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Effect of straight and spiral sugar beet extraction paths and lift acceleration on soil tare and relative soil adherence

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Abstract

The soil tare, *i.e.* the relative amount of soil adhering to sugar beet after harvest, should be reduced to lower the increasing costs of soil disposal and to prevent negative effects on the environment. The loosening up and removal of soil around the beet basically starts upon lifting. Improvement of soil loosening during lifting may be regarded a prerequisite to further increase the effectiveness of cleaning systems on sugar beet harvesters. The soil loosening effects of nine methods of lifting by extraction and one reference treatment were studied by evaluating the net soil tare (on clean beet basis) and the relative soil adherence at the stage between lifting and cleaning of beets produced on marine clay loam soils in 1994 and 1995. In the reference treatment, the beets were dug out carefully. The extraction treatments used were vertical (no spiral), large pitch spiral and small pitch spiral lifting paths at slow, moderate and quick accelerations. The net soil tare was lowest for the quick, small pitch spiral motion: respectively 14% in 1994 and 6% in 1995 for comparable beet properties and normal soil moisture conditions. The relative soil adherence increased significantly with decreasing soil tare. This phenomenon was attributed to the original *in situ* soil adherence: some soil close to the surface of the beet is reinforced by rootlets or is located in surface niches and adheres stronger to the beet. As soil loading during extraction was non-compressive for all extraction treatments, it is highly unlikely that the extraction treatments induced the strong soil adherence at low soil tare.

Keywords: sugar beet, beet lifting, beet extraction, soil tare, soil adherence, harvesting quality

Introduction

The amount of soil adhering to sugar beet after harvest in the Netherlands should be reduced to lower the increasing costs of disposal and to prevent negative effects on the environment. The gross soil tare, *i.e.* the amount of adhering soil in percent of the total mass of beets and soil, is presently about 10% for favourable, 15 to 20% for unfavourable and 35% for extremely unfavourable harvesting conditions on clay soils (Vermeulen, 1995).

Most of the current harvesting systems are very similar: high capacity machinery with shares or discs lifts the sugar beet and various types of mechanical systems clean the beet. Usually, the soil tare does not vary much between these systems, but depends mainly on soil type and soil moisture condition (Duval, 1988; Brunotte *et al.*, 1993), the mean beet mass (Wevers, 1980; Bouma & Cappon, 1988) and the skill of the machine-operator to properly adjust the machine to the prevailing harvesting conditions (Brinkmann, 1986). The highest soil tare occurs on heavy, wet soils, on sugar beet lots with a low mean beet mass. Furthermore, when machinery is adjusted such that the beets are treated very gently, the incidence of beet injury is very low but the soil tare is high (Ditges, 1990).

High soil tare on wet clay soils is attributed to the fact that the cohesion and adhesion tend to increase when the soil is subjected to compression and shear (Vermeulen, 1995). This type of mechanical loading occurs on the soil between lifting share and sugar beet but may also originate from the beet transport or the beet cleaning elements. In the framework of this article, the magnitude of the stresses that cause the soil particles to stick together and to stick to the surface of the beet or to secondary roots will be referred to as soil adherence.

An increase in soil adherence results in a decrease of the effectiveness of cleaning systems (Green, 1957). Thus, drastic improvements in the cleaning effectiveness on conventional harvesters are difficult to achieve without increasing the aggressiveness of cleaning and, thereby increasing damage to the beet. Nevertheless, a soil tare reduction by 20 to 50%, compared with conventional cleaning systems with sieve bars or rotors, has been recently achieved without excessive beet damage by applying axial roller beds combined with brushes or compressed air (Van Der Linden, 1995). To further increase the effectiveness of cleaning systems, a combination of a low quantity of adhering soil and weak soil adherence directly after beet lifting may be regarded a prerequisite.

Removal of beets from the soil with a helical motion (extraction), either by beet pliers (Strooker & De Widt, 1957; Strooker, 1960, 1962) or by experimental beet pullers (Schuh, 1989; Schuh & Höhn, 1991), resulted in a similar soil tare as beet harvesting with conventional machinery with lifting shares. However, the soil adherence was visually observed to be less strong than with conventional lifting shares.

We postulated that soil tare and soil adherence directly after beet extraction may be lowered further by optimizing the beet extraction kinetics, especially the lifting path and the acceleration. Reported here are experiments to determine the effect of straight and spiral sugar beet lifting paths and lift acceleration on soil tare, soil adherence and, less extensively, on other aspects of the harvesting quality of sugar beet, in relation to physical soil and beet properties. Since field methods to characterize the soil adherence have not been reported, a method had to be developed.

Materials and methods

Treatments

Ten treatments with different beet extraction kinetics, including a reference treat-

Table 1. Designation of the extraction treatments.

Lifting path	Vertical acceleration			
	very slow	slow	moderate	quick
No spiral	R	NS1	NS2	NS3
Large pitch spiral	–	LPS1	LPS2	LPS3
Small pitch spiral	–	SPS1	SPS2	SPS3

ment, were applied in the experiments. Each extraction treatment was a combination of a specific lifting path and a vertical acceleration, as presented in Table 1. All ten treatments were applied in 1994, while only the three most interesting treatments, including the reference treament, were applied in 1995.

The previously defoliated beets were extracted by the 'Subitrek'. The Subitrek is a vehicle with an instrumented, hydraulic beet pulling rig mounted in a sub-frame, specially built for these experiments (Figure 1). After steering the Subitrek such that the pulling rig was positioned roughly above a beet, the subframe was lowered to the ground by a hydraulic cylinder. Ground support was necessary to avoid undesired vehicle suspension effects during the beet pulling action. A manual adjustment facility in the subframe was then used to position the pulling rig exactly in vertical line with the centre of the beet crown. The pulling rig consisted of a beet grabber with three teeth, attached both to a vertical hydraulic cylinder and a hydraulic motor

Figure 1. The mobile experimental beet puller 'Subitrek'.

