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Long-term post-harvest field storage of sugar beet (*Beta vulgaris* subsp. *vulgaris*)

William English

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William English
Faculty of Landscape Architecture, Horticulture and Crop Production Sciences
Department of Biosystems and Technology
Alnarp

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Cover: *The Nabla Beet* was adopted as the logo of the study that resulted in Paper IV of this thesis. The Nabla (∇) is mathematical notation applied widely in the science of fluid dynamics and heat transfer to represent vector differential operators; primarily the gradient and divergence. It encompasses multi-dimensional change. The leaves of *The Nabla Beet* are taken from the logo of Nordic Beet Research foundation. It is proudly displayed on the cover of this thesis, symbolising the context of multi-dimensional change in which this research project existed, and as a (not so) subtle nod to NBR.

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© 2023 William English, https://orcid.org/0000-0001-5197-2342
Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Alnarp, Sweden
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Abstract

The post-harvest storage of the sugar beet crop in Sweden occurs in the field. The harvest of roots generally ends along with the month of November, but the processing campaign can continue into February. The loss of quality of the stored roots during this period is economically important. This thesis groups the main mechanisms that results in loss of quality during post-harvest storage in two categories: plant health, and the storage environment. It focuses on the plant health dimension of mechanical properties, and the storage environment dimensions of moisture and temperature.

The relationship between key agronomic inputs and mechanical properties and storability of sugar beet roots was investigated. Growing season available nitrogen and water were found to have little impact on mechanical properties. The storability of roots was found to decrease significantly when irrigation gave an optimal soil water availability throughout the season. This is likely a result of an interaction with an unspecified dimension of plant health. The quantification of sugar beet root mechanical properties with a traditional handheld penetrometer applied in-field was found to be reliable. It was also found that the methods used in the analysis of mechanical properties could be expanded to include the apparent modulus of elasticity and that fall-tests can be used to assess dynamic impacts.

The use of a short, intense period of forced ventilation of a sugar beet bulk was found to lead to dehydration of sugar beet roots in a predictable manner. This resulted in increases to sucrose concentrations that would lead to greater gross income. Computational Fluid Dynamics modelling of the temperature within a clamp proved to be possible and insightful. The fluid dynamics within the clamp are important to include in such modelling.

Keywords: clamp, quality, mechanical properties, handheld penetrometer, forced ventilation, computational fluid dynamics, mass transfer, heat transfer.

Dedication

To the sugar beet growers of Sweden, and the rest of the world.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Hoffmann, C. M., Kleuker, G., Wauters, A., English, W., and Leijdekkers, M. (2022). Root tissue strength and storage losses of sugar beet varieties as affected by N application and irrigation. Sugar Industry, 147(1):34–41.

II. English, W., Ekelöf, J., Vancutsem, F., Leijdekkers, M., Kleuker, G., and Hoffmann, C. M. (2022). Method for in-field texture analysis of sugar beet roots using a handheld penetrometer. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 72(1):623–634

III. English, W. and Larsson Jönsson, H. (2023). Quality and mass transport properties of sugar beet roots under short duration, high airflow post-harvest storage. *Manuscript*

IV. English, W. and Mousavi, S. M. (2023). A Computational Fluid Dynamics Model of Airflow and Temperature in a Sugar Beet Clamp. Submitted to: Biosystems Engineering

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Two additional unpublished exploratory supplementary studies are discussed in this thesis. They are summarised in the conference posters (not reproduced):

SS1. Nilsson, M., English, W., and Telezhenko, E. (2020). Pressure Mapping Sugar Beets. In 77th Congress of the International Institute for Sugar Beet Research, Brussels, Belgium. International Institute of Sugar Beet Research (IIRB)

SS2. Larsson Jönsson, H. and English, W. (2022). Late season water availability and damage and mechanical properties in sugar beet roots. In 78th Congress of the International Institute for Sugar Beet Research, Mons, Belgium. International Institute of Sugar Beet Research (IIRB)

The contribution of William English to the papers included in this thesis was as follows:

I. Conducted fieldwork, with assistance from Hushållningssällskapet Skåne. Conducted laboratory analysis. Drafted manuscript.

II. Developed and formulated research question. Wrote application for funding. Conducted fieldwork, with assistance from Hushållningssällskapet Skåne. Coordinated international fieldwork. Evaluated data. Drafted manuscript.

III. Developed and formulated research question. Wrote application for funding. Designed and constructed experimental unit. Conducted fieldwork, with assistance from Hushållningssällskapet Skåne. Evaluated data. Drafted manuscript.

IV. Developed and formulated research question. Conducted model development. Evaluated data. Drafted manuscript.

SS1. Developed and formulated research question. Wrote application for funding. Conducted fieldwork. Evaluated data. Drafted manuscript.

SS2. Developed and formulated research question. Wrote application for funding. Conducted fieldwork. Evaluated data. Drafted manuscript.

Terms, Abbreviations, Symbols

Terms	
Bulk	General term for a collection of sugar beet roots post-harvest, including in the clamp and pile storage systems, and in experimental systems.
Clamp	System of in-field post-harvest storage of a bulk of sugar beet roots, often employed in Europe.
In-situ storage	System of in-field storage of sugar beet roots in which roots are not harvested after the end of a season's growth.
Industry	The purchaser and processor of sugar beet. Usually also a marketer of processed sugar. Currently Nordic Sugar in Sweden.
Pile	System of large, factory based post-harvest storage of sugar beet roots, often employed in North America.
Abbreviations	
AIR	*Alcohol Insoluble Residues*. Indicative of plant cell wall content.
CFD	*Computational Fluid Dynamics*. A mechanistic modelling approach commonly adopted in the study of fluid dynamics and heat transfer.
COBRI	*Coordination Beet Research International*. Research collaboration between the national sugar beet research organisations of SE, DE, NL, and BE.
ICUMSA	*International Commission for Uniform Methods of Sugar Analysis.*
IfZ	*Institut für Zuckerrübenforschung* [The Institute of Sugar Beet Research]. National sugar beet research organisation of Germany.
IIRB	*International Institute for Sugar Beet Research*. International academic knowledge sharing organisation for sugar beet research.
NBR	*Nordic Beet Research foundation*. National sugar beet research organisation of Sweden and Denmark. Co-sponsor of this project.

SBU	*Sockernäringens BetodlingsUtveckling*. The immediate predecessor to NBR in Sweden.
SSA	*Svenska Sockerfabriksaktibolaget*. The main company involved in the Swedish sugar industry between 1907 and 1992

Symbols

°Cd	Degree-days. Cumulative temperature. Base temperature: 0 °C
∇	Nabla operator. Represents vector differential operators; primarily the gradient and divergence
α	Effective diffusivity
Δc	Water vapour pressure deficit
ε	Porosity
ρ	Density
τ	Convective stress tensor
A_{sf}	Specific surface area
C_p	Specific heat
D	Darcy coefficient
D_{ab}	Diffusivity of water
f	Fluid
F	Forchheimer coefficient, or, Force
h_{sf}	Convective heat transfer coefficient
k_c	Convective mass transfer coefficient
K	Thermal conductivity
L	Characteristic length
m	Mass
$\dot{m}_w$	Mass flux of water
p	Pressure
Qr	Heat of respiration
Re	Reynolds number
s	Solid
S	Source term
Sc	Schmidt number
Sh	Sherwood number
t	Time
T	Temperature
U	Velocity
v	Velocity

1. Introduction

This thesis has a broad focus on the long-term post-harvest field storage of the sugar beet crop. It is a compilation of four research papers. These papers collectively explore: how agronomic inputs can impact mechanical properties and storability of sugar beet roots; the use of a handheld penetrometer to assess sugar beet root mechanical properties; how forced ventilation affects quality of, and movement of water in, a bulk of sugar beet roots; and how numerical modelling can be used to understand the airflow and temperature in sugar beet post-harvest storage systems. The research project was conducted within the context of the clamp system of post-harvest field storage, as employed in Swedish agriculture. This context includes the Swedish natural, market, and research environments. The research project has drawn extensively from knowledge well beyond this context, and the findings are similarly applicable to a wider context. This includes wherever post-harvest storage of sugar beet roots is employed, be it in a clamp or in the sugar beet processing factory based large pile storage system. The research project had a technical focus, but aimed to remain firmly grounded in the physiology and agronomy of the sugar beet crop. The background to the research project is given in Section 1. It first provides definitions for "Long-term post-harvest storage of sugar beet" as found in the title of the thesis (Section 1.1), then reviews the principles of successful post-harvest storage of sugar beet roots (Section 1.2), and finally outlines the context of the research project (Section 1.3). Section 2 presents both the broad, overarching aims of the project as a whole, plus the specific aims of each study within the research project. The methods of research are presented in Section 3. The results and discussion of Section 4 focuses mainly on the broad findings of the research project, with particular attention on the synergies between the individual studies. The main conclusions are given in

Section 5, and a summary of some areas of promise for future research are given in Section 6.

1.1 Long-term post-harvest field storage of sugar beet

1.1.1 Post-harvest field storage system

Storage systems employed for food crops range from the harvested crop being housed in highly controlled environments, through to the crop being left *in-situ* post maturity until it is taken to the next stage in the value chain. The choice of storage system is a combination of the per unit volume value of the crop, and the crop's tendency to degrade in the available environments (Wills et al., 2007a). For sugar beet, three storage systems are in common use. Two of these are post-harvest storage systems, including the smaller *clamp* system located in-field (Figure 1), and the large *pile* system located at the processing factory. A clamp is an old technology used for the post-harvest storage of root crops, consisting simply of a bulk of the crop piled on the earth and covered as necessary with a protective material such as straw or soil (Aliou, 1998). A pile consists of a bulk of harvested roots that can be five meters high and 40 meters wide, or larger (Bugbee, 1982; Gaddie & Tolman, 1952; Shaaban, 2020). The third storage system sees the sugar beet crop left in-situ in the field beyond the end of the period of seasonal growth, where it is protected by the soil and plant canopy. *In-situ* storage can be employed where mild winters are expected, and harvest occurs just prior to delivery. If clamp formation occurs, it is usually only for a short period. In some environments where sugar beet is grown, post-harvest storage is strongly discouraged owing to the unfavourable environment (Orleans & Cotton, 1952).

The research project this thesis describes was focused on the clamp system of post-harvest field storage, but this thesis also has application to the pile post-harvest storage system. A large component of the research referenced in the following discussion on the principles of successful post-harvest storage of sugar beet was conducted in the context of pile storage. A distinction between these two systems is generally not made here, as both are the post-harvest storage of bulks of sugar beet roots. The *in-situ* storage system is generally ignored.

Figure 1. Three clamps in the field: one research clamp (foreground - with harvester unloading to it), and two commercial clamps (with non-woven polypropylene covers). The commercial clamp to the right of the road is approximately 400 m long (ca. 3500 t). A chaser bin is waiting for its next load (right). The storage silo at the Örtofta sugar beet processing factory in Sweden can be seen in the distance (left). Source: Author, Hviderup, Sweden, 2022-11-28.

1.1.2 Long-term storage

There is no single clear definition of "long-term" for sugar beet post-harvest storage given in the literature. As such, a broad definition of long-term is here given as storage with physiological stability, where physiological stability is "a dynamic state of a living organism characterized by the maintenance of one or more physiological parameters within value ranges that vary only slightly in the presence of disruptive elements" (Lebel et al., 2014). For the conditions in which post-harvest storage is employed for the sugar beet crop, long-term storage is taken as that which extends more than two weeks beyond the harvest date. Two weeks is an estimate of the average length of the initial period of wound healing and elevated rates of respiration resulting from the harvest process. It also fits with the definition of greater than 15 days, given in a presentation in 2012 by European leaders in research into sugar beet root storage (Legrand et al., 2012). It should also be noted that the processes occurring during the implied short-term are still of significance to this thesis. In particular, exposure and reaction to extreme weather.

1.2 Principles of successful post-harvest storage of sugar beet

An idea can be seen as a guiding principles when it has been tested in many contexts and situations and still proves effective or correct (Patton, 2015).

As such, two guiding principles for the successful post-harvest storage of sugar beet roots are here postulated:

- healthy sugar beet roots store better than unhealthy roots, and
- sugar beet roots store better when held within an optimal environment.

These are principles that have been found for all agricultural and horticultural products (Wills & Golding, 2016; Yahia, 2019). They are also rather broad, requiring further elaboration before being practical.

Successful storage and quality

Successful storage is ultimately defined by the maintenance of *quality* of the product. Quality standards of the sugar beet crop are defined in relation to processing. This includes primarily a high sucrose concentration and low content of invert sugars (glucose and fructose), polysaccharides of microbial origin (including dextran), and of soluble non-sugars (α-amino nitrogen, sodium, potassium) in the processable sugar beet material. Quality also includes the maintenance of the quantity of processable material in a delivered sample. Non-processable material is anything that is not healthy sugar beet root material. This includes soil and stones, non-root plant material, root material that will wash away, the water in these components, or root material that is known to interrupt the extraction process such as roots that have thawed after being frozen. When this non-processable material is captured in the sample of a delivered load of sugar beet roots, it is referred to as *dirt-tare*. Finally, resistance to cutting is a quality trait of importance in processing (Dutton & Huijbregts, 2006; Vukov, 1977). The term *storability* is used in the description of successful storage, with *good* and *poor* storability relating to the situation of relatively lower and higher loss of quality during storage, respectively.

Loss of quality

Loss of quality occurs when the sucrose concentration reduces, the non-sucrose component increases, or when processable material is lost. The primary mechanisms for loss of quality are respiration, moulds and rots, freezing and thawing, and mechanical damage. There are numerous interactions between these processes and many factors that can drive them. Relative quality before storage should not be taken as an indicator of relative storability. High sucrose concentration roots do likely store better (Hoffmann et al., 2018), but quality prior to storage does not capture a lot of the key determinates of quality after storage.

1.2.1 Healthy sugar beet roots

What is plant health?

In their exposition of the term "plant health", Döring et al. (2012) conclude that "there is no single plant health definition that provides satisfying clarity and consistence." It is a "fuzzy" term that, if it is to remain of value, requires more context in its definition than can be given in a simple dictionary type definition. This notwithstanding, it is useful to here adopt the possibly outdated, definitely circular definition of plant health as the plant being "free from" particular things. For the plant health dimensions discussed below, in the context of this thesis, it is generally the case that less of that dimension will have been shown to result in a higher level of storability.

Respiration rate

The continued respiration of the living harvested sugar beet root is commonly cited as the major source of sucrose loss during post-harvest storage (Bugbee, 1993; Huijbregts et al., 2013; Wyse & Dexter, 1971). As a dimension of plant health, respiration *rate* is considered. As a biennial root crop harvested at the end of its first year of growth, sugar beet is not considered to ripen and thus it is not expected that respiration rate will vary with timing of harvest (Elliott & Weston, 1993; Scott & Jaggard, 1993). Evidence that this has been tested could not be found. Differences in baseline respiration rate have been observed between varieties during post-harvest storage (Lafta & Fugate, 2009; Stout & Smith, 1950), but these are relatively minor in comparison to the differences observed when there is an interaction with other dimensions of plant health or the storage environment. As such, the discussion on respiration rates during post-harvest storage are interspersed throughout the following discussion on the principles of long-term post-harvest storage of sugar beet roots.

Varieties and gene expression

Variety is a collection of stable traits, assessed primarily phenotypically (Gemet, 2023). Differences between varieties in storage losses during long-term storage are commonly observed for sugar beet, and similar to respiration, variety is a factor in the long-term post-harvest storage of sugar beet roots that interacts with many other factors. It cannot be taken as a dimension of plant health *per se*, only as a useful indicator of possible health status of a plant under certain conditions. This may soon change. Relatively new work from both North America and Europe has begun to study the genetic foundations of storability of sugar beet. Madritsch et al. (2020) found clear differences in gene up- and down-regulation during post-harvest storage, Karen K. Fugate et al. (2022) has linked this to respiration rates suggesting it is the transport of sucrose from vacuoles that is controlled and which in turn controls rates of respiration, and Gippert et al. (2022) linked storability to the presence of free amino acids and the down-regulation of genes involved in amino acid degradation. While this work is very exciting for the future of breeding for storage of sugar beet roots, variety is still but a (very useful) proxy for health.

Disease: pre-harvest

Reduced sugar beet root health resulting from diseases of the growing sugar beet plant have been found to increase rates of quality loss during storage. A four year study over 47 fields by NBR in Sweden found correlations between post-harvest storage losses and the prevalence of the pathogen *Aphanomyces cochliodes* (Persson & Olsson, 2009). Campbell and Klotz (2006) compared root suffering from severe Aphanomyces root rot to those suffering from mild infections. They showed that sucrose loss during post-harvest storage for the roots with severe infection was approximately two to three times as large. The same research lab also compared resistant and non-resistant sugar beet grown in fields with the pathogen *Beet necrotic yellow vein virus* which causes Rhizomania (Campbell et al., 2008). The non-resistant varieties had increased loss of sucrose during post-harvest storage of some 20 percentage point (14 % compared to 34 %), and a near 20 fold increase in accumulated invert sugars. The same lab again has also examined Cercospora leaf spot, caused by the pathogen *Cercospora beticola Sacc.* (Karen Klotz Fugate et al., 2022). No differences in losses of quality during post-harvest storage were found. Strausbaugh et al. (2011) studied post-harvest storage systems which included roots from sugar beet infested with Rhizoctonia-bacteria complex and found increased rates of sucrose loss in piles with infected roots. A study ongoing during 2021 and 2022 with the Coordination Beet Research International (COBRI) of which NBR is a member, is investigating the impact on storability of three of the main viruses in the virus yellows complex. An infestation of beet yellows virus, beet mild yellowing virus, or beet chlorosis virus appears to lead to reduced quality during post-harvest storage. A 22 % increase in respiration during post-harvest storage at 5 °C is reported for roots from plants with virus yellows in Vukov (1977, Table 179, with reference to Neeb and Grupe (1960), Zucker., 13). The roots of plant affected with Beet necrotic yellow vein virus were found to freeze more readily than healthy roots (Strausbaugh & Eujayl, 2018). The roots affected by virus yellows, aphanomyces, rhizomania, and rhizoctonia, and the root of plants with cercospora leaf spot, all began post-harvest storage with lower quality (Campbell & Klotz, 2006; Campbell et al., 2008; Karen Klotz Fugate et al., 2022; Strausbaugh et al., 2011). A general conclusion on pre-harvest plant health is that a healthier plant will give healthier roots and better storability. A conclusion in Huijbregts et al. (2013) was that more work is needed around the pre-harvest factors driving root health and quality loss during post-harvest storage. This may include more focus on the incidences of pre-harvest diseases and on disease causing agents outside of those of economic importance to plant growth.

Disease: post-harvest

The fungal organisms *Botrytis cinerea*, *Fusarium* spp., *Penicillium* spp. and *Phoma betae* are generally recognised as the major damage causing pathogens in post-harvest storage of sugar beet (Bugbee, 1975; Bugbee & Cole, 1975; Legrand & Wauters, 2012; Liebe, 2016; Liebe & Varrelmann, 2016). From the work of Liebe and Varrelmann (2016), the conclusion can be draw that the presence of these pathogen is very widespread in the fields of northern Europe were sugar beet is grown, possibly with the exception of *Phoma betae*. *Leuconostoc mesenteroides* subsp. *dextranicum* is a bacteria commonly found to populate damaged cells of sugar beet roots, particularly after roots have been allowed to freeze and thaw. The presence of a post-harvest disease leads to rots. Regions of rotten cells will either be washed away at processing, or will likely have higher concentrations of non-sucrose components. For example, dextran and levan are not present in healthy sugar beet roots, only forming in the presence of rot forming micro-organisms (Harvey & Dutton, 1993), and invert sugars concentrations have repeatedly been shown to increase with rates of mould growth during post-harvest storage (Campbell et al., 2011; Kenter et al., 2006).

The presence of fungal or bacterial organisms does not necessarily mean a root will become unhealthy. Strausbaugh et al. (2011) notes that many of the common bacteria found with sugar beet roots slow the development of

Leuconostoc. Ongoing work presented at the 78th Congress of the International Institute for Sugar Beet Research (IIRB) - Molin (2022) - has found that the fungal and bacterial communities in the soil and on the root post-harvest varied between varieties, and this correlated with their storability. The bacteria ASV-649 was associated with good storability.

Mechanical damage

Mechanical damage is the damage to the crop that occurs from physical actions. For the sugar beet crop, this will be damage related to the actions of machinery. Mechanical damage can occur during the growing season from mechanical weed control or the movement of machinery through the field. It seems reasonable to assume that this source of damage will not be of significance to post-harvest storage. No studies relating storability to mechanical damage occurring during the growing season are known. Mechanical damage at harvest and transport is, conversely, omnipresent and of large consequence. All harvest damage has been shown to reduce the storability of sugar beet roots.

Quality is lost from roots that have suffered mechanical damage through various mechanisms. Cells that have suffered physical damage will heal themselves through a sequence of steps that leads to the development of suberin and lignin-like substances (Ibrahim et al., 2001). This costs energy, which will be drawn from the vacuole stores of sucrose. In damaged cells, the contents including the sucrose stored in cell vacuoles can simply leak away. An open wound is also a relatively easy point of entry to the root for a pathogen. In their study on the infection of *Penicillium* and *Botrytis* in storage piles, Mumford and Wyse (1976) suggest that an open wound is "essential for fungus infection". Finally, if the damage leads to separation of fragments of the root, these may be left in the field. If small fragments do make it to the factory and end up in the test sample, this will likely lead to an increased dirt-tare as they will be washed out of the sample.

Numerous works show higher rates of quality loss during storage as a result of higher rates of damage. Rates of damage are often quantified as rate of exposure to a damage inducing action, such as tumbling in a rotating drum (Kenter et al., 2006). Kenter et al. (2006) found a five to six times greater loss of sucrose during storage from roots exposed to a very high rate of a damage inducing action in comparison to roots harvested under standard conditions. In a commercial setting over 50 days, Ingelsson (2003) found an average loss of sucrose per day of 0.19 % for root that experienced hard harvester cleaning, compared to 0.14 % for a more gentle cleaning. They also reported much higher incidence of moulds post-storage.

Specific types of damage are sometimes quantified, although they are usually found to exist simultaneously. For example, Akeson and Stout (1978) found that with increasing rates of impact, damage types expanded from just bruising, to bruising and surface wounds, and finally to bruising, surface wounds, plus cracking. Ultimately, the pathway to loss of quality from the categories of physical damage are those discussed above.

Akeson and Stout (1978) showed that even at low fall impacts where no surface wounds or cracks were visible, loss of sucrose and accumulation of invert sugars during post-harvest storage was elevated. This was attributed to damage as bruising. Brown et al. (2002) attribute approximately 12.5 % percent of total sucrose losses from damage to bruising.

Damage to the surface of the root, like bruising, is not as obvious as cracking and may be obscured by soil. A NBR supervised student project (Skyggeson, 2016) found high levels of surface damage increases risk of frost damage. Machine harvested but crack free roots, and hand harvested roots were stored at -3 °C for a short period, then 8 °C for 18 days. It was observed that all the machine harvested roots showed signs of frost damage, while none of the hand-harvested roots displayed frost damage. This was attributed to surface damage.

The most extreme versions of mechanical damage are cracks (from impacts) and slices (from machinery), with the extreme version of cracks and slices being when entire fragments of the roots are detached. Mechanical harvest will result in cracks and slices. The tap root will need to be broken for the root to be lifted and the removal of the top of the root by slicing is a requirement of processors to ensure standards of quality. Acknowledging this, the test standards for harvest assessment from the IIRB take a root tip break of two centimetres or less, and a topping diameter of five centimetres or less, as the zero-loss reference levels (Schulze Lammers et al., 2015). Akeson et al. (1974) showed that topping induces high rates of respiration from wound healing, and high rates of moulds and rots later in the post-harvest storage period. This ultimately lead to higher rates of sucrose loss, with 12.6 % lower total sucrose after post-harvest storage in topped roots compared to non-topped roots.

Mechanical harvest and handling in general provides numerous opportunities for mechanical damage: defoliating, topping, lifting, cleaning, transport within the machinery, and transfer between intermediary steps. Olsson (2008) found that 80 - 90 % of mechanical damage occurs in the harvester. The use of force sensors through a harvester showed repeated force applied on the roots of up to 75 impacts over a 12 second period (Tordeur, 2018). The largest transfer of energy has been found to be when there is a large fall, be it into the hopper tank on the harvester, at transfer to a chaser bin, or unloading into a clamp (Steven Aldis, (BBRO, England) 2018-07-11, personal communications). Post-storage, it is commonly observed that loading into transport to the factory is a point at which much kinetic energy is transferred to noise energy when roots land in the trailer: that is, there are large impacts.

Frost damage

Frost damage occurs when the sugar beet root freezes and then thaws again. Freezing causes cell wall damaged from both the expansion of water during solidification and from the formation of sharp crystals. Sugar beet roots freeze at approximately -3 °C (Huijbregts et al., 2013). Frost damage can very quickly lead to complete loss of processing quality owing to leakage or excessive accumulation of dextran in the damaged cells from bacterial activity. Frost damage can occur both while the crop sits in-situ pre-harvest, and post-harvest. The exact tolerance of the in-situ crop will depend on the depth of cold, the length of the cold, and the protection the root is given from the plant canopy (Milford et al., 2002). The average individual sugar beet root left *in-situ* is more susceptible to frost damage than the average harvested root stored in bulk (Milford et al., 2002; Olsson, 2009).

Mechanical properties

Mechanical properties are a dimension of plant health similar to strength or balance in human health. It relates to the physical robustness and the ability of the plant to be functional in its physical environment. Mechanical properties are quantified in a multitude of ways and in reference to how the plant structure reacts to physical force. Many mechanical properties relate to the strength of a root, but properties on the way a root deforms under stress have also been noted as relevant (Vukov, 1977). A healthy sugar beet root is one with adequate mechanical properties. Too little of a mechanical property will mean a root will not tolerate mechanical harvest and handling. Given the need to slice roots at processing, it is also not desirable to have too much of certain properties. The current status of the commercially available sugar beet genetic material is such that there is little concern for there being too much of certain properties.

