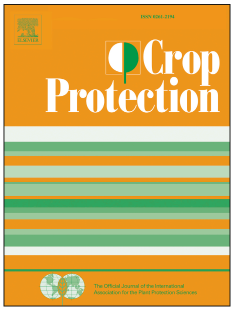


Informing the operation of intelligent automated intra-row weeding machines in direct-sown sugar beet (*Beta vulgaris* L.): Crop effects of hoeing and flaming across early growth stages, tool working distances, and intensities

Margaret R. McCollough, Frank Poulsen, Bo Melander

PII: S0261-2194(23)00384-8

DOI: https://doi.org/10.1016/j.cropro.2023.106562

Reference: JCRP 106562

To appear in: *Crop Protection*

Received Date: 9 June 2023

Revised Date: 26 October 2023

Accepted Date: 11 December 2023

Submitted to Crop Protection

Pages: 50

Tables: 7

Figures: 6

Informing the operation of intelligent automated intra-row weeding machines in direct-sown sugar beet (*Beta vulgaris* L.): Crop effects of hoeing and flaming across early growth stages, tool working distances, and intensities

by

Margaret R. McCollough[a], Frank Poulsen[b], Bo Melander[a*]

[a]Department of Agroecology, Crop Health Section, Aarhus University, Forsøgsvej 1, 4200 Slagelse, Denmark.

[b]F. Poulsen Engineering ApS., Tjoerneager 16, 4330 Hvalsø, Denmark.

*Author with whom correspondence should be addressed. E-mail: bo.melander@agro.au.dk

Short title: Effects of automated intra-row weeding

Abstract

The effective management of intra-row weeds is necessary to preserve crop yields in slow-to-establish direct-seeded crops like sugar beet, and suitable non-chemical control options are limited. However, the advent of automated intelligent intra-row weeding machines has provided a promising solution. These machines identify individual crop plants and selectively hoe or flame weed the between-crop zone, leaving the intra-row close-to-crop zone untreated. To characterize crop tolerance to intra-row weeding and describe optimal tool working intensities and distances, five pot experiments were performed using sugar beet as the test crop. From cotyledon through the four-leaf stage, hoeing could be implemented as close as 1 cm to the center of sugar beet plants before adverse crop effects were observed. Based on crop injury measured, direct flaming of sugar beet at the cotyledon stage is not advised at any intensity, although flaming tolerance was observed to increase with crop growth stage. Direct flaming did not affect sugar beets when the propane dose was ≤ 0.74 kg km^{-1} at the two-leaf stage, ≤ 1.49 kg km^{-1} at the four-leaf stage, and ≤ 5.95 kg km^{-1} at the six-leaf stage. Sugar beets at the two-leaf growth stage were not damaged by flaming at distances ≥ 1.5 cm at a propane dose of 3.72 kg km^{-1}. Field experiments will be necessary to confirm these operational guidelines for next-generation automated intelligent weeders.

Keywords crop tolerance; flame weeding; flaming tolerance; hoeing tolerance; intra-row hoeing; intra-row weed control.

1. Introduction

Sugar beets (*Beta vulgaris* L.) are particularly vulnerable to crop yield and quality losses resulting from competition with weeds. As crop-weed proximity decreases, yield losses increase. For example, in sugar beet, Heisel et al. (2002) observed a 20% reduction in yield when the distance between crop plants and weed species, *Sinapis arvensis* L. and *Lolium perenne* L., decreased from 8 to 2 cm. Sugar beets also possess a slow growth rate throughout early development, making them sensitive to competition from weeds emerging before, concurrently with, or soon after the crop (Kropff, 1998; Kropff et al., 1992). Yield losses resulting from competition with 5 plants m^{-2} of *Chenopodium album* L. emerging on the same date as a sugar beet crop versus ten days after were reported as 79 and 37%, respectively (Kropff and Spitters, 1991). Therefore, to mitigate yield loss in sugar beet, it is necessary to control weeds growing nearest the crop, within the intra-row zone, across early growth stages.