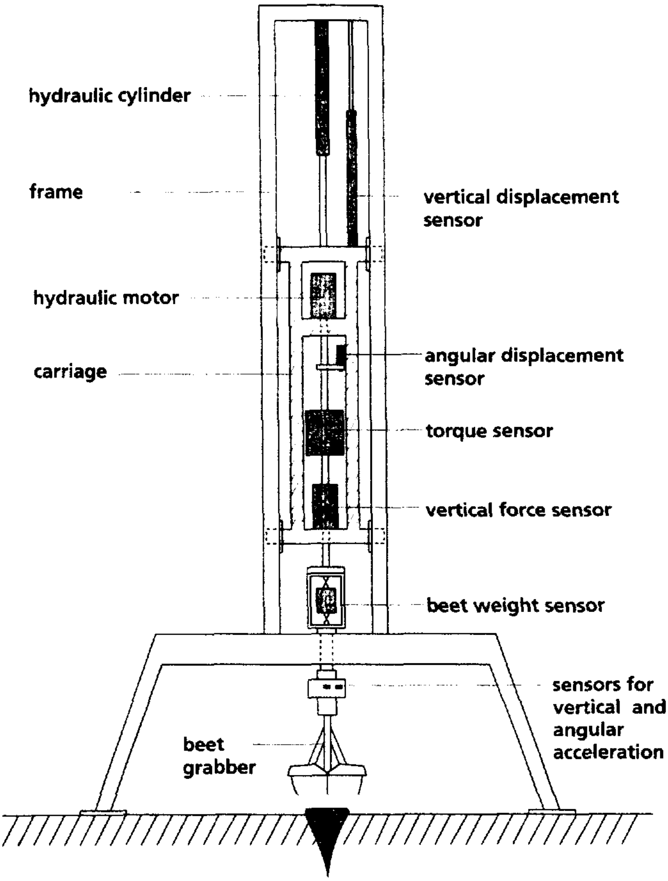

Figure 2. Schematic drawing of the pulling rig.

(Figure 2). Beet grabbing was controlled manually. First, the orifices regulating the oil flow to the hydraulic cylinder and the hydraulic motor, and thus the vertical and rotational accelerations, were adjusted. After fine positioning and lowering of the grabber to the correct grabbing height the grabber was closed. Hereafter control was taken over by a computer. The pull motion was started by opening of hydraulic valves. At the same time data acquisition to characterize the pull dynamics of the beet was started. In 1994, these measurements included time, vertical displacement, vertical pulling force, angular displacement and torque. Vertical and angular acceleration measurements were added in 1995. The sampling time interval was 0.35 ms for quick, 0.81 ms for moderate and 1.89 ms for slow vertical acceleration. In all cases the total sampling time exceeded the duration of the lift action. Since the system characteristics for the vertical and the angular motion were not completely synchronised, the lifting paths designated as 'spiral' were not purely spiral, but started with a pitch smaller than the final, constant pitch. Within an extraction treatment, both the lifting path and the vertical acceleration varied slightly because of the differences in vertical and angular resistance of each individual beet to break loose from the soil. Likewise, a zero-load extraction and a real beet extraction differ in acceleration characteristics. The kinetic characteristics were determined by signal processing, using a GENSTAT procedure. The average kinetic characteristics, based on measurements in 1995, are presented in Table 2.

The reference treatment (R) implied careful digging of 25 cm deep trenches on both sides of the beet row. The trench walls nearest to the beet row were located at a distance of about 15 cm from the centre of the beet row. Thereafter, the beet was lifted by the Subitrek at the lowest possible extraction speed (0.1 m s^{-1}). The avoidance of compressive and shear forces on the soil close to the beet surface in the R treatment was assumed to result in a soil adherence equal to the adherence before extraction.

Considerations for the experimental design

A pre-investigation with 30 beets, extracted from a small area in 1993 showed that the soil tare of individual, extracted beets had a coefficient of variation of about 33%. Due to this variability, it was expected that about 135 beets would be required per treatment to detect differences of interest at a significance level of 0.05. When the lifting capacity is limited and many treatments are to be compared, as in this experiment, this presents a problem. Much of the variance of soil tare and other harvesting qualities after a specific extraction treatment may be explained by the geometrical properties of the beet itself, the position of the beet in the soil and the properties of the soil surrounding the beet. In order to reduce the residual variance, a number of these properties were measured to be used as covariables in statistical analysis. The smallest experimental unit was thus chosen to be an individual beet. Provided that part of the variance is explained by the covariables, a lower number of

Table 2. Average kinetic characteristics of the extraction treatments.

Treatment	Vertical motion				Angular motion				p_f
	t_a	a_{av}	a_{max}	v_f	t_α	α_{av}	α_{max}	ω_f	
R	–	–	–	0.10	–	–	–	–	–
NS1	0.139	2.7	7.4	0.33	–	–	–	–	∞
NS2	0.147	5.2	18.0	0.74	–	–	–	–	∞
NS3	0.197	7.2	32.0	1.38	–	–	–	–	∞
LPS1	0.140	2.6	7.0	0.32	0.102	38	99	3.5	0.57
LPS2	0.140	5.3	18.1	0.73	0.078	114	349	8.3	0.55
LPS3	0.169	8.4	33.8	1.40	0.063	289	929	17.6	0.50
SPS1	0.120	2.9	7.8	0.32	0.088	90	239	7.5	0.27
SPS2	0.124	5.8	19.1	0.71	0.068	265	835	17.2	0.26
SPS3	0.183	7.7	36.2	1.39	0.052	642	2127	31.7	0.27

t_a = vertical acceleration time (s); a_{av} = average vertical acceleration (m s^{-2}); a_{max} = maximum vertical acceleration (m s^{-2}); v_f = final vertical speed (m s^{-1}); t_α = angular acceleration time (s); α_{av} = average angular acceleration (rad s^{-2}); α_{max} = maximum angular acceleration (rad s^{-2}); ω_f = final angular speed (rad s^{-1}); p_f = final pitch (m) beets will be required to detect differences between the results of extraction treatments. Another way to reduce the variance is to restrict the domain. The domain of choice was the variety Univers, clay loam topsoils, naturally-occurring conditions and management practices common in the Netherlands.

