Long Term Storage of Sugar Beets and the Role of Temperature

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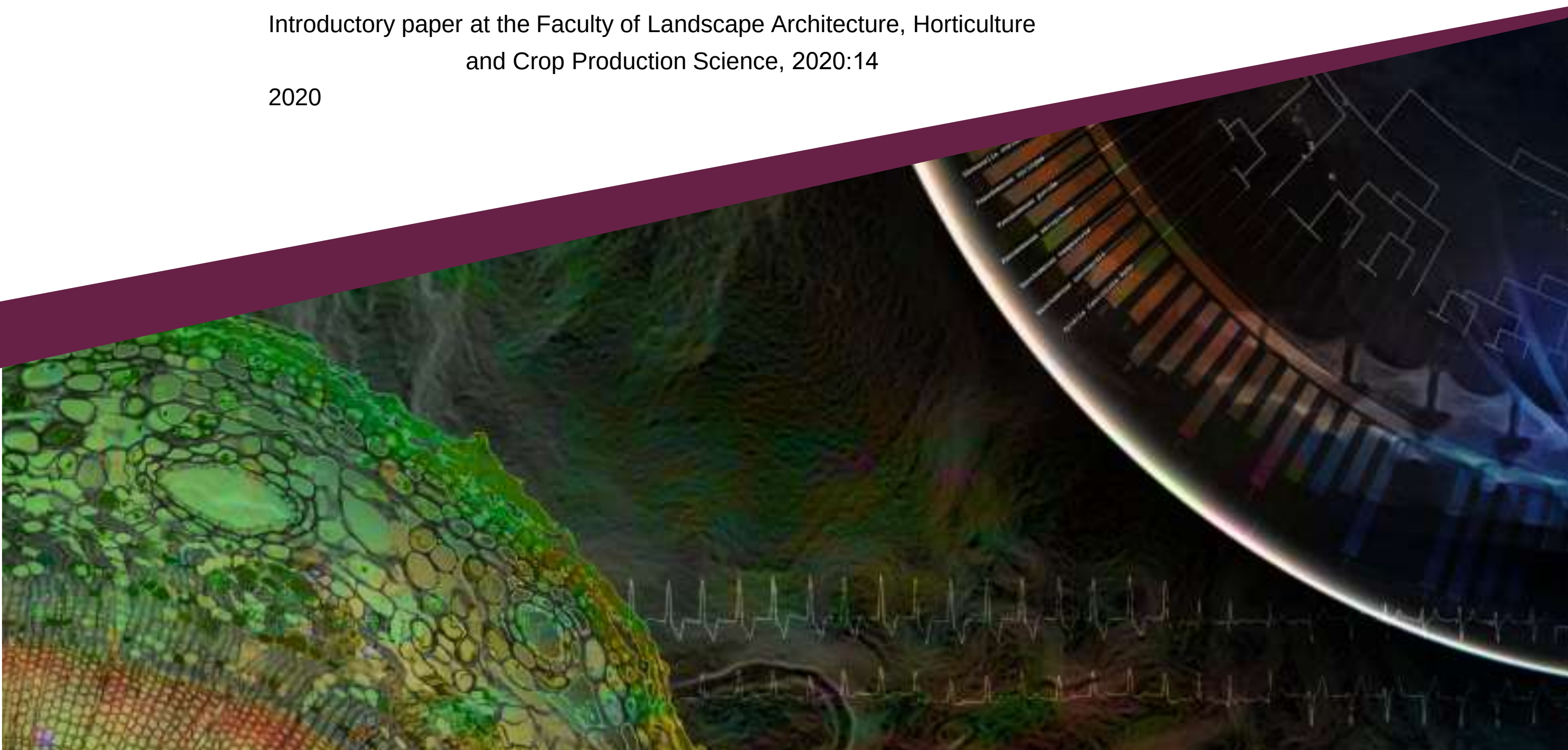

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1 Introduction

This paper is written as part of the course "Introduction paper", given by the Swedish University of Agricultural Sciences' (SLU) graduate research school of the Faculty of Landscape Architecture, Horticultural and Crop Production Sciences (LTV). It provides an overview of research around the role of temperature in the long term storage of sugar beets. The importance of moisture and mechanical damage are also incorporated. The focus is on on-farm storage systems - "clamps". Figure 1 shows uncovered sugar beet clamps in the field.

1.1 Background

Sugar beet is a commercial agricultural crop of economic signficance in many countries of the world and that suffers from economically significant post-harvest losses. Sugar beets provide approximately 20% of the world's sugar, with commercial production spanning every inhabited continent with the exclusion of Australia (Anon, 2020b). Within Europe, 100% of sugar production is from sugar beet. In 2019, Sweden produced 288 000 tonnes of raw sugar, from just under two million of sugar beet root, grown on 26 600 hectares by 1 152 growers (Lindkvist, 2020).

Sugar beet clamps It is not possible to quantify exactly what proportion of sugar beets in Sweden are stored in clamps during a harvest campaign, but as an indication;

- a normal harvest campaign is around 110 days lasting from late September until late January,
- all beets are required by the industry contract to be harvested by 30 November, the approximate mid-date of the campaign.

As such, approximately 50% of all beets will be placed in a clamp for an extended period, up to a maximum of 60 days.

SDG 12.3 Post-harvest losses has been identified specifically within the United Nations Agenda 2023 Sustainable Development Goals (SDGs) as an issue of importance. SDG 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, 2020c). The Food Loss Index of the Food and Agriculture Organisation of the United Nations (FAO) had global food losses in 2016 at 13.8% of food production (Anon, 2020a). For roots and tubers, the total food loss and waste is estimated at an astonishing 45% - the equal highest of any broad food category, along with fruits and vegetables (Anon, 2015).

(a) A long sugar beet clamp, constructed from multiple unloadings

(b) Field transport and angle of repose

Figure 1: Sugar beet clamps in the field

Swedish sugar beets and SGD 12.3 As an industry, Swedish sugar beets most likely do not experience post-harvest losses near the scale of the global all-foods average of 13.8%. Using the figure described later in this work of 0.1% of sugar lost from stored sugar beets per day, on the upper bound of 50% of beets being stored, for an average of 30 days, the food losses during on-farm storage are approximately 1.5% of total sugar production. Even with the addition of handling and processing losses, it is unlikely that the total food losses are greater than 5%. 1.5% is still worth many million kronor. Further, for producers who experience storage conditions that see them lose anything up to 100% of a single clamp, the impact of post-harvest loses are significant.

Temperature in sugar beet clamps Extreme temperature is the most common cause of high post-harvest loss rates; longer periods of sub-zero temperatures can cause beets to freeze and lose all value in processing. In the positive temperature scale, and as further discussed in detail in this work, rates of loss are higher when temperatures are higher, and rates of loss are well linked to temperatures. Multiple research projects by the Swedish and Danish national sugar beet research organisation, Nordic Beet Research, has focused on the question of temperature in sugar beets clamps and shown the importance of managing this factor (see for example Olsson, 2013). Summarising long-term storage of sugar beet in North-Western Europe, Huijbregts et al. (2013, p7) state that "...sugar losses mainly depend on the storage temperature". In general, Willis and Golding (2016) state "Temperature is the single most important factor determining the maintenance of postharvest quality ...".

1.2 Structure

The paper begins with an introduction to the framing of the work, including a description of the disciplinary focus, and an introduction to the systems of analysis. This is undertaken owing to the cross-disciplinary nature of the work. The majority of the paper draws on ideas from the discipline of crop physiology of agronomy. Energy sciences of engineering are also drawn on, especially in Section 3 - Research gaps. While it is not unique to combine these disciplines (see for example, the MeBioS Postharvest research group at KU Leuven (Nicolai, 2020)), it is possible that many of those interested in this work will not be familiar with the norms of one or the other of them. The next section - Section 2 - presents a discussion on how sugar losses in a sugar beet clamp are related to temperature. It includes a review of the literature on key relationships in which temperature is an explanatory variable. Section 3 then focuses on describing areas of research that may be under developed and thus have room for exploration. Controlled climate storage, mechanical properties, and the CFD methodology, are all areas discussed.

1.3 Framing

1.3.1 Discipline focus

Temperature and change in temperature Temperature is the main metric in focus within this work. It is temperature that the research from the agricultural sciences has linked to rates of loss of sugar in clamps. It is a useful and intuitive metric. At the same time, given this study looks at how temperatures change as a result of system interactions, it is pertinent to incorporate discussion on the mechanisms that engineers focus on when describing the transfer of thermal energy that results in temperature changes. This occurs mainly in Section 3, where reference is made to studies of thermodynamic processes. Here, particular care given to maintaining the uses of terminology from engineering sciences.

Discussions on temperature and changes in temperature of substances usually belong to physics or the engineering sciences. In the engineering disciplines of energy science, the subjects of the generation, use, conversion, and exchange of thermal energy are all considered (source). These disciplines are largely the application of the physics discipline of thermodynamics, which looks at the subjects of heat and temperature as they relate to energy and work (sources). Particularly in physics, the definitions of heat and temperature are distinct and clear; heat refers to the transfer of thermal energy between two systems, while temperature measures the average thermal energy of a system. However, given this work draws only engineering, the term "heat transfer" will be used when referring to the transfer of thermal energy. "Heat generation" or simply "temperature change" will be the terms used when referring to the change in thermal energy of a system.

Engineering fields Heat transfer is itself seen as a sub-field of engineering. Practitioners of Heat transfer (with a large H) most often study methods of optimising heat transfer (with a small h) in mechanical systems, such as motors and generators, and in the built environment.

The other particular sub-field of engineering that is of high relevance is that of Fluid mechanics. The actual heat transfer process is usually a coupled process. That is, it occurs in concert with other dynamic processes. The main coupled process of interest is the movement of fluids, where "fluids" includes both gases and liquids, and Fluid mechanics is thus the study of the motion of matter in these states.

Biology While the engineering fields of Heat transfer and Fluid mechanics give the greatest insight to the mechanisms of changes to temperature within a system, this work draws mainly from work completed by researchers from the biological sciences. Given this work focuses on the storage of a food crop, knowledge from the crop physiology field will be incorporated at length. This is particularly so in Section 2. No conflicts between the disciplines are in need of highlighting.