A recently completed doctoral research project has studied mechanical properties of sugar beet roots in detail (Kleuker, 2022). That project shares Paper I of this thesis. That thesis focused on the mechanical properties assessed and method developed in Kleuker and Hoffmann (2019). This includes the resistance to puncture forces at the outer five millimetres of a root, and to compression forces in the core of the root. Clear links between higher values for the mechanical properties and reduced loss of quality during post-harvest storage were found (Hoffmann et al., 2022; Kleuker & Hoffmann, 2020, 2021, 2022). The causal mechanism was consistently identified as reduced mechanical damage and thus reduced need for wound healing and reduced mould establishment. The strongest correlations with mechanical properties were with variety. Prior to Kleuker (2022) and its standardised method, similar results were found in Gorzelany and Puchalski (2000, 2003); Nedomová et al. (2017).

In reference to the post-storage process of slicing at the factory, Vukov (1977) notes that other mechanical properties should be considered. Resistance to cutting is a property that is ideally measured directly, although states that it is comparable to a measure that in its description seems similar to puncture resistance as defined in Kleuker and Hoffmann (2019). This is an example of a non-monotonic dimension of plant health, where roots are graded on their resistance to cutting on the scale Soft - Normal - Suberized - Woody - Extremely woody. Vukov (1977) also cites the modulus of elasticity as an important descriptor of how well roots will slice. It is noted that elastic behaviour will also have a bearing on bulk density and porosity of a bulk of sugar beet roots. It has further been suggested that more elastic fruit should suffer less damage than less elastic fruit from a given impact (Ruiz-Altisent, 1991).

While not a mechanical property *per se*, cell wall content is another property of sugar beet roots that has been linked to storability. Alcohol insoluble residue (AIR) content is a measure of the cell wall content of the root (van Soest et al., 1991) and shows strong correlation with variety and mechanical properties (Kleuker & Hoffmann, 2022). Similarly, marc content is an indication of the post processing pulp content of the root and had been linked to variety and storability (Hoffmann et al., 2018; Vukov, 1977).

Growing season water stress

In a study by Gaskill (1950), it was found that sugar beet roots harvested after growing under moderate drought stress had higher incidences of rot post-storage. After a very long post-harvest storage period of 139 days at approximately 7 °C, the percentage of rots in the drought stressed roots (28.8 %) was double that of roots from sugar beet irrigated until harvest (14.4 %). A follow-up experiment the next year with a shorter two months of post-harvest storage at 18 °C found 9.54 % and 7.85 % losses for the drought stressed and irrigated roots respectively. Kenter and Hoffmann (2008) similarly found increased rates of quality loss from drought stressed roots during post-harvest storage. Higher rates of increase in the concentration of amino N, betaine, total soluble N and invert sugar were observed in the drought stressed roots.

Nutrient deficiencies

A number of nutrient deficiencies have been stated to lead to higher rates of respiration during post-harvest storage. At 5 °C, increased rates of respiration were found from deficiencies of nitrogen (3 % increase in respiration rate), potash (133 %), magnesium (34 %), manganese (12 %) and boron (58 %) (Vukov, 1977, Table 179, with reference to Neeb and Grupe (1960), Zucker., 13). Corresponding increases in the rate of sucrose loss during storage could be expected. The extent of the deficiencies is not known.

1.2.2 An optimal storage environment

Temperature

Temperature is often cited as the most important factor in post-harvest storage (Wills & Golding, 2016). Huijbregts et al. (2013) give the optimum temperature range for the post-harvest storage of non-frozen sugar beet roots under commercial conditions as 2 to 8 °C. The more restricted range of 4 to 6 °C is given in both Bugbee (1993) and English (2020). This minimises the loss of quality per unit time. The temperature should preferably be stable (Wyse, 1978). Within this optimal temperature range, the processes that cause the loss of sucrose stored at the cellular levelled are slowed, as too the rate of loss of processable material. The loss of sucrose is reduced owing to lower respiration (Dilley et al., 1970). Respiration is the primary source of loss of stored sucrose in the early stages of post-harvest storage (out to ca. 300 degree-days (°Cd) - measured in ambient air). Respiration rates in harvested sugar beet roots generally have an early peak at approximately day 3 or 30 °Cd, reach a minimum at approximately 200 °Cd, and then show gradual increase (Akeson et al., 1974; Dilley et al., 1970; Huijbregts, 2009). The early peak has been stated as 2 to 10 times the minimum rate and abates approximately as quickly as it increases (Akeson et al., 1974).

At lower temperatures there will be lower rates of pathogen growth (Sviridov & Kolomiets (2012) quoted in Korobova et al., 2022) and even the avoidance of the growth of some common pathogens (Legrand & Wauters, 2012). Rates of moulds and rots are of increased importance when post-harvest storage extends beyond approximately 250 to 300 °Cd. A large study in six European countries found rates of loss during post-harvest storage correlated most strongly with rates of moulds and rots when storage extended beyond 339 °Cd and out to 996 °Cd (van Swaaij & Huijbregts, 2010). By setting a floor of 4 °C, the accumulation of invert sugars and the trisaccharide raffinose will be less than if it was a lower temperature (Haagenson et al., 2008; Wyse & Dexter, 1971).

Outside of this optimum, temperatures below -2 °C should be avoided (Milford et al., 2002; Wyse, 1978). By avoiding sub-zero temperatures, the severe and acute loss that results when cells freeze and thaw is also avoided. A maximum temperature limit is not known as post-harvest storage is not commonly practiced in climates with ambient temperatures persistently above 15 °C, but it is clear that temperatures above 25 °C should be avoided (Orleans & Cotton, 1952). Given respiration in plants is temperature dependent (Klotz et al., 2008; Vallarino & Osorio, 2019) and seems to increase exponentially in sugar beet roots for the range of temperatures they are commonly stored in post-harvest (Vukov, 1977), there exists the potential for a vicious cycle of temperature and respiration rate to develop in bulks of sugar beet roots. This can rapidly lead to large rates of quality loss.

A generally applicable relationship between temperature and rates of loss of sucrose in stored sugar beet roots under commercial conditions is that loss is 0.02 %/°Cd (Jaggard et al., 1997). Percent is of the total available sucrose at the time of entering post-harvest storage, and the temperature is taken as the ambient temperature. The experimental data that gave these results went out to approximately 700 °Cd. An alternative form of this relationship comes from Legrand and Wauters (2012). They give a rate of loss of 0.013 %/°Cd out to 270 °Cd, and 0.042 %/°Cd between 270 °Cd and 450 °Cd. This gives an average of 0.024 %/°Cd out to 450 °Cd. The increased rate in the second period is again attributed to the increased rates of moulds and rots. Given the aforementioned early peak in rates of respiration, these relationships are only accurate when applied over a long-term post-harvest storage period.

The interaction between temperature and these many other factors suggest it could itself form a principle: that sugar beet roots store better when held within an optimal temperature range. There are, however, two important footnotes that should be appended. The first footnote is that during the initial post-harvest period in which the roots need to heal from the harvest process, the optimal temperature is most likely well above the 4-6 °C range. Fugate et al. (2016) showed that wound healing is more complete in roots stored at 12 °C compared to 6 °C. Only the respiration and transpiration rate of the wounded root stored at 12 °C returned to levels similar to the wound free controls. The loss per degree-day out to the end of the comparable data at ca. 170 °Cd was similar at both temperatures, but it could be expected that the roots initially kept at the higher temperature will store better thereafter. The second footnote is that the absolute best temperature to store roots at to maintain quality over time is that at which the root freeze and remain frozen until processing. An average minimum daily temperature below -9 °C has been suggested as necessary (Bugbee, 1993). This is not a practical solution in the Swedish context, but is achievable in some parts of North America (Backer et al., 1979; Bichel, 1988) and Russia.

The details of the role of temperature in the long-term storage of sugar beet roots is discussed in detail in the literature study written as part of this research project: English (2020).

Moisture

The research into air moisture levels in sugar beet root storage is less extensive than that into air temperature. This is likely due to the situation in naturally ventilated post-harvest storage where air relative humidity levels have been found to be consistently very high and losses from dehydration very low (Huijbregts et al., 2013; Zavrazhnov et al., 2021). Dehydration is the movement of water from the sugar beet root into the surrounding air. It is driven by a differential in the water vapour pressure between the root and the air, and the resistance of the skin of the root to this movement (Carta, 2021b). As relative humidity tends to 100 %, the water vapour pressure differential and thus dehydration tends to zero. For any given relative humidity, the water vapour pressure differential will increase with temperature. The research that has looked at dehydration resulting from low relative humidity originates mainly from North America, where post-harvest storage is longer and active ventilation is used to control temperature in the large pile storage system. It has been shown that lower relative humidity does lead to higher rates of weight loss of roots, but that the effect of temperature when within the ideal range for sugar beet storage (2 – 8 °C) is of little consequence for dehydration (Andales et al., 1980). Over a 15 week storage period in climate chambers at 3.3 to 8.9 °C, mean weight loss at 80-85 %RH was 31 %, while it was only 15 % at 95-100 %RH. Higher rates of electrolyte leakage and respiration rates have also been found in roots stored at lower relative humidity levels (Lafta & Fugate, 2009). Raffinose concentration can increase under mild dehydration, while severe dehydration was found to result in decreased concentrations of many non-sucrose carbohydrates with the exclusion of invert sugars (no change) (Lafta et al., 2020). Pathogen growth does not seem to be increased on dehydrated beets (Bugbee & Cole, 1979). Despite the importance of this transfer of water from sugar beet roots under post-harvest storage, there are no values known to be reported in the literature for rates of transfer per unit root surface area and time (mass flux). Further, it is not well known what the total expected weight loss from dehydration during commercial post-harvest storage is.

Independent of the relative humidity of air, there are also a collection of work that focuses on levels of moisture on the surface of the stored root. It has been noticed that rainfall events have large impacts on the measured dirt-tare and thus payment received. In a NBR supervised student project, Mårtensson (2017) compared the dirt-tare of samples split at harvest and either analysed directly or stored in boxes for between 15 and 50 days. The dirt-tare of the stored samples was stable at 10.15 % ± 0.85%. The dirt-tare of the samples analysed at harvest ranged from 9.6% to 19.6%, clearly increasing with the closeness of the harvest date to rainfall events. The conclusion was that the dehydration of the soil attached to the root is an important quality driver. At the national level, a correlation between increasing soil water at harvest and increasing average dirt-tare is a regularly observed phenomena (Ekelöf, 2017b).

The movement of moisture can also play an important role in the thermodynamics of the storage system. Cannon (1950) notes the cooling potential of evaporation, suggesting that at temperatures below 21 °C it could remove all the heat of respiration. Zavrazhnov et al. (2021) models the heat exchange at the surface of a 6.5 m high unventilated pile during November in the Kursk region of Russia. They estimate that evaporation at the beet surface accounts for approximately 20 % of the total heat exchange.

Airflow

Airflow is an important factor in the consideration of temperature and moisture in sugar beet root storage. Rates of both heat and moisture transfer between the sugar beet roots and the air will be driven by the differential in these factors between the two phases, and the resistance of the surface to this transfer. The temperature and humidity of the air inside of the bulk of roots will depend greatly on how much of the ambient air is permitted to flow through the bulk, which in-turn will impact the differential. The resistance of the surface to transfer is proportional to the speed of airflow. There is one known study that directly measures airflow in a bulk of sugar beet roots. Tabil, Kienholz, et al. (2003) measured under controlled conditions the velocity-pressure relationship of air forced through bulks of sugar beet roots with various sizes and foreign material percentages. This has resulted in a series of data on the permeability of the bulk that can be applied in engineering studies of the fluid dynamics in sugar beet post-harvest storage. The lack of studies that directly measure airflow in sugar beet root stores is likely contributed to both the difficulty of the working environment and the more insidious nature of low and variable airflow in comparison to factors like temperature. Airflow rates in the ventilated pile systems are quoted to be between 10 and 20 cubic feet per minute (cfm) per ton of roots (Backer et al., 1979; Downie, 1950), which is equivalent to approximately 0.018 to 0.037 m^3/h/t.

Oxygen and Carbon

The impact of the levels of gaseous oxygen and carbon in post-harvest storage are generally discussed under the rubric of controlled- or modified-atmosphere storage. Controlled atmosphere refers to the situation where the levels of gas concentrations, temperature and humidity are regulated to the point of control (e.g. constant levels are maintained), while modified atmosphere refers to a lower level of regulation such that the atmosphere is regulated in a certain direction (e.g. accumulated gases are trapped within the storage system). Wyse (1973) is the only known study into how controlled atmosphere storage could be applied to the storage of sugar beet roots. It was found that in comparison to normal air, a 5 % concentration of carbon dioxide did not have a large effect on storability, while a 5 %

concentration of oxygen with 0 % CO_2 reduced sucrose losses from 1.3 % to 0.4 %. It is not known if it is possible to reach and maintain these relatively high and low concentrations, respectively, in an open post-harvest storage environment.

Ethylene

It has been shown that sugar beet roots do react to the concentration of ethylene under storage, but also that the effects are likely of little consequence under commercial conditions (Fugate et al., 2010). When roots were places in controlled atmospheres with the concentrations of 0.020 and 0.11 µL/L, an initial average increase in respiration of 55 % was observed through to 48 hours. This effect had disappeared by 72 hours. At the same time, in a large commercial non-ventilated pile, a maximum concentration of 0.028 µL/L was found after 67 days. Levels were only 0.0057 µL/L at 30 days.

Other treatments

Other post-harvest treatments have been examined in sugar beet root storage. Finger et al. (2021) studied how the volatile organic compound methyl jasmonate effects dehydrated roots, finding a positive but small impact. Iztayev et al. (2021) studied how a high concentration of ozone effects the development of moulds and yeasts in covered piles, finding reductions primarily in yeast development. The ozone concentrations used were toxic to humans, raising safety concerns. The application of lime on stored roots at rates of ca. 1 % w/w has been shown to reduce storage losses, presumably by reducing mould growth (Huijbregts et al., 2013; Olsson, 2012).

1.2.3 Summary of principles

As a final note on the principles of post-harvest storage of sugar beet roots, it should be noted that both principles are required to be in place for successful long-term post-harvest storage. Each principle is individually a necessary condition, but not a sufficient condition. When these principles are viewed as existing on a continuum, the higher the plant health and the closer to the optimum environment, the more successful long-term post-harvest storage will be.

1.3 Swedish conditions

The use of the clamp system of post-harvest field storage as employed in Sweden is determined by the conditions of the industry agreement, and presumably originates from multiple factors in a chain of historical path dependence. The start date of long-term post-harvest storage in Sweden is based on historical climate data and is defined in the industry agreement. The end date and thus length of long-term post-harvest storage depends on the annual level of production and conditions at the processing factory.

1.3.1 The natural environment conditions: Climate

For the years 2013/14 to 2022/23, daily mean temperature for the sugar beet growing region of Sweden (Figure 2) during the period 1 December to 14 February varied between 0 and 5 °C (Figure 3). During this period, extremes of -15 and 14 °C were recorded. The warmest three day period over this time span was an average mean temperature of 9.2 °C in December 2015, and the coldest three day period was an average mean temperature of -6.8 °C in January 2016. Wind speed averaged 4.5 m/s, originating predominantly from the West (25.0 %) and South West (23.5 %) octants. Mean relative humidity over this period was 91.9 % and average cumulative precipitation 124 mm.

Figure 2. The sugar beet growing region of Sweden, 2022, within the red boundary. Adopted from Anon (2022c)

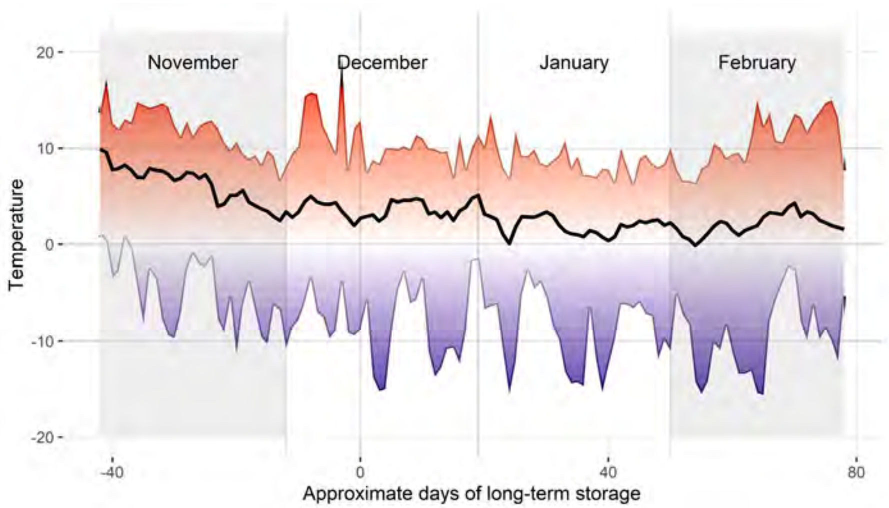


Figure 3. Temperatures in the sugar beet growing regions of Sweden during November to February, 2013-2022. Upper line shows highest recorded daily maximum temperature, heavy dark line shows average recorded mean daily temperature, lower line shows lowest recorded daily minimum temperature. Months delimited by vertical lines. x-axis shows approximate days of long-term storage, 0 = 10 December. Source: Lantmet (2022)

1.3.2 The market conditions: Industry agreement and contracting

Many of the factors relating to harvest and post-harvest storage of the sugar beet crop in Sweden are specified in the collective agreements negotiated between the grower's representative organisation and industry. This includes when a cover should be applied and what properties the cover should have, how much a grower is compensated for the use of the required covers, and how the crop will be transported to the processing factory (Anon, 2019a). The risk of in-situ frost damage varies across the sugar beet growing regions of Sweden (Ekelöf, 2017a). In all locations, this risk is deemed too high in the latter months of the processing campaign and a single critical last date for harvest is codified in the industry agreement, as the Frost protection date (Table 1). This date is occasionally adjusted during the processing campaign as harvest, processing, and post-harvest storage conditions evolve. The varieties of sugar beet grown are those permitted under the agreement between industry and the growers. The information provided on the available varieties was expanded in 2022 to include indication as to which varieties likely store better.

Contracts for delivery are signed with individual growers approximately 12 months prior to the start of a given year's harvest and processing campaign. Following the deregulation of the sugar beet industry across the European Union in 2017, production is not bound by a mandated maximum volume. Industry does, however, set a maximum volume they will contract. Individual growers register the area and approximate volume they wish to grow and deliver. Should the aggregate total of the individual registrations exceed the industry set maximum volume, the individual contacts offered are adjusted accordingly. Otherwise, contracting is based on the registered interest.

Payment for delivered sugar beet is made primarily on clean root weight at 17 % sucrose concentration equivalent, sucrose concentration, and dirt-tare (Anon, 2019a). Clean root weight is calculated as delivered weight multiplied by (1 - dirt-tare). Dirt-tare is calculated as the percentage of the sample that is washed away during testing, plus a fixed deduction. Beyond the conversion from delivered weight to clean weight, a penalty is deducted for dirt-tare, the grower pays for the transport of the dirt-tare fraction of each delivered load, and loads with dirt-tare of 22 % or higher are rejected for delivery. No material that has been frozen and then thawed should be accepted. The conversion of clean root weight to 17 % sucrose concentration equivalent is achieved by multiplying the weight by the fraction of the sucrose concentration of the delivered load over the 17 % reference value. A further price adjustment is made for each tenth of a percentage point difference in sucrose concentration from the 17 % reference content. Bonuses are paid on a sliding scale for early delivery - to compensate for lost growth potential - and for late delivery - to address loss of processable material during post-harvest storage. A per tonne payment is made for roots that are stored under an approved cover after a given date. This was 15 November in 2022 (Anon, 2019a).

The payment schedule guides the growers decisions around harvest timing and rates of harvester based cleaning of the roots. In 2022, and considering the entire harvest and post-harvest storage stage of production in which most of the non-washing cleaning of the crop occurs in the harvester, the balance of the bonuses is to encourage the delivery of healthy entire roots. In previous years in which penalties for higher dirt-tare were greater and the value of the mass of root lower, the payment schedule incentivised clean roots (Olsson, 2017).

1.3.3 Post-harvest field storage under Swedish conditions

Sugar beet harvest in Sweden starts in mid-September. Harvest dates on individual farms will be guided by the contracted delivery schedule, but the recommendation is to as best possible harvest at 5-10 °C and when the soil is sufficiently dry (Anon, 2023a). It is very common that the harvester operator is a contractor. The sugar beet roots are harvested mechanically with tractor-drawn or self-propelled harvesters that have hopper (on-board) tanks of approximately 12 tonnes (see for example Edenhall 753 (Anon, 2009)) up to approximately 30 tonne (see for example Ropa Tiger 6S (Anon, 2019b) or Holmer Tera-Dos T5-40 (Anon, 2019d)). Sugar beet stem and leaf is considered dirt-tare, and the recommendation is for defoliation plus minimal topping to find the balance between damage and regrowth post-harvest (Huijbregts et al., 2013). A similar trade-off between damage and removal of soil occurs in adjusting the cleaning system of the harvester. The harvested roots are then transported through the field either in the harvester or in chaser bins and unloaded into clamps (Figure 1).

In Sweden, harvested sugar beet roots are stored exclusively in clamps. These clamps are up to nine meters wide, and three meters high. The width and thus height of the clamp is limited by the working width of the cleaner-loader machinery that loads the roots for transport to processing. Cleaner-loader operators are exclusively contractors, as specified in the industry agreement. The shape this gives the clamps means they are commonly referred to an "A-shaped" clamp (Huijbregts et al., 2013). Elsewhere, this type of clamp may be referred to as a "Maus" clamp in reference to the cleaner-loader used (J. Anderson (Lantic, Canada), personal communications, 2022-11-09). The length of the clamp is determined by the size and shape of the field, but may be many hundreds of meters.

The use of a cover on the clamp during the period of long-term post-harvest storage is required by the industry agreement. The choice of cover type is left to the grower. The cover used was traditionally straw (Olsson, 2013b), but this has largely been replaced with non-woven polypropylene fleece and plastic sheeting applied as necessary for extra frost protection (Olsson, 2007, 2013a). TopTex® is the leading brand of non-woven polypropylene fleece. These covers can be managed with machinery, but some manual labour is usually required (Olsson, 2014; Thorstensson, 2016). The purpose of the cover has always been to modify the post-harvest storage environment towards the optimum. Polypropylene fleece seems to reduce airflow in an open environment substantially. A NBR supervised student project (Skyggeson, 2016) measured a decrease from 5.50 m/s in front of the fleece, down to 0.50 m/s behind it. This has not been tested in the field. The temperature of the clamp does not seem to be greatly affected by polypropylene fleece, although it does seem to provide extra protection in the negative temperatures close to zero (Olsson, 2013a). This extra frost tolerance of a clamp covered with polypropylene fleece is likely a result of drier roots. Polypropylene fleece restricts "sufficient" rainfall from entering A-shaped clamps (Huijbregts et al., 2013). The combination of sufficient water exclusion with sufficient airflow allows the transfer of moisture out of the clamp and into the open air at a rate that generally is not matched by rainfall. This results in the drying of the roots and the soil attached to the roots (Mårtensson, 2017). A cover of plastic sheeting is used to stop all airflow through a section of the clamp. It can be applied to the entire clamp, or from the ground and two to four meters up the sides with the top of the clamp left open to permit excess heat to escape through natural convection. The use of straw as insulation is still commonplace when extreme cold periods are expected.

Beyond the use of covers, communications from industry around clamp construction reflect the scientific knowledge. This includes recommendations that a clamp is constructed with uniform width and height to reduce the risk of frost pockets forming during period of negative temperatures (Huijbregts et al., 2013; Thorstensson, 2016), that low levels of foreign material – i.e. weeds - are present (Anon, 2023a; Olsson, 2013b), and that ideally only entire, healthy roots harvested from healthy stands of sugar beet plants are stored post-harvest (Anon, 2023a, 2023c; Olsson, 2013b). Aphanomyces, rust, mildew, and ramularia are common diseases in the Swedish sugar beet crop, while virus yellows, cercospora, rhizoctonia and rhizomania are less common. Other factors that have been discussed in interactions with growers but which are not in the recurring communication from industry include the clamp size (English, 2022), the size of roots (Huijbregts et al., 2013), the use of wind-breaks (Olsson, 2009), or the bearing of the clamp. There are no requirements on these factors.

The post-harvest storage system currently employed in the Swedish sugar beet industry is functional and largely successful. Unsuccessful post-harvest storage appears to be associated with extreme weather, the length of the post-harvest storage period, and the level of activity in the management of the cover. The most common moulds found in clamps in Sweden are *Botrytis cinerea*, *Fusarium* spp., and *Penicillium* spp. (Olsson, 2008). A major issue with the management of the cover is information on the temperature. An ongoing NBR and Nordic Sugar project with temperature sensors reporting live information is aiming to remove this impediment.

Table 1. Sugar beet processing campaign dates and post-harvest storage lengths for Sweden, 2013-2022

Year	Campaign start date	Frost protection date [1]	Campaign end date [2]	Campaign length	Days long-term [3]	Percent days long-term
2013	09-17[a]	11-24[e]	01-18[l]	124	42	34%
2014	09-22[a]	11-24[f]	02-06[m]	138	61	44%
2015	10-01[a]	11-24[g]	12-12[n]	73	5	7%
2016	09-15[a]	12-01[h]	01-08[o]	116	25	22%
2017	09-24[a]	12-10[i]	01-18[p]	117	26	22%
2018	09-25[b]	12-01[i]	01-09[q]	107	26	24%
2019	09-26[b]	12-01[i]	02-14[r]	142	62	44%
2020	09-16[b]	12-01[i]	02-09[s]	147	57	39%
2021	09-21[c]	12-01[j]	02-07[t]	140	55	39%
2022	09-18[4,d]	12-01[j]	01-17[u]	122	34	30%
2013-22				123	39	30%

[1] Frost protection start: indicates the approximate last day sugar beets will be harvested. 2017 includes a blanket extension granted. Similar extensions have been granted in other years, but were conditional on delivery dates more than four weeks after the given date.

[2] All campaign end dates are in the following calendar year, with the exception of 2015, which ended in December 2015.

[3] Days long-term: days in campaign beyond Frost protection start + 14 days

[4] Approximately 15% of the Swedish harvest was shipped to Denmark for processing owing to concerns around the gas supply that would be available to the factory in Sweden during the 2022-23 campaign. Date is the start of delivery to Trelleborg harbour for shipping to Denmark. The factory at Örtofta started processing sugar beet 2022-09-22.

