Review: Soil seedbed engineering and its impact on germination and establishment in sugar beet (*Beta vulgaris* L.) as affected by seed-soil contact

Sebastian Blunk[1], Martine I de Heer[2], Craig J Sturrock[1], Sacha J Mooney[1]
[1] Division of Agriculture and Environmental Science – University of Nottingham, Nottingham, UK
[2] Syngenta Ltd, Bracknell, UK
Corresponding author: sebastian.blunk@nottingham.ac.uk ; +44 (0) 1159 516786

Abstract

Seed-soil contact plays an essential role in the process of germination as seeds absorb water through direct contact with the moist soil aggregates that surround them. Factors influencing seed-soil contact can be considered as those pertaining to soil physical properties (e.g. texture, bulk density, porosity, etc.) and those related to environmental conditions (e.g. temperature, rainfall, frost). Seed-soil contact is furthermore influenced by the specific field management processes that farmers apply, which have developed significantly over the last 30 years. However, the precise effect of cultivation on the actual contact area of the seed with the surrounding soil is based on a series of assumptions and still largely unknown. This review considers the influence of soil management and its direct impact on seed-soil contact and establishment. We review the state of the art in methodology for measuring seed-soil contact and assess the potential for soil amendments such as plant residues and waste materials to improve seed-soil contact. Engineering the 'optimal' seed-soil contact remains a challenge due to the localized variation between the interaction with field management techniques and soil texture, climatic conditions and crop type. The latest imaging approaches show great promise to assess the impact of management on germination. Combining the techniques with the latest network models offer great potential to improve our ability to accurately predict germination, emergence and establishment.

Keywords

Seedbed; seed-soil contact; establishment; sugar beet; management; germination

Introduction

Germination is initiated when a quiescent dry seed uptakes water (imbibition) and terminates with the elongation of the embryonic axis (Bewley and Black, 1994; Bewley, 1997). The end of seed dormancy (dormancy types and duration differ between species) is being dependent upon a threshold stimulus that varies widely amongst individuals (Bewley, 1997). The germination process has been described as an interplay of genetic, environmental and seed processing effects (Apostolides and Goulas, 1998; Sadeghian and Yavari, 2004). Imbibition, the initial step, is facilitated by moist aggregates, water films surrounding soil particles as well as water vapor. Additional influences include soil aggregate size and distribution, strength of the top soil and the presence of a soil crust. Currently, there is a knowledge gap in our understanding of the relationships and interactions between soil physical properties and environmental factors and their subsequent effect on germination, emergence and establishment process in plants which we outline in this review. We propose that seed-soil contact, an important, yet frequently ignored factor influences germination and constant yield.

Sugar beet is the second largest global source of sugar besides sugar cane and of high importance, especially for European countries, where climate conditions are unsuited for sugar cane. Globally 270 million tons of sugar beet was produced in 2014 with Europe producing 71.1% (FAOSTAT, 2014). Sugar beet has a small seed in comparison to other crops such as wheat and maize and has been reported as being highly susceptible to changes in climate (e.g. temperature and rainfall) and soil physical condition (e.g. compaction and crust formation) due to its low emergence force. In particular it can be significantly affected by varying soil moisture conditions (Rinaldi et al., 2005).

This review aims to highlight the key factors influencing successful germination and crop development in sugar beet with a specific focus on seed-soil contact and the interaction between soil physical properties and environmental conditions. We outline that field conditions on the day of germination initiation significantly influence the productivity of the early seedling. We explain how typical field management techniques can impact on soil conditions and the subsequent impact for the emerging seedling. We also highlight the latest state of the art in imaging techniques and modelling approaches that are being applied to research in this area to improve the predictability of germination.

The concept and importance of seed-soil contact

The concept of seed-soil contact is based on the notion that seeds should be able to absorb water from water films and moist aggregates that are in direct contact with the seed for imbibition and ultimately for germination. The importance of the area of contact in combination with the soil matric potential for germination was initially described by Sedgley (1963) and Manohar and Heydecker (1964). The wetted area of contact has been found to be one of the factors controlling germination using *Medicago tribuloides* seeds (Sedgley, 1963). Increasing area of contact results in an enhanced germination rate (Manohar and Heydecker, 1964). This was tested by drilling holes of different diameters into an acrylic glass layer (i.e. Perspex) and allowing different parts of the seed to be in contact with varying areas of moist soil. Acknowledging that this was one of the first studies on seed-soil contact, seeds receiving the same treatment (i.e. hole size) were most likely exposed to different soil contact areas due to the heterogeneity of soil aggregates creating differently sized air pockets in between aggregates touching the seed. The micropyle (120 µm x 80 µm in size) has been suggested as the main point of water uptake in pea seeds (Manohar and Heydecker, 1964). The orientation of the seed would therefore be a major influence for all seed-soil contact experiments if it was not in direct contact with a moist aggregate.

Pre-soaking seeds (*M. tribuloides* and *Lactuca sativa)* reduces the importance of the soil matric potential (Collis-George and Hector, 1966). The area of contact is considered important at high matric potentials for the later germinating seeds based on observations of different calculated wetted areas. Thus, the influence of area of contact decreases with a reduction of water potential. As field water potentials are often below water potentials used in laboratory experiments such as Sedgley (1963) and Manohar and Heydecker (1964), the area of contact is probably less important at field scale. A reduction in germination rate and water uptake with a decreasing hydraulic conductivity was reported based on a fixed seed-soil contact (Hadas and Russo, 1974a, 1974b). This work introduced the concept of seed-soil contact under laboratory conditions was not extended to field scale. The main concept we considered is that the size and shape of soil aggregates in the seedbed impact on the establishment of crop seedlings and are responsible for seed-soil contact.

Preparation of the soil seedbed

Centuries of development in agricultural practice have informed our current techniques for sowing seeds. Farmers aim for uniform crop establishment, which can ultimately enhance yield, help to reduce soil nutrient leaching and to increase the ability of the crop to compete with weeds (Håkansson *et al.*, 2002). Several abiotic factors including temperature, sowing depth and soil moisture are all important to achieve optimal germination conditions for the seed. A soil temperature of above 3°C has been proposed as the germination initiation temperature for sugar beet, however, at temperatures below 5°C the germination rate can be slow (Gummerson, 1986; British Beet Research Organisation (BBRO), 2017). The base temperature for the adjusted thermal time (accumulated days above a base temperature adjusted for the specific plant species) is higher than for ryegrass (base temperature of 1.0°C – 2.0°C) and clover (base temperature of 0.0°C – 1.5°C) but lower compared to maize (base temperature of 7.0°C – 9.0°C) (Moot et al., 2000; Trudgill et al., 2000). These temperature requirements make sugar beet an ideal spring sown crop once the temperature rises above the base temperature. Under shallow sowing conditions, seeds experience a higher temperature, however, the temperature decreases with increasing soil water content (Ferraris, 1992).

Heavy rainfall within 48 hours after drilling can have negative effects on sugar beet germination (BBRO, 2017). Rainfall often results in slumping of a bare seedbed to some degree i.e. soil structural collapse and thereby altering the intended seedbed structure as well as influencing the seed-soil contact. As slumping increases soil bulk density and compaction, porosity decreases. In this case an increase in seed-soil contact could therefore reach a critical level due to reduced oxygen availability, though this is hard to assess due to the opacity of soil. At high soil moisture contents, oxygen limitation can occur as the percentage of water filled pores increases at the expense of air filled pores. Oxygen limitation however, has been reported to have a limited influence on germination, certainly lower than the considerable negative influence of waterlogging (Håkansson et al., 2012). It is also likely that oxygen limitation does not influence the germination initiation as the embryo is confined to the pericarp and therefore limited to external oxygen supply. A reduced sugar beet establishment has been found to be due to poor drainage and a water level above seeding depth (Durrant et al., 1988).