1.3.2 System level focus

Two systems The discussion focuses on two distinct idealised systems, at different levels and pertinent to post-harvest storage of sugar beets;

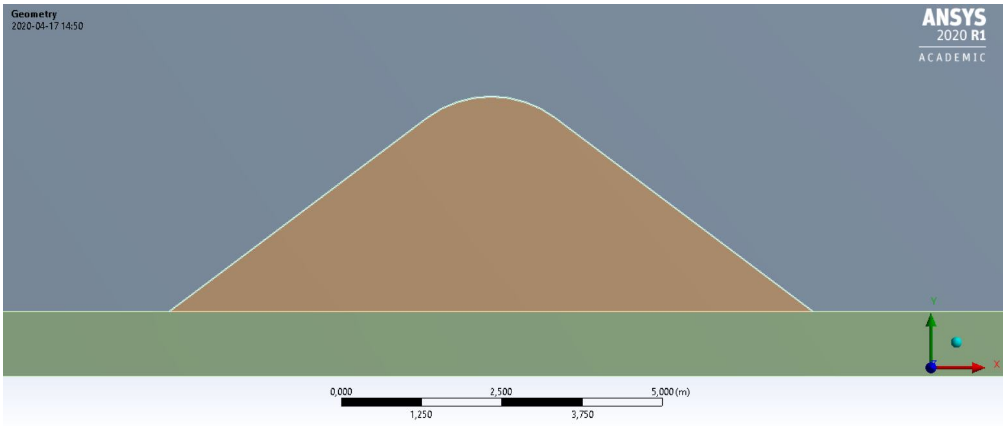
1. *The clamp level system* of multiple sugar beets within a bulk storage unit, with bulk porosity, and situated on bare soil in the open air. This reflects the entire clamp seen in Figure 1 and which is idealised in Figure 2a.

2. *The beet level system* of a single sugar beet, its surface, the surface air layer, and the air space immediately beyond the surface layer; see Figure 2b.

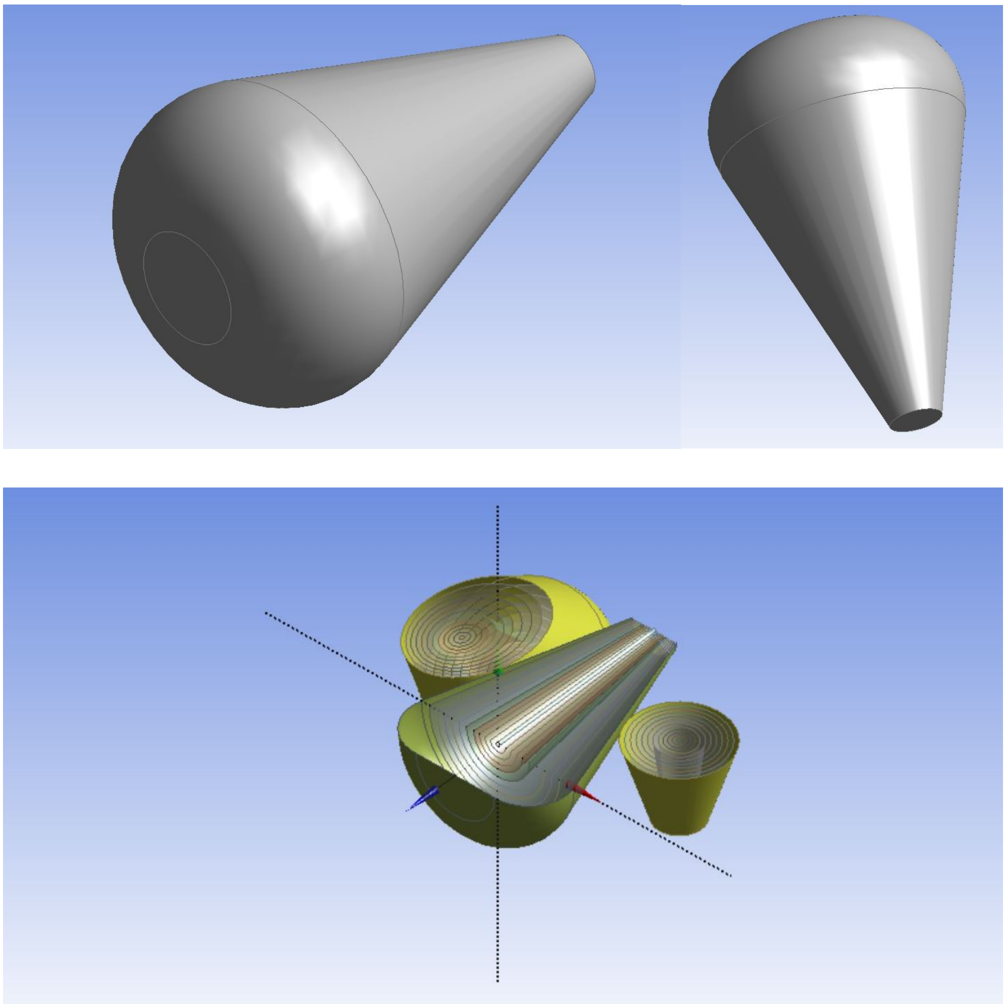
Please note the various research discussed in this work will have been conducted at either of these levels and may not explicitly clear. This will not, however, detract from the conclusions drawn from these works. The discussion focuses primarily on the clamp level system.

The clamp level system The architecture of sugar beets clamps in much of Europe is driven by the practicalities of harvest and transport. The width is bounded by the limits of the machinery used to load the clamp into the transport that takes the crop to the processing plant. Modern loading machinery has a working width that means the maximum recommended width of a clamp is nine meters. It is usual with clamp construction that the clamp width is actually defined by the limits of the unloading technique, bounded by the nine meters restriction of the loading machinery. For example, a very small chaser wagon may only be large enough to construct a clamp of seven meters width. The bound on width coupled with the manner in which the clamp is built and friction forces holding the beets in a pile, defines the clamp height. A clamp built directly from the unloading of the harvester can be much higher than one built from the unloading of chaser wagons that transport the beets from the harvester to the pile. The angle of repose of a clamp - the inner angle the clamp makes with the ground - is not known to be empirically defined, but is approximated to be 33°. A nine meter wide clamp is thus approximately 3 meters high. The length of the clamp will be defined by the size of the field, both in terms of the total harvest and in the space available for any single clamp. Clamp length can vary from as little as twenty meters, to several hundred.

The regularity of the clamp level system Construction of sugar beet clamps rarely results in a regular shape; see Figure 1a. The length often snakes to follow the edge of the field. The height often varies with length, with each load from the harvester, resulting in an irregular wavy pattern along the top and sides of the clamp with a wavelength of several meters. The width at the base of the clamp too can vary with every load coming from the harvester. All these irregularities will impact the heat transfer of the system. The inter-load variations - those on the scale of a few meters - are of interest owing to anecdotal evidence that they create air pockets that can result in the accumulation of excessive moisture, and negative temperatures in the occasion of a frost event.



(a) The clamp level system: Brown area. ca. 9m wide at the base



(b) The beet level system. Top: Single, entire beet. Bottom: Idealised beet between two others, sliced

Figure 2: Examples of the systems of relevance regarding sugar beet storage in clamps

Covering the clamp level system When a clamp is to be in a field for an extended period over which the probability of either rain or frost events is real, it is usually covered to help protect economic value. A range of different covers are in common use, with the choice of cover based on thermodynamic properties. Covers change the properties at the clamp-air interface mainly by restricting convective fluxes: that is, the flow of air, moisture, and thermal energy. Heavier covers are also able to greatly slow diffusive fluxes: they insulate. Some common cover types include.

- None
- Breathable propylene fleece (TopTex ®)
- Plastic
- Straw
- Combination of fleece and plastic
- Combination of straw and plastic

The beet level system The beet level system of this current work is defined at the level of an idealised, entire, sugar beet, and extends into the near space beyond the surface of the beet. This level of resolution is chosen as it reflects the empirical data and allows a concise exploration of the heat transfer processes. The beet level systems as defined here incorporates a number of sub-systems for which it is usual that biological processes are defined and explored on. For example, plant metabolism processes are usually defined at the molecular and cellular level. These processes are the source for the heat generation discussed in Section 2 of this work. However, aggregation to the level of the entire sugar beet does not detract from the discussion and generally reflects the empirical data.

The regularity of the beet level system The form of an entire sugar beet is only approximately regular. That is, there is large variation is the true shape of a sugar beet. To give reference to the dimensions of the system, an idealised beet is considered. This idealised beet is here approximated as an inverted conical shape with a rounded top. Owing to harvest practices, this approximate shape includes a truncated top and bottom. The beet is a length of 23cm, a diameter at widest section of 14cm, and tip diameter along breakage of 3cm: see Figure 2b. The two furrows of the sugar beet, that run twisting slightly on opposites sides of the lateral length of the inverted cone section, will not be considered. The surface of the sugar beet will be considered smooth yet permeable, with different properties on the sections representing the cut-off ends. The internal portions of the sugar beet shown in Figure 2b will generally be considered a homogeneous mass.

1.3.3 Source focus

The focus of the review section - Section 2 - is primarily the academic literature. While on-farm field storage is the target production system, the source material must include literature from both the laboratory scale and from research conducted in the very large factory-located storage systems. Limited reference to research that has not been subject to formal peer review is made when the source is known. Such research has mainly been conducted by industry funded national research organisations.

2 Sugar loss in sugar beet storage and the role of temperature

2.1 Proximal causes of sugar loss

While time and temperature are not the mechanisms through which sugar is lost from sugar beets during storage, it is useful and common to assess losses in these terms.

2.1.1 Time

Over the entire campaign For sugar beets stored for any meaningful period under commercial conditions, total sugar loss over the length of storage is expected to vary from between near zero and 10% of the initially available sugar volume. Higher levels are often observed, and under extreme conditions where beets deteriorate to the point of being unprocessable, commercial losses can be 100%.

Per day In terms of loss per unit of time, studies conducted under normal commercial storage conditions of less than 10°C and between one and three months, have calculated average daily sugar loss to vary from between 0.17 up to 1.4 kilograms of sugar per tonne of beet per day (Downie, 1950; Jaggard et al., 1997). At a sugar concentration of 17% in the sugar beet, that is 0.1 to 0.8% per day. Daily losses also vary within any one clamp. As a general trend, per day losses increase with time, but can be significantly higher during parts of the storage period.

