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Sugar beet response to varied plant populations—Current and historic trial results

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Abstract

Since the end of the 1980s, plant populations (PP) of 80,000–100,000 plants ha^{-1} have been considered optimal for sugar beet (*Beta vulgaris* L.) cultivation without singling in temperate climate. Since then, however, yield levels and growing conditions have changed. To determine the current PP optimum, three field trials with PP from 55,000 to 130,000 plants ha^{-1} were carried out in Germany in 2022 and 2023, measuring canopy ground cover (CGC) via RGB images as well as sugar yield and taproot quality. Additionally, a meta-analysis was carried out including literature data from the past 60 years (18 studies, 111 trials) to record possible changes in the optimum PP over the past decades. In the field trials, the sugar yield increased by 8% when the PP was increased from 55,000 to 100,000 plants ha^{-1}, while the CGC of 85%, indicating complete light interception, was advanced by 160°C day thermal time (base 3°C). In response to the PP variation, thermal time to reach 85% CGC highly correlated with sugar yield. Individual plants had no physiological source limitation, as they could more efficiently build up sugar yield with a higher taproot-to-leaf ratio, partially compensating for the yield loss due to the reduced plant number at lower PPs. PPs above 100,000 plant ha^{-1} produced only little additional yield. The meta-analysis revealed no change in the optimal PP over the past decades. Thus, the PP of 80,000–100,000 plants ha^{-1} is still valid for current sugar beet cultivation with sowing to a stand in temperate climate.

Plain Language Summary

Since the late 1980s, a plant population (PP) of 80,000–100,000 plants ha^{-1} has been seen as best for sugar beet (*Beta vulgaris* L.) growing. However, since then, conditions have changed. To test if another PP is better now, we did three field trials in Germany with PPs between 55,000 and 130,000 plants ha^{-1} and reviewed data from more than 100 trials from the last 60 years to see if there were changes over time. In the new field trials, we found a higher yield for higher PPs, with large effects up to 100,000 plants ha^{-1}. The reason for this might be that the plants covered more of the

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ground earlier at high PPs, through which the whole plant stand can take up more light. A single plant, on the other hand, uses the light better at low PPs. From the old data from the past 60 years, we can say that the best PP was similar over this time. As an overall result, a PP of 80,000–100,000 plants ha^{-1} can still be seen as the best PP for sugar beet growing.

1 | INTRODUCTION

In the first half of the 20th century, sugar beet (*Beta vulgaris* L.) stands of around 65,000 plants ha^{-1} were regarded as optimal for maximum yield (e.g., Verres & Bornscheuer, 1967). In such stands intra-row spacing of plants was equal without missing plants (gaps), and inter-row spacing was 0.45–0.5 m, resulting in an intra-row plant distance of 0.33–0.37 m, respectively. The manual singling of plant stands grown from multigerm seeds was essential to secure the growth of taproots of individual plants to a size suitable for mechanical lifting by specialized harvest machinery (>400 g root^{-1}). The introduction of genetically monogerm cultivars in the 1960s revolutionized sugar beet cropping since it allowed sowing the crop to the targeted final stand and thereby relieved the growers from laborious manual and/or mechanical singling (Francis, 2006).

Compared to dense sowing of multigerm seeds and singling, crops resulting from sowing to the final stand run the risk of irregular plant spacing in the row with gaps of different sizes due to plant losses of one or more seeds. The causes of this heterogeneity were identified as seedbed preparation with significant small-scale variations in tillage depth combined with inappropriate seed placement, which resulted in some seeds lying dry while neighboring seeds were placed too deep into moist and possibly smeared soil, both of which can lead to establishment failures and gaps of one or more plants. The occurrence of fungal diseases, insects, mice, and snails can further exacerbate these effects, all of which can still be observed today. Farmers thus must estimate in advance the field-specific crop emergence rate to decide on the intra-row seed spacing for the optimal plant population (PP).

Furthermore, unlike cereals, oilseed rape (*Brassica napus* L.), and legumes, sugar beet plants do not tiller or branch, and, in addition, plant height is limited to <1 m. In consequence, the potential to compensate for gaps due to missing neighbors is limited, although sugar beet has a high plasticity in the growth of the individual plant. Thus, among other factors, PP and number and size of gaps govern the interception of incident radiation and affect yield formation of sugar beet crops (Jaggard & Qi, 2006).

With the introduction of genetically monogerm varieties, the question arose whether the targeted PP has to be adjusted to the modified, gappy conditions of sugar beet stands. Thus, extended field trials were initiated. Increased PPs of 70,000–80,000 plant ha^{-1} were found as optimal derived from intra-row seed spacings of around 0.2–0.22 m, provided the field emergence rate was at least 75%. At lower field emergence rates down to 50%, seed spacings down to 0.15 m were required (e.g., Bornscheuer, 1970; Winner et al., 1976). After such early field trials, PP trials under temperate European conditions were periodically conducted during the 1980s and in the mid-1990s, revealing only slight changes in the optimum PP. As a result, PPs of 80,000–100,000 plants ha^{-1} were recommended as optimal worldwide (Paul, 2022). Lower PPs down to 30,000–40,000 plants ha^{-1} progressively decrease sugar yield by about 10%–20% (Jaggard & Qi, 2006; Märländer, 1990). However, since the 1960s, modifications in crop management, for example, lower nitrogen (N) fertilizer doses, longer cropping seasons due to the temperature increase, in particular in spring, and thus earlier sowing, and genetic improvements of the cultivated varieties occurred, which might interact with the optimum PP. Yet, only a few trials were conducted worldwide after the 2000s. In particular, no data are available for current European crop management and climate conditions, that is, temperate humid climate.