While effective weed control in the inter-row zone of sugar beet is attainable using direct non-chemical methods (Tillet et al., 2002), non-chemical control of intra-row weeds is arguably much more challenging because of the crop's presence. It is difficult to effectively control weeds in the intra-row zone of sugar beet without causing crop damage that could negatively affect yield. Non-intelligent cultivators designed to operate in the intra-row are available; for example, hoe ridgers, finger weeders, torsion weeders, rotary hoes, and harrows (Bleeker et al., 2002; Champagne, 2022). These devices treat crop plants and weeds uniformly, requiring a substantial size differential between a larger crop and smaller weeds to operate selectively, maximizing weed control while minimizing crop damage (Gallandt et al., 2018). Because sugar beets are slow to establish, this prerequisite is challenging to achieve in a direct-seeded crop. Sugar beet is also sensitive to damages resulting from disturbance throughout early growth; thus, it is recommended to avoid direct cultivation until the four- to six-leaf stage (Melander, 2000; Bleeker et al., 2002). Transplanting sugar beets would help establish an ideal crop-weed size differential; however, this practice is far more labor-intensive than direct seeding and may negatively impact crop quality (Melander, 2000). As a result of the aforementioned constraints, hand weeding remains a necessary but costly weed management strategy for controlling intra-row weeds in sugar beet (Ascard et al., 1995).

Intelligent automated weeding machines provide a promising solution for non-chemical control of weeds established within the crop row. These devices can identify individual crop plants and selectively treat the between-crop zone within the intra-row using cultivators or flame weeders while leaving the close-to-crop zone untreated (Machleb et al., 2020). Machine vision and global navigation satellite systems (GNSS) predominate as the leading methods of crop detection employed among automated intra-row weeders currently on the market (Machleb et al., 2020; Melander and McCollough, 2021). Intra-row weeders employing machine vision systems currently rely on a crop-weed size differential to distinguish larger crop plants from smaller weeds (Melander et al., 2015). In a transplanted crop, where a significant size disparity is present, these automated weeders are capable of operating within the intra-row zone to selectively kill weeds without reducing crop stand or yield (Lati et al., 2016). Whereas, in a direct-seeded crop, stand reduction during operation is likely if crop plants are too small to achieve accurate detection (Lati et al., 2016). The identification of direct-seeded sugar beet thus poses a significant challenge for intelligent intra-row weeders employing machine vision systems, especially across early growth stages when weed control is of utmost importance from a yield preservation perspective. Progress has reportedly been made, however, in the ability of machine vision systems to detect direct-seeded crops via shape recognition, even at high weed pressure, instead of relying on size differential; this advancement in machine vision technology may soon enable accurate intra-row operation as early as the two-leaf growth stage in sugar beet. Intelligent weeders employing GNSS systems achieve intra-row crop detection via seed mapping, recording the precise location of individual crop plants at the time of direct seeding (Machleb et al., 2020; Melander and McCollough, 2021). Because this method does not rely on crop plants' physical presence to pinpoint their location in the field, it permits operation before and immediately after crop emergence, enabling direct intra-row weeding during early growth. However, one drawback of this strategy is that GNSS systems cannot identify where crop plants failed to establish; thus, in instances where there are gaps in the crop row, weeding will not occur in the area defined close-to-crop zone where crop plants are absent.

The development of intelligent intra-row weeding machines capable of operating in direct-seeded row crops constitutes a significant advancement in non-chemical weed management. The ability of these intelligent weeding machines to operate precisely, in close proximity to direct-seeded crops, and across early growth stages is only expected to improve in the near future. However, it must be considered that a trade-off exists when reducing the working distance between a hoeing or flaming implement and crop plants; yield losses resulting from physical damages and yield benefits associated with removing weeds growing nearest the crop are at odds with one another. Thus, the present study aims to inform the development and operation of automated intra-row weeding machines in direct-seeded sugar beet by simulating hoeing and flame weeding to: (i) determine the distance at which hoeing can be performed without inflicting significant crop damages across early growth, cotyledon through four-leaf stage; (ii) determine the intensity at which flaming can be implemented without inflicting significant crop damages across early growth, cotyledon through six-leaf stage; and (iii) determine the proximity at which a 'lethal flaming dose' can be administered at the two-leaf growth stage without inflicting significant crop damages. Ultimately, this information may be used to optimize the selectivity of automated intra-row weeding machines, allowing flaming and hoeing to occur at intensities as high as possible and proximities as close as possible to maximize weed kill while minimizing crop damages. Crop damages are expected to increase as hoeing and flaming distance decrease and as flaming intensity increases. Sugar beet tolerance to weeding tools is also expected to increase as they grow; thus, damages resulting from flaming and hoeing will be greater when implemented at earlier crop growth stages.