A rule of thumb often used in the management of clamps that will stand for more than a week is that between 0.1 and 0.2% of initially available sugar will be lost per day. If 10% total loss is taken as an upper permissible bound, this suggests a clamp can be left to stand for anywhere between 50 and 100 days - a big margin of error.

2.1.2 Temperature

A well established means of refining estimates of levels of loss is to consider the temperature of the clamp, or at least the temperature of the environment in which the clamp stands. The role of temperature as a proximate cause of loss is well documented in the literature, and dates back at least to the late 1940s, when a number of trials on large scale commercial factory storage in the US were being conducted (see for example Gaddie and Tolman, 1952). Subsequent laboratory and field trials have repeatedly verified these results, adding nuance to the point where the relationship is satisfactorily understood both in terms of mechanisms and the correlation, covariates and limits in the relationship.

Degrees (°C) Many studies have shown, all else held constant, that a higher temperature in a field clamp will result in a higher level of sugar loss. For example, for 1948 Downie recorded a sugar loss per ton of beet of 6.2 kg for a pile stored at ca. 4.4°C, compared to a loss of 14.2 kg for a pile stored at 7°C. In 1949, the difference was a lot less, with losses of 7.4 and 8.8 kg per ton of beet at approximately the same temperatures.

More recently and in on-farm clamps, Nordic Beet Research found that by maintaining a temperature difference through active ventilation, sugar concentration reductions during storage could be significantly reduced (Ekelöf, 2019). For a clamp with an average temperature of 9.6°C, sugar concentration reduced from 19.0% at harvest to 18.1% at delivery, some six weeks later. For the ventilated clamp, the temperature averaged 5.5°C for the same period, with sugar concentration at delivery measured at 18.5%. For the small 200 tonnes of beets each clamp consisted of, this difference is equivalent to nearly one tonne of sugar.

Degree-days (°Cd) A meaningful method for defining the relationship between sugar loss and temperature is to measure temperature as accumulated thermal time, given as degree-days (°Cd). It has been shown that accumulated thermal time is able to provide more generalisable relationships with loss, with the relationship between °Cd and loss holding up relatively well against daily, locational, and seasonal variations. In post-harvest storage, degree-days are counted in the positive Celsius scale. For example, storage for 24 hours at 10°C is equivalent to 10°Cd, storage for 10 days at 1°C is equivalent to 10°Cd, or storage for 54 days at 5°C is equivalent to 270°Cd.

°Cd and rates of loss In a trial conducted by Jaggard et al. (1997) under commercial operating conditions across 18 farms in the UK for storage periods of up to 85 days, accumulated thermal time was a strong predictor of sugar loss. They estimated 0.0188% of the initially available sugar was lost per degree-day on average. For this to be equivalent to 0.1% per day, the clamp must be at 5.3°C. At 10°C, the loss per day is 0.18%.

Other studies, such as those of Legrand and Wauters (2012) have found comparable values, although with more nuanced conditions. Legrand and Wauters showed that after 270°Cd, the rates of sugar loss increase greatly. For the period up to 270°Cd, an average loss of approximately 0.013% of initial sugar per degree-days was calculated. Thereafter, for the period from 270 to 450°Cd, an average loss of 0.042% of initial sugar per degree-day was found. The average for the total period of 450°Cd was approximately 0.024% per °Cd. Legrand and Wauters' figures are equivalent to Jaggard's at 337.5°Cd - a value that would be considered to be entering the high risk phase of storage for commercially harvested beets. Table 1 summarises these findings.

Table 1: Sugar loss from sugar beets during storage

Temperature (°C)	Damage	Days	Degree-days	Sugar Loss (%) Total	Per day	Per °Cd	At 270°Cd	Comment	Source
Seasonal	Commercial	$\leq$ 85	na	na	na	0.0188	5.1	Clamp	(Jaggard et al., 1997)
Seasonal	Commercial	$\leq$ 85	0 - 270	na	na	0.013	3.5	Clamp	(Legrand and Wauters, 2012)
Seasonal	Commercial	$\leq$ 85	0 - 450	na	na	0.024	6.5	Clamp	(Legrand and Wauters, 2012)
Seasonal	Commercial	$\leq$ 85	270 - 450	na	na	0.042	11.3	Clamp	(Legrand and Wauters, 2012)
Mostly $\leq$ 4.5	Commercial	40	na	3.8	0.095	na	na	Pile - ventilated	(Downie, 1950, tab. 1)
Mostly $\leq$ 4.5	Commercial	38	na	6.1	0.161	na	na	Pile - ventilated	(Downie, 1950, tab. 1)
$\leq$ 13, $\leq$ 4.5 (16d)	Commercial	40	na	7.0	0.175	na	na	Pile	(Downie, 1950, tab. 1)
$\geq$ 7.0	Commercial	38	na	7.5	0.197	na	na	Pile	(Downie, 1950, tab. 1)
5	Extra[a]	21	105	na	0.00	0.0000	0.0	Controlled	(Kenter et al., 2006, fig. 7)*
5	Minimal	21	105	na	0.05	0.0096	2.6	Controlled	(Kenter et al., 2006, fig. 7)*
5	Normal	62	310	2.29	0.037	0.0074	2.0	Controlled	(Legrand and Wauters, 2012, fig. 1)*
5	Normal	79	395	4.42	0.056	0.0112	3.0	Controlled	(Legrand and Wauters, 2012, fig. 1)*
10	Normal	46	460	4.03	0.088	0.0088	2.4	Controlled	(Legrand and Wauters, 2012, fig. 1)*
10	Normal	30	300	2.66	0.089	0.0089	2.4	Controlled	(Legrand and Wauters, 2012, fig. 1)*
12	Extra[a]	21	252	na	0.15	0.0129	3.5	Controlled	(Kenter et al., 2006, fig. 7)*
12	Minimal	21	252	na	0.03	0.0021	0.6	Controlled	(Kenter et al., 2006, fig. 7)*
15	Normal	20	300	2.06	0.103	0.0069	1.9	Controlled	(Legrand and Wauters, 2012, fig. 1)*
15	Normal	30	450	4.57	0.152	0.0102	2.8	Controlled	(Legrand and Wauters, 2012, fig. 1)*
20	Extra[a]	21	420	na	0.44	0.0221	6.0	Controlled	(Kenter et al., 2006, fig. 7)*
20	Minimal	21	420	na	0.09	0.0045	1.2	Controlled	(Kenter et al., 2006, fig. 7)*
20	Normal	15	300	3.43	0.228	0.0114	3.1	Controlled	(Legrand and Wauters, 2012, fig. 1)*
20	Normal	24	480	4.79	0.2	0.0100	2.7	Controlled	(Legrand and Wauters, 2012, fig. 1)*

* Data extracted from figure. Loss per day calculated as total loss / total days [a] Tumbled in cleaning drum 45 seconds.

Further to adding nuance to the relationship between accumulated temperature and sugar loss, the study of Legrand and Wauters (2012) showed that the relationship between degree-days and sugar loss in sugar beets was comparable for temperature ranges of 5 to 20 °C (see Table 1 for a selection of these results). It is important to note that in Legrand and Wauters (2012), the 270°Cd is taken as the temperature of the ambient air outside of the clamp. This, they note, corresponds to temperatures inside the clamp of 300 to 350°Cd, or ca. 11% to 30% higher.

High temperatures The literature on the storage of sugar beets at high temperatures is very thin, owing surely to the fact it is clear that it is bad commercial practice. One study from California in 1952 highlights this. Losses of approximately 8% of initially available sugar were experienced in just 36 hours when freshly harvested beets were stored at 29°C (Orleans and Cotton, 1952). This percentage loss in just 44 degree-days is equivalent to that expected from approximately 425 degree-days using the results of Jaggard or 333 degree-days if applying the 450 day average of 0.024% per degree-day from Legrand. This highlights both the non-applicability of the degree-day relationship for all conditions, and the need to store beets under low temperatures.

Negative temperatures Within the cumulative temperature framework, the degree-days relationship only holds within the bounds of a limited range of positive temperatures on the Celsius scale. As such, a negative temperature does not contribute to a reduction in degree-days. Indeed, it is usual that exposure to negative temperatures ultimately results in increased total sugar loss compared to the positive yet low temperature range.

Should a beet cell freeze, it is usual that processability is rapidly lost upon thaw. Any resulting rupturing of cell walls permits the leaching of electrolytes and the entry of pathogens. Bacteria that enter the cell after thawing result in the production of the non-processable invert sugars and polysaccharide gums levan and dextran (Oldfield et al (1971) cited in Campbell and Klotz, 2006; Milford et al., 2002). Taking from Wyse (1978, figure 5); using release of carbohydrates as a direct proxy for cell damage, the pre-freezing release level as the base rate in the experiment, and the -8°C release rate as 100%, approximately 8% of sugar beet cells are damaged at -1°C, 14% at -2°C, 39% at -3°C, and 78% at -4°C. Wyse (1978) themselves suggest all cells are frozen or destroyed at -5°C, and about half are thus at -3°C.

It is possible for a beet to withstand short durations of negative temperatures without freezing, owing in large to the lower freezing point of a solution with high sugar content. At 17% sucrose, and 77% water, the freezing point of the liquid component of the beet is approximately -1.2°C (own calculations [1]). The rate at which the cold penetrates the beet and their ability to produce their own heat also contribute. Further into the negative degrees, the losses from a beet that is frozen but not thawed are less than those of the non-frozen beet. Indeed, in commercial processing systems in which it is likely that very low temperatures of ca. -9°C and less will be realised during many weeks and months, beets are usually permitted to freeze in storage. This has been shown to be an effective means of minimising sucrose loss in long-term storage, with temperatures so far below freezing needed to counter the heat generated within the pile of beets (Backer et al., 1979). Frozen beets are usually processed thus to avoid losses from thawing.

The rates of loss of the frozen then thawed beet are large and rapid to the point that it will be the assumption of this work, with its focus on the use of clamps for storing sugar beets, that all freezing should be avoided. Further, subsequent discussions on temperature refer only to positive temperature in the Celsius scale, unless otherwise stated.

