Reduction of soil tare by improved uprooting of sugar beet; a soil dynamic approach

G.D. Vermeulen

Promotor:	prof. ir. U.D. Perdok Hoogleraar in de bodemtechnologie
Co-promotor:	dr. ir. A.J. Koolen Universitair hoofddocent, Departement Agrotechnologie en Voedingswetenschappen
Samenstelling promotiecommissie:	prof. dr. ir. G.P.A. Bot (Wageningen Universiteit) dr. J.H.M. Wösten (Alterra) Prof. Dr.-Ing. K.H. Kromer (Rheinischen Friedrich-Wilhelms-Universität-Bonn, Duitsland) prof. dr. ir. L. Speelman (Wageningen Universiteit)

Reduction of soil tare by improved uprooting of sugar beet; a soil dynamic approach

G.D. Vermeulen

Proefschrift

ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
prof. dr. ir. L. Speelman
in het openbaar te verdedigen
op maandag 24 september 2001
des namiddags te 16.00 uur in de Aula

CIP-gegevens Koninklijke Bibliotheek, Den Haag

Vermeulen, G.D.
Reduction of soil tare by improved uprooting of sugar beet; a soil dynamic approach
Dissertation Wageningen University – With ref. – With summaries in English and Dutch

ISBN 90-5808-483-3

IMAG

This dissertation is also available as publication No. 2001-13 (ISBN 90-5406-198-7) of the Institute of Agricultural and Environmental Engineering (IMAG), P.O. Box 43, 6700 AA Wageningen, the Netherlands

Stellingen

1. Bij het uittrekken van bieten bepaalt de afstand tussen het bezwijkvlak in de grond en het bietoppervlak de grondtarra.
   Dit proefschrift

2. De rol van het wortelstelsel van de biet bij het ontstaan van grondtarra is tot op heden sterk onderschat.
   Dit proefschrift

3. Op basis van textuur-, structuur- en natheidskenmerken is het mechanische gedrag van grond slecht te voorspellen.

4. In navolging van verdichting, bieden verlossing, verzachting en verharding uitkomst ter correcte aanduiding van voor grondbewerking belangrijke, in Nederland evenwel naamloze, veranderingen van de fysische toestand van grond.

5. Een verhouding van 1/3 routinematig, 1/3 strategisch en 1/3 fundamenteel onderzoek is ideaal voor landbouwtechnisch onderzoek.

6. Een goede biologische akker is vrij van natuurlijke begroeiing.

7. Het verhandelen van CO_2 emissierechten is handel in welvaart en in gebakken lucht.

8. Behalve lichters zou men ook oplichters bieten moeten laten rooien.

Stellingen behorend bij het proefschrift

Reduction of soil tare by improved uprooting of sugar beet; a soil dynamic approach

G.D. Vermeulen
Wageningen, 24 september 2001

Aan Hetty, Marleen, Sanny, Jolien en Linda

Aan mijn ouders

ABSTRACT

Vermeulen, G.D., 2001. Reduction of soil tare by improved uprooting of sugar beet; a soil dynamic approach. Dissertation, Wageningen University, Wageningen, The Netherlands, 147 pp.

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

The relative amount of soil in sugar beet lots, called soil tare, should be reduced to curtail the cost and negative aspects of soil tare. Highest soil tare occurs in beet lots harvested out of wet clay soil. The main problem is that commonly-used share lifters press the soil against the beet. Thereafter, the wet clay soil adheres strongly to the beet and is difficult to be removed. The objective of the research was to analyse and improve the uprooting process of sugar beet, in order to reduce soil tare during harvest on wet clay soil.

A new characteristic, the relative soil adherence (*RSA*; 100% = all soil adheres strongly) was introduced to quantify soil adherence. The adhering-soil tare and *RSA* following various experimental beet extraction methods and lifting with a driven rotary-shoe lifter, were compared with conventional share lifting in field experiments, using stand-alone lifters on wet clay soil. Conventional lifting resulted in 50% (*w/w* net; *i.e.* relative to the clean beet mass) adhering-soil tare and an *RSA* of 32%. Quick, small-pitch-spiral extraction, however, resulted in 8% adhering-soil tare and an *RSA* of 40%. The driven rotary-shoe lifter resulted in 13% adhering-soil tare and an *RSA* of 47%. The *RSA* turned out to increase naturally with decreasing adhering-soil tare. When compared at the same level of adhering-soil tare, the *RSA* after beet extraction was significantly lower and the *RSA* after shoe lifting was about equal to the *RSA* after conventional lifting.

To provide theoretical foundation for the observed effects, the soil-beet-lifter system was modelled and the initial stage of uprooting was simulated, using PLAXIS, a geotechnical computer programme. Characteristics of the root system and of the uprooting method had a prominent effect on the stress state in the soil around the beet, and on the resulting zone of initial soil failure. The simulated behaviour of soil agreed well with effects observed in the field experiments, provided that reinforcement of the soil by rootlets was taken into account.

Based on the results of this research, it is estimated that complete harvesting systems with common beet cleaning facilities, on wet clay soil, may at best reach 7 to 15% soil tare by using further-improved conventional beet lifters and 3 to 6% soil tare by using beet lifters that would induce beet rotation at the initial stage of lifting.

ACCOUNT

Parts of this dissertation have been published in or submitted to international scientific journals:

Section 4.1 Vermeulen, G.D., J.J. Klooster, M.C. Sprong & B.R. Verwijs, 1997. Effect of straight and spiral sugar beet extraction paths and lift acceleration on soil tare and relative soil adherence. Netherlands Journal of Agricultural Science 45: 163-184.

Section 4.2 Vermeulen, G.D., J.J. Klooster, M.C. Sprong & B.R. Verwijs, 2001. Effect of uprooting methods on soil tare and other uprooting qualities of sugar beet. Submitted.

Chapter 5 Vermeulen, G.D. & A.J. Koolen, 2001. Soil dynamical analysis of the origination of soil tare during uprooting of sugar beet. Submitted.

For this dissertation, the text of the published article and of the submitted manuscripts was integrally adopted. References and lists of symbols and abbreviations, included in the article and the manuscripts, were pooled to one list of references and to one list of symbols and abbreviations in this dissertation. Editorial changes were made for reasons of uniformity of presentation in this dissertation.

Reference should be made to the original article(s).

CONTENTS

CHAPTER 1

General introduction

1.1 Background

A typical mechanised chain of activities around the harvest of sugar beet (*Beta vulgaris* L.) and the transport of beet[1] to the factory includes the harvest itself, the transport off the field, temporary near-field storage in a beet pile, loading of the beet onto a truck and road transport to the factory (Figure 1.1).

Typically, modern mechanised harvesting is performed by a complete, self-propelled beet harvester, combining the following harvesting phases (Figure 1.2):

- Leaf stripping: removal of most of the leaves (by a leaf stripper);
- Topping: removal of the top of the beet (by a topper);
- Lifting: uprooting of the beet (by beet lifters);
- Cleaning: removal of soil from the beet (by various mechanical devices);
- Hopper loading: transport to the beet hopper (by a chain type elevator);
- Hopper storage: temporary storage of the beet in the hopper;
- Hopper unloading: unload the beet hopper on to a trailer (by a chain type elevator).

The quality of sugar beet lots is determined as standard practice from samples taken at the beet reception station of the sugar factory, to fix the quality parameters for calculation of the payment rate to farmers. For this purpose, the beet lot quality is specified by chemical characteristics of the beet, such as the sugar content and the extractability index, and by the total amount of unwanted material in the beet lot. The relative mass of unwanted material is qualified as total tare, expressed in percent of the total mass of the delivered material. The unwanted material usually consists of loose soil, soil adhering to the beet, loose beet tops, beet tops that were not removed from the beet, leaf remnants, weeds and stones.

During the harvest of sugar beet, always some soil ends up in the truck that transports the beet to the factory, despite the cleaning efforts. This remaining soil, being part of the unwanted material, is called tare soil. The relative mass of the tare

[1] The term 'sugar beet' or 'beet' is used both to indicate the whole plant(s) and to indicate the harvested part(s) of the plant root(s).

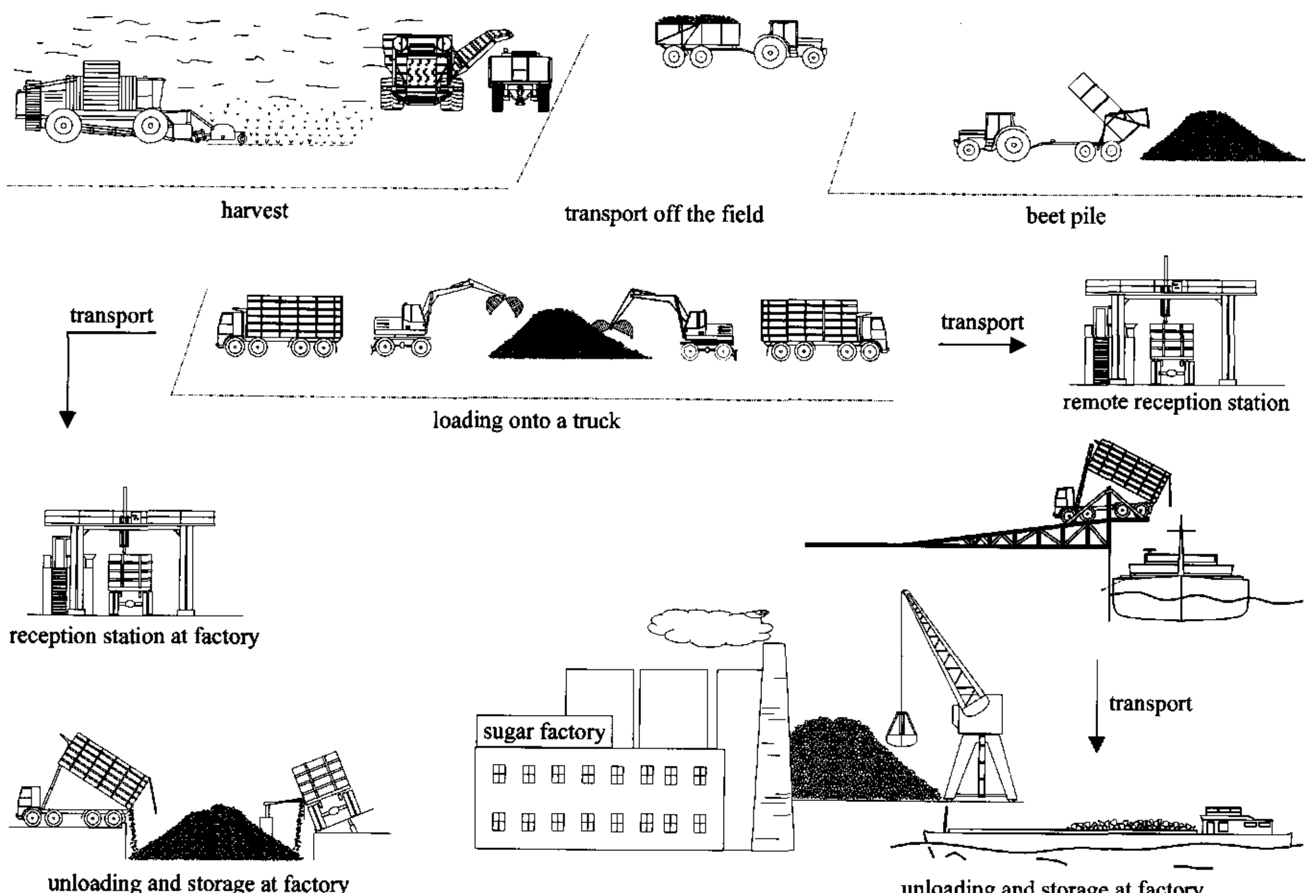


Figure 1.1. Schematic representation of the mechanised chain of activities around the harvest and transport of sugar beet to the factory.

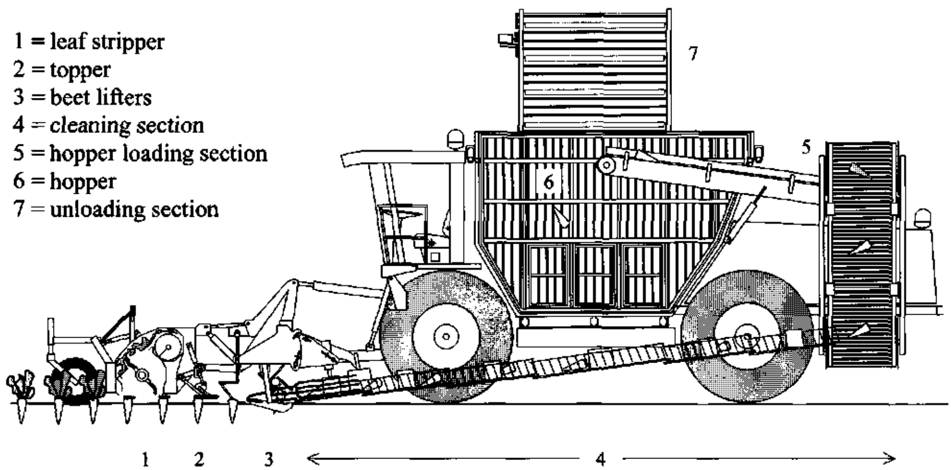


Figure 1.2. Schematic representation of the harvesting process in a complete beet harvester.

soil is usually qualified as soil tare, expressed in percent of the total mass of beet and unwanted material (gross soil tare) or of the clean beet mass (net soil tare). Determination of the soil tare is not part of the standard quality assessment of beet lots at the factory.

Before processing, the beet are cleaned by washing with ample water because the sugar production process requires very clean beet (adhering-soil tare < 1% *w/w*, net). The water stream with soil particles is generally led to sedimentation lagoons, located near the factory. After sedimentation and drying, the soil is removed from the lagoons and used in civil engineering, landscaping projects or other applications.

Recent figures (Maassen & Van Swaaij, 2000; Tijink, pers. comm.) for the Netherlands indicate a decreasing trend in the total yearly amount of soil transported and delivered with sugar beet to the sugar factories, in the period 1972 till 1999 (Figure 1.3). Based on this trend, the expected amount of soil at the factory in 2000 is 600 million kg. The results in Figure 1.3 also indicate that the yearly amount of soil varies considerably. This yearly variation is mainly attributed to differences in soil and weather conditions during the harvesting season.

As the total amount of processed beet increased from 1972 till 1999, the decrease in amount of tare soil is clearly caused by a decline in the average soil tare of sugar beet at the reception station of the factory (Figure 1.4). Due to the handling of the beet and additional cleaning treatments, on their way from the piles near the field to the reception station of the factory, the soil tare may be affected. Handling of the beet during loading onto the truck will usually result in less soil tare. While the

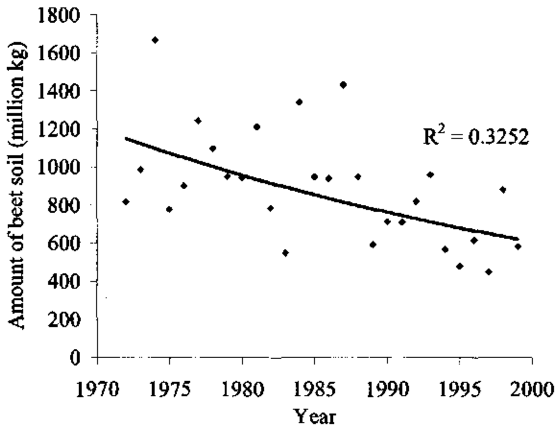


Figure 1.3. Yearly amount of tare soil delivered at the Dutch factories from 1972 till 1999, derived from statistics of IRS (Maassen & Van Swaaij, 2000) and additional data on yearly harvested area, provided by Tijink (pers. comm.).

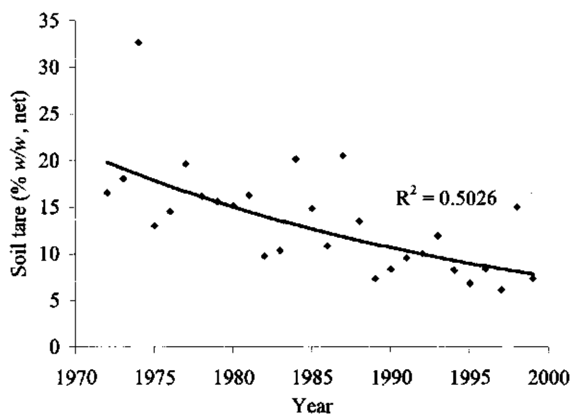


Figure 1.4. Yearly mean net soil tare of sugar beet delivered at the Dutch factories from 1972 till 1999, derived from statistics of IRS (Maassen & Van Swaaij, 2000) and additional data on yearly harvested area, provided by Tijink (pers. comm.).

handling effect may lead to a considerable decrease in soil tare when the soil tare in the beet pile is high (Jorritsma, 1958), the effect will be small when the soil tare in the beet pile is low. When the beet were not stored on a paved location, handling could actually result in an increase in soil tare. In the past ten years, beet lots were additionally cleaned on a limited scale (less than 10% of all beet lots). The additional cleaning occurred at the farm, during loading of the beet from the beet pile near the field onto the truck by a cleaner loader, or at an intermediate sugar beet depot by a cleaning device included in the internal transport system. Because of the additional cleaning, the average soil tare at the reception station of the factory will have been somewhat lower than the soil tare in the beet pile near the field. The total reduction of the average soil tare by beet handling and additional cleaning is estimated to be about one percent in soil tare. Therefore, the projected net soil tare in the beet piles near the field was 10% on average in 1993, the starting year of the research, and 8% in 2000.

The soil tare phenomenon occurs worldwide for all root and bulb crops. In most cases the final product should be clean and, therefore, soil tare is a problem to a certain degree. However, the magnitude of the problem depends on the crop and on local conditions. For sugar beet in the Dutch context, farmers, the industry and society have a common interest in reducing the total amount of tare soil brought to the sugar factories due to several reasons:

- Soil tare is a considerable cost in the chain from harvest to sugar production. It is estimated that the total yearly cost of soil tare of sugar beet in the Netherlands is 25 million euro. About 50% of these cost are directly related to soil tare, such as those of beet cleaning and of the storage, transport and disposal of tare soil. The other 50% of the cost are associated with beet losses due to the cleaning of beet. The cost of soil tare is paid for partly by the industry and partly by the farmers through a soil tare deduction, integrated with the payment system for delivered beet;
- For the farmer, soil tare entails erosion. Under extremely unfavourable conditions the net soil tare may be up to 55%. Therefore, 21 t ha^{-1} of fertile topsoil, corresponding with a soil layer of 1.4 mm, may be lost at a sugar beet yield level of 60 t ha^{-1};
- Soil tare presents also a phytosanitary risk. Soil diseases and weed seeds may spread by recycling the soil batches, originating from numerous locations. Therefore, application of the soil in agriculture is not recommendable;
- A substantial amount of finite or scarce resources such as fossil fuel, clean water and land is spent on all operations that cope with the tare soil. Therefore, reducing the total amount of tare soil enhances the sustainability of sugar beet production.

Opportunities to reduce soil tare turn up at various links in the chain from sowing to delivery of the beet to the factory. The most challenging opportunities to reduce soil tare at low cost occur during the field period of the beet, from sowing to transport off the field. After all, the soil would then remain on the field and further costs for cleaning, cleaning-associated beet losses, and storage, transport and disposal of tare soil are avoided (Strooker, 1962; Bulich & Kromer, 1986). Agronomic measures to reduce soil tare, such as the breeding of low-soil-tare varieties, continuously receive research attention and are expected to contribute to solving the problem on the long term. This thesis deals with the reduction of soil tare at harvest by improving the sugar beet harvesting technology. The focus is on a major improvement of the uprooting process, which may be considered as the first cleaning action performed on the beet. Effective cleaning during this harvesting phase would considerably reduce the need for further cleaning in all following beet treatment phases.

Soil tare varies between years, fields and beet varieties (Vermeulen, 1995). At the start of this research it was already clear that the soil texture and soil wetness have a major effect on soil tare. Soil tare is usually highest on wet clay soils and lowest on sandy soils (Wevers & Andringa, 1979; Duval, 1988). As about 2/3 of the sugar beet in the Netherlands are grown on clay soils and the soil at harvest is often wet, a reduction of the soil tare of beet grown on clay soils and harvested under wet conditions is expected to result in a significant reduction of the total amount of tare soil. Therefore, this thesis focuses on the uprooting of beet from wet clay soils.

Reduction of soil tare cannot be taken on its own, but should be considered within the context of the total performance of the harvesting process, including both the product quality, the product losses and the harvesting capacity. For example: more aggressive mechanical cleaning of the beet usually results in lower soil tare, but also in more beet damage, higher beet losses and, possibly, in slowing down of the harvesting operation. Moreover, when focussing on the uprooting process, one has to consider which intermediate performance is desired in anticipation of the subsequent phases of the harvesting process.

1.2 Research objective

The research objective was to analyse and improve the uprooting process of sugar beet, in order to reduce soil tare during harvest from wet clay soils, taking into account the effects on the total harvesting performance.

1.3 Outline of this thesis

A considerable amount of research and development effort has been dedicated to improve the total performance of sugar beet harvesters and the performance of beet lifters before the research work described in this thesis started. To connect the research as much as possible to practice and other research work, terminology used, definitions of terms used and methods used to assess the performance of harvesters and lifters are reviewed in Chapter 2. Despite efforts to standardise the terminology used in relation to the production and processing of sugar beet by publication of a sugar beet dictionary (Vandergeten *et al.*, 1997), it appeared to be necessary to concisely explain the English terms used in this thesis (Appendix 1), to avoid misinterpretation.

The literature review in Chapter 3 is focussed on the factors that are reported to affect the quality of uprooting and of harvesting, being part of the performance of lifters and harvesters. Except for the harvesting technology used, characteristics of the beet and of the soil are also very important factors that determine the quality obtained. Effects of the characteristics of beet and soil and of known past, current and experimental uprooting and harvesting processes on the quality of uprooting and harvesting are discussed. A striking conclusion from the literature review was that soil tare after beet extraction with beet pliers, grabbing the top of the beet, was sometimes about equal to the soil tare after a complete modern harvesting process. Moreover, it was reported that wet clay seemed to adhere less strongly to the beet surface after extraction than after a complete modern harvesting process. However, no method was reported to quantify the strength of adherence of soil to the beet. As it was expected that weakly-adhering soil can be easily removed from the beet by a cleaning process, improvement of the uprooting process on the basis of beet extraction seemed promising and was adopted as the research direction for the work described in this thesis.

In Chapter 4, two field experiments are reported. The first experiment (Section 4.1) concerns the optimisation of the path and accelerations during extraction (grab lifting) in terms of soil tare and soil adherence. Features of a specially-built mobile experimental beet puller to apply the extraction treatments and a method to quantify the strength of adherence of soil to the beet surface by a parameter called the relative soil adherence are described. Very low soil tare turned out to be possible for spiral extraction paths and high accelerations during extraction. The relative soil adherence increased with decreasing soil tare, irrespective of the extraction treatment.
The objective of the second experiment (Section 4.2) was to compare grab lifting with conventional share lifting. As practical application of grab lifting is problematic, the driven rotary-shoe lifter, with a lifting path and lifting acceleration resembling quick, spiral extraction to some extend, was included in the comparison. Based on the results of this experiment, it was concluded that the driven rotary-shoe lifter might be a suitable means of reducing soil tare on wet clay in practice.

To better understand the fate of the soil surrounding the beet during the uprooting process, including the quantification of the conditions in this particular volume of soil, the uprooting process was further analysed theoretically in Chapter 5. For this purpose, the soil-beet-lifter system was modelled and the initial stage of uprooting was simulated, using PLAXIS, a geotechnical computer programme. It is described how various systems, including beet with and without rootlets and various uprooting methods, were modelled and how the output of the simulations relates to the origination of soil tare and expected soil compaction and plastication due to uprooting.

In Chapter 6 general issues related to research methods used, results obtained and recommendations with respect to future work are discussed and prospects, based on the results, are indicated.

CHAPTER 2

Assessment of the quality of harvesting and of uprooting

The quality of harvesting and of uprooting addresses the quality of these processes, given the input conditions of beet and soil. For the purpose of improvement of harvesting and uprooting, information on the beet quality obtained and losses experienced in specific process phases is desired to locate the phase and location at which problems may occur. The International Institute of Beet Research (IIRB) has published international guidelines for assessment of the performance of sugar beet harvesters (Brinkmann, 1986a), intended for use during sugar beet harvesting demonstrations. Just as in the research work described in this thesis, the objective of the testing of harvesters during demonstrations is mainly to assess the harvesting quality aspect of machinery performance. Currently, the IIRB guidelines are reviewed and extended with other machinery testing procedures to become an IIRB standard. The terminology used in relation to the quality of harvesting is mainly based on the English version of a concept for the new IIRB standard (Vandergeten *et al.*, 1997) and mostly consistent with terms used in the Sugar Beet Dictionary (Anon., 1999). Chapter 2.1 is based on the IIRB guidelines and supplemented with information from other sources. Most of the assessment methods for the harvesting quality are also useful to assess the quality of uprooting processes. However, some characteristics are superfluous and one additional characteristic, the soil adherence, should be considered. The assessment of the quality of uprooting is discussed in chapter 2.2.

2.1 Quality of harvesting

The IIRB guideline consists of three parts:

- Prerequisites of harvesting machinery testing;
- Guideline for describing the characteristics of the sugar beet field used for the tests;
- Guidelines for assessment of the harvesting quality: characteristics of quality to be measured, recommended methods to determine these characteristics and formats for presentation of the results.

The prerequisites of testing of harvesting machinery are that the testing is conducted on a field with a plant density of 50,000 to 120,000 beet per hectare (counting only beet with a diameter > 4.5 cm), that the minimum working speed is 4 km h^{-1} and that the conditions are equal for all machines tested.

The sugar beet field used for the tests should be described by soil type, state of soil, cultural practices, sugar beet variety, type of seed, seed spacing, row width, population density, plant distribution, diameter of the root, yield of clean beet and other details considered relevant.

The recommended characteristics of the harvesting quality to be determined are:

- Topping quality;
- Surface losses;
- Root breakage;
- Soil tare;
- Superficial damage.

A description of each of these characteristics of quality, including background, definitions and assessment methods are presented in the next sections.

Topping quality
The reason for leaf stripping and topping of the beet at harvest is that the leaves and the upper part of the beet root have a negative effect on the sugar extraction process, due to their chemical composition. Therefore leaf parts and beet tops are considered as unwanted material in beet lots. Most of the unwanted components in the beet top are located near the origin of the petioles of healthy plant leaves. The desired level to cut off the beet top depends on the directions given by the sugar factories. In Germany and the Netherlands, the sugar factories prescribe the correct level to be just above the lowest leaf scars (Bulich, 1984; Brinkmann, 1986a, 1986b). The beet is called correctly topped when cut off at this level. In practice, not every beet is correctly topped due to a combination of factors such as the variable height of the beet crowns above the soil, in-row spacing variability, imperfect depth control of the topper and a slanting position of the beet in the soil.
The IIRB recommends subjective assessment of the topping quality by visual inspection of a sample of 1,000 beet. Each single beet in the sample lot is to be classified in one of the classes presented in Figure 2.1. The topping quality is presented as a table of the percentage of beet (n/n) found in each class.
A quantitative approach of the topping quality is possible by measuring the quality in terms of two other elements of quality: top tare and overtopping losses. When the beet is topped too high (undertopped), the relative mass of the left behind leaf parts and beet top section that are unintentionally is called top tare. When the beet is topped at too low a level (overtopped), the relative mass of the unintentionally removed beet section is called topping loss. Top tare and topping loss are expressed in percent of the total clean beet mass.
As a rule of thumb, the topping loss is 7 to 9% and 15 to 20% for topping 1 and 2 cm too deep, respectively (Steenhuis, 1990). These topping loss figures are higher for small beet than for large beet (Heller, 1960).

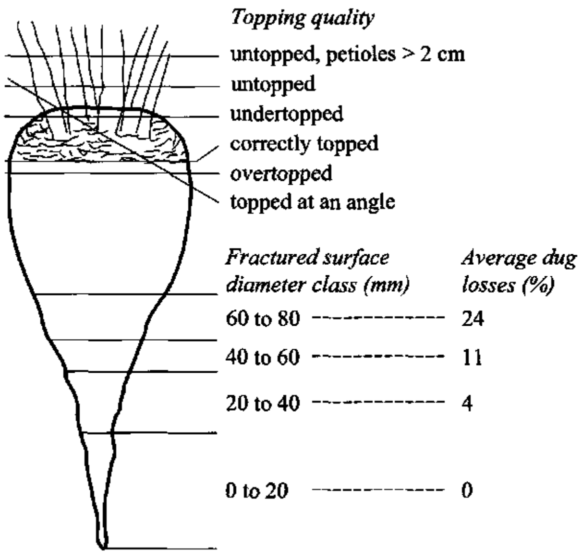


Figure 2.1. Classification system for topping quality and estimation of the average dug losses by measurement of the fractured surface diameter, as recommended by the IIRB (After Brinkmann, 1986b).

The top tare of an untopped beet without leaf parts is estimated to be about 13.5% on clean beet mass basis (Anon., 1984c; Steenhuis, 1990). In practice, the top tare varies between 3 and 8% (Van Der Linden, 1990).

Surface losses

The surface losses are defined as the total mass of whole beet and of beet fragments, other than beet tops and beet tips, left on and in the soil after harvesting, expressed in percent of the clean beet yield. Surface losses are beet losses that occur due to unintentional uprooting of beet during topping, due to missing of beet by the lifters and due to spilling of beet and beet fragments during cleaning, internal transport and unloading. According to the IIRB guidelines, the surface losses are determined by gathering all beet and beet fragments that have a diameter of 4.5 cm or more. The beet and beet fragments are to be gathered after two tillage operations with a cultivator to a depth of 15 to 20 cm, from an area, numerically equal to 50 times the working width of the harvester (per replication) and in four replications. In practice, surface losses are usually low: < 1% of the clean beet yield (Brinkmann, 1986b).

Root breakage

Root breakage develops during the uprooting phase. Uprooting devices apply a combination of vertical and horizontal forces to the upper parts of the root. As the beet is strongly anchored into the soil by an extensive network of rootlets, the applied uprooting forces are resisted by a soil reaction. Consequently, combined bending and direct stresses are set up in the root (Von Hülst *et al.*, 1957; Miller, 1982) and root breakage occurs whenever the set up stress exceeds the strength of the root material. Usually the beet fractures at some point at the lower end of the beet root. The part of the beet root above the fractured surface is harvested and the part below the fractured surface is lost because it is left behind in the ground. For ease of discussion, the lower, broken off part of the beet is called the beet tip. The losses associated with root breakage are called dug losses and are defined as the total mass of the beet tips, expressed in percent of the clean beet yield.

According to the IIRB guidelines, the mean dug loss for a beet lot is estimated via the diameter of the fractured surface (Figure 2.1). Each beet out of a sample of 1,000 is to be assigned to one of the following fractured surface diameter classes: < 2, 2 to 4, 4 to 6 and 6 to 8 cm. The average dug losses for each fractured surface diameter class is determined in advance by weighing the beet tip sections of 500 intact beet, produced by cutting off the tip at diameters of 2, 4, 6 and 8 cm. The figures of dug losses presented in Figure 2.1 are an example of the results of this preparatory work. The mean dug loss for the beet lot is estimated from the mean dug losses per class and the relative number of beet assigned per class (Brinkmann, 1986a).

A fractured surface diameter of 2 cm is considered the minimum feasible. Therefore, losses associated with surface diameters < 2 cm are considered unavoidable and, therefore, are not accounted for in the dug losses (Brinkmann, 1986a). These losses may amount 1 to 1.5% of the clean beet yield. Efforts to avoid these losses during uprooting are also of little use because the fragile tips would break off anyway during later harvesting phases or during transportation to the factory.

When the dug loss is considered for a single beet, both the fractured surface diameter and the beet mass have a strong effect on the dug loss (Heller, 1960). Also the beet shape may affect the dug loss at a specific fractured surface diameter. Moreover, the use of fractured surface classes is not useful. During the research described in this thesis, the dug loss was to be determined from samples containing significantly less than 1,000 beet. Therefore, the accuracy of the dug loss estimation was increased by adopting a continuous method and by accounting for the combined effect of fractured surface diameter, beet mass and beet shape on the dug loss. A detailed description of the dug loss estimation method used is presented in Section 4.1.

Recently, during the harvesting demonstration at Watervliet, Belgium in 1999, a different approach to report the dug losses was adopted. Losses were reported as the loss in t ha^{-1}. The dug losses were determined by associating the fractured surface diameter class with a fixed loss in gram per beet tip (Table 2.1).

Table 2.1. Dug losses, per fractured surface diameter class, expressed in gram per beet tip (Van Der Linden & Vandergeten, 1999).

Fractured surface diameter (cm)	Dug loss (g per beet tip)
0-2	0
2-4	23
4-6	60
6-8	130
> 8	230

Soil tare

All non-beet material present in beet lots, including soil adhering to the beet, loose soil and stones is called tare soil. The IIRB recommends that the amount of tare soil be reported but does not provide guidelines on assessment methods and size of samples for the determination of the amount of tare soil. Usually the amount of tare soil is determined by measuring the weight loss of a sample by thorough cleaning. In the Netherlands, the amount of tare soil is usually expressed as gross soil tare, *i.e.* the mass of the tare soil relative to the total mass of the beet lot, including the tare soil, in percent. In this thesis soil tare is expressed as net soil tare, relative to the total mass of the clean, topped beet. Advantages of using net soil tare are:

- This parameter is proportional to the amount of tare soil in a beet lot;
- The logarithm of the net soil tare is approximately normally distributed (Fauchere, 1989), which eases statistical analysis of results.

For machine testing during harvesting demonstrations, the necessary number and size of samples is determined by the many sources of soil tare variation on the test field, such as the variable machine adjustment and local differences in the harvesting conditions. Currently, 20 samples of 25 kg each are usually taken per harvest (Van Der Linden, pers. comm.), such as at the harvesting demonstration in Selingenstadt (Kromer *et al.*, 2001).

The adhering-soil tare of individual beet under comparable harvesting conditions depends mainly on beet weight and beet shape. Therefore, a sample of a beet lot for adhering-soil tare determination should contain enough beet to represent the mean weight and shape of the beet. If a small sample size is used, it is advisable to increase the accuracy by correcting for weight and shape of the beet in the sample, using a relationship between soil tare and the weight and shape of the beet. This method was adopted in the research described in this thesis. A detailed description of the adhering-soil tare measuring method is given in Section 4.1.

Superficial damage
During the harvesting process, sugar beet are subject to many mechanical impacts, which may cause cutting or bruising of the beet skin. Superficial damage causes increased sugar loss during storage, because of leak of beet juice, and increased respiration due to callus formation (Von Hülst *et al.*, 1957).
At harvesting demonstrations, the usual way to quantify superficial damage is by means of estimation of the total area of bruised skin of 1,000 sugar beet. The size of a bruised area is estimated by multiplying the measured maximum length and maximum width of bruised areas. Superficial damage is expressed as the total bruised skin area in cm^2 per 100 beet. In the research described in this thesis, superficial damage was assessed as described here before, but expressed in cm^2 per beet.

2.2 Quality of uprooting

For correct assessment of the quality of uprooting, the uprooting devices should be operated in a stand-alone configuration, without any subsequent cleaning devices. Assessments should also be performed immediately after uprooting to avoid effects of drying or other moisture transport in the soil adhering to the beet. Only quality characteristics that could change during uprooting need to be considered. As the uprooting operation is not expected to change the topping quality, this characteristic does not need to be considered. In the research described in this thesis, surface losses did not occur and were not reported, therefore. However, crown fracture occurred during some treatments involving the extraction of beet. As crown fracture would lead to surface losses, this characteristic of quality was considered. Root breakage, soil tare and superficial damage may be affected by the uprooting process and need to be considered as characteristics of the quality of uprooting, therefore.

The fact that uprooting is followed by a cleaning operation also needs consideration. Obviously, very low soil tare directly after uprooting would be attractive because this would render cleaning redundant. However, at higher soil tare, it seems equally important that the soil around the beet is in such a (friable or loose) state that the subsequent cleaning operation will be successful. Therefore, a distinction is made between soil adhering to the beet surface and loose soil in various German investigations (Ditges, 1990). In this thesis, a new characteristic of the uprooting quality was introduced: the soil adherence. This characteristic should indicate the magnitude of the stresses that cause the soil particles to stick together and stick to the surface of the beet or to the rootlets. As soil adherence is a new, not-easy-to-grasp phenomenon in soil tare research, this characteristic of quality is not treated in this chapter. Instead, possible ways to define and measure soil adherence are discussed in Section 4.1.

CHAPTER 3

Factors affecting the quality of harvesting and of uprooting

Both the quality of harvesting and the quality of uprooting depend on the characteristics of the beet, of the beet population, of the soil, and of the technique applied (Kromer *et al.*, 1990). Effects reported in the literature, interactions of effects, and possibilities to reduce soil tare are discussed in this chapter.

3.1 Characteristics of the beet

The characteristics of the beet at harvest time, that are reported to affect the quality of harvesting and of uprooting, are the mass (or volume), the shape, the roughness of the surface, and the root system. These characteristics may be influenced by several agronomic measures.

Beet mass

The adhering-soil tare (% *w/w*, net), being defined as the ratio of the mass of the soil adhering to the beet, relative to the mass of the clean beet, decreases with increasing beet mass (Fritzsch *et al.*, 1976, 1977; Wevers, 1980; Bouma & Cappon, 1988). This phenomenon is attributed to the fact that the potential amount of soil adhering to a beet is thought to be proportional to the underground surface of the beet. As the ratio of the total surface area to the mass (or volume) of a beet decreases with increased mass of the beet, also the ratio of the underground beet surface and the mass of the beet decreases with increased mass of the beet, assuming that the underground fraction of the total beet surface is relatively constant. Therefore, also the net adhering-soil tare decreases with increased beet mass. In the experiments described in this thesis, the specific soil-beet contact area, S_s, defined as the ratio of the underground beet surface and the clean beet mass, was adopted as a beet characteristic instead of the beet mass because the adhering-soil tare is expected to be linearly related with S_s.

Low soil tare may occur when the underground fraction of the total beet is lower than usual, *i.e.* when a major part of the beet root grows above the ground. This feature prevails in some fodder beet varieties.

The mean beet mass can be influenced by the population density (Kromwijk, 1972; Märländer, 1989); *i.e.* the mean beet mass decreases at increased density. Therefore, low population density would be a means to reduce soil tare. However, population density also affects other factors like the fresh yield and the sugar content. Based on multiple criteria, the recommendation for population density is fixed on 74,000 plants per hectare on clay soil in the Netherlands. (Van Der Linden, 2001). The mean beet mass is also affected by the developmental stage of the beet at harvesting. The seasonal growth characteristic of sugar beet (Jorritsma, 1985) indicates that the beet mass may increase 10 to 15% during the harvesting period in the Netherlands. Late harvesting may be favourable to reduce soil tare, therefore. However, late harvesting usually coincides with high soil wetness, which has an opposite effect on soil tare. No information was found on the combined effect of high beet mass and high soil wetness, due to late harvesting, on soil tare.

Beet shape and roughness of the beet surface
To a certain extent, the general shape and the surface roughness of the skin are reported to be variety-bound characteristics. An adhering-soil tare, 15 to 46% lower than in commercial varieties, has been obtained in specially-bred beet, having a spherical shape and a smooth surface (Westerdijk, 1989). The effects of the spherical shape and the smooth surface on adhering-soil tare could not be separated. Up till now, the characteristics 'spherical' and 'smooth' could not be introduced as stable characteristics in a new sugar beet variety. Moreover, the sugar content of the specially-bred spherical beet was too low. Commercially available low-soil-tare varieties, that have a relatively regular shape and a relatively smooth surface, also have the disadvantage that they generally are low in sugar (Fauchere, 1989).