Sources: [a] Anon (2018a), [b] Anon (2022a), [c] Dahlgren (2021), [d] Anon (2022b), [e] Anon (2013), [f] Anon (2014a), [g] Anon (2015a), [h] Anon (2016a), [i] Anon (2017a), [j] Anon (2019a), [l] Anon (2014b), [m] Anon (2015b), [n] Anon (2016b), [o] Anon (2017b), [p] Anon (2018b), [q] Anon (2019c), [r] Dahlgren (2020), [s] Anon (2021a), [t] Anon (2022c), [u] Anon (2023b).

1.3.4 Long-term storage under Swedish conditions

Given the definition of long-term in Section 1.1.2 and the conditions of the industry agreement, the start of the period of long-term post-harvest field storage is calculated as the Frost protection start date plus two weeks. For the ten years prior to the conclusion of this project, the period of long-term post-harvest field storage of sugar beet roots in Sweden lasted for an average of 39 days, or 30 % of the total processing campaign (Table 1). These numbers increase to 54 days and 42 % if the two weeks is excluded. The earliest start date for long-term post-harvest field storage was 8 December in 2013 to 2015, with the latest campaign end date being 14 February in 2019.

An average of 1.93 million tonne of sugar beet roots where harvested annually in Sweden between 2013 and 2022, giving an average of ca. 615 000 tonne of roots stored long-term annually. At a bulk density of 700 kg/m^3, that is approximately 880 000 m^3 of roots. At the 2021 1-year fixed price contact price of approximately €30 per tonne (17 % sucrose concentration equivalent), that is €18.5 million worth of roots subjected to long-term post-harvest field storage annually.

1.3.5 The broader conditions

The industrial conditions: Rationalisation and Deregulated

The processing stage in the Swedish sugar beet industry has undergone continual change through industrial expansion and rationalisation. When Svenska Sockerfabriksaktibolaget (SSA) was formed in 1907, there were 27 sugar processing factories in Sweden (Kuuse, 1982). Twenty-one of these sites processed sugar beet, and ten refined raw sugar. When Danisco bought SSA in 1992, five beet processing factories remained. In 2006, the second to last of these factories was closed, leaving Örtofta as the nation's single sugar beet processing factory. From 2022, it also became the nation's only refinery. Danisco Sugar including the Örtofta factory, was purchased by the company Nordzucker AG in 2008 (Reuters Staff, 2008). A reduction in growing regions accompanied the reduction in processing factories, but it did not proceed at the same pace. The increased per factory production was covered from both increased capacity, but also from longer processing campaigns (Huijbregts et al., 2013).

As a member of the European Union, Sweden's sugar production has historically been regulated within the Common Agricultural Policy. The sugar market of the entire European Union (EU) was deregulated 30 September 2017 when the production quota system was removed (European Commission, 2017). The deregulation process was agreed as part of the

Common Agricultural Policy reform of 2006 (European Commission, 2006). The final result of this deregulation process has seen the EU price become more linked to the world market, but has been somewhat neutral in terms of production levels (European Union Market Observatory, 2023). Should greater production be sort in the future, it would need in the short-term to be supported by increased long-term post-harvest storage.

The global conditions: Sustainable Development Goal 12.3

Sustainable Development Goal (SDG) Target 12.3 is to “By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses” (Anon, 2020). This Target mirrors the definition of food loss and food waste given by the Food and Agriculture Organization of the United Nations, with food loss occurring between production and retail, and food waste occurring in retail and the household (English et al., 2019). This current project sits squarely within SDG12.3, given its focus on food loss. Sweden is committed to the SDGs in legislation (Anon, 2021b).

1.3.6 The research conditions: Applied

This research project was instigated by the combined national sugar beet research organisation of Sweden and Denmark: NBR Nordic Beet Research foundation (NBR). NBR was formed on 14 March 2007 by the sugar beet growers and industry (then named Danisco Sugar) of Sweden and Denmark (Olsson, 2007). NBR was a merger of Sockernäringens BetodlingsUtveckling (SBU) in Sweden and Alstedgaard in Denmark, but its ancestry can be traced back to at least the early 1920s when the research focus of the then SSA expanded from only breeding to include soil analysis and growing technique (Kuuse, 1982). Over this time and at its core, the mandate given to the researchers has remained constant: applied research for the advancement of the national sugar beet growers and industry. This project sits firmly within this applied research tradition.

2. Aims and objectives

The overall aim of this research project was to increase the preparedness of the sugar beet industries of Sweden and other nations for long-term post-harvest storage under dynamic conditions. This includes the increased ability to respond to changes in available varieties, the pricing model, industry structure, technology used to harvest and transport the crop, and the climate. The individual studies were to target the key areas identified as drivers of successful long-term post-harvest storage. On top of this and as far as possible, the research was to be: applied; result in practical tools or recommendations; collaborative; consider ongoing developments in industry such as active ventilation; and, remain applicable even if longer post-harvest storage campaigns do not eventuate.

In this context, the specific objectives of this thesis are;

- Assess the impact of nitrogen and water availability during the growing season on the mechanical properties of sugar beet roots, the subsequent rates of damage at harvest, and on quality loss during post-harvest storage (Paper I). This will support commercial agronomic decisions in the face of variation in input prices.
- Assess the reliability of a simple handheld penetrometer in the assessment of sugar beet root mechanical properties (Paper II). This will support the rapid assessment of relative storability of new varieties through the development of a practical and standardised methodology for in-field assessment of mechanical properties.
- Increase understanding of the impact of the movement of air, and of temperature and humidity on the movement of water and on quality parameters in sugar beet post-harvest storage systems (Paper III). This will give insight into how airflow can be managed to improve quality parameters in commercial operations. It will

also support the further development of models of sugar beet post-harvest storage systems.

- Develop a spatial-temporal numerical model of airflow and temperature within a bulk of sugar beet roots (Paper IV). This will give deeper insight into the distribution and dynamics of temperature in clamps. It can also support future research into the management of the sugar beet post-harvest storage environment including studying actively ventilated systems.
- Explore possibilities for measuring alternative mechanical properties of sugar beet roots (Supplementary Studies (SSs)). Specifically, explore methods for the assessment of dynamic forces (SS1 and SS2), and explore the need for the inclusion of the modulus of elasticity in future assessments of mechanical properties (SS2). The SSs were designed only as exploratory studies and do not reach the standards of academic publication.

Papers I and II, and both supplementary studies focus on the first principle of long-term post-harvest storage of sugar beet roots: plant health. Papers III and IV focus on the second principle: the post-harvest storage environment.

3. Methods

The methods applied in this research project include both replicated field trials including laboratory testing (Paper I and II, and SSs), replicated modified environment experiment (Paper III), and mechanistic numerical modelling employing Computational Fluid Dynamics (CFD, Paper IV). The CFD modelling includes unique data sourced from a field survey, mathematical modelling, and laboratory experimentation.

3.1 Experimental design

3.1.1 Field trials including laboratory testing (Paper I and II, and SSs)

Investigating the role of the availability of nitrogen and water during the growing season on the mechanical properties of sugar beet roots (Paper I), the assessment of a methodology for use of a handheld penetrometer to assess the mechanical properties of sugar beet roots (Paper II), and the initial fall-test (SS1 - *falling-beet*) all relied on the same field trials. Field trials of sugar beet were established during 2018 and 2019 in Sweden, the Netherlands, and Belgium. The same three varieties were grown in all trials. Three treatments were applied in six replicates, for a total of 54 plots per site. In the Netherlands and Belgium, the treatment consisted of a ladder of applied nitrogen, at rates of; no additional nitrogen, the recommended application rate, and a high application rate equivalent to the recommended rate plus 80 kg/ha. In Sweden, available growing season water was the focus. The treatment levels were defined as; no supplementary water, optimal water availability for plant growth, and wet during the last month prior to harvest. These treatments were chosen as they represent two of the key agronomic inputs to the growth of the sugar beet crop. The choice of available water in

Sweden was born from many observations in industry where irrigated crops seemed to suffer from relatively high losses of quality after very long post-harvest storage periods. Each plot was split into a quality assessment section, and a mechanical properties and post-harvest storage loss assessment section.

The validation of a method for the application of a handheld penetrometer in-field for sugar beet roots (Paper II) focused on a specific method that had been developed through exploratory work and through a study of the literature. The aim of this method was to be repeatable across as many growing conditions, varieties, and time periods pre- and post-harvest as possible. The method tested stated that the penetrometer should be applied at the same speed, always perpendicular to the root surface, and high on the root but below stem growth (Figure 4). It was only assessed during 2019. The falling-beet test (SS1) also occurred only in 2019 and drew only a sub-sample of the available plots. Within SS1, an additional sample of large and small roots was taken from a commercial field to test the role of root size in the falling-beet test.

The assessment of the second fall-test method (SS2 - *falling-ball*) also included a re-assessment of late season water availability. A single trial site with four replicates was established during 2021. Three agronomic treatments focused on water availability were applied in the final two months prior to harvest: natural rainfall (*untreated*), heavy irrigation 25 and one day prior to harvest (*irrigated*), and the exclusion of additional water (grown under a roof - *roof*). A fourth, post-harvest focused, treatment of natural rainfall plus stored under high airflow conditions was included (*ventilated*). This treatment was similar to the highest airflow treatment of Paper III, with a seven day duration at the highest airflow rate.

3.1.2 Modified environment experiment (Paper III)

Investigating the impact of airflow, temperature, and humidity on the movement of water and on quality parameters in sugar beet roots stored post-harvest in bulk (Paper III) was conducted in a modified atmosphere. The desire to use commercially harvested roots while minimising variation in the harvested material required a large experimental system. A custom built system with one primary and three secondary distributors was constructed (Figure 5. Originally Paper III, Figure 2. See also Paper III Figure 1).

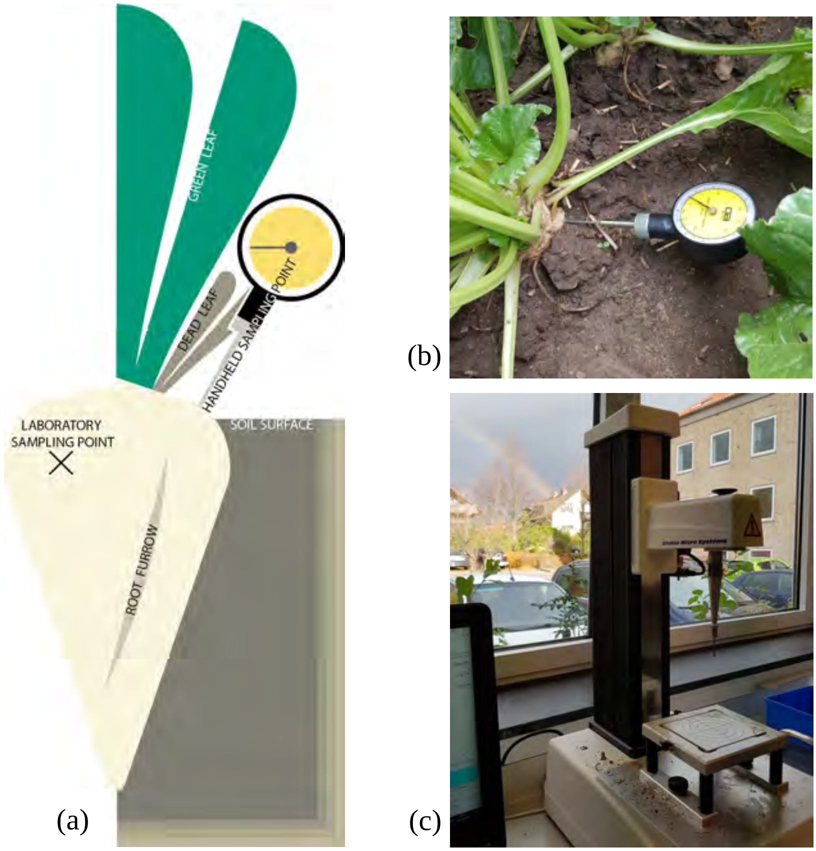


Figure 4. Sampling of textural properties of sugar beet. (a) Schematic of sampling points on the sugar beet root, (b) Handheld penetrometer placed at the sampling point of a sugar beet in the field with a limited sampling area, Sweden August 2019, (c) TA.XT Plus 100 with 2 mm diameter plunger in a laboratory at IfZ, Göttingen. Source: Paper II, Figure 1

Each secondary distributor had 16 ventilation boxes attached, which, with the zero airflow control ventilation boxes, gave a total of 64 ventilation boxes in the system. It was not possible to house this large system in the available controlled atmosphere chambers, so a modified atmosphere chamber was constructed. Four factors were modified and monitored: temperature, humidity, airflow rate, and ventilation duration. Airflow rate was fixed at 11.2, 46.5 and 81.5 m^3/h per ventilation box. These are the levels that would be expected at 1.5, 1.0 and 0.5 meters from a ventilation pipe in a clamp when using the ventilation system developed in the NBR managed European Innovation Program project "Ventilation of sugar beet and potato stored in clamps" (Jordbruksverket project 2017-2390, (Ekelöf & English, 2022)). These are relative airflow rates of 1, 4 and 7. A zero airflow rate control was included. These airflow rates were applied in every run.

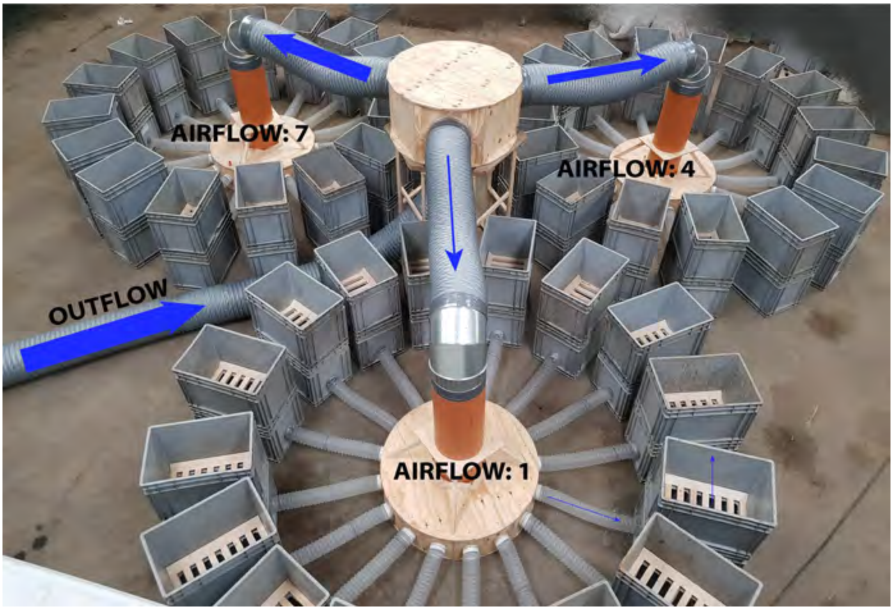


Figure 5. Airflow distribution in modified atmosphere ventilation system. From above, facing west. Grates in ventilation boxes shown. Outflow is from the climate control system. For scale, each ventilation box is 0.365 m x 0.570 m x 0.435 m (W x D x H), each airflow rate group is ca. 3.5 m from the outer edges of opposing ventilation boxes. Source: Paper III, Figure 2.

Each airflow rate was sampled at one, four and seven days, in four replicates. This meant that various combinations of total airflow volume were repeated in the experiment, e.g. 1 day at airflow rate 7 gives the same total airflow volume as 7 days at airflow rate 1. Ventilation boxes were back-filled to maintain the airflow conditions. Roots included in the back-fill after one day were also used to assess changes to density. For each airflow level, four additional ventilation boxes were filled by two reference samples of each of washed roots and soil sampled at harvest (Figure 3, Paper III). The experiment was planned to run for six one week runs, but the decision was taken to abandon the third run (week three from the first harvest). This was based on signs of advanced quality loss in the bulk of roots that the samples were picked from. The majority of roots had visible mould growth. For each run, target temperature and humidity conditions were set, with actual values recorded at 15 minute intervals. The targets were set to give a range of conditions that are commonly found during post-harvest storage in Sweden. The final temperature and humidity conditions were quite stable, but somewhat limited in the coverage they gave.

3.1.3 Computational Fluid Dynamics modelling (Paper IV)

The spatial-temporal numerical model of airflow and temperature (Paper IV) was developed using a modelling structure built on standard Computational Fluid Dynamics (CFD) methods but to the specific requirements of the system being modelled. This model was always intended to be the first step in a long process of model develop, and as such was developed to build a foundation, not as a model of high refinement. The model uses the finite volume method and a porous medium approach. Governing equations for a transient, turbulent, and incompressible system were defined, given below in Equations 1 to 6.

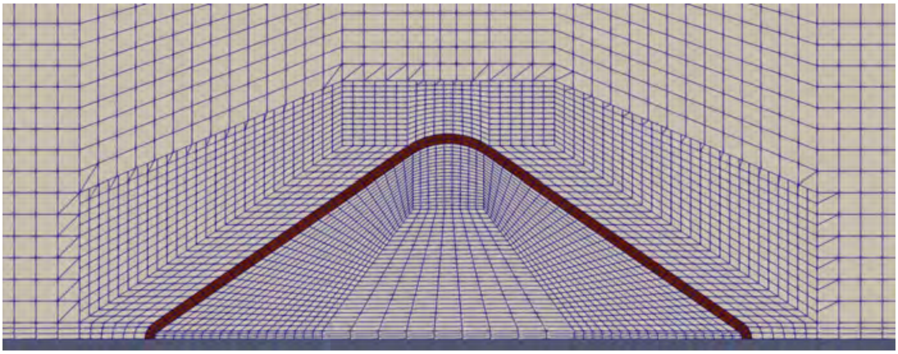


Figure 6 Mesh, focused on the clamp region. Coloured cells: cover region. Inside coloured cells: clamp region. Outside coloured cells: open region. Source: Paper IV, Figure 4.

In the finite volume approach, the model domain is divided up into small cells (Figure 6). The governing equations are also known as balance equations, as they state that for any given cell of the model, the mass of, momentum of, or energy in the fluid must remain in balance. Because of the assumption of an incompressible flow and the finite volume method, the equation for mass (Equation 1) says that the net rate of change in flow of velocity through the walls a cell in the *x*, *y* and *z* axes must equate to zero. The Nabla operator, ∇, symbolises the words "net rate of change ... along the *x*, *y* and *z* axes". It is here the divergence: the vector field equivalent of a derivative. If you were to think of one of the ventilation boxes shown in Figure 5, Equation 1 says that the total amount (mass or volume) of air flowing in through the pipe in the side wall (along the *x*-axis) must be equal to the total amount of air coming out the open top (along the *y*-axis). The equation for momentum (Equation 2) – which is the equation for airflow - states that the change in momentum over time will be equal to the net changes from convection, pressure, viscous forces, and any forces coming from within the volume. The equation for the temperature of the air (Equation 6) states that any changes in the temperature of the air over time will result from the convection of air, conduction within the air, and transfers between the sugar beet roots and the air. Finally, the equation for the temperature of the sugar beet roots (Equation 5) states that any changes in the temperature of the sugar beet roots over time will result from conduction within the roots, transfer between the sugar beet roots and the air, and from the heat of respiration. The transfer of temperature between the sugar beet root mass and the air depends on the surface area within the cell, the resistance of the surface to the transfer of temperature, and the difference in temperature between the air and the roots. The heat of respiration is defined to depend on the temperature of the roots. More formally, the governing equations are given as:

$$\nabla . U = 0 \qquad 1$$

$$\frac{\partial U}{\partial t} + \nabla(UU) = -\nabla p + \nabla \tau + S \qquad 2$$

where U is the vector for velocity, t is time, p is pressure, and τ is the convective stress tensor. The standard *k*-epsilon model of turbulence is applied. The source term is used in the porous medium approach to capture the loss of velocity that occurs as air moves through the porous bulk. The source term S is here defined as the Darcy-Forchheimer equation for a homogeneous porous media:

$$S = -\left(\mu D + \frac{1}{2}\rho U F\right) U \qquad 3$$

where D and F are scalars. The Darcy (D) component of the source term captures viscous loss and is linearly proportional to the velocity, while the Forchheimer (F) component captures the inertial loss and is proportional to the velocity squared.

It is assumed that heat transfer from radiation is negligible within the entire system. Heat transfer is assumed isotropic. Within the solid phase (the sugar beet roots), it is assumed that there is thermal equilibrium and no convection. The energy equations for the fluid (f) and solid (s) phases are given for temperature (T) as:

$$\varepsilon(\rho\ C_p)_f \frac{\partial T_f}{\partial t} + \ \varepsilon(\rho\ C_p)_f U. \nabla T_f = \varepsilon \nabla. \left(K_f \nabla T_f\right) - A_{sf} h_{sf} (T_f - T_s) \qquad 4$$

$$(1-\varepsilon)(\rho\ C_p)_s \frac{\partial T_s}{\partial t} = (1-\varepsilon)\nabla. (K_s \nabla T_s) + A_{sf} h_{sf} \left(T_f - T_s\right) + Q_r \qquad 5$$

As the fluid phase is turbulent, $\varepsilon(\rho\ C_p)_f$ can be given as α_{eff} (see Paper IV, Section 2.3.5). This allows Equation 4 to be stated as:

$$\varepsilon \frac{\partial T_f}{\partial t} + \ \varepsilon U. \nabla T_f = \varepsilon \nabla. \left(\alpha_{eff} \nabla T_f\right) - \frac{1}{\rho\ C_p} A_{sf} h_{sf} (T_f - T_s) \qquad 6$$

Where ε is porosity, ρ is density, C_p is specific heat, K is thermal conductivity, A_{sf} the specific surface area, h_{sf} is the convective heat transfer coefficient, and Qr is the heat of respiration. The parameters are summarised in Paper IV, Table 1 and expanded upon throughout Paper IV.

Model parameters were drawn from literature and new experiments. New data on the permeability (D and F) of the non-woven polypropylene cover used on sugar beet clamps employed an ISO standard laboratory testing procedure of the relationship between pressure and velocity of air through the material (Paper IV, Supplementary material, S1.2). New data on the dimensions of harvested sugar beet roots was sort to define A_{sf}. This employed a survey approach, coupled with a simple mathematical model of the root (Paper IV, Supplementary material, S2). A modified version of Qr was developed to better suit the physiology of sugar beet respiration (Paper IV, Supplementary material, S3).

The model was developed as a more efficient two-dimensional model as it was assumed that the loss of information in comparison to a 3D model would not result in a loss of understanding of the general phenomena under investigation. For discretisation to a numerical model, a second order linear-upwind scheme was applied to the velocity field, and first order linear or upwind schemes applied elsewhere. The model solution was validated against experimental data from previous research conducted by NBR during the 2011-12 storage period (Olsson, 2013a). A sensitivity analysis was conducted to explore how the model solution depended on key parameters around which there was uncertainty.

Open source software was deliberately used to ensure both that the model could be tailored as required, and that it is accessible to all. The model development process was incremental, with the first model included in the final publication being model clamp_43. Many of the first 42 models were refined and rerun without the allocation of a new model number. It was found that the model would gain accuracy and efficiency by having the momentum and the energy equations (air velocity and temperatures) solved separately. The momentum equation was solved first for a 90 second period to obtain a stable solution. This solution was then passed to the energy equation solver as fixed fields. The experimental data the model was to be verified against and the available weather data were in 15 minute intervals and thus the model also progressed in this increment. A somewhat unique feature of this model within the domain of modelling post-harvest storage systems was that the system is outdoors. The major feature this introduces is constant change in the direction of airflow. This was accommodated by creating a symmetrical model domain (Paper IV, Figure 3), taking the normal component of the air velocity as the inlet velocity, and by permitting the inlet and outlet of the model to swap for any progression of the model. Radiation is another phenomena that was considered as important in this environment, but it was ultimately not included in this version of the model.

3.2 Assessment

3.2.1 Quantifying quality

As described in Section 1.2, storability is assessed against quality. Sugar beet root quality was assessed in Papers I and III. For Paper I, assessment was made in the laboratories of the German national sugar beet research centre in Göttingen, Institute of Sugar Beet Research (IfZ-Göttingen). For Paper III, assessment was made at the Nordic Sugar factory at Örtofta, Sweden. Assessment was completed to the same International Commission for Uniform Methods of Sugar Analysis (ICUMSA) standards. Sucrose concentration was determined polarimeterically (ICUMSA Method GS6-3, (ICUMSA, 1994)), amino nitrogen content via the "blue number" (ICUMSA Method GS6-5), sodium and potassium content by flame photometry (ICUMSA Method GS6-7), and dry matter content via drying to a stable weight. In Paper I, total invert sugar content was assessed via glucose content, and alcohol insoluble residues (AIR) via alcohol extraction and filtration. Alcohol insoluble residues is a measure of the cell wall content of the root (van Soest et al., 1991). In Paper I, the marc content was also measured, via water and acetone extraction (Reinefeld & Schneider, 1983) and is described as an estimate of the pulp content of a sample.

In Paper III, additional metrics of quality were included. The final dirt-tare was assessed at Örtofta as the percentage of weight washed away during cleaning. The effect of ventilation on the weight cleaned from the roots post-ventilation was assessed as the loss of weight when the roots were put through a simulated cleaning (Paper III, Figure 4). The volume of the individual roots used in the calculation of changes to density was assessed by weighing the mass of water displaced during immersion.

3.2.2 Quantifying mechanical properties

The laboratory measurement of mechanical properties of sugar beet roots (Papers I and II) followed the method developed in Kleuker and Hoffmann (2019). This includes the three metrics of puncture resistance, tissue firmness, and compression strength. Puncture resistance and tissue firmness are both measured with a 2 mm diameter cylindrical probe (Figure 4c), inserted at a speed of 1 mm/s into an entire root at its widest diameter, to a depth of 5 mm. Puncture resistance is the maximum pressure recorded as the probe pierces the periderm of the root, and tissue firmness the average pressure from approximately 0.5 mm after puncture through to 5 mm (see example pressure-distance output from penetrometer in Figure 9). Compression strength is measured with a flat plate also moving at a speed of 1 mm/s, on an 18 mm diameter core taken from a 20 mm slice from the widest diameter of the root. In SS2, a laboratory penetrometer was used but only with a probe. The apparent modulus of elasticity in SS2 was assessed as the average slope of the curve to puncture. It is termed "apparent" as the elastic behaviour of the root is not actually allowed to express.