2. Materials and Methods

2.1 Design of experiments and treatment specifications

Five pot experiments were performed at the Aarhus University Flakkebjerg Research Center (Slagelse, Denmark; 55.33°N, 11.39°E), evaluating the response of sugar beet (*Beta vulgaris* L., cv. Davinci) to hoeing and flaming, when implemented across early growth stages and at varying proximities or intensities. Hoeing distance experiments ($EXP_{HOE.DISTANCE}$) studied the effect of hoeing proximity across early growth stages, flaming intensity experiments ($EXP_{FLAME.INTENSITY}$) studied the effect of flaming dose across early growth stages when distance was held constant, and flaming distance experiment ($EXP_{FLAME.DISTANCE}$) studied the effect of flaming proximity when dose and growth stage were held constant. $EXP_{HOE.DISTANCE}$ and $EXP_{FLAME.INTENSITY}$ experiments were replicated once in 2019 and once in 2020;

EXP_{FLAME.INTENSITY} was performed once in 2021 only. Table 1 summarizes dates and sugar beet growth stages when performing key treatments within each experiment.

All sugar beets were planted in a growing medium possessing a sand soil texture (90% sand, 4% silt, 6% clay), consisting of a 2:1 mixture by volume of field soil (sourced from Slagelse, Denmark 55.32°N, 11.40°E) and sand (sourced from Dalmose Vognmandsforretning ApS, Lundsgårdsvej 5, DK-4261, Dalmose). Soils were combined using a portable concrete mixer (ATIKA Profi 145, ATIKA GmbH, Ahlen, Germany) and were fertilized uniformly with YaraMila 24-4-10 (DLG, Axelborg, Vesterbrogade 4A, DK-1620, Copenhagen V, Denmark) at a rate of 200 kg of nitrogen ha^{-1}; thus, fertilizer application rates were based on the exposed soil surface area of growing containers.

When planting sugar beets, a template system was used to ensure consistent sowing depth and position at the center of each container. Planting templates were made of prefinished plywood cut to fit snuggly into container openings. After filling containers with soil, seeds were sown through a hole positioned at the center of the template. A consistent sowing depth was achieved by passing a plunger with a fixed stopper through the planting hole, pushing seeds 2 cm into the soil. Two seeds were planted in each container to improve the likelihood of establishment. Following emergence, sugar beets were thinned to one seedling per container. Throughout experimentation, any germinant weeds that established within containers were removed immediately.

2.2 Hoeing distance experiment and simulation

EXP$_{HOE.DISTANCE}$ investigated two factors in a randomized full factorial design with four replications per year: (i) hoeing distance at six levels, 0 (HD_0), 1 (HD_1), 2 (HD_2), 3 (HD_3), 4 (HD_4), and 5 cm (HD_5) relative to the center of sugar beet plants, and (ii) crop growth stage at time of hoeing at three levels, cotyledons unfolded (CS_{10}), first pair of true leaves unfolded (CS_{12}), and second pair of true leaves unfolded (CS_{14}). One untreated control treatment was also included within each block (HD_{CTRL}). Sugar beets were grown in rectangular containers possessing a length, width, and height of 18.0, 24.5, and 6.8 cm, respectively. Experiments were performed under semi-field conditions, in boxes kept outdoors, underneath a polycarbonate roof with open sides. Containers were watered uniformly via manual controls. In 2019, two drip emitters were installed per box, dispensing 2L of water per hour when turned on; in 2020, flood tables were used to irrigate. Hoeing treatments were implemented on all four sides of potted sugar beet plants (Fig. 1, Supplementary Video 1), simulating the disturbance pattern caused by the intelligent automated intra-row weeder, the Robovator (www.visionweeding.com). F. Poulsen Engineering ApS designed the hoeing simulator used to implement treatments within growing containers (Hvalsø, Denmark). The hoeing simulator was comprised of a 3 cm long side knife propelled forward by a compressed air pneumatic cylinder at a speed of 1.4 km h^{-1}. Across all treatments, hoeing was performed at a depth of 2 cm.