Paper pot-planted beet usually have a roundish shape and low soil tare would be expected, therefore. While, Smith *et al.* (1988) observed no difference in soil tare between directly-sown beet and beet planted in paper pots, investigations by IRS (Anon., 1984b) showed that paper pot-planted beet had about 2.5 times less adhering-soil than directly-sown beet. As other factors, such as the usually higher beet mass, the frequent occurence of multiple small tails and the possible effect of the paper pot substrate in the beet grooves may also have influenced the soil tare of paper pot-planted beet, compared with directly-sown beet, evidence of an effect of the roundish shape of the beet on soil tare was not obtained (Anon., 1984a; Van Der Linden, pers. comm.).

Fritzsch *et al.* (1976, 1977) reported that soil tare is higher for fanged than for non-fanged beet, when uprooted by beet extraction. Beet fanginess may be significantly influenced by the soil structure. Effects of tillage and wheel traffic on the soil structure and the subsequent beet shape were reported by Gliemeroth (1953), Czeratzki (1966), Folkerts *et al.* (1981) and Merkes & Von Müller (1986). In general, a sharp transition from loose to dense soil in the root zone enhances the formation of fanged beet. Folkerts *et al.* (1981) observed a significantly lower soil tare and a smaller number of fanged beet in a deeply-loosened sandy loam than in a dense soil. Hartmans (1982), Merkes & Von Müller (1986) and Spoor & Miller (1989) also observed differences in beet fanginess due to soil structure, but no differences in soil tare on beet, harvested with conventional harvesting techniques.

Beet fanginess also occurs when the crop is attacked by soil nematodes (Gliemeroth, 1953; Jorritsma, 1985).

The effect of the roughness of the beet skin on a micro-scale on soil tare has not been investigated. However, the surface roughness is known to affect the soil-material adhesion (Chancellor, 1994), and may, therefore, have an effect on soil tare. The micro-roughness can be measured with a pen-profilemeter (Salokhe *et al.*, 1993).

Winter (1993) classified the irregularity of the beet surface due to the beet grooves as roughness on a meso-scale. The meso-roughness was quantified by measuring the depth of the beet grooves. Green (1956, 1957) reported that relatively much soil adheres to the beet in the neighbourhood of the beet grooves. Explanations for this phenomenon are that:

- The soil in the grooves cannot be reached by most mechanical cleaning devices;
- The soil in the neighbourhood of the beet grooves is interlaced with many rootlets emerging from the grooves; therefore, soil aggregates that would normally fall off freely, hang on to the beet through the rootlets.

Root system

Rootlets emerging from the beet grow through the soil around the beet and build a network, that reinforces the soil. Green (1957) suggested that these rootlets play an important role in determining the adhering-soil tare of any given beet. Gemtos (1979) suggested that a high rootlet density on the beet surface means that the required shear stress to separate the soil, including the rootlets, from the beet surface will be much higher than the stress to cause fracture of the soil at some distance from the beet surface, with only few rootlets present. Therefore, the soil will fracture at some distance from the beet surface and the soil adjacent to the beet will be lifted along with the beet. The occurrence of this phenomenon depends also on the diameter of the rootlets, the magnitude of the anchoring force of the rootlet in the soil, the soil-beet adhesion, the soil cohesion and the depth below the soil surface. By assuming that the occurrence of adhering soil is closely related to the number of rootlets emerging from the beet surface, Gemtos (1979) was able to explain some of the extreme differences in adhering-soil tare that he observed in his experiments:

- The adhering-soil tare in an experiment in Greece under dry growing conditions was only 1 to 3% (*w/w*, net). The rootlets were concentrated near the lower end of the beet. The rootlets broke off the beet together with the beet tip and, thus, a little amount of soil was lifted with the beet;
- In an experiment in England, performed after wet growing conditions, the rootlets were distributed equally over the length of the beet, and the resulting adhering-soil tare was about 100%.

In an experiment of Von Hülst *et al.* (1957) beet were extracted with and without removing the top soil till about half the beet depth. The force to extract the beet appeared to be mainly needed to extract the lower part of the beet, indicating that most of the rootlets must have been on the lower part of the beet. These results were observed under harvesting conditions that resulted in very low soil tare.
A possibility to influence the morphology of the root system was reported by Gliemeroth (1953). He reported that the morphology of the root system of beet is affected by the distribution of nutrients in the soil.

Mechanical characteristics of the beet material
The mechanical characteristics of the beet are likely to affect the sensitivity of beet to fracture and to superficial damage. The mechanical characteristics of the beet show a large variation, partly due to the fact that the inner parts have less strength than the outer parts (Gemtos, 1979; Miller, 1982). Reported values vary for the tensile strength from 600 to 2,800 kPa (Gemtos, 1979; Miller, 1982, 1984), for the shear strength from 300 to 1,480 kPa (Vukov, 1972; Gemtos, 1979; Alizadeh, 1985; Smed, 1998), and for Young's modulus from 6,400 to 14,000 kPa (Miller, 1982; Gemtos, 1979; Bieluga & Bzowska-Bakalarz, 1980; Alizadeh, 1985; Vukov, 1977). Alizadeh (1985) reported that Poisson's ratio for sugar beet tissue is 0.39. Smed (1998) reported that the shear strength of the lower end of the beet differed between varieties (range of 595 to 736 kPa) and that dug losses decreased with increasing shear strength. According to Draht *et al.* (1984), the use of nitrogen fertilizer has a negative effect on the strength of beet material. No information was found on direct effects of the mechanical characteristics of beet on superficial beet damage.

3.2 Characteristics of the beet population

The characteristics of the beet population that are reported to affect the quality of harvesting and of uprooting are the population density and the deviance of beet positions from the centre of the crop row. The effect of the population density on the average beet mass and, consequently, on soil tare have been discussed in Section 3.1. Beet positioned eccentric of the crop row may not be guided in between lifter parts that operate on either side of the crop row. They may be cut up or pulverised by colliding with the lifter parts. These beet are lost. Heller (1960) and Voesten (1993) determined in a practical situation the frequency distribution of the deviance of beet centre locations from the straight row centre line (Table 3.1). Deviances, up to 4 cm to either side of the row centre line, occurred frequently. If large deviances occur frequently, beet loss can be avoided by enlarging the distance between the lifter parts. However, in this case more soil is taken up by the lifter and the soil tare may increase. To a certain extent, this effect can be avoided by the use of self-aligning shares or automatic steering. Jakob (1983) suggested that a maximum deviation of 5 cm would be a suitable starting point for the development of an automatic steering system.

Table 3.1. Frequency distribution (%) of the deviance of beet centre locations from the straight row centre line.

Source	Deviance class (cm)					
	< 0.5	0.5 - 1.0	1.0 - 2.0	2.0 - 3.0	3.0 - 4.0	> 4.0
Heller (1960)	44	27	22	5	2	0
Voesten (1993)	21	24	29	19	6	1

3.3 Characteristics of the soil

The characteristics of the soil that are reported to affect the quality of harvesting and of uprooting are the soil texture, and various parameters and subjective indicators to specify the wetness of the soil, the soil structure and the mechanical behaviour of the soil. Most of the characteristics of the soil are the same during crop growth and at harvest time. Therefore, some characteristics of the soil, such as stratification, have a compound effect on the quality of harvesting and of uprooting: indirectly through the effect on beet characteristics, and directly due to the behaviour of the soil during harvesting. The effect of the soil on the characteristics of the beet, and the subsequent effect on the quality of harvesting and of uprooting have been discussed in Section 3.1. This section focusses on the reported direct effect of characteristics of the soil on the quality of harvesting and of uprooting. The available reports mainly bear reference to the effect on soil tare.

Maggs (1955) observed that soil tare was higher on heavy clay than on sandy loam, and that soil tare generally increases when the soil moisture content increases (Figure 3.1). Only in a narrow range of very high moisture contents of sandy loam, soil tare decreased with increasing moisture content. He reported that the observed soil tare correlated very well with the force needed to separate a steel plate from the soil at the time of harvest, measured with a so-called adhesion meter. This experiment suggests that the soil tare on a given soil type can be explained by a single empirical soil parameter, indicated here as Maggs' adhesion. However, Green (1957) stated that "Although it has been shown that the drier the dirt tare (*soil tare, author*), the more easily it can be removed from the beet by mechanical agitation, the adhesion theory as an explanation of the processes involved has not proved to be entirely satisfactory".

Göhlich & Hingst (1960) reported that the soil tare increases with increasing soil moisture content. Their experiment with three lifter designs was performed on artificially-irrigated soil, ranging from moist tot dry.

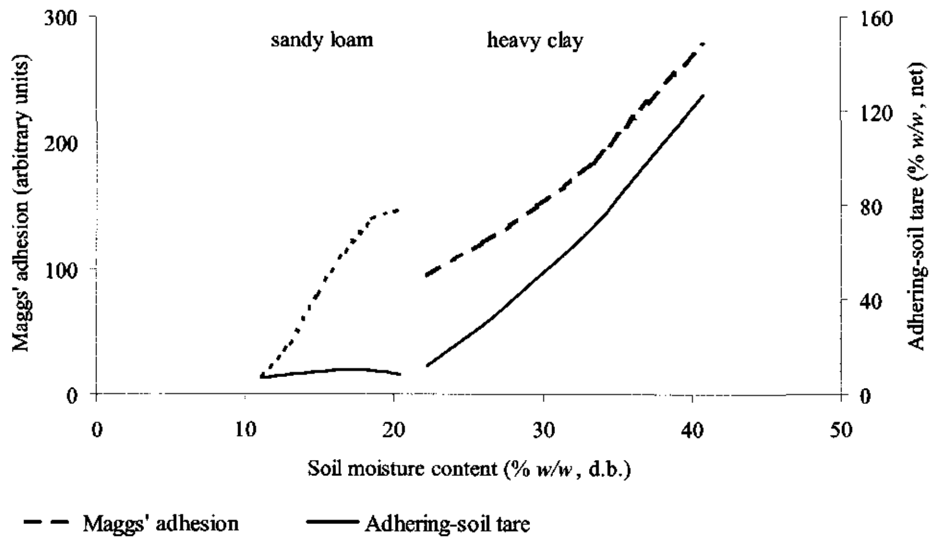


Figure 3.1. Maggs' adhesion, and adhering-soil tare of conventionally-harvested beet as a function of soil moisture content. Reconstructed from data of Maggs (1955).

Fritzsch *et al.* (1976, 1977) reported soil tare data for a wide range of soil moisture conditions, immediately after two beet extraction treatments: one with a straight up extraction path and one with a spiral extraction path. With increasing moisture content, the soil tare decreased at very low moisture contents, increased at medium moisture contents and decreased at very high moisture contents (Figure 3.2). The effect at very low moisture contents is the opposite of the effect observed by Maggs (1955) and Göhlich & Hingst (1960). This discrepancy might be explained by the fact that Fritzsch *et al.* (1976, 1977) extracted the beet, while conventional harvesting technique was used in the other experiments.

Wevers (1980) and Duval (1988) reported data of soil tare after harvest for various soils and various moisture conditions, obtained by measurements in practice using conventional harvesting systems (Table 3.2 and Figure 3.3). The soil tare increases with an increasing content of fine particles of the soil and, for a wide soil moisture condition range, also with an increasing soil wetness. Only for sandy soil (less than 10% soil particles < 16 μm), Wevers (1980) reported somewhat lower soil tare figures for wet than for dry soil. The figures of Duval (1988) indicate that the soil tare is more variable under wet than under dry conditions. The soil tare decreases with an increasing content of lime in the soil (Duval, 1988). Visual assessment of the crumbling properties of heavy soils revealed that the soil tare is lower for easy to crumble soil than for moderately easy or hard to crumble soil (Wevers, 1980).

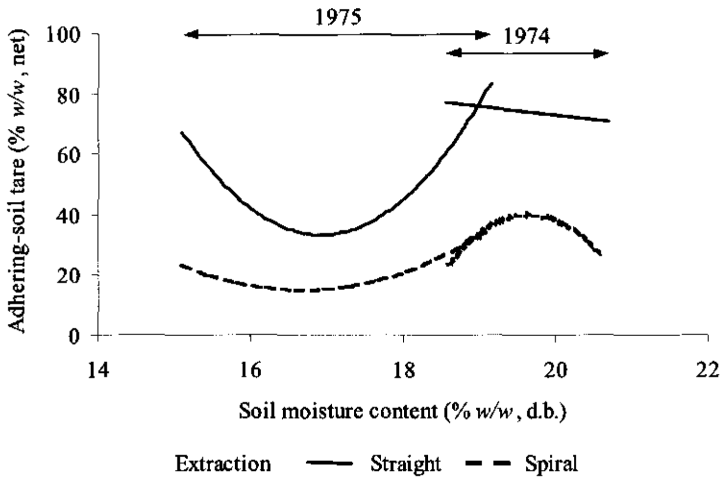


Figure 3.2. Adhering-soil tare directly after uprooting at various soil moisture contents, for beet extraction with a straight-up path and with a spiral path, observed in two experiments (1974 and 1975) on a similar, heavy soil (Fritzsch *et al.*, 1976).

Wayman & Maughan (1966) reported that the soil tare after harvest on heavy soil was not affected by wheel traffic under dry conditions, but was somewhat higher when wheel traffic occurred on wet soil, compared with no wheel traffic. Ditges (1990) measured the soil tare directly after lifting, with and without previous wheel traffic on a silty loam soil. In this case, wheel traffic shortly before lifting resulted in higher soil tare for some of the various lifters tested, but only in case of traffic on wet soil. Apparently, the change in characteristics of heavy soils due to deformation in a wet condition induces high soil tare.

Table 3.2. Soil tare (% *w/w*, net) after conventional harvest for soil varying in condition and in content of particles < 16 μm (Wevers, 1980).

Visual examination of the soil condition	Soil particles < 16 μm (% *w/w*, d.b.)			
	< 10	< 20	20-40	> 40
Dry	5.3	5.9	9.1	13.3
Sticky and/or wet	4.0	14.8	17.9	24.4
Easy to crumble			13.3	16.6
Difficult to crumble			24.1	26.6

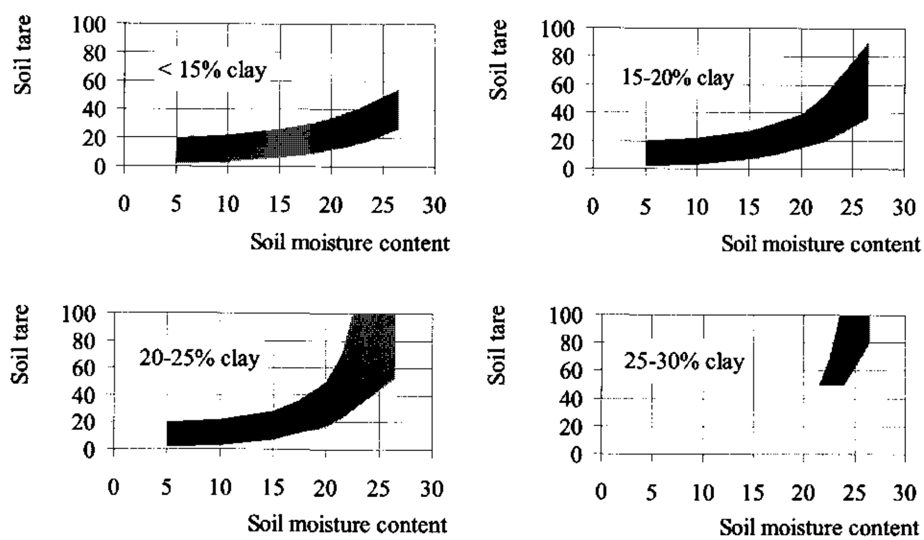


Figure 3.3. Soil tare range (% *w/w*, net) at various soil moisture contents (% *w/w*, d.b.) for four groups of non-calcareous soils, differing in clay content (% *w/w*, d.b.) (Duval, 1988).

3.4 Harvesting technique

The development of harvesting techniques and improvement of their performance, including the quality of harvesting and of uprooting, has a history of about 140 years. The typical, modern harvesting system described in Chapter 1 is the result of these developments. To put the current systems, and the quality of harvesting, in historical perspective, the development of the mechanisation of the sugar beet harvest is summarised in Subsection 3.4.1. The effects of the technique on the quality of harvesting is reviewed for each harvesting phase in Subsections 3.4.2 through 3.4.5. The eventual harvesting quality of a complete harvesting system is the accumulated result of the qualities obtained in each phase. The quality of harvesting of complete harvesting systems is reviewed in Subsection 3.4.6. Throughout Section 3.4, the focus is on the quality of the uprooting process.

3.4.1 Development of mechanised beet harvesting

The development of the mechanisation of the sugar beet harvest has been extensively reviewed by Karwowski (1974), Strooker (1982) and Ditges (1990). A brief summary of the developments, focussed on uprooting devices, is described hereafter.

Traditionally, sugar beet were uprooted by pulling the beet out of the soil by the leaves, assisted by the jacking movement of a narrow spade (beet spade) or fork

inserted into the soil next to the beet. In the initial period, from 1860 till about 1900, several tools were developed to loosen the soil around the beet, to ease the manual labour of pulling the beet out of the soil by the leaves. In the period from 1900 till about 1925, the tools gradually developed towards two rising and converging rods or blades, often called shares, that could lift the beet fully out of the soil. In this period it was also tried to use rotary devices to uproot the beet, either by trapping them between two converging wheels, or by grabbing them with grabs on the outside of a drum.
When it became possible to lift the beet fully out of the soil, topping before mechanical uprooting became more or less standard practice. From 1925 onwards, many different shares and rotary devices were tried in order to optimise the performance of uprooting. Karwowski (1974) and Ditges (1990) reviewed the main types of lifters used (Figure 3.4). The forked share, lifting blade and polder share may be fixed or driven. Driven shares, or blades, may be of the vibrating or walking type. Vibrating shares, or blades, vibrate in horizontal or vertical direction or have a prescribed, cyclic movement in a vertical plane parallel to the direction of the forward machine movement. In walking shares or lifting blades, the left part and the right part of the share or blade make the same movement as the vibrating type of lifter, but have a mutual phase difference of half a cycle. The lifting disc and the wheels of the lifting wheel digger may also be driven. Compared with the fixed lifters, the driven lifters exhibit less congestion, an uprooting motion with less interruptions under moist conditions (Bouma & Cappon, 1988), and better crumbling of the soil around the beet under dry conditions (Ditges, 1990).

In addition to the development of shares, blades and wheel type lifters, also other uprooting tools were developed. Some of the most interesting designs were:

- Combinations of a share for initial uprooting and a rotary device to grab and further lift the beet;
- The driven rotary-shoe lifter, being a rotating device by which the beet are first kicked loose, then grabbed and finally lifted (Figure 3.5);
- Inclined, contrarotating rollers with a helical outer (transport) profile that combine soil loosening and initial lifting by the soil-engaged front of the rollers and further upward transport of the beet by the remaining part of the rollers (Bouma *et al.*, 1983);
- The lifting belt, consisting of two inclined belts between which the leaves are clamped and by which the beet are pulled out of the soil as the belts proceed.

A hand tool to uproot topped beet, called beet pliers (Figure 3.6), was developed in the Netherlands. The uprooting procedure included grabbing the above-ground top of the beet by the pliers, rotating the beet, usually clockwise, by turning the handles of the pliers to loosen the beet and, finally, pulling the beet out of the ground. Beet pliers were used to a great extent to uproot topped beet, both in whole fields and, in field corners that could not be reached by tractor-drawn lifters.

Through the development of combining all harvesting phases in one operation around 1980, a smooth (uninterrupted) transition of the beet from the uprooting device to the subsequent device for transport or cleaning became a new, important aspect of the performance of uprooting devices (Ditges, 1990). Currently, most beet in the Netherlands are harvested by contractors, with self-propelled complete beet harvesters. To operate these machines in a cost-effective manner, their capacity

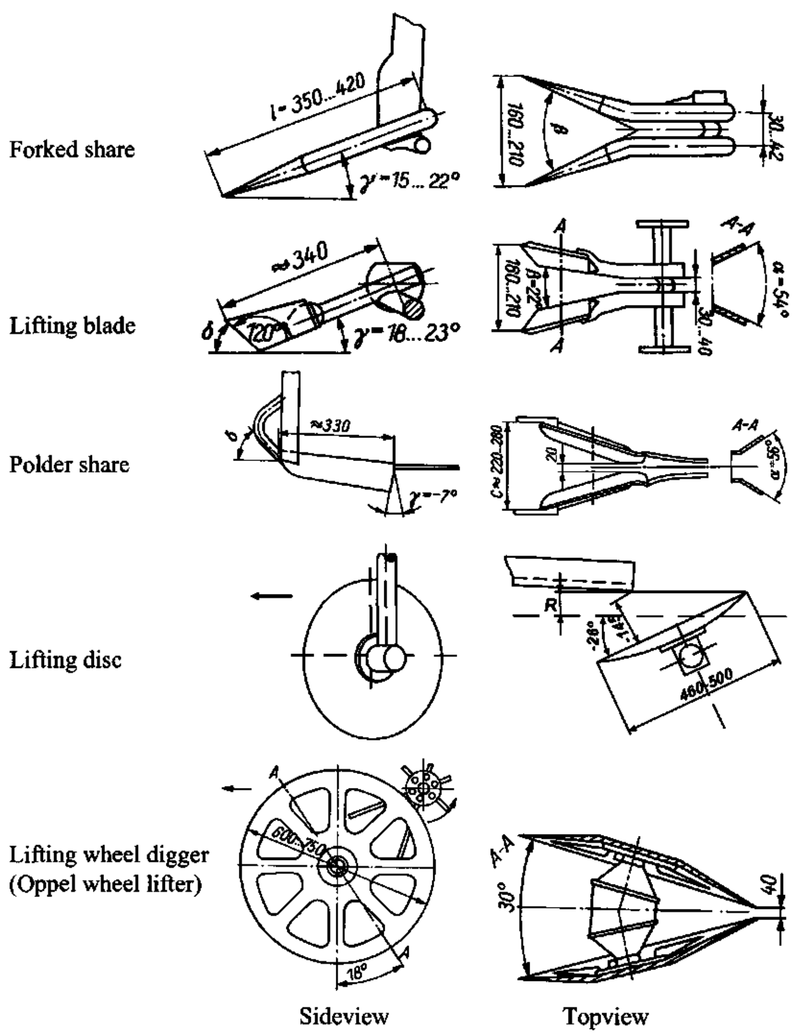


Figure 3.4. Main types of lifters used (Karwowski, 1974; Ditges, 1990). Dimensions in mm.

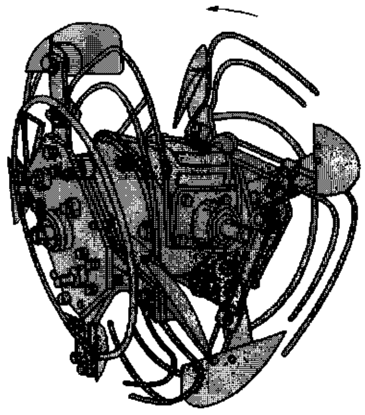


Figure 3.5. Driven rotary-shoe lifter.

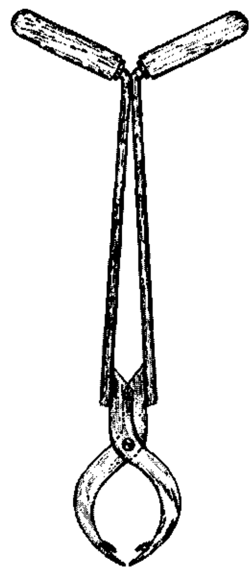


Figure 3.6. Beet pliers (Anon., 1958).

should be high, they must be suitable to operate on a broad range of soil types and soil conditions and they must be mechanically reliable. Therefore, the uprooting devices, used in these harvesters, should also comply with these performance requirements, in addition to the requirement of a satisfactory quality of uprooting. Currently, the most widely-used share type in practice is the polder share. Apparently, this share type complies best with the various performance requirements mentioned. The renewed interest in improving the harvesting quality aspect of machinery performance justifies research aimed at improvement of the uprooting quality of beet lifters, as described in this thesis. However, it should be realised that all performance requirements should be met when introducing newly developed uprooting techniques in practice.

3.4.2 Leaf stripping, crown cleaning and topping

It is generally assumed that the method of leaf stripping and of topping, influences only the topping quality and not the quality of the subsequent uprooting process. However, Bouma & Cappon (1988) and Fritzsch *et al.* (1976, 1977) reported that intentional knocking at the sides, or on top of the beet, in between topping and uprooting can have a decreasing effect on soil tare. This effect occurred when the beet were uprooted by extraction, and did not occur when the beet were uprooted by a conventional lifter (Bouma & Cappon, 1988; Van Der Linden, 1990). Therefore, methods of leaf stripping and of topping that differ in the amount of mechanical agitation of the beet during the process, may influence the quality obtained after uprooting by extraction. During the experimental work described in this thesis, only leaf stripping with the lowest possible beet agitation was applied before uprooting. The possible effect of beet agitation on soil tare was incorporated in the experiments described in this thesis by examining the effect of high lifting accelerations.

3.4.3 Uprooting

To assess the quality of uprooting *per se*, the assessment should be made after uprooting with stand-alone uprooting devices, without any subsequent transport or cleaning. Such data are reported for various lifters (Bouma & Cappon, 1988; Ditges, 1990), for beet pliers (Strooker & De Widt, 1957; Strooker, 1960; Strooker, 1962) and for experimental beet pullers (Fritzsch *et al.*, 1976, 1977; Bouma & Cappon, 1988; Voesten, 1993).

Bouma & Cappon (1988) found no significant differences in adhering-soil tare and in dug losses in an experiment with fixed polder shares and driven polder shares, operated at three driving speeds, on moist clay soil (Table 3.3). Under their experimental conditions, the dug losses were very low. The same authors reported that the adhering-soil tare could be substantially reduced, particularly on wet clay soil, by applying compressed air through a vent in the lifter share. However, the additional power required, about 34 kW per crop row, rendered the system uneconomic.

Ditges (1990) reported that the soil tare at the end of the uprooting phase ranges from 102 to 911 (% *w/w*, net) (Table 3.4). He obtained these data by analysis of the beet-soil mixture, coming off various stand-alone lifters, which he collected on a strip of sheet material, uncoiling just after the lifter. Most of the soil coming off the

Table 3.3. Adhering-soil tare and dug losses after uprooting sugar beet with fixed and driven polder shares, working at 8 cm depth, at three driving speeds, on moist clay soil with 30% (*w/w*, d.b.) particles < 16 μm (Bouma & Cappon, 1988).

Share type	Driving speed ($km\ h^{-1}$)	Adhering-soil tare (% *w/w*, net)	Dug losses (% *w/w*, net)
Fixed	1.6	64	0.2
	3.5	96	0.0
	5.7	75	0.2
Driven	1.6	45	0.2
	3.5	59	0.5
	5.7	56	0.4

lifters was loose soil. The adhering-soil tare varied from 12 to 134% and was lowest for a polder share lifter combined with a lifting rotor, both under favourable (12%) and under unfavourable conditions (68%) on clay soil. The same lifter also resulted in the lowest loose-soil tare figures, 90% under favourable and 204% under unfavourable soil conditions. Mechanical raising of the beet up and above the soil during lifting thus may offer an opportunity to reduce the loose-soil tare and the adhering-soil tare at the end of the uprooting phase, at least under certain conditions.
A summary of the available data on the quality of uprooting by extraction, including those already presented in Figure 3.2, is presented in Table 3.5. The reported adhering-soil tare range after extraction with a combined upwards and rotary motion, is 5 to 43 (% *w/w*, net), which is clearly lower than the range of 10 to 110 (% *w/w*, net) reported after extraction with a straight-up motion. As the beet are elevated above the soil surface, the loose-soil tare of extracted beet is considered to be 0%. At extraction with a straight-up motion, no dug losses occurred. At extraction with a combined upwards and rotary motion, up to 6% dug losses occurred with the highest values under dry soil conditions (Voesten, 1993). Superficial damage was not reported.

Experiments, in which the uprooting quality of beet pliers or beet pullers is directly compared with the uprooting quality of conventional lifters, have not been reported. However, the effect of beet pliers and of an experimental beet puller have been compared with the effect of complete harvesting systems (Table 3.6). These experiments lead to the interesting conclusion that the adhering-soil tare just after

Table 3.4. Soil tare, loose-soil tare and adhering-soil tare after uprooting by various lifters, under favourable (relatively dry) and unfavourable (relatively wet) soil conditions (Ditges, 1990).

Type of lifter	Soil condition	Soil tare (% *w/w*, net)	Loose-soil tare (% *w/w*, net)	Adhering-soil tare (% *w/w*, net)
Polder share	favourable	527	499	28
	unfavourable	574	465	109
Driven polder share	favourable	597	567	30
	unfavourable	547	443	104
Polder share + lifting rotor	favourable	102	90	12
	unfavourable	272	204	68
Lifting wheel digger	favourable	619	604	15
	unfavourable	786	706	80
Lifting disc + subsoiler	favourable	371	359	12
	unfavourable	798	687	111
Forked share	favourable	887	862	25
	unfavourable	911	777	134

uprooting by extraction, with a combined upward and rotational motion, is about equal to the soil tare after a complete harvesting process, including beet cleaning. Moreover, Strooker (1960) and Voesten (1993) suggested, on the basis of visual observation, that the soil adhered weakly to the beet after extraction, compared with the situation after conventional harvesting, including cleaning. Strooker (1960, 1962) collected data during sugar beet harvesting demonstrations. Amongst the harvesting systems tested was also a system with a driven rotary-shoe lifter (Figure 3.5). Compared with other harvesting systems and with uprooting by beet pliers, the soil tare of the system with the driven rotary-shoe lifter was unexpectedly low on heavy clay soil, under very wet conditions (Table 3.6).

No direct comparison of uprooting by extraction and uprooting by stand-alone

Table 3.5. Summary of data reported on the quality of uprooting of beet pliers and (experimental) beet pullers.

Source	Device	Soil type	Indication of the soil condition	Motion of extraction	Adhering-soil tare (% *w/w*, net)	Dug losses (% *w/w*, net)
Strooker & De Widt (1957)	pliers	clay	wet	rotate, then up	26	0
Strooker (1960)	pliers	clay	dry	rotate, then up	12	0.1
Strooker (1962)	pliers	heavy clay	very wet	rotate, then up	36	1.7
Fritzsch *et al.* (1976)	puller	loam	very wet	straight up	75	n.a.
				rotating up	35	n.a.
			moist	straight up	35 - 80	n.a.
				rotating up	15 - 35	n.a.
Fritzsch *et al.* (1977)	puller	loam	wet	straight up	50 - 110	n.a.
				rotating up	20 - 30	n.a.
		sandy loam	moist	straight up	10 - 80	n.a.
				rotating up	10 - 30	n.a.
Bouma & Cappon (1988)	pliers	clay	moist	straight up	56	n.a.
				rotating up	21	n.a.
			wet	straight up	78	n.a.
				rotating up	43	n.a.
Voesten (1993)	puller	heavy clay	n.a. [1])	straight up	25 - 43	0
				rotate, then up	5 - 15	1- 6

[1]) No data available.

lifters was reported. However, we estimate from the results in Tables 3.4, 3.5 and 3.6 that:

- The adhering-soil tare after straight up extraction is about the same as the adhering-soil tare after lifting by stand-alone conventional lifters;
- The adhering-soil tare after extraction with a spiral extraction path is about one-third to half of the soil tare after lifting by stand-alone conventional lifters;
- The loose-soil tare after extraction is 0%.

No quantitative data have been reported to confirm that the soil adheres weaker to the beet after extraction than after lifting by a usual lifter.
Low soil tare was also observed with a lifter that raised the beet higher than normal, above the soil (Ditges, 1990) and, under wet, unfavourable conditions, with a driven rotary-shoe lifter, that agitates the beet more than normal (Strooker, 1962).

Effect of lifter adjustments on the quality of uprooting
Share adjustments that may affect the quality of uprooting are the working depth, the forward speed, the width of the share and, for driven shares, the frequency and amplitude of the vibrating movement.

Table 3.6. Mean adhering-soil tare after uprooting by extraction and after complete harvesting processes, including cleaning.

Source	Soil type	Indication of the soil condition	Harvesting system	Adhering-soil tare (% *w/w*, net)
Strooker & De Widt (1957)	clay	wet	beet pliers	26
			two-stage system	25
			complete system	28
Strooker (1960)	clay	dry	beet pliers	12
			complete system	6
			system with driven rotary-shoe lifter	7
Strooker (1962)	heavy clay	very wet	beet pliers	36
			complete system	51
			system with driven rotary-shoe lifter	11
Voesten (1993)	heavy clay	n.a. [1])	extraction; straight up	43
			extraction; rotate, then up	15
			complete beet harvester	12

[1]) No data available.

The choice of the working depth of lifter shares is a compromise between soil tare and dug losses. When the working depth is small, the horizontal forces applied by the lifter act high on the beet and root breakage occurs easily. The soil tare is low when the shares are adjusted to a small depth, because not much soil is taken up by the shares. The opposite, *i.e.* little root breakage and high soil tare, occurs when the shares work deep in the soil. Under wet conditions, root breakage occurs more easily and soil tare is higher than under dry conditions. Therefore, the working depth of lifter shares is usually set shallower on wet soils than on dry soils (Von Hülst *et al.*, 1957; Göhlich & Von Hülst, 1958; Strooker, 1960; Hingst, 1962; Gemtos, 1979; Wevers, 1980; Miller, 1982; Van Der Bijl, 1989; Van Der Linden, 1992). Göhlich & Von Hülst (1958) and Hingst (1962) reported that root breakage is much less of a problem with lifting wheel diggers than with share lifters, because the beet are lifted almost straight up. The adjustment of the working depth of the lifting wheel digger may be optimised for soil tare only.

The horizontal forces acting on the beet will probably increase with an increase in the forward speed of share lifters, due to inertial effects in the soil. As a result, the bending stress in the beet material will increase and, hence, root breakage will increase. However, Bouma & Cappon (1988) observed no significant effect of the forward speed on the quality of uprooting by a polder share, in the range from 1.6 to 5.7 km h^{-1} (Table 3.3).

Root breakage can be reduced by increasing the width of the shares, *i.e.* by increasing the angle between the shares in the horizontal plane. However, this change of adjustment increases the amount of soil taken up by the lifter and, hence, increases soil tare (Heller, 1960).

For driven shares, the frequency and amplitude of the vibrating movement may be suspected to affect the uprooting quality. Though a wide range of frequencies and amplitudes has been applied on commercial equipment, the effect on the quality of harvesting and of uprooting have not been published.

3.4.4 Cleaning

The objective of the cleaning process is to remove soil, stones and loose leaf parts from the material lifted by the uprooting device. In studies on the cleaning of beet (Brinkmann, 1980; Ditges, 1990), the part to be removed from the incoming material is usually subdivided into the fractions loose soil (including stones and loose leaf parts) and adhering soil, which needs a different cleaning approach. For a specific cleaning device, the adhering soil is sometimes further subdivided into the fractions 'removable' and 'non-removable' adhering soil (Brinkmann, 1985; Ditges, 1990). The adhering soil fraction designated as non-removable comprises soil located in the grooves of the beet, which could not be removed by the cleaning device, even after extended cleaning. The most commonly-used devices for beet cleaning (Figure 3.7) were described in detail by Karwowski (1974) and Ditges (1990).

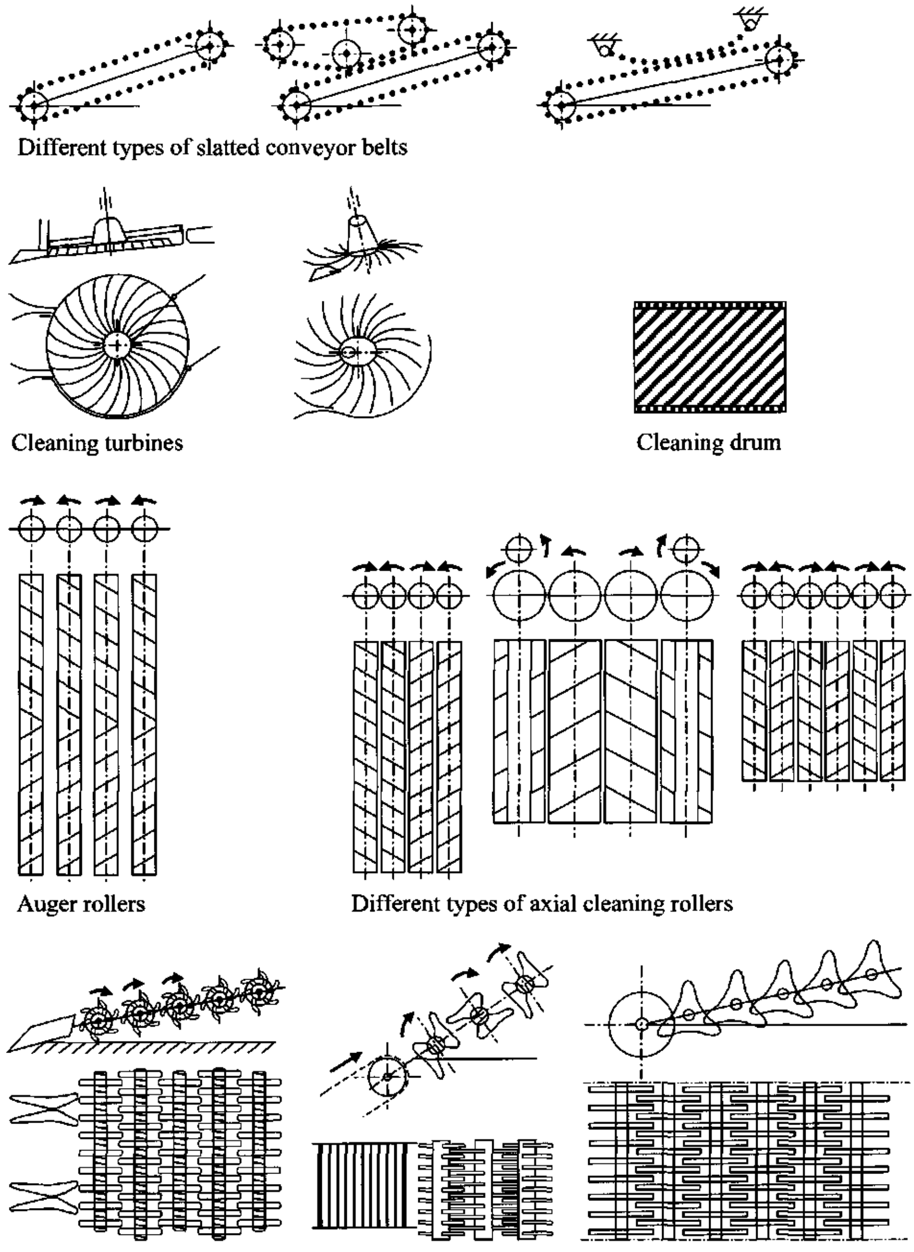


Figure 3.7. Main types of cleaning devices; redrawn and adapted from Karwowski (1974) and Ditges (1990).

The first step in the cleaning process is to remove the loose soil. For this purpose, the main types of cleaning devices use large openings, allowing loose soil aggregates to pass as quickly as possible and preventing beet with a diameter > 45 mm to pass.

The adhering soil is removed in the next cleaning step(s). For this purpose, the same types of devices as for the removal of loose soil are used, although with smaller grate openings. The goal of this part of the cleaning process is to loosen up the adhering soil by a combination of impact, rubbing and scraping and, simultaneously, removing the loosened soil by sieving. Though all common cleaning devices use a combination of cleaning principles, differences between cleaning devices exist due to the emphasis put on one of the principles. Impact occurs mainly due to frontal collision of beet with machine parts and with each other. Due to these collisions, stresses are set up in the adhering soil, either directly by the collision forces or indirectly by inertial forces. In part of the soil these stresses will exceed the failure stress and the soil will crumble or deform, depending on the plasticity of the soil. Rubbing occurs mainly due to sliding collision of beet with machine parts and with each other. Scraping may occur whenever protruding machine parts penetrate the adhering soil.
The cleaning effect improves when the cleaning period is extended and when the devices are adjusted increasingly aggressive, *i.e.* when increasing the system speed and, hence, the forces associated with impact, rubbing and scraping are increased. However, the overall quality of cleaning may worsen due to increasing superficial damage, root fracture and beet losses. Generally, the cleaning effect decreases with increasing throughput of material and, hence, the forward speed of the harvester. Examples of the effects of cleaning period, system speed and forward speed on the quality of cleaning are reported by Ditges (1990) and by Kromer *et al.* (1990), amongst others.