2.2 Mechanisms for sugar loss

The pathways through which temperature impacts the rate of sugar loss of sugar beets in store are broadly well understood. Respiration - both aerobic and anaerobic -, root rot, and mechanical damage have been identified as the major causes of sugar loss during storage. Of these, respiration and root rot are considered temperature sensitive processes. It is of common belief that the temperature at harvest impact rates of damage, but evidence to this in the literature could not be found. Mechanical damage has been shown to be a confounding factor in rates of respiration and rot when interacted with temperature. As such, all three processes will feature further in this work.

2.2.1 Respiration

"Respiration is the process by which carbon compounds are oxidized to provide the metabolic energy and substrates needed for growth and maintenance of all living cells" (Klotz et al., 2008). Harvested roots are heterotrophic - they cannot produce their own energy given they are not actively photosynthesising - and thus respiration of stored compounds provides all metabolic energy and substrates.

Respiration control by temperature In plants, respiration is believed to be controlled by the availability of respiratory substrates, cellular energy status, or total respi-

[1] $\Delta T_1 = K_f m$
K_f water = 1.86
$g_{sucrose} = 17$
Molecular weight of sucrose = 342.32g.mole^{-1}
$mole_{sucrose} = 17/342.32$
$kg_{H_2O} = 0.077$
m = molal = $mole_{sucrose}.kg_{H_2O}^{-1}$

ratory capacity (Klotz et al., 2008). Klotz et al. (2008) also note that respiration pathways of sugar beet are relatively simple, "since respiration occurs from a single substrate (sucrose), and occurs primarily by the linear progression of sucrolysis, glycolysis and the TCA cycle with limited participation by the oxidative pentose phosphate pathway". Klotz et al. (2008) here cites Barbour and Wang (1961) - an early work on metabolism in sugar beets that went a long way in describing the major pathways.

With regard the role of temperature in controlling respiration, Vallarino and Osorio (2019, p217) states: "In general, in all plant tissues, an increase in temperature increases the rate of their metabolism, and hence the consumption of compounds such as sugars and stored TCA cycle acids that serve as metabolic substrates. Modification in organic acid metabolism in response to temperature probably results from the impact of temperature on the reaction rates of glycolysis, TCA cycle respiration, fermentation, and gluconeogenesis by modifying enzyme activities and kinetic properties of the transport systems involved."

The broad general knowledge of respiration in plants and the relative simplicity of the sugar beet respiration pathways does not mean it is fully described, especially for sugar beets under various stress conditions. In what was one of the most comprehensive studies of respiration control in sugar beet up to this point, Klotz et al. (2008) were not able to show that any of the suspected factors were both regulating respiration and temperature dependent, at least not over a 13 day period with the two control temperatures of 1°C and 10°C. Indeed, an answer to the question of what was regulating this process remained allusive; "The lack of regulation of respiration by respiratory capacity, ADP availability or energy status suggests that a respiratory substrate other than ADP restricts respiration in stored sugarbeet roots. Possible substrates that may be limiting include molecular oxygen, NAD+ and reduced carbon compounds whose availability can be limited by a restriction in sucrose cleavage, glycolysis or the TCA cycle." Other studies have focused on temperature, accumulated temperature, and disease stresses (Klotz and Finger, 2004), wounding stress (Klotz et al., 2006), and dehydration stresses (Lafta and Fugate, 2009; Lafta et al., 2020), yet none could conclude that they had described the mechanisms regulating respiration.

An answer? A subsequent study by the same group of researchers with collaborators focused on the above mentioned glycolysis. They were able to draw strong links between the availability of respiratory substrates, glycolysis and respiration rates in sugar beets (Megguer et al., 2017). Temperature was not a factor in this analysis, but glycolysis has been shown to be temperature dependent in other plants.

Temperature dependence of respiration by the numbers Despite the lack of a definitive mechanism behind the relationship between temperature and rates of respiration, the weight of evidence is that respiration in sugar beets is temperature dependent. Average respiration rates at different and stable temperatures have been reported by numerous sources. Table 2 presents respiration rates for these trials. Note that different temperatures and storage lengths and thus number of degree-days, and levels of damage are reported.

Table 2: Respiration rates for sugar beets stored at stable temperatures.

Temperature (°C)	Damage	Days	Degree-days	Respiration Rate Units	Average	Per °C	Peak	Last	Source
-1.0	Normal	126	0	A	3.7†		4.9 (19w)	4.9	(Wyse, 1978, fig. 4A)*
1.0	Minimal	13	13	B	2.6	2.6	5.0 (13d)	5.0	(Klotz et al., 2008, fig. 1)*
1.0	Extra	13	13	B	2.4	2.4	4.6 (13d)	4.6	(Klotz et al., 2008, fig. 1)*
1.5	Normal	133	200	A	5.2†	3.5	6.8 (19w)	6.8	(Wyse, 1978, fig. 4A)*
2.0	Minimal	11	22	A	7.1	3.5	16.8 (5hr)	4.8	(Wyse and Peterson, 1979, fig. 2)*
2.0	Extra[a]	11	22	A	9.2	4.5	21.1 (5hr)	6.6	(Wyse and Peterson, 1979, fig. 2)*
2.0	Minimal	90	180	A	7.5	3.8	11.5 (85d)	10.7	(Wyse and Peterson, 1979, fig. 2)*
2.0	Normal	90	180	A	10.5	5.2	16.2 (85d)	15.0	(Wyse and Peterson, 1979, fig. 2)*
2.0	Extra[b]	90	180	A	10.2	5.1	15.0 (5d)	11.0	(Wyse and Peterson, 1979, fig. 2)*
5.0	Minimal	7	35	C	0.12†	0.036	0.29 (1d)	0.07	(Kenter et al., 2006, fig. 5)*
5.0	Bruised	7	35	C	0.13†	0.026	0.29 (1d)	0.07	(Kenter et al., 2006, fig. 5)*
5.0	Extra[d]	7	35	C	0.17†	0.033	0.21 (1d)	0.08	(Kenter et al., 2006, fig. 5)*
5.0	Normal	133	665	A	6.2†	1.1	8.1 (19w)	8.1	(Wyse, 1978, fig. 4A)*
6.0	Minimal	28	168	A	5.2†	0.8	10.5 (1d)	2.9	(Fugate et al., 2016, fig. 7)*
6.0	Extra[c]	28	168	A	10.1†	1.7	14.3 (3d)	4.8	(Fugate et al., 2016, fig. 7)*
10.0	Normal	126	1260	A	13.2†	1.3	17.1 (18w)	17.1	(Wyse, 1978, fig. 4A)*
10.0	Minimal	13	130	B	2.30	0.2	3.3 (11d)	1.9	(Klotz et al., 2008, fig. 1)*
10.0	Extra	13	130	B	3.63	0.4	5.4 (2d)	3.1	(Klotz et al., 2008, fig. 1)*
10.0	Minimal	12	120	A	10.6	1.1	16.0 (2d)	8.5	(Wyse and Peterson, 1979, fig. 1)*
10.0	Normal	12	120	A	13.5	1.4	17.9 (2d)	10.7	(Wyse and Peterson, 1979, fig. 1)*
10.0	Extra	12	120	A	16.7	1.7	23.2 (3d)	12.2	(Wyse and Peterson, 1979, fig. 1)*
10.0	Minimal	11	110	A	13.6	1.4	25.8 (20hr)	9.4	(Wyse and Peterson, 1979, fig. 2)*
10.0	Extra[a]	11	110	A	16.5	1.6	33.6 (10hr)	11.0	(Wyse and Peterson, 1979, fig. 2)*
12.0	Minimal	28	336	A	5.7†	0.5	9.3 (2d)	2.9	(Fugate et al., 2016, fig. 7)*
12.0	Extra[c]	28	336	A	9.5†	0.8	19.3 (1d)	4.8	(Fugate et al., 2016, fig. 7)*
20.0	Minimal	7	140	C	0.24†	0.012	0.43 (1d)	0.15	(Kenter et al., 2006, fig. 5)*
20.0	Bruised	7	140	C	0.24†	0.012	0.43 (1d)	0.16	(Kenter et al., 2006, fig. 5)*
20.0	Extra[d]	7	140	C	0.36†	0.018	0.54 (1d)	0.25	(Kenter et al., 2006, fig. 5)*

Respiration rate given as A: $mg\ CO_2.kg^{-1}.hr^{-1}$, B: $mmol\ O_2.kg^{-1}.hr^{-1}$, C: $g\ sucrose.kg\ beet^{-1}.d^{-1}$. Units in Peak column indicate resolution of available data. * Data extracted from figure. † Respiration rate derived from fitted linear curve. [a] Individually dropped 1.5m onto asphalt. [b] Individually dropped 2.0m onto metal plate. [c] Scraped with steal brush 2-3 times. [d] Tumbled in cleaning drum 45 seconds.

Comment on the table The results shown in Table 2 show a wide variation in the rates of respiration at any given temperature. This is likely mainly a result of the different conditions within the different experiments. As such, to most clearly see the relationship with temperature, it is best to looking within a single study.

Low temperatures As seen in Table 2, lower average respiration rates have been recorded for sugar beets stored at constant and lower temperatures. Wyse (1978) reported that in beets that had been stored for around 500°Cd, when the temperature went from 5°C to 1°C, respiration rates approximately halved, from around 8 $mg\ CO_2.kg^{-1}.hr^{-1}$ to around 4 $mg\ CO_2.kg^{-1}.hr^{-1}$. It seems, however, that the relationship between respiration rate and temperature is not linear as the temperature approaches zero. There is also evidence that at temperatures closer to 0°C, respiration rates may even at times be similar to at higher temperatures. Klotz et al. (2008) found that on average over 13 day period, there were no great difference in total respiration of unwounded beets at 1°C and 10°C. Indeed, at the end of this period, the respiration rates for the beets stored at 1°C (stored for equivalent of 13°Cd) had a respiration rate of approximately $5mmol.h^{-1}.kg^{-1}$ while those stored at 10°C (stored for equivalent to 130°Cd) had a corresponding value of less than 2. They note that cold-induced increases in respiration have been reported in other plant products post-harvest, but it was not described in sugar beets.