The assessment of the accuracy of the method adopted for the handheld penetrometer (Paper II) was made in relation to the laboratory equipment. The first test of the method was whether it gave the same general patterns. The statistical analysis focused on the correlation between the results from the two penetrometers. The efficiency of the handheld method was also an important consideration. This was assessed on the number of samples needed to find stable results, the variation in results between operators, and on the time it took to take the required number of samples. The application of the handheld penetrometer in Paper III followed the method developed in Paper II.

3.2.3 Measurement of dynamic impacts

In SS1, sugar beet roots were dropped from one meter onto a 10 mm thick smooth plastic plate sitting on a concrete floor. It was felt that dropping the root would give flexibility in adjusting the drop height, and would capture the actual force at impact and how it is distributed. The force of impact is measured as impulse:

$$\int_{t_1}^{t_2} F\,dt = m\Delta v$$

where: $t_1 = 0$, and is the point when the root makes contact with the plastic plate; t_2 is the time at which the downward movement of the root stops; m is the root mass; and Δv is the change in velocity during contact. Identifying t_2 was achieved with a high speed camera (960 frames per second, Samsung S10). Velocity at t_1 was calculated based on drop height and acceleration from gravity. Velocity at t_2 is zero, and therefore $\Delta v = v_{t_1}$. Mass was measured prior to the drop test. To translate the average force of impact to average pressure at impact, the area of impact was measured as a carbon paper transfer captured at impact (Figure 7) with image analysis conducted in Adobe Photoshop. The practicality of the method was assessed subjectively.

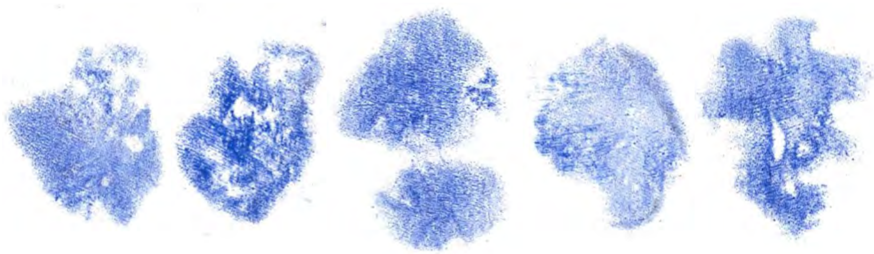


Figure 7. Examples of impact area from drop tests in SS1, captured with carbon paper. Also presented on Nilsson et al. (2020).

In SS2, the fall was inverted, with the root fixed in a bulk of sand and a 70 mm diameter, 1.4 kg steel ball dropped on the root from a height of 0.93 m (Figure 8). The impact site was assessed for level of visible surface damage on a scale of 0-5, with 0 equal to 0 % visible damage and 5 equal to 100 % of the impact site showing damaged cells. The number and total length of cracks was measured from the centre of the impact site. Force and pressure measurements were not taken.

(a) (b) (c)

Figure 8. Falling-ball test (SS2). Steel ball approaching root (a) and at point of impact (b), and the root after impact (c) showing cracks and contact point damage. Images (a) and (b) are frames taken from high-speed camera during fall.

3.2.4 Modified environment conditions

The temperature and humidity of the modified atmosphere system (Paper III) was controlled with a commercial greenhouse climate control unit. Measurement of temperature and humidity was with one Hobo Pro v2 logger per airflow rate, placed in one of the boxes attached to the secondary distributors. Airflow rates were set and regularly verified using grid sampling in the inflow pipe to the secondary distributors (orange pipes in Figure 5). A Testo 405i hot wire anemometer was used.

3.2.5 Mass transfer, water vapour deficit, convective mass transfer coefficients, diffusivity

In the modified atmosphere experiment (Paper III), the rate of mass transfer was reported as mass flux, $\dot{m}_w$ [mol/m^2/s]. Mass flux was taken as

$$\dot{m}_w = k_c \Delta c \qquad 7$$

where k_c is the convective mass transfer coefficient and Δc is the water vapour deficit. Mass flux was calculated as weight loss per unit surface area and time, with weight loss taken from the experiment and assumed to be just water. The surface area calculation assumed a spherical object. The diameter of this sphere was calculated via volume, which was taken as (weight of total sample) ÷ (roots per sample) ÷ (density as described in Section 3.2.1). The level of contact between the roots in the sample was not considered. Water vapour deficit was calculated using Tetens equation (Monteith & Unsworth, 2008), with the water activity of the roots taken as 98.5 % (Chirife & Fontan, 1982). The convective mass transfer coefficients calculated from the experiment were compared to estimates from dimensional analysis, using the Sherwood-Reynolds-Schmidt correlation (Carta, 2021b):

$$Sh = \frac{k_c L}{D_{ab}} = 2 + 0.552 Re^{0.5} Sc^{0.33} \qquad 8$$

where: L is the characteristic length [m] calculated as diameter via weight, density and the assumption of a sphere; D_{ab} is water diffusivity [m^2/s]; Re the dimensionless Reynolds number; and Sc the dimensionless Schmidt number. Estimates of D_{ab} were taken from the airflow rate 0 samples. Re is dependent on airspeed.

3.2.6 CFD model functionality and accuracy

Assessment of the functionality of the CFD model was based on its ability to operate without error, its speed, and inspection of the time series to assess if it behaved as expected. All parameters in the CFD model were recorded at 15 minute intervals at points in the clamp region of the model of equivalent location to the temperature loggers used in the original 2011/12 experiment. Assessment of the accuracy of the CFD model was based on the mean absolute error (MAE) of the recorded temperature time series in comparison to the experimental series. Further checks on the system of solvers were run. Mesh independence was tested on a mesh of approximately half (2688 cells) and approximately double (10752 cells) the number of cells in the mesh used in the analysis (6123 cells). Testing of the stability of the airflow field at points in the open air region was conducted to understand if there was the potential to improve the efficiency of the system of solvers and the 90 second time period applied in the solving of the momentum equation (Paper IV, Supplementary material, Figure S4.1).

3.2.7 Economic analysis

A single economic analysis was conducted in this research project. The impact of ventilation on the gross income per harvested tonne was assessed in Paper III using the commercial payment schedule from Sweden's single processor for 2021.

4. Results and discussion

4.1 Plant health and the long-term post-harvest storage of sugar beet roots

4.1.1 Agronomic inputs and storability

Quality

The assessment of the impact of agronomic inputs on the storability of sugar beet roots (Paper I) showed that the available water during the growing seasons had a large effect on the changes to quality of roots during post-harvest storage. The accumulation of invert sugars and the loss of sucrose during post-harvest storage approximately doubled for the optimum water availability treatment (Paper I, Figure 2 E-F). The availability of N during the growing season had no effect on the rate of change in quality of roots during post-harvest storage. This study had the underlying assumption that differences in changes to quality during post-storage between the agronomic treatment levels would be a result of differences in mechanical properties and thus mechanical damage.

Mechanical properties

Paper I showed that the level of nitrogen available during the growing season only has a minor negative impact on the mechanical properties of sugar beet roots (Paper I, Figures 1 A-B). The available water during the growing season had a statistically significant ($\alpha = 0.05$) but minor effect. The plants with optimal soil water availability over the duration of the growing season had higher puncture resistance and tissue firmness in comparison to the plants that were wet during the last month prior to harvest and the no supplementary water control (Paper I, Figures 2 A-C). The differences in mechanical properties were mainly between varieties and environment, where environment is a combination of site and year (Paper I, Table 2). This is a common finding in the examination of mechanical properties in sugar beet (Kleuker & Hoffmann, 2020, 2021, 2022). As nitrogen and water are two of the major agronomic inputs to the sugar beet crop, Paper I suggests that if a management goal is to ensure high values for mechanical properties, then agronomic inputs in a given growing season are likely of little consequence. Choice of variety is much more important. The variation in mechanical properties attributed to environment in Paper I is important to note, primarily because it is not a very descriptive category as it includes all the variation that occurs between sites. This includes historical management and soil properties. This suggests that exploration into the mechanisms behind variations in mechanical properties beyond variety has potential.

Similar results for the relationship between growing season available water and the mechanical properties puncture resistance and tissue firmness were found in the falling-ball experiment (SS2). Here the roots from plants that were irrigated during the last month did have a puncture resistance lower than that from the roots with additional water excluded during the last month (*roof*), but were not different from the control treatment (Figure 9 and Table 2). No differences in tissue firmness were seen. The apparent modulus of elasticity for the irrigated roots was different from the other two agronomic treatments, resulting from the combination of lower puncture resistance and a greater distance to puncture. This suggests that well irrigated roots may suffer from less damage from a given impact (Ruiz-Altisent, 1991), but also be more difficult to slice at processing (Vukov, 1977).

Table 2. Mean mechanical property values from falling-ball test in SS2. Number of observations per treatment = 40. Letters indicate significant groupings from post-hoc Tukey test.

Treatment	**Puncture resistance** [MPa]	**Tissue firmness** [MPa]	**Distance to puncture** [mm]	**Apparent modulus of elasticity** [MPa/mm]
Irrigated	5.83[a]	5.12[a]	1.51[b]	3.93[b]
Untreated	6.07[ab]	5.35[a]	1.43[ab]	4.27[a]
Roof	6.17[b]	5.31[a]	1.39[a]	4.47[a]
Ventilated	6.14[b]	4.81[b]	1.76[c]	3.51[c]

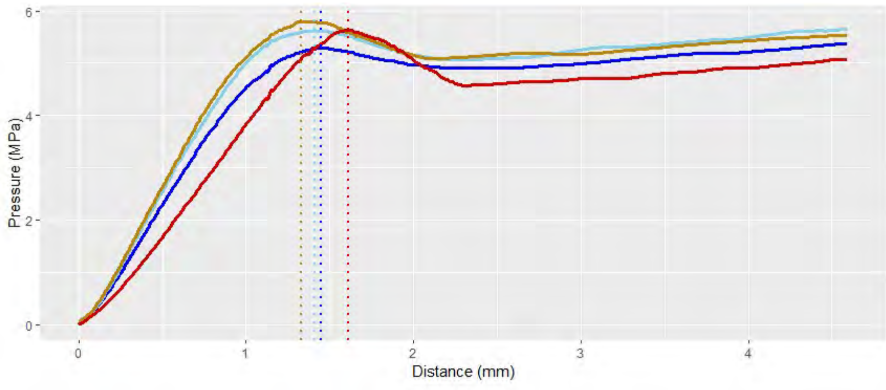


Figure 9. Mean pressure by distance by treatment from laboratory penetrometer in SS2. Blue line: irrigated, Brown line: roof, Turquoise line: untreated, Red line: ventilated. Peak pressure is puncture resistance. Vertical lines indicate distance at puncture. Mean of the tail of the curve is tissue firmness. Number of observations per treatment = 40.

Mechanical damage

Paper I showed that neither the level of nitrogen nor water available during the growing season effected the rate of mechanical damage to the roots prior to post-harvest storage, measured as root tip breakage (Paper I, Figures 1D and 2D). Given the small differences in mechanical properties, this fits within the expectations of the study. The falling-ball test (SS2), measuring damage as cracking and contact point surface damage, concurred the results for the late season water availability treatment in comparison to the control treatment of no supplementary water (Table 3).

Table 3. Mean rates of damage from falling-ball test in SS2. Number of observations per treatment = 40. Letters indicate significant groupings from post-hoc Tukey test.

Treatment	**Surface damage** [0-5]	**Cracks** [count]	**Cracks** [cm]
Irrigated	1.50^{a}	1.25^{a}	8.64^{a}
Untreated	1.25^{a}	1.18^{a}	5.61^{a}
Roof	1.49^{a}	1.08^{a}	6.90^{a}
Ventilated	0.80^{b}	0.03^{b}	0.13^{b}

Other health dimensions and agronomic inputs

The focus of Paper I was on mechanical properties and a single level of mechanical damage. These two dimensions of plant health were not able to explain the observed differences in storability under constant post-harvest storage conditions. It stands to reason then that the link to loss of quality for the agronomic input of available water during the growing season is through a different dimension of plant health. In Paper I, the possible explanation of an increased disease load was given. The suggestion was that the creation of the optimum soil water conditions for plant growth also created optimum conditions for the growth of the soil borne pathogen *Aphanomyces cochliodes*: a high incidence of secondary aphanomyces infection was observed in the field trial (Figure 10). This was not quantified, but the disease was so widespread in the field in 2018 that the section of the plots sown for yield and dirt-tare analysis had to be harvested with the section that was sown for mechanical property and post-harvest storability analysis, so as to ensure enough roots of a normal form could be sources. There was evidence of the disease in 2019, but not to the same extent. This plant disease hypothesis is supported by the findings of Campbell and Klotz (2006). It also aligns with the recommendation in Sweden to only store roots from healthy plants.

Figure 10. Examples of the secondary Aphanomyces infestation in the field at harvest, Paper I, 2018.

The accumulation of invert sugars in the roots from the optimum water availability treatment also suggests the disease dimension of plant health is a likely mechanism (Campbell et al., 2011; Kenter et al., 2006). It was not reported in Paper I, but there was a large increase in mould formation within this treatment during post-harvest storage. In the first year of the trial, approximately 25 % of roots from the optimum water availability treatment scored 2 or 3 on a 0 to 3 scale of mould infestation, while it was less than 5%

for the control and wet during the last month prior to harvest treatments (see Kleuker and Hoffmann (2020) Figure 7B, *NBR*). It is not clear whether this increase was a result of an increased pre-harvest disease level, or greater harvest damage on a dimension that was not quantified.

Two other interesting findings from the work within this COBRI project support the conclusion in Huijbregts et al. (2013) that more work is needed around the pre-harvest factors driving root health and quality loss during post-harvest storage. The roots from the Netherlands repeatedly returned rates of loss of sucrose during post-harvest storage beyond those that could be expected from their appearance. The roots were generally very clean and entire, but rates of loss were the highest of all countries. This has again been observed in the collaboration's work on virus yellows.

The second observation was from exploratory work using roots taken from a field in Sweden with a liming trial. Roots from sections of the field where the equivalent of 8 t/ha CaO was applied six years previous were compared to roots from sections that had no lime at that time. The mechanical properties showed no difference at all, but the rates of sucrose loss during post-harvest storage were slightly more than double for the roots from the control section of the field. This work is unpublished. Given calcium is an important element in the formation of cell walls (Marschner, 2012), it was expected that the mechanical properties would test higher for the roots from the limed sections of the field. That this was not observed means a different dimension of plant health has to be considered. A possible explanation is again in the soil microbiology. Lime, especially at such a high rate, is expected to have a sanitising effect on the soil, reducing the prevalence of pathogens such as *Aphanomyces cochliodes* (Huijbregts et al., 2013) or some other unspecified disorder (Wills et al., 2007b). Alternatively, it may have changed the distribution of the soil microbiology, permitting more of the beneficial microbes like those reported by Molin (2022) to flourish. The possibility that the effect of lime on the soil structure lead to lesser rates of surface damage should also be considered.

The inclusion of the treatment of the available water during the growing season in the COBRI project that gave Paper I was a result of discussions with growers where they had observed high rates of quality loss during post-harvest storage from sugar beets that were irrigated and grown in sandy soils. This work has shown that the available water dimension cannot be excluded in the examination of sugar beet root storability, but it has also shown that the soil, and the interaction between available water and the soil, needs greater attention.

Assessment of mechanical properties

The assessment of a method for use of a handheld penetrometer in the sugar beet crop (Paper II) showed that the handheld penetrometer was able to provide a reliable assessment of the tissue strength of sugar beet roots. It was very successful in ranking varieties, finding the same patterns for firmness as those found by the laboratory penetrometer for puncture resistance and tissue firmness (Paper II, Figures 2). The ranking of varieties with the handheld penetrometer was also shown to be stable across years in the Swedish national variety trials (Paper II, Figure 6). The handheld penetrometer has a much lower capital cost than the laboratory equipment. Sampling is quicker, with a sampling rate of double the laboratory equipment. It can be applied when the roots are still growing in the field, avoiding the need for extra research plots and the transport of material. It can also be applied well before harvest, permitting earlier reporting of results. A well-documented issue with handheld penetrometers is the inter-operator variability (DeJong et al., 2000; Harker et al., 1996). While this did not appear as an issue in Paper II (Paper II, Figure 5), the paper would have benefited from a greater formal investigation of these differences between operators. Clear operating procedures and training of the operators was noted as a critical component of the application of the handheld penetrometer.

Defining the analogous laboratory metric to the handheld penetrometer in Paper II was quite interesting. The handheld penetrometer records only the maximum force during each sample. Using the instrument with a sampling depth of 5 mm, it appears that this maximum is when the probe punctures the periderm. This suggests that puncture resistance will be the metric from the laboratory penetrometer that is most similar. On analysis of the results, however, it appeared the values more closely mirrored the tissue firmness measurement of the laboratory penetrometer (Paper II, Figure 3 & 4). There was also a conflict with the nomenclature. Abbott (1999) notes that the values obtained from a handheld penetrometer are commonly referred to as firmness and have been for most of the approximately 100 years of the use of the device. However, in Paper II it was felt that this would conflict with the term tissue firmness from Kleuker and Hoffmann (2019) and thus the term handheld pressure was adopted. In Paper III, free from this direct conflict, the term firmness is used.

The major limitation of the handheld penetrometer is that it only records a single metric. This is of particular importance to note when an application is outside the scope of known applications. The difference in results between Paper III and SS2 is an example of this. In Paper III, the handheld penetrometer was not able to find differences in firmness in any dimension. This was an a-priori expectation, but this expectation changed during the experiment owing to the tactile observations of a rubbery feel to the roots with high weight loss from ventilation. It was this observation that lead to the supplementary study SS2. Differences in mechanical properties using the laboratory penetrometer were subsequently found in SS2.

The apparent modulus of elasticity

The rubbery feeling observed from roots with high weight loss in Paper III was investigated in SS2. The results showed that the puncture resistance of the roots that had been exposed to the ventilated treatment - a treatment similar to the highest airflow treatment of Paper III - was not different to the untreated roots or roots grown under a roof for 56 days prior to harvest (Table 2 and Figure 9). At the same time, tissue firmness, the apparent modulus of elasticity, and the rates of damage where all much lower. A single short crack was observed from the 40 roots from the ventilated treatment, while there was on average more than one crack per root for the other three treatments. It is not possible to say that the difference in damage is more closely related to the tissue firmness or the apparent modulus of elasticity. Indeed, it is reasonable to expect that these two metrics are highly correlated given they relate to the ability of the cells structure within the root to move (Ruiz-Altisent, 1991). The results do suggest that it should be explored if the apparent modulus of elasticity should be included in an expansion of the standard methodology from Kleuker and Hoffmann (2019). This is particularly so given the required data is already available from the laboratory equipment, and that elasticity has been identified as an important mechanical property in relation to slicing of roots at the factory (Vukov, 1977).

Dynamic impacts

The first fall test with the falling-beet (SS1) was not able to find differences in impact force or pressure between the three varieties used in Papers I and II (Table 4). It is likely that neither the sample size nor the resolution of the measurements was sufficient. The high speed camera progressed in increments of 1.04 milliseconds, and the average impact time was approximately 3.5 milliseconds - a similar value to that found for dynamic impacts on sugar beet roots in Kołodziej et al. (2023). When the method was applied to roots of different sizes, significant differences were found for all metrics (Table 4). From a drop height of one meter, large roots had an average impact pressure of 1.3 MPa compared to 2.2 MPa for the small roots. This somewhat counter-intuitive result stems from the larger momentum at impact being spread over a longer time and a larger area of impact.

Table 4. Mean results of drop test in SS1. Sugar beet roots dropped from a height of one meter, with impact at widest point of root. No differences between varieties were significant at $\alpha = 0.05$. All differences between root size were significant at $\alpha = 0.05$.

Parameter		**Variety**			**Root size**		
		1	2	3	Large	Small	Ratio
Weight of root	[kg]	0.98	1.10	1.06	2.56	0.90	2.8
Time of impact	[ms]	3.7	3.4	3.3	5.3	3.1	1.7
Impact force	[N]	1219	1419	1427	2217	1317	1.7
Impact area	[cm2]	6.3	9.6	6.9	19.4	6.2	3.1
Impact pressure	[MPa]	1.9	1.5	2.1	1.3	2.2	0.6
Observations		15	15	15	30	30	

The falling-beet test (SS1) was developed in response to discussion about how the size of a sugar beet root would affect rates of damage and thus storability. It was clear that a greater mass would result in greater kinetic energy for a given fall height, but not how this greater energy would affect rates of damage. The results from this supplementary study suggest that larger roots are likely to have less damage. This result must be qualified with reference to the method, in which the roots were dropped on their sides with the impact at the widest diameter of the root.

Root size

Other insights have been gained from this research project on the role of root size and the damage caused by dynamic impacts beyond those associated with the assessment of mechanical properties. As part of the data collection for the modelling of the specific surface area (A_{sf}) of sugar beet roots for the CFD modelling of clamp airflow and temperature (Paper IV), surface damage was also assessed. The results suggest that damage to the surface per unit of surface area increase with root size (Table 5). These results do not include tip breakage and top scalping area. Further, it must be remembered that assessing surface damage is notoriously difficult.

Table 5. Relationship between root size and surface damage. Source: field work from Paper IV. SA = Surface area.

Root size	Weight per root	SA per root	SA per gram root	Damage to surface	Damage to surface	Damage per gram root	Obs.
	[g]	[cm^2]	[cm^2/g]	[cm^2]	[%]	[cm^2/g]	[n]
Small	641	371	0.58	5.2	1.4	0.008	80
Random	1390	632	0.45	19.0	3.0	0.014	120
Large	2650	958	0.36	34.3	3.6	0.013	80

Fall-test usability

The method used in the falling-beet experiment (SS1) was developed as it gave a controlled simulation of the impact identified as the largest in the commercial setting: a fall (Steven Aldis, (BBRO, England) 2018-07-11, personal communications). The second fall test, the falling-ball test (SS2), was developed in response to the difficulty in the method of the falling-beet test to control the impact site. The root often rotated and missed the desired point of impact: a problem also experience by Wilczek et al. (2020) in their project that similarly involved the controlled dropping of sugar beet roots. It was also not possible from the falling-beet test to assess the rate of damage from a fixed impact given the force at impact varied with the root weight.

Force and pressure assessment was only conducted with the falling-beet test, but could be applied to the falling-ball method. There was a relatively large data analysis component in assessing force and pressure from a dynamic impact. This could be improved with more automated systems for image analysis, but that would likely also be costly. The use of digital pressure mapping tools (Tekscan T-Scan system) was explored in the falling-beet experiment, but the temporal resolution was not sufficient to ensure the full force profile would be captured.

Sampling with the falling-ball method without the measurement of dynamic forces was able to proceed at the same speed as the sampling with the laboratory penetrometer. There is no reason to suspect the falling-beet test without force assessment would be slower. Both methods require the diversion of material in the same manner required for assessment with the laboratory penetrometer and thus it is simple to pair the assessments.

The two fall-test methods have their use cases. The falling-beet method simulates the actual commercial situation with a fixed fall height and the energy at impact being in relation to the size of the root. The falling-ball method permits the application of a constant dynamic force, simulating a root sitting in the pile or being struck by a piece of machinery. Both methods have the ability to link static mechanical properties, dynamic response to impact, and rates of damage from dynamic impacts at the level of the individual root.

4.2 Storage environment and the long-term post-harvest storage of sugar beet roots

4.2.1 Moisture and mass transfer

Quality and moisture

The modified environment experiment (Paper III) found that it was possible to use ventilation to manipulate sugar beet root quality. It showed that a short, intense period of forced ventilation could result in large increases in the sucrose concentration in roots while not having a negative impact on the quality traits of the concentration of amino nitrogen, potassium, or sodium, or on the dirt-tare or puncture resistance of the roots (Paper III, Figure 6 and Table 3). An increase in sucrose concentration of 16.6 % (3.0 pp) was observed under the most extreme conditions (Run 2, Air 7, Days 7). A decrease in sample weight concomitant with the increase in sucrose concentration was observed (Paper III, Figure 6). The weight loss observed under the most extreme conditions was 13.5 %. This weight loss and the corresponding increase in sucrose concentration was attributed to the dehydration of the roots: no decreases in total sucrose were observed (Paper III, Table 3).

Paper III had a clear focus on a short and intense period of forced ventilation. The application of the results beyond the scope of the research is not recommended. If a system was implemented to deliberately increase quality through dehydration, it would ideally occur directly before delivery and processing. This could be at the end of a period of long-term post-harvest storage. Higher loss of quality is expected from dehydrated sugar beet roots during long-term post-harvest storage (Lafta & Fugate, 2009). Forced ventilation could also decrease clamp temperature and thus rates of wound healing at the start of a period of long-term post-harvest storage (Fugate et al., 2016). It was not possible to assess invert sugar levels in this study owing to a technical failure in the laboratory and as such the question of the impact of intense ventilation will have on this quality trait remains. It can, however, be expected that no significant changes will occur given both the findings of Lafta et al. (2020) and that the lack of change in total sucrose suggests respiration is not adversely impacted. The potential impact of dehydration on processing should also be considered. The previously mentioned rubbery feel to roots from the higher airflow treatments in the modified atmosphere experiment (Paper III) and the increased elastic behaviour of the roots in the falling-ball supplementary study (SS2) suggests the dehydrated roots will be more difficult to slice at processing (Vukov, 1977).

The commonly quoted airflow rate in ventilated piles of 20 cfm per ton (Backer et al., 1979; Downie, 1950) is equivalent to approximately 0.037 m^3/h/t, or about one-tenth the Air 1 rate of Paper III. No field data is available on the rate of airflow in clamps under natural ventilation. The solutions from the CFD modelling of airflow (Paper IV) for the uncovered clamp suggests that the air speed was about 0.44 m/s under the first layer of roots, and 0.40 m/s in the middle of the clamp when the wind speed was the average of the long-term post-harvest storage period in Sweden of 4.5 m/s. In the relative airflow level treatments of Paper III, this is would be treatment level Air 12. This suggests that the average airflow in a clamp may be sufficient to drive considerable dehydration of roots during storage. This is yet to be verified. It is also subject to the practicalities of commercial operation in the field in which the airflow is variable, rainfall occurs, and where covers are used.