Physiologically, differences between PPs regarding sugar beet growth and final yield are primarily governed by a different ability of the plant stands to intercept the incident radiation (Jaggard & Qi, 2006). In temperate climate with sowing not earlier than mid-March to avoid bolting induction, canopy formation in spring must be as early as possible to secure maximum light interception. At optimal water and nutrient supply, temperature predominantly governs leaf growth, and at row spacings of 0.45–0.5 m and a PP of 90,000 plants ha^{-1} canopy closure and a sufficiently high leaf area index of 3 m^2 m^{-2} were reported to be reached at about 880°C day thermal time (Hoffmann, 2019; base temperature 3°C). At lower PP, thermal time required for canopy closure is supposed to be higher, or closure will even remain incomplete, resulting in below maximum light interception and thus ultimately below maximum yield (Jaggard & Qi, 2006). This shortcoming is exacerbated if plants are irregularly spaced within rows, resulting in large gaps that cannot be compensated for by neighboring plants. It has long been known that the leaf area index and the canopy ground cover (CGC) are suitable for quantifying the photosynthetic potential of crops. In their studies conducted with dense and regular crop stands,

Steven et al. (1986) showed a CGC of 85%–90% as sufficient for maximum sugar beet light interception and yield, that is, below 85% CGC yield losses are to be expected.

To address uncertainties in the understanding of PP effects under conditions with missing plants, that is, effects of plant stands with gaps of different number and size on current sugar beet growth and yield, we conducted field trials in 2022 and 2023 on two loessial soils in Germany typical for temperate European sugar beet cropping to answer the following questions: (i) Which PP is optimal for sugar beet yield and quality under current cropping conditions? (ii) How does PP affect the thermal time required to achieve 85% CGC? (iii) To what extent do differences in early leaf development contribute to the effect of PP on sugar beet yield? (iv) Is the yield reduction at low PP due to a physiological source limitation?

Because of the great changes in yield level and cropping conditions since the 1960s, an additional research question arose: Has the optimal PP changed since the introduction of genetically monogerm seeds in Central Europe? To answer this question, the literature published since 1965 was reviewed in a meta-analysis and compared to the results of the field trials conducted for this study.

Core Ideas

- There are only a few recent studies on sugar beet plant population despite changed growing conditions.
- The current study includes three recent trials and a meta-analysis of 111 trials since the 1960s.
- Results show that 80,000–100,000 plants ha^{-1} remains the optimum plant population.
- Main reason for yield loss at lower populations is a delayed or non-occurring canopy closure.
- Yield loss at lower populations is partially compensated for by increased individual plant growth.

2 | MATERIALS AND METHODS

2.1 | Field trials 2022–2023

2.1.1 | Study sites, experimental design, and crop management

The field experiments were located near Göttingen (Central Germany, 160 m asl; Sieboldshausen: 51.46996 N, 9.90674 E; Wolbrechtshausen: 51.62965 N, 9.87177 E). At the sites the soils were classified as Luvisols (IUSS Working Group WRB, 2022) with a rootable depth of >1 m. In the topsoil (0–30 cm), texture consisted of 120–150 and 750–850 g kg^{-1} of clay and silt, respectively, and organic carbon (C) and total N concentration were 12–13 and 1.2–1.3 g kg^{-1}, respectively; the pH (0.0125 m $CaCl_2$) was around 7 and the gravel content zero. Long-term annual precipitation was 624 mm and mean air temperature was 9.5°C (DWD, 2022). The main growing seasons (May–September) in 2022 and 2023 were characterized by higher temperatures (16.8°C and 16.9°C, respectively) and lower rainfalls (124–264 mm, respectively) compared to the long-term average for this period (15.1°C, 301 mm). Despite such modifications, the conditions were in the regular range of a humid, cool-temperate climate, and thus no growth limitations due to these factors could be expected or were observed in the field. Table 1 gives more details on the weather characteristics of the growing season.

The experiments were designed in randomized complete blocks with four replicates; randomization was done individually for each trial. Six PPs were included: 55,000, 70,000, 85,000, 100,000, 115,000, and 130,000 plants ha^{-1}. Plots were 8 m long with six rows with an inter-row distance of 0.45 m. The different PPs were established starting from dense sowing with 0.057 m intra-row seed spacing. Next, in the four- to six-leaf stage, plants were manually singled to 47 plants row^{-1} resulting in an average distance of 0.175 m. In case of missing plants, neighbors were left to reach the targeted number of 47 plants row^{-1}. In a third step, surplus plants were removed to reach the target PP according to the method proposed by Neeb (1963). Here, the number and size of gaps (number of missing plants in a row) follow differences in the percentage of field emergence (42%, 54%, 65%, 77%, 88%, and 100%, respectively). Roughly, the lower the field emergence, the higher the number of gaps and the bigger their size. Gaps were randomly distributed within each row, ensuring that each row starts and ends with a plant. For each row, an individual gap distribution was randomly calculated and executed in the field, consisting of gaps of the first order (one plant missing), second order (two plants missing), and so on. The number of first-order gaps per hectare was 16,667; 24,074; 23,148; 21,296; 17,593; and 3704; that of second-order gaps was 5556; 8333; 11,111; 5556; 0; and 0; and that of third-order gaps was 6481; 926; 926; 0; 0; and 0 for the PPs of 55,000, 70,000, 85,000, 100,000, 115,000, and 130,000 plants ha^{-1}, respectively. Fourth- or higher order gaps occurred only in the 55,000 and 70,000 plants ha^{-1} treatments at a number of 5556 and 4630 ha^{-1}, respectively.

Sugar beet was grown after winter wheat (*Triticum aestivum* L.) as the preceding main crop and white mustard (*Sinapis alba* L.) as the autumn-sown cover crop. Pre-crop residues remained in the field. Spring soil tillage was conducted with a rigid tine cultivator 0.15 m deep a few days before sowing after glyphosate spraying (3 L ha^{-1}) in early to mid-March to control perennial weeds as standard procedure. For seedbed preparation, two passes with a light

TABLE 1 Site and weather characteristics of field trials on plant population effects on sugar beet yield near Göttingen in 2022 and 2023.