Crusting of the topsoil may occur in some soils, especially finer textured which reduces the chance of emergence for weaker seedlings (Aubertot *et al.*, 2002). Sugar beet is highly susceptible to variations in soil physical conditions in the field due to the low seedling emergence force (i.e. force of the hypocotyl) of 0.15 N (Souty and Rode, 1993). Previous work has recommended that the physical stress should not exceed a weight equivalent to a force of 0.10 N for at least 50% of the seedlings to successfully emerge (Souty and Rode, 1993). Seedbed preparation has therefore to be executed at specific times to avoid crust formation due to rainfall within the first few days after drilling. As sugar beet seeds are also heavily susceptible to water stress under drought conditions, seed priming (pre-germinating the seeds in the presence of small amounts of water) is used to enhance the drought tolerance for sub-optimal conditions whereas a prolonged steeping (a type of priming including an acid steeping step) process increases the tolerance even further (Durrant and Mash, 1991). Seedbed preparation is a crucial step for sugar beet farmers not only due to the influence of weathering on the seedbed but also as seedling emergence is influenced by soil physical properties (e.g. soil texture, bulk density and water content), climate, tillage, and drilling procedures (Aubertot *et al.*, 1999). Soil compaction (a decrease in pore space and increase in bulk density) poses a serious problem for the sugar beet industry as conventional field preparation techniques result in subsoil compaction reducing root development and yield (Marinello et al., 2017). The ideal conditions for a seedbed are thought to consist of both fine and coarse aggregates to prevent erosion (erosion prevention facilitated by a proportion of coarse aggregates) and to ensure sufficient soil-seed and soil-root contact (improved contact facilitated by a proportion of fine aggregates) whilst minimizing compaction which represents a challenge to the farmer (Figure 1) (Braunack and Dexter, 1989).

A seedbed has previously been defined as a loose and shallow managed surface layer (Håkansson *et al.*, 2002). The surface layer is ideally prepared to a depth of 5 to 7 cm with a minimum of 30% aggregates below 3 mm for improving the moisture availability around the seed (BBRO, 2017). Aggregate size and position above the seed in the seedbed influences the emergence probability of the seedling (Bouaziz and Bruckler, 1988; Souty and Rode, 1993; Boiffin *et al.*, 1994) as well as the soil aggregate roughness (Richard and Dürr, 1997; Aubertot *et al.*, 1999). This is likely to be due to the limited emergence force of the young sugar beet seedling. Increasing bulk density and aggregate size results in a delay of seedling emergence, as shown for wheat by Nasr and Selles (1995). A higher abundance of aggregates > 5 mm has been reported within the 0 – 3 cm layer compared to the 3 – 10 cm layer using tillage techniques segregating aggregate classes and being preferable for seedbeds (Kritz, 1983). Soil aggregate size has a significant impact on the seed-soil contact. Testing different aggregate size classes to simulate different seed-soil contacts has been used to identify accelerated germination for the finest seedbed aggregate sizes (tested on peanut seeds) (Khan and Datta, 1987). This is attributed to increased seed-soil contact and thus enhanced water availability. The increase in germination and emergence time can also be attributed to a change in hydraulic conductivity, soil-water diffusivity, the soil moisture flux, the thermal conductivity and oxygen flux. However, the treatments used by Khan and Datta (1987) consisted of >70% aggregates within the specific size class which leaves up to 30% of smaller aggregates within each treatment. Assuming that a third of the aggregates were smaller, we hypothesize these probably filled the larger pores in the coarser treatments therefore influencing the seed-soil contact into the point that it is difficult to conclude which factor had the strongest impact. The presence of larger aggregates has also been reported to result in detrimental effects with an exponential decrease in emergence found using aggregates > 10 mm incorporated into the seedbed (Dürr and Aubertot, 2000). Seedbeds composed mainly by larger aggregates are not suitable for most agricultural purposes due to reduced establishment caused by reduced seed-soil contact and also due to the limiting emergence force of the seedling. However, they do offer the benefit of protection against erosion (Lyles and Woodruff, 1962; Keller et al., 2007;

Obour et al., 2017). A balance is therefore needed between the ratio of larger aggregates for reducing erosion and smaller aggregates to improve the establishment rate, however not exceeding a critical level determined by the emergence force (Boiffin, 1986; Duval and Boiffin, 1994; Håkansson et al., 2002).

Soil aggregate size can influence soil water content through the provision of macropores between aggregates and micropores within aggregates , as well as soil physical properties (Dürr and Aubertot, 2000). Field management techniques, particularly those concerned with seedbed preparation significantly influence aggregate size distributions with small aggregated seedbeds provide a higher contact area between soil aggregates and the sugar beet seed and therefore improving water transfer (Bruckler, 1983; Schneider and Gupta, 1985; Braunack and Dexter, 1989; Braunack, 1995; Dürr and Aubertot, 2000).

A firm adjacent basal sublayer consisting of soil with a higher bulk density was recommended as preferable for Swedish soils (Håkansson et al., 2002). However, an open porous soil structure with larger aggregates is the current recommendation by the British Beet Research Organisation (BBRO 2017). The structure of the lower layer of soil is generally not tilled which can result in a drought stress as root growth can be restricted. The incorporation of the sugar beet seeds within the dense sublayer, however, could enable access to a higher moisture content through an increased contact area between the seed and the soil (Gummerson, 1989). The idea of accessing a higher water source through an adjacent layer is an interesting one as the seed would benefit from both the fine seedbed as well as the water source. However, this would require sowing at a higher precision than is currently employed in most field cases as slight unevenness of the seed surface would result in misplacement of the seed. Therefore, the seed would either be placed within the fine seedbed or deep within the compacted sublayer which would have a negative impact on emergence time. Current recommendation aim for an even seedbed as unevenness may lead to yield loss due to reduced establishment and increased harvester losses (BBRO, 2017). Additionally, the BBRO (2017) highlight the timing and procedure of cultivation management techniques can reduce the final yield by 30% under sub-optimal conditions.

These previous studies highlight that water and temperature related environmental factors have a very significant influence on seed germination and plant growth. Whereas the soil physical factors, which directly affecting seed-soil contact and chance of emergence can be adjusted and influenced to a larger extent through appropriate cultivation and management techniques.