The effect of uprooting quality on cleaning quality is of major interest in relation to the objective of the research work described in this thesis. Green (1957) particularly addressed this question. Beet were used, that were carefully dug out of moist heavy clay soil (moisture content 21.6-36.1 (% *w/w*, d.b.)) and out of wet heavy clay soil (moisture content 37.6-40.7 (% *w/w*, d.b.)), having an adhering-soil tare of 60 to 72 (% *w/w*, net) and 78 to 88 (% *w/w*, net), respectively. These beet were fed into a slatted drum, which rotated around its horizontal axis. The loss of mass was recorded for each rotation of the drum and the adhering-soil tare was calculated (Figure 3.8). The decrease in adhering-soil tare per rotation of the drum was substantially bigger for the moist than for the wet soil. Particularly for adhering-soil tare levels below about 20%, the decrease in adhering-soil tare per rotation of the drum was very small for the wet soil. Green (1957) stated that this phenomenon was 'probably due to the soil being puddled (*plasticated, author*), and packed into the grooves of the beet by the action of the drum'. Consequently, Green (1957) suggested that packing and plastication of the soil should also be avoided during

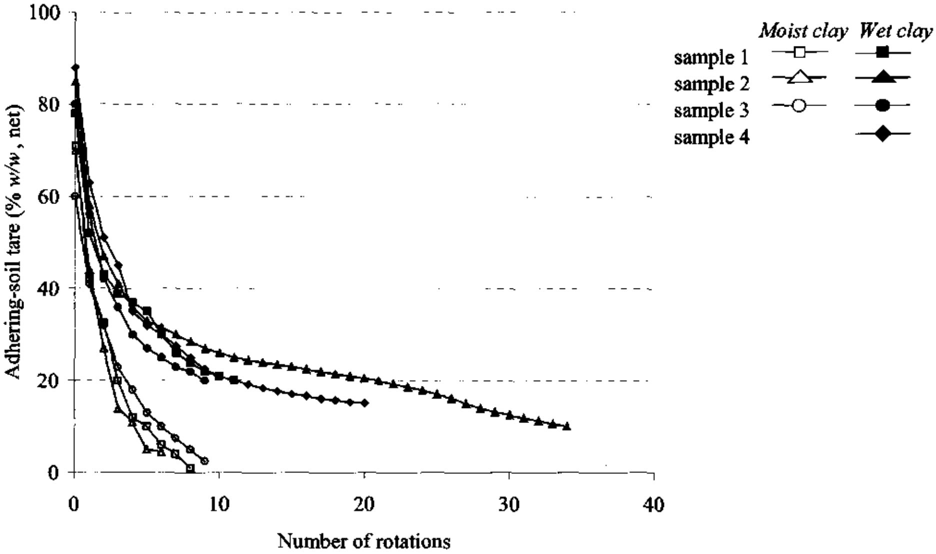


Figure 3.8. Adhering-soil tare of sugar beet after consecutive rotations (expressed as the total number of rotations) of a slatted drum filled with carefully uprooted beet, for moist (m = 21.6 to 36.1 (% *w/w*, d.b.)) and wet (m = 37.6-40.7 (% *w/w*, d.b.)) heavy clay soil, based on data of Green (1957).

uprooting, which led to his practical statement that 'beet should be cleaned on lifting by an action working on the beet crowns and not the sides'.
Bulich & Kromer (1986) reported that the (output) soil tare after cleaning decreases with decreasing (input) soil tare of the beet fed into the cleaning section of the harvester by the uprooting device. In their experiment, the total input soil tare used was 1000 or 500 (% *w/w*, net), with a difference only in the loose-soil tare. The output soil tare, using equal cleaning treatments, was 34 and 11 (% *w/w*, net), respectively. The experiment was performed using moist soil conditions, when the soil crumbled under stress. For wet soil, no data are reported.

In all common cleaning devices, stresses in the soil are induced by loading with solid machine parts or by inertial forces. It was concluded from the reports on the cleaning of beet that the best potential for cleaning occurs when the uprooting quality is such that:

- Loose-soil tare and adhering-soil tare are minimal;
- The soil adhering to the beet is not plasticated;
- The soil is not packed in the grooves of the beet.

3.4.5 Hopper loading, hopper storage and hopper unloading

During hopper loading, hopper storage and hopper unloading, the harvesting quality may be affected due to impact, when beet are not delivered smoothly from one transport device to the other, or when drop heights are excessive. These effects are not expected to be factors that play a role in establishing the desired quality of uprooting, and therefore not further discussed in this thesis.

3.4.6 Complete harvesting system

The harvesting quality of complete harvesting systems is regularly measured at sugar beet harvesting demonstrations. One may assume that the manufacturers of harvesting machines see to it that the best possible harvesting performance is obtained at these occasions. Progress has certainly been made in terms of increased capacity, reduction of labour requirement and the ability to work under adverse conditions. To get an impression of the progress made in harvesting quality, results of demonstrations under favourable and under unfavourable soil conditions, on heavy soil, were selected from around 1960 and around 1990 (Table 3.7). The soil condition was qualified as favourable when the soil was dry and easy to crumble, and as unfavourable when the soil was wet and sticky, based on the available information, which was also qualitative in nature. The harvesting systems from around 1990 are not considerably improved in terms of obtainable quality of harvesting, compared with the systems from around 1960. Based on Tabel 3.7, Brinkmann (1986b) and Kromer (1989), it is roughly estimated that the soil tare (% *w/w*, net) on heavy soil, in the hopper of the harvester, was about:

Table 3.7. Quality of harvesting obtained at harvesting demonstrations on heavy soil, around 1960 and around 1990.

Source	Year	Soil condition	Mean soil tare (% *w/w*, net)	Total losses (% *w/w*, net)	Superficial damage (cm^2 $beet^{-1}$)
Strooker (1960) [1]	1959	very favourable	6.6	1.2 - 6.1	n.a. [6]
Strooker (1962) [2]	1961	very unfavourable	48.8 [5]	4.4 -11.7	n.a.
Kromer *et al.* (1990) [3]	1988	favourable	12.1	3.0 - 5.4	1-7
Anon. (1991) [4]	1991	very unfavourable	61.3	4.7 - 8.2	n.a.

[1]) Rozenburg, the Netherlands.
[2]) Elst, the Netherlands.
[3]) Seligenstadt, Germany.
[4]) Revelon, France.
[5]) Excluding the Vicon-Steketee systems with a driven rotary-shoe lifter, which performed extremely well at this demonstration; the mean soil tare of these systems was 10.7 (% *w/w*, net).
[6]) No data available.

- 7% under very favourable conditions (relatively dry and friable);
- 12% under favourable conditions (relatively medium wet and friable);
- 20% under unfavourable conditions (relatively medium wet and firm);
- 55% under very unfavourable conditions (relatively wet and sticky).

Systems with additional beet cleaning by brushes, sieve belts and cleaning rollers, amongst others, have been tried in practice since about 1980 and were reported to lower the soil tare, particularly on the lighter soils (Wevers, 1980; Brinkmann, 1986b; Bouma & Cappon, 1988; Ditges, 1990; Van Der Linden, 1995a, 1995b). Currently, net soil tare levels exceeding 25% (*i.e.* 20% *w/w*, gross) are considered extremely high, even when harvesting took place under very unfavourable conditions. This reduction in soil tare, compared with 1990, has been reached by a combination of shallower adjustment of the lifting shares, sometimes at the expense of increasing the dug losses, extended cleaning facilities on the harvester, and by cleaning more aggressively, sometimes at the expense of increasing the superficial beet damage (Van Der Linden, pers. comm.). Additional cleaning equipment has been build in many harvesters in the Netherlands since 1996, when investment in equipment to lower the soil tare was made tax deductible.

Some harvesting systems were reported to show low soil tare under certain conditions, but were never applied on a large scale in practice, or are less popular at the moment.
The first system that should be mentioned is the extraction of beet with beet pliers or beet pullers. While this system was relatively popular when harvesting was done by manual labour, it gradually disappeared when the harvest was mechanised. Obviously, the capacity of beet pliers was very low compared with the harvesting machines. Beet extraction was not mechanised because of the complexity of the engineering involved (Green, 1957; Schuh, 1989; Schuh & Höhn, 1991).
A two-stage harvesting system in which the beet are uprooted and left in a swath on the field to dry up or to let the adhering soil weather, may result in low soil tare in practice (Van Der Bijl, 1989; Brooymans, 1992; Van Der Linden, 1990, 1992). Under drying conditions, much of the adhering-soil tare is easily removed during loading of the beet in a trailer. The effect of wet weather conditions during field drying on soil tare has not been properly investigated. The main disadvantage under the conditions in the Netherlands, where harvesting is mostly performed by contractors, is that the planning of operations for the two-stage harvest is more complex than for the one-stage harvest. Reasons for this complexity are that each beet field has to be treated twice and that the second operation is critical in terms of weather conditions. Another disadvantage of the two-stage system is that beet in a swath are prone to frost-damage.
Systems applying uprooting by a driven rotary-shoe lifter have shown to perform well, especially on heavy soil under very wet conditions (Strooker, 1962; Remijn, 1986). These systems were used on many Dutch farms around 1960, but disappeared gradually because the manufacturer stopped production. Reasons

mentioned for quitting the production include disappointing uprooting quality of multiple-row units, compared with the original one-row unit, non-competitiveness with the relatively low-cost share lifters and excessive superficial beet damage. These reasons could not be found out from first hand, however.

Systems with additional beet cleaning by brushes, sieve belts and cleaning rollers have been tried in practice since about 1980 and were reported to lower the soil tare, particularly on the lighter soils (Wevers, 1980; Brinkmann, 1986b; Bouma & Cappon, 1988; Ditges, 1990). Additional cleaning equipment has been build in many harvesters in the Netherlands since 1996, when investment in equipment to lower the soil tare was made tax deductible.

3.5 Uprooting techniques with potentiality to reach low soil tare

A very interesting conclusion from the previous literature review is that soil tare after beet extraction with beet pliers or beet pullers, grabbing the top of the beet, was sometimes about equal to the soil tare after a complete modern harvesting process. The best results are reported for extraction with a combined straight upwards and rotating motion. It was also reported that the adhering soil after extraction seems to adhere less strongly to the beet surface than after a modern harvesting process. It is to be expected that, potentially, beet with weakly-adhering soil are easier to clean than beet with strongly-adhering soil. Therefore, improvement of the uprooting process on the basis of beet extraction seems promising and was adopted as the first direction of research for the work described in this thesis. Another interesting reported effect is that beet agitation just before uprooting can reduce the soil tare after uprooting, especially when beet are extracted. Beet agitation means that the beet is strongly accelerated during a very short time. Therefore, a high initial acceleration of the beet, integrated in the extraction process, might also reduce the soil tare after extraction. For this reason, investigation of the effect of beet acceleration during extraction was adopted as the second direction of research for the work described in this thesis. Revealing the causes of low soil tare and weak soil adherence after beet extraction might offer a point of departure for developing improved uprooting devices other than complex mechanised beet pullers.

The polder share is currently the most widely used uprooting device with great practical value in terms of meeting the requirements of all aspects of machinery performance including an acceptable uprooting quality. Therefore it seemed logical to adopt this device as a reference. The driven rotary-shoe lifter, which has proven to be applicable in practice, was included in the experiments to confirm that this device shows low soil tare on wet clay soil, as was reported once. Considering the fact that the emphasis is currently on the quality aspect of machinery performance, the driven rotary-shoe lifter might be developed to meet the current requirements of machinery performance.

CHAPTER 4

Field experiments

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

4.1.1 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 adhering-soil tare (on clean beet basis) and the relative soil adherence at the stage between lifting and cleaning of beet produced on marine clay loam soils in 1994 and 1995. In the reference treatment, the beet were dug out carefully. The extraction treatments used were vertical (non-spiral), large-pitch-spiral and small-pitch-spiral lifting paths at slow, moderate and quick accelerations. The soil tare was lowest for the quick, small-pitch-spiral motion: respectively 14% in 1994 and 6% in 1995 for comparable beet characteristics 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

4.1.2 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 beet 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 machines 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, 1986b). 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 beet 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 thesis, 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 slatted conveyor belts or turbines, has been recently achieved without excessive beet damage by applying axial roller beds combined with brushes or compressed air (Van Der Linden, 1995a, 1995b). 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 beet 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 machines 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 optimising 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 adhering-soil tare, soil adherence and, less extensively, on other aspects of the uprooting quality of sugar beet, in relation to characteristics of the soil and the beet. Since field methods to characterise the soil adherence have not been reported, a method had to be developed.

4.1.3 Materials and methods

Treatments

Ten treatments with different beet extraction kinetics, including a reference treatment, were applied in the experiments. Each extraction treatment was a combination of a specific lifting path and a vertical acceleration, as presented in Table 4.1.1. All ten treatments were applied in 1994, while only the three most interesting treatments, including the reference treatment, were applied in 1995.
The previously defoliated beet were extracted by the 'Subitrek' (Figure 4.1.1). The

Table 4.1.1. Designation of the extraction treatments.

Lifting path	Vertical acceleration			
	very slow	slow	moderate	quick
Non-spiral	R	NS1	NS2	NS3
Large-pitch-spiral	-	LPS1	LPS2	LPS3
Small-pitch-spiral	-	SPS1	SPS2	SPS3

Figure 4.1.1. The mobile experimental beet puller 'Subitrek'.

Subitrek is a vehicle with an instrumented, hydraulic beet pulling rig mounted in a sub-frame, specially built for these experiments. 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 4.1.2). 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 angular accelerations, were adjusted. After fine positioning and lowering of the grabber to the correct grabbing height the grabber

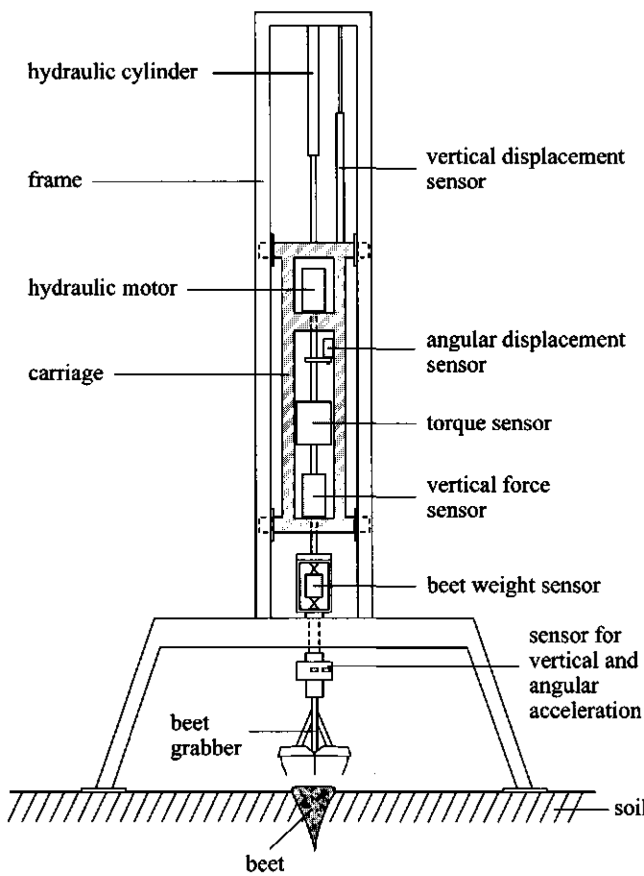


Figure 4.1.2. Schematic drawing of the pulling rig.

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 characterise 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 a '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 4.1.2.

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.

Table 4.1.2. Average kinetic characteristics of the extraction treatments.

Treatment	Vertical motion				Angular motion				Pitch
	t_a	a_{av}	a_{max}	v_f	t_α	α_{av}	α_{max}	ω_f	p_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	2,127	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 rev^{-1}).

Considerations for the experimental design

A pre-investigation with 30 beet, extracted from a small area in 1993 showed that the soil tare of individual, extracted beet had a coefficient of variation of about 33%. Due to this variability, it was expected that about 135 beet 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 uprooting qualities after a specific extraction treatment may be explained by the geometrical characteristics of the beet itself, the position of the beet in the soil and the characteristics of the soil surrounding the beet. In order to reduce the residual variance, a number of these characteristics 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 beet 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 characteristics 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 characteristcs were assumed to show little variation. Within each sub-block 40 beet were extracted, 4 per treatment in 1994. In 1995, each sub-block contained 12 beet, 4 per treatment on three days and 30 beet, 10 per treatment on the other six days.

Field and crop characteristics

The experimental fields were situated near Slootdorp (Wieringermeer Polder, north-western 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 4.1.3.

Table 4.1.3. Topsoil (0-25 cm) characteristics of the experiment fields in 1994 and 1995.

	Particle size range (% of mineral parts *w/w*)					
	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.

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 4.1.4.

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.

Characterisation 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 & Bakhtin, 1975); Hendrick & Bailey, 1982; Salokhe *et al.*, 1993; Tong *et al.*, 1994).

Table 4.1.4. Total soil porosity (% *v/v*) of the experiment fields in 1994 and 1995 (*se* = 0.6).

	Depth (cm)				
	0-5	5-10	10-15	15-20	20-25
1994	-	57.2	58.8	59.7	59.5
1995	55.2	55.2	55.7	55.8	56.2

The soil moisture content (m_d, % w/w, 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 characterised 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, % w/w, 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, % w/w, d.b.) was defined as m_d - m_r.

Characterisation of the individual beet
The parameters measured to characterise the geometry of each individual beet (Figure 4.1.3) included the height of the untopped beet above the soil surface (h, mm), the length of the untopped beet excluding the flexible part of the taproot (l_b, mm), the top height (l_c, mm), the length of the topped beet ($l = l_b - l_c$, mm), the underground length ($l_u = l_b - h$, mm) and the largest diameter (d, mm). In addition the clean mass of the topped beet (w_b, kg), the clean mass of the beet top (w_c, kg), the mass of the untopped beet ($w = w_b + w_c$, kg) and the number of tails 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, mm), the soil-beet contact area (S, dm^2) and the specific soil-beet contact area (S_s, dm^2 kg^{-1}) were estimated by:

$$d_s = \frac{l_u}{l} * d \qquad (4.1.1)$$

$$S = \frac{\pi}{100} * \frac{d_s}{2} * \sqrt{(\frac{d_s}{2})^2 + l_u^2} \qquad (4.1.2)$$

$$S_s = \frac{S}{w_b} \qquad (4.1.3)$$

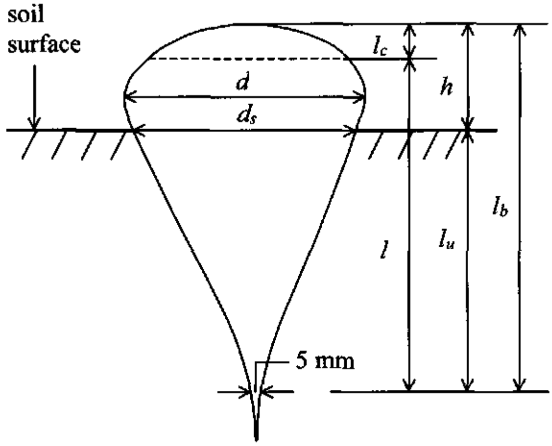


Figure 4.1.3. Parameters used to characterize the geometry of individual beet.

Measurement of adhering-soil tare

The adhering-soil tare (% *w/w*, net) 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 top 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 top 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 secondary roots. In principle, these compound stresses could be characterised 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 characterised by the energy to remove all soil from the beet but by the fraction of adhering soil, remaining after a specified cleaning treatment. This cleaning treatment was chosen such that virtually no soil was removed from beet 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:

$$RSA = T_s / T_a \qquad (4.1.4)$$

where

T_s = strongly-adhering-soil tare, remaining after a 'standard' cleaning treatment (% *w/w*, net);

T_a = adhering-soil tare before the 'standard' cleaning treatment (% *w/w*, net).

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 4.1.4). While rotating the beet round its length axis at 60 rpm in the grabber, the tube was pressurised (500-550 kPa) during one revolution of the beet.

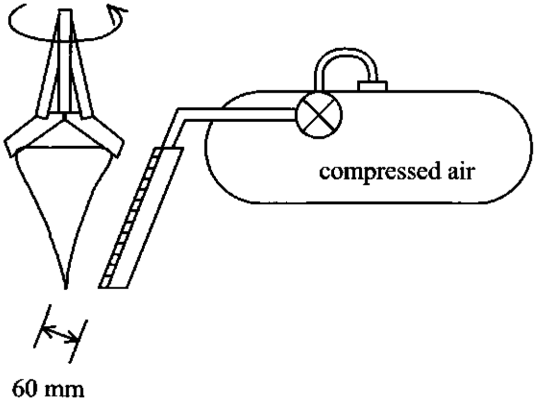


Figure 4.1.4. Schematic drawing of the 'standard' cleaning equipment.

Measurement of dug losses, superficial damage and crown fracture

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

$$\ln (DL) = C + a \ln (d_f / d) \qquad (4.1.5)$$

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 4.1.5 explained 86% of the total DL 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. Superficial damage clearly caused by other factors than the beet lifting action was not taken into account.

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

Statistical analysis

Effects of the extraction treatments on T_a and RSA were analysed with generalised 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 characteristics. The factor sub-blocks 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 (Payne *et al.*, 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 beet were used to calculate the expected uprooting quality of a reference beet lot for various circumstances. This reference beet lot was arbitrarily chosen to contain beet with characteristics equal to all those lifted in our beet experiments in 1995. The relevant characteristics of the reference beet lot are presented in Table 4.1.5.

Table 4.1.5. Distribution of the number of beet, 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^{-1})	Number of beet		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 beet	1,464	604	1.12	0.692	0.307	2.7

Due to the low occurrence of dug losses and superficial damage, the number of data pertaining to these uprooting qualities was insufficient for statistical analysis.

4.1.4 Results

Adhering-soil tare

It was concluded from statistical analysis of the data (Appendix 4.1.1) that the extraction treatments, the differential moisture content (Δm, % *w/w*, d.b.), the specific soil-beet contact area (S_s, dm^2 kg^{-1}) and the beet shape (normal or fanged) had a significant effect ($P < 0.05$) on the adhering-soil tare (T_a) 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 T_a 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 T_a (Figure 4.1.5). The T_a of fanged beet was higher than the T_a of normal beet, respectively by a factor 1.5 in 1994 and 1.2 in 1995.

The measured T_a data for the various extraction treatments in 1994 and 1995 were converted to values for the reference beet lot (T_{ar}) at three levels of Δm by model calculation (Table 4.1.6). In both years, increasing the vertical acceleration from very slow (treatment R) to quick resulted in a continuous reduction of T_{ar} by a factor 2 (for treatment NS3). Reducing the pitch from infinite (reference: treatment R) to 0.27 m rev^{-1} resulted in a systematic reduction of T_{ar} by at least a factor 3 (for treatment SPS1 in 1994). The combined use of high vertical acceleration and small

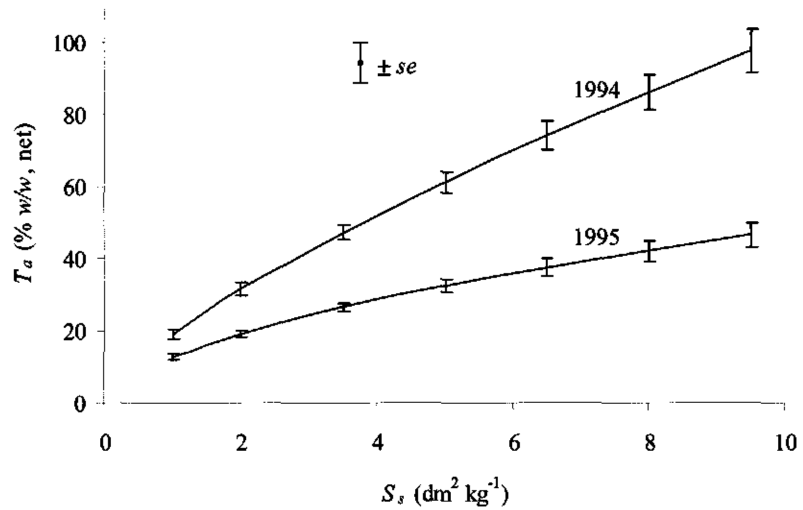


Figure 4.1.5. Relationship between the soil tare (T_a) and the specific soil-beet contact area (S_s) in 1994 and 1995 for extraction treatment NS3, normal soil moisture conditions (Δm = 0.5) and normally shaped beet.

pitch (treatment SPS3) led to a T_{ar} reduction factor of 6 and 8 for 1994 and 1995, respectively, when compared with treatment R. T_{ar} increased when the soil became wetter, irrespective of year and extraction treatment. Beet extracted from relatively wet soil (Δm = 5%) had *ca* 1.5 times as much soil tare as beet extracted from relatively dry soil (Δm = -4%).
Although estimated for comparable soil moisture conditions and beet characteristics in both years, T_{ar} appeared to be 1.6 to 2.3 times higher in 1994 than in 1995.

Relative soil adherence
It was concluded from statistical analysis of the data (Appendix 4.1.2) that the adhering-soil tare (T_a) 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 T_{ar} decreased, irrespective of the extraction treatment (Figure 4.1.6). This effect became substantial when T_{ar} became lower than *ca* 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 4.1.7 for normal beet with an adhering-soil tare of 10% (*w/w*, net).

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-soil tare of treatment R (T_s(R)). During a specific extraction treatment (X), a fraction of this soil (φ_l) was loosened and

Table 4.1.6. Measured adhering-soil tare (T_a) and adhering-soil tare calculated for 'standard' beet characteristics and soil conditions (T_{ar}, % *w/w*, net) 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 adhering-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 beet fanged; *cv* of T_a = 0.05.

[2]) Median adhering-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 beet fanged; *cv* of T_a = 0.04.

[3]) Predicted adhering-soil tare for the reference beet lot per extraction treatment and for differential soil moisture contents (Δm, % *w/w*, d.b.) of -4 (dry soil), 0.5 (normal soil) and 5 (wet soil). Reference beet lot (Table 4.1.5): median S_s = 2.7 $dm^2\,kg^{-1}$ (mean beet mass = 1.12 kg); 29% of beet fanged. *cv* of T_{ar} = 0.13.

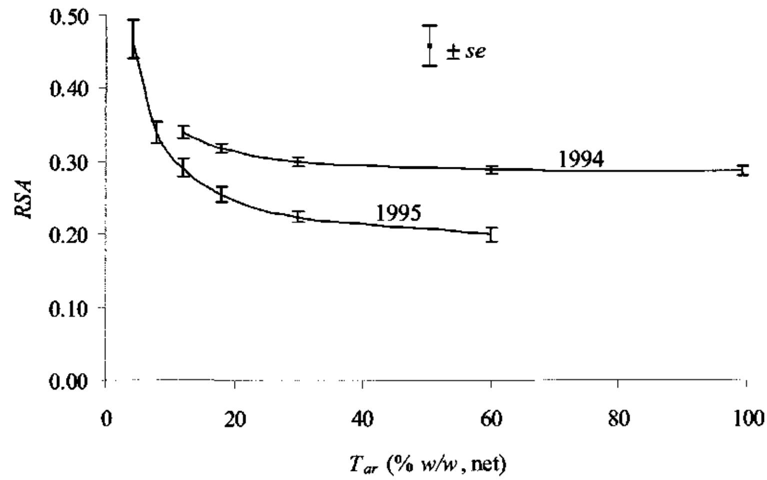


Figure 4.1.6. Relationship between the relative soil adherence (*RSA*) and the adhering-soil tare (T_{ar}) in 1994 and 1995 for the reference beet lot.

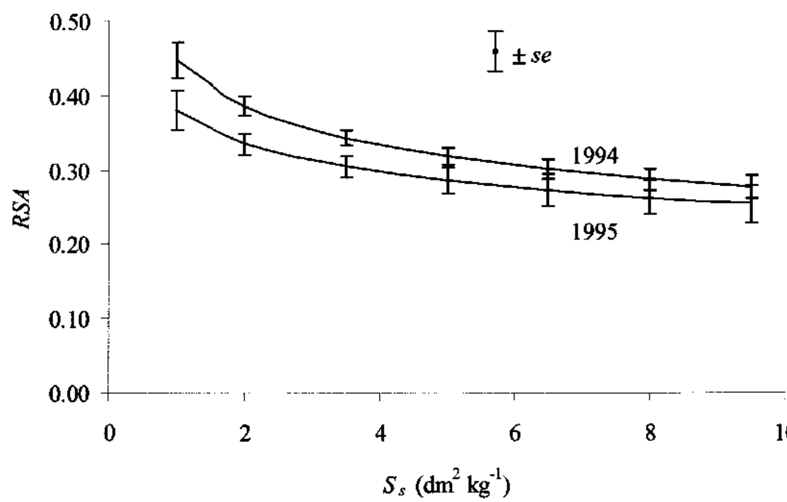


Figure 4.1.7. Relationship between the relative soil adherence (*RSA*) and the specific soil-beet contact area (S_s) in 1994 and 1995 for normally shaped beet and a soil tare of 10% (*w/w*, net).

removed by gravitational forces, a fraction (φ_w) was converted to weakly-adhering soil and a fraction (φ_s) remained strongly adhering. The soil fractions belonging to these adherence classes after the various extraction treatments were calculated as:

$$\varphi_l = 100 - \varphi_s - \varphi_w \qquad (4.1.6)$$

$$\varphi_w = 100 * \frac{T_{ar}(X)}{T_s(R)} - \varphi_s \quad (condition: \frac{T_{ar}(X)}{T_s(R)} \leq 1) \qquad (4.1.7)$$

$$\varphi_s = 100 * \frac{RSA(X) * T_{ar}(X)}{T_s(R)} \qquad (4.1.8)$$

The total soil loosening effect was characterised 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 4.1.8), being the treatment with the highest extraction acceleration and smallest pitch.

Dug losses, superficial damage and crown fracture
The highest mean dug losses per year were 0.5% for treatment SPS3 in 1995, which is very low compared with about 3.5% dug losses found for conventional harvesters (Anon., 1996). Therefore, analysis of the difference in dug losses between treatments was considered of little relevance.
Every beet showed three very small damaged spots where the grabber teeth had

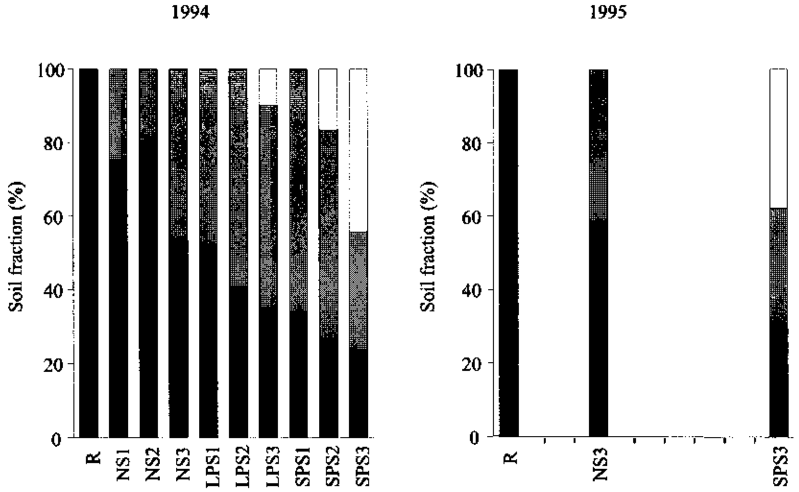


Figure 4.1.8. The amount of soil in the adherence classes strong (■), weak (▩) and zero (□) (loose soil) after the various extraction treatments, expressed in % (*w/w*) of the amount of strongly-adhering soil of treatment R in 1994 and 1995. The data pertain to the reference beet lot and normal soil moisture conditions ($\Delta m = 0.5$).

entered the beet. None of the treatments showed any further superficial damage as a result of the extractions.

In some cases crown fracture clearly happened because of the excessive extraction forces associated with beet 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 beet with a normal shape. Crown fracture tended to increase with increasing vertical acceleration and with reducing the pitch (Table 4.1.7). Thus, crown fracture was highest for treatment SPS3.

4.1.5 Discussion

The use of characteristics of soil and beet as covariables in the statistical analysis increased the precision of T_a estimation. This sophistication appeared to be superfluous for the purpose of detecting T_a differences between extraction treatments in this experiment. Even without accounting for the variation due to soil and beet characteristics, T_a 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 beet per treatment in 1994 and 1995, respectively) was sufficiently large to average out most of the differences due to the individual beet characteristics and the condition of the soil surrounding the beet. When comparing T_a values from various locations and beet lot characteristics, 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 T_a (Appendix 4.4.1). Statistical models with these factors, derived for each year of the experiment, were used to calculate T_{ar} for 'standard' beet characteristics and soil conditions (Table 4.1.6). The big differences in T_{ar} found between 1994 and 1995 were only partly explained by the predictors in the models, indicating that other non-measured soil and beet characteristics were responsible for the differences found for 'standard' conditions between years. The visually-observed fact that the

Table 4.1.7. Total number of beet extracted (n) and crown fracture (CF, % n/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

soil was much more friable in 1995 than in 1994 might explain why T_{ar} 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 characteristics 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 T_a 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 T_a 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 T_a 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 4.1.8 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 T_a on *RSA* might be detected by comparing the relationships between *RSA* and T_a 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 beet.

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 adhering-soil tare found for extraction treatment SPS3 (a_{av} = 8 m s^{-2}, p_f = 0.27 m rev^{-1}) was 5.3 to 17.6% (*w/w*, net) for the reference beet lot and a representative range of soil moisture conditions (Table 4.1.6). Since 55 to 75% of the tare soil after treatment SPS3 adhered weakly, it may be expected that further cleaning of the beet can be performed efficiently.

Dug losses and superficial 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 rev^{-1} to prevent excessive crown fracture and subsequent surface losses (> 3.5%) for the grabber design used. However, these conditions would severely restrict the potential to reach low T_a.

Practical application of a quick, small-pitch-spiral 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 grab lifting of individual beet, as described in this paper, needs complex engineering development and meeting the high capacity demands is problematic. Therefore, the potential for practical application of grab lifting 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-spiral extraction motion used in treatment SPS3. This lifter was used successfully 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 T_a and low *RSA*.

4.1.6 Acknowledgements

The personnel of the experimental farm 'Oostwaardhoeve' and B. Kroesbergen, S.H. Pronk and E.J. Wassink of the Soil Tillage Laboratory of the Agricultural University Wageningen are kindly thanked for their assistance in this research. We thank A. Keen (posthumously) and B. Engel (DLO Agricultural Statistics Group) for statistical assistance. This research was financially supported by the Ministry of Agriculture, Nature Management and Fisheries and the Institute of Sugar Beet Research (IRS) at Bergen op Zoom.

Appendix 4.1.1 Statistical analysis of data on adhering-soil tare

The statistical model for the expected $\ln(T_a)$ of individual beet was:

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

Description and estimated values and standard errors for the parameters in models for $\ln(T_a)$.

Parameter	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 content				
a	coefficient for Δm	0.055	0.004	0.041	0.008
$\overline{\Delta m}$	weighted mean of Δm	1.229		-0.867	
$\ln(S_s)$	ln (specific beet-soil contact area)				
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 T_a appeared to be significant only between one tail and more tails ($P < 0.05$). Therefore, this predictor was introduced in the model as the factor 'shape' having the values 'normal' and 'fanged'.

Appendix 4.1.2 Statistical analysis of data on relative soil adherence

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

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

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
$\ln T_a$	ln (soil tare)				
a	coefficient for $\ln T_a$	-0.438	0.101	-0.707	0.087
$\overline{\ln(T_a)}$	weighted mean of $\ln T_a$	3.713		2.810	
$(\ln T_a)^2$	(ln (soil tare))^2				
b	coefficient for $(\ln T_a)^2$	0.051	0.014	0.072	0.016
$\overline{\ln(T_a)^2}$	weighted mean of $(\ln T_a)^2$	14.47		9.03	
$\ln(S_s)$	ln (spec. beet-soil contact area)				
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	

4.2 Soil tare and relative soil adherence after uprooting of sugar beet by a share lifter, a driven rotary-shoe lifter and a grab lifter

4.2.1 Abstract

The soil tare of sugar beet from wet clay soils should be reduced to lower the cost and prevent some negative effects of soil tare. Commonly used share lifters press the soil on the sugar beet and, thereafter, the soil adheres strongly to the beet and is difficult to be removed by mechanical cleaning systems. With the objective to reduce adhering-soil tare and soil adherence, a grab lifter (extraction, three variants) and a driven rotary-shoe lifter were compared with a conventional driven polder share lifter in a field experiment on clay soil. Adhering-soil tare after quick extraction with a small-pitch-spiral motion was reduced by a factor 3.8 to 6.2, depending on the wetness of the soil. Relative soil adherence was reduced by a factor 1.5. Adhering-soil tare after lifting with a driven rotary-shoe lifter was reduced by a factor 3.7, irrespective of the soil wetness. Relative soil adherence was not reduced. For both uprooting methods, dug losses were slightly higher and superficial beet damage was lower compared with share lifting. While complex engineering and crown fracture hinder practical application of grab lifting, the driven rotary-shoe lifter offers good potential for reduction of soil tare in practice.

Keywords: sugar beet uprooting, soil tare, soil adherence.

4.2.2 Introduction

The soil tare, *i.e.* the relative amount of soil in sugar beet lots after harvest, should be reduced to lower the costs of transport, handling, separation and disposal. Lower soil tare also prevents associated soil erosion, spreading of soil born diseases and other possible negative effects on the environment. The soil tare, based on the clean beet mass (*w/w*, net), is usually highest for beet grown on heavy soils. *Anno* 1990, the expected soil tare, directly after harvest, was about 10% under favourable harvesting conditions to 55% under extremely unfavourable conditions. As about 2/3 of the sugar beet in the Netherlands are grown on clay soils and the soil at harvest is often wet, a significant reduction of soil tare under these conditions is expected to result in a significant reduction of the total amount of tare soil.

High soil tare on wet clay soils is attributed to the fact that currently used lifting shares compress and shear the soil around the beet. This action causes wet clay soil to be plasticated (*i.e.* show plastic behaviour and loss of the aggregate structure), and to adhere strongly to the beet, which renders the usual mechanical cleaning systems on beet harvesters ineffective (Green, 1957). To further increase the effectiveness of cleaning systems, a combination of a low quantity of adhering soil and weak soil adherence after uprooting of the beet may be regarded a prerequisite. Therefore, uprooting should preferably be performed such that the soil around the

beet does fracture without being compressed after fracture.
From a soil dynamical point of view, wet clay soil may fracture without subsequent compression when tensile stresses are generated in the soil, resulting in tensile failure. Because a beet is anchored in the soil, it is possible to generate tensile stresses by grabbing the beet by the crown and pull it out of the soil. Vermeulen *et al.* (1997) investigated various extraction treatments, using an experimental beet grabber. For this purpose, the ability of soil particles to stick together and to stick to the surface of the beet or to the rootlets, was quantified by the relative soil adherence (*RSA*), defined as the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment. They reported that:

- Very low adhering-soil tare (T_a) is possible on wet clay soil when beet are extracted with a spiral motion and high acceleration;
- *RSA* increases with decreasing adhering-soil tare, irrespective of the extraction variant, suggesting a natural cause for soil close to the beet surface to adhere stronger to the beet than soil far from the beet surface.