Site	Sieboldshausen				Wolbrechtshausen	
Year	2022		2023		2022	
Sowing date	March 31		April 27		Mach 25	
Soil mineral N in spring (0–0.9 cm, kg N ha^{-1})	66		28		72	
Variety	Annarosa KWS		Calledia KWS		Ludovika KWS	
Fertilizer N dose (kg N ha^{-1})	94		110		88	
Drone flight 1, date	June 2		June 9		June 2	
Days after sowing	63		43		69	
Thermal time (°C day)[a]	509		439		549	
Drone flight 2, date	June 22		July 7		June 22	
Days after sowing	83		71		89	
Thermal time (°C day)	801		877		839	
Drone flight 3, date	July 20		August 4		July 20	
Days after sowing	111		99		117	
Thermal time (°C day)	1250		1311		1287	
Harvest date	October 17		October 24		October 4	
Weather characteristics	Rain (mm)	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)	Temp. (°C)
May 1–September 30	125	16.9	264	16.9	141	16.8

Note: Temp., air temperature.

[a]Base temperature 3°C.

harrow were applied. Dates of sowing and varieties used are given in Table 1. The topsoil macro- and micro-nutrient level of the field was adequate to secure optimal plant growth; for securing an optimum N supply level of 160 kg N ha^{-1} (soil mineral N in spring 0- to 0.9-m depth + fertilizer N), adjusted amounts of ammonium–nitrate–urea solution were applied shortly after sowing. Weeds, pests, and diseases were controlled effectively and uniformly, following the recommendations of the regional federal state extension services adapted by the personal experiences of the technicians responsible for the trials.

At three dates during the growing season (Table 1), RGB aerial photographs were acquired with a DJI Zenmuse X7 camera (35 mm F2) mounted to a DJI Matrice 210 RTK V2 drone. Flight routes were planned with the UGCS software (SPH Engineering). According to the flight height of about 30 m and the speed of 1.2–1.3 m s^{-1}, pixel size was roughly 0.3 × 0.3 cm $pixel^{-1}$. The images were processed with Pix4Dmapper software (Pix4D SA) to produce orthogonal maps. The reflectance of the three bands was extracted using QGIS (version 3.28.4) to calculate the visible atmospherically resistant index [VARI; (green − red)/(green + red − blue)]. CGC was derived by applying a VARI threshold value of 0 to separate green leaf area (VARI > 0) from bare soil for the six rows of the individual plots. VARI was shown to accurately estimate the green leaf area development of maize plants (Sakamoto et al., 2012) and was assumed to be valid for sugar beet as well. The leaf area index is closely correlated to CGC of sugar beet (Andrieu et al., 1997). For precise positioning of plots, four ground control points were installed at the four edges of the trial area with RTK GPS technique. Mean daily air temperature minus a base temperature of 3°C was used to derive the thermal time from sowing to each flight date (Milford et al., 1985).

In October, leaves and crowns of plants from three center rows per plot were manually cut off the taproot immediately below the insertion level of the eldest green leaf petioles at the crown. Leaves and crowns were weighed, and a representative subsample of 15–20 individuals was taken to the lab, where the material was macerated and homogenized, and a subsample was dried to constant weight at 105°C to determine the dry matter content. Next, beets of the three rows per plot were harvested with a one-row plot harvester, washed, and weighed in the tare house to determine the fresh matter yield of clean taproots. Clean taproots were processed to a representative subsample of taproot brei (4 × 25 g fresh matter). After Al-sulfate clarification, sugar concentration was determined polarimetrically and amino-N with the blue-number method, both from frozen taproot brei extract according to ICUMSA (1994). Sugar yield was obtained by multiplying taproot fresh matter yield and sugar concentration. Single plant sugar yield was calculated by dividing sugar

yield by the number of plants ha^{-1} counted at harvest. For determining the taproot dry matter content, an additional subsample was taken from the taproot brei and treated like the leaf material. Dry matter yield of both plant fractions was calculated from fresh matter yield and dry matter content. Taproot dry matter yield was divided by leaf dry matter yield to derive the mass ratio of the two fractions.

For clearer elucidation of PP effects on yield and quality across site/years, data are shown in relative terms, referenced to a PP of 85,000 plants ha^{-1}, which is in the range of the recommended PP for Germany (BISZ, 2025).

2.1.2 | Statistical analyses and calculations for the field trials

The statistical data evaluation was carried out with SAS Version 9.4 (SAS Institute Inc.). For taproot yield and quality parameters, a three-factorial analysis of variance was performed using year/site, PP, and its interaction as fixed effects. Residuals of the models were checked for homoscedasticity by Levene's test and graphically, and for normal distribution by Shapiro–Wilk's test as well as graphically. If the respective factor was found significant by the F-test ($p \leq 0.05$), least square means were compared by calculating least significant differences by Tukey's or Tukey–Kramer's test ($p \leq 0.05$).

The relationships between PP (x) and yield (y), as well as the parameters for taproot quality (y), were analyzed using the quadratic equation.

$$y = a + bx + cx^2. \quad (1)$$

To derive the thermal time required for 85% CGC, we first calculated the quadratic regression between the thermal time at the CGC measurement date as an independent parameter (x) and CGC as a response variable (y). For each PP, the thermal time to reach 85% CGC was then derived by transforming Equation (1) setting CGC to 85%.

$$\text{Thermal time 85\% CGC} = (b/c/2) - \left((b/c/2)^2 - ((a-85)/c)\right)^{0,5}. \quad (2)$$

Further, the linear regression between thermal time to reach 85% CGC and measured sugar yield variation caused by PP was calculated. Regression analyses and visualizations of results were conducted with SigmaPlot 14.5 (Grafiti LLC).

2.2 | Meta-analysis on PP effects since the 1960s

Literature was reviewed to collect data from PP trials conducted since the mid-1960s. Keywords "sugar beet," "plant population," "plant density," "population density," and "plant population density" were searched for in Google Scholar. Certain requirements were set to include the study: at least three PP levels with at least one PP in the range of 70,000–85,000 plants ha^{-1}, trials with replicates, and determination of taproot yield, sugar concentration, sugar yield, and amino-N-related compounds in the taproots. Amino-N data given per unit of sugar were converted to amino-N in mmol 100 g^{-1} of taproot fresh matter. Mean values for the single PP levels were used, covering a range from 20,000 plants ha^{-1} up to at least 70,000 plant ha^{-1}; PPs > 150,000 plants^{-1} were excluded. Inter-row spacing was mostly 0.45 m with a range of 0.35–0.6 m (Table 2).