Cultivation and management techniques

Structural variations in the seedbed are primarily caused by tillage operations and drilling machinery (man-made) or by wetting-drying / freeze-thaw cycles and biological actions (natural) (Aubertot *et al.*, 1999). Seedbeds are commonly prepared into a fine and homogenous state using tillage operations such as harrowing, ploughing, discing or by tines (Obour et al., 2017). Reduced tillage techniques in comparison to conventional tillage, reduces the number of passes through the fields and the intensity and depth (usually the upper 5 cm) of cultivation (Halvorson and Hartman, 1984). Fields managed under no tillage conditions prepare the seedbed via the action of the soil biota and wetting and drying cycles (Tisdall, 1994; Degens, 1997; Romaneckas et al., 2009). Dense soil surface layers commonly found on no tillage managed fields can adversely affect establishment due to a low emergence force (Koch, 2009) though literature in this area is sparse. Strip tillage procedures are used for partial or complete removal of the soil surface layer by tilling narrow strips to control erosion (for both wind and water), reduce evaporation and avoid loss of soil organic matter (Jabro et al., 2014). Similar yields for sugar beet have been reported compared to intensive tillage. One third of the sugar beet grown in the US is managed by strip tillage as the number of passes is reduced from five (conventional tillage) to one (strip tillage) and therefore fuel usage is reduced as well (Evans et al., 2010; Cane, 2015; Stevens et al., 2015; Tarkalson et al., 2016). Strip tillage can however increase the time until emergence by up to 5 to 7 days in a silt loam (Lower Saxony, Germany) most likely due to an uneven coarse seedbed in comparison to intensive tillage and reduced tillage (Laufer and Koch, 2017). Further research is needed concerning the preferred tillage system for optimized seedbed preparation however reduced and no-tillage techniques show considerable promise providing the soil bulk density does not exceed a critical level.

Sugar beet fields in European countries are commonly ploughed in the previous year as clod strength reduction (tilth mellowing) facilitated by weathering is considered to help the seedbed composition throughout the winter period (wetting-drying as well as freeze-thaw cycles) (Utomo and Dexter, 1981). The effectiveness of this method of soil breakdown by tilth mellowing is determined by the soil consistency (i.e. resistance to deformation in a wet and dry state) (Larney et al., 1988). For heavy textured soils in the UK, ploughing is recommended before the end of October whereas for lighter textured soils from October onwards is preferable (BBRO, 2017). Light soils (i.e. high sand content) should only be ploughed directly before drilling to avoid drying, slumping and erosion (caused by friable soil structure). Spring cultivations, for creating a level and consolidated seedbed, are thought to be optimal for high seed-soil contact, though this is hypothesized rather than based on actual measurements, and therefore a successful uniform establishment and high yield (BBRO, 2017). Based on these recommendations, farmers need to consider both field conditions (e.g. soil texture, bulk density and soil strength) as well as the average weather conditions (e.g. rainfall, temperature as well as base temperature for the specific crop) to make an informed decision on appropriate field management techniques which adds to the challenge.

Cultivations aim to optimize the structure of the seedbed and therefore ensuring consistent and homogeneous establishment and stand (Håkansson *et al.*, 2002). The "Speeding Up Sugar Yield" (SUSY) project investigated the yield differences between historic production between 2002 and 2006 (10 Mg ha^{-1} (Hanse *et al.*, 2011)) and optimal potential (23 Mg ha^{-1} (de Wit, 1953)) in the Netherlands. Top yielding farmers typically use less cultivation steps compared to average yield farmers as well as earlier sowing dates based on the comparison of total yield from previous years (Hanse et al., 2011). Statistical modelling (REML) showed soil hydraulic conductivity (i.e. a measure of a soils drainage rate), tillage operation depth as well as soil structure had the highest impacts on obtaining a good yield.

A combination harrow is recommended for a final depth of 5 to 7 cm, however, only one pass is optimal so as to avoid excessive compaction (BBRO, 2017). Commonly, seedbeds are rolled during sowing to increase seed-soil contact using small press-wheels attached to the seed-drill (Sadeghpour *et al.*, 2015). Rolling is a controversial practice in this regard as excess pressure results in high compaction and thus severely reduced establishment (Jaggard, 1977; Hebblethwaite and McGowan, 1980; Brereton *et al.*, 1986). Whereas beneficial effects on yield have been reported using single passes with press-wheels indicating an increase in seed-soil contact while avoiding oxygen limitation (Håkansson *et al.*, 2011; Arvidsson *et al.*, 2012). Again, the opacity of soil making it hard to visualize seed-soil contact has remained an obstacle to understanding of the mechanical processes concerned with seedbed preparation. For many decades, seed-soil contact has been a mere concept and the real influence of compaction of seed-soil contact however is largely unknown. The changes in yield after compaction could be due to difference causes (i.e. water retention, avoidance of erosion). The current drilling practice however, does require a slight compaction as a channel in the soil is opened that would leave the seeds exposed without the use of press wheels. Cultivation techniques in comparison to reduced tillage and no-tillage have been reported to result in a more consistent and high yield, however, being susceptible to compaction due to multiple passes needed for preparing optimal seedbed conditions remains a significant but poorly understood problem.

Impact of soil amendments on seed-soil contact

Without doubt different management techniques have a variable impact on seed-soil contact and are dependent on the physical force of machinery. An alternative but emerging approach includes the incorporation of other, non-soil materials into the seedbed including plant residue, plastic or glass that alter the contact area of the seed with the soil.

Since the increase in adoption of minimum and no-tillage systems, the incorporation of plant residue has become a more regular practice depending on the type of cultivator used (Morris *et al.*, 2009). Incorporation of plant residue can serve several functions for the soil including (1) the reduction of soil erosion, (2) the supplementation of plant nutrients, (3) the functionality as a mulch reducing soil water loss and (4) the modification of soil temperature (Wilhelm *et al.*, 1986). Furthermore, increased aggregate stability has been reported on a ten year no-tillage site using crop residue management (Karlen et al., 1994). The application of conservation tillage (>30% plant residue cover) can improve important soil quality indicators (e.g. soil structure, aggregation and organic matter) (Rasmussen and Rohde, 1988; Daughtry *et al.*, 2006). Besides an improved water availability (Evans and Young, 1970; Carson and Peterson, 1990), the incorporation of plant residue can reduce seed-soil contact (Fowler, 1986; Chambers, 2000; Rotundo and Aguiar, 2005). This reduction in seed-soil contact is thought to be caused by the seed being positioned directly next to plant residue or the residue creating larger pore spaces than would be there otherwise. The direct contact may also exhibit positive effects for nutrient transfers however, decomposing plant residues in a moist environment can also attract pathogens which have negative effects on germination and early growth. Additionally, a reduced soil temperature and germination was reported using a straw cover (Børresen and Njoes, 1990). A reduced germination efficiency in seeds has been found in the presence of plant residue in direct contact for oilseed rape which was attributed to the reduced seed-soil contact (Morris *et al.*, 2009). This negative effect of plant residue was investigated using wheat straw in varying quantities either in direct contact with the seed or incorporated into the soil. Straw residue positioning has been shown to be the primary factor of establishment reduction whereas the impact of the amount of residue was lower and did not reduce establishment significantly highlight the impact of the contact area reduced by residue (Morris et al., 2009).

An increase in seed longevity has been shown for *Bromus pictus* seeds placed within a layer of plant litter but a reduction in germination rate for seeds surrounded by plant litter (no seed-soil contact) (Rotundo and Aguiar, 2005). A lack of seed-soil contact (for sugar beet and oilseed rape seeds) was shown by placing a seed on wheat residue, resulting in a reduced emergence rate by 30% (this method simulates ‘broadcast sowing’, common for oilseed rape when distributing the seed on the soil surface) (Morris et al., 2009). This effect was reversed when placing residue on top of the soil leading to rapid emergence due to the reduced evaporation (simulating an Autocast system that distributes straw above the seeds following sowing from a hopper attached to a combine harvester) (Morris et al., 2009). Uneven distribution of straw can therefore result in a patchy establishment with a 50% reduction of biomass growth which was verified using oilseed rape and sugar beet by mixing the residue into the soil or placing it onto the surface (HGCA, 2002; Morris *et al.*, 2009). Placement of plant residue is therefore crucial as beneficial effects such as a reduction in evaporation and supply of nutrients can accelerate the emergence rate, however, there can be severe negative impacts. For weaker seedlings like sugar beet, the use of plant residue is only advisable if the seedlings emergence force can overcome the surface cover and the residue is not placed in direct contact with the seed.

