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Modeling crown temperature of winter sugar beet and its application in risk assessment for frost killing in Central Europe

E. Reinsdorf, H.-J. Koch*

IfZ, Institute of Sugar Beet Research, Germany

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ABSTRACT

The cultivation of sugar beet as a winter crop in Central Europe will require tolerance of severe frost. Due to the large variation of survival rates in different environments it is necessary to quantify the risk of frost killing for potential growing regions. The objectives of our study were, (i) to determine the lethal temperature of sugar beet taproot crown tissue as an indicator of frost damage, (ii) the development of a regression model that properly estimates the temperature of crown tissue from standard weather data, and (iii) a risk assessment for frost killing in four beet cultivation regions, representing different climatic conditions in Central Europe. In field trials at six environments, temperatures were measured above the beet canopy (0.3–0.5 m height), at the soil surface, 5 cm deep in the soil, and in the taproot crown. Survival rates were determined after winter.

The survival rates of sugar beets were highly dependant on the maximum taproot diameter (optimal size: 1–2.5 cm) and the environmental conditions. A crown tissue temperature below −6 °C was a reliable indicator for frost killing, even though the exact lethal temperature of optimal sized sugar beets could not be identified. The crown temperature was accurately predicted from available weather data using multiple linear regression models. It was estimated best by combining the parameters 'daily mean air temperature', 'daily mean soil temperature at 5 cm depth' (closest correlation to crown temperature) and 'daily snow depth'. The prediction was further improved by adding the air and soil temperatures of the previous day and the 2-fold interactions of regressors to the model.

Risk assessment for frost killing in Central European beet growing areas was based on weather data of the past 20 years provided by Germany's National Meteorological Service (Deutscher Wetterdienst, DWD). Our approach showed that at locations with mild winters, such as Cologne, the successful cultivation of winter sugar beet is possible with little risk of frost killing. On the contrary, growing winter sugar beet at places like Göttingen and Regensburg holds a high risk for frost killing. Finally, the presented approach needs to be improved with more accurate estimates of crown tissue temperature, and more precise determination of the lethal temperature of winter beets with the optimal taproot diameter.

1. Introduction

The sugar beet (*Beta vulgaris* L. subsp. *vulgaris*, Lange et al., 1999) crop is cultivated in the temperate zones of the world, where it is mostly sown in spring and harvested before winter. Alternatively, in Morocco, Egypt and some southern parts of Italy, Spain and California it is cultivated over winter. The possibility of growing sugar beet as a winter crop under Central European conditions was already mentioned by Achard (1809) at the very beginning of sugar beet breeding. Since then, there have been several investigations on the overwintering of summer and autumn sown sugar beets in the field, as described by Eichholz and Röstel (1962). During the early 1970s, Wood and Scott (1975) conducted further trials with September sown sugar beets in the United Kingdom. In recent years, studies on winter sugar beet have been reported by Hoffmann and Kluge-Severin (2010, 2011), Kirchhoff et al. (2012) and Kluge-Severin et al. (2009).

The cultivation of sugar beet as a winter crop has focused on one of the two following targets: (i) cold conditioning (vernalization) to get the biennial plants into the floral stage if the crop is grown for

Abbreviations: A_M, daily mean air temperature; A_{Max}, daily maximum air temperature; A_{Min}, daily minimum air temperature; A_MP1, yesterday's mean air temperature; aSS_{Min}, daily minimum air temperature at the soil surface; Co, Cologne, North Rhine-Westphalia, Germany; DWD, Deutscher Wetterdienst (Germany's National Meteorological Service); Gö, Göttingen, Lower Saxony, Germany; iR_{Min}, daily minimum crown tissue temperature; iS_M, daily mean temperature at 5 cm soil depth; Ki, Kiel, Schleswig-Holstein, Germany; LT, lethal temperature; MTD, maximum taproot diameter; *r*, Pearson's correlation coefficient; Re, Regensburg, Bavaria, Germany; SN, daily snow depth; SR, survival rate.

* Corresponding author at: Institute of Sugar Beet Research, Holtenser Landstraße 77, 37079 Göttingen, Germany. Tel.: +49 551 50562 50; fax: +49 551 50562 99.
E-mail address: Koch@ifz-goettingen.de (H.-J. Koch).

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seed production and (ii) a substantial increase in root yield when cultivated for sugar or biomass production.

A potential sugar yield increase of 26% on average resulted from a simulation study conducted by Jaggard and Werker (1999). Wood and Scott (1975) found a 20-fold higher biomass of September sown compared to spring sown sugar beets when harvested before bolting in June. However, this increase in biomass of winter sugar beet was gradually lost, when the plants started bolting later in season; hence, non-bolting after winter is necessary to achieve a gain in taproot yield.

Recently, the discussion on the development of winter sugar beets has started again for two major reasons: (i) more knowledge about the genetics of flowering and bolting means that this may be prevented in root crops (Jung and Müller, 2009; Pin et al., 2012) and (ii) interest on sugar beet as an energy crop, since sugar beet is one of the crops with the highest biomass and net energy yield in Europe (Hoffmann and Stockfisch, 2010), additionally offering very good properties as substrate for biogas production (Starke and Hoffmann, 2011). Winter sugar beets might be harvested early in summer and ensure a continuous supply of beet substrate for anaerobic digestion.