In trials conducted in the 1960s, a few experiments aimed to elucidate PP effects depending on either even or gappy intra-row plant spacing, specifically at low PPs, obtained from either sowing to a stand in combination with varied field emergence or manual singling of dense stands followed by the random implementation of gaps of various sizes. Since PP effects did not differ between such spatial arrangements, both were retained in the dataset. Further, only studies conducted on loamy soils in humid cool-temperate climate (UK, NL, AT, GER, IRL, NZ) were considered, since trials conducted under arid conditions mostly with irrigation (Western United States, CHN, TUR, IRN, CRO, EGY, PAK) were much less frequent and not sufficiently evenly distributed over time. Further, data from trials with transplanting beets (JPN) and beets grown in raised beds with varying inter-row spacings were excluded.

Varieties used in the trials changed over time and were representative for commercial sugar beet cropping in each period and country. Similarly, fertilizer supply was adequate for high-yielding crops, and weeds, pests, and diseases were effectively controlled. Irrigation was applied in very few cases only. In total, 18 studies (including the present one) with 111 trials were included in the analysis (Table 2). Since the absolute levels of sugar yield and amino-N content varied largely among individual trial datasets, data were related to the mean of PPs in the range of 70,000–85,000 plants ha^{-1} = 100% to enable meaningful comparisons. The total dataset was split up into data originating from trials conducted over three (23) 20-year periods, from 1962 to 1984, 1985 to 2004, and 2005 to 2024. For 1962–1984, a total of 12 studies and 51 trials were available, for 1985–2004, six studies and 45 trials, and for 2005–2024, two studies and 15 trials. Two studies reported trials spanning two of the chosen 20-year periods. In case of the present study, a fourth trial conducted in the trial series was used in addition to the three trials described in detail in the present study. This trial had unusual growing conditions and differed strongly from the others in terms of early sugar beet development, yet resulted in comparable and plausible yield data, so that it was deemed suitable for the meta-analysis.

TABLE 2 Data sources for the meta-analysis concerning the effect of plant population on sugar beet yield.

Reference	Study years	Country	Row distance(cm)	Range of plant populations[a]	Number of trials	Number of plots
Verres and Bornscheuer (1967)	1965	Germany	42	39–98	1	8
Neeb and Winner (1969)	1965–1967	Germany	37–50	20–89	6	30
Bornscheuer (1970)	1967–1968	Germany	42	41–101	6	42
Draycott and Webb (1971)	1965–1969	United Kingdom	51	22–133	4	4*
Barocka et al. (1972a, 1972b)	1969–1971	Austria	42	49–101	6	6*
Harris (1972)	1962–1964	United Kingdom	56	35–145	4	16
Draycott et al. (1974)	1970–1972	United Kingdom	51	19–78	3	3*
Winner and Merkes (1975)	1973−1974	Germany	35–50	30–80	8	37
von Müller and Winner (1976)	1970–1972	Germany	50	40–90	3	14
O'Connor (1983)	1977−1978	Ireland	50–60	50–101	2	8
Bürcky and Winner (1986)	1983–1985	Germany	50	31–87	3	12
Märländer (1990)	1980–1988	Germany	45	35–110	12	66
Smit (1993)	1985–1986	The Netherlands	50	30–80	6	36
Kemp et al. (1994)	1990	New Zealand	50	60–140	1	5
Stockfisch and Koch (1999)	1996−1998	Germany	45	55–115	29	145
Bavorova et al. (2000)	1998–1999	Germany	45	50–108	2	8
Jaggard et al. (2011)	2006−2008	United Kingdom	50	40–178	11	66
Present study	2022–2023	Germany	45	55–130	4	24

Note: Asterisks (*) indicate average values over several study years.
[a]1000 plants ha^{-1}.

3 | RESULTS

3.1 | Field trials 2022–2023

Year/site effects were significant for all parameters, whereas PP had a significant effect on taproot fresh and dry matter yield, sugar yield, amino-N concentration, and sugar yield per plant only (Table 3). Interactions were insignificant for all yield and quality parameters (not shown). Yields increased with increasing PP up to 85,000 plants ha^{-1}, which was significant for all parameters except leaf yield. In contrast, the amino-N concentration decreased, and sugar concentration and taproot-to-leaf ratio were not affected by PP. Sugar yield per plant consistently decreased with increasing PP.

Referenced to 85,000 plants ha^{-1} (=100%), taproot and sugar yield increased from 95% to 103%, and sugar concentration from 99% to 100% with increasing PP from 55,000 to 130,000 plants ha^{-1}; amino-N concentration decreased from 120% to 91% in relative terms (Figure 1). Remarkably, the increase in sugar yield per plant was 42% when decreasing the PP from 85,000 (=100%) to 55,000 plants ha^{-1}, whereas the decrease in PP was only 35% (not shown).

For CGC, the interaction of year/site and PP was significant at each sampling date (not shown). However, such differences were not relevant for PP effects and will thus be disregarded for interpretation. In absolute terms, CGC varied from 11% to 97%, depending on sampling date, site/year, and PP (Table 4). The development of CGC revealed a close quadratic relationship to thermal time. Clear differences occurred between PPs (Figure 2): increasing PP caused a consistent increase of the intersect value and the linear and quadratic coefficients; both the intersect and quadratic coefficients had negative signs (not shown). Conversely, thermal time for reaching 85% CGC consistently decreased in steps of 965°C, 889°C, 846°C, 802°C, 782°C, and 763°C day for PPs of 55,000, 70,000, 85,000, 100,000, 115,000, and 130,000 plants ha^{-1}, respectively. Calculated with the average data across the 3 years/sites, CGC variation due to differences in PP was highly correlated with the final sugar yield at each of the three flight dates ($R^2_{adj} = 0.94 - 0.96$, Figure 3). The thermal time for reaching 85% CGC correlated even closer with sugar yield ($y = 23.89 - 7.93 \times 10^{-3}\ x$; $R^2_{adj} = 0.99$).