Mass flux

The relative rates of mass flux in the controlled environment experiment broadly followed expectations. Mass flux will be greater with a greater water vapour pressure deficit and thus, given Tetens equation and the assumption of thermal equilibrium in the system, at higher temperatures (Monteith & Unsworth, 2008). It would therefore be expected that in Paper III Run 1 and 4 would have the lowest mass fluxes, followed by Run 2, 3 and 5 (Paper III, Table 1). With some error, this is the pattern observed (Paper III, Table 4). It is also possible to compare runs with the same mean temperature and different mean relative humidity (Run 3 and 4), or runs with the same mean relative humidity and different mean temperature (Run 2 and 4), and see that the relationships between mass flux and temperature and humidity codified through Tetens equation (Paper III, Equation 3. Monteith and Unsworth (2008)) hold. The relationship between mass flux and air speed is codified in the Reynolds (*Re*) component of the Sherwood-Reynolds-Schmidt correlation (Equation 8 or Paper III, Equations 5 and 6). The four airflow rates of the modified atmosphere experiment had relative levels of 0, 1, 4, and 7. In the Sherwood-Reynolds-Schmidt correlation, the square root of Reynolds number is taken: $Re^{0.5}$. This suggests that the ratio of convective mass transfer coefficients, k_c, and thus mass flux in the experiment will be 0.0 : 1.0 : 2.0 : 2.6. These ratios are similar to the weight loss and mass flux observed (Paper III, Figure 5 and Table 4).

The modified atmosphere experiment was developed early in this research project with the intent to focus on the quality aspects of ventilated post-harvest storage. Its value as a work in the field of fluid dynamics and mass transfer was not realised until after the completion of the experiment. Had the initial focus been mass flux, defining diffusivity of water, and verifying the Sherwood-Reynolds-Schmidt correlation, it is likely a different experimental design would have been adopted. Most studies on mass flux in post-harvest storage systems are in highly controlled environments and measure single fruit (eg Caleb et al., 2013; Mahajan et al., 2008; Xanthopoulos et al., 2014; Xanthopoulos et al., 2017). This study would have benefited from greater control of the experimental environment, but the measurement of weight loss in a bulk hopefully gives a set of results that are practicable in the modelling of the commercial post-harvest storage system.

Modelling mass transfer

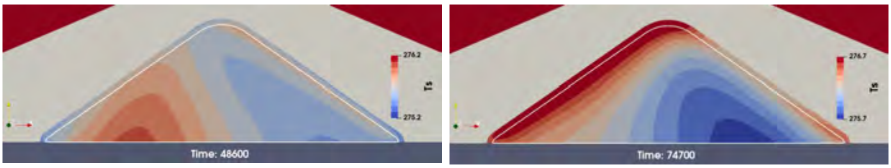
The results of the modified atmosphere experiment (Paper III) can be used in the modelling of mass transfer in a similar way that temperature and heat transfer has been modelled using Computational Fluid Dynamics (Paper IV). The convective mass transfer coefficient, k_c, is required to model the transfer of water from sugar beet roots to air. The Sherwood-Reynolds-Schmidt correlation can be used to compute estimates of k_c in the presence of a variable airflow, using an estimate of the diffusivity of water of the system and known properties of air (Carta, 2021b). Paper III found an average diffusivity of water of 2.43 E-05 m^2/s for commercially harvested sugar beet roots ventilated in bulk, under experimental conditions. It also showed that the Sherwood-Reynolds-Schmidt correlation was sufficiently accurate in providing estimates for k_c under the relatively high airflow conditions of the experiment (Paper III, Table 4).

Accurate modelling of mass transfer would be beneficial in the assessment of long-term field storage as it could help the understanding of changes to quality through changed sucrose concentration. It could also make estimates of temperature more accurate. The role of the heat of evaporation in heat transfer in bulks of sugar beet roots has been suggested as significant (Cannon, 1950; Zavrazhnov et al., 2021). Accurate modelling of mass transfer is also needed to understand the economics of long-term post-harvest field storage. The assessment of the gross income per harvested tonne in the modified environment experiment showed that a short duration, high airflow forced ventilation would lead to higher payments of up to 9.7 % (Paper III, Figure 8). This was primarily a result of the increased sucrose concentration being more highly valued than the loss in the mass of processable material. The design of the price model in Sweden is to pay for total sucrose and incentive quality. The results of the economic analysis reflect this. This assessment was only possible as the weight loss was known. Comprehensive data on rates of weight loss in sugar beet roots during long-term post-harvest field storage is difficult to find. Modelling mass transfer with the results of the modified atmosphere experiment (Paper III) can help fill this gap.

Any modelling of the transfer of water in a sugar beet post-harvest store would need complementary field research. Field research could focus on the transfer of water as weight loss from the roots as a bulk. Aggregate data would support the economic analysis. Preferably, field research would assess weight loss from the roots across the profile of the store. It would ideally include methods that capture the movement of moisture from, and back to, the soil attached to the roots. Paper III suggests that the transfer of water from this attached soil was relatively much quicker than from the roots, especially under high airflow conditions (Paper III, Table 3). It is also known that the water in this soil has large impacts on quality as dirt-tare (Mårtensson, 2017). The open environment in which clamps exist exposes them to rainfall, which would lead to re-hydration of surface attached soil. The permeability to air of the cover most commonly used on clamps - non-woven polypropylene fleece - was tested in Paper IV. Similar laboratory testing would be needed for permeability to water, including how this changes with duration of rainfall. Another challenge in modelling the transfer of water is in capturing the observed phenomena of condensation at the edges of clamps when covered with plastic. In addition to weight loss, surface moisture, and condensation, monitoring of the airflow would be highly recommended. The estimates of k_c from the Sherwood-Reynolds-Schmidt correlation depends on air speed, and as seen in the CFD modelling of temperature (Paper IV), validation of the air velocity field in sugar beet bulks is required.

4.2.2 Temperature and heat transfer

The modelling of temperature in a sugar beet clamp (Paper IV) was deemed as successful. The model successfully captures the general trends of heat transfer, in that the solution for temperature follows the general trends of the experimental data. This model is the first that gives insight to the variation within a bulk of sugar beet roots while giving consideration to the fluid dynamics inside of the bulk. The rate of variation of temperature in the experimental data showed strong correlation with air speed and the model was able to capture this, with more rapid change in temperature with increased inlet air speed normal to the clamp (Paper IV, Figures C1-C6). The work of Tabil, Kienholz, et al. (2003) was extremely important in this endeavour: this was the only source of experimental data on the fluid dynamics of sugar beet bulk known to exist. The results of the model suggest that taking temperature from a single measurement point is not sufficient to capture the true distribution. For Figure 11a (Paper IV, Figure 6a), the experimental temperature sensors at 0.5 and 2.0 m from the top of the clamp on its central axis, read the same temperature. Variation through the clamp is still evident. For Figure 11b (Paper IV, Figure 6b), the difference between the same sensors is at its greatest point in the first 100 000 seconds of the simulation. Even then, there is variation within the clamp beyond this range.



(a) (b)

Figure 11. Example distributions of temperature of sugar beet roots (T_s) from simulation of an uncovered clamp. Baseline Series, Period 1. Clamp and Cover region shown. Colour scale intervals of 0.1 K, range 275.65 K to 276.65 K. Source: Paper IV, Figure 6

The model appeared to be operationally sound. The mesh independence test showed that the mesh of 6123 cells was sufficient (Paper IV, Figure B1). The solutions did not appear to show nonphysical results. It was able to progress at speeds well above real time, with the most computationally demanding time period (highest average inlet velocity) progressing at approximately six simulation seconds per clock second.

Quality and temperature

The relationship between temperature and quality of sugar beet roots is very important in the long-term post-harvest storage of sugar beet roots. Its importance was an underlying assumption of the CFD modelling (Paper IV), it was the rationale for the innovation project focused on force in-field ventilation that this research project was developed alongside (Ekelöf & English, 2022), and it was given a lot of attention in the literature review conducted as part of this research project (English, 2020). There is, however, very little new insight to this relationship as a result of this project. The modified atmosphere experiment (Paper III) did show that higher temperatures lead to more rapid mass flux and thus potentially more rapid changes in quality, and while possibly a novel finding for the sugar beet crop, it is a relationship already codified in Tetens equation as used to estimate water vapour pressure deficit.

One aspect of the relationship of quality to temperature that has repeatedly been considered during this research project is the difference between the temperature of the fluid air and the temperature of the solid roots. It is an important distinction but it is often difficult to explicitly know which temperature is being discussed in the available literature. The majority of research has focused on the temperature of air, usually ambient air (eg Jaggard et al., 1997; Legrand & Wauters, 2012), presumably primarily because this is much more simple to assess. It is also likely that it is sufficiently accurate. Some applications in the assessment of clamp temperature only require a single temperature input. This includes the estimation of the heat of respiration. The small but consistent difference between the air temperature and the temperature of the root found in the CFD modelling (Paper IV, Figure S5.1) suggest that while the use of air temperature is likely sufficient, the use of root temperature would be more accurate. Other applications require that both the air and root temperature is known. This includes the modelling of heat transfer between roots and the air over a temperature difference, as done in the CFD modelling (Paper IV), or the application of Tetens equation when thermal equilibrium between the air and the root is not assumed. The next level of complexity is then to remove the assumption of thermal equilibrium within the root, as applied in Paper IV. It is likely here that the same team of researchers that made it possible to include convection in the CFD modelling of clamp temperature - Tabil, Kienholz, et al. (2003) - will hold the key. Their 20 year old research on sugar beet thermal properties - Tabil, Eliason, et al. (2003) - plus the rates of cooling reported in the NBR supervised student project Skyggeson (2016), will be invaluable.

Areas for improvement for the temperature model

The solution from the model lags the experimental results (Paper IV, Figures 5 and C3). This is particularly so at the edges of the clamp region. Steps to improve the accuracy of the model could initially include testing changes to the porosity in the edge zone, in line with this zone being the interface with the open region. Any improvement of the model at the edges will likely have flow-on consequences to the rest of the solution, likely reducing the lag the model experiences. It would also be important for the application of the model in Sweden, where loss of material in clamps from frost occurs first at the edges. These modifications should be tested with new, high quality field data for temperature and airflow. The model has been developed without validation of the airflow fields. The collection and analysis of field data on airflow rates within the clamp is required to iterate the model with confidence.

This model was always meant to be a foundation for further development, in the knowledge that important components of the system were absent from this first version. The main shortcomings noted in Paper IV include the exclusion of the thermal properties of soil, of natural convection, and of radiation. The 'chimney' effect of heat escaping out the top of a clamp is often raised in discussions about the use of plastic covers on clamps (Olsson, 2013b). This phenomena does not seem to occur when a non-permeable cover is included in the model. This specification was tested subsequent to the submission of Paper IV. The inclusion of buoyancy in the model, for example through the Boussinesq approximation, would likely see this phenomena occur (Carta, 2021a). In another test subsequent to the submission of Paper IV, the model has been tested against a long period of freezing temperatures in December 2022. This period was accompanied by very low or zero air speeds. When this weather data was applied to the model, it showed that the inlet air temperatures were not able to flow into the model domain as they likely should. No such scenarios with long periods of zero airflow were tested in Paper IV, so this issue was not highlighted then. As noted in Section 4.2.1, to further improve the accuracy of heat transfer within the CFD model, it may be necessary to include mass transfer of water in the system.

5. Conclusions

This thesis addressed issues related to the long-term post-harvest field storage of sugar beet roots. It was guided by the context of Swedish agriculture and the applied research environment it was born in. Two principles of long-term post-harvest storage of sugar beet roots were proposed; healthy sugar beet roots store better than unhealthy roots, and sugar beet roots store better when held within an optimal environment. With respect to plant health pre-storage, this thesis has shown;

- Growing season available nitrogen does not have a significant impact on the mechanical properties of sugar beet roots, nor their storability.
- Growing season available water does not have large impacts on mechanical proprieties of sugar beet roots, nor rates of damage at harvest. It can have an impact on quality loss during storage, which seems to be through an interaction with an unspecified dimension of plant health.
- A traditional handheld penetrometer is a viable tool for assessing the mechanical properties of sugar beet roots. It has benefits and drawbacks that should be considered in its adoption.
- The assessment of mechanical properties outside of the current standard methodology, such as responses to dynamic impacts and the apparent modulus of elasticity, is valuable to consider.

In the context of rapid turn-over of varieties and high capacity mechanical harvesting, the assessment of mechanical properties will remain valuable. Assessment of mechanical properties is an efficient means of assessing likely rates of damage and the consequential loss of quality during post-harvest storage. As noted in Paper II, the method for the assessment of mechanical properties of sugar beet roots described in Kleuker and Hoffmann (2019) remains the gold standard. This thesis suggests that the metrics included in this method should not be taken as the only metrics to consider. This thesis has also reinforced that mechanical properties are not the only dimension of plant health that matters for post-harvest storage of sugar beet roots. There remained a high degree of variation in storability related to the growing site. The suggestion was made that NBR might need to get back to its roots (pun intended) and again have a major focus on soil assessment, including both physical properties and the biological aspects.

With respect to the optimum post-harvest storage environment aspect of successful long-term storage of sugar beet roots, this thesis has shown;

- The deliberate dehydration of sugar beet roots during post-harvest storage with short duration, high airflow ventilation can improve quality and lead to increased gross income. It can also have negative impacts on mechanical properties.
- The dehydration of roots within a sugar beet post-harvest storage system is predictable and could be modelled.
- The temperature of roots within a sugar beet post-harvest storage system is predictable and possible the model. The inclusion of airflow within the bulk of roots is important.
- Further development of the understanding of fluid flow and heat transfer within the post-harvest storage system through further field experimentation would improve the accuracy and applicability of the model developed in this research project.

In the context of the highly variable open field storage environment, a changing climate, and a large volume crop, being able to assess changes to the post-harvest system through modelling has great potential. Ideas can be examined more rapidly and with much lower risk. The development of models and choice of parameters to include needs careful consideration. Modelling will never replace applied field research, but it can be a valuable complement.

6. Outlook

Healthier roots

The results of this project suggest that there are a number of avenues the work on plant health and successful post-harvest storage should pursued. The first is a focus on the "environment" source of variation in storability. This includes soil physical properties and soil microbiology. The methods of analysis exist or are rapidly developing, they just need to be applied. If gains are made in the understanding of the soil microbiome, this can likely be applied to quality related issue outside of long-term post-harvest storage. The COBRI network of which NBR is a member, is well placed to take up this work, given it is established, effective, and has the background scientific knowledge. It also has the interesting test case of the Netherlands. Some of the leading scientific knowledge lies outside of NBR and COBRI, so new partnerships may be necessary. The assessment of the established metrics such as mechanical properties and mechanical damage should not be excluded to the preference of the new. If gains are made reducing rates of mechanical damage in harvest and transport equipment, the scale of use of these machines means the gains will diffuse relatively quickly and internationally. The importance of mechanical properties in the down-stream process of root slicing is an important factor to remember.

Root morphology, including root size, is also an interesting avenue of exploration. The factors of root size pull in different directions. Larger roots have more energy during a fall impact, suggesting more damage. The opposite was observed in this research project, but what about in reality? Larger roots suggest larger pores in the clamp and thus higher air permeability. This was seen in this research project, but it did not seem to be of large consequence. The bottom line for post-harvest storage is how does damage and loss per unit weight of sucrose vary with root size. Even then, that is not sufficient as it does not take into account loss in the field through the whole season. It will be interesting to see what the doctoral research project out of Harper Adams College in the UK focusing on root morphology reveals.

A more controlled storage environment

Dramatic changes to the general form of the post-harvest storage system adopted in Sweden in the near term seem unlikely. There is not a strong demand from industry to investigate new systems of storage, and there does not seem to be plans to dramatically increase production and thus a need for greatly extended long-term storage campaigns. The system of forced ventilation developed through the NBR lead innovation project was successful in decreasing post-harvest storage losses, but further development has been paused until the economics demand it. This said, any incremental innovation that includes the right combination of changes in quality, risk, and cost including management effort, will always be adopted. An example of a low risk research project that extends the work of this current project is in the search for practical solutions to the issue of frozen roots at the edge of the clamp. The effects of different cover types can be relatively easily tested with the CFD model. A more exploratory extension could be in the search for systems that permit a controlled dehydration through greater passive ventilation. Computational Fluid Dynamics modelling could also be used in support of this work.

Modelling

The continued development of the CFD model to include buoyancy, soil thermal properties, radiation, and a baseline version of the transport of water are all achievable without further experimentation. The work would always benefit from the collection of the appropriate field data for model validation, with information on the airflow in the clamp being most critical. Improvements to the functionality of the model are also possible to pursue directly. There are a number of achievable extensions of the model, including connecting it with a clamp temperature reporting network. It would then be able to act as a live digital twin, which growers can use to make better informed decisions around the use of covers.

Cross validation of heat and mass transfer

It has been discussed above that the CFD model can be expanded to consider mass transfer through the inclusion of the Sherwood-Reynolds-Schmidt correlation to calculate convective mass transfer coefficients (k_c). An alternative approach to the inclusion of this correlation alongside the Ranz-Marshall correlation in the model is to include one and then apply the appropriate analogy between energy and mass transfer: the Lewis analogy. The Lewis number is $Le = h_{sf} \div (k_c \times \rho_a \times C_f)$, where ρ_a is the density of air and C_f is the heat capacity of air. By setting this equal to 1, the Lewis analogy states $h_{sf} = k_c \times \rho_a \times C_f$. Thus, with either of the Sherwood-Reynolds-Schmidt or Ranz-Marshall correlations, the other convective transfer coefficient can be derived. The value of testing such an approach is that it can cross-validate the accuracy of the results presented in Papers III and IV. The coefficients h_{sf} and k_c were calculated from two different experiments, conducted under different conditions, times and locations. The gains from such an approach in the form of increased computational efficiency are likely minimal.

Understanding the different storage systems

In North America, it is common that no on-farm post-harvest storage is used (N. Wulfekuhle (Minn-Dak, USA), personal communications, 2022-11-08; J. Anderson (Lantic, Canada), personal communications, 2022-11-09; M. Garner-Skiba, personal communications, 2022-11-10). The majority of harvesters have very small hopper tank capacity, with roots loaded directly into transport moving alongside the harvester. Post-harvest storage occurs not on farm but in large piles at the processing factory. This system is not employed in Sweden and an exact explanation for this is not known. It would be interesting to dig deeper into the reasons, benefits, and costs of the different storage systems employed for the sugar beet crop around the world. This thesis has benefited from looking at the different systems, but a more structured and collaborative investigation of why the different systems are employed and what each system can learn from the other could prove valuable.

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Popular science summary

Every winter, mounds of sugar beet roots dot the landscape of southern Sweden. Built from the toil of the season, these field "clamps" have been adopted as the means of minimising food loss in the period between harvest and processing. Beneath their fleece coverings hide many secrets. It is not that sugar beet growers do not have an understanding of the general state of the clamp, it is just that the scale and complexity of the system makes it difficult to fully quantify. This project wanted to do more than just take a peak beneath the covers. It looked to deepen our understanding in two areas. The first area was what sugar beet growers can do to impact the physical robustness (mechanical properties) of their roots, what this means for storability, and how we can easily measure this. The second area was how temperature and moisture move and vary across the entire clamp profile.

A non-result is still a result: an oft forgotten rule of science, which could similarly be stated as "a statistically non-significant result can still be practically significant". It turns out that growing season water and nitrogen availability do not have any marked impact on the mechanical properties of sugar beet roots. The benefit of this is that it means growers have one less agronomic relationship to worry about. However. It was also found that water availability during the season did change how well roots tolerated being in storage. More research is needed here.

Everything old is new again. The 100 year old technology of the analogue handheld penetrometer was shown to have value in the assessment of the mechanical properties of sugar beet roots. Understanding the average mechanical properties of the roots gives insight to the likely rate of degradation whilst stored in a clamp. It was also shown that dropping beats or dropping things on beets is not only fun, but could be used to investigate their mechanical properties.

Is the [beet] half full or half empty? Maybe it can be both. Great effort is usually expended to avoid dehydration of fresh produce during post-harvest storage, as it results in a loss of quality and value. Using forced ventilation over a short period, it was found that it is possible to achieve a high rate of dehydration in sugar beet roots without loss of quality, which in-turn could lead to increased payment per harvested tonne of the crop.

How's the weather? Using the same method used to model if tomorrow will be dry or wet, cold or warm, the beginnings of a model of the weather across the entire sugar beet clamp profile was developed. This model focused just on the temperature, but could use the results of the above mentioned forced-ventilation project to expanded coverage to include moisture. An oft (ad nauseam?) quoted saying relating to modelling is that “All models are wrong but some are useful” (George Box, 1976). How this model is wrong is embraced. How it will be useful is still under development.

Populärvetenskaplig sammanfattning

Varje vinter förändras landskapsbilden i södra Sverige med högar av sockerbetor. Dessa ”stukor” är uppbyggda för att motverka säsongens påfrestningar och minska livsmedelsförluster mellan skörd och bearbetning. Under täckningsmaterialet göms många hemligheter. Sockerbetsodlarna har kontroll på vad som sker och hur betorna i stukorna mår, på ett övergripande plan, men det storskaliga och komplexa i systemet gör det svår att fullt ut överblicka helheten. Med detta projekt ville jag göra mer än bara ta en titt under täcket. Projektet avsåg att fördjupa vår kunskap inom två områden. Det första området handlar om vad odlaren kan göra för att öka den fysikaliska motståndskraften (mekaniska egenskaper) hos betan, och vad det betyder för lagringsdugligheten, och hur vi, på ett enkelt sätt, kan mäta detta. Det andra området behandlar hur temperatur och fukt rör sig och varierar genom hela stukans profil.

Ett icke-resultat är fortfarande ett resultat. En ofta glömd regel i vetenskapen, vilken också kan uttryckas som ”ett resultat utan statistiskt signifikanta skillnader, kan fortfarande har signifikant praktiskt betydelse”. Det visade sig att förhållandena under tillväxtsäsongen eller vatten- och kvävetillgången inte hade någon avgörande betydelse för sockerbetans mekaniska egenskaper. Fördelen med detta är att odlaren har ett odlingsmässigt samband mindre att ta hänsyn till. Dock visade det sig att tillgången på vatten under säsongen förändrade hur väl betan tolererade lagring. Här behövs mer forskning.

Allt gammat blir nytt igen. En 100 år gammal teknik med en analog handhållen penetrometer visade sig vara värdefull vid undersökningen av sockerbetornas mekaniska egenskaper. Förståelse för betornas genomsnittliga mekaniska egenskaper ger insikt om den troliga graden av nedbrytning som kommer att ske under lagringen i stukan. Det visade sig också att släppa betor, eller släppa saker på betor, inte bara är roligt, men kunde även användas för att undersöka betornas egenskaper.

Är [betan] halvfull eller halvtom? Kanske kan den vara bägge delar. Stor möda läggs ofta på att färska grödor inte ska torka under efterskördslagring då det leder till sämre kvalitet och minskat värde. Användningen av forcerad ventilation under en kort period visade dock att det är möjligt att uppnå en hög grad av dehydrering av sockerbetor utan att kvaliteten minskar, vilket i sin tur kan leda till bättre betalning per skördat ton betor.

Hur blir vädret? Genom att använda samma metod som används för att förutse om morgondagen blir torr eller regnig, kall eller varm, har en modell börjat utvecklas som kan bestämma vädret tvärs igenom profilen av en stuka med sockerbetor. Denna modell fokuserar här bara på temperaturen men den kan även använda resultaten från det ovannämnda projektet med forcerad ventilation för att expanderas till att även täcka in fuktighet. Ett (alltför?) ofta använt talesätt i relation till modeller är att ” Alla modeller är fel men en del kan vara användbara” (George Box, 1976). De sätt på vilka denna modell är felaktig välkomnas. Hur den kommer att vara till nytta är fortfarande under utveckling.

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It’s not a doctoral research project without a university. I count myself fortunate that even here, at SLU, my colleagues in the group and department are not only great people, but are focused first and foremost on the people they serve.

This project has benefited greatly from research collaborations. Papers I and II were both built on an established collaboration through the Coordination International Sugar Beet Research (COBRI). This collaboration has proven very productive and I hope it continues. I'm very grateful to Prof. Dr. Christa Hoffmann and (the now Dr.) Gunnar Kleuker for hosting me at IfZ-Göttingen during the assessment of the mechanical properties of the sugar beet roots from Sweden. Paper IV simply would not have been possible without collaboration with experts in the use of Computational Fluid Dynamics. A particular thank you to those at Lund University who were so generous with their knowledge and resources: Prof. Christer Fureby, Dr. Hesameddin Fatehi, (the now Dr.) Seyed Morteza Mousavi, and Alessandro Ercole.

I

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Christa M. Hoffmann; Gunnar Kleuker; André Wauters; William English; Martijn Leijdekkers

Root tissue strength and storage losses of sugar beet varieties as affected by N application and irrigation

Textur und Lagerungsverluste von Zuckerrübensorten in Abhängigkeit von N-Gabe und Bewässerung

There is some evidence that sugar beet root tissue strength affects damage susceptibility and storage losses. This study aimed at analyzing the effect of N application and of irrigation on tissue strength of sugar beet varieties, on root composition, and on root tip breakage and storage losses. For this purpose, field trials in six replicates with three sugar beet varieties were carried out with three N doses in The Netherlands and Belgium in 2018 and 2019, alternatively with three irrigation treatments in Sweden in 2018 and 2019. Results show a low impact of N application and irrigation on puncture resistance, tissue firmness and compressive strength of the roots, while varieties differed always stronger and significantly. Cell wall composition (pectin, hemicellulose, cellulose, lignin) did not differ markedly in roots from different environments (sites, years) and varieties, giving no explanation for differences in tissue strength. However, the percentage of cell wall material (AIR, marc) and of dry matter were higher in roots with higher tissue strength. Root tip breakage and sugar losses during storage tended to be lower when root compressive strength of varieties was higher. Hence, root tissue strength could serve as an indirect selection criterion for reduced damage susceptibility and improved storability of sugar beet varieties.