In principle, random effects and effects of the soil and beet properties may occur in the following strata: year, *e.g.* due to the field properties, climatic conditions or management practices; time in the season, *e.g.* due to the average soil moisture status of the field or the physiological development stage of the sugar beet crop; specific locations on the field, *e.g.* due to variation in soil fertility, soil texture, soil structure, soil water balance or soil moisture status during extraction; and individual beet, *e.g.* due to genetic variation or infestation. To measure in a practically relevant range of these many sources of variation, the extraction treatments were replicated for a number of individual beet, in time and on several locations in the field.

Experimental design

The experiments were carried out on 11 test days in 1994 and on 9 days in 1995, equally spaced over the harvesting seasons. Location specific variation was assumed to be low at small distances and high at large distances. It was impracticable to replicate all treatments within a test day at random over the field. Therefore, one block was harvested on each test day. This block was subdivided into three sub-blocks in which the soil properties were assumed to show little variation. Within each sub-block 40 beets were extracted, 4 per treatment in 1994. In 1995, each sub-block contained 12 beets, 4 per treatment on three days and 30 beets, 10 per treatment on the other six days.

Field and crop characteristics

The experimental fields were situated near Slootdorp (Wieringermeer Polder, northwestern part of The Netherlands). Mean annual rainfall at this location is 810 mm. The topsoil is clay loam (Anon., 1951). Analytical data of the topsoils in 1994 and 1995 are given in Table 3.

The total soil porosity was determined once per season by taking twenty core samples in the layers 0–5, 5–10, 10–15, 15–20 and 20–25 cm randomly over the field. Data on total porosity are given in Table 4.

Table 3. Topsoil (0–25 cm) characteristics of the experiment fields in 1994 and 1995.

Year	Particle size range (% of mineral parts, *m/m*)			$CaCO_3$ (%, *m/m*)	pH (KCl)	Organic matter[1] (%, *m/m*)
	clay (< 2 μm)	silt (2–50 μm)	sand (> 50 μm)			
1994	34–48	37–42	9–27	9.9	7.1	1.7
1995	41–50	39–42	8–19	13.4	7.4	1.3

[1] Istscherekov-elementary.

Table 4. Total soil porosity (%, v/v) of the experiment fields in 1994 and 1995 (se = 0.6).

Year	Depth (cm)				
	0–5	5–10	10–15	15–20	20–25
1994	–	57.1	58.8	59.7	59.5
1995	55.2	55.2	55.7	55.8	56.2

The fields were mouldboard-ploughed in the autumn of the year preceding the experiment. A seedbed was prepared in spring using a low ground pressure tractor and a rotary harrow, working at an average depth of 2.5 cm. Seed of *Beta vulgaris* L. (variety Univers) was sown with a precision drilling machine at 50 cm distance between rows and 18 cm distance in the row. The working width of the sowing machine was 12 m (gantry) in 1994 and 6 m in 1995. The plant density after germination was 80,000 plants ha^{-1} in 1994 and 81,200 plants ha^{-1} in 1995. Rows which were free of wheel ruts from sowing or crop protection operations on either side of the row were selected for the experiment.

Characterization of the soil surrounding the beet

The initial cohesion and adhesion just before extraction and the effect of mechanical loading on these properties are the most likely determinants of the amount of adhering soil and the soil adherence just after extraction (Gill & Vanden Berg, 1967; Kalachev, 1974; Zadneprovskii, 1975; Chancellor, 1994). Cohesion and adhesion are reported to depend on the soil composition, in particular the type and fraction of clay particles, the soil structure and the soil moisture content (Söhne, 1953; Fountaine, 1954; Payne, 1956; Domzal, 1970; Nikolaeva and Bakhtin, 1975; Hendrick and Bailey, 1982; Salokhe *et al.*, 1993; Tong *et al.*, 1994).

The soil moisture content (m_d in % m/m, d.b.) was determined per sub-block in the layers 0–5, 5–10, 10–15, 15– 20 and 20–25 cm. Seven samples were taken at random per layer, at a distance of 25 cm from the beet row, directly after extraction. The samples were pooled to one sample per depth.

The experimental fields were selected and managed such that the soil texture and structure differed as little as possible in each year, so that the soil would be mainly characterized by its soil moisture content. Nevertheless, the soil moisture content showed large variation between sub-blocks. Therefore the soil moisture content alone was not considered a suitable characteristic of the soil on the test day and was replaced by two new parameters. The first parameter was a reference moisture content to account for differences in moisture content due to the local soil texture and intra-aggregate structure. The moisture content of aggregates, equilibrated at a soil water matric potential of −10 kPa (pF2) was taken as this reference moisture content (m_r in % m/m, d.b.). Soil samples collected at random from the top 5 cm of the soil on 3 locations in each sub-block were used to determine m_r. These samples were stored until the end of the season and analysed all at the same time. After air drying of the samples in a thin layer, cylinders were filled with the 3.4–5.0 mm aggregate fraction. The aggregates were slowly saturated on a sand box, then drained to a soil water matric potential of −10 kPa for two days and, finally, analysed.

The second parameter was the deviation of the moisture content from m_r, called the differential moisture content, which accounts for differences in moisture content due to the temporal moisture condition of the soil. The differential moisture content (Δm in % *m/m*, d.b.) was defined as $m_d - m_r$.

Characterization of the individual beet

The parameters measured to characterize the geometry of each individual beet (Figure 3) included the height of the untopped beet above the soil surface (h in mm), the length of the untopped beet excluding the flexible part of the taproot (l_b in mm), the cap height (l_c in mm), the length of the topped beet ($l = l_b - l_c$ in mm), the underground length ($l_u = l_b - h$ in mm) and the largest diameter (d in mm). In addition the clean mass of the topped beet (w_b in kg), the clean mass of the beet cap (w_c in kg), the mass of the untopped beet ($w = w_b + w_c$ in kg) and the number of secondary roots with a basal diameter of 20 mm or more were determined. Assuming a pure conical beet shape, the diameter at the soil surface (d_s in mm), the soil-beet contact area (S in dm^2) and the specific soil-beet contact area (S_s in $dm^2\ kg^{-1}$) were estimated by:

$$d_s = \frac{l_u}{l} * d \qquad (1)$$

$$s = \frac{\pi}{100} * \frac{d_s}{2} * \sqrt{(\frac{d_s}{2})^2 + l_u^2} \qquad (2)$$

$$s_s = \frac{s}{w_b} \qquad (3)$$

Measurement of net soil tare

The net soil tare (*NT*) is defined as the percentage of adhering soil on the basis of the mass of the clean, topped beet. The dirty, untopped beet mass directly after lifting was measured when the beet was still in the grabber by a weighing facility built in the Subitrek. After cleaning the beet with a high pressure water cleaner and topping the beet by hand, the beet cap and the topped beet were weighed in the laboratory. To account for the mass of the adhering water after cleaning, the mass of the topped beet and the beet cap was multiplied by a factor 0.986 and 0.955, respectively, to calculate the proper clean mass.