3.2 | Meta-analysis on PP effects since the 1960s

Mean absolute taproot and sugar yield were 47, 68, and 69, and 7.9, 11.7, and 11.9 Mg ha^{-1} for the three periods 1962–1984, 1985–2004, and 2005–2024, whereas amino-N

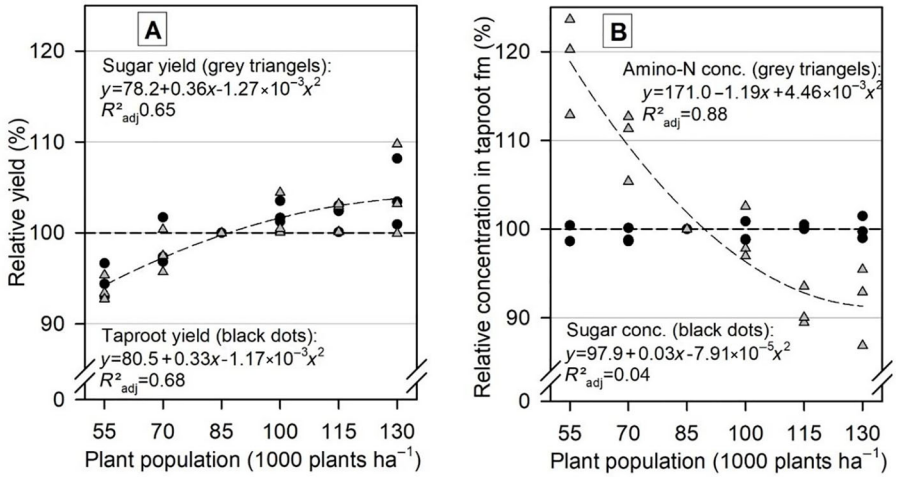


FIGURE 1 Relative values of taproot and sugar yield (A), and sugar and amino-N concentration in taproot fresh matter (B) as affected by plant population (85,000 plants ha^{-1} = 100%). Mean values from 3 years/sites with four replicates each ($N = 18$). The dashed line in figure (A) represents the graph for sugar yield. The regression for taproot yield was very similar and is not shown as a line here.

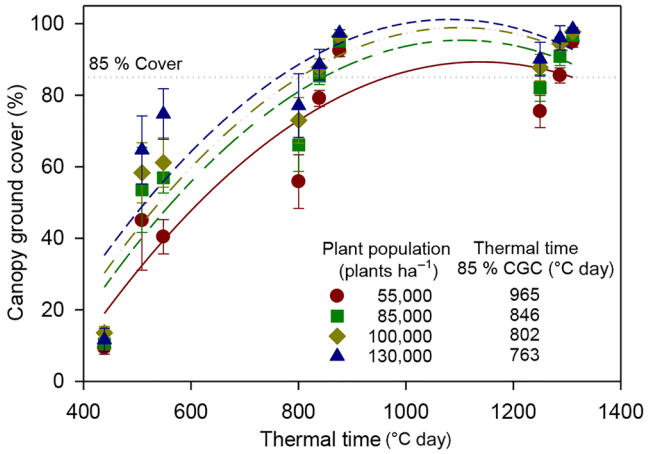


FIGURE 2 Relationship between canopy ground cover of sugar beet as affected by plant population and thermal time from sowing. Thermal time for reaching 85% canopy ground cover (CGC) is indicated. Three dates in June to July/August across three trials at Göttingen 2022–2023.

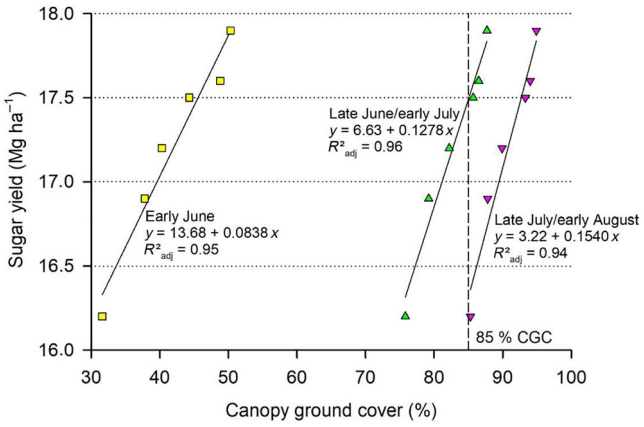


FIGURE 3 Relationship between canopy ground cover at three dates of the growing season and final sugar yield. Variation caused by different plant populations. Mean of three field trials at Göttingen 2022–2023. $N = 6$. CGC, canopy ground cover.

concentration decreased from 1.94 to 1.71 and 0.74 mmol 100 g^{-1} of taproot fresh matter (Figure 4). The relationship between relative sugar yield (referenced to values between 70,000 and 85,000 plants ha^{-1} = 100%) and PP was best described by a two-parameter exponential equation with rise to maximum sugar yield, which was reached at 101.9%, 99%, and 95% of the maximum sugar yield (at 101.9%), and was obtained at around 85,000 and 62,000 plants ha^{-1}, respectively (Figure 5). The distribution of data indicates no difference between the three 20-year periods in the response of yield to increasing PP. This was likewise the case for the amino-N concentration, for which a three-parameter exponential decay approach fitted best (Figure 6).