Traditionally, sugar beet fields have been drilled in the preceding autumn to winter burying all stubbles, depending on the soil type (Ecclestone, 2004). However, non-inversion tillage systems retain residue at the soil surface. Furthermore, the position of plant residues in the seedbed can have phytotoxic effects on developing seedlings due to the production of phenolic compounds during their decomposition especially under anaerobic conditions (Wuest *et al.*, 2000). Besides beneficial effects on soil biochemical properties, significant improvements in yield were shown over a period of four years for maize with wheat residue, however incorporation of residue from the same crop used for the following season depressed yield significantly (Sidhu and Beri, 1989). However, this is more attributed to the biochemical influences than the seed-soil contact alterations by incorporating chopped residue (likely to have produced inhibiting metabolites).

Alternative research has considered the benefits of waste materials as soil amendments to improve seedling emergence and crop establishment. The effect of fine (< 6 mm) and coarse (6 – 15 mm) glass debris incorporated into the soil or as a mulch material was tested as the incorporation of glass into soil is a possible option for glass disposal (De Louvigny et al., 2002). Although concerns regarding a potential chemical and physical alteration of the soil as well as an effect on the growth behavior of plants have been raised (Ngoya *et al.*, 1997). High glass contents within the soil were achieve by creating a paste made of glass, water and soil which was air dried and cut into aggregates of different sizes. These aggregates have been used within the seedbed (layered with 5 mm of fine soil) or laid on the soil surface. Final sugar beet emergence rate was not significantly reduced, however, it slowed when the glass-contents as a portion of the soil was > 80% (De Louvigny *et al.*, 2002). Higher glass-soil contents also resulted in the trapping of seedlings below rough glass surfaces. With the incorporation of high levels of glass (> 80%), increased temperature, on average of about 2°C per day and significantly increased sowing depth has been reported (De Louvigny et al., 2002). While the increased temperature has beneficial effects for accelerated germination, an increased sowing depth would reduce establishment count, especially under water restricted growth caused by the high glass content. Furthermore, as high glass contents were realized by creating artificial aggregates containing glass, the difference in seed-soil contact cannot be quantified directly but rather the impact on emergence.

Calculation of seed-soil contact

Soil aggregate size distribution from field structured soil can be determined by measuring fractions of the total soil sample size after sieving (Kemper and Chepil, 1965) or by the measurement of mass proportions of aggregates within sublayers (Kritz, 1983). Soil embedded in resin can be used to identify aggregate and air space distribution, but this is typically restricted to a 2D view of the soil matrix unless serial sections are collected which is a laborious process (Protz *et al.*, 1987; Bresson and Boiffin, 1990; Dexter, 1991). Quantification of seed-soil contact has proven challenging and field management decision have been selected based on the assumption of its effect. Only few approaches have been made that have attempted to estimate seed-soil contact, typically resulting in subjective descriptions such as ‘poor’ or ‘good’.

Until very recently, the best approach to estimate seed-soil contact has been based on simplistic simulations and modelling such as that by Brown *et al.* (1996) and Zhou *et al.* (2014).

The influence of aggregate size and macroporosity was simulated using deformable spheres of a uniform size and a rigid disc or sphere as a seed which is only a coarse assumption due to the heterogeneity of soil aggregates and particles (Brown et al., 1996). Using a colored liquid poured over the sample from multiple directions, an increase of contact with decreasing macroporosity was found upon dismantling of the sample (Brown et al., 1996). A Discrete Element Method (DEM) by using a distinct sphere as the seed and a randomly generated set of differently sized spheres to represent soil aggregates was used to calculate the area of contact by Zhou et al. (2014). They found 0 to 33 contact points with 0 to 41 mm^2 area of contact with varying sowing depths. A soil to seed size ratio of 1.33 and 1.75 was considered as exhibiting the highest contact area. A simulation of rolling using press wheels increased the modelled seed-soil contact significantly. Both approaches fail to account for the heterogeneity of soil due to varying soil aggregate structures (e.g. size, roughness, and tortuosity). An additional challenge is posed by the presence of mineral stones and organic matter in varying sizes and shapes (not considered in models) that can be in direct contact with the seed or create air pockets reducing the seed-soil contact. Even if those are not in direct contact to the seed but rather in proximity, the hydraulic conductivity and the pore network is amended compared to a modelled pure soil structure.

X-ray Computed Tomography (X-ray CT) has previously shown great promise for quantifying soil properties like bulk density and porosity (Steude *et al.*, 1994; Atkinson *et al.*, 2007, 2009). The application of this imaging approach offers the opportunity to overcome the limitation of soil opacity and actually visualize and measure the seed-soil contact under field conditions. A recent approach using X-ray CT quantified the actual soil matrix and pore space surrounding a sugar beet seed at a resolution of 20 µm (Blunk et al., 2017). An interesting increase in seed-soil contact percentage for round-shaped seeds in comparison to untreated star-shaped sugar beet seeds was reported in the same work (Blunk et al., 2017). Blunk et al. (2017) developed an imaging method to measure in 3D the precise seed-soil contact based on visualization of the soil aggregates and pore geometry in relation to a sugar beet seed validated on laboratory prepared and field collected samples (Figure 2). This research has shown how the advancements in imaging technologies can assist us to overcome the limitations associated with the opacity of soil and will undoubtedly provide new data to inform the future modeling approaches to improve their accuracy.

Future perspectives

Seed-soil contact as a concept has been well known for several decades but has lacked direct assessment until recently. Research into its measurement has been limited by the inability to observe it directly but with the recent developments in imaging techniques, seed-soil contact can be investigated at an appropriate resolution and the impact of management techniques on the seedbed and the resulting area of contact assessed. Future research should be able to directly assess the impact of soil management practices on the seed-soil contact that is achieved and the impact on germination. However, a potential problem to the adoption of new agricultural practices is that farmers tend to rely on former experience. BBRO (2017) provide recommendations for the appropriate soil structure of the seedbed, however, there is only little quantitative knowledge concerning the effects of the different preparation techniques (e.g. harrow, tine, frost action) under present conditions (e.g. temperature, rainfall, soil moisture, soil texture, previous crop) on the resulting seedbed. Laser range scanners have shown considerable promise for mapping the seedbed surface structure to give indications of the ultimate effect of tillage operations including surface roughness (Jensen *et al.*, 2017). These laser range measurements can also be used to estimate aggregate size distribution which could be extrapolated to estimate seed-soil contact (Jensen *et al.*, 2016) and provide data for future modelling efforts.

