaker less dense layer below. Care is required in such situations, to ensure that the surface layer itself is fissured rather than deformation being restricted to the weaker layer below. In such situations the subsoiler points should work at a depth of no more than 5 cm (2”) below the compacted layer. If the points work at a greater depth, they may only compact the weaker soil around them rather than lifting and fissuring the compact layer above. As a result, the compacted layer may not be broken except for a slit cut through the layer by the subsoiler’s leg (Figure 20).

Very big clods can be formed when heavy soils are subsoiled, resulting in a very uneven surface. In order to minimize this problem, one can loosen the soil in an incremental way by making a first pass shallower than the desired depth. The use of leading tines can also reduce this problem.

Soil surface after one pass at a 33 cm (13”) depth (a)



Soil surface after a second pass at 42 cm (17”). The entire compact layer was loosened (b).

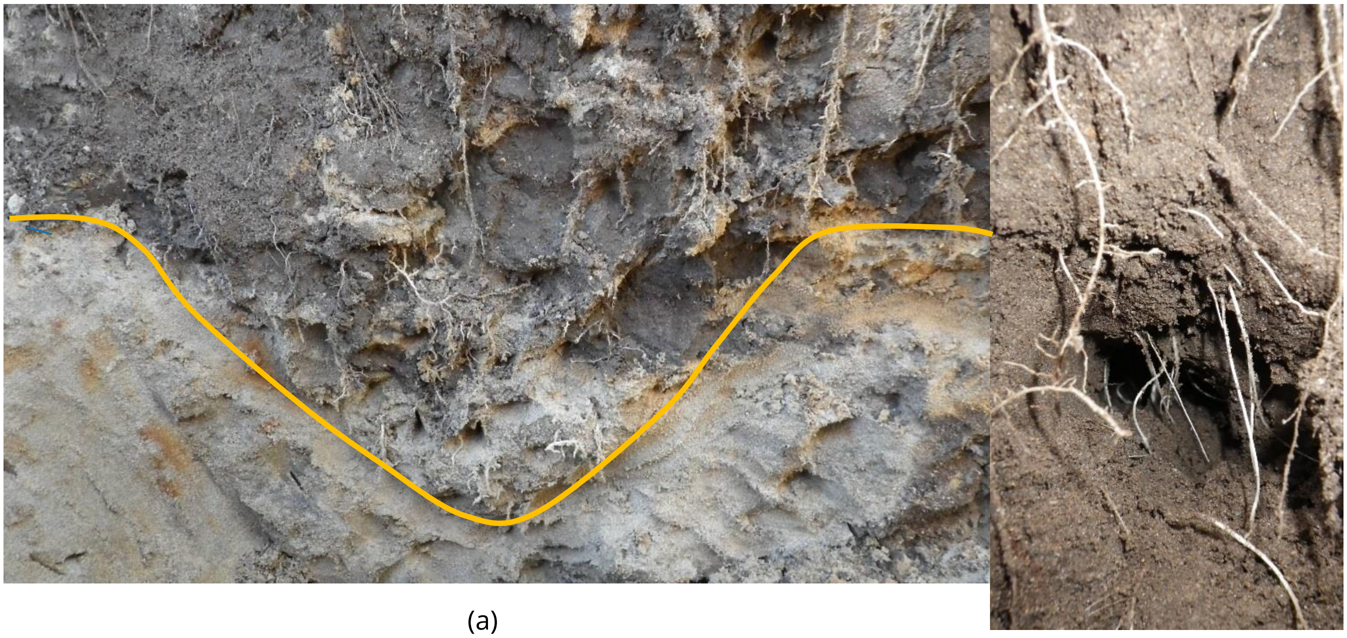
Figure 25. Soil surface after one pass or two passes.

Table 6. Strategies for increasing the volume of loosened soil in order to obtain complete loosening of the profile as a function of soil or tractor limitations.

Strategies	Required conditions
Case 1: The required working depth can be achieved, i.e., the critical depth is not reached, the required power is available, and the subsoiler can be adjusted.	
1a. Decrease tine spacing until complete loosening achieved	Refer to section 3. The soil may cease to flow between the tines if the tines are too close in a single row. Ensure that there are enough tines to loosen the soil across the tractor width including behind the tractor wheels.
1b. Add wings.	Refer to section 3. The wings must be sufficiently wide.
1c. Add leading tines.	Refer to section 3.
Case 2: The required depth can be achieved, i.e., the critical depth is not reached and the required power is available, but the subsoiler cannot be adjusted.	
2a. Make two consecutive passes at angles to each other	This is only possible on clay soils when they are dry enough, otherwise the second pass will re-compact the loosened soil.
2b. Make two consecutive parallel, offset passes.	The tine spacing for each pass must be twice the desired overall spacing. In addition, one of the tines must run just behind each of the tractor's wheels. The spacing must also allow for the tractor's wheels during the second pass to run on the undisturbed strips left after the first pass. In Quebec, in most cases the spacing is 75 cm (30"). A second pass would result in a final spacing of 37 cm (15") which is fairly narrow (sometimes narrower than desired). The second pass should be slightly deeper (3 cm (1 1/4") than the first in order to prevent the subsoiler from moving sideways into the previously loosened zone.
2c. Plan soil loosening on a longer period: make sequential passes over several years.	Such a strategy limits the risk of having a soil not firm enough in the spring.
Case 3. The required depth cannot be achieved in one pass, i.e., the critical depth or tractor power are limiting.	
Make two passes, such as suggested in 2a or 2b, with the second pass going a little deeper than the first (Figure 25).	The first pass is established as a function of the tractor power. The second pass is then made at the desired depth.
Use a subsoiler equipped with leading tines.	Refer to section 3.