Measurement of soil adherence

The term soil adherence was introduced to indicate the magnitude of the stresses that cause the soil particles to stick together and stick to the surfaces of the beet or the

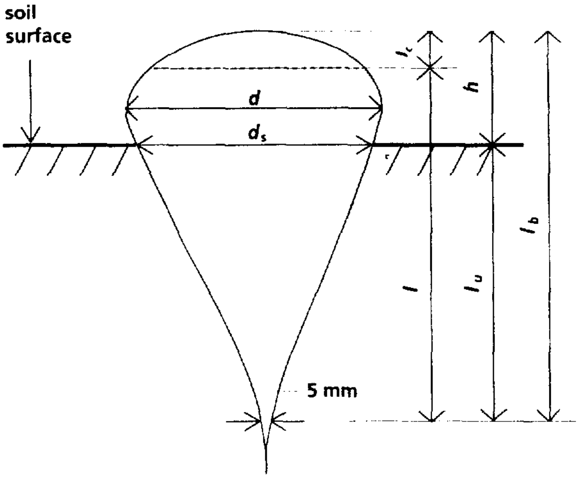

Figure 3. Parameters used to characterize the geometry of individual beets.

secondary roots. In principle, these compound stresses could be characterized by measuring the total energy required to remove all soil from the beet surface. However, the measurement of this energy presents a number of practical problems. Few methods are suitable to remove all soil from the beet surface and the energy required for cleaning depends on the efficiency of the method used. This hurdle can be partly taken by adopting a 'standard' cleaning method, to enable relative comparisons. Another complication is that not all soil surrounding the beet adheres equally strongly. Part of the tare soil may adhere very strongly, for instance because it is located in niches on the beet surface or is reinforced by rootlets. Therefore, the total energy requirement for cleaning may be mainly determined by the (surplus) energy required to remove the most sticky soil fraction and may not reflect the adherence of the major part of the soil.

To circumvent this problem the soil adherence was not characterized by the energy to remove all soil from the beet but by the remaining soil fraction after a specified cleaning treatment. This cleaning treatment was chosen such that virtually no soil was removed from beets that were lifted and cleaned in a conventional manner from wet, sticky clay soil. The remaining soil fraction after the specified cleaning treatment was considered a good indicator for the relative soil adherence (*RSA*). Notably, when all soil remains, *RSA* has the value 1, and when no soil remains *RSA* has the value 0. *RSA* was calculated as:

$$RSA = NT_s / NT \quad (4)$$

where

NT_s = strongly adhering net soil tare, remaining after a 'standard' cleaning treatment in % *m/m*, dry basis,

NT = net soil tare before the 'standard' cleaning treatment in % *m/m*, dry basis.

To prevent that the soil adherence would increase because of the cleaning itself, as could happen in the case of a mechanical cleaning method, a cleaning method with compressed air was adopted. The 'standard' cleaning treatment consisted of directing compressed air to the surface of the beet from 16 orifices, 2 mm in diameter and 20 mm apart, drilled in a tube. The tube was placed such that the orifices were at a distance of approximately 60 mm from the beet surface (Figure 4). While rotating the beet round its length axis at 60 rpm in the grabber, the tube was pressurized (500–550 kPa) during one revolution of the beet.

Measurement of tip losses, skin damage and crown fractures

The tip loss (TL in % m/m), caused by fracture of the tap root, was estimated for each beet from the tip fracture surface diameter (d_f in mm) and the beet diameter (d in mm). The relationships between TL, d_f and d were established by measuring TL of tap root sections cut off at d_f = 40, 60 and 80 mm from beets with known properties, 314 beets in 1994 and 567 beets in 1995. Only beets with a single taproot were used for these assays. Data with a TL exceeding 30% were omitted. The data were transformed to the arithmetic scale and analysed by linear regression:

$$\ln (TL) = C + a \ln (d_f / d) \quad (5)$$

Values found for C and a were respectively 3.796 (se = 0.013) and 2.295 (se = 0.029) in 1994 and 3.491 (se = 0.017) and 2.064 (se = 0.022) in 1995. Equation 5 explained 86% of the total TL variation in 1994 and 84% in 1995.

Each beet was examined for damage of the outer surface of the beet. The surface area of each damaged spot was estimated visually. Skin damage clearly caused by other factors than the beet lifting action were not taken into account.

The number of beets showing crown fracture caused by the beet grabber was counted per extraction treatment.

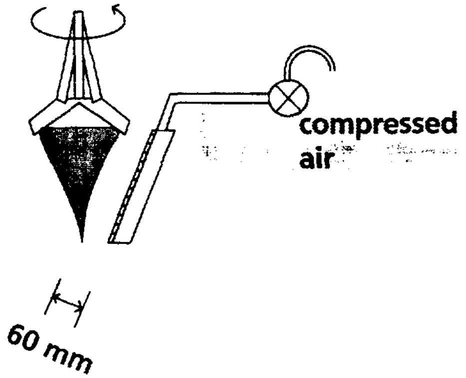

Figure 4. Schematic drawing of the standard cleaning equipment.