Furthermore, the relationship between factors influencing germination, emergence and establishment requires a deeper understanding for choosing appropriate management techniques. Modelling approaches that take multiple factors into account represent a first step into the right direction. The soil quality of establishment (SQE) statistical model (Atkinson et al., 2007, 2009) uses field measurements (e.g. bulk density or shear strength), macrostructure properties and management techniques to predict establishment in wheat, however, it does currently not account for environmental factors like rainfall and temperature. The SUCROS model predicts sugar beet yield based on emergence time, establishment count, leaf area at emergence and leaf area growth rate which are highly dependent on soil texture, weather, seedbed preparation, sowing technique and seed lot characteristics (Spitters et al., 1989; Boiffin et al., 1992; Dürr et al., 1992; Guérif and Duke, 1998). SUCROS however is a function of thermal time and does not include soil water as a limiting factor (Rinaldi et al., 2005). The SIMPLE (SIMulation of PLant Emergence) model, in comparison, is used to predict the effect of tillage and sowing operations for sugar beet (Dürr et al., 2001). This model uses texture, aggregate size distribution, position in the seedbed, sowing depth, soil temperature, rainfall, seed characteristics, germination time and hypocotyl elongation distribution to create a 3D seedbed based on aggregates and seed characteristics and predicts the duration until emergence based on the thermal time of the seed (Dürr et al., 2001). However, a more complex model is needed that adjusts relevant factors based on the relationship towards other factors (e.g. a change in soil compaction affects aggregate size distribution, porosity, hydraulic conductivity, etc.). The basis of this are more sophisticated seedbed analysis approaches to quantify relevant factors influencing germination, emergence and establishment and their impact on seed-soil contact. Furthermore, quantitative image data generation using X-ray imaging can be used as a basis for modelling approaches and therefore improving the predictability under specific conditions. Further investigations that seek to quantify field structured seedbeds and screening of field environmental conditions are urgently needed to inform the selection of future management techniques especially in the face of environmental and climatic change.

Conclusions

Factors of soil seedbed preparation affecting germination and establishment in sugar beet have received much attention, however their interaction with each other has not been fully explored. Imbibition, the initial step of germination, is known to be influenced by seed-soil contact which is affected by a variety of soil physical and environmental factors but is challenging to assess not least due to the inability to observe the seed within the soil due to its opacity. The suite of field management techniques represents the extent of the limited options farmers are able to impose on the field and these are well known to have been shown to be affected by high variability of seed-soil contact. Engineering what might be considered an ‘optimal’ seed-soil contact can only be achieved using appropriate field management techniques at precise times (due to variation between soil texture, climatic conditions and crop). We consider the present soil and environmental conditions on the sowing day and the consecutive two to three days as the decisive factors affecting seedling emergence as the early seedling is dependent on seed reserves and its activation. A non-favorable germination initiation due to poor soil conditions (e.g. seed-soil contact) could affect the seedling early resulting in a struggle to keep up with seedlings under optimal conditions. Future modelling efforts concerning the interactive network of factors influencing seed-soil contact should be sought to improve the predictability of germination, emergence and establishment based on image derived data. The image data will help to comprehend the impact that tillage operations pose on the seedbed and the actual contact to the seed. Deeper understanding of how plant establishment can be influenced altering seed-soil contact and therefore adjusting management and sowing techniques is fundamental for the improvement of future farming practices.

Acknowledgements

This work was financially supported by Syngenta.

Financial support

This work was financially supported by Syngenta.

Conflict of interest

None

Ethical standards

None

References

Apostolides, G., and Goulas, C. (1998). Seed Crop Environment and Processing Effects on Sugar Beet (Beta vulgaris L.) Certified by Hybrid Variety Seed Quality. Seed Sci.Tech. *26*, 223–235.

Arvidsson, J., Bölenius, E., and Cavalieri, K.M.V. (2012). Effects of compaction during drilling on yield of sugar beet (Beta vulgaris L.). Eur. J. Agron. *39*, 44–51.

Atkinson, B.S., Sparkes, D.L., and Mooney, S.J. (2007). Using selected soil physical properties of seedbeds to predict crop establishment. Soil Tillage Res. *97*, 218–228.

Atkinson, B.S., Sparkes, D.L., and Mooney, S.J. (2009). Effect of seedbed cultivation and soil macrostructure on the establishment of winter wheat (Triticum aestivum). Soil Tillage Res. *103*, 291–301.

Aubertot, J.-N., Dürr, C., Richard, G., Souty, N., and Duval, Y. (2002). Are penetrometer measurements useful in predicting emergence of sugar beet (Beta vulgaris L.) seedlings through a crust? Plant Soil *241*, 177–186.

Aubertot, J.N., Dürr, C., Kieu, K., and Richard, G. (1999). Characterization of Sugar Beet Seedbed Structure. Soil Sci. Soc. Am. J. *63*, 1377–1384.

BBRO (2017). BBRO Sugar Beet Reference Book.

Bewley, J.D. (1997). Seed Germination and Dormancy. Plant Cell Online *9*, 1055–1066.

Bewley, J.D., and Black, M. (1994). Seeds: Physiology of Development and Germination (New York: Plenum Press).

Blunk, S., Malik, A.H., de Heer, M.I., Ekblad, T., Bussell, J., Sparkes, D., Fredlund, K., Sturrock, C.J., and Mooney, S.J. (2017). Quantification of seed–soil contact of sugar beet (Beta vulgaris) using X-ray Computed Tomography. Plant Methods *13*, 71.

Boiffin, J. (1986). Stages and time-dependency of soil crusting in situ. In Proceedings of the International Symposium on the Assessment of Soil Surface Sealing and Crusting, D. F Callebaut, and G. and M. de Boodt, eds. pp. 91–98.

Boiffin, J., Durr, C., Fleury, A., Marin-Lafleche, A., and Maillet, I. (1992). Analysis of the variability of sugar beet(Beta vulgaris L.) growth during the early stages. I. Influence of various conditions on crop establishment. Agronomie *12*, 515–525.

Boiffin, J., Dubrulle, P., Dürr, C., and Richard, G. (1994). Modelling sugar beet seedling emergence and early growth. In 13th ISTRO Conference, S. HE Jensen, P Schjnning, and M. and K. Madsen, eds. (Aalborg, Denmark), pp. 1143–1148.

Børresen, T., and Njoes, A. (1990). The effects of three tillage systems combined with different compaction and mulching treatments on soil temperature and soil thermal properties. Nor. J. Agric. Sci. *4*, 363–371.

Bouaziz, A., and Bruckler, L. (1988). Modelling Wehat Seedling Growth and Emergence: II. Comparison with Field Experiments. Soil Sci. Soc. Am. Journal1 *53*, 1838–1846.

Braunack, M. V. (1995). Effect of aggregate size and soil water content on emergence of soybean (Glycine max, L. Merr.) and maize (Zea mays, L.). Soil Tillage Res. *33*, 149–161.

Braunack, M., and Dexter, A. (1989). Soil Aggregation in the Seedbed: a Review. II. Effect of Aggregate Sizes on Plant Growth. Soil Tillage Res. *14*, 281–298.

Brereton, J.C., McGowan, M., and Dawkins, T.C.K. (1986). The sensitivity of barley, field beans and sugar beet to soil compaction. F. Crop. Res. *13*, 223–237.

Bresson, L.-M., and Boiffin, J. (1990). Morphological characterization of soil crust development stages on an experimental field. Geoderma *47*, 301–325.

Brown, A.D., Dexter, A.R., Chamen, W.C.T., and Spoor, G. (1996). Effect of soil macroporosity and aggregate size on seed-soil contact. Soil Tillage Res. *38*, 203–216.