Practical application of a spiral extraction motion with high acceleration will require the development of a technique to transfer the required extraction and acceleration forces to the individual beet with a low incidence of crown fracture, and a work capacity competing with the currently-used polder share lifters. Application of individual beet grabbing needs complex engineering development, and meeting the high capacity demand is problematic (Swinkels, 1996). Therefore, the potential for practical application of individual beet grabbing is considered low on a short term, as also suggested by Schuh & Höhn (1991).

The driven rotary-shoe lifter, according to the Vicon-Steketee system, has been successfully used in practice around the year 1960 in the Netherlands. This lifter loosens the beet from the ground by a number of kicks with steel shoes, alternatingly from the left and the right side. The shoes have a working depth of about 5 cm. At the moment of contact with the beet, the relatively high circumferential speed of the shoe is in the direction opposite to the forward speed of the lifter. The resulting uprooting motion is expected to be more or less vertical with a high vertical acceleration. Torque, resulting in beet rotation, is also expected because beet-shoe contact occurs only on one side of the beet per kick. Therefore, compared with a share lifter, the uprooting principle of a driven rotary-shoe lifter was considered to closer resemble uprooting by accelerated spiral extraction, and might provide a practical means to achieve low soil tare and low soil adherence.

The objective of the research was to reduce soil tare and soil adherence of beet from wet clay soil by changing the beet lifting method. Therefore, the adhering-soil tare, relative soil adherence and other uprooting qualities of beet grabbing and a driven rotary-shoe lifter were compared with those of a conventional driven polder share. The results of a series of field experiments to compare these methods of uprooting are reported in this thesis.

4.2.3 Materials and methods

Five uprooting treatments were applied on previously-defoliated beet: lifting by a conventional driven polder share (PS), lifting by a driven rotary-shoe lifter (RS) and three variants of extraction by a beet pulling rig. The extraction treatments coincided with the variants that came forward as the most promising variants in experiments to optimise the extraction motion (Vermeulen *et al.*, 1997), and included:

- Very slow, non-spiral motion (R);
- Quick, non-spiral motion (NS3);
- Quick, small-pitch-spiral motion (SPS3).

The lifting treatments were performed with stand-alone lifters, *i.e.* without any transportation or beet cleaning. The conventional driven polder share (Figure 4.2.1.a) was mounted in a beet harvester on which the modules for leaf stripping, crown cleaning and topping were inactivated, and from which the axial rollers behind the lifting section, intended to form a beet swath, had been removed. The driven rotary-shoe lifter (Figure 4.2.1.b) was mounted in an original machine, trailed and driven by a tractor. The cleaning section on this machine was removed. Technical characteristics and adjustments of the uprooting equipment considered relevant in relation to soil tare, soil adherence and other uprooting qualities are presented in Table 4.2.1.

The extraction treatments were performed with a computer-controlled, instrumented beet pulling rig (Figure 4.2.1.c). After manually-controlled beet grabbing, control was taken over by the computer to perform a pull motion with the desired kinetic characteristics for each treatment (Table 4.2.2). A detailed description and operational details of the pulling rig are reported by Vermeulen *et al.* (1997).

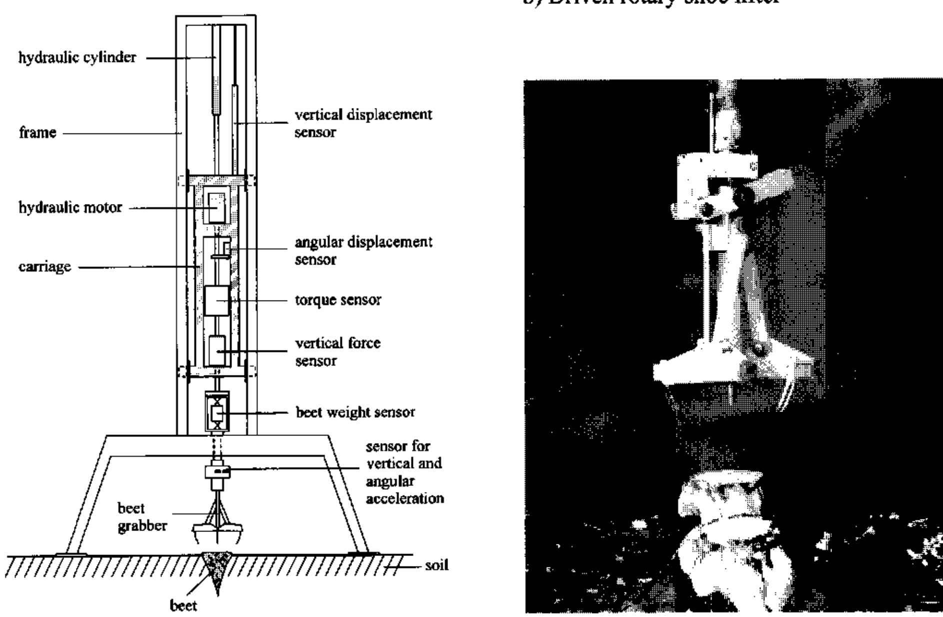
Table 4.2.1. Technical characteristics and adjustments of the beet lifters.

Characteristic	Driven polder share lifter (PS)	Driven rotary-shoe lifter (RS)
Average forward speed (m s^{-1})	0.91	1.20
Share drive type	vibrating, horizontally	-
Drive frequency (Hz)	7.16 (430 rpm)	-
Drive amplitude (mm)	10	-
Rotor speed (rad s^{-1})	-	18.85 (180 rpm)
Average working depth (mm)	32	48
Minimum space between shares (mm)	30	-

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 pulling rig 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 status of soil adherence equal to that prior to extraction.

a) Polder share lifter

b) Driven rotary-shoe lifter



c) Beet pulling rig (left) and detail of beet grabber (right).

Figure 4.2.1. Uprooting tools used in the experiment.

Table 4.2.2. Average kinetic characteristics of the extraction treatments: very slow, non-spiral motion (R), quick, non-spiral motion (NS3) and quick, small-pitch-spiral motion (SPS3).

Treatment	Vertical motion				Angular motion				Pitch
	t_a	a_{av}	a_{max}	v_f	t_α	α_{av}	α_{max}	ω_f	p_f
R	-	-	-	0.10	-	-	-	-	∞
NS3	0.197	7.2	32.0	1.38	-	-	-	-	∞
SPS3	0.183	7.7	36.2	1.39	0.052	642	2,127	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 rev^{-1}).

The field experiments were carried out on 6 days, equally spaced over the harvesting season 1995. Location specific variation was assumed to be low at small distances and high at large distances. As it was impracticable to randomly replicate all treatments within a test day over the field, one block was harvested on each test day. This block was subdivided into three sub-blocks in which the soil characteristics were assumed to show low variation. Within each sub-block, 10 consecutive beet in a beet row were collected and analysed per uprooting treatment, 50 in total.

The experimental field was situated in Slootdorp (Wieringermeer Polder, north-western part of The Netherlands). Mean annual rainfall at this location is 810 mm. The topsoil is clay loam (Anon., 1951). Analytical data of the topsoil are presented in Table 4.2.3. The field was mouldboard-ploughed in the autumn of 1994. 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 6 m. The plant density after germination was 81,200 ha^{-1}. Rows which were free of wheel ruts from sowing or crop protection operations on either side of the row were selected for the experiment.

Table 4.2.3. Topsoil (0-25 cm) characteristics of the experimental field.

Particle size range (% of mineral parts *w/w*)			$CaCO_3$ (% *w/w*)	pH (KCl)	Organic matter [1] (% *w/w*)
clay (< 2 μm)	silt (2-50 μm)	sand (> 50 μm)			
41-50	39-42	8-19	13.4	7.4	1.3

[1]) Istscherekov-elementary.

The total soil porosity in the layers 0-5, 5-10, 10-15, 15-20 and 20-25 cm was 55.2, 55.2, 55.7, 55.8 and 56.2% (*v/v*), respectively, determined once by taking twenty core samples randomly over the field (*se* = 0.6).
The wetness of the soil was characterised per sub-plot by the differential moisture content (Δm) of the top 5 cm of the soil. Δm was defined as the difference between the actual moisture content and a reference moisture content (% *w/w*, d.b.).
The actual soil moisture content (m_d) 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 moisture content of aggregates, equilibrated at a soil water matric potential of -10 kPa (pF2) was taken as the reference moisture content (m_r). 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 at the same time. After air drying of the samples in a thin layer, cylinders were filled with the aggregate fraction 3.4-5.0 mm. 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 parameters measured to characterise the geometry of each individual beet (Figure 4.2.2) included the height of the untopped beet above the soil surface (h, mm), the length of the untopped beet excluding the flexible part of the taproot (l_b, mm), the top height (l_c, mm), the length of the topped beet ($l = l_b - l_c$, mm), the underground length ($l_u = l_b - h$, mm) and the largest diameter (d, mm). In addition, the clean mass of the topped beet (w_b, kg), the clean mass of the beet top (w_c, kg), the mass of the untopped beet ($w = w_b + w_c$, kg) and the number of tails 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, mm), the soil-beet contact area (S, dm^2) and the specific soil-beet contact area (S_s, dm^2 kg^{-1}) were estimated by:

$$d_s = \frac{l_u}{l} * d \tag{4.2.1}$$

$$S = \frac{\pi}{100} * \frac{d_s}{2} * \sqrt{(\frac{d_s}{2})^2 + l_u^2} \tag{4.2.2}$$

$$S_s = \frac{S}{w_b} \tag{4.2.3}$$

The adhering-soil tare (T_a) was defined as the percentage of adhering soil on the basis of the mass of the clean, topped beet (% *w/w*, net). The dirty, untopped beet mass after lifting (treatments PS and RS) was measured by collecting the dirty beet by hand directly from the field, transport them carefully to the field laboratory and weigh them as soon as was feasible. For the extracted beet, the dirty, untopped beet

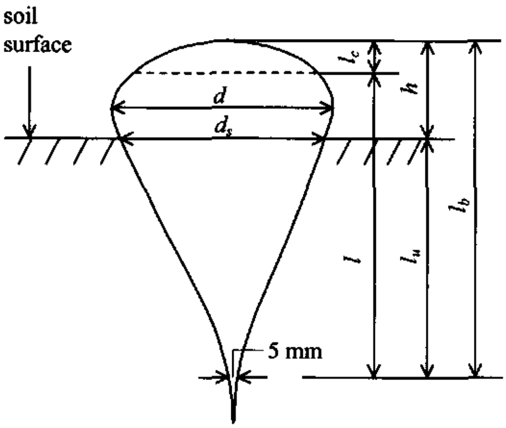


Figure 4.2.2. Parameters used to characterise the geometry of beet.

mass after uprooting was measured when the beet was still in the grabber, by a weighing facility built in the pulling rig. After cleaning the beet with a high pressure water cleaner and topping the beet by hand, the beet top 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 top was multiplied by a factor 0.955, to calculate the proper clean beet mass.

The relative soil adherence (*RSA*) was defined as the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment. The 'standard' cleaning treatment consisted of jetting compressed air from 16 orifices, 2 mm in diameter and 20 mm apart, drilled in a tube, to the (dirty) surface of the beet. The tube was placed such that the orifices were at a distance of approximately 60 mm from the beet surface (Figure 4.2.3). While rotating the beet round its longitudinal axis at 60 rpm in the grabber, the tube was pressurised (500-550 kPa) during one revolution of the beet. *RSA* was calculated per individual beet from the masses just after uprooting, after the 'standard' cleaning treatment and after cleaning with a high pressure water cleaner. Details of the method are described by Vermeulen *et al.* (1997).

Dug losses (% *w/w*), caused by fracture of the tap root, and superficial beet damage (cm^2 $beet^{-1}$), being other important factors affecting the harvesting quality, were estimated for each beet as described by Vermeulen *et al.* (1997). The relative number of beet showing crown fracture, caused by the beet grabber was counted per extraction treatment. Crown fracture results in total loss of the beet and adds to the total surface losses (missed beet and beet fragments left on the soil surface), therefore.

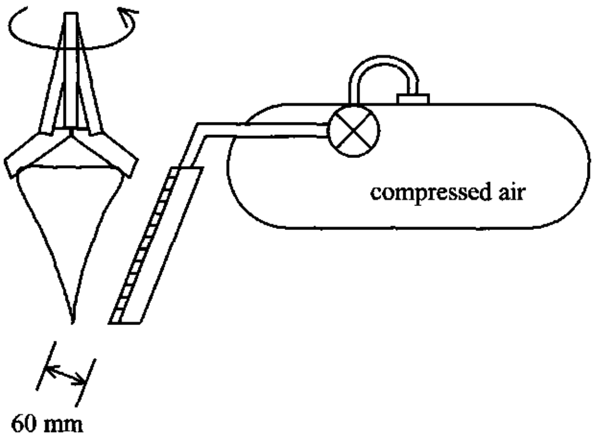


Figure 4.2.3. Schematic drawing of the 'standard' cleaning equipment.

The data on T_a were statistically analysed to investigate the effects of uprooting treatment, with soil and beet characteristics as covariables. The analysis was performed by multiple linear regression on a logarithmic scale, with generalised linear mixed models, employing inferential procedures described by Engel & Keen (1994). Model selection was performed on the basis of best fit, mutual independence of the predictors and significance of the predictor effects ($P < 0.05$). Estimation of the model parameters was performed by the maximum likelihood procedure with a gamma distribution for the response variable. Calculations were performed with the IRREML procedure (Keen, 1994), written in the statistical programming language Genstat 5 (Payne *et al.*, 1993). The selected model for individual beet was used to transform the measured T_a data to fitted values, *i.e.* without the random variation component. These fitted values were used to present the results.

It appeared that some characteristics of the beet and the wetness of the soil had a significant effect on T_a. For presentation of effects of uprooting treatments, the model for individual beet was used to calculate the expected values of T_a per uprooting treatment for a reference beet lot (T_{ar}) for three levels of soil wetness. Corresponding to the reference situations used by Vermeulen *et al.* (1997), the reference beet lot contained beet with characteristics equal to all those uprooted in the experiments in 1995 (Table 4.2.4) and the soil wetness levels (*w/w*, d.b.) were chosen within the range that occurred in the experiment:

- Relatively wet (Δm = 5%);
- Moist (Δm = 0.5%);
- Relatively dry (Δm = -4%).

Table 4.2.4. Mean mass of clean, topped beet (w_b) and median specific soil-beet contact area (S_s) per class of beet mass, and distribution of the number and total mass of all beet over the classes of beet mass and shape of the reference beet lot.

Mass class (kg beet^{-1})	Mean w_b (kg)	Median S_s (dm^2 kg^{-1})	Number of beet		Fraction of total mass	
			normal	fanged	normal	fanged
< 0.50	0.41	4.2	135	31	0.024	0.005
0.50-0.75	0.63	3.4	287	105	0.078	0.029
0.75-1.00	0.88	3.0	293	125	0.110	0.047
1.00-1.25	1.12	2.7	262	97	0.126	0.047
1.25-1.50	1.38	2.4	195	93	0.116	0.055
1.50-1.75	1.61	2.2	123	65	0.085	0.045
1.75-2.00	1.87	2.1	83	39	0.067	0.031
2.00-2.25	2.11	2.0	46	29	0.042	0.026
> 2.25	2.57	1.8	40	20	0.044	0.022
All beet	1.12	2.7	1,464	604	0.692	0.307

For statistical analysis of the data on *RSA*, the three extraction variants in this experiment were pooled to a new treatment, Extraction (EXTR), because the soil loading of these treatments was of a very similar, non-compressive type. Effect of the extraction variant on *RSA* is not expected, therefore (Vermeulen *et al.*, 1997). The effect of the uprooting treatments PS, RS and EXTR were statistically analysed with the same method as used for T_a. As *RSA* and T_a are expected to be strongly correlated (Vermeulen *et al.*, 1997), T_a was investigated as a covariable in the analysis, in addition to soil and beet characteristics.

4.2.4 Results

Adhering-soil tare

The uprooting treatments, the differential moisture content (Δm, % (*w/w*, d.b.)), the specific soil-beet contact area (S_s, dm^2 kg^{-1}) and the beet shape (normal or fanged) had a significant effect ($P < 0.05$) on the adhering-soil tare (T_a) of an individual beet (Appendix 4.2.1). The effects of uprooting treatments and Δm showed interaction. Other terms were not included into the statistical model, because they were strongly related to one of the factors in the selected model, or because the effect was not significant.

The T_a for large beet (low S_s) was much lower than for small beet (high S_s). Increasing S_s by a factor 2 resulted on average in a 1.6 times higher T_a. The T_a of fanged beet was a factor 1.2 higher than the T_a of normal beet.

The median T_a value in the experiment and the adhering-soil tare for the reference beet lot (T_{ar}), calculated with the model for three levels of Δm, are presented in Table 4.2.5. As the characteristics of the beet harvested in the experiment were almost identical to the characteristics of the beet of the reference beet lot, the measured and statistically-calculated values for the reference lot agree very well.

Compared with the lifting of sugar beet by a conventional driven polder share (treatment PS), slow extraction with minimal soil disturbance (treatment R) resulted in a 1.6 times higher T_{ar}, on average. Quick extraction with a non-spiral motion (treatment NS3) and quick extraction with a small-pitch-spiral motion (treatment SPS3), respectively, led to average reductions in T_{ar} by a factor 1.4 and 4.9, compared with treatment PS. The driven rotary-shoe lifter (treatment RS) lifted the beet with 3.7 times lower T_{ar} than treatment PS.

T_{ar} increased when the soil became wetter for all uprooting treatments, but the sensitivity for wetness of the soil differed between treatments. With a factor 2.3 and 2.2 difference in T_a between relatively wet (Δm = 5%) and relatively dry (Δm = -4%) soil for treatments PS and RS, respectively, these lifter treatments were most sensitive to wetness of the soil. Treatment R showed an intermediate sensitivity with beet extracted from relatively wet soil having *ca* 1.9 times as much adhering-soil tare as beet extracted from relatively dry soil. The extraction treatments NS3 and SPS3 were least sensitive for wetness of the soil: T_{ar} on relatively wet soil was 1.5 and 1.4 times as high, respectively, as on relatively dry soil.

Table 4.2.5. Measured median adhering-soil tare (% *w/w*, net) and calculated median adhering-soil tare, for the reference beet lot and three levels of soil wetness, per uprooting treatment.

Treatment	T_a, measured [1])	T_{ar}, calculated for 'standard' conditions [2])		
		relatively dry	moist	relatively wet
R	49.4	38.2	52.7	72.6
NS3	24.3	19.4	23.9	29.4
SPS3	6.3	5.7	6.8	8.0
PS	34.1	21.6	32.8	50.0
RS	8.3	5.9	8.8	13.2

[1]) T_a = Median adhering-soil tare (averaged on arithmetic scale) for the individual beet per treatment; mean Δm = -0.9% (*w/w*, d.b.); median S_s = 2.6 dm^2 kg^{-1} (mean beet mass = 1.13 kg); 32% of beet fanged; *cv* of T_a = 0.05.

[2]) T_{ar} = Predicted adhering-soil tare for the reference beet lot per uprooting treatment and for differential soil moisture contents (Δm, % (*w/w*, d.b.)) of -4 (relatively dry soil), 0.5 (moist soil) and 5 (relatively wet soil). Reference beet lot (Table 4.2.4), median S_s = 2.7 dm^2 kg^{-1}, (mean beet mass = 1.12 kg), 29% of beet fanged. *cv* of T_{ar} = 0.17.

Relative soil adherence

The uprooting methods and the adhering-soil tare (T_a) had a very significant effect ($P < 0.01$) on the relative soil adherence *(RSA)* of an individual beet (Appendix 4.2.2). Other terms, such as Δm, S_s and the beet shape, were not included into the statistical model because they were strongly related to T_a or because the effect was not significant.

RSA increased progressively when T_a decreased for all uprooting treatments (Figure 4.2.4). Compared at the same level of T_a, the *RSA* of the pooled extraction treatments (EXTR) was a factor 1.5 lower than the *RSA* of treatment PS. The difference in *RSA* between the lifter treatments PS and RS was not statistically significant ($P < 0.05$).

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

The total soil loosening effect of the uprooting treatments was evaluated by the change in adhering-soil tare, compared with the adhering-soil tare of beet, uprooted with minimal soil disturbance (treatment R). Treatment R represents the soil adherence conditions prior to beet uprooting. For the analysis, the adhering soil was divided into weakly-adhering-soil and strongly-adhering soil, being soil that was and was not removed by the 'standard' cleaning treatment, respectively. For all treatments, except PS, weakly-adhering-soil tare and strongly-adhering-soil tare decreased by the uprooting action (Figure 4.2.5), indicating that these uprooting treatments had a soil loosening effect. Only in case of the driven polder share (PS), the strongly-adhering-soil tare increased, indicating that at least some volume of

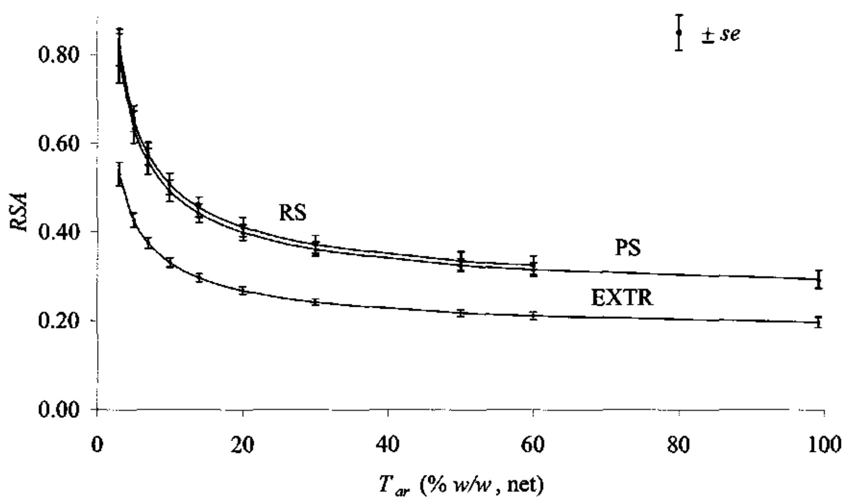


Figure 4.2.4. Relative soil adherence (*RSA*) at various levels of adhering-soil tare (T_{ar}) for uprooting treatments driven polder share (PS), driven rotary-shoe lifter (RS) and the pooled extraction treatments (EXTR).

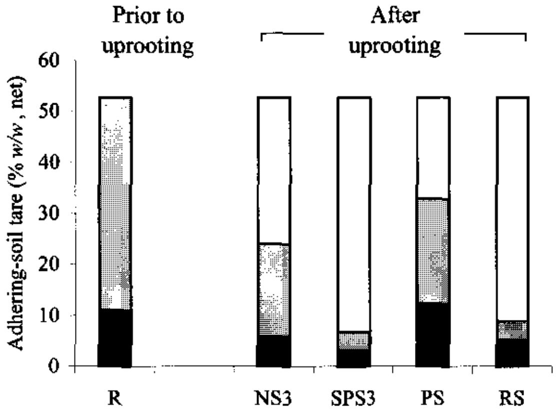


Figure 4.2.5. The adhering soil tare in the adherence classes strong (■), weak (▒) and zero (□) (loose soil), prior to uprooting (treatment R), and after uprooting by various methods. The data pertain to the reference beet lot and moist soil conditions (Δm = 0.5%).

weakly-adhering-soil was converted into strongly-adhering-soil, due to compaction and plastication of the soil.

Dug losses, superficial damage and crown fracture

Dug losses for treatments R and NS3 were negligible (Table 4.2.6). Compared with the dug losses for the currently-used uprooting method (PS), the dug losses of treatments SPS3 and RS were somewhat higher. Dug losses of all treatments were considered to be acceptable, compared with typical dug losses after a complete harvesting process in practice of 2 to 3%. Superficial beet damage was negligible

Table 4.2.6. Mean dug loss, mean superficial damage and crown fracture after uprooting by very slow, non-spiral extraction (R), quick, non-spiral extraction (NS3), quick, small-pitch-spiral extraction (SPS3), a conventional driven polder share (PS) and a driven rotary-shoe lifter (RS).

Treatment	Mean dug loss [1] (% *w/w*, net)	Mean superficial damage [2] (cm^2 $beet^{-1}$)	Crown fracture [3] (% *n/n*)
R	0.0	0.0	0
NS3	0.0	0.1	0.9
SPS3	1.0	0.1	12.3
PS	0.3	4.8	0
RS	1.0	1.4	0

[1]) *se* = 0.14.
[2]) *se* = 0.47.
[3]) Insufficient data for statistical analysis.

for all extraction variants. Uprooting method RS showed lower superficial beet damage than the conventional method PS. Crown fracture, which means total loss of a beet, occurred for extraction treatments NS3 and SPS3 only. While the relatively low occurrence of crown fracture for NS3 would be acceptable compared with the usual surface losses (< 1%) of conventional harvesting systems, the percentage of crowns fractured for treatment SPS3 is 12.3% and would not be acceptable.

4.2.5 Discussion

The broader objective of comparing lifting method RS with conventional lifting (PS) and extraction (EXTR) was to asses the potential of the driven rotary-shoe lifter for obtaining low soil tare and weak soil adherence in practice. The results show that T_a of treatment RS is low compared with treatment PS and only little higher than the T_a obtained by the most aggressive extraction treatment SPS3. However, when compared at the same level of T_a, the *RSA* of RS was equal to the *RSA* obtained for PS and much higher than the *RSA* obtained for SPS3. The question arises whether this result shows good or bad potential for reducing soil tare in practice. Considering that T_a directly after treatment RS on relatively wet clay soil was 13.2% (*w/w*, net), and that about half of the soil adhered weakly to the beet, a T_a of 6.6% after cleaning seems feasible. When comparing this value with the estimated mean soil tare of 7.8% in Dutch beet piles in 1995, we conclude that practical application of the driven rotary-shoe lifter in a complete sugar beet harvesting system offers good potential to lift beet under unfavourable conditions, *i.e.* on wet clay soil, with relatively low soil tare. The loose-soil tare as a result of the lifting treatments was not measured in this experiment. While the loose-soil tare resulting from beet extraction may be assumed to be 0%, uprooting with a polder share lifter or a driven rotary-shoe lifter will result in a considerable amount of loose soil being lifted and fed into the cleaning section of the harvester. Even for soil that crumbled under stress, Bulich & Kromer (1986) found that increasing the loose-soil tare results in higher (final) soil tare after conventional mechanical beet cleaning. Therefore, the amount of loose soil lifted by the share lifter and the driven rotary-shoe lifter may be expected to negatively affect the final soil tare, compared with beet extraction.

It was assumed that the lifting kinetics of the driven rotary-shoe lifter resemble that of extraction treatment SPS3 to a certain extend because of the more or less vertical lifting motion, the high vertical acceleration and the possible rotation of the beet round its longitudinal axis due to the one-sided, sliding impact of the shoes. Therefore, low T_a and weak *RSA* were expected. It was found, however, that treatment RS resulted in a somewhat higher T_a and much stronger soil adherence, compared with treatment SPS3. A possible explanation for this result is that the lifting motions of treatment SPS3 and RS may be similar, but they are generated by different external force systems. In treatment SPS3, the pulling force acts on the beet and, therefore, all soil round the beet is indirectly loaded via beet displacement. In treatment RS, part of the soil around the beet, *i.e.* in between the shoes and the beet surface, may be compressed before the shoes reach the beet surface. This part of the soil may exhibit an increase in soil adherence due to compaction and plastication, therefore. However, a large part of the soil around the beet may be loaded indirectly via beet displacement, and will react in the same manner to high vertical acceleration and beet rotation as for treatment SPS3: low T_a and weak *RSA*.

Proper determination of the 'natural' relationship between *RSA* and T_a prior to uprooting is necessary to reveal the true effect of uprooting on the soil surrounding the beet *in situ*. Based on the assumption, that the combinations of *RSA* and T_a, found for the various extraction treatments, produce a reasonable approximation of this 'virgin' soil adherence curve, we conclude that the treatments PS and RS cause an increase in *RSA*, compared with the situation prior to uprooting, due to compaction and plastication of the soil. However, the extraction treatments, particularly the more aggressive variants, may have been much more effective in producing weakly-adhering-soil than the 'standard' cleaning treatment on which the *RSA* is based. Consequently, the *RSA* prior to uprooting is likely to be underestimated for T_a levels below *ca* 50% (found for treatment R). Therefore, conclusive proof of an increase in *RSA* by treatment RS, compared with the *RSA* prior to uprooting, has not been established. The best approximation of the *RSA* prior to uprooting, at low T_a levels, is possibly obtained by measuring *RSA* and T_a after repeated 'standard' cleaning of beet that are carefully dug out of the soil with minimal soil disturbance (treatment R), similar to the experiments of Green (1957). Investigation of this procedure is recommended for future field experiments.
The effect of uprooting methods on the soil surrounding the beet *in situ* can also be approached theoretically by analysing stresses and strains in the soil during uprooting, in various soil-beet-lifter systems (Chapter 5). In a theoretical approach, the use of the empirical parameter *RSA* is avoided and soil adherence is to be characterised by a number of intrinsic soil characteristics.

4.2.6 Conclusions

Compared with the uprooting quality of a conventional driven polder share lifter on humid clay soil:

- The adhering-soil tare after quick extraction with a small-pitch-spiral motion was reduced by a factor 3.8 under relatively dry and a factor 6.2 under relatively wet soil conditions. The relative soil adherence was reduced by a factor 1.5, when compared at the same level of adhering-soil tare. The mean dug losses (1%) were a factor 3 higher, but still low compared with the usual dug losses after a complete harvesting process (2-3%). Superficial beet damage (0.1 cm^2 $beet^{-1}$) was a factor 50 lower. The expected surface losses were unacceptably high (12.3%) due to the occurrence of crown fracture, probably caused by the type of grabber used;

- The adhering-soil tare after lifting with a driven rotary-shoe lifter was reduced by a factor 3.7, irrespective of the wetness of the soil. The relative soil adherence was not different, when compared at the same level of adhering-soil tare. The mean dug losses (1%) were a factor 3 higher, but still low compared with the usual dug losses after a complete harvesting process (2-3%). Superficial beet damage (1.4 cm^2 $beet^{-1}$) was a factor 3.4 lower.

Though the lifting motions and vertical lifting accelerations of quick, small-pitch-spiral extraction and lifting by a driven rotary-shoe lifter show some similarity, these treatments did not result in a similar combination of adhering-soil tare and soil adherence, possibly due to differences in the external loading system.

The driven rotary-shoe lifter, built in a complete sugar beet harvesting system, offers good potential to reduce soil tare on wet clay soil.

4.2.7 Acknowledgements

The personnel of the experimental farm 'Oostwaardhoeve' and B. Kroesbergen, S.H. Pronk and E.J. Wassink of the Soil Tillage Laboratory of Wageningen University are thanked for their assistance in this research. We thank late A. Keen (posthumously) and B. Engel (DLO Agricultural Statistics Group) for statistical assistance. This research was financially supported by the Ministry of Agriculture, Nature Management and Fisheries and the Institute of Sugar Beet Research (IRS) at Bergen op Zoom.

Appendix 4.2.1 Statistical analysis of data on adhering-soil tare

The statistical model for the expected $\ln(T_a)$ of individual beet was:

$$E\,\ln(T_a) = C + F_{ut} + (a + F_{ut,\Delta m})\,(\Delta m - \overline{\Delta m}) + b\,(\ln(S_s) - \overline{\ln(S_s)}) + F_{sh}$$

Description and estimated values and standard errors for the parameters in the model for $\ln(T_a)$.

Parameter	Description	Estimate	*se* [1])
C	Constant	3.803	0.054
F_{ut}	factor for treatment R	0.000	0.062
	factor for treatment NS3	-0.756	
	factor for treatment SPS3	-2.008	
	factor for treatment PS	-0.504	
	factor for treatment RS	-1.809	
Δm	differential soil moisture content		
a	coefficient for Δm	0.071	0.015
$\overline{\Delta m}$	weighted mean of Δm	-0.890	
$F_{ut,\Delta m}$	interaction factor for treatment R and Δm	0.000	0.021
	interaction factor for treatment NS3 and Δm	-0.025	
	interaction factor for treatment SPS3 and Δm	-0.033	
	interaction factor for treatment PS and Δm	0.022	
	interaction factor for treatment RS and Δm	0.017	
$\ln(S_s)$	ln (specific beet-soil contact area)		
b	coefficient for $\ln(S_s)$	0.695	0.053
$\overline{\ln(S_s)}$	weighted mean of $\ln(S_s)$	0.942	
F_{sh}	factor for normal beet shape [2])	0.000	0.043
	factor for fanged beet shape	0.179	

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

[2]) The effect of the number of taproots on T_a appeared to be significant only between one tail and more than one tail per beet ($P < 0.05$). Therefore, this predictor was introduced into the model as the factor 'shape' having the values 'normal' and 'fanged'.

Appendix 4.2.2 Statistical analysis of data on relative soil adherence

The statistical model for the expected ln(RSA) of individual beet was:

$$E\ \ln(RSA) = C + F_{upt} + a(\ln(T_a) - \overline{\ln(T_a)}) + b((\ln(T_a))^2 - \overline{(\ln(T_a))^2})$$

Description and estimated values and standard errors for the parameters in the model for ln(T_a).

Parameter	Description	Estimate	se [1]
C	constant	-1.197	0.026
F_{upt}	factor for treatment EXTR [2]	0.000	0.045
	factor for treatment PS	0.399	
	factor for treatment RS	0.454	
$\ln(T_a)$	ln (adhering-soil tare)		
a	coefficient for $\ln(T_a)$	-0.520	0.069
$\overline{\ln(T_a)}$	weighted mean of $\ln(T_a)$	2.722	
$(\ln(T_a))^2$	(ln (adhering-soil tare))^2		
b	coefficient for $(\ln(T_a))^2$	0.045	0.012
$\overline{(\ln(T_a))^2}$	weighted mean of $(\ln(T_a))^2$	8.488	

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

[2]) For the analysis of the data on RSA, the uprooting treatments R, NS3 and SPS3 were pooled to a new treatment EXTR (Extraction).

CHAPTER 5

Soil dynamical analysis of the origination of soil tare during uprooting of sugar beet

5.1 Abstract

High soil tare of sugar beet on wet clay soil after uprooting with share lifters is usually attributed to the fact that the soil becomes sticky due to mechanical impact during uprooting. Results of field experiments have shown good potential for obtaining low soil tare of sugar beet on wet clay soil by beet extraction with a high average vertical acceleration and a spiral extraction path with a small pitch. The objective of this research was to provide models for soil-beet-lifter systems and simulate some of the observed effects of the uprooting method on soil tare and soil adherence. As the root system turned out to play an important role in the origination of soil tare, a way of modelling the root system was part of the study. A constitutive soil model, assuming elastic-perfectly-plastic soil behaviour, was used as a basis for modelling soil-beet-lifter system variants, including beet with and without rootlets, uprooting by extraction, by rotation and by extrusion and uprooting with low and high vertical acceleration. The origination of soil tare is presented on the basis of the calculated zone of initial soil failure during extraction. Expected soil adherence is discussed in relation to the stress state of the soil. The calculated effects of the methods of uprooting and of the vertical acceleration of uprooting on initial soil failure and stress state of the soil agreed well with experimental results in a qualitative way.

Keywords: soil tare, soil adherence, sugar beet lifting, soil dynamics

5.2 Introduction

The amount of soil adhering to sugar beet after harvest in the Netherlands should be reduced to lower the increasing cost of disposal and to prevent possible negative effects on the environment. Most of the current harvesting systems are very similar: high capacity machines with shares to lift the sugar beet and various types of mechanical systems to 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), characteristics of the beet (Gemtos, 1979; Wevers, 1980; Bouma & Cappon, 1988) and the skill of the machine-operator to properly adjust the machine to the prevailing harvesting conditions (Brinkmann,

1986b). The highest soil tare usually occurs on heavy, wet soils, in sugar beet lots with a low mean beet weight. Furthermore, when machinery is adjusted such that the beet are treated very gently, the incidence of beet injuries is very low but the soil tare is high (Ditges, 1990).
For harvesting systems with share lifters, operating in wet clay soil, the adhering-soil tare is roughly 100% (*w/w*, net) at the end of the uprooting phase (Ditges, 1990) and may be up to 55% at the end of the harvesting process. The high soil tare figures on wet clay soils are attributed to the fact that the soil around the beet becomes sticky due to mechanical impact during uprooting and, thereafter, adheres strongly to the beet (Green, 1957). This deformation of soil in a wet state (soil plastication) results in a low effectiveness of cleaning systems (Green, 1956, 1957). In fact, the mechanical impact during cleaning may result in further plastication of the adhering soil. Thus, drastic improvement in the cleaning effectiveness of conventional harvesters is difficult to achieve without increasing the aggressiveness of cleaning and, thereby increasing damage to the beet.
The best potential for reducing soil tare by improvement of harvesting systems on wet clay soil turns up during the uprooting phase, when the soil is not yet plasticated. Vermeulen (1995) concluded that the objectives of uprooting should be twofold:

- Minimising the quantity of adhering soil directly after uprooting;
- Prevention of the soil being plasticated during uprooting, to ensure a good potential for further cleaning.

Field experiments showed that the method of uprooting, including the accelerations during uprooting, might have considerable effect on adhering-soil tare and soil adherence after uprooting. Potentially, uprooting of beet by extraction from wet clay soil, results in a lower adhering-soil tare than uprooting by conventional lifters. The former technique did not increase beet losses due to root breakage (Strooker & De Widt, 1957; Strooker, 1960, 1962; Schuh, 1989; Schuh & Höhn, 1991; Voesten, 1993; Vermeulen, 1995, 1998). Extraction with a combined upward and rotating motion results in lower soil tare than extraction with a straight upward motion (Voesten, 1993; Vermeulen *et al.*, 1997). Also, increasing the acceleration of extraction decreases soil tare (Vermeulen *et al.*, 1997). The same authors reported that the relative soil adherence, defined as the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment, depends mainly on the adhering-soil tare itself: the relative soil adherence increases exponentially with decreasing adhering-soil tare. When considering beet with the same adhering-soil tare, the relative soil adherence of beet that were uprooted by different extraction motions was equal, but the relative soil adherence of extracted beet was lower than that of conventionally-uprooted beet (Vermeulen, 1998).
The objective of the present study was to provide a theoretical background to model some of the soil-beet-lifter systems used in field experiments on wet clay soil, and

to simulate the effects of uprooting method and uprooting acceleration on soil tare and soil adherence. In agreement with the suggestions of Gemtos (1979), it became evident during the first simulations that the root system of the sugar beet is a very important factor in the origination of soil tare. Therefore, simulation of the effect of the root system on soil tare was included in the study.

5.3 Materials and methods

Outline of method

Differences in adhering-soil tare and soil adherence, found for different root systems, methods of uprooting and uprooting accelerations, are caused by differences in the reaction of the soil around the beet to the external loads applied during uprooting. Therefore, a model describing the reaction of soil to external loads was adopted to simulate the behaviour of the soil around the beet. Differences in amount of adhering-soil tare between treatments were indicated by the distance between the calculated zone of initial soil failure and the beet surface. The relative soil adherence, being an empirical parameter, can not be calculated by the model. As soil adherence is affected by the stress state of the soil, some indication of the soil adherence after uprooting can be given, based on the stress state during uprooting.

Investigated soil-beet-lifter systems

A number of beet-uprooting systems (Table 5.1) were mutually compared, all on wet clay soil, to investigate the effect of the root system, the uprooting method and the uprooting acceleration on the amount of adhering soil, and soil adherence.

Modelling of the soil-beet-lifter system and soil behaviour

The behaviour of soil as a result of external loads is basically described by relationships between stress and strain of the soil. For short duration loads and large deformations or fracture of the soil, such as during uprooting of sugar beet, various types of stress-strain relationships are needed to simulate the behaviour of the soil. In soil dynamics, sets of relationships between stress and strain of soil are usually described in so-called constitutive models, formulated through mathematical equations, describing various kinds of ideal material response. Several constitutive models exist, varying in complexity and field of application. The most commonly used constitutive model is the Mohr-Coulomb model, assuming elastic soil behaviour until the soil fails in shear, and perfectly plastic behaviour after initial failure. The Mohr-Coulomb model was also selected for the uprooting problem because it is known to be robust, well suited to simulate soil behaviour for a broad range of soils and load systems and based on parameters that are known for some agricultural soils.