Statistical analysis

Effects of the extraction treatments on *NT* and *RSA* were analysed with generalized linear mixed models, employing inferential procedures described by Engel & Keen (1994). Because the number of treatments differed in 1994 and 1995, the results of both years were analysed separately. The measured soil and beet variables were considered as covariables in the models. The variable time in the season (in days from the beginning of the harvesting period) was considered as a fixed effect in the models. However, the effects of Δm and time in the season could not be distinguished because Δm was positively correlated with time in both years. Therefore, the variable time in the season was removed from the model, assuming that the effects in time were caused by the changes in soil and beet properties. The factor subblocks within blocks was entered as a random effect with corresponding component of variance. The estimation procedure approximated maximum likelihood assuming a gamma distribution for the residuals. Calculations were performed with the IRREML procedure (Keen, 1994) written in the statistical programming language Genstat 5 (Anon., 1993). The selection of predictors in the model was performed on the basis of best fit, mutual independence of the predictors and significance of the predictor effects.

The models obtained for individual beets were used to calculate the expected harvesting quality of a reference beet lot for various circumstances. This reference beet lot was arbitrarily chosen to contain beets with properties equal to all those lifted in our beet experiments in 1995. The relevant characteristics of the reference beet lot are presented in Table 5.

Due to the low occurrence of tip fractures and skin damage, the number of data pertaining to these harvesting qualities was insufficient for statistical analysis.

Table 5. Distribution of the number of beets, the total mass and the specific soil-beet contact area (S_s) of the reference beet lot over the beet mass and shape classes.

Mass class (kg/beet)	Number of beets		Mean beet mass (kg)	Fraction of total mass		Median S_s (dm^2 kg^{-1})
	normal	fanged		normal	fanged	
< 0.50	135	31	0.41	0.024	0.005	4.2
0.50–0.75	287	105	0.63	0.078	0.029	3.4
0.75–1.00	293	125	0.88	0.110	0.047	3.0
1.00–1.25	262	97	1.12	0.126	0.047	2.7
1.25–1.50	195	93	1.38	0.116	0.055	2.4
1.50–1.75	123	65	1.61	0.085	0.045	2.2
1.75–2.00	83	39	1.87	0.067	0.031	2.1
2.00–2.25	46	29	2.11	0.042	0.026	2.0
> 2.25	40	20	2.57	0.044	0.022	1.8
All beets	1464	604	1.12	0.692	0.307	2.7

Results

Net soil tare

It was concluded from statistical analysis of the data (Appendix 1) that the extraction treatments, the differential moisture content (Δm in % *m/m*, d.b.), the specific soil-beet contact area (S_s in $dm^2\ kg^{-1}$) and the beet shape (normal or fanged) had a significant effect ($P < 0.05$) on the net soil tare (*NT*) of an individual beet. Other measured variables were not included in the statistical model because they were strongly related to one of the factors in the final model or because the effect was not significant.

The *NT* for a large beet (low S_s) was much lower than for a small beet (high S_s). Increasing S_s by a factor 2 resulted on average in a 1.4 times higher *NT* (Figure 5). The *NT* of fanged beets was higher than the *NT* of normal beets, respectively by a factor 1.5 in 1994 and 1.2 in 1995.

The measured *NT* data for the various extraction treatments in 1994 and 1995 were converted to values for the reference beet lot (NT_r) at three levels of Δm by model calculation (Table 6). In both years, increasing the vertical acceleration from very slow (treatment R) to quick resulted in a continuous reduction of NT_r by a factor 2 (for treatment NS3). Lowering the pitch from infinite (reference: treatment R) to 0.27 m resulted in a systematic reduction of NT_r by at least a factor 3 (for treatment SPS1 in 1994). The combined use of high vertical acceleration and small pitch (treatment SPS3) led to a NT_r reduction factor of 6 and 8 for 1994 and 1995, respectively, when compared with treatment R. NT_r increased when the soil became wetter, irrespective of year and extraction treatment. Beets extracted from wet soil (Δm = 5%) had about 1.5 times as much soil tare as beets extracted from dry soil (Δm = –4%).

Although estimated for comparable soil moisture conditions and beet properties in both years, NT_r appeared to be 1.6 to 2.3 times higher in 1994 than in 1995.

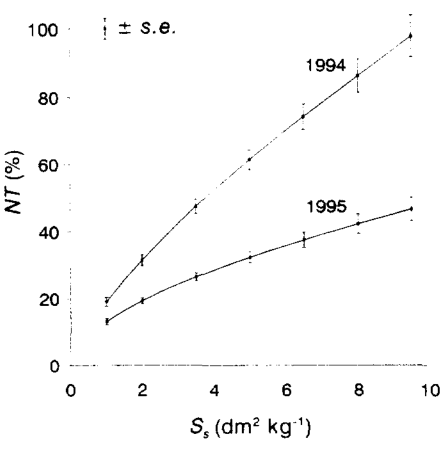

Figure 5. Relationships between the net soil tare (*NT*) and the specific soil-beet contact area (S_s) in 1994 and 1995 for extraction treatment NS3, normal soil moisture conditions (Δm = 0.5) and normally shaped beets.

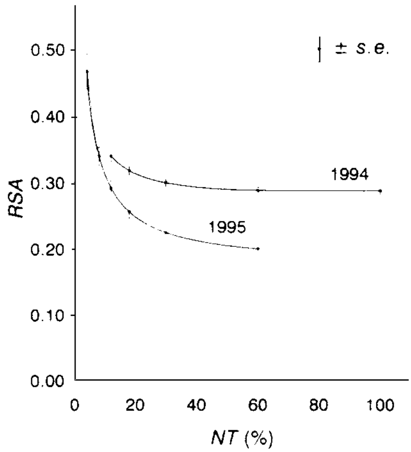

Figure 6. Relationships between the relative soil adherence (*RSA*) and the net soil tare (*NT*) in 1994 and 1995 for the reference beet lot.

Relative soil adherence

It was concluded from statistical analysis of the data (Appendix 2) that the net soil tare (*NT*) and the specific soil-beet contact area (S_s) had a significant effect ($P <$ 0.01) on the relative soil adherence (*RSA*) of an individual beet. Other measured variables were not included in the statistical model because they were strongly related to one of the factors in the final model, because the effect was not significant (P < 0.05) in both years or because the effect was inconsistent between years.