Bruckler, L. (1983). Rôle des propriétés physiques du lit de semences sur l’imbibition et la germination. I. Élaboration d’un modèle du système “terre-graine”. Agronomie *3*, 213–222.

Cane, T.L. (2015). Strip tilling and planting sugar beets into established alfalfa. J. Sugar Beet Res. *52*, 92.

Carson, W.P., and Peterson, C.J. (1990). The role of litter in an old-field community - impact of litter quantity in different seasons on plant species richness and abundance. Oecologia *85*, 8–13.

Chambers, J.C. (2000). Seed movements and seedling fates in disturbed sagebrush steppe ecosystems - implications for restoration. Ecol. Appl. *10*, 1400–1413.

Collis-George, N., and Hector, J. (1966). Germination of seeds as influenced by matric potential and by area of contact between seed and soil water. Aust. J. Soil Res. *4*, 145–164.

Daughtry, C.S.T., Doraiswamy, P.C., Hunt, E.R., Stern, A.J., McMurtrey, J.E., and Prueger, J.H. (2006). Remote sensing of crop residue cover and soil tillage intensity. Soil Tillage Res. *91*, 101–108.

Degens, B.P. (1997). Macro-aggregation of soils by biological bonding and binding mechanisms and the factors affecting these: a review. Aust. J. Soil Res. *35*, 431.

Dexter, A.R. (1991). Statistical structure of tilled soil as determined by image analysis of sections.

Dürr, C., and Aubertot, J.-N. (2000). Emergence of seedlings of sugar beet (Beta vulgaris L.) as affected by the size, roughness and position of aggregates in the seedbed. Plant Soil *219*, 211–220.

Dürr, C., Boiffin, J., Fleury, A., and Coulomb, I. (1992). Analysis of the variability of sugar beet (Beta vulgaris L.) growth during the early stages. II. Factors influencing seedling size in field conditions. Agronomie *12*, 527–535.

Dürr, C., Aubertot, J.-N., Richard, G., Dubrulle, P., Duval, Y., and Boiffin, J. (2001). SIMPLE: A Model for SIMulation of PLant Emergence Predicting the Effects of Soil Tillage and Sowing Operations. Soil Sci. Soc. Am. J. *65*, 414–423.

Durrant, M.J., and Mash, S.J. (1991). Sugar-beet seed steep treatments to improve germination under cold, wet conditions. Plant Growth Regul. *10*, 45–55.

Durrant, M.J., Dunning, R.A., Jaggard, K.W., Bugg, R.B., and Scott, R.K. (1988). A census of seedling establishment in sugar-beet crops. Ann. Appl. Biol. *113*, 327–345.

Duval, Y., and Boiffin, J. (1994). Daily emergence disturbance index for sugar beet based on soil crusting. In 13th ISTRO Conference1, H.E. Jensen, P. Schjnning, S.A. Mikkelsen, and K.B. Madsen, eds. (Aalborg, Denmark), pp. 633–638.

Ecclestone, P. (2004). To plough or not to plough. Br. Sugar Beet Rev. *72*, 7–9.

Evans, R.A., and Young, J.A. (1970). Plant litter and establishment of alien weed species in rangeland communities. Weed Sci. *19*, 697–702.

Evans, R.G., Stevens, W.B., and Iversen, W.M. (2010). Development of strip tillage on sprinkler irrigated sugarbeet. Appl. Eng. Agric. *26*, 59–69.

Ferraris, R. (1992). Seedbed factors affecting establishment of summer crops in a Vertisol. Soil Tillage Res. *23*, 1–25.

Fowler, N.L. (1986). Microsite requirements for germination and establishment of three grass species. Am. Midl. Nat. *115*, 131–145.

Guérif, M., and Duke, C. (1998). Calibration of the SUCROS emergence and early growth module for sugar beet using optical remote sensing data assimilation. Eur. J. Agron. *9*, 127–136.

Gummerson, R.J. (1986). The Effect of Constant Temperatures and Osmotic Potentials on the Germination of Sugar Beet. J. Exp. Bot. *37*, 729–741.

Gummerson, R.J. (1989). Seed-bed cultivations and sugar-beet seedling emergence. J. Agric. Sci. *112*, 159–169.

Hadas, A., and Russo, D. (1974a). Water uptake by seeds as affected by water stress, capillary conductivity and seed soil contact. I. Experimental study. Agron. J. *66*, 643–647.

Hadas, A., and Russo, D. (1974b). Water uptake by seeds as affected by water stress, capillary conductivity and seed soil contact. II. Analysis of experimental data. Agron. J. *66*, 647–652.

Håkansson, I., Myrbeck, Å., and Etana, A. (2002). A review of research on seedbed preparation for small grains in Sweden. Soil Tillage Res. *64*, 23–40.

Håkansson, I., Rydberg, T., Keller, T., and Arvidsson, J. (2011). Effects of seedbed properties on crop emergence: 3. Effects of firming of seedbeds with various sowing depths and water contents. Acta Agric. Scand. Sect. B Soil Plant Sci. *61*, 701–710.

Håkansson, I., Keller, T., Arvidsson, J., and Rydberg, T. (2012). Effects of seedbed properties on crop emergence. 4. Inhibitory effects of oxygen deficiency. Acta Agric. Scand. Sect. B Soil Plant Sci. *62*, 166–171.

Halvorson, A.D., and Hartman, G.. (1984). Reduced seedbed tillage effects on irrigated sugar beet yield and quality. Agron. J. *76*, 603–607.

Hanse, B., Vermeulen, G.D., Tijink, F.G.J., Koch, H.J., and Märländer, B. (2011). Analysis of soil characteristics, soil management and sugar yield on top and averagely managed farms growing sugar beet (Beta vulgaris L.) in the Netherlands. Soil Tillage Res. *117*, 61–68.

Hebblethwaite, P.D., and McGowan, M. (1980). The effects of soil compaction on the emergence, growth and yield of sugar beet and peas. J. Sci. Food Agric. *31*, 1131–1142.

HGCA (2002). Establishing Oilseed Rape Using Autocast. Home Grown Cereal. Authority, London Topic Sheet No. 59.

Jabro, J.D., Stevens, W.B., Iverson, W.M., Evans, R.G., and Allen, B.L. (2014). Crop water productivity of sugarbeet as affected by tillage. Agron. J. *106*, 2280–2286.

Jaggard, K.W. (1977). Effects of soil density on yield and fertilizer requirement of sugar beet. Am. Appl. Biol. *86*, 301–312.

Jensen, T., Green, D., Munkholm, L.J., and Karstoft, H. (2016). Fourier and granulometry methods on 3D images of soil surfaces for evaluating soil aggregate size. Am. Soc. Agric. Biol. Eng. Appl. Eng. Agric. *32*.

Jensen, T., Karstoft, H., Green, O., and Munkholm, L.J. (2017). Assessing the effect of the seedbed cultivator leveling tines on soil surface properties using laser range scanners. Soil Tillage Res. *167*, 54–60.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., and Jordahl, J.L. (1994). Crop residue effects on soil quality following 10-years of no-till corn. Soil Tillage Res. *31*, 149–167.

Keller, T., Arvidsson, J., and Dexter, A.R. (2007). Soil structures produced by tillage as affected by soil water content and the physical quality of soil. Soil Tillage Res. *92*, 45–52.