Low temperatures may also lead to inefficiencies in the metabolism of the sugar beet. Wyse and Dexter (1971) showed that at low temperatures, accumulation of the non-productive trisaccharide raffinose was much higher than at higher temperatures. Among the different sets of results reported by these authors, their figure 1 permits something of a comparison by accumulated temperature, for a single variety. After 290°Cd, at 2.0, 4.5, 7.2, and 12.8°C, raffinose content was reported as approximately 1750, 1000, 800, and 650 $mg.kg^{-1}$. Similarly, although not in terms of accumulated temperature, at low temperatures - 2 and 6°C - Haagenson et al. (2008) found a negative relationship with metabolism of raffinose.

Below 0°C In beets that had been stored for around 500°Cd, when the temperature went from +1°C to -1°C, the stable rates of respiration where similar, at around $4mg\ CO_2.kg^{-1}.hr^{-1}$ (Wyse, 1978). They observed, however, a large spike in respiration rates as the temperature was changing and crossed 0°C, peaking at around $12mg\ CO_2.kg^{-1}.hr^{-1}$.

Way below 0°C Wyse (1978) showed that as temperatures gradually decreased, once the root temperature moved below approximately -5°C, respiration rates slow dramatically. Wyse states the temperature of -8°C as the point of this change, but the graphical results (Wyse, 1978, Figure 3 of) suggest the slowing of respiration starts at a root temperature higher than this: it is possible that -8°C was the air temperature at the point respiration rates begin to sharply decline, or that the graphical representation of the results is inaccurate. Regardless of which is the precise temperature of this turning point, it is clear that once the beets passed it, respiration rates slowed dramatically to near zero. At -18°C, respiration rates are negligible.

Fluctuating temperatures. Similar to the spike occurring when the temperature went into the negative temperatures, Wyse (1978) also observed a large spike in respiration when the temperature rose above 0°C again. When the temperature went from -1°C to 5°C, respiration rates spiked from approximately $5mg\ CO_2.kg^{-1}.hr^{-1}$ to $24mg\ CO_2.kg^{-1}.hr^{-1}$, then settled at around double the pre-freezing rate: from around $8mg\ CO_2.kg^{-1}.hr^{-1}$ to around $14mg\ CO_2.kg^{-1}.hr^{-1}$. Similar spikes in respiration rates, lasting 24 to 48 hours, were observed in subsequent tests every time the temperature passed 0°C. Further, Wyse (1978) was able to find higher stable respiration rates resulting from fluctuations. This was particularly clear in the beets that fluctuated between a negative (-1.0°C) and a positive temperature. For a positive temperature component of 1.5°C, 5°C and 10°C, the stable respiration rates in the positive temperature periods increased by a factor of 2.0, 1.6, and 1.2 respectively over a 20 week period.

A general trend A general trend in respiration can be derived from these studies. The trials with sufficient temporal resolution report an early post-harvest spike. Most of these occur between 5 and 48 hours and can be up to three times the long term stable trend. After this spike, rates are generally stable or decreasing, but are ultimately increasing towards the end of very long storage periods (beyond ca. 500°Cd). This suggests something of a divergence between rates of loss - increasing throughout the length of storage under commercial conditions, out to ca. 300°Cd - and the rates of respiration.

Heat of respiration One major issue for the management of temperature and respiration is the circular nature of the process: a higher temperature leads to more respiration, which leads more heat generation and thus a higher temperature. The heat of respiration in sugar beets can be derived from the rate of respiration, the efficiency of sucrose metabolism in plants, and exothermic heat of sucrose metabolism.

A metabolic efficiency rate of 44% applied by Shaaban et al. (2014) is at the upper limit of the known estimates. Respiration is both complex and exothermic. Overall, the process results in the formation of molecules with more stable bonds, and a transformation of energy. Campbell and Klotz (2006) estimated that a total of 5764 $kJ.mole^{-1}$ of energy is available for metabolism of sucrose in sugar beets. Another older estimate from Burke et al. (1979), is for the release of 5671 $kJ.mole^{-1}$. Either way, this equates to approximately 16.5 kJ per gram of sucrose. Burke et al. (1979) notes that, under ideal conditions, approximately 40 to 44% of this energy is used by the plant, with the remaining 56 to 60% released as heat. Campbell and Klotz (2006) suggests this release of energy as heat is more likely in the range of 66 to 69%.

Assuming 56% conversion efficiency, chemical energy of sucrose is converted to heat energy as a rate of 9.285 $kJ.g^{-1}$ (Burke et al., 1979). Taking the loss rates reported previously of 0.0188% of initially available sugar per degree day and an initially available sugar of 16%, and further assuming that all sugar loss is from respiration, the heat production of a tonne of beets can be imputed as 27.8 MJ per degree day. Taking the upper bound estimate from Campbell and Klotz (2006) of 69% or 11.5 $kJ.g^{-1}$ and a high initial sugar concentrations of 20%, this increases to 42.8 MJ per tonne of beets per degree day. What does that mean? If all the heat energy released stayed completely contained within the beets, the most conservative estimate of 27.8 MJ per degree day would be capable of heating the beets 7.8 °C. 42.8 MJ is equivalent to 12.1 °C. This is equivalent to a small clamp of 100 tonne at 5 °C being heated by one 2000W heaters running all day.

2.2.2 Root rot

Root rot is the second major cause of sugar loss during storage. Rotting beet material is subject to leakage, accumulation of impurities, and will generally be removed during the sugar extraction process. Measuring the cost of rot in terms of lost material when the beets are sent for processing, Legrand and Wauters (2012) suggest that around 2% of the mass of beet material is lost at 270°Cd. Rots are the major driver of the accumulation of invert sugar in sugar beets as a result of the secretion of sucrolytic enzymes from the microbes that cause the rot (Klotz and Finger, 2004). Root rots form as a result of microbial growth. The fungal species *Botrytis cinerea*, *Fusarium* spp., *Penicillium* spp., and *Phoma betae* are the most commonly identified in association with root rot in sugar beets (Liebe and Varrelmann, 2016). Some bacterial species have also been associated with rot formation, and their rates of prevalence have been found to be very high (100% by Liebe and Varrelmann (2016)), but it is generally recognised that they play a minor role in relation to that of fungal species.

Root rot pathogen rates It is generally believed that all genera of post-harvest rot-causing fungi are present in all sugar beet fields and thus in all sugar beet clamps. Liebe and Varrelmann (2016) found *Botrytis* sp. in 12 of 24, and *Fusarium* spp. in 20 of 24 fields at harvest, and *Botrytis* sp., *Fusarium* spp., *Penicillium* spp., and *Phoma betae* in 24, 24, 22 and 1 of 24 post-harvest samples, respectively. These beets were stored for between 728 and 824°Cd, giving ample time for the difference fungi to develop.

The general temperature dependence of fungal infection has been shown to be positive. In an experiment by Gaskill (1950) in which beets were stored at 45°F and 65°F (7°C & 18°C) for two months, rates of rot seven times as great were seen at the higher temperature. This difference increased to 15 times as great when the beets were drought stressed at harvest. Legrand and Wauters (2012) suggest that the presence of significant infections of the different genera is temperature dependent. *Penicillium* and *Botrytis* were observed in beets stored at temperatures ranging from 5 to 20°C, while *Tricoderma* was only observed in beets stored at 10°C, *Fusarium* only in beets stored at 15°C, and *Rhizoctonia* present in beets stored at 15 and 20°C. All these beets were stored for between 450 and 500°Cd.

Klotz and Finger (2004) state that sucrose synthase predominates sucrolytic activity regardless of storage temperature, yet it is not highly impacted by temperature (see figure 1 in Klotz and Finger (2004)). Soluble acid invertase activity was the major activity correlated with the increase in the presence of fungal activity over time, increasing by around 650% between weeks 4 (168°Cd) and 20 (840°Cd), while insoluble acid invertase decreased by a similar magnitude over the same period. Fructose and glucose concentrations increased by 1920 and 295 % over this same period.

Root rot and Degree-days In terms of rates of infection and accumulated temperature, Legrand and Wauters (2012) noted that *Penilillium* and *Botrytis* start to be visible around 150°Cd, with about 70% contamination rate after 450°Cd. This was consistent for storage temperatures of 5, 10, 15 and 20°C. The same authors importantly note that the increase in the rate of sugar losses in the period beyond 270°Cd, as previously discussed, was largely attributed to the increase in moulds and root rot. In another study that permits a comparison based on accumulated temperature, Wyse (1978, p37) state that low (5°C) and constant temperature can see beets remaining in good condition for at least 20 weeks (700°Cd), while at 10°C, mould was clear at 8 weeks (540°Cd). This suggests a non-linearity in the mould-cumulative temperature relationship.

In a large European study on the rates of sugar loss during storage from 2008/09 and 2009/10, in which beets were stored from 339 to 996°Cd, in 6 countries, for 12 genotypes, and under various harvest and storage conditions, rates of moulds and rot correlated very closely with rates of sugar loss at the level of the variety (van Swaaij and Huijbregts, 2010). Correlation coefficients of 0.87 and 0.88 between sugar loss and moulds and sugar loss and rots respectively, were found. The correlation between sugar loss and surface damage and sugar loss and tip breakage were 0.37 and 0.66 respectively. This highlights the significance of rots for sugar loss under long term storage.

2.2.3 Mechanical damage

The literature suggests that mechanical damage is something of an x-factor in sugar loss during storage. It is not a significant source of loss per se, but the interaction between rates of mechanical damage and rates of respiration and root rot is very important. The role of temperature in this interaction is largely as per the main effect of respiration and rot - more is more - but there are some important nuances that will be discussed.

What is mechanical damage Mechanical damage to sugar beet roots includes any damage to the beet incurred from handling. Surface damage is the most obvious and likely the most economically important damage, but internal bruising is also of significance, if not well understood. Surface damage includes root tip breakage, abrasions from sheer forces, cracks and other surface openings from impacts, and cuts made to the beet in handling - primarily in the removable of leaf material in the processes known as "topping".

From the storage perspective, it is important to note that this damage occurs from handing prior to storage - namely harvest and transport to the field store. Damage during storage is possible, but it is not common that the beets are handled during this period. As such the temperature of the beets as points of mechanical damage will largely reflect the temperature of the soil during harvest. In Northern Europe, harvest occurs from late September to late November, so the soil temperature will commonly range from the high teens down to near zero.