RSA increased progressively when *NT* decreased, irrespective of the extraction treatment (Figure 6). This effect became substantial when *NT* became lower than about 30%.

An increase of S_s by a factor 2 resulted in a decrease of the *RSA* by a factor 0.9. Thus, the *RSA* for a large beet (low S_s) was stronger than the *RSA* for a small beet (high S_s). An example of the relationships between *RSA* and S_s in 1994 and 1995 is shown in Figure 7 for normal beets with a net soil tare of 10%.

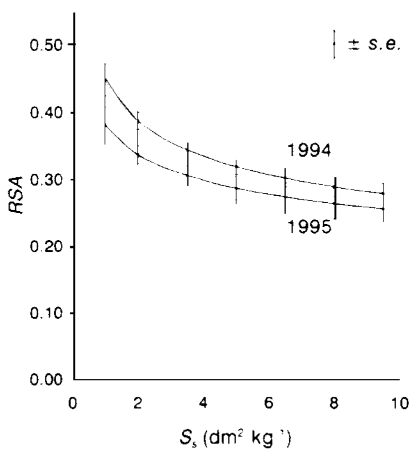

Figure 7. Relationships between the relative soil adherence (*RSA*) and the specific soil-beet contact area (S_s) in 1994 and 1995 for normally shaped beets and a net soil tare of 10%.

Table 6. Measured net soil tare (*NT*, % *m/m*, dry basis) and net soil tare calculated for 'standard' beet properties and soil conditions (NT_r) for the extraction treatments in 1994 and 1995.

Treatment	1994				1995			
	measured[1]	calculated [3]			measured [2]	calculated [3]		
		dry	normal	wet		dry	normal	wet
R	101.1	66.0	84.5	108.4	49.5	41.5	49.9	60.0
NS1	85.2	49.9	64.0	82.0				
NS2	77.9	48.5	62.1	79.6				
NS3	56.2	34.4	44.0	56.4	24.1	19.8	23.8	28.6
LPS1	59.1	34.7	44.4	57.0				
LPS2	42.9	26.7	34.2	43.8				
LPS3	32.1	17.4	22.3	28.6				
SPS1	39.9	22.4	28.7	36.8				
SPS2	28.6	16.1	20.6	26.4				
SPS3	19.4	10.7	13.8	17.6	6.0	5.3	6.4	7.7

[1] Median net soil tare (averaged on arithmetic scale) for the individual beet per treatment; mean Δm = 1.2 %; median S_s = 3.4 dm^2 kg^{-1} (mean beet mass = 1.04 kg); 27 % of beets fanged. Coefficient of variation of *NT* = 0.05.

[2] Median net soil tare (averaged on arithmetic scale) for the individual beet per treatment; mean Δm = –0.9 %; median S_s = 2.5 dm^2 kg^{-1} (mean beet mass = 1.17 kg); 34 % of beets fanged. Coefficient of variation of *NT* = 0.04.

[3] Predicted net soil tare for the reference beet lot per extraction treatment and for differential soil moisture contents (Δm , in % *m/m*, d.b.) of –4 (dry soil), 0.5 (normal soil) and 5 (wet soil). Reference beet lot (Table 5): median S_s = 2.7 dm^2 kg^{-1}; (mean beet mass = 1.12 kg); 29 % of beets fanged. Coefficient of variation of *NT* = 0.13.

Total effect of extraction treatments on the soil surrounding the beet in situ

The total soil loosening effect of the extraction treatments may be evaluated by the fate of the amount of strongly adhering soil prior to beet extraction, here represented by the strongly adhering net soil tare of treatment R (NT_s(R)). During a specific extraction treatment (X), a fraction of this soil (ϕ_l) was loosened and removed by gravitational forces, a fraction (ϕ_w) was converted to weakly adhering soil and a fraction

Table 7. Total number of beets extracted (*n*) and crown fracture (*CF*, % of *n*) per extraction treatment in 1994 and 1995.

Year	Extraction treatment									
		NS1	NS2	NS3	LPS1	LPS2	LPS3	SPS1	SPS2	SPS3
1994	*n*	128	132	177	131	131	132	131	129	172
	CF	0	2.3	4.0	0.8	6.1	6.8	5.3	4.6	12.2
1995	*n*			216						389
	CF			0.9						12.3

(ϕ_s) remained strongly adhering. The soil fractions belonging to these adherence classes after the various extraction treatments were calculated as:

$$\phi_l = 100 - \phi_s - \phi_w \quad (6)$$

$$\phi_w = 100 * \frac{NT(X)}{NT_s(R)} - \phi_s \quad (condition: \frac{NT(X)}{NT_s(R)} \leq 1) \quad (7)$$

$$\phi_w = 100 * \frac{RSA(X) * NT(X)}{NT_s(R)} \quad (8)$$

The total soil loosening effect was characterized by the sum of the fractions ϕ_l and ϕ_w. The loosening up of soil around the beet was most effectively performed by treatment SPS3 (Figure 8), being the treatment with the highest extraction acceleration and smallest pitch.

Tip loss, skin damage and crown fracture

The highest mean tip loss per year was 0.5% for treatment SPS3 in 1995, which is very low compared to about 3.5% tip loss found for conventional harvesters (Anon., 1996). Therefore, analysis of the tip loss differences between treatments was considered of little relevance.

Every beet showed three very small damaged spots where the grabber teeth had entered the beet. None of the treatments showed any further skin damage as a result of the extractions.