Key words: puncture resistance, tissue firmness, compressive strength, storability, root tip breakage, sugar loss

Es gibt Hinweise darauf, dass die Textur von Zuckerrüben deren Beschädigungsempfindlichkeit und Lagerungsverluste beeinflussen könnte. Ziel der Studie war es, den Einfluss der N-Düngung und der Bewässerung auf die Textureigenschaften von Zuckerrübensorten, auf die Zusammensetzung der Rübe sowie auf Wurzelbruch und Lagerungsverluste zu analysieren. Dazu wurden in den Jahren 2018 und 2019 Feldversuche mit drei Zuckerrübensorten in sechs Wiederholungen und mit drei N-Stufen in den Niederlanden und Belgien, zudem mit drei Bewässerungsvarianten in Schweden durchgeführt. Die Ergebnisse zeigen nur einen geringen Einfluss der N-Düngung und der Bewässerung auf den Penetrationswiderstand, die Gewebefestigkeit und die Druckfestigkeit der Rübe, während sich die Sorten in jedem Versuch deutlich und signifikant unterschieden. Die Zellwandzusammensetzung (Pektin, Hemicellulose, Cellulose, Lignin) unterschied sich nur geringfügig in verschiedenen Umwelten und Sorten und bot daher keine Erklärung für die Unterschiede. Allerdings war der Anteil des Zellwandmaterials (AIR, Mark) bei Rüben mit höherer Gewebefestigkeit höher. Wurzelspitzenbruch und Zuckerverluste während der Lagerung waren geringer, wenn die Druckfestigkeit der Sorten höher war. Somit könnte die Festigkeit der Rübe als indirektes Selektionskriterium für eine geringere Beschädigungsempfindlichkeit und verbesserte Lagerfähigkeit von Zuckerrübensorten dienen.

Schlagwörter: Penetrationswiderstand, Gewebefestigkeit, Druckfestigkeit, Lagerfähigkeit, Wurzelspitzenbruch, Zuckerverlust

1 Introduction

Sugar beet roots are exposed to multiple mechanical stresses during harvesting and processing (Steensen 2002, Smed et al. 1996). Mechanical strain causes losses of whole root parts in the field and the factory yard, but leads also to more inconspicuous injuries, such as abrasions and bruises (Wiltshire and Cobb 2000, Brown et al. 2002). In consequence, damages at harvest increase sugar losses during storage (Hoffmann and Schnepel 2016, Schnepel and Hoffmann 2016, Steensen and Augustinussen 2002), as the wound healing process requires energy and moreover, injuries offer entry points for pathogen infestation (Akeson 1978, Campbell and Klotz 2006a). Recent studies suggest that damage susceptibility and storage losses of sugar beet roots will be lower if the tissue strength is higher (Kleuker and Hoffmann 2022, Nause et al. 2020). The tissue strength of sugar beet roots is influenced by the genotype, and furthermore, by the environmental conditions under which the crop is grown (Kleuker and Hoffmann 2021). It is assumed that these impacts are attributable to the changes in the composition of the root, which then alters the mechanical behaviour and thus the resistance to damage.

The most important environmental conditions concerning crop growth are weather and soil conditions. Among the con-

ditions that can be influenced during cultivation, N application has the greatest effect on sugar beet yield, but also on the composition of the root. Increasing N supply usually alters the composition as more water and nonsugar substances are stored with increasing cell size, resulting in a reduced dry matter content (Milford and Watson 1971, Hoffmann 2005).
Another factor altering root composition is water availability. Severe drought stress was demonstrated to affect tissue strength of sugar beet roots considerably (Kleuker and Hoffmann 2021). Usually, irrigation leads to a dilution of all soluble cell compounds resulting in a lower dry matter content. With increasing cell size due to water uptake, the cell walls as structural components get a lower proportion of the root fresh matter. It is therefore assumed that an altered composition can affect the firmness of the root, causing a lower tissue strength with high N supply and with irrigation.
Kleuker and Hoffmann (2020) and (2021) reported significant differences in the tissue strength of sugar beet varieties. Varieties with higher tissue strength tended to have lower root tip breakage and lower sugar losses during storage (Kleuker and Hoffmann 2022). These effects could not be found for roots from all locations, but only under conditions (in environments) that resulted in high sugar losses occurring in general. It is not yet clear how changes in root composition and texture due to N supply or irrigation may influence root tip breakage and storage losses.
The objective of the study was to analyse the effect of N supply and of irrigation on tissue strength and composition of roots of different sugar beet varieties, and furthermore, to find out if differences in tissue strength affect root tip breakage and storage losses.

2 Material and Methods

2.1 Field trials

In 2018 and 2019 field trials with different N application were conducted at a site in Belgium (IRBAB: 2018 in Hannut, 2019 in Lens) and a site in the Netherlands (IRS: 2018 in Colijnsplaat, 2019 in Lelystad) as block design with six replicates. Two factors were varied: three sugar beet varieties with different yield type were included, furthermore, N fertilizer application was varied with a control treatment (N_{min}: mineral N in soil in spring), a treatment according to the regional advice (N_{adv}: around 120 kg N ha^{-1}) and a treatment with an extra 80 kg N ha^{-1} in addition to the N_{adv} treatment (N_{adv}+80).
In Sweden field trials with the same three varieties in three irrigation treatments (No irrigation, optimal irrigation, heavy irrigation before harvest) were carried out in 2018 and 2019 (NBR: Löddeköpinge) (Table 1).

Tab. 1: Water supply of plots with growing season precipitation and irrigation, Sweden (NBR) 2018 and 2019 (number of irrigations shown in brackets)

Growing season	No irrigation (mm)	Optimal irrigation (mm)	Irrigation before harvest (mm)
24.04. to 15.10.2018	152	152 + 135 (5)	152 + 60 (2)
10.04. to 24.10.2019	359	359 + 118 (4)	359 + 35 (1)

All field trials were sown beginning of April, dependent on soil and weather conditions. They were run according to the national guidelines and were kept as free as possible of weeds, pests, and diseases.

2.2 Storage experiments

In October and November 2018 and 2019 plots were machine harvested. Roots were sent to Göttingen (IfZ). The 80 to 100 roots per plot were randomly divided into reference (prior to storage) and storage samples according the description from the IIRB (Legrand et al. 2016).
Prior to storage the root tip breakage was determined at ten roots per plot, measuring the average diameter at the root tip with a ruler.
The storage sample consisted of two air-permeable bags, which were separately weighed (weight before storage). Samples were stored in climate containers at constant temperature. The samples were covered with an additional layer of beets to reduce possible position effects through differences in transpiration. The average temperature was 8.6 °C in 2018 and 8.3 °C in 2019 with a relative humidity of 99%. Roots were stored for 70 days in 2018, and for 74 days (IRS, NBR) and 50 days (IRBAB) in 2019. After storage, samples were weighed and the difference to the weight before storage was calculated.

2.3 Texture measurements

Puncture and compression tests were performed with five beets per plot with a Texture Analyser with a 100 kg load cell (TA.XTplus 100, Stable Micro Systems, Godalming, UK) as described in detail by Kleuker and Hoffmann (2019). Sugar beet roots were washed and allowed to dry before measurement.
Puncture tests were conducted with a cylindrical probe (Ø = 2 mm) at three measurement points per root around the biggest root diameter. Root groove and crown were omitted. The measurement determines the puncture resistance as force to penetrate the periderm and the tissue firmness as average resistance of the underlying tissue (until 5 mm depth).
Compression tests were conducted with the same roots. A root slice of at least 20 mm height was cut at the biggest root diameter. From the slice, two cylindrical samples (near the center, more to the outside) with a diameter of 18 mm were cut with a cork borer and trimmed to a height of 20 mm. Results show the compressive strength as mean value of the two cylinders.
All parameters describing root texture (puncture resistance, tissue firmness, compressive strength) are summarized as tissue strength.

2.4 Analysis

Beet quality was determined for the reference samples and the stored samples. A homogeneous brei sample was produced, shock frozen and stored at −20 °C until analysis. For the analysis of sugar, potassium, sodium, and amino-N (blue number

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method) brei was clarified with 0.3% Al-sulphate solution. The analysis was conducted with an automated beet laboratory system (Anton Paar OptoTex GmbH, Seelze, Germany) according to routine methods as described by ICUMSA (1994, 2007a, 2007b). Glucose content was determined using an immobilized enzyme biosensor (Firma Dr. Müller, Freital, Deutschland); (ICUMSA 2019).The invert sugar content was calculated by multiplication of the glucose content with the factor of 1.735 (Vermeulen 2015).

The DM content was determined after drying at 105 °C until constant mass. Alcohol insoluble residues (AIR) describes the alcohol insoluble components in the sugar beet root that remain after two times extraction of the beet brei with 95% ethanol (McFeeters and Armstrong 1984, Sila et al. 2005). AIR was dried at 105 °C for 24 h to constant mass and is expressed as percentage of root fresh matter. From AIR the cell wall composition was determined according to van Soest et al. (1991). Cell wall components, soluble and insoluble pectin, hemicellulose, cellulose, and lignin were quantified by the solubility in different detergents. The cell wall components are expressed as percentage of AIR. The marc content includes all components, which remain after four times extraction with water and lastly acetone and is used in the sugar industry to estimate the pulp content of beet (Reinefeld and Schneider 1983).

2.5 Calculation of storage loss

The relative sugar loss during storage was calculated as difference between the amount of sugar before and after storage, which was set in relation to the initial amount of sugar and was referred to thermal time (°Cd; accumulated mean daily temperature) to compare roots with different storage periods. The amount of sugar before storage was calculated from the weight of the storage sample before storage, and soil tare and sugar content of the reference. The amount of sugar after storage was calculated from the weight of the stored sample, the soil tare, and the sugar content after storage. The soil tare in % was calculated for both the reference and storage samples as mass difference between washed and unwashed roots in relation to the washed roots.

2.6 Statistics

Data were checked for normal distribution and homogeneity of variance (Kozak and Piepho 2018). Sites and years were summarized as environments for the ANOVA. The analysis was run with the SAS Desktop-Version 9.4 (SAS Institute, Inc., Cary, NC, USA) using PROC MIXED followed by a Post Hoc Tukey Test on plot means. Variance components were estimated with the PROC VARCOMP function using REML method. Significant effects are indicated with *, ** or *** for $p \leq 0.05$, 0.01 or 0.001, while ns. is not significant. Different letters indicate significant differences among varieties for a given treatment.

3 Results

The impact of N supply on sugar beet root texture parameters is shown in Figures 1 A–C. Increasing N supply significantly affected puncture resistance (Fig. 1 A), tissue firmness (Fig. 1 B) and compressive strength (Fig. 1 C), but the effect was rather low. By contrast, variety had a substantial impact on tissue strength. Variety 3 had the highest values for tissue firmness, compressive strength, and for puncture resistance, although the latter was not significantly different to variety 2. Variety 2 had the lowest compressive strength, but significantly higher puncture resistance and tissue firmness than variety 1. There was no significant interaction between N supply and variety for puncture resistance and tissue firmness (Table 2).

Root tip breakage before storage was not affected by N supply (Fig. 1 D). Variety 3 had a significantly lower root tip breakage than variety 1 and 2, which did not differ. The ranking of varieties was similar for the invert sugar content and the sugar loss after storage (Figs. 1 E, F), while the N supply affected only the invert sugar content after storage.

The dry matter (DM) and AIR content of the roots was significantly affected by N supply (Figs. 1 G–H). However, the effect of varieties on composition was much more pronounced (Fig. 1 I). Variety 1 had a considerably lower dry matter content compared to variety 2 and 3, which did not differ. All varieties differed significantly in their AIR and marc content with variety 3 featuring the highest, variety 1 the lowest values. There was no interaction between N supply and variety.

Puncture resistance and tissue firmness were significantly affected by irrigation, with irrigated beets being slightly stronger. Compressive strength was not affected by the irrigation treatment (Figs. 2 A–C). Variety effects were similar as in the N treatments: variety 1 had a significantly lower puncture resistance than variety 2 and 3, while for tissue firmness variety 2 and 3 differed significantly. In compressive strength, variety 2 showed the lowest value, variety 3 the highest. There was no interaction between irrigation and variety.

Table 2: Variance components of texture parameters, root tip breakage, invert sugar content after storage and sugar loss during storage of sugar beet; three varieties in four environments (site × year) in Belgium (IRBAB) and the Netherland (IRS) in 2018 and 2019; in % of total variance

	Environment (E)	Variety (Var)	Fertilizer (F)	E × Var	E × F	Var × F	E × Var × F	Block (E)	Block (E × F)	Error
Puncture resistance in MPa	47.0	16.3	4.1	3.2	5.1	0.0	1.1	0.0.	0.8	22.4
Tissue firmness in MPa	14.7	64.1	0.9	3.6	2.0	0.0	1.6	0.5	0.0	12.6
Compressive strength in MPa	6.1	63.8	6.8	4.6	0.6	1.3	0.7	0.0	0.0	16.0
Root tip Breakage in cm	14.8	30.9	0.7	0.6	0.0	0.0	0.0	0.0	2.1	50.9
Invert sugar in mmol $kgFM^{-1}$	42.3	11.4	3.2	9.8	3.0	2.7	0.0	2.1	1.2	24.3
Sugar loss per 100 °Cd in %	16.7	25.0	0.0	8.5	1.5	1.5	0.0	2.7	1	43.1

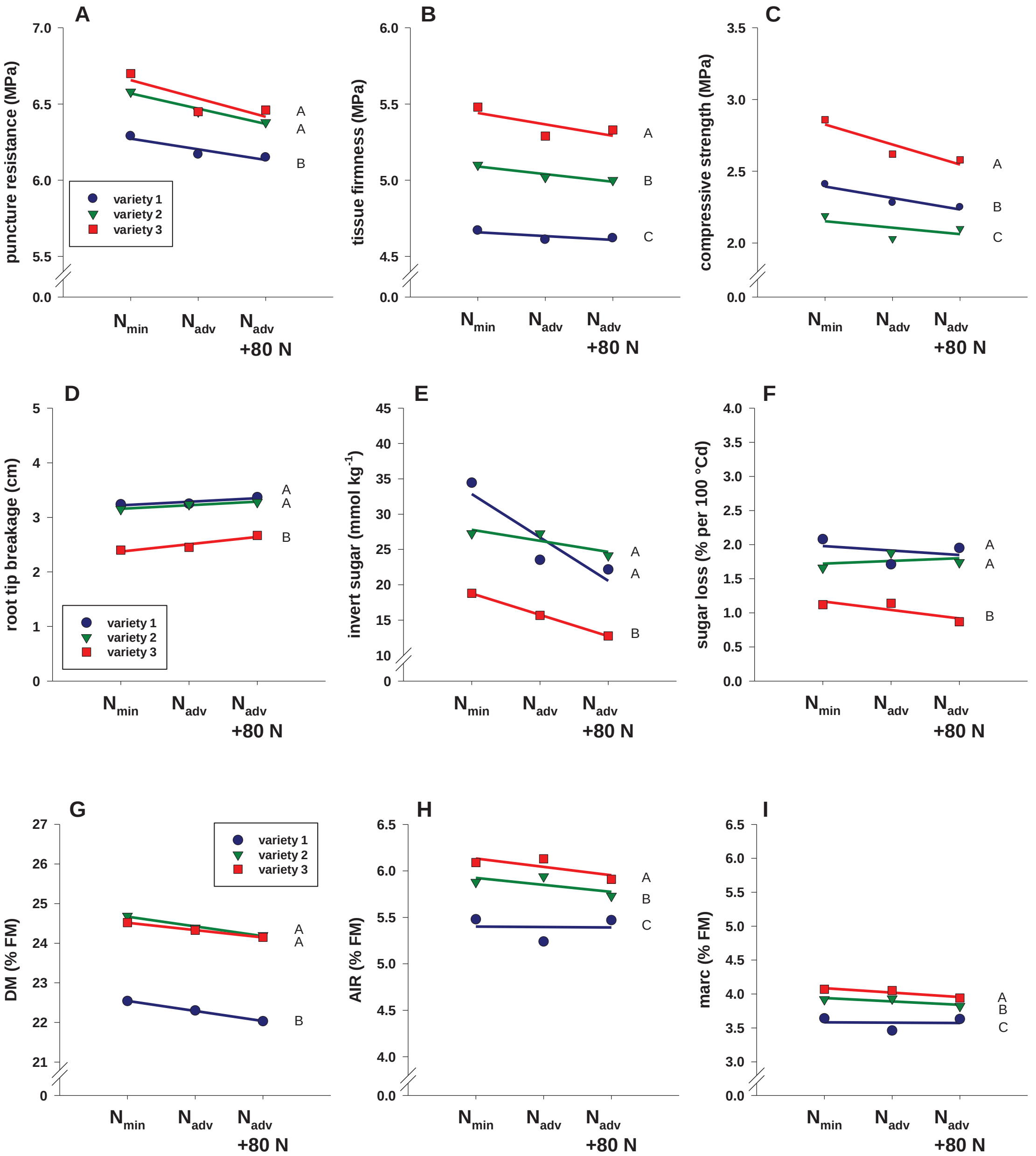

Fig. 1: Effect of N application on root texture (A, B, C), storage (D, E, F) and root composition (G, H, I) of three sugar beet varieties, mean of sites in Belgium (IRBAB) and the Netherlands (IRS) in 2018 and 2019. Sugar loss: 100% = sugar mass before storage, DM = dry matter, AIR = alcohol insoluble residues (cell wall material), marc = water insoluble residues. Different letters indicate significant differences between varieties as mean of the treatments, Tukey Test $p < 0.05$.

Irrigation had no effect on root tip breakage, whereas variety effects occurred with variety 3 obtaining the lowest root tip breakage (Fig. 2 D). For the invert sugar content and sugar loss after storage, highest values occurred for the irrigated crops (Fig. 2 E, F), whereas there was no difference between no irrigation and irrigation before harvest. Variety 3 had the lowest invert sugar content and sugar loss irrespective of irrigation, while variety 1 and 2 showed higher values.

The composition of AIR with the individual cell wall components is shown in Fig. 3. A major part of cell wall components was pectin with around 60% of the AIR, followed by hemicelluloses (20%), celluloses (15%) and lignin (5%). In the composition of the cell walls, there was neither much difference between the environments (Fig. 3 A) nor between the varieties (Fig. 3 B), although the percentage of AIR differed.

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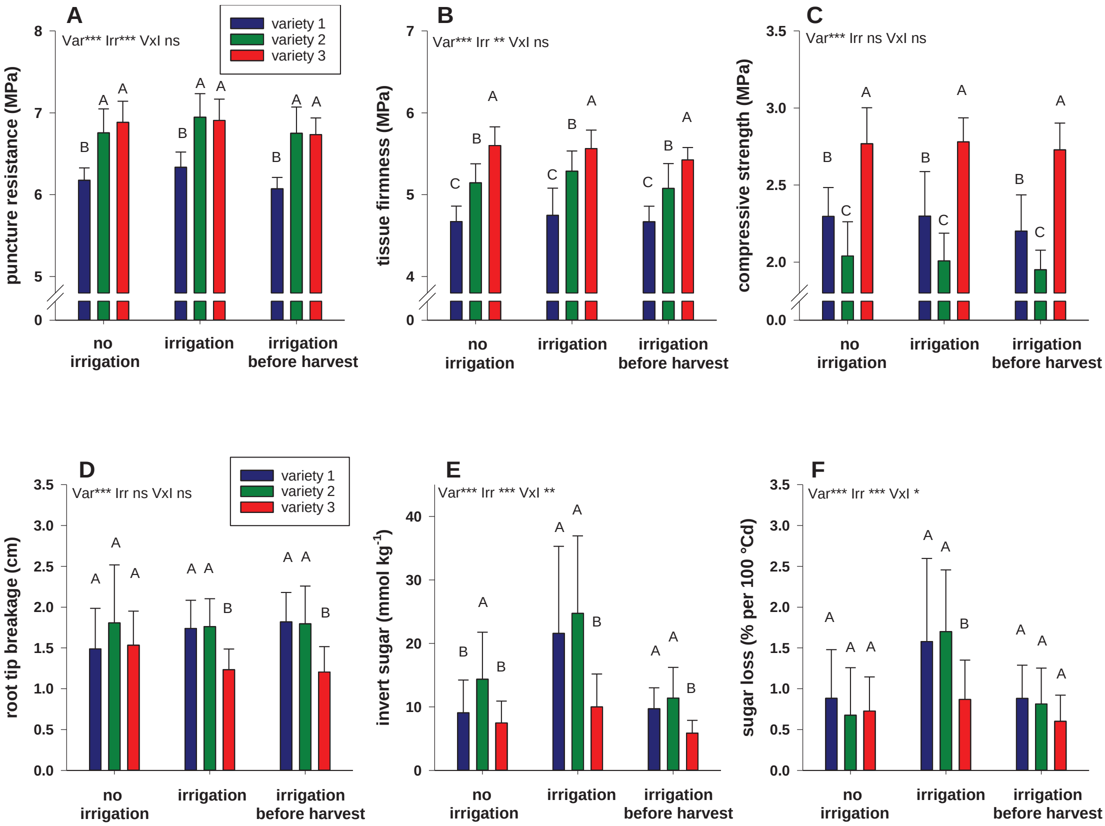

Fig. 2: Effect of irrigation on root texture (A, B, C) and storage (D, E, F) of three sugar beet varieties, Sweden (NBR), mean of sites in 2018 and 2019. Sugar loss: 100% = sugar mass before storage. Different letters indicate significant differences between varieties for the treatments, Tukey Test $p < 0.05$.

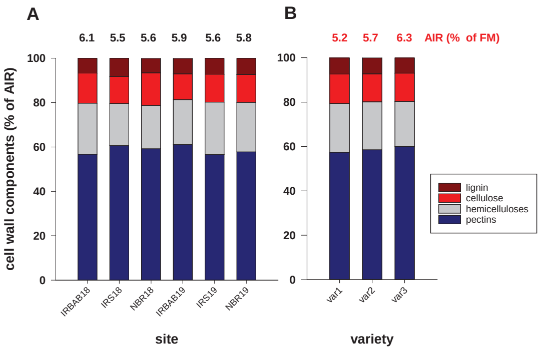

Fig. 3: Alcohol insoluble cell wall material (AIR) content and cell wall composition of sugar beet at different sites (A) and for different varieties (B); sites: mean of three varieties with three treatments (IRBAB: N application, IRS: N application, NBR: irrigation); varieties: mean of six sites with three treatments.

The relation of root tip breakage and storage losses of the three varieties to their compressive strength in the trial years is presented in Fig. 4 A, C, E and at the six trial sites (Fig. 4 B, D, F). For the varieties, it is obvious that a higher compressive strength of the root resulted in lower root tip breakage, lower invert sugar content after storage and lower sugar losses. Only if root tip breakage, invert sugar content and sugar loss were at a generally very low level, then the compressive strength of the root had a lower impact.

4 Discussion

First studies have demonstrated a high genotype effect with low genotype by environment interaction for texture parameters of sugar beet roots (Kleuker and Hoffmann 2020, 2021). In these studies, all crops were cultivated at different sites using standardized cultivation methods. The effect of increasing N application and different irrigation treatments was now studied under the assumption that these are the management operations which exert the dominant impact on the composition of the sugar beet root, and therefore possibly may affect root tissue strength.

4.1 N effect

Increasing N supply usually alters the composition of the root by increasing cell size. The dry matter content is reduced with

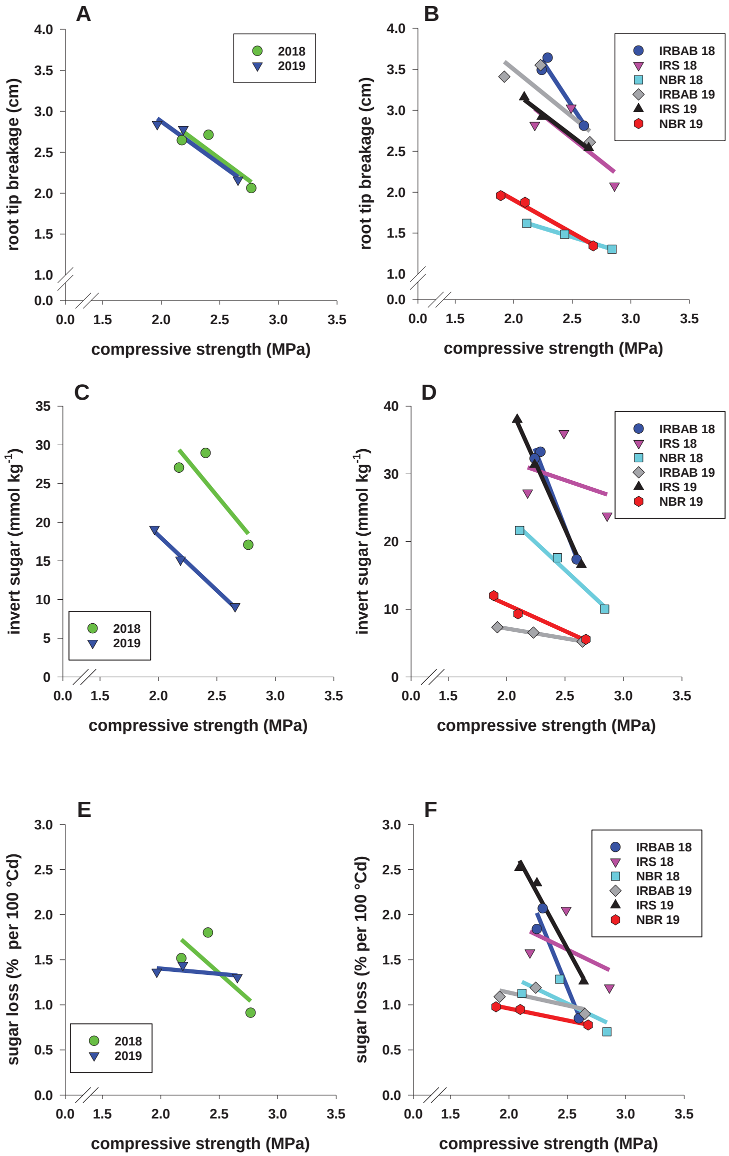

Fig. 4: Relationship between root tip breakage (A, B), invert sugar content after storage (C, D) and sugar loss during storage (E, F) and compressive strength of roots of three sugar beet varieties for years (A, C, E) as mean of three sites with three treatments (N application or irrigation) per year, and for sites (B, D, F) as mean of three treatments.
Sugar loss: 100% = sugar mass before storage

high N application, as it tended to be in the present study. But as the dry matter of sugar beet mainly consists of sugar (ca. 74%; Hoffmann 2010), the impact of N application on the cell wall components – determined as AIR and marc – was very low. This confirms results by Schäfer et al. (2020) with different *Beta* varieties, where increasing N supply with excess N doses did not alter root composition significantly. N application had no effect on monomer composition of polysaccharides, degree of acetylation and methylation of pectin, and on cell wall bound phenolic components (ferulic acids) (Schäfer et al. 2020).