SUBSOILING WITHOUT DISTURBING THE SOIL SURFACE

It can be useful to subsoil through an established green manure, hay field or pasture to allow the penetration of roots into the newly loosened soil (Figure 26). It may also be necessary to subsoil a recently established or direct-seeded crop.



(a)

(b)

Figure 26. Zone loosened by a subsoiler tine that worked at a depth of 42 cm (17") and subsequently exploited by the roots of a green manure (a). Development of numerous new roots in the channel created by the subsoiler's point (b).

In certain cases, such as in green manures, some surface disturbance may be acceptable while in others, such as for hay and pastures, the soil surface should remain as even and level as possible.

In order to minimize surface disturbance it is necessary to:

- Attach straight cutting disks ahead of the tine leg in order to cut through the crop (Figure 27). These disks are essential to avoid damaging the crop (hay or pasture). The disks must work deep enough in order to cut through all plant material; this is especially important in the presence of quackgrass. If quackgrass rhizomes aren't fully cut they will collect on the tines, damaging the crop as the subsoiler advances (Figure 27). Moist surface conditions allow for easier disk penetration;
- Use straight tines or parabolic tines in clay soils; in sandy soils curved tines may also be used (Figure 28 and 29);
- Use tines that only lift the soil slightly in prairie or pasture, to minimize soil mixing in the profile;
- Avoid using a straight toolframe with tines aligned in one row in clay soil, because the soil can block and collect between the tines and be raised above the surface (Figure 30);

- Ensure adequate power, weight and good balancing of the tractor, as wheel slippage can damage the crop (Figure 31);
- Use a packer roller to flatten any clods that are left on the surface after subsoiling (Figure 32);
- For prairies and pastures, plan to subsoil when the soil is dry enough but not excessively dry. It is also preferable to work before a rain;
- Work a little deeper than you would otherwise, while staying above the above critical depth, to reduce the amount of soil lift.

Disk placed ahead of the subsoiler's tine, avoiding damage to the hay crop as the subsoiler passes

Efficacy of disks working at sufficient depth

Inefficiency of disks working at insufficient depth

Figure 27. Straight cutting disks ahead of the tine leg which cut through the crop.

Straight tines (a).

Curved tines (b).

Figure 28. Effect of straight and curved tines on the surface disturbance of a clay soil

Figure 29. Use of curved tines in a sandy soil with disks cutting ahead of the tines in a clover and ryegrass hay field. Note: if the soil contains enough clay to form clods the crop will be damaged.

Figure 30. Straight toolframe combined with narrowly spaced tines 60 cm (24") in a clay soil. The soil collected between the tines and was lifted above the surface.

Figure 31. Excessive wheel slippage damaging the crop. In this photo the clods were raised above the surface by the combined effects of wheel slippage and the tines. The soil must be dry enough in order to perform such a procedure.

Subsoiler designed for hay fields with cutting disks ahead and roller packer behind.

Roller packer which crushed the clods that were raised by the combined effects of wheel slippage and tines.

Figure 32. Panbuster subsoiler adapted for hay and pasture work. Straight cutting disks cut through the crop ahead of the tines. The tines have a low lift height and the packer roller crushes the clods.

CONCLUSION

Subsoiling can help alleviate compaction but it also can be ineffective and even detrimental to the soil if the operation is not well planned or if it is carried out under poor soil conditions. Even when done in good conditions, the volume of loosened soil can be insufficient and, in some cases, the soil can be compacted at depth instead of being loosened.

Successful subsoiling depends not only on soil conditions. Other factors such as tractor power and balancing, tine protection mechanism strength, and subsoiler adjustments play an essential role in obtaining good results.

Working depth, and tine spacing and geometry must be taken into account in order to succeed. If it is not possible to work at the desired depth or when the subsoiler cannot be adjusted, alternative strategies are available in order to achieve proper soil loosening.

Some subsoilers can be adjusted to work in established crops, especially green manures and hay fields, which allows roots to stabilise the loosened soil.

Understanding all the factors conducive to successful subsoiling should help farmers to successfully loosen their compacted soils. Subsoiling, however, is only a remedial measure to mitigate compaction problems. Developing and implementing systems that minimize compaction in the first place should be a priority for every farming operation.

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