Kemper, W.D., and Chepil, W.S. (1965). Siye Distribution of Aggregates in Methods of Soil Analysis. In Black C. A. et Al. Methods of Soil Analysis, pp. 499–510.

Khan, A.R., and Datta, B. (1987). Effect of Aggregate Size on Water Uptake By Peanut Seeds. Soil Tillage Res. *3*, 171–184.

Koch, H.J. (2009). Relations between soil structural properties and sugar beet yield on a Luvisol. *13*.

Kritz, G. (1983). Physical conditions in cereal seedbeds. A sampling investigation in Swedish spring-sown fields. Ph. D. Thesis. Swedish Univ. Agric. Sci. Uppsala, Reports from Div. Soil Manag. *65*, 187.

Larney, F.J., Fortune, R.A., and Collins, J.F. (1988). Intrinsic soil physical parameters influencing intensity of cultivation procedures for sugar beet seedbed preparation. Soil Tillage Res. *12*, 253–267.

Laufer, D., and Koch, H.J. (2017). Growth and yield formation of sugar beet (Beta vulgaris L.) under strip tillage compared to full width tillage on silt loam soil in Central Europe. Eur. J. Agron. *82*, 182–189.

De Louvigny, N., Dürr, C., Fiès, J.C., and Bruckler, L. (2002). Emergence of sugar beet (Beta vulgaris L.) from seedbeds after glass waste deposition on soil. Soil Tillage Res. *66*, 35–46.

Lyles, L., and Woodruff, N.P. (1962). How Moisture and Tillage Affect Soil Cloddiness for Wind Erosion Control. Agric. Eng. *43*, 150–153.

Manohar, M.S., and Heydecker, W. (1964). Effects of water potential on germination of pea seeds. Nature *202*, 22–24.

Marinello, F., Pezzuolo, A., Cillis, D., Chiumenti, A., and Sartori, L. (2017). Traffic effects on soil compaction and sugar beet (Beta vulgaris L.) taproot quality parameters. Spanish J. Agric. Res. *15*, 1–8.

Moot, D.J., Scott, W.R., Roy, A.M., and Nicholls, A.C. (2000). Base temperature and thermal time requirements for germination and emergence of temperate pasture species. New Zeal. J. Agric. Res. *43*, 15–25.

Morris, N.L., Miller, P.C.H., Orson, J.H., and Froud-Williams, R.J. (2009). The effect of wheat straw residue on the emergence and early growth of sugar beet (Beta vulgaris) and oilseed rape (Brassica napus). Eur. J. Agron. *30*, 151–162.

Nasr, H.M., and Selles, F. (1995). Seedling emergence as influenced by aggregate size , bulk density , and penetration resistance of the seedbed. Soil Tillage Res. *34*, 61–76.

Ngoya, C., Hensley, D., and Murdoch, C. (1997). Evaluation of recycled glass and compost as a turfgrass media. J. Turfgrass Manag. *2*, 1–14.

Obour, P.B., Lamandé, M., Edwards, G., Sørensen, C.G., and Munkholm, L.J. (2017). Predicting soil workability and fragmentation in tillage: a review. Soil Use Manag. *33*, 288–298.

Protz, R., Shipitalo, M.J., Mermut, A.R., and Fox, C.A. (1987). Image analysis of soils - present and future. Geoderma *40*, 115–125.

Rasmussen, P.E., and Rohde, C.R. (1988). Long-term tillage and nitrogen fertilization effects on organic N and C in a semi-arid soil. Soil Sci. Soc. Am. J. *44*, 596–600.

Richard, G., and Dürr, C. (1997). Conséquences de l’état du profil cultural sur les peuplements végétaux : Réssite de la levée en relation avec l’état du lit de semences. In Le Travail Du Sol Dans Les Systèmes Mécanisés Tropicaux. Presented at Colloque, Montpellier, FRA, pp. 49–54.

Rinaldi, M., Di Paolo, E., Richter, G.M., and Payne, R.W. (2005). Modelling the effect of soil moisture on germination and emergence of wheat and sugar beet with the minimum number of parameters. Ann. Appl. Biol. *147*, 69–80.

Romaneckas, K., Romaneckiene, R., Šarauskis, E., Pilipavicius, V., and Sakalauskas, A. (2009). The effect of conservation primary and zero tillage on soil bulk density, water content, sugar beet growth and weed infestation. Agron. Res. *7*, 73–86.

Rotundo, J.L., and Aguiar, M.R. (2005). Litter effects on plant regeneration in arid lands: A complex balance between seed retention, seed longevity and soil-seed contact. J. Ecol. *93*, 829–838.

Sadeghian, S.Y., and Yavari, N. (2004). Effect of Water-Deficit Stress on Germination and Early Seedling Growth Stage of Sugar Beet. *190*, 138–144.

Sadeghpour, A., Hashemi, M., Jahanzad, E., and Herbert, S.J. (2015). Switchgrass Stand Density and Yield as Influenced by Seedbed Preparation Methods in a Sandy Loam Soil. Bioenergy Res. *8*, 1840–1846.

Schneider, E.C., and Gupta, S.C. (1985). Corn emergence as influenced by soil temperature, matric potential and aggregate size distribution. Soil. Sci. Soc. Am. J. *49*, 415–422.

Sedgley, R.H. (1963). The importance of liquid seed contact during germination of Medicago tribuloides Dew. Aust. J, Agric. Res *14*, 646–653.

Sidhu, B.S., and Beri, V. (1989). Effect of crop residue management on the yields of different crops and on soil properties. Biol. Wastes *27*, 15–27.

Souty, N., and Rode, C. (1993). Emergence of sugar beet seedlings from under different obstacles. Eur. J. Agron. *2*, 213–221.

Spitters, C.J.T., Keulen, H. Van, and Kraalingen, D.W.G. Van (1989). A simple and universal crop growth simulator: SUCROS87. Simul. Syst. Manag. Crop Prot. / , R. Rabbin. S.A. Ward, H.H. van Laar. 147–181.

Steude, J.S., Hopkins, F., and Anders, J.E. (1994). Industrial X-ray Computed Tomography Applied to Soil Research. In Tomography of Soil-Water-Root Processes, pp. 29–41.

Stevens, W.B., Evans, R.G., Iversen, W.M., Jabro, J.D., Sainju, U.M., and Allen, B.L. (2015). Strip tillage and high-efficiency irrigation applied to a sugarbeet–barley rotation. Agron. J. *107*, 1250–1258.

Tarkalson, D.D., Bjorneberg, D.L., and Moore, A. (2016). Effects of Tillage System and Nitrogen Supply on Sugarbeet Production. J. Sugarbeet Res. *52*, 30–39.

Tisdall, J.M. (1994). Possible Role of Soil-Microorganisms in Aggregation in Soils. Plant Soil *159*, 115–121.

Trudgill, D.L., Squire, G.R., and Thompson, K. (2000). A thermal time basis for comparing the germination requirements of some British herbaceous plants. New Phytol. *145*, 107–114.

Utomo, W.H., and Dexter, A.R. (1981). Tilth Mellowing. J. Soil Sci. *32*, 187–201.

Wilhelm, W.W., Doran, J.W., and Power, J.F. (1986). Corn and Soybean Yield Response to Crop Residue Management Under No-Tillage Production Systems. Agron. J. *189*, 184–189.

de Wit, C.T. (1953). A physical theory on placement of fertilizers.