Table 5.1. Beet-lifter systems used to investigate the effect of root system, method of uprooting and acceleration of uprooting on adhering-soil tare and soil adherence.

Effect of	Beet variants	Lifter system
Root system	without rootlets	extraction; low acceleration
	medium rootlet density [1])	extraction; low acceleration
	high rootlet density [2])	extraction; low acceleration
Method of uprooting	high rootlet density	extraction; low acceleration
	typical rootlet pattern at 8 cm depth	rotation; low acceleration
	high rootlet density	extrusion; low acceleration
Acceleration of uprooting	high rootlet density	extraction; low acceleration
	high rootlet density	extraction; high acceleration [3])

[1]) Comparable to the density of rootlets, typically occurring in a vertical plane through the beet center and perpendicular to a vertical plane through the beet grooves.

[2]) Comparable to the density of rootlets, typically occurring in a vertical plane through the beet grooves.

[3]) A constant vertical acceleration of 29.4 m s^{-2}.

PLAXIS, a geotechnical computer program (Brinkgreve & Vermeer, 1994, 1998), was chosen to perform the calculations for the analysis of the uprooting process. The computational program PLAXIS has been developed, originally by the Delft University of Technology in the Netherlands, as a finite element package, specifically intended for the analysis of deformation and stability in geotechnical engineering. PLAXIS was selected because it was readily available and because the program has the basic features needed to analyse the uprooting process. These basic features are: support of the Mohr-Coulomb constitutive model, extended with equations to include tensile failure of the soil; the possibility to define the geometric outline and the material characteristics of a beet, standing in the soil; a choice of loading methods suited to simulate various uprooting methods; the possibility to simulate accelerations. The sign convention used for soil stresses in PLAXIS is positive for tensile stress and negative for compressive stress.

Basically, the Mohr-Coulomb model requires two elasticity parameters, Young's modulus of elasticity (E) and Poisson's ratio (ν), and three plasticity parameters, cohesion (c), angle of internal friction (ϕ) and angle of dilatancy (ψ).
The Mohr-Coulomb failure condition is an extension of Coulomb's friction law to general states of stress. In fact, this condition ensures that Coulomb's friction law is obeyed in any plane within a continuum. The Mohr-Coulomb failure condition can conveniently be formulated in terms of principal stresses (σ_1, σ_2, and σ_3) and involves three yield functions:

$f_1 = ½\,|\sigma_2 - \sigma_3| + ½\,(\sigma_2 + \sigma_3)\sin\phi - c\cos\phi$

$f_2 = ½\,|\sigma_3 - \sigma_1| + ½\,(\sigma_3 + \sigma_1)\sin\phi - c\cos\phi$

$f_3 = ½\,|\sigma_1 - \sigma_2| + ½\,(\sigma_1 + \sigma_2)\sin\phi - c\cos\phi$

During the uprooting of a sugar beet, also tensile stress will develop in the soil, which is not usual in foundation engineering problems, for which the Mohr-Coulomb model is developed. It is known that the Mohr-Coulomb model overpredicts the tensile strength of highly cohesive soils, such as a wet, heavy clay. To overcome this limitation, a so-called tension cut-off is available in PLAXIS as an advanced option. By activating the tension cut-off, a sixth parameter, the allowable tensile strength (σ_t) is added to the Mohr-Coulomb model and three additional (tensile) failure functions are introduced:

$f_4 = \sigma_1 - \sigma_t$

$f_5 = \sigma_2 - \sigma_t$

$f_6 = \sigma_3 - \sigma_t$

All yield functions together can be represented as a failure surface in the space of principal stresses. For the case that $\phi = 0$ and $\sigma_t > 0$, the failure surface has the shape of a hexagonal cylindrical prism, the so-called Tresca yield surface (Figure 5.1).

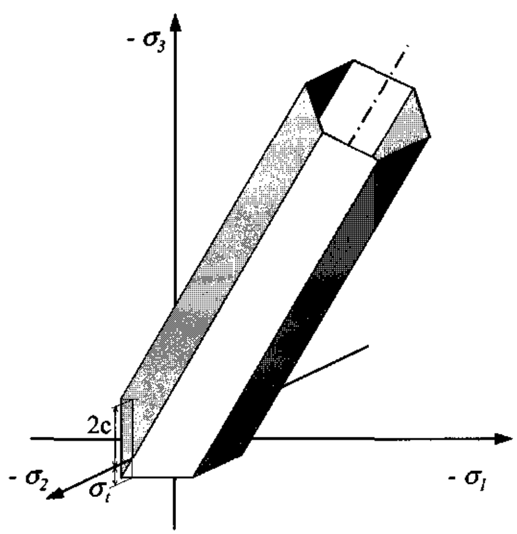


Figure 5.1. Tresca failure surface in the space of principal stresses (σ_1, σ_2, σ_3) with tension cut-off at σ_t.

Input of basic soil characteristics

The simulations of beet uprooting were performed using a Wageningen, moderately heavy silty clay loam in a wet condition, for which most input parameters for PLAXIS were known (zone 00 in Table 5.3). Core samples of this soil were taken in October 1985 in a field of mature sugar beet (Dawidowski & Koolen, 1987). With these samples, standard quick triaxial tests were run at an initial water tension of 3 kPa, a σ_3 of 200 kPa, a vertical strain rate of 0.02 s^{-1}, to a maximum vertical strain of 0.45. Initial air-filled pore space was 5%. Barneveld (1994) derived from the measured stress-strain curve E and ν values by applying Boyle's law to the entrapped air. The angle of internal friction of the soil, ϕ, was zero. The cohesion, c, was derived from the measured shear strength. Dilatancy was assumed to be absent at these large strains. The tensile strength of the soil was estimated to be σ_t = 0.25 * c (kPa). As all input parameters are obtained from undrained tests on wet field samples, the values relate to total stress and not to effective stress. Also in PLAXIS, total stress was analysed by choosing drained soil for the calculations, implying that the generation of additional hydrostatic pressure in PLAXIS was prevented.

Input of beet characteristics

The root system of a solitary sugar beet, as described by Kutschera (1960), was assumed to be a typical example of the root system of sugar beet. The soil and the root system were considered up to 50-cm depth and up to 60-cm left and right of the beet center (Figure 5.2, top). The influence of the root systems of neighbouring beet was neglected. Most of the rootlets emerge from the beet grooves of the tap root (the pear-shaped sugar beet), and form a dense network in the top soil around the beet, up to about 30 cm from the beet centre. From the lower end of the taproot, lateral roots branch off and grow into deeper soil layers. All roots, except the tap root are further referred to as rootlets. Based on visual examination of the rootlet pattern, the total volume of soil under consideration was divided into eight zones of assumed uniform rootlet-length-density (*RLD*, *i.e.* the total length of rootlets per unit of soil volume (cm cm^{-3})). The *RLD* and, therefore, the mechanical characteristics differed between the zones (Figure 5.2).

The soil-beet-lifter systems for uprooting by extraction and extrusion were considered in two vertical cross sections: in planes through the beet grooves, and perpendicular to the plane through the beet grooves. The system for uprooting by rotation was considered in a horizontal cross-section at a depth of 8 cm below the soil surface. As no description of the shape of the root system in a horizontal plane was available, a schematic shape was assumed (Figure 5.2, bottom).

The increase in cohesion, Δc (kPa), and the increase in tensile strength, $\Delta\sigma_t$ (kPa), of the soil due to rootlets were estimated for the various soil zones of equal root-length-density. The average rootlet diameter and the associated tensile strength of the beet rootlets were estimated for each zone. To simplify the assessment, the following assumptions were made:

- The contribution of the rootlets to the cohesion and the tensile strength of the soil is uniform and isotropic in nature;
- No sliding of rootlets through the soil occurs;
- The stress at which rootlets fail in shear is equal to the stress at which they fail in tension, implying that $\Delta c = \Delta \sigma_t$.

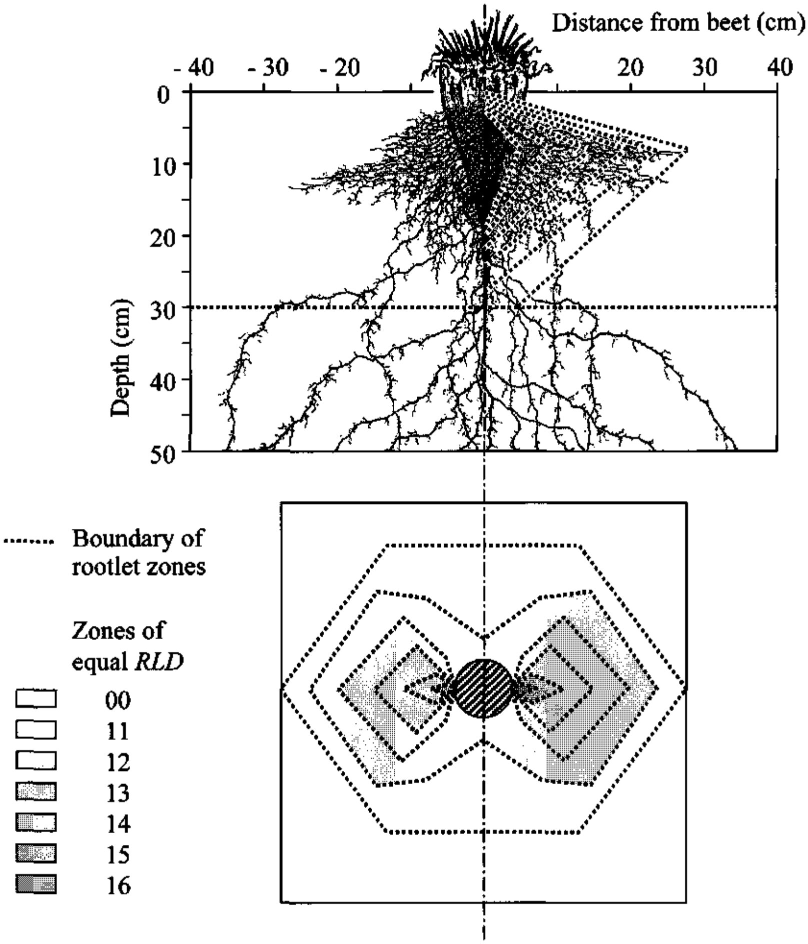


Figure 5.2. The root system of sugar beet in the vertical plane, according to Kutschera (1960), including boundaries of projected zones of assumed equal rootlet-length-density (top), and the assumed geometric outline of the root system in the horizontal plane, at a depth of 8 cm below the soil surface, visualised by zones of equal root-length-density (bottom).

Windt (1995) reported that the *RLD* in the topsoil layer (0-20 cm) is about 3 (cm cm^{-3}). On the basis of this figure, we assumed that the *RLD* close to the beet grooves is 6 and decreases with increasing distance from the beet grooves to a value of 0 for non-rooted soil. The *RLD* found below 30-cm depth was about 0.35. We assumed that the number of rootlets contributing to the cohesion and the tensile strength of the soil is *RLD*/3 per cm^2, due to the three principal directions of rootlet growth in the 3-dimensional space.

Windt (1995) also reported that the mean diameter (d_r) of rootlets in the soil layer of 0 to 30-cm depth was 0.25 (mm), which coincides with a cross sectional area (S_r) of about 0.05 (mm^2). Below 30-cm depth, d_r was 0.37, on average. We assumed that the diameter of the rootlets in the soil layer of 0 to 30-cm depth is 0.40 close to the beet and tapers off to a diameter of 0.15 at the end of the rootlet.

Gemtos (1979) expressed the tensile strength of rootlets of the sugar beet as a function of their cross-sectional area:

$$\ln(10^{-3} * \sigma_{t\,\mathrm{rootlet}}) = 1.74 - 0.27 * \ln(S_r) \qquad (5.1)$$

where: $\sigma_{t\,\mathrm{rootlet}}$ = tensile strength of the rootlet (kPa).
S_r = cross-sectional area of the rootlet (mm^2).

In Gemtos' experiments, the smallest rootlets were in the order of 1 mm in diameter, for which the tensile strength is 6,080 kPa, according to equation (5.1). Using equation (5.1) for rootlets with a diameter smaller than 1 mm results in unrealistically high tensile strength values. Therefore, we estimated that rootlets with a diameter equal or smaller than 1 mm exhibit a constant tensile strength, $\sigma_{t\,\mathrm{rootlet}}$, of 6,000 kPa. This estimate is high, compared with the tensile strengths of small roots of sunflower seedlings (700 kPa), leek seedlings (1,600-3,000 kPa) and wheat seedlings (2,200-5,700 kPa), reported by Ennos (1989, 1990, 1991), but low, compared with the tensile strength of tree roots (10,000-70,000 kPa) reported by Glinski & Lipiec (1990) and Cofie (2001).

The increases in cohesion, Δc, and in tensile strength, $\Delta\sigma_t$, of the soil (Table 5.2) were calculated for each soil zone, indicated in Figure 5.2, as:

$$\Delta c = \Delta\sigma_t = 10 * (RLD/3) * F_r \text{ (kPa)} \qquad (5.2)$$

in which: F_r = Force at which a rootlet fails in tension,
calculated as: $F_r = \sigma_{t\,\mathrm{rootlet}} * S_r * 10^{-3}$ (N)

The mechanical characteristics of the sugar beet itself were entered into PLAXIS just as was done for the soil. The mechanical characteristics of the beet show a large variation, partly due to the fact that the inner parts have less strength than the

Table 5.2. Summary of the characteristics of the root system of sugar beet and of the calculated additional cohesion and real tensile strength of the soil.

Zone	*RLD* (cm cm^{-3})	d_r (mm)	S_r (mm^2)	$\sigma_{t\ rootlet}$ (kPa)	F_r (N)	Δc (=$\Delta\sigma_t$) (kPa)
00	0	-	-	-	-	0
11	1	0.15	0.018	6,000	0.11	3
12	2	0.20	0.031	6,000	0.19	13
13	3	0.25	0.049	6,000	0.29	30
14	4	0.30	0.071	6,000	0.42	56
15	5	0.35	0.096	6,000	0.58	96
16	6	0.40	0.126	6,000	0.75	151
20 [1])	0.35	0.37	0.108	6,000	0.65	7

RLD = root-length-density; d_r = diameter of rootlets; S_r = cross-sectional area of rootlets; $\sigma_{t\ rootlet}$ = tensile strength of rootlets; F_r = tensile failure force of rootlets; Δc = additional cohesion due to rootlets; $\Delta\sigma_t$ = additional tensile strength due to rootlets.
[1]) > 30 cm below the soil surface.

outer parts (Gemtos, 1979; Miller, 1982). However, for the calculations in PLAXIS, equal characteristics were assumed for the whole beet, based on reported values for the lower end of the beet. Reported values for the tensile strength vary from 600 to 2,800 kPa (Gemtos, 1979; Miller, 1982, 1984). A tensile strength of 2,000 kPa, reported to be a typical value for the lower beet end (Miller, 1982), was taken for the calculations.

Assuming that the angle of internal friction, ϕ, is zero for beet material, the cohesion was taken to be equal to the shear strength of sugar beet. Reported shear strengths vary from 300 to 1,480 kPa (Vukov, 1972; Gemtos, 1979; Alizadeh, 1985; Smed, 1998). A relatively high value of 1,000 kPa was taken for the PLAXIS calculations, considering that:

- Theoretically, the shear strength should be at least 0.5 * σ_t;
- The shear strength tends to increase with decreasing fractured surface diameter;
- Measured shear strength values are always lower than real values because of the advancing nature of the shearing process.

Values reported for Young's modulus vary from 6,400 to 14,000 kPa (Miller, 1982; Gemtos, 1979; Bieluga & Bzowska-Bakalarz, 1980; Alizadeh, 1985; Vukov, 1977). For the calculations, an average value of 10,000 kPa was adopted. Alizadeh (1985) reported that Poisson's ratio for sugar beet tissue is 0.39. The angle of dilatancy was assumed to be zero. A summary of the input parameters of non-rooted soil, rooted soil and sugar beet, used for the calculations in PLAXIS, is presented in Table 5.3.

Input for simulating uprooting methods and acceleration

The three investigated uprooting methods were extraction, rotation and extrusion, being simulations of the following practical uprooting methods:

- Grab the beet crown, using beet pliers, and pull the beet straight up (extraction);
- Grab the beet crown, using beet pliers, and rotate the beet in the horizontal plane (rotation; to be followed by extraction);
- Lift the beet by using a share lifter (extrusion). Close simulation of a share lifter requires a complicated, three-dimensional geometric set-up. In this study, the share lifter was simulated by a simple geometric set-up: a cylindrical ring in the soil around the beet, that squeezes the beet out of the soil when the ring is contracted.

The uprooting methods were simulated in PLAXIS by imposing prescribed displacements on the beet or on the squeeze ring, typical for the uprooting method. The prescribed displacements result in the set-up of reaction stress in the soil, which develops in the course of the model calculations.

The input in PLAXIS of the mechanical characteristics of the squeeze ring, 70 mm high and 10 mm thick, consisted of the axial stiffness and the flexural rigidity, which were estimated such, that a rigid ring was simulated.

Accelerated extraction (a = 29.4 m s^{-2}) was simulated pseudo-dynamically by increasing the value of gravity in the model from 1g to 4g.

Table 5.3. Input data of soil and beet, used for simulation of the uprooting of beet [1]) [2]).

Zone	c_R (kPa)	σ_{tR} (kPa)	E (kPa)	ν	γ_w (Mg m^{-3})	K_0
Beet	1000	2000	10000	0.39	1.000	0.6
00	82	20	2200	0.45	1.874	0.8
11	85	23	2200	0.45	1.874	0.8
12	95	33	2200	0.45	1.874	0.8
13	112	50	2200	0.45	1.874	0.8
14	138	76	2200	0.45	1.874	0.8
15	178	116	2200	0.45	1.874	0.8
16	233	171	2200	0.45	1.874	0.8
20	89	27	2200	0.45	1.874	0.8

[1]) For all zones: angle of internal friction (ϕ) = 0°; angle of dilatancy (ψ) = 0°; saturated water permeability (Γ) = 1 m day^{-1}; simulations were performed for drained conditions.

[2]) c_R = real cohesion; σ_{tR} = real tensile strength; E = Young's modulus (stiffness); ν = Poisson's ratio (pseudo-elasticity constant); γ_w = wet bulk density; K_0 = ratio of horizontal stress to vertical stress.

Mesh generation, calculations and output

A medium mesh coarseness, 15 nodes per element, and an automatic calculation step size procedure were selected for the finite element calculations. For extraction and extrusion, considered in a vertical plane, an axi-symmetric geometric set-up was chosen. The initial stresses in the soil, due to the mass of the soil, were generated by the K_0 procedure. For rotation, considered in a horizontal plane, a plane strain geometric set-up was adopted, and gravity was disabled, resulting in zero initial stress. Due to the fact that expected deformations are relatively large, an updated mesh calculation type was chosen.

The zone of initial failure of the soil around the beet was calculated for a series of increasing displacement of the beet or the squeeze ring for each uprooting variant. From each of these series the displacement was selected at which the zone of initial soil failure became visible in the graphical output of PLAXIS, through the locations of the plastic failure points, developed in the soil around the beet.

The calculation process included the calculation of the stress state and the displacements of each nodal point during the prescribed displacement of the beet or the squeeze ring. In the zones of soil failure, two types of plastic failure points (see Figure 5.1) indicated the stress state of the soil:

- Plastic Mohr-Coulomb points indicating shear failure, for which the main principal stress is usually compressive (negative);
- Tension cut-off points indicating tensile failure, for which the main principal stress is usually tensile.

To give an indication of the stress state of the soil outside the zones of soil failure, isobars for the mean principal stress were generated in the graphical output of PLAXIS.

Qualitative assessment of soil adherence on the basis of the stress state of the soil

The term soil adherence is used to refer to the ability of the soil particles to stick together and to stick to the surface of the beet or rootlets, when subjected to external loads and subsequent deformation. Strong soil adherence is associated with high plasticity and high adhesion of the soil (Vermeulen, 1995). High plasticity means that the soil deforms, but does not fracture under external loads (Gill & Vanden Berg, 1967). High adhesion of the soil means that a high stress is needed to separate soil from another material (Fountaine, 1954; Bowden & Tabor, 1964; Wu, 1982). Major constraints in the quantification of plasticity and adhesion and, therefore, soil adherence are that the behaviour of the soil depends on the nature of the externally applied load and that soil characteristics may change during loading. Therefore, several subjects, related to soil adherence, have been approached in an empirical way. A first subject is the quantification of the sticking of soil to soil-engaged tools by the so-called stickiness of the soil (Chancellor, 1994). A second subject is the quantification of workability limits for tillage, in terms of the soil moisture content, by recognising specific behaviour in workability tests. Examples

are the Atterberg limits, determined by recognising the plasticity of the soil after a number of kneading actions and the workability criterion of Perdok & Hendrikse (1982), determined by specifying a minimum air-permeability after a specific uni-axial load. Likewise, Vermeulen *et al.* (1997) quantified the adherence of soil to a sugar beet by the relative soil adherence, *i.e.* the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment.
Just before the uprooting of sugar beet, wet clay soil is usually in an aggregated condition and has no recent loading history. In this study, the focus is on the observation that such soil behaves differently under compressive stress, compared with tensile stress.

When subjected to compressive stress, wet clay soil deforms in a plastic way (Gill & Vanden Berg, 1967), thereby altering its characteristics. Known effects of compressive normal stress in wet clay soil, adjacent to a material surface are:

- An increase in soil plasticity (softening or plastication), meaning a decrease of soil cohesion (Murayama & Hata, 1957) and, probably, a decrease of tensile strength;
- A sharp decrease in air-permeability of the soil (Perdok & Hendrikse, 1982);
- An increase of soil-material adhesion in tangential direction (Söhne, 1953; Hendrick & Bailey, 1982; Koolen & Kuipers, 1983);
- An increase of soil-material adhesion in normal direction (Fountaine, 1954; Kalachev, 1974).

When subjected to tensile stress, the soil may easily fracture or separate from the beet, provided that the soil has such an air-filled pore system, that entry of air into the soil or low-suction expansion of entrapped air is possible. This observation agrees with results of stickiness experiments in wet clay soil, which showed that the stickiness under tensile stress is generally very low but increases considerably when the clay soil is subjected to compressive stress just before the tensile stress is applied (Mil'tsev, 1966; Domzal, 1970; Kalachev, 1974; Nikolaeva & Bakhtin, 1975). The changes in characteristics of the soil, due to plastic deformation, may hamper the removal of soil from a surface to which it adheres. One reason for this could be that the possibilities for air entry or air expansion are severely restricted. Therefore, in combination with plastication of the soil, tensile failure would not result in fracture of the soil any more, but in plastic deformation. Another reason could be that, independent of the type of loading, failure will always occur in the soil and not at the interface of beet and soil because the values for tangential and normal adhesion have become higher than the values for cohesion and tensile strength, as observed in experiments of Fountaine (1954).

Summarising, it was estimated in this study that the strength of adherence of the soil to the beet after uprooting, compared with the situation before uprooting, will:

- Increase when the soil is subjected to compressive stress (in this study: negative mean principle stress), especially when soil failure (Mohr-Coulomb failure points) and subsequent plastic deformation (plastication) occurs;
- Remain unchanged when the soil is subjected to tensile stress, even when soil failure (Tension cut-off points) and subsequent fracture occurs.

5.4 Results

Effect of the root system

Extraction of a (hypothetical) beet without rootlets resulted in a zone of tension cut-off points, and thus a fractured surface, very close to the beet surface (Figure 5.3.a). Therefore, the expected adhering-soil tare for a beet without rootlets is very low. The adherence characteristics of the soil, located in between the fractured surface and the beet surface is expected to be the same as before uprooting, because the mean principal stress in the fracture area is slightly positive (tensile).

Extraction of a beet with a small number of rootlets emerging from the beet surface, such as in the plane perpendicular to the beet grooves (Figure 5.3.b), also induced a zone of tension cut-off points, located near the beet surface. Only at the lower end of the beet, this zone was at some distance of the beet surface. Therefore, the expected adhering-soil tare is low, but somewhat higher than the soil tare of a beet without rootlets. Due to the slightly positive mean principal stress in between the fracture zone and the beet surface, no changes in soil adherence are to be expected.

During extraction of a beet with many rootlets emerging form the surface, such as near the beet grooves (Figure 5.3.c), a zone of tension cut-off points developed close to the beet surface at the upper and lower end of the beet, but far from the beet surface at the middle section of the beet. It is to be expected, therefore, that the adhering-soil tare will be high in this case, compared with the adhering-soil tare of a beet without rootlets. The mean principal stress between the fracture zone and the beet surface is positive. Therefore the soil adherence is expected to be equal before and after uprooting.

Effect of the uprooting method

While beet extraction induced soil failure far from the beet surface, at a depth of 8 cm (Figure 5.4.a), rotation of the beet around its vertical axis induced a tension cut-off zone very close to the surface all around the beet, even near the grooves (Figure 5.4.b). It may be expected, therefore, that beet rotation (before extraction) will result in very low adhering-soil tare. The soil adherence after rotation is expected to be comparable to the soil adherence before rotation, because the main principal stress in the failure zone is positive (tensile).

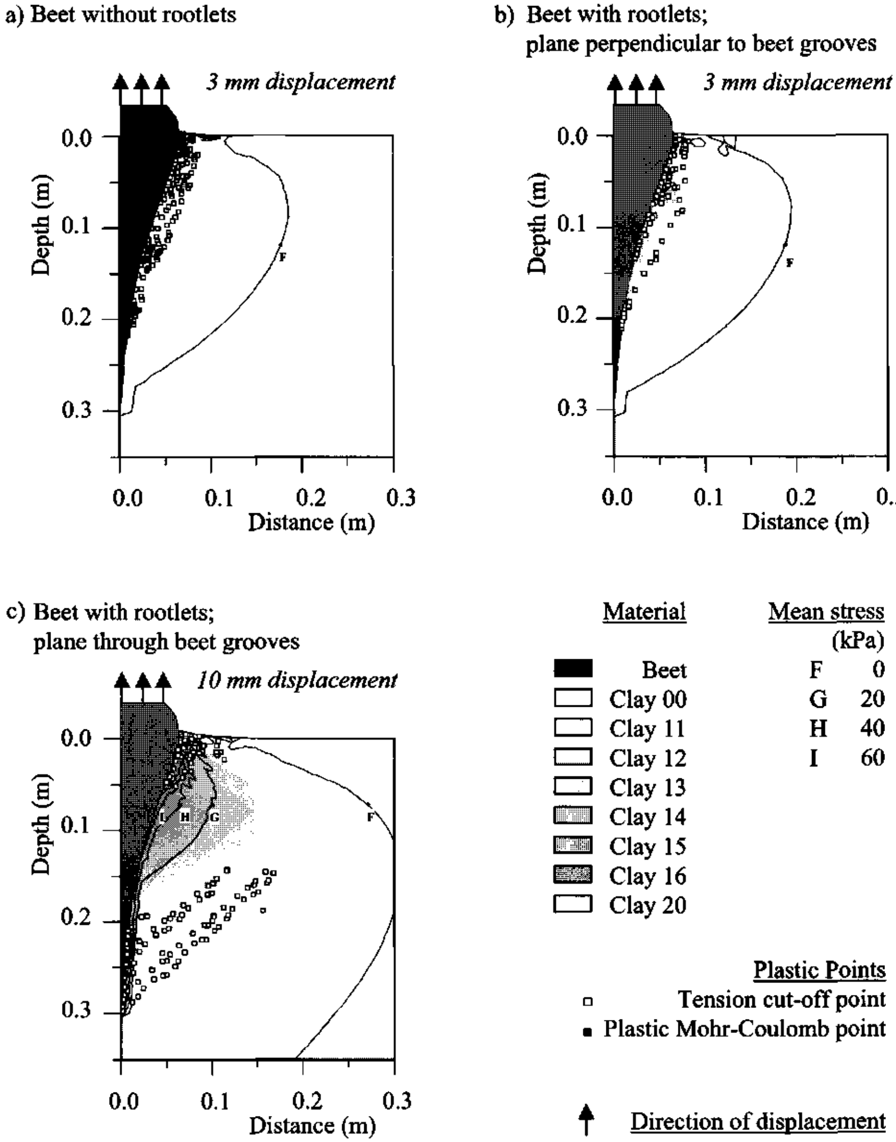


Figure 5.3. Soil failure pattern and mean principal stress, developed during the extraction of beet with and without rootlets, both with low acceleration.

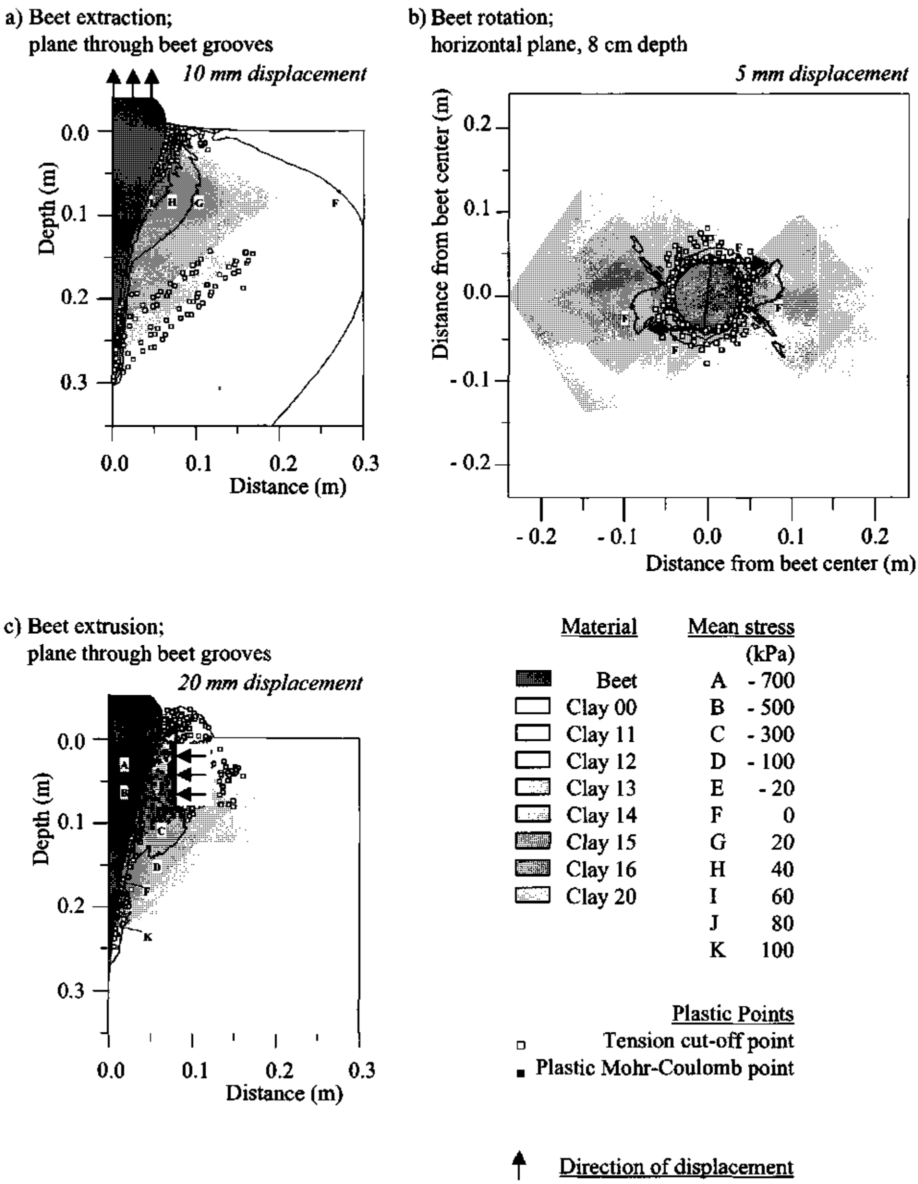


Figure 5.4. Soil failure pattern and mean principal stress, developed during beet extraction, beet extrusion and beet rotation, all with low acceleration.

Beet extrusion induced a zone of soil failure close to the beet surface over the full length of the beet (Figure 5.4.c), in which both tension cut-off points and plastic Mohr-Coulomb points occur. The zone of plastic Mohr-Coulomb failure was located in between the squeeze ring and the beet surface. As Mohr-Coulomb failure is expected to cause plastic deformation of the soil, without fracture, the soil in the Mohr-Coulomb failure zone will not be separated from the beet, but form adhering soil. The mean principal stress of all soil in between the squeeze ring and the beet was lower than -300 kPa (Figure 5.4.c, isobar C) and plastic deformation is to be expected.
Therefore, it may be assumed that the soil in between the squeeze ring and the beet will adhere stronger to the beet after extrusion than before extrusion. At the lower and upper end of the beet, a zone of tension cut-off points occurred, which is situated much closer to the beet surface than in the case of beet extraction. Therefore, the amount of soil adhering to these beet sections will be low, and the soil adherence will be the same as before uprooting. It is to be expected that the overall effect of beet extrusion from wet clay soil will be less soil tare, but stronger soil adherence, compared with beet extraction with low acceleration.

Effect of vertical acceleration during extraction
Compared with the soil failure pattern during beet extraction with low acceleration (Figure 5.5.a), extraction with a vertical acceleration of 29.4 m s^{-2} (Figure 5.5.b) resulted in zones of tension cut-off points that were located slightly closer to the beet surface. Therefore, it may be expected that the adhering-soil tare after accelerated extraction is slightly lower than after non-accelerated extraction. As the mean principle stress was positive in both cases, no effect on the soil adherence is expected.

5.5 Discussion and conclusions

Several simplifications and assumptions were made for the purpose of modelling the soil-beet-lifter system to calculate the stress distribution and the initial soil failure zone during the uprooting of sugar beet. Some of them are discussed hereafter and may need to be reconsidered because reality was oversimplified.

The assumption was made that uprooting was performed on a solitary beet. Because the root system of a beet is usually larger than the space occupied by a beet in the field, the root systems of neighbouring beet will overlap in reality. Therefore, the assumed soil zones with equal rootlet-length-density might differ considerably from those assumed in this study. The effect of neighbouring beet on the origination of soil tare deserves further investigation, therefore.

To model the behaviour of soil interwoven with rootlets, the assumptions were made that no sliding of rootlets through the soil occurs, that rootlets and soil have equal elasticity, and that the contribution of the rootlets to cohesion and tensile strength are numerically equal. In reality, rootlets may slide or cut through the soil and the elasticity of rootlet tissue is usually higher than the elasticity of soil. This means that when rooted soil is stretched, the rootlets may slide through the soil and the soil may fail before the rootlets develop their full strength. Consequently, part of the soil in between the beet surface and the simulated fracture zone might actually fracture during extraction but still adhere to the beet through intact rootlets. During beet extraction experiments, the adherence of soil aggregates to the beet through intact rootlets was actually observed.

One of the basic assumptions in soil dynamic calculations is isotropy, *i.e.* the uniformity of the characteristics of soil and rootlets in space. In reality, soil may be aggregated and rootlets are locally active and may vary in diameter and strength.

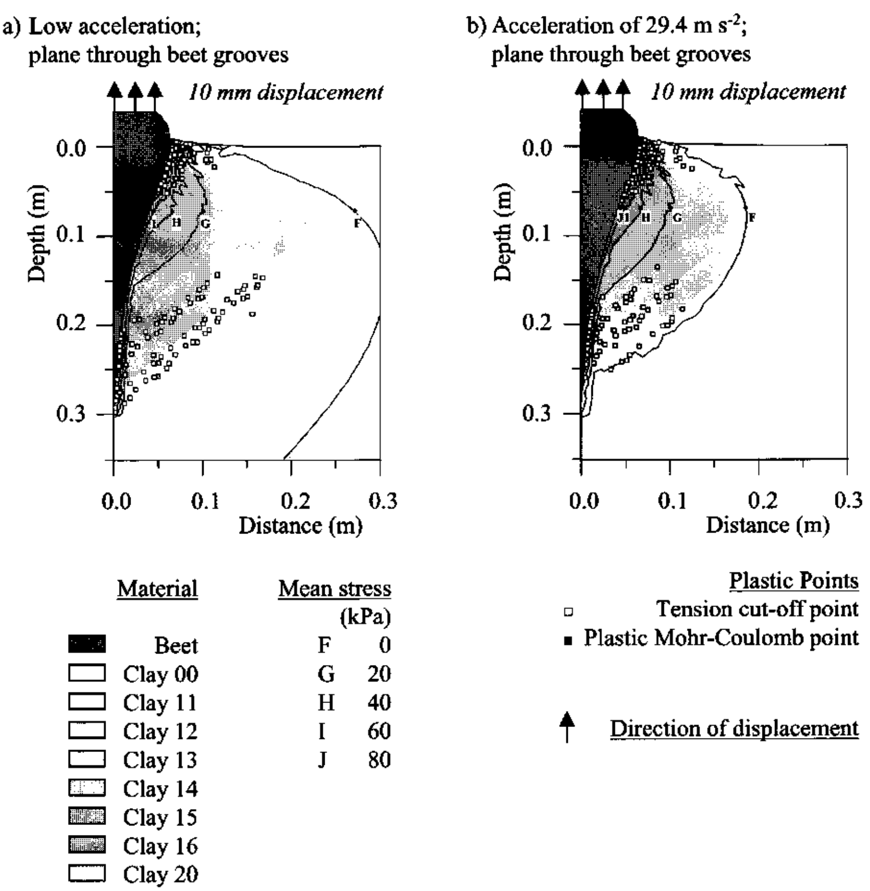


Figure 5.5. Soil failure pattern and mean principal stress, developed during beet extraction with low acceleration and with an acceleration of 29.4 m s^{-2}.

The assumption of isotropy may be reasonable when soil fails in shear, under compressive load, because compressive loads tend to homogenise the soil. However, when soil fails in tension, the non-uniformity of soil might play an important role because failure and fracture will occur at locations with the lowest tensile strength, *i.e.* in between aggregates and at locations with relatively few rootlets. It is to be expected, therefore, that the fractured surface in the soil is more irregular than simulated in PLAXIS. When soil is aggregated, the inter-aggregate tensile strength and cohesion may be much lower than the values derived from laboratory tests. Therefore, it is to be expected that the contribution of the root system to the characteristics of the soil is relatively more prominent in aggregated soil than in non-aggregated soil, which may increase the potential adhering-soil tare. Theoretically, the soil characteristics near the beet surface might be affected during the growing period, due to the increasing volume of the beet. This phenomenon was not reflected in the model input because no quantitative data were available. The possible effect of beet growth on the soil characteristics near the beet surface deserves further investigation, possibly by simulating beet growth in PLAXIS.

A single stress-strain relationship is used, assuming perfectly-plastic soil deformation after initial soil failure. This assumption implies that the failure stress is maintained after initial soil failure. With increasing vertical displacement of the beet during extraction, the volume of soil that failed increases and, therefore, also the calculated total extraction force continuously increases. As the force-displacement relationship during beet extraction was measured in field experiments, a rough check on the correctness of the calculated extraction force is possible by comparing measured and calculated forces. The measured extraction force shows a clear maximum value at a certain displacement, contrary to the calculated extraction force. At displacements larger than the displacement at the peak of the measured extraction force, the calculated extraction force is unrealistically high compared with the measured force. This discrepancy can be explained by the fact that, in reality, the stress level in the soil adjacent to a crack is reduced from the level of failure stress to zero during fracture, thereby reducing the total extraction force. Therefore, the elastic-perfectly-plastic stress-strain relationship may be realistic for the behaviour of soil after plastic Mohr-Coulomb failure, but it is totally unrealistic when the soil fractures after tensile failure. Due to this shortcoming in the model, it was not possible to check the correctness of the estimations of strength characteristics of soil and rootlets by comparison of the measured and the calculated total extraction force.