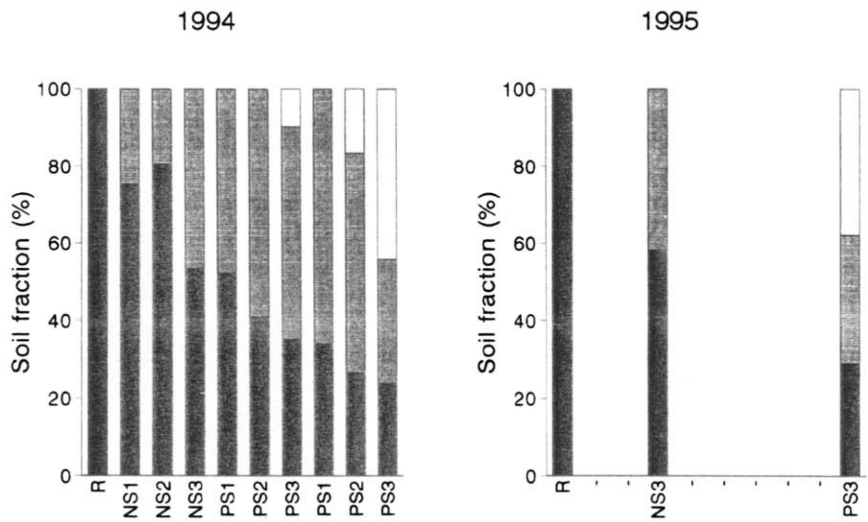

Figure 8. The amount of soil in the adherence classes strong (■), weak (■) and none (□) (removed soil) after the various extraction treatments, expressed in % *m/m* of the amount of strongly adhering soil of treatment R in 1994 and 1995. The data pertain to the reference beet lot and normal soil moisture conditions (Δm = 0.5).

In some cases crown fracture clearly happened because of the excessive extraction forces associated with beets that were severely fanged or had grown crooked. In few cases the crown already started to crack when the grabber teeth entered the beet. However, in most cases crown fracture must have been caused by the extraction and acceleration forces required for beets with a normal shape. Crown fracture tended to increase with increasing vertical acceleration and with a lowering of the pitch (Table 7). Thus, crown fracture was highest for treatment SPS3.

Discussion

The use of soil and beet properties as covariables in the statistical analysis increased the precision of *NT* estimation. This sophistication appeared to be superfluous for the purpose of detecting *NT* differences between extraction treatments in this experiment. Even without accounting for the variation due to soil and beet properties *NT* differences between extraction treatments were all statistically significant ($P < 0.05$) within years. Apparently, the total sample size per year (ca 150 and ca 210 beets per treatment in 1994 and 1995, respectively) was sufficiently large to average out most of the differences due to the individual beet properties and the condition of the soil surrounding the beet. When comparing *NT* values from various locations and beet lot properties, the statistical model used in this experiment might explain a significant part of the variation.

Extraction treatment, differential moisture content, specific beet-soil contact area and beet shape were identified as factors with a significant effect on *NT* (Appendix 1). Statistical models with these factors, derived for each year of the experiment, were used to calculate *NT* for 'standard' beet properties and soil conditions (Table 6). The big differences in *NT* found between 1994 and 1995 were only partly explained by the predictors in the models, indicating that other non-measured soil and beet properties were responsible for the differences found for 'standard' conditions between years. The visually-observed fact that the soil was much more friable in 1995 than in 1994 might explain why *NT* and *RSA* were so much lower in 1995 despite the slightly heavier texture of the soil. Therefore it is suggested that the effect of soil factors that may influence the friability of the soil, such as texture, structure, moisture history, type of clay and possibly the cationic species on the adsorption complex needs further investigation. Some beet properties that were not measured or could not be analysed in these experiments but may explain some of the variation between years are groove depth, the number and location of rootlets on the beet and smoothness of the skin.

Because of their strong relationship, extraction treatment and *NT* were exchangeable predictors in the models considered for statistical analysis of the *RSA* data. Therefore, one of these predictors had to be chosen. For two reasons *NT* was selected for the models on *RSA*. Firstly, it is well known that tare soil is increasingly difficult to remove as the soil tare decreases. Secondly, there is no reason to suspect that the extraction treatments associated with a low *NT* would increase the *RSA* of the soil adhering to the beet after the treatment because the soil loading was of a very similar, non compressive type for all treatments. Notably, the data presented in Figure 8 suggest that the extraction treatments caused systematic loosening of part of the soil (ϕ_w) that adhered to the beet after extraction. In further studies, the separate effects of the extraction treatments and *NT* on *RSA* might be detected by comparing the relationships between *RSA* and *NT* for each extraction treatment with a true 'virgin' soil adherence curve, which is determined independent from the extraction method. Such a virgin soil adherence curve might be estimated by measuring *RSA* after repeated standard cleaning of carefully dug out beets.

Practical implications

The results show a good potential for obtaining low soil tare of sugar beet on clay soil by combining a high average vertical extraction acceleration (a_{av}) and a spiral extraction path with a small pitch (p_f). The net soil tare found for extraction treatment SPS3 (a_{av} = 8 m s^{-2}, p_f = 0.27 m) was 5.3 to 17.6% for the reference beet lot and a representative range of soil moisture conditions (Table 6). Since 55 to 75% of the tare soil after treatment SPS3 adhered weakly, it may be expected that further cleaning of the beets can be performed efficiently.

Tip losses and surface damage were low, irrespective of the extraction kinetics. However, crown fracture, which leads to a total loss of the beet, was unacceptably high when extracting with high a_{av} and small p_f. Roughly estimated, a_{av} should be lower than 5 m s^{-2} and p_f should exceed 0.55 m to prevent excessive crown fracture losses (>3.5%) for the grabber design used. However, these conditions would severely restrict the potential to reach low *NT*.

Practical application of a quick, small pitch extraction motion will require the selection of a technique to transfer the required extraction and acceleration forces to the beet with a low incidence of crown fracture and a work capacity competing with currently used share lifters.

The application of individual beet grabbing, as described in this paper, needs complex engineering development and meeting the high capacity demands is problematic. Therefore, the potential for practial application of indiviual beet grabbing is considered low on a short term, as also suggested by Schuh & Höhn (1991).

The extraction motion of a driven rotary-shoe lifter shows similarity with the quick, small pitch extraction motion used in treatment SPS3. This lifter was used succesfully in Dutch agricultural practice as long ago as 50 years. Therefore, it is suggested that the lifting principle of the driven rotary-shoe lifter might provide a practical means to achieve low *NT* and low *RSA*.