Wuest, S.B., Albrecht, S.L., and Skirvin, K.W. (2000). Crop residue position and interference with wheat seedling development. Soil Tillage Res. *55*, 175–182.

Zhou, H., Chen, Y., and Sadek, M.A. (2014). Modelling of soil-seed contact using the Discrete Element Method (DEM). Biosyst. Eng. *121*, 56–66.

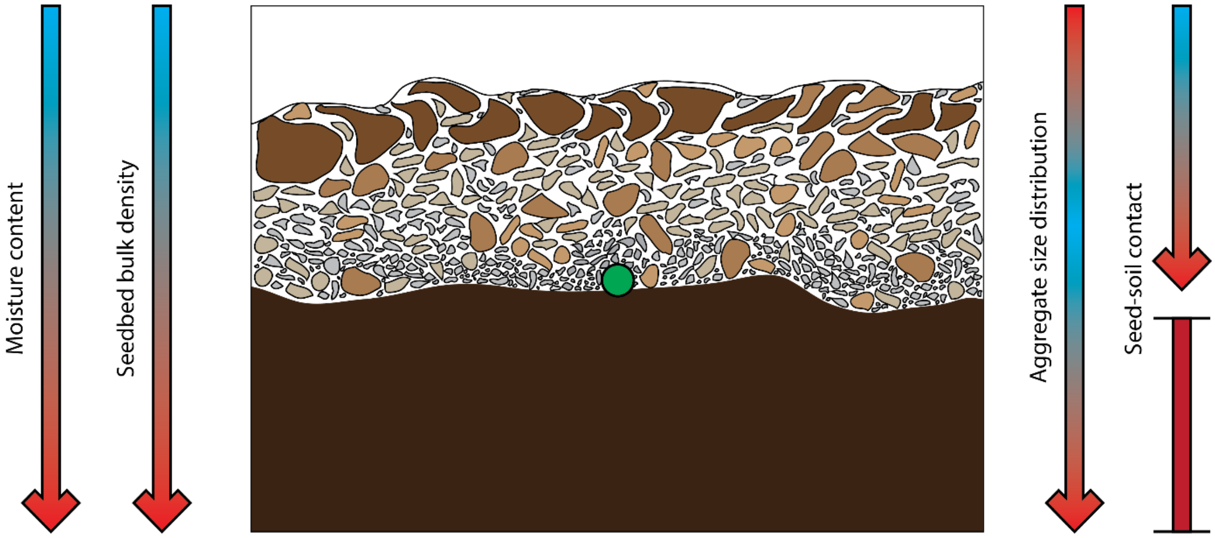

Figure 1: Schematic representation of a typical sugar beet seedbed covering a dense layer. The aggregate size decrease from top to bottom whereas the moisture content increases. Seed-soil contact is high at the lowest point of the seedbed and too high within the dense sublayer due to compaction. The green symbol indicates the ideal positioning of the seed being slightly incorporated into the firm sublayer and in contact with a high abundancy of small aggregates (Adapted from Hakansson et al., 2002).

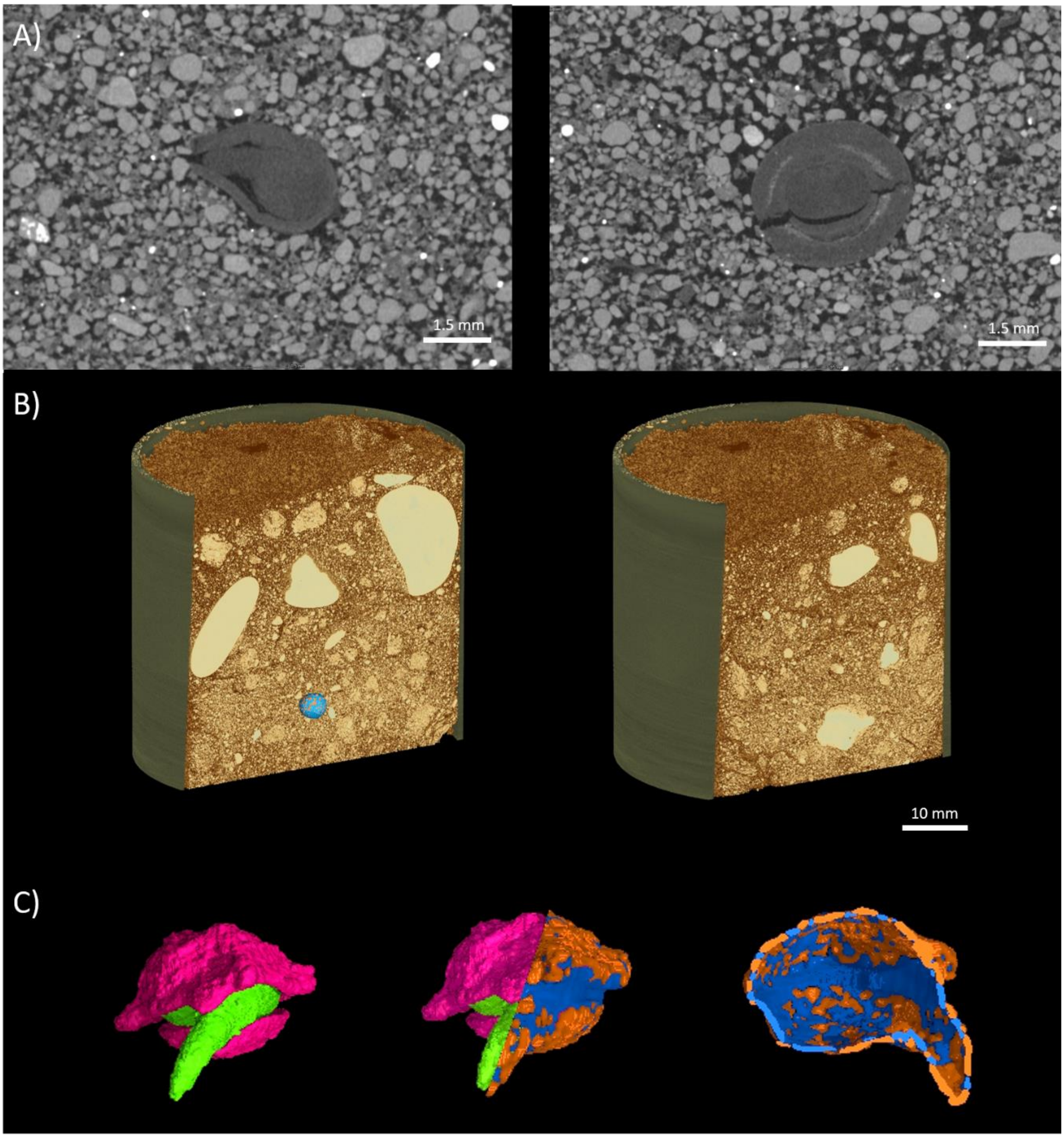

Figure 2: X-ray CT quantification of seedbed properties. A) 2D slice of a naked star-shaped seed and a pelleted and coated round-shaped seed within an artificially created seedbed sieved < 1 mm. B) 3D reconstruction of a pelleted and coated round-shaped seed within a field structured seedbed. C) 3D reconstruction of surrounding soil and air space around a naked star-shaped seed. Pink = Pericarp; Green = Embryo; Orange = Soil; Blue = Air.