The application in PLAXIS of a stress-strain relationship, in which the failure stress is improperly maintained after tensile failure, also means that the calculations will become less accurate when the number of tension cut-off points increases. Due to the increasing number of nodes with an incorrect stress state, the total stress pattern in the soil will be increasingly influenced and, consequently, the prediction of the location of the next failure point will be less accurate. Though the results of the PLAXIS calculations presented in this study pertain to the minimum displacement at which the shape of the initial failure zone became evident, the shape may already have been influenced by the occurrence of tension cut-off points. The possibility to adapt the constitutive soil model, such that a reduction of the stress to a very low level occurs after fracture of the soil, should be explored.

The three-dimensional lifting path of a beet can be described realistically in a two-dimensional calculation model, such as the PLAXIS version used, when the geometric outline and the lifting path is symmetric in at least one cross-sectional plane. Thus, the uprooting variants 'extraction' and 'rotation', could be simulated by prescribing a displacement in an axi-symmetric and in a plane strain geometric set-up, respectively. The displacements during lifting with a polder share are not symmetric in any plane. Therefore, the action of the polder share was approximated in this study by the symmetric 'extrusion' variant. The approximation of the polder share by a squeeze ring demonstrates the principal differences in state of stress and failure of the soil during extraction, rotation and lifting with a polder share. However, a more realistic approximation of uprooting by a polder share, including the forward motion of the share and the resulting beet motion, requires the use of a three-dimensional model. Also for simulation of a spiral lifting motion, a three-dimensional model is required.

On the basis of the discussion, the soil-beet-lifter models may be improved on several points. However, despite the shortcomings, the simplifications and the assumptions made, the qualitatively-described effects of uprooting method and extraction acceleration on adhering-soil tare and soil adherence agreed well with the results found in field experiments. It may be concluded from the analysis that:

- Rootlets play an important role in the origination of adhering-soil tare in wet clay because they reinforce the soil around the beet;
- Beet rotation was the most effective method to induce a zone of tensile soil failure close to the beet surface, which is conducive to achieving low adhering-soil tare, compared with beet extrusion;
- Compressive failure, and subsequent soil plastication of wet clay soil, occurs in between a share lifter and the beet, which may explain the strong soil adherence following share lifting, compared with beet extraction, as was observed in field experiments.

Modelling of the soil-beet-lifter systems can be a helpful tool to quickly investigate the effect of numerous beet shapes, root system characteristics, uprooting methods, uprooting accelerations and soil conditions on soil tare and soil adherence, in order to select promising objects for field experiments.

CHAPTER 6

General discussion

Sticky behaviour of soil, as a result of externally-applied pressure, is generally recognised as the cause of high soil tare after harvesting sugar beet out of wet clay soil. Notably, sticky soil causes conventional mechanical beet cleaning systems to be ineffective. Aiming at a reduction of soil tare, this thesis focuses on opportunities to uproot beet such that further cleaning becomes easier or even superfluous. A thorough characterisation and understanding of the sugar beet uprooting process, including the quality of uprooting, is necessary to identify opportunities for such improvement of uprooting. Aimed at upgrading knowledge in this field, the research described in this thesis included a review of literature, the development of research tools, field research and modelling of sugar beet uprooting. The discussion in this chapter deals with the coherence of this work, assessment of the quality of uprooting, effect of characteristics of soil and of beet, effect of uprooting methods, including analysis of the uprooting process, practical implications and research opportunities.

6.1 Coherence of the investigations

Based on reportedly low soil tare and relatively weak soil adherence following beet extraction on wet clay soil, the work in this thesis started with field experimentation, aimed at optimising the lifting path and the extraction kinetics. A mobile pulling rig, capable of executing beet extraction and monitoring the path and the kinetics of the extraction motion was built for this purpose. Many characteristics of soil and individual beet were determined, which permitted investigation of their effect on the quality of uprooting, thereby contributing to understanding of the uprooting process. A method was developed to characterise the strength of adherence of the soil to the beet surface, as a new characteristic of the quality of uprooting. Very low adhering-soil tare was possible by extracting beet with a quick, small-pitch-spiral motion. The observed increase in soil adherence with decreasing ahering-soil tare, following beet extraction, led to the conclusion that the soil adherence prior to uprooting was causing this phenomenon. It became also clear that characteristics of soil and beet, other than those measured in the experiment, should be identified to explain observed differences in soil tare between years. In the second experiment, the most interesting extraction treatments, conventional share lifting and lifting with a driven rotary-shoe lifter were investigated and compared. The driven rotary-shoe lifter was included because its lifting path and lifting kinetics are, to a certain extend, similar to quick, small-pitch-spiral extraction, but application in practice is much easier. Quick, small-pitch-

spiral extraction and lifting with the driven rotary-shoe lifter resulted in relatively low adhering-soil tare, compared with conventional lifting. All treatments again resulted in the general trend of increasing soil adherence as the adhering-soil tare decreases. However, when compared at the same level of adhering-soil tare, the soil adhered relatively strongly after lifting with the two practical lifters, compared with quick, small-pitch-spiral extraction.
Explanation of the effects of the uprooting treatments on adhering-soil tare and soil adherence, as observed in the two field experiments, required consideration of the behaviour of soil during uprooting in terms of loosening, compaction and plastication. A step forward in understanding the behaviour of soil during uprooting has been the modelling of the soil-beet-lifter systems and the simulation of the initial stages of uprooting, using PLAXIS (Chapter 5). The situation prior to uprooting was described quantitatively by the geometrical outline of soil-beet-lifter systems and the material properties of soil and beet, including the rootlets. Based on stress-strain relationships of wet clay soil, described in the Mohr-Coulomb constitutive soil model, the initial zone of soil failure and the stress state of the soil following beet and lifter displacements could be visualised. These simulations revealed that the root system plays a major role in the origination of soil tare and basically causes the increase of adherence with decreasing adhering-soil tare. Also, plausible explanation of the observed effects of some of the various uprooting treatments on adhering-soil tare and soil adherence could be given.

6.2 Assessment of the quality of uprooting

The usual characteristics of the quality of uprooting are soil tare, dug losses and superficial beet damage. Brinkmann (1980) and Ditges (1990) distinguish between loose-soil tare and adhering-soil tare, because removal of loose soil is easy compared with adhering soil. They further draw a distinction between 'removable soil' and 'non-removable' adhering soil. Non-removable soil was used to indicate the fraction of soil that ended up in the beet grooves in a compacted and plasticated state and, therefore, could not be removed by usual cleaning devices. In this thesis, the focus is also on adhering soil. The adhering-soil tare (T_a) and the strength of adherence of the soil to the beet, defined on a relative, continuous scale (*RSA*), were adopted as characteristics of the quality of uprooting. Assuming that weak soil adherence means easy removal of the soil, it was postulated that a combination of low T_a and low *RSA* represents a favourable quality of uprooting.

Originally, soil adherence was described as 'an indication of the stresses that cause the soil particles to stick together and stick to the surface of the beet or the rootlets' (Section 4.1). During the course of the execution of the research, it was realised that the effort needed to remove soil from a beet not only depends on adhesive and cohesive binding stresses, but may also depend on:

- The principle of cleaning;
- The ability of the soil to yield in a plastic way upon externally applied stress, in stead of yielding by fracturing;
- The degree of reinforcement of the soil by the rootlets.

Therefore, the description of soil adherence was revised as 'the ability of soil particles to stick together and stick to the surface of the beet or the rootlets' (Appendix 1).

The difficulty of cleaning of beet, *alias* the soil adherence, was quantified by the relative soil adherence (*RSA*), determined as the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment. (Section 4.1). During 'standard' cleaning, an increase in soil adherence due to compaction and plastication of the soil by the cleaning method itself was to be prevented. The first tried cleaning method was based on inducing only tensile stress in the soil by rotating the beet round it longitudinal axis. The adhering clay soil of beet, taken from the hopper of a harvester, started to break away at an angular speed of about 84 rad s^{-1} (800 rpm). This method was abandoned because most of the beet became unstable at this high an angular speed, and were launched from the clamp. The next tried cleaning method was based on compressed air, as described in Section 4.1, and proved to be a useful 'standard' method for the assessment of *RSA*.

It should be realised that the *RSA* provides only an indication of the difficulty of cleaning of beet. In practice, the cleaning efficiency will depend on the applied principle of cleaning and the condition of the soil. Cleaning systems based on mechanical impact may not fully benefit from a low *RSA* when cleaning beet out of wet clay soil, because these systems may compact and plasticate part of the weakly-adhering soil. In relatively dry soil, these cleaning systems may be much more efficient than the 'standard' cleaning method, using compressed air.

6.3 Effect of characteristics of soil and of beet

Many characteristics of soil and of beet were variables in the field experiments, within the chosen humid clay domain. The large number of characteristics to be analysed presented the problem of selection of mutually independent parameters for inclusion in the statistical models for adhering-soil tare and relative soil adherence. As many parameters show mutual dependency and interaction, the selection of parameters in the statistical models for soil tare was performed with utmost care, involving also investigations of mutual dependency of determined characteristics.

The statistical models for adhering-soil tare, obtained for the experiments in 1994 and 1995, could explain a significant part of the variation in the data and were very similar (Chapter 4), containing only the specific soil-beet contact area, beet fanginess and soil wetness as predictors. This similarity suggests that these characteristics are the most important factors that determine the adhering-soil tare resulting from a specific uprooting method on a specific field, in a specific year and, within the chosen domain (clay soil and variety Univers). The main source of unexplained variation in the data was the difference in adhering-soil tare between years, indicating that non-measured characteristics of soil and beet were responsible for this difference. The work described in Chapter 5 connects to this indication by the conclusion that the root system of a beet plays a major role in the origination of soil tare. Notably, the characteristics of the root system develop during the growing season, as a result of prevailing weather conditions and of management practices. Therefore, these characteristics may be expected to differ between years and may explain a significant part of the differences in adhering-soil tare observed between years. It is strongly recommended, therefore, that characteristics of the root system of sugar beet be determined in future investigations of the uprooting process.

The specific beet-soil contact area (S_s) had a significant effect on adhering-soil tare. Generally, this effect is explained from the mathematical fact of decreasing S_s with increasing beet mass (or volume), combined with the assumption of a constant amount of adhering soil per unit surface area of the beet. However, the results in Chapter 5 show that the soil adheres mainly in the neighbourhood of the beet grooves, due to the abundant presence of rootlets. As the beet grooves develop when the beet grows, the total length and, probably, the depth of the beet grooves increases as the volume and the surface area of the beat increase. Therefore, the real cause of increasing adhering-soil tare with increasing S_s might be relationships between the amount of adhering soil and characteristics of the root system, such as the total length and depth of the beet grooves. Inclusion of such characteristics, relative to the mass of the beet, in future statistical models for the adhering-soil tare will possibly result in better explanation of the variability in adhering-soil tare (including year effects) than the present inclusion of S_s and might make inclusion of S_s superfluous.

Inspection of the root system of a beet revealed that the rootlet-length-density increases when approaching the beet surface and, on the beet surface, when approaching the beet grooves (Chapter 5). This observation means that soil located closer to the beet surface and to the beet grooves exhibits stronger soil adherence, because the soil adherence may be expected to increase when the rootlet-length-density increases. Consequently, a decrease in adhering-soil tare also means an increase in soil adherence, as was observed as a general trend in the field experiments. In addition to the adhering-soil tare, T_a, the specific soil-beet contact area (S_s) was selected as a parameter in the statistical model for *RSA*, despite the fact that T_a is strongly related to S_s. The reason for inclusion was that the model explained a much larger share of the variability in the data when S_s was included as a predictor. The effect of S_s and characteristics of the root system on *RSA* needs further investigation.

6.4 Effect of uprooting methods

Much time and effort was expended on the development of the 'Subitrek', in 1993 and 1994, which resulted in a mobile, hydraulic pulling rig, able to precisely execute and accurately monitor the desired extraction paths and extraction accelerations in the field experiments. The objective of the accurate monitoring of the extraction kinetics was to gain understanding of the extraction forces in relation to the extraction path and the extraction accelerations. Such basic data are required to check the correctness of calculated forces by simulation of uprooting. As only simulation of extraction was planned originally, the share lifter and the driven rotary-shoe lifter were not equipped with instruments to monitor the lifting kinetics.

The adhering-soil tare and relative soil adherence of each uprooting method could be determined with high confidence (Chapter 4). The most challenging part of the research was to provide plausible explanations for the observed differences between uprooting treatments by analysing what happens to the soil during uprooting. Three approaches were adopted to gain understanding of this process:

- Analysis of changes in characteristics of the adhering soil due to uprooting;
- Simulation of the uprooting process;
- Analysis of the measured data on the extraction kinetics.

These approaches are discussed hereafter.

Analysis of changes in characteristics of the adhering soil due to uprooting
The *in situ* characteristics of soil and of beet, and the behaviour of the soil during uprooting in terms of loosening, compaction and plastication of the soil, determine the weakly-adhering-soil tare and the strongly-adhering-soil tare. This logic led to the conclusion that the relative soil adherence, *RSA*, could also be used to characterise the change in characteristics of the soil due to uprooting, by determining the '*RSA in situ*' and the *RSA* after uprooting. The reference uprooting treatment, R, in the field experiments was specifically intended to assess the *RSA in situ*. This set-up failed however, because the *RSA* was not a constant characteristic of most of the soil around the beet, such as originally assumed, but turned out to increase when the soil is located closer to the beet surface, *i.e.* when the adhering-soil tare decreases. In Section 4.2, it was assumed that the adhering soil after beet extraction was relatively undisturbed, because loosened-up soil would be removed by gravity. Consequently, the *RSA* values after beet extraction provided the best approximation of the *RSA in situ*. Based on this assumption, we conclude that, compared with the situation prior to uprooting, the polder share and the driven rotary-shoe lifter cause an increase in *RSA*, due to compaction and plastication of the soil. In reality, soil that has been loosened-up by an extraction treatment may actually not break away, but hang on the beet through the rootlets. Therefore, the extraction treatments, particularly the more aggressive variants, may have had a

loosening effect on some of the adhering soil, which resulted in underestimation of the *RSA in situ*.
In future research, aimed at revealing changes in *RSA* due to uprooting, the relationship between the *RSA in situ* and T_a, the so-called virgin soil adherence curve, should be properly determined for the full range of adhering-soil tare. The determination of *RSA* and T_a after repeated 'standard' cleaning of carefully-dug-out beet, similar to the method applied in the experiments of Green (1957), is suggested for this purpose.

Simulation of the uprooting process
The theoretical approach of the uprooting process by modelling of the soil-beet-lifter system and simulation of soil behaviour, using PLAXIS, should be considered as a first attempt to unravel the uprooting process. Simulation of uprooting provided a very useful tool to describe the zone of initial soil failure and the stress state of the soil at the initial stage of uprooting. The behaviour of soil beyond the point where a zone of tensile failure developed around the beet could not be simulated realistically because the calculated stress state became demonstrably inaccurate. Despite this limitation, the qualitative indications of adhering-soil tare and soil adherence following various uprooting methods agreed surprisingly well with the results obtained in the field experiments. It is suggested, therefore, that the origination of adhering-soil tare mainly happens at the initial stage of uprooting.

In principle, it is possible to calculate the adhering-soil tare after beet extraction from the volume of soil in between the beet surface and the fractured surface in the soil. In this investigation, the calculations became increasingly inaccurate as the number of tensile failure points increased, which had two consequences, making such quantification of the adhering-soil tare impossible:

- A zone, instead of a surface, of tensile failure points developed;
- The simulation had to be stopped before the complete surface of tensile failure points developed.

For beet extrusion (representing share lifting) the problem of quantification of soil tare is more complex than for beet extraction, because of the uncertainty about the behaviour of soil in between the beet and the squeeze ring in terms of soil fracture, loosening, compaction and plastication.

Quantification of the adherence of soil, based on its state of stress state or, more correctly, its strain history, requires a number of presently unavailable research inputs, such as a definition of soil adherence in terms of intrinsic characteristics of soil, a correctly calculated stress path and quantitative data on the change in characteristics of soil due to a specific strain history.

During the simulations of uprooting in PLAXIS, the extraction force and the torque continuously increased with increasing beet displacement, due to the incorrect stress-strain relationship used as was mentioned previously. Further verification of the correctness of the simulations by comparing measured and simulated extraction force and rotation torque was pointless, therefore.

The basic cause of calculation inaccuracy is the stress-strain relationship used, which results in unrealistic maintenance of maximum tensile stress after tensile soil failure. To overcome this problem, it is recommended to further explore the potential of the option 'staged construction' in PLAXIS to avoid this feature, and stress the need for user-definable stress-strain relationships in the user panels of PLAXIS.

Analysis of the measured data on the extraction kinetics

The kinetic data of beet extraction, recorded by the 'Subitrek' on three field days in 1995, were processed to further analyse the effect of the extraction path and the vertical acceleration on soil tare (Vermeulen, 1997). It was concluded that the measured adhering-soil tare of a beet was explained equally well when replacing the treatment factor (F_{et}) in the statistical model for the adhering-soil tare (Appendix 4.1.1) by two variables that characterised the initial extraction kinetics: the initial vertical acceleration and the initial pitch (Figure 6.1). Hereby, the initial stage of extraction was defined as the period from the start of uprooting till the first occurrence in time of the maximum force or the maximum torque. The beet

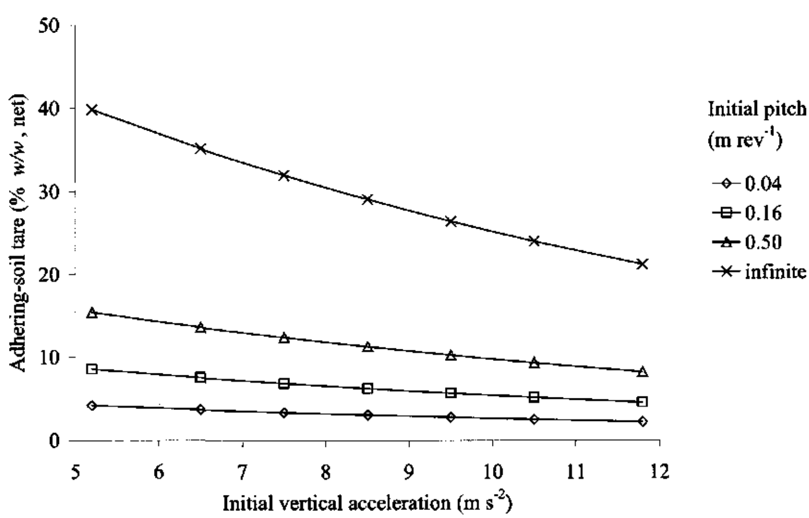


Figure 6.1. Adhering-soil tare, calculated for various levels of the initial vertical acceleration and initial pitch for a non-fanged beet with S_s = 2.64 dm^2 kg^{-1} (beet mass ≈ 1 kg) and soil with Δm = 0.5 % (*w/w*, d.b.), using a statistical model derived from measurements on three days in 1995.

displacements associated with the initial stage of extraction were 7 to 12 mm vertical displacement and 8° to 20° angular displacement (Table 6.1).
The results of the simulations of uprooting, indicating that the adhering-soil tare is mainly determined by the initial stage of uprooting are supported by these findings. The essential role of the initial stage of uprooting, in achieving low soil tare, is important in relation to the design of sugar beet lifters.

6.5 Practical implications

The research described in this thesis shows that, compared with currently used lifters, a significant reduction of adhering-soil tare and soil adherence at the stage directly after lifting is possible, in principle, by improved uprooting. The following principles came forward as ways to reduce the adhering-soil tare and soil adherence on wet clay soil:

- A minimum volume of the soil around the beet that is subject to compressive stress during lifting;
- Beet rotation; the lifting path should be spiral with as small a pitch as possible, until the beet is rotated 8° to 20°, depending on the pitch;
- Beet agitation; the accelerations, vertical and angular, of the beet should be as high as possible until the beet is lifted 7 to 12 mm and rotated 8° to 20°.

Table 6.1. Average maximum force, average maximum torque, and corresponding beet displacements of the extraction treatments, based on statistical analysis of data collected on three days in 1995, and calculated for a non-fanged beet with $S_s = 2.64$ dm^2 kg^{-1} (beet mass ≈ 1 kg) and soil with $\Delta m = 0.5$ % (*w/w*, d.b.).

Treatment	$\overline{F_{max}}$ [1])	$\overline{z_{F\,max}}$ [2])	$\overline{M_{max}}$ [3])	$\overline{\beta_{M\,max}}$ [4])
NS1	444	7	-	-
NS2	557	7	-	-
NS3	532	7	-	-
LPS1	431	7	11	8
LPS2	429	8	23	12
LPS3	285	9	40	17
SPS1	337	8	22	12
SPS2	259	9	38	15
SPS3	120	12	49	20

[1]) $\overline{F_{max}}$ = average maximum vertical extraction force (N); *cv* of $F_{max} = 0.09$.

[2]) $\overline{z_{F\,max}}$ = vertical beet displacement (mm) when F_{max} occurs; *cv* of $z_{Fmax} = 0.06$.

[3]) $\overline{M_{max}}$ = maximum extraction torque (Nm); *cv* of $M_{max} = 0.07$.

[4]) $\overline{\beta_{M\,max}}$ = angular beet displacement (degree) when M_{max} occurs; *cv* of $\beta_{Mmax} = 0.07$.

The work described in this thesis was focussed on reducing the adhering-soil tare and the soil adherence following uprooting, to ease beet cleaning on the harvester. However, Ditges (1990) reported that the (final) soil tare, at the end of the harvesting process, can also be reduced by raising the beet up and above the soil as part of the uprooting process, thus reducing the loose-soil tare. Therefore, this extended beet lifting is looked upon as a fourth 'low-soil-tare' principle of uprooting. Though not determined in the experiments, loose-soil tare should be taken into account when discussing the effect of the quality of uprooting on the final soil tare. Practical application of the four low-soil-tare principles in lifter designs has not been achieved by this work and continues to be a great challenge. However, the results described in this thesis may provide valuable guidance for the design of beet lifters. The potential for applying these principles on conventional lifters, the driven rotary-shoe lifter and future lifter designs, and the subsequent potential for reduction of the final soil tare, is discussed hereafter. While aware of the importance of versatility of technical solutions with respect to soil type and soil wetness, the discussion does not address the overall potential for soil tare reduction, but focuses on suitable technology for wet clay.

Improvement of conventional lifters

The most suitable type of conventional lifters seem to be those that compress as little soil as possible in between the tool and the beet surface, and also prevent compressive stress in front and behind the beet (considered in the direction of forward travel) by lifting the beet straight upwards. In this case, most of the soil surrounding the beet would fail in tension, and the lifting principle resembles non-spiral extraction. This view agrees with the ideas of Göhlich & Von Hülst (1958), who preferred the lifting wheel digger for this reason, compared with the forked share and the polder share. Göhlich & Hingst (1960) reported indeed, that the lifting wheel digger showed lower soil tare than the forked share and the polder share. Another lifter for which these features are claimed by some farmers and contractors, is the so-called 'Kuiken' lifter, which resembles the driven polder share but has very slim shares that cut easily through wet soil and has a share drive-system with larger amplitude (25 mm) and higher frequency (1200 rpm) than normal (10 mm and 500 rpm, respectively).

It may be expected that further application of 'low-soil-tare' principles to conventional lifters may result in reducing the volume of compressed soil, in increasing the initial vertical lift acceleration, and in extended lifting. However, beet rotation or other agitation during lifting will be problematic. Therefore, improvement of conventional lifters may at best result in the uprooting quality that was obtained for quick, non-spiral extraction on relatively wet clay: 0% loose-soil tare; 30 to 60% adhering-soil tare (*w/w*, net); about 75% of the soil adhering weakly. Assuming that it will be possible to remove the fraction weakly-adhering soil by beet cleaning, the final soil tare of systems equipped with improved lifters could potentially be between 7 and 15% on wet clay soil.

Application of the driven rotary-shoe lifter

The driven rotary-shoe lifter was given research attention on very practical grounds: several sources indicated that the soil tare of this lifter used to be low on wet clay soil. From a scientific point of view, the extraction motion induced by the driven rotary-shoe lifter is of interest because it resembles, to a certain extend, the quick, small-pitch-spiral extraction motion, used in treatment SPS3, for which the adhering-soil tare and soil adherence were relatively very low. The field experiments showed that the driven rotary-shoe lifter produced 13% adhering-soil tare under relatively wet conditions on clay, and that about 55% of this soil adhered weakly. Dug losses (1% *w/w*, net) and superficial damage (1.4 cm^2 $beet^{-1}$) were acceptable. Suggested explanations for the relatively low adhering-soil tare of this lifter are:

- The beet is rotated by the action of the rotating shoes;
- The shoes knock the sides of the beet, inducing sidewards displacements prior to uprooting;
- The repeated impact of the shoes causes a soil loosening process comparable to mechanical cleaning.

Further investigation of the uprooting process of the driven rotary-shoe lifter is needed to discover the definite causes of the relatively low adhering-soil tare and the relatively high soil adherence on wet clay. However, the proven low adhering-soil tare was of great practical value and resulted in further testing of the driven rotary-shoe lifter in complete harvesting systems. A first test on medium wet clay soil of a self-propelled complete harvester, equipped with driven rotary-shoe lifters, showed 30% reduction in final soil tare, compared with a conventional system with share lifters (Vermeulen *et al.*, 1998). Field tests of a one-stage harvesting system with driven rotary-shoe lifters (system de Regt/IRS) in 2000, on heavy clay, showed 40% reduction compared with a conventional system with share lifters (Anon., 2001). The loose-soil tare of the driven rotary-shoe lifter was not determined, but was considerable during the field experiment described in Section 4.2. As beet and soil are thrown up relatively high in the air by the shoes, it may be possible to find ways to separate the loose soil and the beet almost completely. Assuming that it will also be possible to remove the fraction weakly-adhering soil by beet cleaning, the final soil tare of systems equipped with improved lifters could potentially be about 6% on wet clay soil.

Beet extraction

All four low-soil-tare principles were applied experimentally by grab lifting with a small-pitch-spiral motion. The capacity was extremely low due to the experimental set-up. On relatively wet clay, the adhering-soil tare was 18% in 1994 and 8% in 1995, while 55% and 75% of the soil adhered weakly, respectively. Dug losses (1 % *w/w*, net) and superficial damage (0.1 cm^2 $beet^{-1}$) were low, but about 12% of the beet were lost due to crown fracture. As the penetration of the grabber teeth into the beet was held responsible for this crown fracture, techniques based on clamping of the beet are recommended for future research on grab lifting. A study, conducted parallel to the work described in this thesis, revealed that practical application of grab lifting is currently not feasible, in spite of the available technologies for beet recognition and subsequent grabbing of individual beet. Therefore, the challenge of practical application of quick, small-pitch beet extraction is to develop techniques to transfer the required forces to the beet with a low incidence of crown fracture and, with a work capacity competing with currently used share lifters. Assuming that the fraction weakly-adhering soil can be removed by beet cleaning, the final soil tare of systems using such uprooting techniques could potentially be about 3 to 6%.

6.6 Research opportunities

The collection of data on beet characteristics, on lifting kinetics, and on the quality of uprooting per individual beet, in combination with simulation of the uprooting process, proved to be a suitable means to perform in-depth studies of the uprooting process. As the root system plays a major role in the origination of soil tare further investigation of the effect of characteristics of the root system is recommended. Determination of various characteristics of the root system, such as the rootlet-length-density distribution in the soil around the beet and the depth and total length of the beet grooves, in addition to the data collected in the present field experiments, is considered tedious, but feasible for a small number of beet. Such data may be used for further improvement of the soil-beet-lifter models, may considerably contribute to further characterisation and understanding the uprooting process. It may also be possible to characterize the root system in a practical way, for instance through measurement of the extraction force, which would allow the characterisation of the root system of a large number of beet, under various conditions of soil and of crop. Possibly, such investigations will yield statistical models for adhering-soil tare and soil adherence with sufficient predictive power to serve as a valuable management tool.

The definition and determination of the relative soil adherence, *RSA*, has been very helpful in demonstrating the increasing strength of adherence of soil to the beet *in situ*, when approaching the beet. The combination of adhering-soil tare and *RSA* also improved the characterisation of the quality of uprooting, by adding a characteristic of the strength of soil adherence and, thus, of the potential difficulty of cleaning. It is felt that the *RSA* could be a useful characteristic of the strength of adherence at different stages of beet cleaning and thus reveal soil compaction and soil plastication effects of various cleaning steps in future research on the cleaning of beet.

The qualitative indications of adhering-soil tare and soil adherence as a result of various uprooting methods, derived from the simulations in PLAXIS, agreed well with results found in the field experiments, despite shortcomings of the calculation method and the simplifications and assumptions made for modelling purposes. The development team of PLAXIS has announced that future options are being developed, that will make it possible to perform calculations with a user-defined stress-strain relationship. Such a feature will probably improve the accuracy of calculations related to tensile failure problems, *i.e.* within the limits imposed by the application of the finite element calculation method. It may be concluded, therefore, that simulation of uprooting will become an increasingly valuable tool to gain understanding of the uprooting process, and will provide useful indications of adhering-soil tare and soil adherence, but also of root breakage, for a variety of characteristics of soil, of beet and of lifting methods.

References

Alizadeh, H., 1985. Physical properties of sugar beet. ASAE Paper 85-3032, 12 pp.

Anon., 1951. Soil Survey Manual. U.S. Department of Agriculture Handbook 18 (revised). U.S. Govt. Printing Office, Washington, 503 pp.

Anon., 1958. Beproeving bietenrooitang van Merkus. ILR, Wageningen, ILR bulletin, no. 77, 4 pp.

Anon., 1984a. Bringen gepflanzte Rüben höhere Erträge? *Top Agrar* 3: p. 60-62.

Anon., 1984b. IRS Jaarverslag 1983. Instituut voor Rationele Suikerproduktie, Bergen op Zoom, 102 pp.

Anon., 1984c. Tarra beperken door doelmatig werken. Tarrawerkgroep Nederlandse Suikerindustrie , Bergen op Zoom, 16 pp.

Anon., 1991. Materiels de recolte demonstration de Revelon le 20 novembre 1991. Compte rendu des travaux effectués en 1991, ITB, Paris, p. 363-393.

Anon., 1996. Jaarverslag 1995. IRS, Bergen op Zoom, 106 pp.

Anon., 1999. Sugar Beet Dictionary - in English, French, German. Brussels, Belgium, International Institute for Beet Research (IIRB), 397 pp.

Anon., 2001. IRS Jaarverslag 2000. Instituut voor Rationele Suikerproduktie, Bergen op Zoom, 102 pp.

Barneveld, A.S., 1994. Determination of agricultural soil parameters that can be used in PLAXIS finite element code. In: Proc. 2nd Int. Conf. on Soil Dynamics, 23-27 August 1994, Silsoe College, Cranfield University, Silsoe, Bedford (UK): 7-9.

Bieluga, B. & M. Bzowska-Bakalarz, 1980. Investigations of the mechanical properties of roots and some sugar beet varieties. In: Proc. 2nd Int. Conference Physical Properties of Agricultural Materials, Godöllo, Hungary. Paper no. 35, 8 pp.

Bouma, J. & A. Cappon, 1988. Onderzoek naar de beperking van grondtarra bij de oogst van suikerbieten. IMAG, Wageningen, IMAG-rapport, no. 101, 97 pp.

Bouma, J., A. Bouman & A. Cappon, 1983. Tarra-probleem bij de oogst van suikerbieten. *Landbouwmechanisatie* 34: p. 279-281.

Bowden, F.P. & D. Tabor, 1964. Friction and lubrication of solids. Oxford Clarendon Press, London, 327 pp.

Brinkgreve, R.B.J. & P.A. Vermeer (Eds), 1994. PLAXIS. Finite Element Code for Soil and Rock Analyses. Material models manual. Version 5. Balkema, Rotterdam, the Netherlands, 60 pp.

Brinkgreve, R.B.J. & P.A. Vermeer (Eds), 1998. PLAXIS. Finite Element Code for Soil and Rock Analyses. Reference manual. Version 7. Balkema, Rotterdam, the Netherlands, 170 pp.

Brinkmann, W., 1980. Möglichkeiten und Grenzen der Erdanteilsreduzierung in den Zuckerrübenerntemaschinen. *Die Zuckerrübe* 29 (6): p. 18-21.

Brinkmann, W., 1985. Verringerung des Erdanteils in der Zuckerrübenerntemaschine. *Zuckerindustrie* 110: p. 1063-1072.

Brinkmann, W., 1986a. Die Testung der Arbeitsqualität von Zuckerrübenerntemaschinen. Die internationale Methode des IIRB. *Die Zuckerrübe* 35: p. 144-148.

Brinkmann, W., 1986b. Chancen für die Verbesserung der Zuckerrübenernte. *Die Zuckerrübe* 35: p. 278-285.

Brooymans, P.W.A.M., 1992. Tarra-beperking belangrijker. *CSM Informatie* 468, p. 6-7.

Brunotte, J., E. Isensee, H. Tilch & K. Winter, 1993. Einfluss der Bodenbearbeitung auf Bestand und Erdanhang der Zuckerrübe. *Landtechnik* 48: p. 226-229.

Bulich, C., 1984. Die Wirkung von Erntemaschinen und -Systemen auf die Qualitaet der Zuckerrübe. In: Proceedings, 47th Winter Congress of the International Institute for Sugar Beet Research, 15-16 February 1984, Bruxelles (Belgium), p. 275-288.

Bulich, C. & K.H. Kromer, 1986. Die Erde auf dem Acker lassen: durch sorgfältige Einstellung kann man hohe Erdanteile an Zuckerrüben vermeiden. *DLG-Mitteilungen* 101: p. 870-873.

Chancellor, W.J., 1994. Chapter 2: Soil physical properties. In: S.K. Upadhyaya, W.J. Chancellor, J.V. Perumpral, R.L. Schafer, W.R. Gill & G.E. Vanden Berg (Eds), Advances in soil dynamics. American Society of Agricultural Engineers, St. Joseph, Michigan, ASAE monograph, 12, Vol. 1, 313 pp.

Cofie, P., 2001. Mechanical properties of tree roots for soil reinforcement models. Wageningen University, the Netherlands, PhD Thesis, 165 pp.

Czeratzki, W., 1966. Die Charakterisierung von bearbeitungsbeeinflussten Bodeneigenschaften in Beziehung zum Pflanzenwachstum. Landbauforschung Völkenrode, 16 (1) p. 37-44.

Dawidowski, J.B. & A.J. Koolen, 1987. Changes of Soil Water Suction, Conductivity and Dry Strength During Deformation of Wet Undisturbed Samples. *Soil & Tillage Research* 9: 169-180.

Ditges, K.O., 1990. Untersuchungen zur Reduzierung des Erdanteils bei der Zuckerrübenernte. Dissertation, Rheinischen Friedrich-Wilhelms-Universität, Bonn, 235 pp.

Domzal, H., 1970. Preliminary studies of the influence of moisture on physio-mechanical properties of some soils with regard to estimation of optimum working conditions of implements. *Polish Journal Soil Science* 3: p. 61-70 (cited by Chancellor, 1994).

Draht, L., R. Strauss & H. Schiweck, 1984. Untersuchungen über die mechanischen Eigenschaften von Zuckerrüben. II. Einflussfaktoren auf die Bruchfestigkeit von Rüben. *Zuckerindustrie* 109: p. 993-1007.

Duval, Y., 1988. Pour reduire la tare, connaitre et observer ses sols. Une etude du groupe tare du CIPS [Comite Interprofessionnel des Productions Sacchariferes]. *Sucrerie Française* 129: p. 425-428.

Engel, B. & A. Keen, 1994. A simple approach for the analysis of generalised linear mixed models. *Statistica Neerlandica* 48: 1-22.

Ennos, A.R., 1989. The mechanics of anchorage in seedlings of sunflower, Helianthus annuus L. *New Phytologist* 113: 185-192.

Ennos, A.R., 1990. The anchorage of Leek Seedlings: The effect of Root Length and Soil Strength. *Annals of Botany* 65: 409-416.

Ennos, A.R., 1991. The mechanics of Anchorage in Wheat Triticum aestivum L.; 1. The anchorage of wheat seedlings. *Journal of Experimental Botany* 42 (245): 1601-1606.

Fauchere, G., 1989. Reducing dirt tare during sugar beet harvesting. In: Proceedings, 52nd Winter Congress of the International Institute for Sugar Beet Research, 15-16 February 1989, Bruxelles (Belgium), p. 65-77.

Folkerts, H., J.K. Kouwenhoven & U.D. Perdok, 1981. Mogelijkheden voor de rijbanenteelt. *Landbouwmechanisatie* 32: p. 499-504.

Fountaine, E.R., 1954. Investigations into the mechanism of soil adhesion. *Journal of Soil Science* 5: p. 251-263.

Fritzsch, K., E. Winnig, W. Wilhelm, F. Müller & K. Hänsch, 1976. Grundlagenforschung zu neuen Rodeelementen für Rübenerntemaschinen des Zeitraums um 1990; Abschlussbericht 1979. Martin-Luther-Universität, Halle, MLU 24/102/76/9, 126 pp.

Fritzsch, K., E. Winnig, W. Wilhelm, F. Müller & K. Hänsch, 1977. Grundlagenforschung zu neuen Rodeelementen für Rübenerntemaschinen des Zeitraums um 1990; Erganzungsbericht 1977. Martin-Luther-Universität, Halle, MLU 24/124/77/10, 58 pp.

Gemtos, T.A., 1979. Physical aspects of sugar beet lifting by pronged shares related to losses due to fractures of roots in the field. Reading University, UK, Department of Agriculture and Horticulture, Thesis, 428 pp.

Gill, W.R. & G.E. Vanden Berg, 1967. Soil Dynamics in Tillage and Traction. Agriculture Handbook 316. United States Department of Agriculture, 511 pp.

Gliemeroth, G., 1953. Beinigkeit und Wurzelwachstum der Zuckerrüben. *Zucker* 6: p. 573-578.

Glinski, J. & J. Lipiec, 1990. Soil physical conditions and plant roots. CRC Press, Florida, 250 pp.

Göhlich, H. & H. Von Hülst, 1958. Untersuchungen an Rodewerkzeugen für Zuckerrüben. *Zucker* 11: p. 154-156.

Göhlich, H. & K. Hingst, 1960. Die Arbeitsweise von Zuckerrüben-Rodescharen bei unterschiedlichen Bodenbedingungen. *Landtechnik* 15: p. 182-184.

Green, H.C., 1956. The cleaning of sugar beet. *Journal of Agricultural Engineering Research* 1: p. 175-177.

Green, H.C., 1957. Some experiments on the cleaning of sugar beet. *Journal of Agricultural Engineering Research* 2: p. 209-216.

Hartmans, D., 1982. Nadelige invloeden van grondbewerkingssporen op de kieming en de groei van suikerbieten. *Landbouwmechanisatie* 33: p. 123-127.

Heller, C., 1960. Sichtbare Verluste in der Zuckerrübenernte durch die Rodeorgane. *Landtechnische Forschung* 10: p. 117-121.

Hendrick, J.G. & A.C. Bailey, 1982. Determining components of soil-metal sliding resistance. *Transactions of the ASAE* 25: p. 845-849.

Hingst, K., 1962. Untersuchung von Zuckerrüben-Rodescharen in einem Bodenkanal. *Landtechnische Forschung* 12: p. 71-76.

Jakob, P., 1983. Investigations on automatic steering of a beet harvesting machine; Untersuchungen zur automatischen Lenkung einer Rübenerntemaschine. *Agrartechnik* 33 p. 38-39.

Jorritsma, J., 1958. Tarra- en losse grond problemen bij het rooien en verwerken van suikerbieten. In: Strooker, E., N. Hoogendoorn & J. Jorritsma, 1958. Mechanisatie van de suikerbietenoogst. ILR, Wageningen, Publicatie, no. 45, p. 44-54.