4 | DISCUSSION

4.1 | PP effects on amino-N as an indicator for beet quality

In our field data, the absolute concentration of amino-N in taproot fresh matter as an important beet quality parameter, representing melassigenic substances, was in a range similar to other current and previous studies conducted under low disease, water, and nutrient stress in the temperate climate of Europe, North America, and Asia (Allison et al., 1994; Hoffmann, 2010; Afshar et al., 2019; Fei et al., 2019; Ebmeyer et al., 2021). Similar to our study, across several decades and thus a variety of growing conditions, a multitude of researchers found a substantial reduction in root impurities

TABLE 3 Year/site and plant population main effects on yield and quality of sugar beet. Mean and standard error of six plant populations (for year/site) and three trials at Göttingen 2022–2023 (for plant population).

	Taproot yield (fm) (Mg ha^{-1})	Sugar yield (Mg ha^{-1})	Sugar conc. (%)	Amino-N conc. (mmol kg^{-1})	Leaf yield (dm) (Mg ha^{-1})	Taproot yield (dm) (Mg ha^{-1})	Taproot-to-leaf ratio (dm) (−)	Sugar yield per plant (g plant^{-1})
Year/site								
22Siebo	84.1 ± 0.88B	15.7 ± 0.18B	18.7 ± 0.07A	9.3 ± 0.17A	3.76 ± 0.23B	20.6 ± 0.21B	5.49 ± 0.14A	180 ± 1.8B
22Wol	104.3 ± 0.88A	18.0 ± 0.18A	17.2 ± 0.07B	7.6 ± 0.17B	5.83 ± 0.23A	23.4 ± 0.21A	4.07 ± 0.14B	209 ± 1.8A
23Siebo	107.9 ± 0.90A	17.9 ± 0.18A	16.6 ± 0.07C	5.9 ± 0.17C	6.49 ± 0.23A	23.4 ± 0.21A	3.68 ± 0.14B	208 ± 1.8A
Plant population (plants ha^{-1})								
55,000	93.5 ± 1.18C	16.2 ± 0.22C	17.4 ± 0.07	8.9 ± 0.19A	4.91 ± 0.24	21.1 ± 0.29C	4.49 ± 0.12	288 ± 2.7A
70,000	97.3 ± 1.12BC	16.9 ± 0.21BC	17.4 ± 0.07	8.1 ± 0.19B	4.97 ± 0.24	22.0 ± 0.28BC	4.62 ± 0.12	239 ± 2.5B
85,000	98.6 ± 1.12AB	17.2 ± 0.21AB	17.6 ± 0.07	7.4 ± 0.19BC	5.23 ± 0.24	22.5 ± 0.28AB	4.48 ± 0.12	203 ± 2.5C
100,000	100.6 ± 1.12AB	17.5 ± 0.21AB	17.5 ± 0.07	7.3 ± 0.19C	5.79 ± 0.24	22.9 ± 0.28AB	4.35 ± 0.12	175 ± 2.5D
115,000	100.3 ± 1.12AB	17.6 ± 0.21AB	17.6 ± 0.07	6.8 ± 0.19C	5.49 ± 0.24	22.9 ± 0.28AB	4.33 ± 0.12	152 ± 2.5E
130,000	102.4 ± 1.12A	17.9 ± 0.21A	17.6 ± 0.07	6.9 ± 0.19C	5.76 ± 0.24	23.4 ± 0.28A	4.22 ± 0.12	138 ± 2.5F

Note: Different letters indicate significant differences within each group (Tukey's test, $p \leq 0.05$).
Abbreviations: dm, dry matter; fm, fresh matt

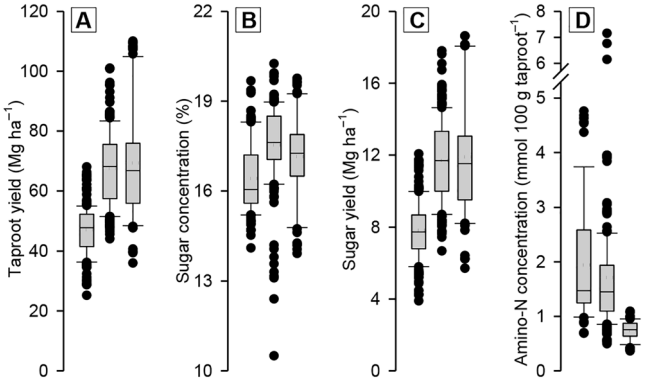


FIGURE 4 Distribution of data of the meta-analysis on plant population effects on taproot yield (A), sugar concentration (B), sugar yield (C), and amino-N concentration (D) in different periods. For each parameter, the figures show values from the periods 1962 to 1984 (left), 1985 to 2004 (center), and 2005 to 2024 (right). Box and whiskers indicate the 10th, 25th, 75th, and 90th percentiles, dots show outliers. Line and dotted line indicate median and mean values, respectively. $N = 205$, 196, and 83 for taproot yield; 194, 196, and 83 for sugar concentration; 200, 232, and 84 for sugar yield; and 64, 192, and 65 for amino-N for the three periods, respectively.

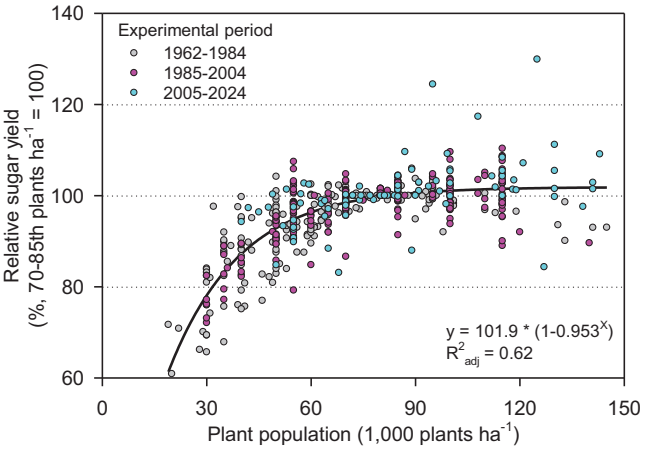


FIGURE 5 Relationship between relative final sugar yield and plant population of sugar beet in temperate climate in different periods, setting 70,000–85,000 plants ha^{-1} as 100% for each year/site. $N = 208$, 232, and 83 for the periods 1962–1984, 1985–2004, and 2005–2024, respectively. Data from a meta-analysis of 17 references and the current study, including 111 trials.