Effects of temperature on damage As previously mentioned, it has not been possible to find research on the effect of temperature on rates of mechanical damage at harvest for sugar beets, and at the same time is of common belief that temperature does cause variation in rates of damage. The literature on damage rates in relation to temperature in fruits and vegetables is often conflicting, with lower temperatures sometimes being found to be related to lower damage, and sometime with higher. A short review by Hussein et al. (2020) suggests that variations in the turgor of the product is a major pathway through which rate of damage are influenced by temperature. In sugar beets, harvest directly after rainfall is discouraged partly because of the increased turgor of the roots and subsequent increased rates of cracking. If temperature is also able to influence turgor, it too can affect damage.

Damage as an x-factor

Damage and loss Independent of the inclusion of temperature as a variable, it has repeatedly been shown that sugar loss in storage is increased by rates of damage. For example, Legrand and Wauters (2012) included different rates of damage on the beets, induced by passing the beets through a cleaning turbine taken from a commercial harvester for 10 seconds at the speed of either 40 or 60 rounds per minute. After 450°Cd in storage, the beets subjected to 40 rpm averaged 6% loss in sugar, while those subjected to 60 rpm averaged 10%. The rates of damage were not quantified.

Damage and loss x temperature The inclusion of temperature sees the on the loss-temperature relationship. Kenter et al. (2006) reported the rates of loss in storage for beets stored for 21 days at 5, 12 and 20°C. This corresponds to 105, 252, and 420°Cd, respectively. Beet were initially carefully handled and selected for low damage rates, with half the sample then subjected to 45 seconds of damage causing rotation in a cleaning drum. Table 1 presents the findings regarding loss at different temperatures for damaged and non-damaged beets, applying the fitted curves presented in Kenter et al. (2006, fig. 7). Note that the data for loss per day and per degree-day both suggest a non-linearity to the relationship. The fitted curves presented by the authors in figure 7 were exponential. Note also that the values for the damaged beets correspond well with the results from Legrand and Wauters (2012): at 12°C and 252°Cd, the average loss per degree-day is 0.0129%.°Cd $^{-1}$, while over 270°Cd Legrand and Wauters (2012) had an avareage loss rate of 0.013$

Damage and respiration Elevated respiration in response to wounding, is well documented in sugar beet. Wyse and Peterson (1979) were able to show that progressively higher rates of damage through each step of processing lead to higher rates of respiration. Akeson and Stout (1978) note that "wound respiration is responsible for the higher losses during the early storage period". They found that during the first 25 days of storage, beets wounded by falling impacts had increased respiration rates of 2%, 7%, and 13% when dropped from 0.46, 0.91, and 1.83 meters respectively. These are the averages of three surfaces of varied stiffness - steel, hard rubber, and spring rubber. The surface averages over all heights were increases in respiration of 11%, 7% and 5% respectively. The type of damage was not explicitly quantified, but noted to include bruises, tip breakage and cracks. The beets were dropped in lots of 20 to 25 lbs, with the impact site not controlled.

Damage and respiration x temperature Numerous studies have been able to find that the relationship between respiration rates and temperature is impacted by the rates of damage. For Wyse and Peterson (1979, fig. 2), at both 2 and 10°C over 10 days, respiration rates in the damaged beets were around 2-3$mgCO_2.kg^{-1}.hr^{-1}$, or 25 and 15% on average respectively. The uninjured beets at 2°C respired at around half the rate of those at 10°C.

Two more recent studies have found that respiration rates at lower temperatures are impacted less, or not impacted at all, by damage. Klotz et al. (2008) found 67% more respiration from damaged compared to non-damaged beets, over a 13 day period, stored at 10°C. In the same experiment, beets stored at 1°C had an average decrease in respiration of 8% over the same period, although only one of the 10 readings was significant as a point estimate. Kenter et al. (2006) found that at 5°C, respiration rates for damaged beets was 17.5% higher over 7 days, while for beets stored at 20°C for 7 days, rates were 54.5% higher. This suggests a non-linear interaction. Uniquely, Kenter et al. (2006) were able to also assess respiration for beets that were only bruised, but had no surface damage. For these beets, damage did not increase the rates of respiration at either 5 or 20°C. In both these studies, the characteristic early spike in respiration does not seem to be uniquely impacted by damage rates.

In their discussion on the lack of a respiratory response to damage at 1°C in comparison to the large response at 10°C, Klotz et al. (2008) note that the only metabolic substances they saw differences in compared to the non-damaged beets are not factors linked to respiratory control. They conclude. "Previous research, however, has shown that the activities of the early glycolytic enzymes, fructokinase, hexokinase and phosphofructokinase, are induced in wounded roots at 10°C prior to the increase in respiration (Klotz et al., 2006). Further research will be needed to establish whether the induction of these enzymes has a regulatory role in providing carbon substrates needed for wound-induced respiration as well as in determining the role that the availability of reduced carbon compounds and other respiratory substrates have in controlling respiration in nonwounded sugarbeet roots."

Damage and rot While observation of the development of rot clearly sees them develop first at sites of damage, exact numbers on the rates of rot as a result of levels of mechanical damage to beets are scant in the literature. Liebe and Varrelmann (2016, tab 5., data for 2013) suggests that the prevalence of rot causing fungi is higher in beets subjected to tumbling for 45 seconds in a cleaning drum. Legrand and Wauters (2012) notes that sites of mechanical damage, namely tip breakage, top, and lateral damage, are the locations on the beet at which root rots occur.

Healing time Post-harvest, beets will heal and close points of entry to pathogens and points of exit to moisture. Legrand and Wauters (2012) notes the existence of a phase of cicatrisation (scar forming) that sugar beets go through directly after harvest, during which greater rates of sugar loss occur - the "wound induced respiration" noted by Klotz et al. (2008). Their work, however, does not focus on the issue. It is possible that if healing is inhibited, the loss of processable material can be accelerated. Cool temperatures may actually prove such an inhibitor. Fugate et al. (2016) showed that maintaining a higher temperature leads to higher daily rates of melanin formation, lignification and suberization. They also show that permitting healing time at temperatures above those that might be considered preferable for slowing respiration and root rot can result in a net reduction in respiration during long-term storage. For heavily damaged roots, total respiration over a 28 day period appeared to be less when stored at 12°C than at 6°C. Indeed, respiration rates were less in the damaged beets stored at 12°C from the third day until the end of the experiment at 28 days. This is attributed to wound healing, with the proviso that the beets stored at the higher temperature did transpire much more and lose much more weight, ending the experiment at 90.5% of their harvest weight compared to 93.5% for the beets stored at 6°C. The Fugate work suggests a healing time of up to a week at around 10 degrees and high humidity might be beneficial in the long-run. While no further research on this topic for sugar beets could be found, this is a known issue in other food crops such as carrot and potatoes.

2.2.4 Moisture loss

Somewhat like mechanical damage prior to storage, moisture loss from the beet during storage does not cause loss of sugar per se, but can interact with the processes of respiration and rates of rot. It can result in direct loss through leakage if severe. It is not, however, an issue that generally is of concern in commercial production system. A major reason for this is that the moisture levels in the air space of the clamp - clamp humidity - is usually very high. Jaggard et al. (1997) found little weight loss in commercial clamps after 84 days.

Lafta et al. (2020) note 6.5% and 4.5% moisture loss as representative of the inner sections of large commercial piles, and 23% and 18% as representative of the outer sections. Given that they were able to achieve such rates of moisture loss in the laboratory by storing beets at 85% and 40% relative humidity over 28 days (temperature not known), it does seem possible that beets in field clamps would also incur some degree of moisture loss.

Should large moisture loss from beet in field clamps occur, the potential losses could be significant. Lafta and Fugate (2009) showed that excessive moisture loss in beets was strongly correlated with increased rates of respiration. For two varieties, the increase in respiration rate was 0.03 and 0.05μg.kg^{-1}.s^{-1} per percentage decrease in weight Lafta and Fugate (2009, figure 5). Electrolyte leakage was also a major issue. The beets stored at 45% humidity at 10°C lost between 45 and 50% of their weight, and a similar (ca. 45%) proportion of electrolytes when cut in disks. The comparable values for beets stored at 85% humidity were 15 to 20% of weight and approximately 5% of electrolytes. They note that this large increase in electrolyte leakage was most likely a result of cell membrane damage caused by the dehydration.

Fugate et al. (2016) measured rates of transpiration of non-damaged and damaged beets over 28 days. Over 28 days, at 6°C, average rates were were 11.3 and 21.3mg.cm^{-2}.h^{-1}, respectively - a 188% increase. At 12°C, rates were slightly lower, at 18.4 and 9.4mg.cm^{-2}.h^{-1}, respectively - a 196% increase. As seen in Table 2 the beets stored at 12°C had high average rates of respiration of the 28 days. They also lost a larger proportion of their weight; approximately 10% for both the damaged and non-damaged beets, compared to the 6.6% and 4.6%, respectively, for the beets stored at 6°C (see Table 3).

The above studies show that moisture loss is much more strongly driven by humidity rather than temperature. This is in line with the descriptions of moisture transfer from fluid dynamics. Convective drying - more commonly known as evaporation - is responsible for the transport of moisture and thermal energy out of a solid and into the fluid phase of a system. Rates of moisture loss at the surface of the solid food stuff are commonly described with the convective mass transfer coefficient, h_m, which shows that moisture transfer is driven by the vapour pressure differential of the solid and the fluid - i.e. the humidity at the wall of the solid and the humidity of the air (Hoang et al., 2004):

$$h_m = \frac{g_{c,s}}{p_s^v - p_f^v}$$

where;

$g_{c,s}$ is the convective mass flux normal to the wall of the solid
c is convection
p is pressure
v is vapour
s is at the wall of the solid
f is somewhere in the air away from the wall of the solid.

Table 3: Mosiutre loss from beets stored at stable temperatures.