Jorritsma, J., 1985. De teelt van suikerbieten. Terra, Zutphen, Groene reeks, 286 pp.

Kalachev, V.Y., 1974. Stickiness of clay soils (In Russian). Dissertation, Moscow State University (cited by Chancellor, 1994).

Karwowski, T., 1974. Hackfruchterntemaschinen. VEB Verlag Berlin, 290 pp.

Keen, A., 1994. Procedure IRREML. In: P.W. Goedhart & J.T.N.M. Thissen (Eds). Genstat 5. GLW-DLO Procedure Library Manual, Release 3[1]. Report LWA 94-16. GLW-DLO, Wageningen, 300 pp.

Koolen, A.J. & H. Kuipers, 1983. Agricultural soil mechanics. Advanced series in agricultural sciences,13, Springer-Verlag, Berlin, 241 pp.

Kromer, K.H., 1989. Entwicklung der Zuckerruben-Erntetechnik. *Landtechnik* 44: p. 341-343.

Kromer, K.H., 1990. Erdabscheidung uni Beschädigung: Vergleich verschiedener Erntemaschinen. In: Proceedings, 53rd Congress of the International Institute for Sugar Beet Research, 14-15 February 1990, Bruxelles (Belgium), p. 173-183.

Kromer, K.H., S. Krauland & J. Strätz, 1990. Verfahrenstechnische Möglichkeiten der Beeinflussung von Erdanteil und Oberflächenbeschädigung bei der Zuckerrübenernte. *Die Zuckerrübe* 39: p. 214-218.

Kromer, K.H., J. Strätz & M. Tschepe, 2001. Technischer Stand der Zuckerrübenernte. *Landtechnik* 56: p. 78-79.

Kromwijk, P.A.M., 1972. Actualiteiten bij teelt en onderzoek van suikerbieten. *Bedrijfsontwikkeling* 3 (9): p. 819-828.

Kutschera, L., 1960. Wurzelatlas mitteleuropäischer Ackerunkräuter und Kulturpflanzen. DLG-Verlag, Frankfurt am main, Germany, 574 pp.

Maassen, J. & A.C.P.M. Van Swaaij, 2000. Bietenstatistiek 1999. Instituut voor Rationele Suikerproduktie (IRS), Bergen op Zoom, 43 pp.

Maggs, E., 1955. Cleaning beet; Overcoming the problems on heavy land. *Farm Mechanization* 7 (78), p. 407.

Märländer, B., 1989. Bestandesdichte im vereinzelungslosen Zuckerrübenbau: ein Faktor von unterschätzter Bedeutung für Ertrag uni Qualität? *Die Zuckerrübe* 38: p. 106-110.

Merkes, R. & A. Von Müller, 1986. Einfluss einer Bodenverdichtung unter dem Saatbett auf Wuchsform uni Erdanhang der Zuckerrübe. *Zuckerindustrie* 111: p. 19-23.

Miller, P.C.H., 1982. The mechanics of sugar beet lifting. Cranfield Institute of Technology, NIAE, Silsoe, UK, Ph.D-thesis, 219 pp.

Miller, P.C.H., 1984. The prediction of the fracture of sugar beet roots loaded horizontally. *Journal Agricultural Engineering Research* 30: 211-220.

Mil'tsev, A.I., 1966. Sticking and friction of soil on metals and plastics (In Russian) In: Studies of working tools of agricultural machines. Reports of Conference of Young Scientists, Moscow (cited by Chancellor, 1994).

Murayama, S. & S. Hata, 1957. On the effect of remolding clay. 4th. Internatl. Conf. Soil Mech. and Found. Engin. Proc., London, vol. 1, p. 80-82 (cited by Gill & Vanden Berg, 1967).

Nikolaeva, I.N. & P.U. Bakhtin, 1975. Stickiness of dark chestnut heavy loam soils of the kustani oblast under conditions of vertical tearing and of tangential shear (In Russian). *Soil Science* 4, p. 68-78, Moscow (cited by Chancellor, 1994).

Parker, S.P., 1989. McGraw-Hill dictionary of scientific and technical terms. McGraw-Hill Book Company, New York, 2088 pp.

Payne, P.C.J., 1956. A field method of measuring soil/metal friction. *Journal of Soil Science* 7: p. 235-241.

Payne, R.W., P.W. Lane, P.G.N. Digby, S.A. Harding. P.K. Leech, G.W. Morgan, A.D. Todd, R. Thompson, G. Tunnicliffe Wilson, S.J. Welham & R.P. White, 1993. Genstat 5 Release 3 Reference manual. Clarendon Press, Oxford, 796 pp.

Perdok, U.D. & L.M. Hendrikse, 1982. Workability test procedure for arable land. In: Proceedings 9th Conference of ISTRO, Osijek, Yugoslavia, 1982, p. 511-519.

Remijn, A., 1986. Steketee: Ideeën en ontwerpen (2). *Landbouwmechanisatie* 37: p. 714-715.

Salokhe, V.M., M. Hoki & K. Sato, 1993. Why does soil not stick to enamel coating? *Journal of Terramechnics* 30: p. 275-283.

Schuh, J.P., 1989. Untersuchungen von Wirkprincipen der Rodewerkzeuge zur zielgerichteten, beimengungsarmen Einzelrübenrodung. Dissertation, Wilhelm-Pieck-Universität, Rostock, 126 pp.

Schuh, J.P. & K. Höhn, 1991. Zuckerrüben künftig ziehen? *Landtechnik* 46: p. 425-429.

Smed, E., 1998. Sugar loss in beet tails as related to the morphology and the shear strength of the beet. *Zuckerindustrie* 123: p. 128-134.

Smith, J.A., C.D. Yonts, R.G. Wilson, J.G. Robb & E.D. Kerr, 1988. Transplanted sugarbeet yield response to in-row spacing. *Transactions of the ASAE* 31: p. 1322-1325.

Söhne, W., 1953. Reibung und Kohäsion bei Ackerböden. *Grundlagen der Landtechnik* 5: p. 64-80.

Spoor, G. & S.M. Miller, 1989. Investigations into improved soil management and traffic control practices in the sugar beet crop. Final report on joint British

Sugar/ Silsoe College soil management project to Sugar Beet Research and Education Committee, 123 pp.
Steenhuis, F., 1990. Bietverliezen in de praktijk. *CSM-Informatie* 453: p. 8-9.
Strooker, E., 1960. Rooigereedschap en werktuigen op de demonstratie. In: Jorritsma, J., K.E. Krolis, E. Strooker & J. Terpstra, 1960. Mechanisatie van de suikerbietenoogst. Verslag van de landelijke Bietenoogstdemonstratie 1959 te Rozenburg. ILR, Wageningen, Publikatie No. 54, p. 24-43.
Strooker, E., 1962. De machines en hun resultaten. In: Jorritsma, J., E. Strooker & J. Terpstra. Mechanisatie van de suikerbietenoogst. Verslag van de landelijke bietenoogstdemonstratie 1961 te Elst (Bet). ILR, Wageningen, Publikatie No. 62, p. 9-35.
Strooker, E., 1982. Harvest mechanization. In: Boiteau, R., R.A. Dunning & C. Winner (Eds). 1932-1980, 50 years of sugar beet research. International Institute for Sugar Beet Research (IIRB), Brussels, 126 pp.
Strooker, E. & R.A. De Widt, 1957. Het machinaal rooien van suikerbieten. ILR, Wageningen, Gestencilde Mededeling, no. 2, 11 pp.
Swinkels, J.J.A., 1996. Ontwerp van een enkelbietrooisysteem; een haalbaarheidsonderzoek. Stan Ackermans Instituut, Eindhoven, 89 pp.
Tong, J., L. Ren, B. Chen & A.R. Qaisrani, 1994. Characteristics of adhesion between soil and solid surfaces. *Journal of Terramechanics* 31: p. 93-105.
Vandergeten, J.P., J.P. Van Der Linden, M. Armstrong, P. Jarvis & K.H. Kromer (Coordinator), 1997. Test procedures for measuring the quality in sugar beet production - seedquality, precision seeders, harvesters, cleaner loaders (concept for IIRB standard). Bonn, Institut für Landtechnik der Rheinischen Friedrich-Wilhelms-Universität, 22 pp.
Van Der Bijl, W.J.M., 1989. Tarra en puntbreuk. *Loonbedrijf* 41: p. 49-51.
Van Der Linden, J.P., 1990. Tarrabeperking bij de oogst. *Loonbedrijf* 11: p. 26-27.
Van Der Linden, J.P., 1992. Afstelling oogstmachines belangrijk. *CSM-Informatie* 468: p. 15-16.
Van Der Linden, J.P., 1995a. Beet harvesting is going to change - towards cleaner beet (In Dutch). *Landbouwmechanisatie* 46: 26-27.
Van Der Linden, J.P., 1995b. Resultaten onderzoek tarrabeperking 1994. *CSM-Informatie* 488: p. 15-16.
Van Der Linden, J.P., 2001. Het effect van plantaantallen op de opbrengst en kwaliteit van suikerbieten. IRS, Bergen op Zoom, IRS publicatie 01P01, 17 pp. + bijlagen.
Van Der Linden, J.P. & J.P. Vandergeten, 1999. Machines onderling vergelijken. In: Anonymous, 1999. Bietenrooidemonstratie '99. Gids internationale bietenrooidemonstratie 13 oktober 1999 te Watervliet (België). KBIVB, Tienen, Belgium, 32 pp.
Vermeulen, G.D., 1995. Grondtarravermindering door enkelbietrooien; een voorstudie. IMAG-DLO, Wageningen, rapport 95-27, 51 pp.

Vermeulen, G.D., 1997. Effect of sugar beet extraction methods on soil tare and relative soil adherence. In: Program and abstracts, 3rd Int. Conf. on Soil Dynamics, Tiberia, Israel, August 1997, p. 83.

Vermeulen, G.D., 1998. Effect of sugar beet lifting methods on soil tare and relative soil adherence. In: Proceedings AgEng 98, Oslo, paper no. 98-A-064, 8 pp.

Vermeulen, G.D., J.J. Klooster, M.C. Sprong & B.R. Verwijs, 1997. Effect of straight and spiral sugar beet extraction paths and lift acceleration on soil tare and relative soil adherence. *Netherlands Journal of Agricultural Science* 45: 163-184.

Vermeulen, G.D., J.P. Van Der Linden, D. Blaauw, M.C. Sprong & B.R. Verwijs, 1998. Preventie van grondtarra bij suikerbieten door toepassing van een aangedreven sloffenlichter. IMAG-DLO, Wageningen, nota P 98-06, 43 pp.

Voesten, E.W.H.M., 1993. Beperking van grondtarra bij de oogst van suikerbieten. LUW, Vakgroep Agrotechniek en -fysica, Wageningen, Scriptie voor afstudeervak werktuigkunde, 55 pp.

Von Hülst, H., H. Göhlich & B. Söchting, 1957. Untersuchungen an Rodewerkzeugen für Zuckerrüben. *Zucker* 10: p. 535-538.

Vukov, K., 1972. Physik und Chemie der Zuckerrübe als Grundlage des Verarbeitungsverfahren. Akadémia Kiadó, Budapest, 458 pp.

Vukov, K., 1977. Physics and chemistry of sugar-beet in sugar manufacture. Elsevier, Amsterdam, Netherlands, 595 pp.

Wayman, J.A. & G.L. Maughan, 1966. The effect of soil compression by tractor wheels on sugar beet dirt tare. *Agricultural Engineering Research* 11: p. 206-209.

Westerdijk, C.E., 1989. Minder tarra bij een betere bietvorm. *Landbouwmechanisatie* 40: p. 14-15.

Wevers, J.D.A., 1980. Tarrabeperking bij de suikerbietenoogst. *Landbouwmechanisatie* 31: p. 1039-1042.

Wevers, J.D.A. & J.T. Andringa, 1979. Grondtarra bij suikerbieten. Verslag van een orienterend onderzoek naar grondtarra bij de oogst van suikerbieten met overwegend zesrijige machines. Wageningen, CLA, 64 pp.

Windt, A., 1995. Entwicklung des Faserwurzelsystems der Zuckerrübe sowie dessen Beziehung zum Wachstum der Gesamtpflanze und der Nährstoffaufname. Cuvillier Verlag, Göttingen, Dissertation Universität Göttingen, Germany, 90 pp.

Winter, K., 1993. Wirkung von Bodenbearbeitungsverfahren für Zuckerrüben auf Ertragsentwicklung und Erdanhang. Institut für Landwirtschaftliche Verfahrenstechnik, Kiel, Diplomarbeit, 85 pp.

Wu, S., 1982. Polymer interface and adhesion. Marcel Dekker Inc., New York, 625 pp.

Zadneprovskii, R.P., 1975. The influence of pressure, time of contact and temperature on the adhesion of soils to working tools (In Russian). Kiev, Teknika, Mining, Construction and Highway Machines, No. 19, p. 23-31 (cited by Chancellor, 1994).

Summary

After harvest of sugar beet and transportation to the sugar factory, beet lots always contain some soil. This soil is called tare soil and the weight fraction of tare soil in a beet lot is called soil tare. In the year 2000, the amount of tare soil delivered to the sugar factories in the Netherlands was about 600 million kg. Less tare soil is desired by all parties involved in the beet sugar production chain, for various reasons:

- The considerable yearly cost of beet cleaning, of storage, transport and disposal of tare soil and of beet losses due to the cleaning of beet (about 25 million euro in total);
- The yearly soil erosion of agricultural land may be up to 21 t ha^{-1} (5.5 t ha^{-1}, on average, in 2000);
- Tare soil presents a phytosanitary risk;
- Considerable amounts of energy and clean water are needed each year, to cope with the tare soil.

Opportunities to reduce the amount of tare soil turn up at various links in the chain from sowing to delivery of the beet to the factory. Reduction of soil tare at the harvesting link is to be preferred, because the soil will then remain on the field and the negative effects of soil tare are avoided. *This thesis addresses the reduction of soil tare by improving the sugar beet harvesting technology.* The focus is on a major improvement of uprooting (also called lifting), one of the phases of harvesting. Low soil tare directly after uprooting will considerably reduce the need for further cleaning in all following beet treatment phases. The *research objective* was to analyse and improve the uprooting process, in order to reduce soil tare during harvest on wet clay soils, taking into account the effects on the total harvesting performance.

Assessment of the quality of harvesting and of uprooting
The total performance of the harvesting process includes the quality of harvesting (product quality and product losses) and the harvesting capacity. The quality of harvesting is characterised by: surface losses, dug losses, soil tare and superficial beet damage. The quality of uprooting is the quality of harvesting in between uprooting and beet cleaning. In addition to the above-mentioned characteristics, the condition of the soil adhering to the beet is an important characteristic of the quality of uprooting in the sense that easy cleaning of the beet after uprooting is preferred. Therefore, a new characteristic of the quality of uprooting was introduced, to indicate the strength of adherence of soil to the beet surface.

Factors affecting the quality of harvesting and of uprooting

The quality of harvesting and of uprooting is mainly affected by characteristics of the beet, of the soil and of the harvesting technique. The effects of these characteristics, focused on the effect on adhering-soil tare (T_a, *i.e.* the mass of non-beet material, which adheres to the beet, relative to the mass of the beet[1]), were reviewed. Important characteristics of the beet in relation to soil tare are beet size, beet shape, roughness of the beet surface and, still poorly defined, characteristics of the root system. Beet size and specific soil-beet contact area (S_s in dm^2 per kg beet) are strongly related and, therefore, are exchangeable characteristics. S_s was selected for use in this thesis, because its relationship with T_a was expected to be simple. Generally, large beet (relatively low S_s) show less soil tare than small beet (relatively high S_s). Relatively much soil adheres to the beet in the neighbourhood of the so-called beet grooves; longitudinal cavities in the beet surface from which many rootlets emerge. Specially-bred spherical beet without beet grooves (smooth surface) have shown to be low in soil tare. However, varieties having these characteristics are expected to become commercially available only on the longer term. Currently available 'low-soil-tare' varieties, that have a relatively regular shape and a relatively smooth surface, generally have the disadvantage of being relatively low in sugar content. Beet fanginess is reported to affect soil tare only when beet are uprooted by extraction, and not when harvested with conventional harvesting techniques. A high density of rootlets in the soil around the beet is suggested to enhance soil tare, but methods to substantiate and quantify this effect have not been reported.

Characteristics of the soil have a compound effect on soil tare. Indirectly, soil tare may be affected by the influence of the soil on the beet characteristics. Soil texture, soil structure and soil wetness[2] affect the mechanical behaviour of soil during uprooting and cleaning and, thus, affect soil tare directly. The general trend is that the adhering-soil tare is high on clayey soil and low on sandy soil. The effect of soil wetness on soil tare goes mostly parallel with the effect of the ease of crumbling of soil as a result of externally-applied stress (the workability of the soil). The adhering-soil tare as a result of uprooting is lowest at a soil wetness level at which the soil crumbles most easily. Particularly when the soil becomes wetter than this wetness level, the soil becomes more difficult to crumble, and the adhering-soil tare increases. An exception occurs when the soil wetness is extremely high; in that case wet clay soil turns into a colloidal suspension upon pressure, which may drip off the beet, resulting in relatively low adhering-soil tare. The effect of soil wetness on the ease of crumbling is much more pronounced in clay soil than in sand. In wet clay

[1] Figures of soil tare and beet losses are on the basis of clean, correctly topped beet (% *w/w*, net) in this summary.

[2] Soil wetness is a term used to indicate the moisture condition of the soil. Soil wetness is often described qualitatively, but sometimes also quantitatively, for instance by the soil moisture content, the soil water matric potential or the degree of water saturation of the soil.

soil, in particular, externally-applied stress may result in compaction and plastication (*i.e.* an increase of the plasticity) of the soil. Removal of compacted and plasticated soil from the beet by cleaning devices is very difficult.

Traditionally, sugar beet were uprooted by pulling the beet out of the soil by the leaves. This job was made easier by the jacking movement of a narrow spade or fork, inserted into the soil next to the beet. It is briefly described in this thesis how mechanised beet harvesting developed from tools, intended to further ease manual labour by loosening the soil around the beet, towards self-propelled, complete beet harvesters. Modern harvesters perform leaf stripping, topping, lifting and cleaning at high capacity in one operation. They have facilities to temporarily store the harvested beet and unload them onto a trailer. Research and development of harvesting systems is always geared towards optimising the total harvesting performance (quality and capacity) and, eventually, towards minimising the overall cost of harvesting. When the research described in this thesis started, 1992, most harvesters were equipped with more or less standard share lifters and standard mechanical cleaning devices. These systems resulted in a final soil tare (*i.e.* the soil tare at the end of the harvesting process) on clay soil of about:

- 7% under very favourable conditions (relatively dry and friable soil);
- 12% under favourable conditions (medium wet and friable soil);
- 20% under unfavourable conditions (medium wet and firm soil);
- 55% under very unfavourable conditions (relatively wet and sticky soil).

Since 1992, much attention has been paid to the reduction of soil tare. Old as well as new techniques to reduce soil tare have been applied and machinery adjustments were geared to low soil tare, to meet the current requirements of harvesting performance. Currently, soil tare figures exceeding 25% are considered to be extremely high, even under very unfavourable conditions in the Netherlands.

The final soil tare is mainly affected by the techniques used for uprooting and cleaning of the beet. For reduction of soil tare by improved uprooting, the potential for successful cleaning of the uprooted beet is important. It was concluded from reports on the cleaning of beet that the best potential for cleaning occurs when:

- Loose-soil tare and adhering-soil tare, as a result of uprooting, are minimal;
- The soil, that adheres to the beet, is not plasticated and not compacted in the beet grooves during the uprooting process.

Stand-alone, conventional share lifters on wet clay lift beet typically with 450% loose-soil tare and 100% adhering-soil tare. Plastication or compaction of the soil due to uprooting by conventional share lifters was often observed visually, but has never been quantified. Uprooting techniques with a reported higher quality of uprooting than conventional share lifters, on wet clay soil, are:

- Beet extraction: compared with a complete modern harvesting process, a helical extraction motion results in a much lower level of soil tare and the soil is suggested to adhere less strongly to the beet surface;
- Raising of the whole beet up and above the soil during lifting: typically, conventional share lifters, equipped with additional lifting rotors, reduce the loose-soil tare to 200% and the adhering-soil tare to 70%;
- Beet agitation: Intentional knocking of the beet at the sides or on top of the beet reduces the soil tare following beet extraction. Kicking the beet out of the soil by a driven rotary-shoe lifter resulted in extremely low soil tare of 11% at a harvesting demonstration under very unfavourable conditions on heavy clay soil.

As this research was aimed at achieving a considerable reduction in soil tare, it was concluded that analysis and optimisation of beet extraction, in terms of the extraction path and acceleration of extraction, was a promising direction of investigation. The acceleration of extraction was included because of the reported favourable effects of beet agitation on soil tare.

Field experiments
Two field experiments were conducted to investigate and compare uprooting techniques with potentiality to reduce the soil tare significantly. Before the field experiments started, a field method was developed to quantify the strength of adherence of soil to the beet by a characteristic called the relative soil adherence (*RSA*). *RSA* was defined as the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment.

In the first experiment (conducted twice, in 1994 and 1995), the effect of straight and spiral extraction paths and lift acceleration on the uprooting quality on wet clay soil, was investigated. The 'Subitrek', a vehicle with an instrumented, hydraulic pulling rig, was built and extensively tested to correctly perform the extraction treatments on individual beet, and log the kinetic characteristics of the extraction motion. Many characteristics of beet and soil were measured, as covariables, to reveal, as accurate as possible, the effect of the extraction method applied, by statistical analysis of the data. Very low adhering-soil tare occured when a beet was lifted with a small-pitch-spiral extraction path and high vertical acceleration of extraction. For wet clay, the adhering-soil tare was 18% in 1994 and 8% in 1995. It was discovered that when soil was located closer to the beet surface, the *in situ* strength of adherence to the beet increased. Therefore, also the *RSA* correlated strongly with the adhering-soil tare, irrespective of the extraction treatment. The *RSA*, corresponding to the above mentioned soil tare figures, was 33% in 1994 and 40% in 1995. Dug losses and superficial damage were low, irrespective of the extraction treatment. However, crown fracture, which leads to a total loss of the beet, was unacceptably high (12% of all beet extracted) after the quick, small-pitch-spiral extraction method. These results imply that very low soil tare is attainable on wet clay soil. However, practical application of quick, small-pitch-spiral extraction requires the development of a technique to transfer the required forces to the beet with a low incidence of crown fracture, in addition to the more general requirement of developing a grab lifting system with high capacity. Though technologies for beet recognition and subsequent grabbing of individual beet have improved considerably over the last decades, a study, conducted parallel to the work described here, revealed that practical application of grab lifting was not feasible in 1996.

As lifting path and lifting acceleration of the driven rotary-shoe lifter (system Vicon-Steketee, in use around 1960) and of quick, small-pitch-spiral extraction show similarity, this lifter was investigated in a second experiment, integrated into the first experiment in 1995. Conventional share lifting was also included in this experiment as a reference. On wet clay, conventional share lifting resulted in 50% adhering-soil tare and *RSA* was 32%. With the driven rotary-shoe lifter, 13% adhering-soil tare and an *RSA* of 47% was obtained. Quick, small-pitch-spiral extraction resulted in 8% adhering-soil tare and an *RSA* of 40%. Contrary to the results after various extraction treatments, lifting treatments had a significant effect on *RSA*, in addition to the effect of adhering-soil tare itself. This finding implies that the change in soil characteristics, due to soil loosening, soil compaction and soil plastication, differed between lifting treatments. Thus, quantitative evidence of the occurrence of soil plastication or compaction during lifting with conventional shares was obtained as an increase in *RSA*, compared with the *RSA* of beet that were carefully dug out by hand, representing the *in situ* soil condition. Based on the results, and considering the total performance of uprooting, it was concluded that, on wet clay soil, the driven rotary-shoe lifter might in practice be able to reduce the adhering-soil tare prior to cleaning by a factor 3 to 4.

Soil dynamical analysis of the origination of soil tare during uprooting

To provide theoretical foundation for some of the observed effects of uprooting methods on soil tare and soil adherence, the soil-beet-lifter system was modelled and the initial stage of uprooting was simulated, using PLAXIS, a geotechnical computer programme. The Mohr-Coulomb constitutive soil model, assuming elastic-perfectly-plastic soil behaviour, was used as a basis for modelling. The soil model was extended to allow for increased tensile strength of the soil. A moderately heavy silty clay loam, of which most input parameters were known, was adopted for the simulations. A number of system variants were modelled and evaluated, including beet with and without rootlets and various uprooting methods. The root system of a sugar beet was modelled as increases in cohesion and tensile strength of the soil due to rootlets. The soil around the beet was divided into a number of zones of equal rootlet-length-density. For each zone, the rootlet-length-density and, as a result of the rootlets, the increase in cohesion and tensile strength of the soil were estimated. Mechanical characteristics of beet and rootlets were adopted from data reported in the literature. Three uprooting methods were modelled: beet extraction, beet rotation and beet extrusion. The latter method represented the principle of uprooting by a share lifter, modelled by a cylindrical ring in the soil around the beet. By contracting this ring, the beet is squeezed out of the soil. The origination of soil tare could be presented on the basis of the calculated zone of initial soil failure. The strength of soil adherence could be analysed on the basis of the calculated stress state of the soil. Accelerated extraction was simulated pseudo-dynamically, by increasing the value of gravity to $4g$. The simulations revealed that rootlets play a dominant role in the origination of soil tare. Contrary to a normal beet with rootlets, for a hypothetical beet without rootlets, the zone of initial soil failure develops at, or very near to the beet surface, which results in very low adhering-soil tare. Simulated soil behaviour agreed well with observed trends in adhering-soil tare and *RSA* for the uprooting treatments in the field experiments, provided that reinforcement of the soil by rootlets was taken into account. It was concluded that modelling of soil-beet-lifter systems and simulation of uprooting is a helpful tool to get an impression of the effect of beet shape, root system, uprooting method and soil condition on soil tare and soil adherence.

Scientific results

The work described in this thesis has particularly improved the understanding of the following aspects of the uprooting process on wet clay soil:

- Simultaneous measurement of many characteristics of beet, soil, and the uprooting quality per individual beet made it possible to investigate mutual relationships between the characteristics and, therefore, to select the most influential and independent characteristics of beet and soil for inclusion into the statistical models for adhering-soil tare. As a result, soil wetness, the specific beet-soil contact area and the beet shape (normal or fanged) were identified as the main factors that determine the adhering-soil tare on clay soil, for a specified uprooting method.
- The strength of adherence of soil to the beet was quantified by the relative soil adherence (*RSA*). *RSA* results indicated that the *in situ* strength of soil adherence, prior to uprooting, increased as the distance to the beet surface decreased. Therefore, *RSA* also increased naturally with decreasing adhering-soil tare. This implies that avoidance of soil compaction and soil plastication during uprooting in itself is not sufficient to reach the combination of low adhering-soil tare and weak soil adherence, that is desired for effective further cleaning. For this purpose, active loosening of the soil adjacent to the beet by the lifting action will be necessary.
- The dominant role of rootlets in the origination of soil tare was clarified by simulation of the behaviour of soil during uprooting. It was found that the strength of soil increased as the rootlet-length-density increased. As the rootlet-length-density increased with decreasing distance to the beet surface, the

calculated high strength near the beet corresponded with the field observation of high *RSA* close to the beet.

Practical implications

The developed method for quantifying the strength of soil adherence, by *RSA*, allows a better assessment of the quality of uprooting. Notably, the combination of loose-soil tare, adhering-soil tare and *RSA* gives an indication of the difficulty of further cleaning. Therefore, this method might considerably facilitate cost-effective field testing and (further) development of beet lifters in a cost-effective way.

Principles of uprooting that came forward as conducive to low soil tare on wet clay soil were:

- A lifting path which raises the beet up and above the soil;
- A minimum volume of soil that is subject to compressive stress during lifting;
- Beet agitation during the initial stage of lifting, by high angular acceleration (investigated up to 12 m s^{-2}) and high vertical acceleration;
- Beet rotation (8° to 20°) during the initial stage of lifting.

Further improvement of conventional lifters may be achieved by utilising the first two 'low-soil-tare' lifting principles and high vertical acceleration. The best uprooting quality of such methods on wet clay soil expected to be feasible equals the quality obtained as a result of quick, non-spiral extraction: 0% loose-soil tare, 30 to 60% adhering-soil tare, and 75% of the adhering soil being weakly-adhering (*RSA* = 25%). Assuming that it will be possible to remove the fraction weakly-adhering soil by beet cleaning, the final soil tare of complete harvesting systems, equipped with such improved conventional lifters, could be between 7 and 15% on wet clay soil.
The driven rotary-shoe lifter produced 13% adhering-soil tare under relatively wet conditions on clay. Of this soil tare, 75% adhered weakly (*RSA* = 25%). The loose-soil tare was considerable. Dug losses (1%) and superficial damage (1.4 cm^2 $beet^{-1}$) were acceptable. Assuming that it will be possible to remove all loose soil and all weakly-adhering soil by cleaning, the final soil tare of harvesting systems with driven rotary-shoe lifters could be 6% on wet clay soil. During field testing, after the experiments described in this thesis, such harvesting systems produced 30 to 40% less soil tare than systems using share lifters.
The results of uprooting by extraction with a quick, small-pitch-spiral motion show that 0% loose-soil tare, 8 to 18% adhering-soil tare and an *RSA* of 33 to 40% is obtainable on wet clay soil, in principle. However, new engineering solutions will be required to realise a sufficient capacity and to realise beet rotation during extraction, without damaging the beet. Assuming that the weakly-adhering soil can be removed by beet cleaning, systems utilising all previously-mentioned 'low-soil-tare' principles may potentially reach a final soil tare between 3 and 6% on wet clay soil.

In conclusion, a considerable reduction of soil tare during the harvest of sugar beet on wet clay soil is attainable by using the acquired insight into the uprooting process, which controls the origination of soil tare and the soil adherence, and innovative uprooting techniques.

Samenvatting

Na de oogst en het transport van suikerbieten naar de fabriek bevatten de partijen bieten altijd nog wat grond. Deze grond wordt tarragrond genoemd en de gewichtsfractie tarragrond van een partij bieten wordt aangeduid met grondtarra. In het jaar 2000 werd bij de Nederlandse suikerfabrieken ongeveer 600 miljoen kg tarragrond aangeleverd. Om diverse redenen wordt minder tarragrond gewenst door alle partijen in de bietsuikerproductieketen:

- De jaarlijks gemaakte kosten voor reinigen, opslag, transport en afzet van tarragrond en bietverliezen ten gevolge van de reiniging van bieten zijn aanzienlijk (totaal ongeveer 25 miljoen euro);
- De jaarlijkse erosie van landbouwgrond kan oplopen tot 21 t ha^{-1} (het gemiddelde in 2000 was 5,5 t ha^{-1});
- Het risico bestaat dat plantenziekten verspreid worden via tarragrond;
- Een aanzienlijke hoeveelheid energie en schoon water is jaarlijks nodig voor de verwerking van de tarragrond.

Mogelijkheden om de hoeveelheid tarragrond te verminderen doen zich voor bij verschillende schakels in de keten van inzaai tot aflevering van bieten bij de fabriek. Vermindering van grondtarra tijdens de schakel 'oogst van het veld' verdient de voorkeur, omdat de grond daarbij op het veld achterblijft, waardoor de genoemde nadelige effecten van grondtarra in de resterende schakels vermeden worden. *Dit proefschrift gaat over vermindering van grondtarra door verbetering van de oogsttechniek voor suikerbieten.* De aandacht is vooral gericht op sterke verbetering van één van de oogstfasen: het rooien van bieten (het uit de grond halen, ook vaak lichten genoemd). Lage grondtarra direct na het rooien zal de noodzaak voor reiniging tijdens latere fasen van het oogstproces aanzienlijk verminderen. De *doelstelling* van het onderzoek was om het rooiproces te analyseren en te verbeteren, teneinde de grondtarra bij de oogst op natte kleigrond te verminderen, rekening houdend met effecten van het rooien op de totale oogstprestatie.

Vaststelling van de oogst- en rooikwaliteit
De totale prestatie van het oogstproces wordt vooral bepaald door de oogstkwaliteit (productkwaliteit en productverliezen) en de oogstcapaciteit. Kenmerkend voor de oogstkwaliteit zijn: het verlies op het land, het puntverlies, de grondtarra en de bietbeschadiging. De rooikwaliteit is een tussentijdse kwaliteit van het oogstproces, direct na het rooien. In aanvulling op de hiervóór genoemde kenmerken is voor de rooikwaliteit ook de toestand van de aan de biet hangende grond belangrijk, in die zin dat de voorkeur uitgaat naar makkelijk reinigbare bieten. Daarom werd in dit

proefschrift een nieuw kenmerk voor de rooikwaliteit geïntroduceerd om de mate van hechting van grond aan het bietoppervlak te karakteriseren.

Factoren die de oogst- en rooikwaliteit beïnvloeden
De oogst- en rooikwaliteit wordt voornamelijk beïnvloed door kenmerken van de bieten, de grond en de oogsttechniek. Door middel van een literatuuronderzoek werd nagegaan wat bekend is over de invloed van deze kenmerken op de rooikwaliteit, met name op de aanhanggrondtarra (T_a, gedefinieerd als het gewicht van de aanhangende grond gedeeld door het gewicht van de biet of de bieten[1]).

Belangrijke bietkenmerken in verband met grondtarra zijn de grootte en de vorm van de biet, de ruwheid van het bietoppervlak en, nog onvoldoende gedefinieerd, kenmerken van het wortelstelsel. Omdat het specifieke grond-biet contactoppervlak (S_s in dm^2 per kg biet) sterk afhangt van de bietgrootte zijn S_s en bietgrootte uitwisselbaar als kenmerk van de biet. In dit proefschrift werd S_s gebruikt, omdat verwacht werd dat dit kenmerk een eenvoudige relatie vertoont met T_a. In het algemeen vertonen grote bieten (relatief lage S_s) minder grondtarra dan kleine bieten (relatief hoge S_s). Relatief veel grond blijft aan de biet hangen in de buurt van de zogenaamde wortellijsten; gleuven in de lengterichting van de biet waaruit veel zijwortels tevoorschijn komen. Speciaal veredelde ronde bieten zonder wortellijsten (glad oppervlak), vertoonden een lage aanhanggrondtarra. Verwacht wordt echter, dat rassen met zulke kenmerken pas op langere termijn beschikbaar zullen komen. Huidige 'lage grondtarra' rassen, met een relatief regelmatige vorm en een relatief glad oppervlak, hebben in het algemeen het nadeel van een relatief laag suikergehalte. Verschil in aanhanggrondtarra tussen vertakte en niet vertakte bieten werd alleen waargenomen na het uittrekken van bieten en niet na oogsten met gangbare techniek. Geopperd wordt, dat een hoge dichtheid van zijwortels in de grond rondom de biet een verhogend effect heeft op grondtarra, maar methoden om dit effect te staven en te kwantificeren zijn niet gerapporteerd.

Bodemkenmerken hebben een tweeledig effect op grondtarra. Indirect kan de grondtarra beïnvloed worden doordat de bodem de bietkenmerken mede bepaalt. De textuur, de structuur en de natheid[2] van de grond hebben een direct effect op grondtarra omdat zij het mechanische gedrag van de grond tijdens het rooien en reinigen bepalen. De algemene trend is dat de aanhanggrondtarra hoog is op kleigrond en laag op zandgrond. Het effect van de natheid van de grond op aanhanggrondtarra loopt vrijwel parallel met het effect van de verkruimelbaarheid van grond bij extern uitgeoefende krachten (bewerkbaarheid van de grond). De

[1] In deze samenvatting zijn alle genoemde cijfers voor grondtarra en bietverliezen uitgedrukt op basis van schone, correct gekopte bieten (% *w/w*, netto).
[2] De natheid van grond is een begrip om de vochttoestand van de grond aan te duiden. Vaak wordt de natheid kwalitatief beschreven, soms ook kwantitatief d.m.v. bijvoorbeeld het vochtgehalte, de vochtspanning of de waterverzadigingsgraad van de grond.

aanhanggrondtarra na het rooien is het laagst als de natheid van de grond zodanig is, dat deze het makkelijkst te verkruimelen is. Vooral als de natheid van de grond hoger is dan dit niveau, wordt de grond steeds moeilijker te verkruimelen en neemt de aanhanggrondtarra toe. Als uitzondering op deze trend neemt de aanhanggrondtarra weer af als de grond uitzonderlijk nat wordt, doordat de klei bij beroering dan verandert in een suspensie, die van de biet af kan druipen. Het effect van de natheid van de grond op de verkruimelbaarheid is veel sterker voor kleigrond dan voor zandgrond. Vooral in natte kleigrond kan extern uitgeoefende druk verdichting en versmering (dit is een toename van de plasticiteit) van de grond tot gevolg hebben. Het verwijderen van verdichte en versmeerde grond van de biet door reinigingsapparatuur is erg moeilijk.

Suikerbieten werden vroeger gerooid door de biet bij het blad vast te pakken en uit de grond te trekken. Dit werk werd vergemakkelijkt door de hefboombeweging van een smal schopje of vorkje, dat naast de biet in de grond gestoken werd. In dit proefschrift wordt beknopt beschreven hoe de mechanisatie van de bietenoogst zich ontwikkelde van werktuigen om het handwerk verder te verlichten door de grond rond de biet los te maken, tot zelfrijdende bunkerrooiers. Moderne bietenoogstmachines verwijderen het blad en koppen, rooien en reinigen de bieten in één werkgang. Zij zijn uitgerust met voorzieningen om de geoogste bieten tijdelijk op te slaan en te lossen in een wagen. Onderzoek aan en ontwikkeling van oogstsystemen is steeds gericht op het optimaliseren van de oogstprestaties (kwaliteit en capaciteit) en, uiteindelijk, op het minimaliseren van de totale oogstkosten. Op het moment dat het in dit proefschrift beschreven onderzoek begon, 1992, waren de meeste bietenrooiers uitgerust met min of meer standaard typen scharenlichters en reinigingsmodules. Hiermee werd op kleigrond een eindgrondtarra (d.w.z. de grondtarra aan het eind van het oogstproces) behaald van ongeveer:

- 7% onder zeer gunstige omstandigheden (relatief droge, verkruimelbare grond);
- 12% onder gunstige omstandigheden (vochtige, verkruimelbare grond);
- 20% onder ongunstige omstandigheden (vochtige, slecht verkruimelbare grond);
- 55% onder zeer ongunstige omstandigheden (relatief natte, klevende grond).

Sinds 1992 heeft vermindering van grondtarra veel aandacht gekregen. Zowel oude als nieuwe technieken om grondtarra te verminderen werden toegepast en machine-afstellingen werden gericht op minder grondtarra om aan de nieuwe eisen te voldoen. Momenteel wordt in Nederland een grondtarra hoger dan 25% beschouwd als extreem hoog, zelfs onder zeer ongunstige omstandigheden.

De eindgrondtarra wordt vooral beïnvloed door de toegepaste techniek voor rooien en reinigen van de bieten. Voor verlaging van grondtarra door verbetering van het rooien is de reinigbaarheid van de gerooide bieten belangrijk. Op grond van de literatuur werd geconcludeerd dat bieten het beste te reinigen zijn als:

- De lossegrondtarra en de aanhanggrondtarra na het rooien minimaal zijn;
- De aan de biet hangende grond niet versmeerd is en niet in de wortellijsten samengedrukt is tijdens het rooien.