In addition to bolting resistance, high frost tolerance is required for successful winter sugar beet cultivation in Central Europe. The environment has a crucial impact on the survival rates (SRs) (∼0 to ∼90%) of *B. vulgaris* L. (Kirchhoff et al., 2012; Pohl-Orf et al., 1999). Positive effects of a cover of snow or other materials such as straw on the SR of winter beet have been reported by Kirchhoff et al. (2012) and Senff (1961), which were due to insulating as well as wind breaking effects, protecting the plant from freezing temperatures.

It is well known that frost tolerance significantly differs between plant species, and that freezing resistance may also change markedly with season and developmental stage (Burke et al., 1976). Frost tolerance can be quantified by the lethal temperature of plant tissue (LT), which in terms of *B. vulgaris* L. depends on the genetics (Kirchhoff et al., 2012) and the size of the taproot, with an optimum of 1–2 cm top taproot diameter (Kockelmann and Meyer, 2006; Senff, 1958). There is no generally accepted threshold temperature for frost killing of winter sugar beet, neither as a minimum air or soil temperature, nor as a LT of the plant tissue, as described for, e.g. wheat (Porter and Gawith, 1999). Moreover, there is no information about how the temperature in the crown tissue of the taproot responds to climatic and crop conditions and how it can be estimated accurately from standard weather data. The crown tissue of the taproot bears the buds which must survive the winter for regrowth of the leaves in spring and simultaneously is exposed to the worst of the frost.

To date, neither reliable short-term predictions for frost killing in distinct locations and years nor accurate regional long-term risk assessments for frost-induced winter kills have been reported. In view of the large variation of winter beet SRs that were found in different environments by Kirchhoff et al. (2012) and Pohl-Orf et al. (1999), it is essential to quantify the risk of frost killing for potential growing regions.

The objectives of our study were: (i) to determine the LT of sugar beet crown tissue, (ii) to develop a regression model that accurately estimates the temperature of crown tissue from readily available weather data, and (iii) to assess the risk for frost killing in four regions of beet cultivation, representing different climatic conditions in Central Europe. This should help to identify locations which are suitable for successful cultivation of winter sugar beet.

2. Materials and methods

The data used in this study were taken from a series of field trials conducted to investigate the phenotypic variability of winter hardiness and biomass formation of bolting winter beets (cultivar Theresa KWS) in Germany.

2.1. Site conditions

In 2009/10, 2010/11 and 2011/12 field trials were conducted at the research farm Hohenschulen (Christian-Albrechts-University of Kiel), Schleswig-Holstein, Germany (54° 18′N, 9° 58′E), and Göttingen, Lower Saxony, Germany (51° 28′N, 9° 54′E). The annual mean temperature and precipitation from 1987 to 2009 was 9.1 °C and 756 mm, respectively, at Kiel, and 9.4 °C and 635 mm, respectively, at Göttingen. The soil was a sandy to clayey loam (Cambisol, Luvisol) at Kiel, and a silty loam (Luvisol) at Göttingen.

2.2. Experimental design

The experiments were arranged in a 2-factorial randomized split plot design with 4 replicates. The main plots were three sowing dates: April, June and August. The sub-plots were three plant densities (148, 246 and 370 thousand plants ha^{-1}). At 2- to 4-leaf-stage, the sugar beets were manually singled from denser stands (seed spacing was 3 cm). A broad range of plant sizes was generated by using these large ranges of sowing dates and plant densities. Each sub-plot consisted of 6 rows 8 m long: rows were 0.45 m apart.

2.3. Temperature measurements

From October to March/April, temperature was measured within one sub-plot per sowing date at a plant density of 246,000 plants ha^{-1} in 2009/10 and 2010/11, and 370,000 plants ha^{-1} in 2011/12. Measuring positions were: (i) directly above the beet canopy (30–50 cm above soil surface) (1 sensor per sub-plot), (ii) 5 cm above the soil surface; between the rows, (iii) 5 cm deep in the soil. Positions (ii) and (iii) used 2 sensors per sub-plot: the sensors were 4-wire Pt100 temperature sensors (Th2, UMS GmbH, Munich, GER). The air temperature directly above the beet canopy corresponded closely to the temperature measured using the standard protocol (2 m height).

The temperature was measured in the taproot crown of April-sown and June-sown plants (4–10 plants per sub-plot). In 2010/11, temperature measurements were additionally conducted in the upper part of August-sown taproots (4 plants per sub-plot). Measurements in the taproots used special 4-wire Pt100 temperature sensors of 1 and 2 mm diameter (KWT 10-60-3000 and KWT 20-100-3000, Unitherm Messtechnik GmbH, Bruchköbel, GER).

Temperature was measured every minute and data were recorded as hourly mean values using DL2e-Data logger (Delta T Devices Ltd., Burwell, Cambridge, UK). Daily mean temperatures were calculated as the arithmetic mean of hourly values, which were also used to derive daily maximum and minimum values.

At Göttingen in 2011/12, two of the four replicates were covered with chopped wheat straw in a 10 cm thick layer for frost protection. For these beets, the crown temperature was estimated by adding a temperature difference between covered and not covered beets of +2 °C to the hourly values measured in the uncovered treatment. This difference was derived from measurements 1 cm deep in the soil, where temperatures under the straw were 1.5–2 °C higher during frost periods than temperatures without straw cover at the same location (Loel, 2012, personal communication).

2.4. Determination of the maximum taproot diameter

In November the plants were harvested from the three center rows per sub-plot. Each plant was classified according to the maximum diameter of its taproot. The 8 diameter classes were 0.01–2.29, 2.3–2.9, 2.91–4.9, 4.91–7.2, 7.21–9.2, 9.21–11.2,