by about 25% with increasing PP in the range from 50,000 to 130,000 plant ha^{-1}, whereas the sugar concentration was increased, but to a much lesser extent of only 2% (Bornscheuer, 1970; Draycott & Webb, 1971; Barocka et al., 1972a; Winner & Merkes, 1975; von Müller & Winner, 1976; Bürcky & Winner, 1986; Märländer, 1990; Stockfisch & Koch, 1999). In the early studies by Verres and Bornscheuer (1967) and Neeb and Winner (1969), however, including PPs even below 50,000 plants ha^{-1}, an exponential increase by about 100% for

TABLE 4 Year/site and plant population effects on sugar beet canopy ground cover (%) at three dates in June–July/August. Mean of six plant populations (for year/site) and three trials at Göttingen 2022–2023 (for plant population) with standard errors.

	43–69 DAS (early June)	71–89 DAS (late June/early July)	99–117 DAS (late July/early August)
Year/site			
22Siebo	56.0 ± 3.6A	68.2 ± 2.1C	84.1 ± 1.2C
22Wol	59.2 ± 3.6A	84.9 ± 2.1B	91.5 ± 1.2B
23Siebo	11.4 ± 3.6B	95.4 ± 2.1A	97.0 ± 1.2A
Plant population (plants ha^{-1})			
55,000	31.6 ± 2.3E	75.8 ± 1.3D	85.3 ± 0.8C
70,000	37.8 ± 2.3D	79.2 ± 1.3C	87.8 ± 0.8B
85,000	40.3 ± 2.3CD	82.2 ± 1.3B	89.9 ± 0.8B
100,000	44.3 ± 2.3BC	85.7 ± 1.3A	93.3 ± 0.8A
115,000	48.8 ± 2.3AB	86.5 ± 1.3A	94.0 ± 0.8A
130,000	50.3 ± 2.3A	87.7 ± 1.3A	94.9 ± 0.8A

Note: Different letters indicate significant differences within each group (Tukey's test, $p \leq 0.05$).
Abbreviation: DAS, days after sowing.

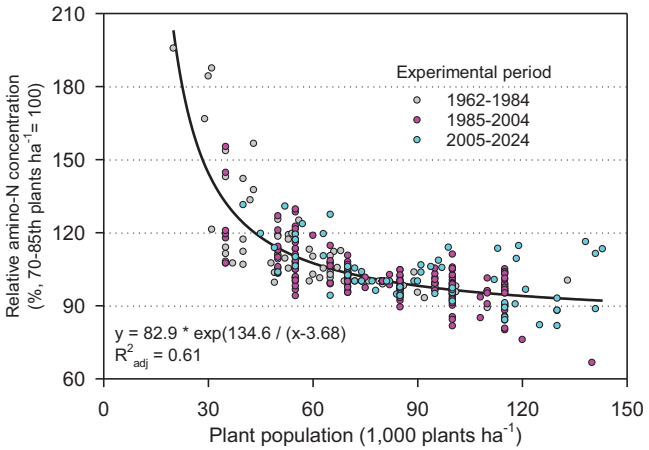


FIGURE 6 Relationship between relative concentration of amino-N-related parameters in the taproot and plant population of sugar beet in different periods in temperate climate, setting 70,000–85,000 plants ha^{-1} as 100% for each year/site. $N = 92$, 191, and 65 for the periods 1962–1984, 1985–2004, and 2005–2024, respectively. Data from a meta-analysis of 10 references and the current study, including 70 trials.

amino-N-related parameters in the range of 50,000 down to 20,000 plants ha^{-1} was detected, whereas the decrease of the sugar concentration was much less pronounced by only 5%. More recent studies no longer considered such low PPs. The observed discrepancy in the response of amino-N and sugar concentration to the variation in PP is addressed in detail in Section 4.4.

Breeding progress caused a substantial decrease in the absolute concentrations of melassigenic substances in beet fresh matter in the past decades (Hoffmann et al., 2020). Simultaneously, N fertilizer doses have been considerably decreased in sugar beet cultivation since the 1970s (Märländer et al., 2003). Because of these great changes, it was hypothesized that the impact of PP on such parameters has decreased accordingly, so that today's beet quality is only slightly influenced by PP. However, despite a much lower absolute concentration, the distribution of amino-N-related data as affected by PP was similar for the decades considered. Therefore, this hypothesis could not be confirmed. Apparently, no interaction exists between PP effects and the absolute level of compounds affecting beet processing quality.

4.2 | PP required for maximum sugar yield

In the current field trials, conducted with gappy plant stands as typical for current sugar beet cultivation in most parts of the world with sowing to the final stand, sugar yield increased by roughly 5% from 50,000 to 85,000 plants ha^{-1}, which was almost completely caused by an increase in root yield, whereas the sugar concentration increased only slightly. Despite large changes in absolute yield and quality levels over the decades since the 1960s, a comparable response to PP changes was found in the long-term meta-analysis data (not shown for sugar concentration and root yield). Below 50,000 plants ha^{-1}, yield losses became increasingly greater, and above 85,000 plants ha^{-1}, yield gains became very small. Overall, the data imply that PPs should not fall below 75,000–80,000 plants ha^{-1}, whereas PPs up to 130,000 plants ha^{-1} have the potential to further increase yield by about 2% only, indicating that a yield plateau seems to be reached at such a high PP. Although only a limited number of studies, mostly conducted in the past 20 years, included such high PPs, the optimum PP of 80,000–100,000 plants ha^{-1} reported by many

other studies in the past conducted under various soil and climatic conditions is confirmed herewith.

From a practical point of view, it can be noted that PPs in the optimum range of 80,000–100,000 plants ha^{-1} result from typical inter-row spacings of 0.45–0.5 m with intra-row seed distances of 0.16–0.18 m at a field emergence of 65%–80%. If field emergence is ensured to be higher than 85%, intra-row spacing might be enlarged to 0.21–0.23 m without PP falling below the critical value of 80,000 plants ha^{-1}.