Op natte kleigrond zijn een lossegrondtarra van 450% en een aanhanggrondtarra van 100% typerend voor conventionele scharenlichters. Versmering en verdichting van de grond als gevolg van het rooien met conventionele scharenlichters werd vaak visueel waargenomen, maar nooit gekwantificeerd. Rooitechnieken, waarmee op natte klei een betere rooikwaliteit gerapporteerd werd dan met conventionele scharenlichters zijn:

- Het uittrekken van bieten: vergeleken met een compleet, modern oogstproces resulteert draaiend uittrekken in een veel lagere grondtarra en de grond lijkt minder sterk aan de biet gehecht te zijn;
- Het voortzetten van de lichtbeweging totdat de gehele biet boven de grond is: typerend voor conventionele scharenlichters met extra lichtrotoren zijn een lossegrondtarra van 200% en een aanhanggrondtarra van 70%;
- Het geven van een krachtimpuls aan de biet: gericht kloppen tegen de zijkanten of op de bovenzijde van de biet vermindert de grondtarra na het uittrekken van bieten. Bieten uit de grond 'schoppen' met een sloffenkruislichter resulteerde in een extreem lage grondtarra van 11% tijdens een bietenrooidemonstratie onder zeer ongunstige omstandigheden op zware kleigrond.

Omdat dit onderzoek gericht was op een aanzienlijke vermindering van grondtarra, werd uit het literatuuronderzoek geconcludeerd dat analyse van het uittrekproces en optimalisatie van de uittrekbeweging en -versnelling een veelbelovende richting van onderzoek was. De uittrekversnelling werd in het onderzoek opgenomen vanwege het gerapporteerde gunstige effect op grondtarra van een krachtimpuls op de biet.

Veldexperimenten
Twee veldexperimenten werden uitgevoerd om rooitechnieken met potentieel voor aanzienlijke vermindering van grondtarra te onderzoeken en te vergelijken. Voordat het veldonderzoek begon werd een methode ontwikkeld om in het veld de mate van hechting van grond aan de biet te kwantificeren door middel van de zogenaamde relatieve grondhechting (*RSA*; relative soil adherence). *RSA* werd gedefinieerd als de massa van de grond, die na een 'standaard' reiniging met perslucht nog aan de biet hangt, gedeeld door de massa van de grond die aanhing voorafgaand aan deze reiniging.

In het eerste experiment (twee keer uitgevoerd, in 1994 en 1995), werden de effecten van recht opgaand en draaiend uittrekken en van de uittrekversnelling op de rooikwaliteit onderzocht op natte kleigrond. De 'Subitrek', een voertuig met een hydraulische trekinstallatie uitgerust met meetinstrumenten, werd gebouwd en uitgebreid getest om de uittrekbehandelingen op individuele bieten correct uit te kunnen voeren en om de kinetische kenmerken van de uittrekbeweging te registreren. Veel kenmerken van bieten en grond werden als co-variabele gemeten om zo nauwkeurig mogelijk het effect van de uittrekmethoden te kunnen bepalen door middel van statistische analyse van de waarnemingen. De aanhanggrondtarra was zeer laag als de biet via een spiraalvormige baan met kleine spoed en met een hoge verticale versnelling (hierna genoemd: snel, sterk draaiend uittrekken) uitgetrokken wordt. Op natte klei was de aanhanggrondtarra 18% in 1994 en 8% in 1995. Ontdekt werd dat naarmate de grond in situ dichter bij het bietoppervlak lag, de mate van hechting aan de biet toenam. Daarom was ook de *RSA* sterk gecorreleerd met de aanhanggrondtarra, ongeacht de uittrekbehandeling. De bij de bovengenoemde grondtarracijfers behorende *RSA* was 33% in 1994 en 40% in 1995. Voor alle uittrekbehandelingen was het puntverlies laag en kwam weinig bietbeschadiging voor. Kopbreuk, leidend tot een totaal verlies van de biet, kwam echter onacceptabel veel voor (bij 12% van de bieten) na de snelle, sterk draaiende uittrekbeweging. Deze resultaten betekenen dat zeer lage grondtarra op natte kleigrond bereikbaar is. Echter, voor praktische toepassing van snel, sterk draaiend uittrekken dient een grijperrooisysteem ontwikkeld te worden dat, behalve aan de voorwaarde van hoge capaciteit, ook voldoet aan de voorwaarde dat de benodigde kracht zodanig op de biet wordt overgebracht dat weinig kopbreuk optreedt. Hoewel de technologie voor bietherkenning en het daaropvolgende grijpen van individuele bieten in de afgelopen decennia sterk verbeterd is, was de uitkomst van een studie, die parallel aan het hier beschreven onderzoek werd uitgevoerd, dat praktische toepassing van grijplichters anno 1996 niet haalbaar was.

Omdat de baan en de versnelling van de rooibeweging bij de aangedreven sloffenkruislichter (systeem Vicon-Steketee, dat in gebruik was rond 1960) verwant zijn aan die bij de snelle, sterk draaiende uittrekbeweging, werd deze lifter onderzocht in een tweede veldexperiment, geïntegreerd in het eerste experiment in 1995. Ook de conventionele scharenlichter werd als referentiebehandeling in het tweede experiment opgenomen. Bij de scharenlichter was de aanhanggrondtarra 50% en de *RSA* was 32%. Bij de aangedreven sloffenkruislichter was de aanhangrondtarra 13% en de *RSA* was 47%. Snel, sterk draaiend uittrekken resulteerde in 8% aanhanggrondtarra en een *RSA* van 40%. In tegenstelling tot het resultaat bij verschillende uittrekmethoden hing de *RSA* niet alleen af van de waarde van de aanhanggrondtarra zelf, maar ook van de rooimethode. Dit betekent dat de verandering in grondkenmerken door losmaking, verdichting en versmering van de grond verschilde per rooimethode. Op deze wijze werd kwantitatief bewijs verkregen voor versmering en samendrukking van grond door conventionele rooischaren, in de vorm van een toename van de *RSA* vergeleken met de *RSA* van voorzichtig met de hand uitgegraven bieten, die de in situ bodemtoestand vertegenwoordigden. Op basis van de resultaten en de totale rooiprestatie, werd geconcludeerd dat de aangedreven sloffenlichter in de praktijk in staat kan zijn om op natte kleigrond de aanhanggrondtarra voorafgaand aan het reinigen van de bieten te verminderen met een factor 3 tot 4.

Bodemdynamische analyse van het ontstaan van grondtarra tijdens het rooien.
Ter onderbouwing van de waargenomen effecten van de rooimethode op grondtarra en op de hechting van grond aan de biet, werd het grond-biet-lichtersysteem gemodelleerd en werd het beginstadium van het rooien gesimuleerd met PLAXIS, een geotechnisch computerprogramma. Het grondmodel van Mohr-Coulomb, dat uit gaat van elastisch, zuiver plastisch gedrag van de grond, werd gebruikt als basis voor de modellering. Daarbij werd het grondmodel uitgebreid met vergelijkingen om het grondgedrag bij een hoger dan normale treksterkte van de grond te beschrijven. Een middelzware kleigrond waarvan de meeste invoergegevens voor het grondmodel bekend waren, werd gebruikt voor de simulaties. Een aantal systeemvarianten werd gemodelleerd en onderzocht, waaronder bieten met en zonder zijwortels en een aantal rooimethoden. Het wortelstelsel van een biet werd gemodelleerd als een toename van de cohesie en de treksterkte van de grond tengevolge van de aanwezigheid van zijwortels. De grond rondom de biet werd ingedeeld in een aantal zones van gelijke wortellengtedichtheid. Voor elke zone werd de wortellengtedichtheid en, als gevolg daarvan, de toename van de cohesie en de treksterkte geschat. Voor de mechanische kenmerken van de biet en de zijwortels werden in de literatuur vermelde cijfers gebruikt. Drie rooimethoden werden gemodelleerd: uittrekken van de biet, bietrotatie en extrusie van de biet. De laatstgenoemde methode werd representatief geacht voor het rooiprincipe van een scharenlichter en werd gemodelleerd door middel van een cilindrische ring in de grond rondom de biet. Door contractie (verkleining van de diameter) van deze ring wordt de biet uit de grond geperst. Het ontstaan van grondtarra kon aanschouwelijk gemaakt worden door middel van de berekende bezwijkzone in de grond. De mate van hechting van grond aan de biet kon geanalyseerd worden op basis van de berekende drukken in de grond. Versneld uittrekken werd pseudo-dynamisch gesimuleerd, door de zwaartekrachtversnelling te verhogen tot 4*g*. De simulaties gaven aan dat zijwortels een dominante rol spelen bij het ontstaan van grondtarra. In tegenstelling tot bij een normale biet met zijwortels, ontwikkelt de bezwijkzone in de grond bij een hypothetische biet zonder zijwortels op of heel dicht bij het bietoppervlak, hetgeen leidt tot zeer lage aanhanggrondtarra. Het gesimuleerde gedrag van de grond stemde goed overeen met de waargenomen trends van aanhanggrondtarra en *RSA* voor de rooibehandelingen in de veldexperimenten, op voorwaarde dat rekening gehouden werd met de wapening van grond door zijwortels. De conclusie was dat het modelleren van grond-biet-lichtersystemen en simulatie van het rooien een waardevol hulpmiddel is om een indruk te krijgen van het effect van bietvorm, wortelstelsel, rooimethode en bodemomstandigheden op grondtarra en op de mate van hechting van de grond aan de biet.

Wetenschappelijke resultaten
Het onderzoek dat in dit proefschrift beschreven wordt verschafte met name een beter inzicht in de volgende aspecten van het rooiproces op natte kleigrond:

- Gelijktijdige meting van veel kenmerken van de biet, de bodem en de rooikwaliteit per individuele biet heeft het mogelijk gemaakt om onderlinge relaties tussen de kenmerken te onderzoeken en daarmee de belangrijkste en onafhankelijke biet- en bodemkenmerken te selecteren in de statistische modellen voor aanhanggrondtarra. Als resultaat hiervan bleken de natheid van de grond, het specifieke biet-grond contactoppervlak en de vorm van de biet (normaal of vertakt) de belangrijkste factoren te zijn die aanhanggrondtarra op kleigrond bepalen, bij een bepaalde rooimethode.
- De mate van hechting van de grond aan de biet werd gekwantificeerd door middel van de relatieve grondhechting (*RSA*). De *RSA* resultaten duiden erop dat de mate van grondhechting in situ, dat wil zeggen voorafgaand aan het rooien, toeneemt naarmate de afstand tot het bietoppervlak kleiner was. *RSA* neemt daarom ook van nature toe naarmate de aanhanggrondtarra afneemt. Dit betekent dat het voorkómen van verdichting en versmering van grond tijdens het rooien op zichzelf niet voldoende is om een combinatie van lage grondtarra en een zwakke hechting van grond aan de biet te bereiken, hetgeen wenselijk is voor effectieve verdere reiniging. Voor dit doel zal het noodzakelijk zijn om, door middel van het rooien, de grond naast de biet actief los te maken.
- Door simulatie van het gedrag van grond tijdens het lichten werd duidelijk dat zijwortels van de biet een dominante rol spelen bij het ontstaan van grondtarra. De bodemsterkte bleek groter te worden naarmate de wortellengtedichtheid toenam. Omdat de wortellengtedichtheid toeneemt met afnemende afstand tot het bietoppervlak, was de berekende hoge bodemsterkte dicht bij de biet in overeenstemming met de hoge *RSA* dichtbij de biet, zoals waargenomen in het veld.

Praktische betekenis
De ontwikkelde methode om de mate van grondhechting te kwantificeren, door middel van de *RSA*, maakt een betere inschatting van de rooikwaliteit mogelijk. Immers, de combinatie van lossegrondtarra, aanhanggrondtarra en *RSA* geeft een goede indruk van de moeilijkheidsgraad van verdere reiniging. De methode zou daarom het testen in het veld en (verdere) ontwikkeling van bietenlichters aanzienlijk kunnen vergemakkelijken en, daarmee, de kosten van onderzoek verminderen.

Als rooiprincipes die grondtarraverlagend werken op natte kleigrond kwamen naar voren:

- Een zodanige bietverplaatsing dat de gehele biet boven de grond komt;
- Een minimaal volume grond die samengedrukt wordt tijdens het lichten;

- Een krachtimpuls, werkend op de biet aan het begin van de rooibeweging, door hoge verticale versnelling (onderzocht tot 12 m s^{-2}) en hoge hoekversnelling;
- Het roteren (8° tot 20°) van de biet aan het begin van de rooibeweging.

Verdere verbetering van conventionele lichters zou kunnen worden bereikt door benutting van de eerste twee genoemde 'lage grondtarra' rooiprincipes en van een hoge verticale versnelling. De best mogelijke rooikwaliteit die hiervan op natte kleigrond mag worden verwacht is de kwaliteit die verkregen werd bij snel, niet draaiend uittrekken: 0% lossegrondtarra, 30 tot 60% aanhanggrondtarra en 75% van de aanhangende grond zwak gehecht (*RSA* = 25%). In de veronderstelling dat het mogelijk is om de fractie zwak gehechte grond door reiniging te verwijderen, zou de eindgrondtarra van oogstsystemen met zulke verbeterde conventionele lichters op natte klei tussen de 7 en 15% kunnen komen.
De aangedreven sloffenkruislichter resulteerde op natte klei in 13% aanhanggrondtarra en 75% van de aanhangende grond was zwak gehecht (*RSA* = 25%). De lossegrondtarra was aanzienlijk. Het puntverlies (1%) en de bietbeschadiging (1,4 cm^2 $biet^{-1}$) waren acceptabel. Aannemende dat verwijdering van alle losse en zwak gehechte grond door reiniging mogelijk is, zou de eindgrondtarra van oogstsystemen met aangedreven sloffenkruislichters op natte kleigrond ongeveer 6% kunnen zijn. Bij testen van dergelijke oogstsystemen, na uitvoering van het hier beschreven veldonderzoek, werd 30 tot 40% minder grondtarra bereikt dan bij systemen met scharenlichters.
De resultaten van rooien door snel, draaiend uittrekken tonen aan dat 0% lossegrondtarra, 8 tot 18% aanhanggrondtarra en een *RSA* van 33 tot 40% in principe mogelijk is op natte kleigrond. Nieuwe technische oplossingen zullen echter nodig zijn om voldoende capaciteit te halen en om draaiing van de biet tijdens het uittrekken te realiseren zonder bietbeschadiging. Aannemende dat het mogelijk is om de zwak gehechte grond door reiniging te verwijderen, kan met oogstsystemen waarin alle bovenstaande 'lage grondtarra' principes worden toegepast op natte kleigrond potentieel tussen de 3 en 6% bereikt worden.

De eindconclusie is dat met het verkregen inzicht in het rooiproces, dat bepaalt hoeveel grondtarra ontstaat en hoe sterk de grond aan de biet hecht, en met innovatieve rooitechniek een aanzienlijke vermindering van grondtarra tijdens de oogst van suikerbieten op natte kleigrond mogelijk is.

Nawoord

Nu de tekst waar het om gaat eenmaal op papier staat is het prettig om even kort terug te blikken op de aanleiding en het verloop van dit grondtarra-onderzoek. Deze mooie gelegenheid neem ik ook waar om mijn dank uit te spreken aan degenen die het onderzoek en het voltooien van dit boekje mogelijk gemaakt hebben.

Tijdens het maken van de eerste plannen voor dit grondtarra-onderzoek, in 1992, werd grondtarra al langere tijd als een probleem gezien, met name vanwege de hiermee samenhangende kosten. De directe aanleiding tot hernieuwd onderzoek naar mogelijkheden voor vermindering van grondtarra was echter dat tarragrond, achteraf bezien ten onrechte, binnen de milieuregelgeving als licht verontreinigd beschouwd dreigde te worden, met alle gevolgen van dien. Als reactie op deze dreiging werd door de suikerindustrie onder anderen de vraag om tarra-arme oogsttechniek bij het Instituut voor Rationele Suikerproductie (IRS) neergelegd. In dit kader werden door het Instituut voor Milieu- en Agritechniek (IMAG), deels in opdracht van IRS, twee projecten uitgevoerd, die de basis voor dit proefschrift vormden:

- Een voorstudie naar de mogelijkheden van grondtarravermindering door enkelbietrooien (1994-1995);
- Een veldonderzoek naar betere rooitechniek voor bieten, met name het uittrekken van bieten (1993-1995).

In 1996 en 1997 werd met financiële steun van het ministerie van VROM (via Novem) door IMAG, IRS en Agrifac (fabrikant van bietenrooiers) gewerkt aan toepassing van de aangedreven sloffenkruislichter in een zesrijige bunkerrooier. De mijns inziens zeer bemoedigende resultaten van dit praktisch gerichte project, die overigens niet in dit boekje opgenomen zijn, hebben helaas niet geleid tot directe beschikbaarheid voor de praktijk. Mijn complimenten gaan uit naar loonwerkbedrijf de Regt, dat al ver vóór het 'Novem project' zelfstandig met de ontwikkeling van een zesrijige sloffenkruislichter bezig was en afgelopen jaar, met steun van IRS, een goedwerkend éénfase oogstsysteem met sloffenkruislichters wist te demonstreren.
In 1998 en 1999 haperde het grondtarra-onderzoek, deels door gebrek aan fondsen en deels doordat prioriteit aan acquisitie en ander onderzoek werd gegeven. Ik ben dan ook zeer dankbaar voor het feit dat de directie van IMAG en de leiding van de Leerstoelgroep Bodemtechnologie van Wageningen Universiteit mij, ondanks de algehele krapte van fondsen voor onderzoek, vanaf 1 mei 2000 alsnog in de gelegenheid gesteld hebben om, ter afronding, geconcentreerd aan het promotie-onderzoek te werken. Deze tijd werd dankbaar benut voor het uitvoeren van de modelstudie naar het gedrag van grond rondom de biet en voor het schrijven van dit proefschrift.

Mijn dank gaat in de eerste plaats uit naar de leden van de begeleidingscommissie. Udo Perdok, mijn promotor, dank voor je vertrouwen en in het bijzonder ook voor je beschouwelijk-relativerende inbreng en de steun op kritieke momenten. Een speciaal woord van dank geldt voor Frans Tijink, die mij heeft aangezet tot promoveren op 'het gedrag van grond rondom de biet' en mij in het hele traject altijd met enthousiasme en vertrouwen, voluit gesteund heeft, aanvankelijk als mijn baas bij IMAG en, vanaf 1994, als directeur van IRS. Hans Breteler dank ik met name voor zijn zeer gewaardeerde rol als meest positiefkritisch wetenschappelijk lezer, taalfanaat en repetitor. Jos Koolen, mijn co-promotor, dank voor je begeleiding.

Ben Verwijs, jij was bij alle facetten van het onderzoek nauw betrokken en was onmisbaar in het hele project. Ik denk dan met name aan je rollen als 'Subitrek operator', producent van tekeningen en vormgever van de inhoud dit boekje. Ben, hartelijk dank daarvoor.

Piet van der Linden van IRS is van het begin tot het eind nauw bij dit project betrokken geweest. Piet, onze discussies, samenwerking en de inbreng van jouw gedetailleerde kennis van de bietenoogsttechniek en de praktijk heb ik zeer op prijs gesteld.

Peter Wennekes, prof. F.H. Fockens, Anton Bransen, Frans van Korlaar, Leen Oudshoorn, Wim Haalboom en de mensen van de toenmalige werkplaats van TFDL dank ik voor hun grote bijdrage aan de ontwikkeling van de technisch best wel ingewikkelde Subitrek, waarmee cruciale gegevens in dit onderzoek verzameld werden. De overige onderzoeksmachines en hulpapparatuur werden op IMAG proefbedrijf 'Oostwaardhoeve' ontwikkeld. Peter Goedbloed, bedrijfsleider, en Theo van Schriek, toenmalig hoofd van de werkplaats, ik bewonder jullie praktische kundigheid, vindingrijkheid en enthousiasme. Mijn dank voor jullie grote inzet.

De vaste Wageningse ploeg voor het veld- en laboratoriumonderzoek, bestaande uit Jan Klooster, Ben Verwijs, Rinus Sprong en Jos Kroesbergen, heeft uitstekend werk verricht. Daarnaast hebben Servé Pronk en Evert-Jan Wassink in het kader van hun afstudeeropdrachten voor de Leerstoelgroep Bodemtechnologie van Wageningen Universiteit wezenlijke bijgedragen aan het onderzoek. Alle medewerkers en van IMAG proefbedrijf 'Oostwaardhoeve', onder leiding van Peter Goedbloed en Cor Sonneveld, hebben aan het tarraonderzoek meegewerkt, waarbij Meindert Lawerman, Tonnie Koudenburg, Gerard Haverkamp en Han Noppe in de periode 1993 t/m 1995 de meeste tarra-uren op hun naam hebben staan. Aan jullie allen, die het veldonderzoek zo succesvol en plezierig maakten, mijn hartelijke dank.

Wijlen Bertus Keen ben ik dankbaar voor zijn zo doeltreffend gebleken adviezen bij de statistische opzet van de veldproeven. Bas Engel, Margriet Hendriks en Valentijn van den Berg dank ik voor hun hulp bij de statistische verwerking van de data, als het moeilijk werd.

In de afgelopen anderhalf jaar is veel tijd gaan zitten in het nu voorliggende boekje en een aantal andere zaken moest ook gewoon doorgaan. Ik ben mij er terdege van bewust dat mijn wijze van omgang met het thuisfront, waartoe ik alle Nijburgers reken, en met vrienden en bekenden veel te wensen overliet. Hiervoor mijn welgemeende verontschuldiging en mijn dank voor jullie niet aflatende belangstelling en loyaliteit. Hetty, Marleen, Sanny, Jolien en Linda: goed dat het nu echt af is.

Curriculum vitae

Naam	Gijsbert Dirk Vermeulen.
Geboren	8 november 1950 te Nieuwer-Amstel (thans Amstelveen).
1963-1968	Chr. Lyceum Amstelveen, HBS-B.
1968-1977	Landbouwhogeschool, Wageningen, Studierichting Landbouwtechniek, tropische oriëntatie, Afstudeervakken en -onderwerpen: - Grondbewerking: Energieverbruik bij de hoofdgrondbewerking; - Werktuigkunde: Scheidingsprincipe voor graan en stro; - Landbouwwerktuigkunde: Mechanisatie van de cassaveteelt.
1976-1979	Werkzaam bij de 'Ahmadu Bello University, Institute of Agricultural Research, Department of Agricultural Engineering', Zaria, Nigeria, als wetenschappelijk medewerker (uitgezonden via het Ministerie van Buitenlandse Zaken, DGIS). Praktijkonderzoek naar aangepaste grondbewerkingsmechanisatie en protocolontwikkeling voor lokale machinebeproeving.
1980-1983	Werkzaam bij het Ministerie van Landbouw, Landbouwproefstation, Paramaribo, Suriname (uitgezonden via het Ministerie van Buitenlandse Zaken, DGIS) als hoofd onderzoek mechanisatie. Onderzoek naar mechanisatie van de teelt en verwerking van pinda en van de grondbewerking in de rijstteelt.
1984-1986	Werkzaam bij het Instituut voor Arbeid, Mechanisatie en Gebouwen (IMAG), Wageningen als bibliothecaris en informatiespecialist, bibliotheek Centrum Techniek, Wageningen.
1986-heden	Werkzaam bij het Instituut voor Milieu- en Agritechniek (IMAG), Wageningen als wetenschappelijk onderzoeker. Belangrijkste onderwerpen van onderzoek, gezien in de tijd: 1986-1994 Het tegengaan van bodemverdichting als gevolg van berijding met landbouwvoertuigen; lagedruk berijding. 1993-heden Vermindering van grondtarra bij suikerbieten. 1996-heden Technologie voor biologische reiniging van verontreinigde baggerspecie in combinatie met de teelt van wilgen. 1997-2000 Grondbewerking voor de rijstteelt in Nickerie, Suriname. 1999-heden Mechanische en fysische onkruidbestrijding.

Het in dit proefschrift beschreven onderzoek betreft een groot deel van het onderzoek naar vermindering van grondtarra bij suikerbieten, dat in opdracht van IMAG in de periode van 1993 tot 2001 verricht werd.

Appendix 1: Explanatory list of terms

Sugar beet terminology

Sugar beet, beet	Indicates both the whole plant(s), the harvested part of the root(s) and the harvested bulk of *Beta vulgaris* L.
Beet lot	A specific quantity of beet.
Beet grooves	Two grooves on opposite sides of the beet surface from which most of the rootlets emerge and, running from the top end to the lower end of the beet, usually vertical and straight but sometimes forming a spiral around the beet.
Tap root	Main central root of the beet, tapering to a single narrow tail.
Tail	Lower end of the tap root.
Lateral root	A root, branching off of the tap root.
Rootlet	Any root except the tap root.
Rootlet-length-density	Total length of rootlets per unit volume of soil.
Beet lot quality	The quality of a beet lot, expressed by the combined values of a set of quality characteristics; the set of characteristics depending on the purpose of the quality determination.
Beet quality	As for beet lot quality, but for a single beet or for a beet sample.
Fangy beet	Distorted beet with more than one tail.
Fanginess	Indication of the degree of beet distortion of a fangy beet or for the fraction of fangy beet in a beet sample or beet lot.
Fresh beet	Beet in a condition such as that found just after harvesting.
Clean beet	A single beet, a beet sample or a beet lot without any of the soil tare constituents.
Superficial damage	Total damaged area of the beet surface, *excluding* the cutting plane caused by the beet topper and the fractured surface area due to root breakage, usually expressed in cm^2 per 100 beet, but in cm^2 per beet in this thesis.
Surface damage	Total damaged area of the surface of 100 beet in cm^2, *including* the cutting plane caused by the beet topper and the fractured surface area due to root

	breakage (used for assessment of the quality of cleaning).
Root breakage	Phenomenon of tap root fracture during uprooting due to the forces set up in the beet material by the uprooting action.
Beet tip	The portion of the lower end of the tap root broken off during uprooting.
Dug loss, dug losses	Total mass of broken off root parts (beet tips) remaining in the soil after uprooting due to root breakage, relative to the clean beet yield.
Fractured surface diameter	Diameter of the fractured surface of the beet tip.
Beet top	The portion of the upper end of the tap root that should be removed during harvest because of its negative effect on the sugar extraction process.
Overtopping	Topping to low, thereby removing the top and a portion of the valuable root section.
Undertopping	Topping to high, thereby removing only part of the beet top.
Overtopping loss	Mass of valuable beet material lost due to overtopping, relative to the clean beet mass.
Surface losses	Mass, relative to the clean beet yield, of whole beet and beet fragments lost during harvesting through spill-over and fall-through during cleaning, internal transport and unloading and due to missed beet during uprooting.
Beet fragment	Broken off beet part with a largest diameter > 4.5 cm.
Tare soil	Soil at the factory, produced as by-product during sugar production, which mainly contains the soil originating from delivered beet lots (loose and adhering to the beet).
Soil tare	Mass of non-beet material in a beet lot, including soil adhering to the beet, loose soil and stones, either expressed as 'gross soil tare', *i.e.* relative to the total mass of the beet lot (% *w/w*, gross) or as 'net soil tare', *i.e.* relative to the mass of the clean beet (% *w/w*, net).
Loose-soil tare	Mass of non-beet material present in beet lots which does not adhere to the beet, relative to the mass of the beet (% *w/w*, net or % *w/w*, gross).
Adhering-soil tare	Mass of non-beet material present in beet lots which adheres to the beet, relative to the mass of the beet (% *w/w*, net or % *w/w*, gross).

Weakly-adhering-soil tare — Mass of non-beet material present in beet lots which adheres weakly to the beet, such that it is removed by a 'standard' cleaning treatment, relative to the mass of the beet (% *w/w*, net or % *w/w*, gross).

Strongly-adhering-soil tare — Mass of non-beet material present in beet lots which adheres to the beet after a 'standard' cleaning treatment, relative to the mass of the beet (% *w/w*, net or % *w/w*, gross).

Top tare — Mass of unwanted beet material in a beet lot due to undertopping, relative to the mass of the beet (% *w/w*, net or % *w/w*, gross).

Total tare — Mass of unwanted material, including soil, leaf remnants, loose beet tops, non-removed beet tops and stones in a beet lot, usually expressed relative to the mass of the dirty beet lot (% *w/w*, gross).

Soil terminology

Soil mechanics — The part of engineering concerned with equilibrium (statics) and motion (kinematics and dynamics) of soil.

Soil dynamics — Engineering doctrine of phenomena of re-arrangement of particles in the soil matrix as a result of stresses, usually of short duration and induced by machines. For terms used in soil dynamics, one is referred to handbooks for this field of science.

Constitutive soil model — Relationship between stress and strain of soil, formulated through mathematical equations, describing various kinds of ideal material response.

Elastic-perfectly-plastic — Refers to a specific type of mechanical behaviour of soil, characterised by elastic behaviour until the soil fails and, thereafter, perfectly-plastic behaviour.

Soil condition — The temporal condition of the soil, often in a qualitative way, to indicate the position of the temporal condition between two extreme conditions, such as its wetness or density.

Differential moisture content — Deviation of the actual moisture content of soil from its moisture content at a soil water matric potential of −10 kPa.

Soil wetness — Temporal moisture condition of the soil, either expressed quantitatively by the differential moisture content (Δm) of the soil (% *w/w*, d.b.) or qualitatively by means of classification on the scale from saturated to oven-dry. When used in a

	qualitative way in this thesis, the following indications are used for humid clay soil: relatively dry ($\Delta m \approx$ -4%); normal or moist ($\Delta m \approx$ 0.5%), relatively wet ($\Delta m \approx$ 5%) and very wet ($\Delta m >$ 5%).
Soil workability	Semi-quantitative reference to the temporal condition of the soil in relation to its suitability for tillage, often expressed as workability limits in terms of the soil moisture content or the soil water matric potential, based on workability tests. In some cases, however, the workability is based purely on visual assessment of, for instance, the ease of crumbling of the soil by hand, using qualitative terms such as friable when the soil is easy to crumble, firm when moderately easy to crumble and sticky when difficult to crumble.
Soil loosening	Breaking-up of soil into aggregates or particles, usually associated with an increase in bulk volume.
Soil compaction	Decreasing the bulk volume of soil.
Soil plastication	Increasing the plasticity of soil, usually associated with plastic deformation of wet clay and loss of the aggregate structure of the soil (plasticate = to soften a material by heating or kneading: Parker, 1989).
Soil adherence	Term used to refer to the ability of soil particles to stick together and stick to the surfaces of the beet or the rootlets.
Relative soil adherence	Characteristic of the soil adherence, defined as: the mass of soil adhering after a 'standard' cleaning treatment by compressed air, divided by the mass of soil adhering before this treatment.
Loose soil	Soil in a beet sample or in a beet lot which does not adhere to the beet.
Adhering soil	Soil in a beet sample or in a beet lot which adheres to the beet.
Weakly-adhering soil	Soil in a beet sample or in a beet lot which adheres weakly to the beet, such that it is removed by a 'standard' cleaning treatment.
Strongly-adhering soil	Soil in a beet sample or in a beet lot which adheres to the beet after a 'standard' cleaning treatment.

Harvesting terminology

Harvesting	The process of removing the industrially valuable parts of sugar beet plants from their growing location in the field, including leaf and crown

	removal, beet lifting, cleaning and loading onto a trailer.
Harvesting phase	Part of the harvesting process in which one of the necessary actions on the sugar beet plant is performed.
Two-stage harvesting	Performing the harvesting process in two operations, usually due to temporary storage of the beet in swaths on the field.
Leaf stripping	Harvesting phase in which most of the leaves of a sugar beet plant are removed, including the further processing and disposal of the leaves. Common names of machines or system modules that perform leaf stripping include: leaf stripper, mincer, chopper, leaf blower and leaf spreader.
Crown cleaning	Optional harvesting phase in which leaf remnants are removed following leaf stripping. Common names of machines or system modules that perform crown cleaning include: crown cleaner, top flail and rubber flail.
Topping	Harvesting phase in which the beet top is removed from the taproot. Names of machines or system modules that perform topping include: feeler wheel, topper, topping knife, scalper, scalper knife, crowning knife, rotary topping disc, feeler wheel crowner and scalper crowner.
Uprooting	Harvesting phase in which the sugar beet is removed from its growing location in the field, including its transfer to a windrow in the field or to the cleaning section of a beet harvester.
Beet lifting	Uprooting of the beet by any principle.
Beet lifter	Any device used for beet lifting.
Grab lifter	Lifter with a grabber to lift the beet.
Blade lifter	Lifter with inclined and converging blades to lift the beet.
Disc lifter	Lifter with a disc to lift a rim of soil containing the beet.
Digging wheel lifter	Lifter with two wheel diggers to clamp and lift the beet.
Driven rotary-shoe lifter	Lifter with steel shoes on two driven rotors that alternatingly kicks the beet from left and right to cause uprooting.
Share lifter	Lifter with inclined and converging shares to lift the beet.
Beet pliers	Manually operated grab lifter.

Beet extraction	Uprooting of the beet by pulling the beet out of the soil.
Beet extrusion	Uprooting of the beet by squeezing a soil volume around the beet.
Beet cleaning	Harvesting phase in which soil and other unwanted material is removed from the beet. For common names and a description of various cleaning devices one is referred to Chapter 3 of this thesis.
Hopper loading	Harvesting phase in a complete beet harvester in which the beet are transported from the cleaning section to the hopper. Names of system modules that perform hopper loading include rod link chain, chain type elevator, open web elevator, elevating web and tank feed web.
Hopper storage	Harvesting phase in which the beet are temporarily stored in a hopper.
Hopper unloading	Harvesting phase in which the beet are transported from the hopper on to a trailer. Names of system modules that perform hopper unloading include discharge web and discharge system.
Harvesting system	A system, including one or more stages and one or more operations, in which all harvesting phases are performed.
Multi-stage harvesting system	Harvesting system in which harvesting is divided over two or more stages, carried out at different points in time.
Complete beet harvester	Machine which performs all harvesting phases combined in one operation. Such a machine is also known as a sugar beet tanker, carting off beet harvester or carrier harvester.
Cleaner loader	Machine used in a multi-stage harvesting system, which performs the harvesting phases: collection from a swath, cleaning and loading of the beet on to a trailer.
Quality of performance	Quality aspect of the performance of a machine or process.
Quality of harvesting	Quality of the total harvesting process, possibly including the quality of some distinct harvesting phases.
Quality characteristic	Characteristic for assessment of the quality of materials, products and processes.
Quality of topping	Quality of the topping process, defined in terms of fractions of beet in a beet lot that are untopped, undertopped, correctly topped, overtopped and

	topped at an angle, or in terms of top tare and overtopping losses.
Untopped	No part of the beet top was removed by the topping process.
Undertopped	Topped too high; only part of the beet top was removed by the topping process.
Correctly topped	Topped correctly (sugar factory determines what it considers to be a correctly topped beet).
Overtopped	Topped too low; the top and a portion of the valuable root section was removed by the topping process.
Quality of uprooting	Quality of the uprooting process, defined in terms of soil tare, relative soil adherence (in this thesis), dug losses and superficial beet damage.
Harvesting demonstration	Field demonstration of sugar beet harvesting machinery, often including a measurement programme to assess the quality of harvesting.

Appendix 2: List of symbols and abbreviations

Symbols used for additional specification of units

n/n	on number of units basis
v/v	on volume basis
w/w	on mass basis
d.b.	on the basis of dry material
gross	in relation to soil tare: on the basis of dirty beet
net	in relation to soil tare: on the basis of clean and correctly topped beet

Abbreviations used for the treatments in the experiments

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
NS1	non-spiral extraction motion with slow acceleration
NS2	non-spiral extraction motion with moderate acceleration
NS3	non-spiral extraction motion with quick acceleration
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
R	reference treatment: extraction with minimal soil disturbance
PS	lifting with a conventional driven polder share lifter
RS	lifting with a driven rotary-shoe lifter

Other symbols and abbreviations

α_{av}	average angular acceleration (rad s^{-2})
α_{max}	maximum angular acceleration (rad s^{-2})
ϕ	angle of internal friction (degree)
γ_w	wet bulk density of the soil (Mg m^{-3})
φ_l	amount of soil that was loosened by an extraction treatment and removed by gravity forces, relative to the amount of strongly adhering soil of treatment R (% *w/w*)
φ_s	amount of soil that was converted to weakly adhering soil by the extraction treatment, relative to the amount of strongly adhering soil of treatment R (% *w/w*)

φ_w	amount of soil that remained strongly adhering during the extraction treatment, relative to the amount of strongly adhering soil of treatment R (% *w/w*)
ν	Poisson's ratio
$\sigma_1, \sigma_2, \sigma_3$	principal stresses (kPa)
σ_t	tensile strength (kPa)
$\Delta\sigma_t$	increase in tensile strength of the soil due to rootlets (kPa)
$\sigma_{t\,\mathrm{rootlet}}$	tensile strength of rootlet (kPa)
σ_{tR}	real tensile strength of soil interwoven with rootlets (kPa)
ω_f	final angular speed (rad s^{-1})
Γ	saturated water permeability (m day^{-1})
ψ	angle of dilatancy (degree)
a, b, c	coefficients in statistical models for T_a, *RSA* and *DL*.
a	vertical acceleration (m s^{-2})
a_{av}	average vertical acceleration (m s^{-2})
a_{max}	maximum vertical acceleration (m s^{-2})
c	cohesion (kPa)
Δc	increase in cohesion of the soil due to rootlets (kPa)
c_R	real cohesion of soil interwoven with rootlets (kPa)
cv	coefficient of variation
d	largest beet diameter (mm)
d_f	fractured surface diameter (mm)
d_s	beet diameter at the soil surface (mm)
d_r	mean diameter of rootlets (mm)
h	height of the untopped beet above the soil surface (mm)
l	length of topped beet, excluding the flexible part of the tap root (mm)
l_b	length of untopped beet, excluding the flexible part of the taproot (mm)
l_c	height of beet top (mm)
l_u	underground beet length, excluding the flexible part of the taproot (mm)
m_d	soil moisture content (% *w/w*, d.b.)
m_r	reference soil moisture content (% *w/w*, d.b.), at a soil water matric potential of -10 kPa
Δm	differential moisture content, (m_d - m_r), (% *w/w*, d.b.)
n	number of extracted beet
p_f	final pitch (m rev^{-1})
se	standard error of the estimated value
t_α	angular acceleration time (s)
t_a	vertical acceleration time (s)
v_f	final vertical speed (m s^{-1})
w	mass of the untopped beet (kg)
w_b	clean mass of the topped beet (kg)
w_c	clean mass of the beet top (kg)

$f_1 \ldots f_6$	yield functions of the soil
pF2	common indication for a soil water matric potential of -10 kPa
C	constant in statistical models for T_a, *RSA* and *DL*.
CF	fraction of beet of which the crown fractured (% *n/n*)
DL	dug losses (% *w/w*, net)
E	Young's modulus of elasticity (kPa)
F_r	force at which a rootlet fails in tension (N)
RLD	rootlength-density (cm cm^{-3})
RSA	relative soil adherence, dimensionless
RSA(X)	relative soil adherence of treatment X
S	soil-beet contact area (dm^2)
S_r	cross-sectional area of a rootlet (mm^2)
S_s	specific soil-beet contact area (dm^2 kg^{-1})
T	soil tare (% *w/w*, net or % *w/w*, gross)
T(X)	soil tare of treatment X (% *w/w*, net or % *w/w*, gross)
T_a	adhering-soil tare (% *w/w*, net)
T_{ar}	adhering-soil tare (% *w/w*, net), calculated for a reference beet lot
T_w	weakly-adhering-soil tare (% *w/w*, net)
T_s	strongly-adhering-soil tare (% *w/w*, net)
K_0	ratio of horizontal soil stress to vertical soil stress

The research described in this dissertation was carried out at the Institute of Agricultural and Environmental Engineering (IMAG) and the Department of Agrotechnology and Food Sciences of Wageningen University. Parts of the work presented in this dissertation were financially supported by:

- The Ministry of Agriculture, Nature Management and Fisheries (LNV), research programme 198, 'Technology for sustainable field crop production';
- The Dutch sugar industry, through the Institute of Sugar Beet Research (IRS);
- The Ministry of Housing, Spatial Planning and the Environment (VROM), through the Netherlands agency for energy and the environment (Novem), research programme 'Stimulation of practical experiments on prevention and recycling of waste materials, 1996' (PH96).

All support for the work is gratefully acknowledged.

Printed by Ponsen & Looijen, Wageningen

Cover: Studio Dap, Ede