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Appendix 1. Statistical analysis of the data on net soil tare

The statistical model for the expected ln(*NT*) of individual beets was:

$$E\ \ln(NT) = C + F_{et} + a(\Delta m - \Delta\bar{m}) + b(\ln(S_s) - \overline{\ln(S_s)}) + F_{sh}$$

Description and estimated values and standard errors for the parameters in models for ln(*NT*)

Para-meter	Description	Values and standard errors[1] 1994 estimate	1994 *se*	1995 estimate	1995 *se*
C	constant	4.538	0.047	3.781	0.050
F_{et}	factor for treatment R	0.000	0.065	0.000	0.055
	factor for treatment NS1	−0.278			
	factor for treatment NS2	−0.308			
	factor for treatment NS3	−0.652		−0.741	
	factor for treatment LPS1	−0.643			
	factor for treatment LPS2	−0.906			
	factor for treatment LPS3	−1.331			
	factor for treatment SPS1	−1.079			
	factor for treatment SPS2	−1.412			
	factor for treatment SPS3	−1.815		−2.051	
Δm	differential soil moisture cont. (% *m/m*, dry basis)				
a	coefficient for Δm	0.055	0.004	0.041	0.008
$\Delta\bar{m}$	weighted mean of Δm	1.229		−0.867	
$\ln(S_s)$	ln (specific beet-soil contact area ($dm^2\ kg^{-1}$))				
b	coefficient for $\ln(S_s)$	0.727	0.043	0.563	0.052
$\overline{\ln(S_s)}$	weighted mean of $\ln(S_s)$	1.236		0.931	
F_{sh}	factor for normal beet shape[2]	0.000	0.033	0.000	0.049
	factor for fanged beet shape	0.433		0.199	

[1] the standard errors of factor values refer to the standard error of differences.

[2] the effect of the number of taproots on *NT* appeared to be significant only between one taproot and more taproots ($P < 0.05$). Therefore, this predictor was introduced in the model as the factor 'shape' having the values 'normal' and 'fanged'.

Appendix 2. Statistical analysis of the data on relative soil adherence

The statistical model selected for the expected ln(*RSA*) of individual beets was:

$$E\ lnRSA = C + a(\ln NT - \overline{\ln NT}) + b((\ln NT)^2 - (\overline{\ln NT})^2) + c(\ln(S_s) - \overline{\ln(S_s)})$$

Description and estimated values and standard errors for the parameters in models for ln(*RSA*)

Parameter	Description	Values and standard errors 1994		1995	
		estimate	*se*	estimate	*se*
C	constant	−1.216	0.013	−1.226	0.038
$\ln NT$	ln (net soil tare) (*NT* in % *m/m*, clean basis)				
a	coefficient for $\ln NT$	−0.438	0.101	−0.707	0.087
$\overline{\ln(NT)}$	weighted mean of $\ln NT$	3.713		2.810	
$(\ln NT)^2$	(ln (net soil tare))^2 (*NT* in % *m/m*, clean basis)				
b	coefficient for $(\ln NT)^2$	0.051	0.014	0.072	0.016
$\overline{\ln(NT^2)}$	weighted mean of $(\ln NT)^2$	14.47		9.03	
$\ln(S_s)$	ln (spec. beet-soil contact area) (S_s in $dm^2\ kg^{-1}$)				
c	coefficient for $\ln(S_s)$	−0.211	0.036	−0.177	0.048
$\overline{\ln(S_s)}$	weighted mean of $\ln(S_s)$	1.236	0.931		

List of abbreviations

α_{av}	average angular acceleration in rad s^{-2}
α_{max}	maximum angular acceleration in rad s^{-2}
Δm	differential moisture content ($m_d - m_r$) in % on dry mass basis
ϕ_l	mass fraction of Nt_s(R) that was loosened by the extraction treatment and removed by gravity forces (in %)
ϕ_s	mass fraction of Nt_s(R) that was converted to weakly adhering soil by the extraction treatment (in %)
ϕ_w	mass fraction of Nt_s(R) that remained strongly adhering during the extraction treatment (in %)
ω_f	final angular speed in rad s^{-1}
a_{av}	average vertical acceleration in m s^{-2}
a_{max}	maximum vertical acceleration in m s^{-2}
CF	crown fracture in % fractured beets of the total number beets
d	largest beet diameter in mm
d.b.	on the basis of dry material
d_f	tip fracture surface diameter in mm
d_s	beet diameter at the soil surface in mm
h	height of the untopped beet above the soil surface in mm
l	length of the topped beet in mm
l_b	length of the untopped beet excluding the flexible part of the taproot in mm
l_c	beet cap height in mm
LPS1	large pitch spiral extraction motion with slow acceleration
LPS2	large pitch spiral extraction motion with moderate acceleration
LPS3	large pitch spiral extraction motion with quick acceleration
l_u	underground beet length in mm
m_d	soil moisture content in % on dry mass basis
m/m	on mass basis
m_r	reference soil moisture content at pF2 in % on dry mass basis
n	number of extracted beets
NS1	no spiral extraction motion with slow acceleration
NS2	no spiral extraction motion with moderate acceleration
NS3	no spiral extraction motion with quick acceleration
NT	net soil tare in % on the basis of dry, clean and topped beet
NT_r	net soil tare in % on the basis of dry, clean and topped beet for the reference beet lot
NT_s	strongly adhering net soil tare, remaining after the 'standard' cleaning treatment, in % on the basis of dry, clean and topped beet
NT_s(R)	NT_s of treatment R
NT(X)	net soil tare of treatment X
p_f	final pitch in m
pF2	soil water matric potential of −10 kPa
R	reference treatment
RSA	relative soil adherence, dimensionless
RSA(X)	relative soil adherence of treatment X
S	soil-beet contact area in dm^2
se	standard error of the estimated value
SPS1	small pitch spiral extraction motion with slow acceleration
SPS2	small pitch spiral extraction motion with moderate acceleration
SPS3	small pitch spiral extraction motion with quick acceleration
S_s	specific soil-beet contact area in dm^2 kg^{-1}
t_α	ngular acceleration time in s
t_a	vertical acceleration time in s
TL	tip loss in % on the basis of dry, clean and topped beet
v/v	on volume basis
v_f	final vertical speed in m s^{-1}
w	mass of the untopped beet in kg
w_b	clean mass of the topped beet in kg
w_c	clean mass of the beet cap in kg