Due to this small impact of N application on tissue composition, it was not surprising that the effects on root tissue strength were also low, even if different to expectations. Consistently, for increasing N supply neither a clear effect on root tissue strength, root tip breakage and storage losses, nor on the composition of the structural components of the storage root was detected.

4.2 Irrigation effect

It was expected that extra water supply, in particular given shortly before harvest, would make the root tissue weaker. However, irrigation did not have a strong effect on tissue strength. From the reduction in root mass (data not shown) it can be deduced that the treatment not receiving irrigation water experienced drought stress. This would have been only very moderate in 2019, but in 2018 it would have been similar to the severe stress described in Kleuker and Hoffmann (2021). In their study, severe drought stress resulted in very low tissue strength associated with high storage losses as compared to sites with better water supply. This effect is not seen in the current study. Further, irrigation did not alter the dry matter content and composition of the roots (data not shown), pointing to a minor impact on the water content.

A possible explanation for the greater storage loss for the irrigated roots independent of tissue strength is disease load. Perhaps the water supply under irrigation was more than optimal, so that additional factors such as certain diseases could arise. In 2018 the roots under irrigation in Sweden suffered from a severe infestation of chronic *Aphanomyces*. *Aphanomyces* has been shown to reduce the storability and severely enhance sugar losses during storage (Campbell and Klotz 2006b). It seems likely this infestation would have been more severe in the irrigated treatment owing to the wetter microclimate during the months of the growing season when temperatures are optimal for infections. The excessive supply (in relation to the crop demand) in combination with pathogen infections is most likely the reason for the adverse effect of irrigation on storability, which was not related to root strength. In their response on irrigation, significant differences between the varieties occurred indicating genotypic differences in the susceptibility to various pathogens.

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4.3 Variety effect

The results confirm the substantial effect of the variety for root tissue strength as also reported by Kleuker and Hoffmann (2020, 2021). This can probably be explained by the fact that the structure of internal tissue (cambium rings, cell number) in the root of different sugar beet types is established very early (Artschwager 1926, Milford 1973). All other yield and quality traits start to develop gradually during the growing period, so that their development is much more prone to environmental changes during the season.
The composition of the cell walls turned out to be rather similar among varieties, as also reported by Kleuker and Hoffmann 2022. Schäfer et al. (2020) carried out extensive analyses of cell wall components of *Beta* varieties. In their study even single cell wall polysaccharides, their cross-linkage and cell wall bound phenolic compounds were not related to the pronounced differences in tissue strength of *Beta* varieties. The cell wall composition of the four *Beta* varieties (two distinct sugar beet varieties, fodder beet, garden beet) was surprisingly similar. Therefore, the authors suggested that compositional differences of the cell wall do not provide convincing explanations for differences in root strength. The most pronounced difference also in the current trial was the dry matter content and the AIR content in fresh matter of the varieties. This suggests that the cell size with the respective difference in water content might play a decisive role for their strength. Nause et al. (2020) found first indications that cell sizes differ in varieties with different root strength. For two varieties with different storability Madritsch et al. (2020) showed differences in the number of parenchyma cells, cell area and periderm thickness. However, it has to be tested in further experiments with more varieties, if this is a causal relation and if the number of cambium rings with the higher percentage of vascular tissue and/or the cell size and periderm thickness are related to the root tissue strength of sugar beet varieties.

4.4 Root tissue strength and storability

Root tissue strength was analyzed not only as an interesting new trait of sugar beet, but primarily with the aim to identify the relation to harvest damage and storage losses. Results show that root tip breakage, invert sugar content after storage and sugar losses of varieties were closely related to compressive strength, when storage losses had reached a certain level. As there is a generally close correlation between the three texture parameters (Kleuker and Hoffmann 2021), damage susceptibility and storage losses are also related to puncture resistance and tissue firmness. Varieties with a higher tissue strength (puncture resistance, tissue firmness, compressive strength) had lower root tip breakage losses, less damage, hence lower pathogen infestation during storage and finally tended to have lower storage losses as also reported by Kleuker and Hoffmann (2022). However, even if the variety ranking did not change between sites, the absolute root tissue strength and storage losses did. It is therefore only possible to compare the absolute tissue strength of varieties grown under the same conditions, and not to compare varieties from different sites (fields) or to estimate absolute storage losses from the tissue strength.
Despite this constraint, the determination of tissue strength could be an interesting trait to approach the damage susceptibility and storability of sugar beet varieties. Previously the marc content was suggested as a trait also related to storability (Schnepel and Hoffmann 2014, 2016), which could be regarded as an indirect criterion and is closely related to root texture. As the tissue strength has no interaction between environments and genotypes (Kleuker and Hoffmann 2021), only few trial sites will be needed to get a good estimate of the root tissue strength of different genotypes.

5 Conclusions

Surprisingly, root tissue strength of sugar beet was much more influenced by the variety than by the most important treatments usually affecting root composition, N supply and water availability. It can therefore be assumed that other agronomic treatments will most likely not alter root texture either. An exception could be diseases, in particular root rots such as rhizoctonia, but probably also infection with virus yellow (Hossain et al. 2020) and SBR (Syndrome basses richesses; Pfitzer et al. 2020), which will most likely lead to a reduction of root tissue strength because of rotten tissue and a general disorder of root metabolism. The effect of irrigation on storage losses was independent of tissue strength; underlying causes should thus be further investigated.
Root tissue strength of varieties turned out to be a major factor influencing root tip breakage, invert sugar content after storage and sugar losses. Kleuker and Hoffmann (2021) showed also in commercial sugar beet varieties surprisingly high variation in root tissue strength, indicating a potentially large effect on the functionality of roots. Because of the close correlation, tissue strength could serve as an indirect selection criterion for reduced damage susceptibility and improved storability of sugar beet varieties. It has to be evaluated in which relation high root tissue strength is to other breeding targets, in particular to the performance of varieties. Kleuker and Hoffmann (2021) found a negative correlation for varieties between root yield and tissue strength, so that there could be trade-offs. Furthermore, a target value concerning root strength for the factory processing quality must be discussed as well, as that could additionally differ from demands for beet cultivation and storage.

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Author Contributions

Christa M. Hoffmann: Conceptualization; Project administration; Investigation; Visualization Writing-original draft; Writing-review & editing
Gunnar Kleuker: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing-review & editing
André Wauters: Trial cultivation; Writing-review & editing
William English: Trial cultivation; Writing-review & editing
Martijn Leijdekkers: Conceptualization; Trial cultivation; Writing-review & editing

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Author's addresses: Prof. Dr. *Christa M. Hoffmann*, *Gunnar Kleuker*, Institut für Zuckerrübenforschung (IfZ), Göttingen, Germany; *André Wauters*, IRBAB, Tienen, Belgium; William English, NBR, Borgeby, and Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Alnarp, Sweden; Dr. *Martijn Leijdekkers*, IRS, Dinteloord, The Netherlands; e-mail: hoffmann@ifz-goettingen.de

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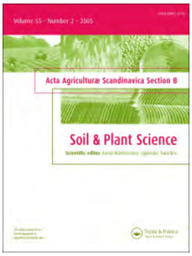

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Method for in-field texture analysis of sugar beet roots using a handheld penetrometer

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Method for in-field texture analysis of sugar beet roots using a handheld penetrometer

William English [a,b], Joakim Ekelöf[a], Françoise Vancutsem[c], Martijn Leijdekkers[d], Gunnar Kleuker[e] and Christa M. Hoffmann [e]

[a]NBR, Nordic Beet Research Foundation, Bjärred, Sweden; [b]SLU, Swedish University of Agricultural Sciences, Alnarp, Sweden; [c]IRBAB-KBIVB, Institut Royal Belge pour l'Amélioration de la Betterave, Tienen, Belgium; [d]IRS, Institute of Sugar Beet Research, Dinteloord, The Netherlands; [e]IfZ, Institut für Zuckerrübenforschung, Göttingen, Germany

ABSTRACT

Methodology for analysing textural properties of sugar beet roots in the laboratory has previously been established. It has been shown to be reliable and of value in exploring relationships between textural properties, damage rates, and storability of varieties. In this paper, a methodology for the assessment of textural properties in-field, prior to harvest, using an inexpensive handheld penetrometer is examined. Three sugar beet varieties were grown in Belgium, the Netherlands, and Sweden during 2019. Textural properties were assessed in-field with the handheld penetrometer 2, 1 and 0 months prior to harvest, and with the laboratory penetrometer directly after harvest. Comparison of the results showed generally strong correlations. A power analysis suggests a difference in mean Handheld Pressure of 0.10 MPa could be found significant within a large trial with a block design. The reliability of the handheld penetrometer was further assessed in the Swedish national variety trials over three years (2019-2021). Correlation coefficients of 0.86 and 0.94 were found between mean Handheld Pressure for 2019 and 2020, and 2020 and 2021 respectively. The handheld penetrometer can be applied as an economic means of quantifying differences in textural properties of sugar beet varieties. Clear operating procedure and training must exist.

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Introduction

Mechanical damage to sugar beet, *Beta vulgaris* ssp. *vulgaris* L., occurs during harvest and handling, and generally leads to increased rates of sugar loss during storage (Kenter et al. 2006; Huijbregts et al. 2013; Kleuker and Hoffmann 2021). The ability of a sugar beet root to withstand mechanical damage varies with its textural properties (Kleuker and Hoffmann 2020, 2022). Textural properties analysed for sugar beet roots include puncture resistance, compressive strength, and deformation (Gorzelany and Puchalski 2000; Nedomová et al. 2017; Kleuker and Hoffmann 2019, 2022). Differences of these traits between varieties have been shown to be strong and stable (Kleuker and Hoffmann 2020, 2021).

The determination of textural properties of sugar beet has been achieved using laboratory equipment. The specific metrics sort and methodology applied varies. For example, resistance to penetration was analysed by Gorzelany and Puchalski (2000) using an 8 mm diameter steel probe at a crosshead speed of 30 mm min^{-1} during the loading process, with samples taken somewhere in the top third and middle third of the sugar beet root. Nedomová et al. (2017) used a 6 mm diameter steel probe at 20 mm min^{-1} with samples taken at an unspecified point. The forces at puncture from Nedomová et al. (2017) are approximately one-fifth the magnitude of those of Gorzelany and Puchalski (2000). Neither publication specified a sampling depth. Identifying gaps and variability in the applied methodology, Kleuker and Hoffmann (2019) sort to develop a standardised and repeatable method that would permit 'uniform and comparable implementation in future studies'. The method they developed is tightly specified. For Puncture Resistance, the method involves taking three penetration samples per harvested and washed sugar beet root, using a 2 mm diameter cylindrical probe, at a speed of 60 mm min^{-1}, at the widest point of the beet, not in the root furrow, and to a depth of 5 mm. This method has subsequently been adopted in Kleuker and Hoffmann (2020), Schäfer et al. (2020), Kleuker and Hoffmann (2021) and Hoffmann et al. (2022).

CONTACT William English we@nbrf.nu Borgeby Slottsväg 11 SE 237 91 Bjärred

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Operating procedures for the testing of fruit with penetrometers are well established and standardised. They require the harvest, often the removal of skin, and then the insertion of a probe of given diameter into the fruit to a given depth (Blanpied et al. 1978). A slow and consistent speed of insertion is required to ensure a consistent testing force across samples (Abbott 1999). Magness and Taylor (1925), Feng et al. (2011) and Li et al. (2016) have all shown that a high measurement speed of a penetrometer consistently lead to higher readings than a slower speed. For Li et al. (2016) the difference was only significant for soft fruit, and for Feng et al. (2011) resistance increased with measurement speed at a decreasing rate.

The use of handheld mechanical penetrometers to assess textural properties of fruits and vegetables dates back at least to the 1920s and Murneek (1921) and Magness and Taylor (1925). There is, however, no known application to sugar beet. Handheld penetrometers are a widely adopted version of the technology owing in large to their ease of use, their accessibility owing to their low cost, and the ability to apply them rapidly during the growing season. Small mechanical handheld penetrometers fit easily in the hand, weigh as little as 100 g, and cost less than €300. They have also been shown to be as reliable as laboratory equipment when applied correctly (Harker et al. 1996; Lehman-Salada 1996).

Handheld penetrometers are often analog, and in the large can only report the single metric of maximum resistance force. In contrast to laboratory texture analyser methods, they have issues around variability in the application of the testing procedure between operators resulting primarily from variability in application speed, depth, and angle. Harker et al. (1996) showed a consistent inter-operator variation of 10% among well-trained operators testing apples and kiwifruit. DeJong et al. (2000) reported that softer fruit was indicative of greater operator variability but were unable to find significant differences. In a comparison of penetrometers in kiwifruit, Feng et al. (2011) reported that the handheld penetrometer was occasionally applied at a speed of 600 mm sec^{-1} when the recommended speed was 240 mm sec^{-1}. Controlling the depth of insertion was noted as an issue by both Harker et al. (1996) and DeJong et al. (2000). Jantra et al. (2018) highlight the importance of a consistent probe angle to maintain a consistent contact area and loading rate, although Harker et al. (1996) could not find differences resulting from angle of application.

Further limitations in the application of a handheld variant of a penetrometer pre-harvest are foreseeable in the case of sugar beet. Sampling in the field introduces a greater risk for soil contamination at the sampling point. Uniform selection of a sampling point can also be challenging. This is required to avoid the variations in strength that are present along the length of the root (Kleuker and Hoffmann 2019). The widest part of the sugar beet root – the sampling point in Kleuker and Hoffmann (2019) – is often situated under the soil surface until harvest. The root surface area that is accessible above the soil surface will vary with time, growing conditions, and variety. No roots are accessible during early stages in the growth cycle. For some varieties, the lack of access to a sampling point in the root could extend across the full commercial growth cycle, precluding the pre-harvest use of a handheld penetrometer entirely. These drawbacks notwithstanding, the usability of handheld penetrometers makes them an attractive tool in the assessment of food crop quality if standardised, efficient, and proven methods exist.

In this study, comprehensive tests were conducted to assess the reliability of a method to measure mechanical strength of sugar beet roots that employs a handheld penetrometer applied pre-harvest. Measurements taken with a handheld penetrometer during the growing season were assessed against the results of measurements taken post-harvest in the laboratory, applying the method of Kleuker and Hoffmann (2019). An analysis of the sample size needed with the handheld penetrometer to find expected differences in mean strength as significant is presented. The inter-operator variation in the application of the handheld penetrometer is also briefly assessed. The reliability of the handheld penetrometer is then assessed in the Swedish national sugar beet variety trials. The description of the methods will allow uniform and comparable implementation in future research applications.

Materials and methods

Field trials and plant material

Sugar beets for this experiment were taken from field trials undertaken during the 2019 growing season. Trial plots were established for three varieties of differing yield formation, chosen to give variation in textural properties. These varieties can be classified as Variety 1: E-type, Variety 2: N-type, and Variety 3: Z-type (Bosemark 1993), but should not be considered as representative of these type classes. For each variety at each trial site, there were six replicates. Three agronomic treatments were also applied in these trail in a split-plot design. This gave a total of 18 plots per variety, and 54 plots total, per trial site. The agronomic treatments are

Table 1. Description of trial site and growing conditions, season 2019.

Country	BE	NL	SE
Location	Lens	Lelystad	Löddeköpinge
Latitude	50.569	52.544	55.768
Longitude	3.899	5.543	13.035
Soil type	Loam	Clay-loam	Clay-loam
Sowing date	1 April	9 April	10 April
In-season rainfall	390 mm	395 mm	359 mm
Plot size	14.3 m^2	36.0 m^2	46.1 m^2
Plant population	79 140 ha^{-1}	109 500 ha^{-1}	99 900 ha^{-1}

BE = Belgium, NL = the Netherlands, SE = Sweden.

not considered in this work, but are described in Hoffmann et al. (2022) and the ParentProjectDesign.pdf document in the project's data repository.

The trials were established in the sugar beet growing regions of Belgium (BE), the Netherlands (NL), and Sweden (SE). Table 1 summarises each trial site and the growing conditions. All trials were grown in accordance with national standards of Good Agronomical Practice.

Field textural properties analysis – handheld penetrometer

Field measurements of the sugar beet root mechanical strength were taken with an Effegi type FT011 handheld penetrometer (QA Supplies, Norfolk, Virginia, U.S.A.) with a 2 mm diameter cylindrical probe (Figure 1(b)). Measurements were taken in situ at a soil and damage free point on the root directly below all petiole insertions (Figure 1 (a)). This sampling point was chosen as it was deemed the only point on the root that would be consistently assessable on all varieties and during all sampling occasions. The probe tip was placed on the root surface, then the probe inserted perpendicular to the root surface, by hand, at a slow and constant speed, and to approximately 5 mm. The maximum resistance force was recorded. Force was recorded as pounds and to the nearest single decimal place, then converted to pressure as megapascals through a conversion factor of 1.4159. While measurements from handheld penetrometers are usually referred to as Firmness (Abbott 1999), to distinguish the in-field measurement from the laboratory measurements, it is here termed Handheld Pressure.

Ten sugar beet plants per plot were randomly selected for sampling. Each root was measured once as the restricted sampling area precluded the ability to take multiple samples per root. Excessively small or large roots were excluded from measurement. No strict criteria of size were applied, with instruction given to select only roots of a normal size for a fully populated stand at the given stage of development. This assessment made was at the discretion of the operator, all of whom were experienced with sugar beet cultivation. Field measurements were taken at three occasions; two months prior (−2 Months), one month prior (−1 Month), and directly prior (−0 Months) to the planned harvest date (Table 2). The same beets were not necessarily included at each occasion. To provide insight to the magnitude of inter-operator variability, a second operator (SE-2) assessed all plots independently in SE in occasions −1 Month and −0 Months. This data is only applied in the Effect of operators analysis – all other data for SE is from operator SE-1.

Successful sampling with the handheld penetrometer was achieved at all sampling locations and occasions, with the exception of SE during the earliest (−2 Months) occasion. At this time, sampling was not possible in 12 of the 54 plots owing to the sugar beet roots being too small for a sampling point to be accessible. Of the 18 plots per variety, 16, 12 and 14 plots were sampled for Variety 1, 2 and 3 respectively. All other Handheld Pressure results for each variety are presented as the mean of 10 roots per plot and 18 plots per site. A limited amount of soil was observed to adhere to the surface of individual roots, but was not prohibitive in the selection of a soil and damage free sampling point. Roots were not observed to move during sampling. Sampling took approximately 3 h per field and occasion, for a sampling rate of 180 observations per hour.

Laboratory texture analysis

Assessment of textural properties in the laboratory was undertaken to provide benchmark data against which the reliability of the handheld penetrometer was assessed. After harvest, the sugar beet roots were directly transported to IfZ in Göttingen, Germany for assessment. Owing to travel distances and the size of the experiment, assessment in the laboratory occurred between 2 and 7 days after harvest. Roots were stored at 6°C, then washed and stored at room temperature (20°C) one day prior to assessment. Laboratory assessment employed a texture analyzer equipped with a 100 kg load cell (TA.XTplus100, Stable Micro Systems, Godalming, UK). Assessment was made of Puncture Resistance, Tissue Firmness, and Compression Strength (Kleuker and Hoffmann 2019). Compression Strength is not reported further in this paper. Puncture Resistance is defined as the force required to rupture the sugar beet root periderm. This value is usually the maximum resistance force recorded in any one sample. Tissue Firmness is taken as the mean resistance over the distance from 0.5 mm after rupture to 5 mm into the sugar beet root. Both Puncture Resistance and Tissue Firmness were measured using a 2 mm diameter cylindrical probe, employed at the widest part of the sugar beet

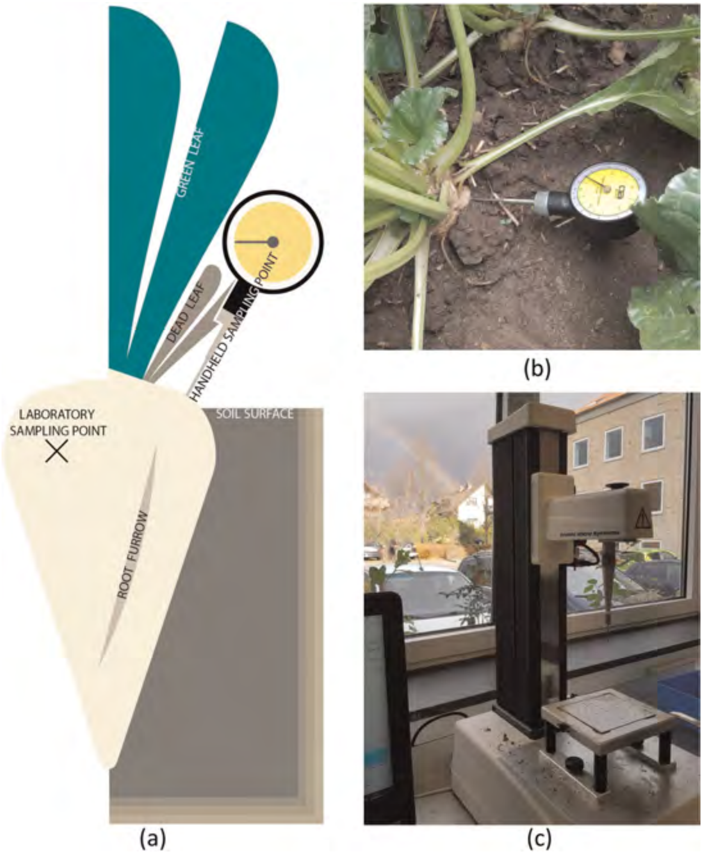

Figure 1. Sampling of textural properties of sugar beet. (a) Schematic of sampling points on the sugar beet root, (b) Handheld penetrometer placed at the sampling point of a sugar beet in the field with a limited sampling area, Sweden August 2019, (c) TA.XT Plus 100 with 2 mm diameter plunger in a laboratory at IfZ, Göttingen.

root, in an area free from damage and not in the root furrow. In the roots in which a handheld penetrometer sampling point was visible, no damage from a disease or insect incursion was observed to have developed and thus handheld sampling did not interfere with the laboratory sampling. Five sugar beet roots per plot were assessed, with three measurements taken per root, for a total of 15 samples per plot. Two hundred seventy measurements were taken per variety × country for each of these metrics. Successful sampling in the laboratory was achieved for all plots. Sampling rate with the laboratory analyzer when running only penetration tests is estimated at 95–115 observations per hour. This does not include the time to harvest, transport, store, or wash material.

Table 2. Sample occasion (2, 1, & 0 months prior to planned harvest date) and harvest dates of sugar beet at each of the three trial sites in 2019.

Country	BE	NL	SE
−2 Months	29 August	22 August	16 August
−1 Month	3 October	23 September	11 September
−0 Months	13 November	17 October	18 October
Harvest	15 November	25 October	24 October

BE = Belgium, NL = the Netherlands, SE = Sweden.

Reliability study

To assess the reliability of the handheld penetrometer in providing stable rankings of Handheld Pressure between years, an assessment of the national variety trials in SE was undertaken over three years. The same field textural properties analysis methodology was applied. The assessment was conducted within the constraints of the national variety trials, and as such a reduced sampling strategy was applied. Varieties were assessed at one, two, and two sites, in 2019, 2020 and 2021 respectively. Each trial had four replicates. Ten observations per plot were taken in 2019, five in 2020, and six in 2021. The final sample consisted of nine varieties assessed in both 2019 and 2020, and 18 varieties assessed in both 2020 and 2021. A sampling rate of 130–170 observations per hour was achieved, with the slower rate occurring in 2020 when relatively more time was spent moving between plots.

Statistics

Comparison of measurement procedures

Statistical analysis was carried out with the program R v4.1.2 (R Core Team 2021) within RStudio v2021.09.0 (RStudio Team 2021). Results are presented as the Least square means at the variety × country × measure level for the laboratory measures, and variety × country × occasion level for Handheld Pressure. Means were computed with plot level observations and the emmeans package. A linear mixed effects model including a random block effect was employed. Significant differences in means were assessed with an analysis of variance (ANOVA) using post-hoc Tukey tests, $\alpha \leq 0.05$. For visualisation of the comparison of Handheld Pressure and the laboratory measures, plot level observations were standardised using country and occasion (handheld), or country and measure (laboratory) specific means and standard deviations. Pearson's Correlation was used as the measure of association between the handheld and laboratory measures.

Effect of sample size

A power analysis was conducted to find the number of samples required to find statistical significance based on both a survey research design and a block design. The differences of mean Handheld Pressure used in this analysis were taken from the reliability study in 2020, plus some marker mean differences and sample sizes. The standard deviation applied to the analysis of a survey design was taken as the mean of the three within variety standard deviations for SE at −0 Months, for observations at the level of the individual root: s.d. = 0.2836. This is the most conservative mean standard deviation on Handheld Pressure from this occasion (BE: s.d. = 0.2218, NL: s.d. = 0.2378). The standard deviations applied to the analyses of the block design were taken as the average within site and between plot values from the two extreme cases of samples per plot in the reliability study. For 2020 – five samples per plot – s.d. = 0.1826. For 2019 – ten samples per plot – s.d. = 0.1389. In a power analysis, α represents the willingness to accept statistical Type I error, and Power is the inverse of willingness to accept statistical Type II error. α was set to 0.05, Power set to 0.90.

Effect of operators

Comparison of mean Handheld Pressure of the two operators in SE was done with a linear mixed effects model including an operator-variety interaction term and a random block effect. Assessment was made of the significance of the main operator effect and operator × variety interaction. Significant differences were assessed using post-hoc Tukey tests, $\alpha \leq 0.05$.

Reliability study

Statistical analysis in the reliability study followed the comparison of measurement procedures methodology for the calculation of means and correlations.