4.3 | Relationship between PP, CGC, and sugar yield on plant stand level

Our data confirmed that, under optimal conditions concerning soil structure, water, nutrients, pests, and diseases, sugar beet canopy development is primarily governed by temperature (Milford et al., 1985). Hoffmann (2019) reported canopy closure occurring at a thermal time around 880°C day, which is close to the values obtained from our data for 85% CGC at PPs of 70,000–85,000 plants ha^{-1}, corresponding to a sugar beet leaf area index of 3–3.5 according to Andrieu et al. (1997). Moreover, at widely used row spacings in the range of 0.4–0.6 m, the canopy development, and thus light interception, is strongly affected by PP (Röver, 1994). Increasing PPs lowered the thermal time required for 85% CGC, indicating maximum capture of radiation (Milford, 2006), to 763°C day at 130,000 plants ha^{-1}. Strikingly, thermal time required for 85% CGC correlated with the average sugar yield across the three sites/years with an R^2 of close to 1 ($N = 6$), thereby clearly confirming the significance of early canopy development and a sufficient plant number for final yield. Consequently, sugar yield of a plant stand can be estimated from the CGC and the timepoint of reaching 85% canopy cover as stated by Jaggard and Qi (2006).

Questions remain open about the physiological cause for the yield reduction at low PP. In general, assimilate production and storage, and, ultimately, crop yield can be limited by source and/or sink limitation and by limited transport capacity between those two (Monteith, 1977; Marcelis, 1996; Hoffmann, 2019). Since CGC is indicative of the crop's source capacity at plant stand level, our data seem to indicate that delayed canopy closure, and thus source limitation at the plant stand scale, was the main cause for the lower yield at low PPs.

4.4 | PP effects at individual plant level

So far, PP effects have been regarded on field scale and were shown for the plant stand. However, in order to analyze physiological processes, the growth and development of the individual plant at different PPs must be considered. When different PPs are reached by different seed spacings within the row, the individual plants develop more or less uniformly, provided they emerge more or less simultaneously. In that case, the size of the individual plants consistently increases with decreasing PP and increasing space for each plant (Bavorova et al., 2000; Jaggard & Qi, 2006). For different PPs resulting from gaps, thus reflecting low field emergence with randomly distributed plant losses, the case is different: even at low PP it can be assumed that individual plants develop similarly to the plants at high PP, provided they are not neighboring a gap, which would be true for most of the plants. Hence, those plants should produce the same yield (taproot, leaf, and sugar yield) without any yield restriction as plants at other PPs.

The effect of the lower PP must therefore result solely from the missing plants in the gaps and from the plants neighboring a gap. Plants growing next to a gap experience different growing conditions compared to plants with neighbors. They can utilize a larger soil volume and thus a higher availability of water and nutrients and, moreover, intercept light impinging from the open sides of the plant leaves. The higher nutrient supply and uptake is the reason why sugar beet plants at lower PPs have higher concentrations of non-sugar compounds, in particular N compounds, but also potassium (K) and sodium (Na) (Märländer, 1990). Because of the better N supply, plants grow larger, which is mainly an effect of N on cell volume accompanied by a proportional increase of non-sugar dry matter and water per cell (Milford & Watson, 1971). When the optimal cell size for sugar storage is exceeded, additional sugar storage by cells decreases (Milford, 1976), explaining the lower sugar concentration at lower PP.

To test whether the yield reduction is solely caused by missing plants, the yield of individual plants was calculated for the field trials of this study. It turned out that at low PP the sugar yield (despite the lower sugar concentration) was much higher for an individual plant and, in relative terms, more than proportionally higher compared to the reduction in PP. Therefore, the capacity of the missing plants appears to be compensated for and even overcompensated for by additional growth and yield formation of the remaining plants, especially since the rough calculation did not take into account that only the plants adjacent to a gap are different.

Despite the reduction in leaf formation, canopy cover, and thus radiation interception at lower PPs, the yield reduction resulting from lower PPs is much lower than what could be expected from the missing plant number. A limitation by the source capacity can therefore be excluded for the single plant. On the contrary, plants even achieved a higher root-to-leaf ratio pointing to a more efficient sugar storage under lower PP compared to optimal or higher PP. The smaller canopy thus had the capacity to form root and sugar yield more efficiently, and thereby partially compensate for the missing plants. When 130,000 plants ha^{-1} is a plant stand without any missing

plants, neighboring plants can apparently fully compensate for gaps with their greater yield to a PP of 80,000 plants ha^{-1}. Thus, there is no indication for a physiological source limitation, but just a lack of a sufficient number of plants as the higher efficiency of the individual plants neighboring a gap cannot fully compensate for the missing plants between 55,000 and 80,000 plants ha^{-1}, despite reducing the yield loss strongly.

5 | CONCLUSIONS

The data from the recent field trials show a later canopy closure because of missing plants, and thus source limitation due to reduced light interception on the crop stand scale, but not a physiological source limitation at individual plant level as cause for yield reductions at low PPs. The long-term data analysis, including the trials from this study, clearly shows that, for sugar beet cultivation in temperate climate and with sowing to the final stand at 0.4–0.6 m inter-row spacing, PPs in a range of 85,000–100,000 plants ha^{-1} are still optimal for high yields with low impurity concentrations. The recent field trials point to a small potential for gaining an additional 2% sugar yield increase at PPs of 110,000–130,000 plants ha^{-1}, whereas planned PPs below 80,000 plants ha^{-1} are at risk to cause yield losses up to 5% when PP falls to 60,000 plants ha^{-1} due to low field emergence. Simultaneously, beet impurity concentrations detrimental to sugar processing increase disproportionally at lower PPs. Such relationships have apparently not changed over the past decades despite breeding progress and modified cropping conditions.

AUTHOR CONTRIBUTIONS

Heinz-Josef Koch: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Dennis Grunwald**: Data curation; writing—review and editing. **Christa M. Hoffmann**: Conceptualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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