Temperature (°C)	Humidity (%)	Wind speed ($m.s^{-1}$)	Days	Degree-days	Damage	Moisture Loss (%) Total	Per °Cd	Per RH Def	Source
6.0	94	Unkown	28	168	Minimal	4.6	0.027	0.027	(Fugate et al., 2016, fig. 1B)*
6.0	94	Unkown	28	168	Extra[a]	6.6	0.039	0.039	(Fugate et al., 2016, fig. 1B)*
10.0	85	Unkown	28	280	Minimal	18.0	0.064	0.043	(Lafta and Fugate, 2009, fig. 1A)*
10.0	85	Unkown	28	280	Minimal	18.6	0.066	0.044	(Lafta and Fugate, 2009, fig. 1B)*
10.0	40	Unkown	28	280	Minimal	46.5	0.166	0.028	(Lafta and Fugate, 2009, fig. 1A)*
10.0	40	Unkown	28	280	Minimal	45.5	0.163	0.027	(Lafta and Fugate, 2009, fig. 1B)*
12.0	94	Unkown	28	336	Minimal	9.8	0.029	0.058	(Fugate et al., 2016, fig. 1B)*
12.0	94	Unkown	28	336	Extra[a]	9.5	0.028	0.057	(Fugate et al., 2016, fig. 1B)*

Per RH Def: Per % Relative Humidity below 100/ * Data extracted from figure. [a] Scraped with steal brush 2-3 times.

3 Research gaps and opportunities

Given the above review of key literature, this section now aims to highlight some areas in which significant knowledge gaps exist. The inclusion of any of these gaps in the research of this doctoral project will be highlighted. As a whole, it seems reasonable to state that the relationship between temperature and rates of sugar loss in sugar beet clamps is sufficiently well described and can only be improved by focusing on the mechanisms through which loss occur, or by refining the ability to measure variations in temperature across the profile of a clamp and under different conditions. Also of note in the context of this doctoral project as an industry sponsored project, the ability to improve and make accessible the measurement of the key metrics of interest outlined in this work is of high interest.

3.1 Temperature in clamps

Respiration This work has discussed at length how respiration rates vary with temperature. In addition to this, it is also known that there are varietal differences in the post-harvest rates of respiration of sugar beets and that these varieties do tend to lose more sugar during storage Legrand et al. (2016). It does not seem to have been quantified whether varieties that are known to have higher respiration rates when stored in a commercial setting also accumulate thermal energy and thus degree-days quicker than other varieties.

Heat transfer This work has so far focused primarily on the relationships with static temperature and the generation of heat within the beet clamp system. It has not discussed the dynamic transfer of heat within the system. Such research would focus on the mechanisms and rates of heat transfer, and as alluded to in the introduction section, require drawing on the engineering sciences of Heat transfer and Fluid dynamics. The extent of this research will not here be reviewed. Of note, however, is that numerous studies such as Jaggard et al. (1997) and Olsson (2013) have found that there is often large variation in the temperature within the clamp, and that management practices such as choice of cover type have large impacts on this distribution as well as the absolute temperature values. It is also of value to note that, within the literature, most if not all the information needed to gain a thorough understanding and populate a model of these processes is available. For example, Tabil et al. (2003b,a) provides many of the thermodynamics parameters of a sugar beet bulk, and Ekelöf (2015) provides useful information at the level of the individual beet and the thermodynamic properties of covers.

Air flow in clamps Of all heat transfer processes, convection is likely the largest within the sugar beet clamp system. Yet, no study is known to have successfully mapped airflow within a sugar beet clamp. Studies of large scale commercial stores in the USA from the middle of the twentieth century were able to discuss the effect of different flow rates during active ventilation (see for example Downie, 1950; Stout, 1950; Hansen, 1950), and the study of Tabil et al. (2003b) has measured air flow in small scale controlled experiments, but none have given a disaggregated full profile of how air flow through a clamp can vary. Air flow through the clamp as a function of the bulk porosity, trash level, beet size, cover type, wind speed, and wind angle are all questions that need addressing if a full understanding of temperature and moisture within the system is to be made.

Achieving such an understanding through experimental work will not be easy. Reliably measuring air speed across a full profile requires numerous sensors, such as those used in apples (Geyer et al., 2018) - which are not commercially available - and requires placing these sensors in a known location with known surroundings. This placement within a commercial clamp would be very challenging given the tendency of beets to move during loading, beets size and shape to vary greatly, and trash to be somewhat random within a harvester load, making it near impossible to accurately define local porosity and permeability. Using selected beets to construct a clamp likely to be within specified bounds for one of the treatments (eg beet size) would similarly be a mammoth task, requiring some 100 000 beets to be selected for a 100 tonne clamp - a very small, yet large enough clamp size to provide realistic conditions. The alternative metric of air pressure, as applied to a pile of mine tailings in Amos et al. (2009) and translatable to air velocity thanks to the laws of physics, may require more simple monitoring equipment, but is still subject to issues of variable control.

Building a scale model of a clamp is one means of controlling the environment in which experiments run, and which permits year-round experimentation. This idea has been explored and deemed currently un-economical - quotes for 100 000 solid plastic model 1:5 scale sugar beet exceeded one million Swedish kronor (Tojos Plast AB, personal communications, 2019-02-15). Another approach is to use computer modelling.

3.1.1 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a computer modelling technique of note here. Through the application of methods from the engineering sciences, CFD has large potential for furthering research around temperature in the storage of sugar beet clamps.

Understanding heat transfer and fluid dynamics in systems is tackled in three main ways within engineering; analytical methods, numerical methods, and experimental methods. Analytical methods involve solving known equations for a system. Numerical methods are usually based on computer simulations and involve approximations of these same equations being repeatedly solved at a myriad of linked positions in the system. Experimental methods involve taking measurements from the system directly, or from a scaled and/or simplified physical model. Each of these methods has its advantages and drawbacks, and thus suit different applications. It is the second of these methods - numerical methods - that the following discussion focuses on.

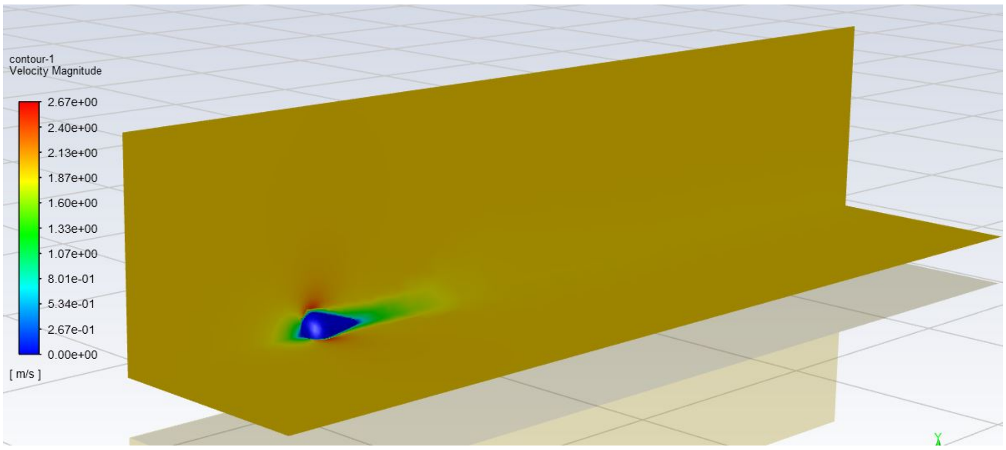
The method is favoured among engineers as it gives great insight to the important physical processes within a system given that it is a mechanistic method of modelling, based on fundamental laws of physics. The method generally defines a rate of change in a property, such as mass, air speed, or temperature, as a function of fluxes from convection, conduction, and sources. CFD modelling have been used successfully in the analysis of other post-harvest storage systems, such as that of pears (Gruyters et al., 2020), chicory roots (Hoang et al., 2004), apples (Ambaw et al., 2013), beef (Delele et al., 2019), and in understanding post-harvest food drying processes (Defraeye, 2014), among many others.

The CFD Process The application of numerical methods as the Computational Fluid Dynamics process is often described as a quasi-linear multi-step process, in which the physical and the physics of a system are related through a given sequence. This sequence usually begins with the physical;

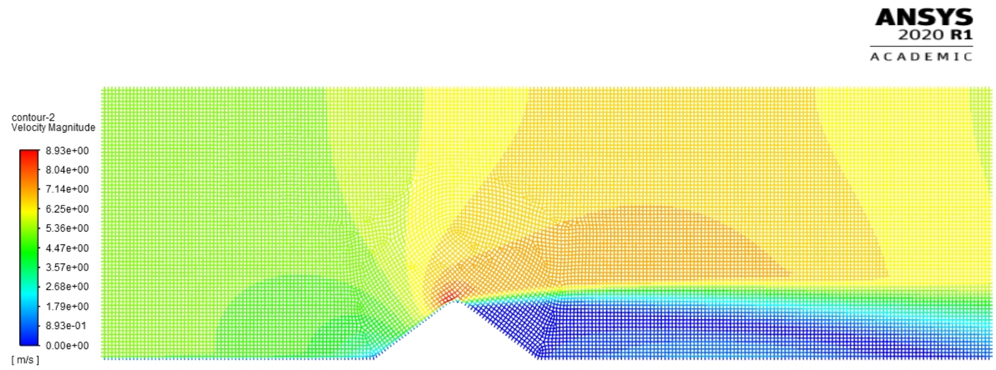
1. Pre-processing (the physical)
    1.1. Geometry: a computer aided design model of the physical system: see Figure 2
    1.2. Mesh: division of the geometry into small discrete sub-units ("elements"): note the grid-like pattern in Figure 3a
2. Modelling the system (the physics)
    2.1. Governing equations, their form, and their simplification: what is the relevant physics
    2.2. Materials of the system: defining the physical properties of the fluid and solid parts being modelled
    2.3. Boundary conditions: what happens at the limits of the model
3. Solution methods (combing the physical and physics)
    3.1. Spatial discretization: for any given element, which and how much of the surrounding elements are relevant to the dynamics
    3.2. Pressure-velocity coupling: how will the system of linear algebraic equations be linked to each other such that they can be solved
    3.3. Solution technique: how is the system of linear algebraic equations solved
4. Post-processing
    4.1. Presentation and analysis of results: see Figure 3

In reality, the CFD process is not simple and linear. For example, ideally the results will be tested on their independence from the mesh, requiring that a mesh be run with models, modified, and rerun. Similarly, the analysis of the solving process or results can suggest some modelling choices or assumption made in the process are inadequate and require modification. Fortunately, commercial software for CFD analysis is advanced and has been developed to make the process as integrated as possible, meaning a small change in the early steps of the process easily flow down the line.