Results

Average textural properties

The textural properties for each variety in each country are presented as laboratory measurement or Handheld Pressure at each occasion (Figure 2). The Puncture Resistance for Variety 1 was less than for Variety 2 and 3 in all countries. For Tissue Firmness, the three varieties were ranked Variety 1: Variety 2: Variety 3 in all countries. This ranking was also found for Handheld Pressure in seven of the nine country × occasion combinations. The exceptions were NL during occasion −0 Months and SE during occasion −2 Months, where no significant difference was found between Variety 2 and Variety 3.

Values of Puncture Resistance ranged from 5.98 MPa for Variety 1 in NL, to 6.73 MPa for Variety 3 in SE. Tissue Firmness ranged from 4.42 MPa for Variety 1 in NL to 5.51 MPa for Variety 3 in BE. The Handheld Pressure values ranged from 5.06 MPa for Variety 1 in BE in occasion −2 Months, to 7.18 MPa for Variety 3 in SE in occasion −0 Months. The range of values within country are shown in Table 3. The range of Handheld Pressure was lowest at occasion −0 Months for both BE and NL, while this occasion had the largest range for SE. Occasion −2 Months also tended to have the largest standard deviations for Handheld Pressure (Figure 2) and standard deviations for Handheld Pressure were generally larger than for the laboratory measures.

Handheld Pressure values tended to increase with time. In both BE and SE, this increase was from occasion −2 Months and through the −1 Month occasion to the

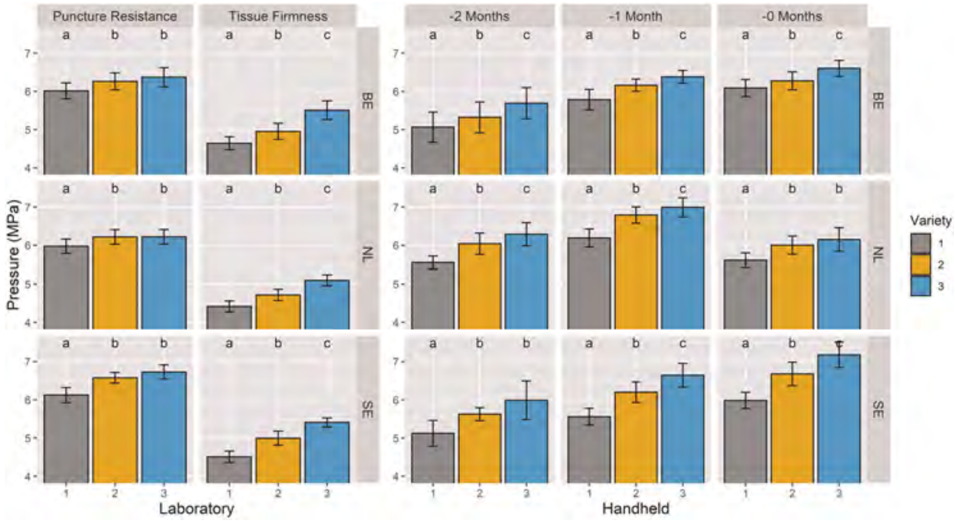

Figure 2. Textural properties of roots of three sugar beet varieties for laboratory measures (left) and Handheld Pressure at field sampling occasion (right), by country, 2019. Vertical bars indicate standard deviation. Letters indicate significance grouping within country and measure (laboratory) or occasion (handheld), post-hoc Tukey test, $\alpha = 0.05$. $N = 18$ per variety. BE = Belgium, NL = the Netherlands, SE = Sweden.

−0 Month occasion. For NL, the values from the −0 Months occasion were on average comparable to −2 Months.

Comparison of measurement procedures

Comparisons of the laboratory Puncture Resistance and Tissue Firmness measurements to the Handheld Pressure measurements at the plot level are presented in Figures 3 and 4 respectively. The 1:1 line in these figures indicates the ideal agreement of measurements. Any point above the line tested relatively stronger in the field than in the laboratory. Correlation coefficients for each sub-figures show that all comparisons were found to have a significant association at $\alpha = 0.05$, with the exception of Puncture Resistance in BE at −2 months.

Both Figure 3 and 4 show a general trend of Variety 1 with lower values to Variety 3 with higher. Correlation coefficients are above 0.60 in 12 of the 18 comparisons. Handheld Pressure showed better agreement with Tissue Firmness than with Puncture Resistance, as indicated by the higher correlation coefficients. Eight of nine correlation coefficients for Handheld Pressure and Tissue Firmness were greater than 0.60. Only four of nine correlation coefficients are above 0.60 for the comparison with Puncture Resistance. All correlation coefficients for NL were less than 0.35 in the comparison with Puncture Resistance.

Effect of sample size

The power analysis shows that at an α of 0.05, Power of 0.90, and the standard deviation calculated for a survey design with the data from SE in occasion 3 (s.d. = 0.2836), a mean difference of 0.100 MPa is expected to be found significant with a sample size of 86.5 per variety (Table 4). 30.0 samples per variety would find differences to be significant when the mean difference

Table 3. Range of textural properties of roots of three sugar beet varieties, by country, measure (laboratory) or sampling occasion (handheld) (MPa).

	Laboratory		Handheld pressure			
	Puncture resistance	Tissue firmness	−2 Months	−1 Month	−0 Months	All occasions
BE	0.36	0.87	0.63	0.60	0.51	1.54
NL	0.24	0.68	0.73	0.80	0.54	1.43
SE	0.51	0.90	0.87	1.08	1.19	2.06
All countries	0.75	1.09	1.23	1.43	1.57	2.12

Sampling occasions were 2, 1 and 0 months prior to planned harvest date. BE = Belgium, NL = the Netherlands, SE = Sweden.

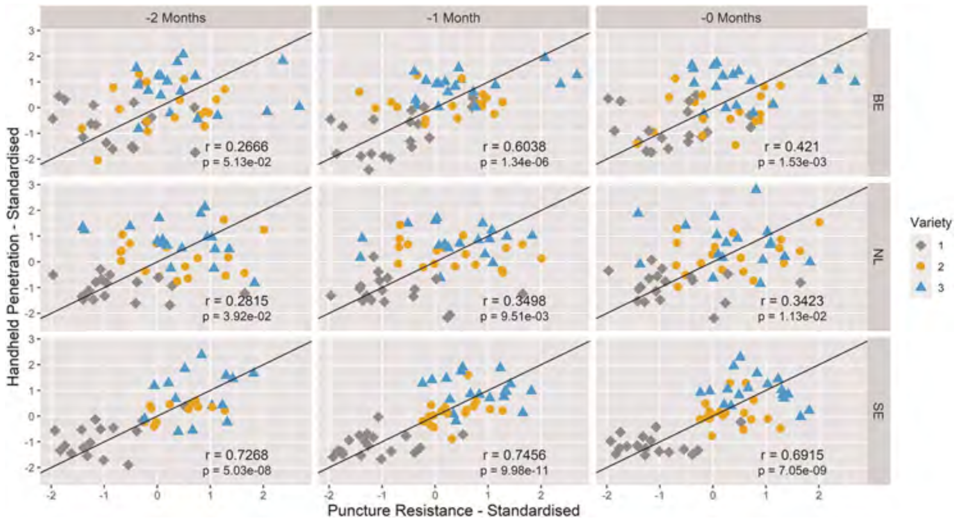

Figure 3. Comparison of handheld pressure and puncture resistance of roots of three sugar beet varieties, by country and field sampling occasion, 2019. Plot level standardised values. Pearson's *r* correlation and associated *p*-values shown. 1:1 line shown. *N* = 10 per plot and occasion (Handheld Pressure), 15 per plot (Puncture Resistance). BE = Belgium, NL = the Netherlands, SE = Sweden.

was 0.174 MPa. For the standard deviations from the SE national variety trials in 2019 and 2020, with the block design in four replicates (s.d. = 0.1389 and s.d. = 0.1826), a difference of 0.100 MPa is expected to be found significant with a sample size of 22.3 and 37.0 per variety respectively. At a sample size of four plots per variety, a difference of 0.35 and 0.46 MPa, respectively, would be expected to be found significant.

Effect of operators

Operator SE-2 had a tendency to measure higher Handheld Pressure values than operator SE-1 (Figure 5). The exception was for Variety 3. In the linear mixed effects models, the operator effect was significant at both sampling occasions; $t(102) = 4.85$, $p =$ 4.63e-6, and $t(102) = 3.86$, $p = $ 1.98e-4. The operator SE-2x Variety 3 interaction was significant in both sampling occasions; $t(102) = -3.97$, $p =$ 1.38e-4, and $t(102) = -2.92$, $p = 0.043$. Other interaction effects were not significant at $\alpha = 0.05$. Operator SE-1 tended to have a higher standard deviation in their measurements than operator SE-2.

When the data from operator SE-2 replaces operator SE-1 in the above comparisons of methods, some changes in the results are found. The mean differences for Handheld Pressure in SE (Figure 2) remain highly significant. The highest *p*-value on the post-hoc contrast for mean difference when using the data from operator SE-2 is equal to 0.0040 for Varieties 2 and 3 in occasion −1 Month; this was 2.97 e-5 for operator SE-1. The correlations between Handheld Pressure and the laboratory measures weakened slightly, at 0.7179 and 0.6934 with Puncture Resistance in occasions −1 Month and −0 Months respectively, and at 0.7645 and 0.7699 with Tissue Firmness during these occasions. There was a large change in the standard deviation used in the power analysis. This would decrease from 0.2836 to 0.1711, resulting in the need for much smaller sample sizes in the analysis of a survey design. For the mean differences of 0.100 MPa, samples of 32.7 and 18.4 respectively would be required for operator SE-2 – down from 86.5 and 47.0.

Reliability study

For the assessment in the national variety trials in SE, the correlations between 2019 and 2020, 2020 and 2021, and 2019 and 2021 were: $r\ (9) = 0.8566$, $p = 3.12$ e-3; $r\ (18) = 0.9449$, $p = 3.62$ e-9; and $r\ (7) = 0.7448$, $p =$ 5.48 e-2. For 2020 and 2021, the shared sample consisted of 18 varieties, and the varieties occupying the highest three and lowest four rank positions were identical (Figure 6). The correlation value between 2019 and 2021 is based on a shared sample of only seven varieties and has a *p*-value greater than 0.05. Handheld Pressure values were generally greatest in 2020, and least in 2019.

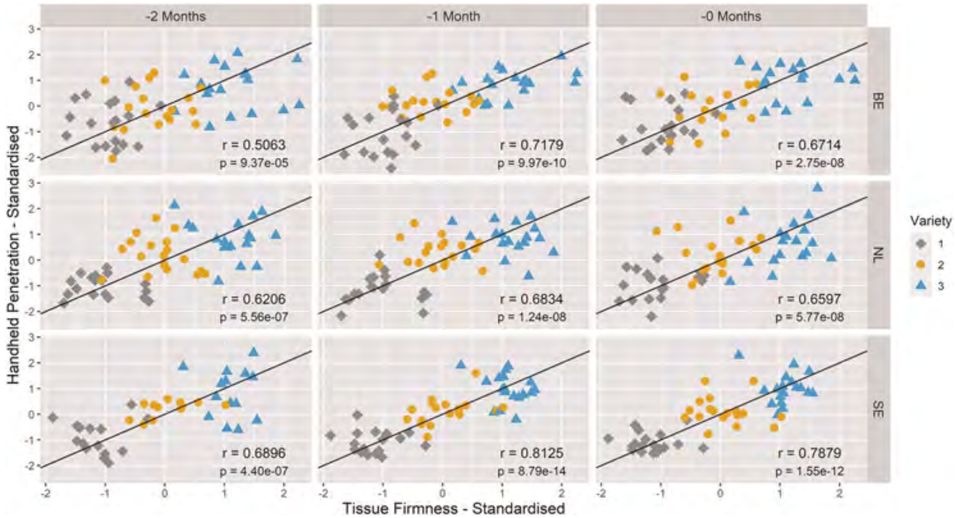

Figure 4. Comparison of Handheld Pressure and Tissue Firmness of roots of three sugar beet varieties, by country and field sampling occasion, 2019. Plot level standardised values. Pearson's *r* correlation and associated *p*-values shown. 1:1 line shown. $N = 10$ per plot and occasion (Handheld Pressure), 15 per plot (Tissue Firmness). BE = Belgium, NL = the Netherlands, SE = Sweden.

Table 4. Power analysis for handheld pressure in sugar beet field trials in Sweden (SE) 2019 and 2020.

Source	Fixed value		SE 2019		SE variety 2019		SE variety 2020	
s.d.			0.2836		0.1389		0.1826	
Design			Survey		Block (10 obs. per plot, 4 reps)		Block (5 obs. per plot, 4 reps)	
	Mean diff.	*n*	Mean diff.	*n*	Mean diff.	*n*	Mean diff.	*n*
SE variety 2020 min.	**0.01**			8452.9		2029.1		3505.4
SE variety 2020 mean	**0.04**			530.1		128.6		220.9
Marker	**0.10**			86.5		22.3		37.0
Marker	**0.30**			11.5		4.6		6.1
Marker	**0.60**			4.6		2.9		3.3
SE variety 2020 max.	**0.97**			3.2		2.4		2.6
SE variety		**4**	0.71		0.35		0.46	
Marker		**30**	0.17		0.09		0.11	

$\alpha = 0.05$, Power = 0.90. Standard deviations shown in table. Mean diff. = Mean difference in handheld pressure (MPa). *n* = sample size. Fixed values in bold. Values below the horizontal line are for the analysis of fixed sample size. 'SE Variety' indicates Swedish national variety trials. 'Marker' indicates a round fixed value taken from within the range of SE variety 2020.

Discussion

Average textural properties and comparison of measurement procedures

The values obtained for Handheld Pressure reflect the laboratory measures. The ranking of varieties was stable over sampling occasion and trial site (Figure 2), and over the three years of the reliability study (Figure 6). This also reflects the findings in the laboratory for sugar beet roots in Kleuker and Hoffmann (2021). This suggests that the handheld penetrometer is an acceptable method for assessing the textural properties of sugar beet roots. The absolute magnitude of the variety mean Handheld Pressure values was similar to Puncture Resistance (Figure 2), but the range in values was most similar to Tissue Firmness (Table 3). The similarity in range of the Handheld Pressure values to Tissue Firmness, coupled with the high correlation coefficients for these two measures in all countries at all occasions (Figures 3 and 4), suggests the handheld penetrometer is able to capture data of high value; Kleuker and Hoffmann (2020) found that tissue strength is an indicator of rates of damage during harvest and transport of sugar beets, and of subsequent post-harvest storage loss. Statistically, the stronger associations between Handheld Pressure and Tissue Firmness can be contributed to

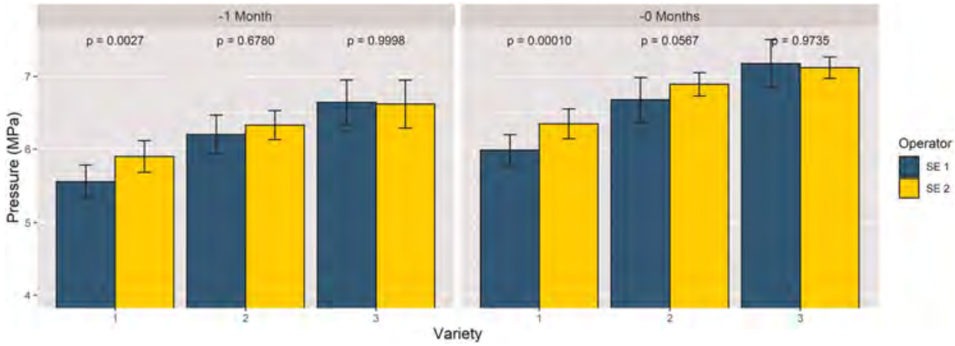

Figure 5. Comparison of mean Handheld Pressure of roots of three sugar beet varieties for two operators in Sweden (SE) during occasions −1 Month and −0 Months. 2019. Numbers over clustered bars indicate *p*-values from post-hoc Tukey test for operator comparison for each variety × occasion. Vertical bars indicate standard deviation. $N = 18$ per variety and occasion.

the greater between variety variation of the Tissue Firmness values in comparison to Puncture Resistance – (Figure 2, Table 3). This is reflected on the scatter plots as a distribution that more clearly clusters by variety while also forming around the 1:1 line (Figures 3 and 4). It has to also be kept in mind that the varieties were chosen with regard to creating differences in mechanical properties, and as evidenced in the reliability study, small mean differences are unlikely to be found as significant.

The similarity of the magnitude of Handheld Pressure to Puncture Resistance reflects the similarity in the mechanics of the measurements. The handheld penetrometer records the maximum force over the sample range of 0–5 mm, and Kleuker and Hoffmann (2019) show that the maximum force over the 0–5 mm sampling range in a sugar beet root is typically the force required to rupture the periderm; that is, the Puncture Resistance (Table 3). The greater range of values measured for Handheld Pressure than for Puncture Resistance despite the similarity in the parameters, then becomes noteworthy. This is possibly a result of operator control in the application of the handheld penetrometer. This would be similar in mechanism to the issue of application speed as discussed by Abbott (1999) in which the greater viscous behaviour of the softer material leads to a lesser loading rate and a lesser measured resistance. This difference may alternatively originate from the selection of the sampling point on the sugar beet root with the handheld penetrometer. Smaller beets may have been sampled higher on the root, as the available root surface above the soil becomes limited. Kleuker and Hoffmann (2019) found variations in Puncture Resistance along the length of the root and the higher concentration of vascular tissue over parenchyma tissue suggests the crown

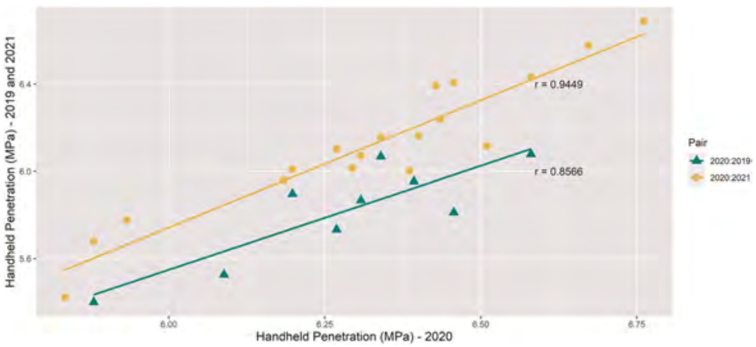

Figure 6. Comparison of handheld pressure (MPa) of sugar beet roots from Swedish national variety trials 2019, 2020 and 2021. Correlation coefficients shown.

region of the beet should be stronger (Gemtos 1999). Observation in the field suggested that at any one point in time, there was an inverse relationship between sugar beet root strength and the size for the three varieties used in this research. This could mean that stronger beets may have been sampled at a point of typically stronger cell tissue, which would accentuate any differences in tissue strength. For this to hold, however, it must be assumed that the general increase in Handheld Pressure occurring over the season and at the same time as a general increase in root size, is a result of a general increase in tissue strength. Given sugar beet is a biennial plant that neither undergoes senescence or ripens prior to harvest in commercial systems (Elliott and Weston 1993; Scott and Jaggard 1993), changes in Handheld Pressure over time will not capture maturity as it may in other crops. In a situation with sugar beet roots of different sizes, being able to reliably select a uniform sampling point is paramount.

The generally larger standard deviations for Handheld Pressure in comparison to the two laboratory measures (Figure 2) can also be attributed to the ability of the operator to control the handheld penetrometer. Even if the sampling point and speed and angle of insertion were relatively easy to control, it is simply not possible for a human operator to match the consistency of speed of application achieved by the mechanical drive motor of the laboratory analyser. The need for a reasonable sample size was highlighted in the large increase in the average standard deviation that accompanied the large decrease in within plot sample size from 2019 to 2020 in the reliability study (Table 4).

Timing of data collection

The results in general do not indicate a preferred sampling occasion. The ranking of Handheld Pressure values was consistent over the three occasions (Figure 2), each of the three trial sites had the largest range in Handheld Pressure during a different sampling occasion (Table 3), and the pattern of correlations between the field and laboratory measures were similarly variable (Figures 3 and 4). A similar conclusion could be drawn from Nause et al. (2021), who recently showed that the ranking of textural properties of different sugar beet varieties was stable over the period August to November. However, given the issues with variable resistance at different points along the length of the root, the issues with accessing the sampling points in SE in occasion −2 Months, and the slightly higher standard deviations in the first sampling occasion, sampling in the last month prior to harvest appears preferable.

The general increase in Handheld Pressure with sampling occasion (Figure 2) suggests that comparisons of absolute strength are only valid when sampling occurs within a single period. This should be coupled with the conclusions of Kleuker and Hoffmann (2021), who show that such comparisons are only valid within a single growing environment. The decrease in mean Handheld Pressure in NL between occasions −1 Month and −0 Months also highlights this point. The reason for this decrease is not known but likely reflects beet physical properties that differ with varying environment conditions between sampling occasions, such as beet cell turgor.

Sample size

The power analysis (Table 4) demonstrates that rapid sampling with a handheld penetrometer to rank varietal strength is feasible, but also that the sampling size is highly dependent on the expected standard deviation of measurements. With the survey design, 86.5 samples were needed to find a mean difference of 0.10 MPa significant (Figure 5). This is a similar sample size to the 90 employed per variety and location in Kleuker and Hoffmann (2021). Being able to identify mean differences of 0.10 MPa as significant would increase the number of significant groups in the reliability study for 2020 from seven to 14. The reliability study, however, used a block design. The 37.0 and 22.3 observations the power analysis showed where needed to find a mean difference of 0.10 MPa significant with the standard deviations from the block designs, is an unrealistic number of plots for most experiments. For large trials, like the national variety trials of Sweden with six sites and four replicates per site (24 plots in total), it could be achieved. Kleuker and Hoffmann (2022) state that the inclusion of measures of tissue strength in variety trials could be of benefit to industry through the provision of information around the underlying storage potential of varieties. The power analysis suggests the handheld penetrometer would be able to achieve this with sufficient accuracy.

Comparison of operators

The results from the second operator in SE further support the proposition that the handheld penetrometer is a viable tool for assessing the textural properties of sugar beet roots. The rank of the varieties remained constant, and the differences remained significant (Figure 5). The absolute values varied only marginally, and the reduction of within variety variation – from an average standard deviation of 0.2836 for operator SE-1 to a standard deviation of 0.1711 for operator SE-2 – suggests it is possible to find smaller between variety difference for a survey design with a given sample size than the original power analysis suggested. However, given this comparison only covers two operators in two time periods, it is difficult to draw conclusive generalisations on what between operator variation can be expected.

Following Li et al. (2016), a possible explanation for the operator differences is in the measurement speed applied. In this case, operator SE-2 applied a higher speed and the between operators differences disappear for samples with higher resistance. Following Gemtos (1999) and Kleuker and Hoffmann (2019) selection of sampling point is an alternative explanation. In this case, operator SE-1 may have selected points relative to the soil surface instead of relative to the crown, resulting in the selection of points that were lower and weaker for the larger roots of Variety 1. Whatever the reason for these differences, it highlights the need to standardise method and operator training.

Choice of penetrometer

The inherit repeatability of the laboratory penetrometer method commends it as the preferred choice of method in analysing textural properties when a more controlled testing environment is desired. The laboratory method also has the advantage of supplying multiple metrics and more detailed and automated data – it remains the benchmark method. Given the reliability of the handheld penetrometer method, as tested here, its application can be recommended in large-scale experiments, as an economic additional test in ongoing experiments, or in circumstances in which the financial demands of the laboratory equipment is too great. The handheld equipment has much lower costs in terms of capital, but also in avoiding the need to expand trials to provide material for laboratory testing, to divert this material from the field, and in a quicker sampling rate. Examples of its potential use include examinations of the strength of sugar beet varieties on national lists, surveys of intra-national or inter-farm variation in sugar beet root strength, or surveys of variation in sugar beet root strength near to harvest time or during storage. It should be kept in mind that comparisons of the absolute strength of sugar beet roots is only valid under constant growing conditions, and the results from any penetrometer cannot be used to draw direct conclusions about harvest damage or post-harvest losses, but can be used in an indicative manner. While the focus of this work has been on varieties, using the handheld penetrometer within a variety but across agronomic conditions or treatments would also be viable, as long as sufficiently large differences in Handheld Pressure are expected. Standard procedure and operator training is essential.

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No potential conflict of interest was reported by the author(s).

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Notes on contributors

William English is Industrial doctoral student at the Swedish University of Agricultural Sciences, and employed at NBR Nordic Beet Research Foundation in Sweden, studying the management of sugar beet clamps under Nordic climate conditions.

Joakim Ekelöf is Project Manager at NBR Nordic Beet Research Foundation in Sweden and Denmark, responsible for the organisation's research in harvest and storage. Doctoral degree in Agricultural Science in 2014 from the Swedish University of Agricultural Sciences.

Françoise Vancutsem is former Project Manager at IRBAB-KBIVB, Institut Royal Belge pour l'Amélioration de la Betterave, Tienen, Belgium.

Martijn Leijdekkers is Project Manager and Head of the Analysis Department at IRS, Institute of Sugar Beet Research, Dinteloord, the Netherlands. Doctoral degree in Food Chemistry in 2015 from Wageningen University.

Gunnar Kleuker is doctoral student at the University of Göttingen, studying the relationships between textural properties and storability in sugar beet.

Christa M. Hoffmann is Professor of Crop Science and Head of the Physiology group at IfZ, Institute for Sugar Beet Research, Göttingen, Germany – part of the University of Göttingen.

Data availability statement

Data and script from this project can be found here: https://github.com/Nordic-Beet-Research/COBRI-Handheld_penetrometer.

ORCID

William English http://orcid.org/0000-0001-5197-2342
Christa M. Hoffmann http://orcid.org/0000-0002-8673-7016

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Sugar beet roots are stored post-harvest in the field in Sweden and much of Europe for periods of up to two months. This thesis investigated the interaction between key agronomic inputs and the mechanical properties of sugar beet roots and their storability, methods for the evaluation of mechanical properties in sugar beet roots, and the transfer of water and heat across the entire sugar beet root bulk during storage.

William English received his graduate education at the Department of Biosystems and Technology, SLU, Alnarp. His undergraduate degrees are BSc. Agricultural Science (Hon.) and BSc. Commerce, received at The University of Melbourne, Parkville, Victoria, Australia.

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