Examples of the CFD method The following gives examples of the results obtained by the CFD method, when applied to the beet level and clamp level systems of the sugar beet clamps.



(a) Air velocity at walls of the beet level system with $2m.s^{-1}$ air speed at inlet. Note the system has been simplified to only include one-quarter of a beet within a large empty space



(b) Air velocity through a cross section of the clamp level system with $5m.s^{-1}$ air speed at inlet. Note that air is not permitted to flow through the clamp in this simplified example

Figure 3: Examples of velocity in systems for sugar beets, derived using CFD methods

Previous CFD models of sugar beet clamps Only two previous applications of CFD to sugar beet clamps are known. Both of these have been verified to match experimental data, but the details of the processes within the system are generally lost in their simplicity. Shaaban et al. (2014) developed a 2D model of temperature within the clamp as a function of air speed, wind direction, relative humidity, and ambient temperature. The authors themselves note that their model excludes the important factors of heat generated from within the clamp and the clamp architecture including porosity. Their model is also static, not being able to show how an external temperature change would flow through the clamp.

The more recent attempt of Potia (2017) was able to include heat generation from sugar beet respiration, give insight to the within-clamp variation in temperature and find reasonable congruence with experimental data in some instances. They, however, excluded convection flows - those of the air moving through the clamp. This meant they were required to use grossly inflated variables for other heat transfer processes and grossly underestimated rates of temperature change when strong winds were blowing.

Both the above examples used a space averaging approach. This approach assumes that the entire sugar beet bulk is homogeneous, with a fixed proportion of sugar beet, air, and permeability. The alternative approach to that of space averaging is the direct CFD method, in which the actual heterogeneous solid sugar beets and air pores are modelled. The space averaging approach allows, for a given computational power, for the modelling of a larger bulk than the direct CFD modelling approach and is still able to capture variations through the bulk. It does not, however, permit the investigation of intricacies such as soil caused blockages. The previous two application of CFD to sugar beet clamps also both used simple geometry and spatial discretization methods. While the existence of these models is extremely valuable, there is great room for development of the application of the CFD methods to sugar beet clamps.

In the research plan This doctoral project is planning on both developing and applying a CFD model of a clamp. The planned model is able to draw on data already available. The raw data from the large studies conducted by Nordic Beet Research (Olsson, 2013) is available to prove the model. It is also part of the plan to include a simplified version of the model that can be used in communication with sugar beet farmers.

The direct experimental measurement of airflow is not included in the current research plan. The practical and financial considerations in controlling the environment for the previously mentioned parameters - bulk porosity, trash level, beet size, cover type, wind speed, and wind angle - places this beyond the means of the available resources. While such data would be very valuable, including in validating a CFD model, collecting data from clamps for the proxy of temperature is both manageable and sufficient.

There are no plans to include the measurement of respiration rates in the project, or how these relate to clamp temperature. Knowledge of respiration rates may be able to complement knowledge of the mechanical properties of sugar beets, and in unison be used provide something of a storability index. This would be particularly so if it was possible to simply, cheaply, and stably measure respiration rates pre-harvest, as may be the case with mechanical properties.

3.2 Mechanical damage

Rates of mechanical damage of beets depend upon both the way in which the beets are handled, and the mechanical properties of the beets themselves.

Handling of sugar beets The importance of effective handling of beets during harvest and transport has lead to the development of highly efficient machinery capable of move hundreds of tonnes of beets per hour. This work has largely been the domain of private industry and thus published research is not extensive. However, given the practical and important nature of these processes - it is here that damage actually occurs - most national sugar beet research organisations have undertaking related research. For example, NBR in Denmark has asked the question of whether there is value in treating beets carefully during harvest to maintain maximum beet material, if the subsequent handling during loading to transport results in the same total rates of loss plus more soil on the beets Nielsen (2019). Like much of the work in this area, the conclusion of the NBR project is that the optimal practice will be very contextual; the combination of soil type and soil moisture level at harvest, storage conditions including humidity and length, and the payment schedule for the given year, plus the need to complete the task at hand, will all lead to different recommendation around handling procedures aimed at either minimising damage, minimising sample dirt tare, or maximising throughput.

Mechanical properties

Strength Quantification of the mechanical strength of beets is well developed. Kleuker and Hoffmann (2019) is one more recent publications in which the mechanical strength of different varieties of beets, grown under different environmental and management conditions, is undertaken and linked to rates of damage and storability. This work is able to find reliable relationships between these factors, with stronger beets ultimately experiencing less damage, less rot, and less loss during storage. Similar relationships are found in Hoffmann et al. (2018).

The most direct question around mechanical strength and temperature is whether mechanical strength varies with temperature or not. While beets are harvest and handled throughout the day over the harvest period, it may be that such processes should be avoided during particular weather conditions to avoid excessive mechanical damage. It appears that the mechanical strength of the beets changes with accumulated temperature, i.e. storage period Gorzelany and Puchalski (2000); Nedomová et al. (2017).

While mechanical strength has a high correlation with storability, largely through the damage x temperature relationship, it is neither fully explained nor fully explanatory. That is, the full extent of the mechanisms through which stronger beets store better is not explained, nor is the relationship perfect. Respiration rates, beet nutrient content, and beet size have all arisen as possible cofactors. The broader research project from which the Kleuker and Hoffmann (2019) and Hoffmann et al. (2018) publications came is run within the COBRI collaboration of the national sugar beet research organisatios of Germany (IfZ), the Netherlands (IRS), Belgium (IRBAB), and Sweden and Denmark (NBR). Within this broader project, certain varieties that were found to have high strength and experience low rates of damage still experienced high rates of loss during storage. Respiration rates has been touted as a possible co-factor here. Regarding nutrient content, an exploratory study also within this broader project found that beets from long-term liming trials in which high rates of calcium had been applied had much greater storability than beets from the non-limed areas, yet the mechanical strength of the two sets of beets was not significantly different. Finally, regarding beet size, there is a tendency that the varieties of beets with lower strength are also of larger size. This begs the question as to whether these beets sustain greater rates of damage in the harvesting and handling processes per beet and per specific area owing to their size, rather than their mechanical strength.

Stiffness In terms of mechanical properties of a substance, stiffness is the extent to which deformation is resisted by an elastic object when a force is applied. Stiffness is quantified simply as displacement / force, with a stiffer object experiencing less deformation than a less stiff object, for the same applied force. If strength is the amount of force required to cause a sugar beet to rupture, stiffness explains a lot of the behaviour of that same beet up to this point.

At the level of the clamp, variation in beet stiffness, for example from varietal differences or from a loss of turgor, could mean variation in the clamp architecture. Reduced stiffness could mean that when stacked, beets would form more around each other, with the beet-to-beet contact area increased. Subsequently, the porosity of the clamp would decrease, with the potential issues of reduced air flow and temperature increases becoming more likely. Further, the specific area that is not in contact with air would increase, potentially increasing the rates of rot. While some research such as Gorzelany and Puchalski (2000) has shown that stiffness does decrease with storage and dehydration, no research was found to study if any consequential changes in the clamp architecture and thermodynamic properties result from this change.

Measuring stiffness of beets can be achieved using methods from material sciences. Studies like Gorzelany and Puchalski (2000) and Kleuker and Hoffmann (2019) employ penetrometers to measure distance to rupture. Nilsson (2020) was able to use both static tests with a hydraulic press and pressure contact sensors, and dynamic drop tests with contact area measuring film and high speed cameras, to measure varietal differences in contact area and time, and thus how the varied sugar beets stiffnesses resulted in different force and pressure profiles from impacts. At the clamp level, it may be possible to use 3D models developed using drone sourced imaging to measure the clamp volume and any changes. The success of this method would depend largely on the resolution that can be achieved, and any results would only proximally indicate a change in stiffness given a clamp could settle for other reasons.

In the research plan Two works around the mechanical properties are included in the doctoral research plan. The first is a continuation of the Kleuker and Hoffmann (2019) study as part of the COBRI collaboration, in which mechanical strength, mechanical damage, and storability will be assessed. This will be organised from the office of the project leaders at IfZ Gottingen in Germany. The second work is lead from NBR in Sweden and will validate the accuracy of an handheld penetrometer in relation to the high-end laboratory penetrometer the project employs. While neither of these works explicitly includes temperature, their findings will be very useful in adding nuance to the sugar loss as a function of temperature relationship when applied elsewhere.

The project plan does not include any research around the actual machinery used in harvest and transport. No formal projects will be conducted around stiffness. Exploratory studies about changes in stiffness owing to dehydration will be conducted where capacity permits within the project on moisture loss mentioned below. Similarly, exploratory studies into the change in clamp architecture using 3D models are planned where capacity allows.

3.3 Moisture loss

Given that the air moisture condition of nearly all previous storage trials are either not known or measured as 100% relative humidity, it seems that there is room for research around the impact of air moisture content as well as around changes in the moisture content of the beets themselves. An important issue around the cooling of sugar beets in storage through greater ventilation is the greater rates of moisture loss from the beets that can be expected. If beets are to be dehydrated by greater ventilation (either active or passive), then it is valuable to know whether dehydrated beets lose sugar at the same rate as non-dehydrated beets, and whether differences exist only during the drying process or are sustained. Further, it needs to be known at what rates sugar beets lose moisture for a given air flow, temperature and humidity. Further still, what do changes in the water content of a sugar beet mean for its mechanical and/or physical properties - does a dehydrated beet lose strength and/or stiffness, does a 10% decrease in water content also lead to a 10% decrease in volume? These are again important questions for how they interact with heat generation, heat transfer, and rates of mechanical damage.

In the research plan The doctoral project plan includes a controlled experiment on the rates of sugar and moisture loss for beets subjected to active ventilation at given air speeds, temperature, and humidity. This work aims to quantify numerous factors, including whether increasing air flow within a clamp can reduce the total water content of the sugar beet bulk, including in both the soil and beet portions. This reduction in water has the potential to reduce the dirt tare in a sample by reducing the water content of the soil attached and induce greater cleaning of attached soil at loading. Further, it can increase the sugar concentration of a sample by reducing the water content of the sugar beets, which would decrease transport costs and increase bonus payments.

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