2.3 Flaming intensity experiment and simulation

EXP$_{FLAME.INTENSITY}$ also studied two factors in a randomized full factorial design with four replications per year: (i) flame weeding intensity at six levels, 0.1 ($FI_{0.1}$), 0.2 ($FI_{0.2}$), 0.4 ($FI_{0.4}$), 0.8 ($FI_{0.8}$), 1.6 ($FI_{1.6}$), and 3.4 ($FI_{3.4}$) seconds of flaming exposure to sugar beet plants, and (ii) crop growth stage at time of flaming at three levels, CS_{12}, CD_{14}, and third pair of true leaves unfolded (CD_{16}) in 2019 and CD_{10}, CD_{12}, and CD_{14} in 2020. Crop growth stage treatments differ among experimental years due to a logistical error, whereby the opportunity to flame weed at CD_{10} was missed in 2019; therefore, treatments were deferred one growth stage. One untreated control treatment was also included within each block (FI_{CTRL}). Sugar beets were grown in two-liter round pots under the same semi-field conditions described for $EXP_{HOE.DISTANCE}$. While irrigation was controlled separately for $EXP_{HOE.DISTANCE}$ and $EXP_{FLAME.INTENSITY,}$ identical irrigation systems were used to water pots in 2019 and 2020; the only exception being that one drip emitter was installed per pot in 2019. Flame weeding treatments were implemented twice per pot in sequence and on opposite sides of the plant (Fig. 2). Flaming treatments were implemented with an experimental flaming simulator built from a ROBOVATOR thermal weeding unit (F. Poulsen Engineering ApS., Hvalsø, Denmark) augmented so that a single flaming nozzle could be activated for precise intervals of time (Supplementary Video 2). Across all $EXP_{FLAME.INTENSITY}$ treatments, flame-emitting nozzle height was 7.5 cm, and flame angle was 50° relative to the soil's surface. Flaming distance, the point at which the flame made contact with the soil's surface, was held constant at 2 cm relative to the center of sugar beet plants. In $EXP_{FLAME.INTENSITY}$, the flame was aimed at crop plants to study crop tolerance to direct flaming when the flaming dose increased and flaming distance was constant (Fig. 2).

2.4 Flaming distance experiment and simulation

$EXP_{FLAME.DISTANCE}$ studied only one factor in a randomized complete block design with eight replications: (i) flaming distance at nine levels, 0.0 ($FD_{0.0}$), 0.5 ($FD_{0.5}$), 1.0 ($FD_{1.0}$), 1.5

($FD_{1.5}$), 2.0 ($FD_{2.0}$), 2.5 ($FD_{2.5}$), 3.0 ($FD_{3.0}$), 3.5 ($FD_{3.5}$), and 4.0 cm ($FD_{4.0}$), as well as an untreated control treatment (FD_{CTRL}). Sugar beets were grown under glass-house conditions in two-liter round pots on flood tables, receiving uniform watering via manual controls. Treatments were implemented using the same flaming simulator and set up as was described for $EXP_{FLAME.INTENSITY}$. However, at $FD_{0.0,}$ the flame's contact point with the soil's surface was centered on the crop plant, and flaming distance increased perpendicular to the theoretical crop row; this allowed for the evaluation of flaming distance when flaming dose and crop growth stage were held constant (Fig. 3). All flaming treatments were performed on the same day (Table 1) in an attempt to treat sugar beet plants at the two-leaf growth stage uniformly. However, on the day of flaming treatment, 8%, 29%, 18%, and 46% of sugar beets were observed to be at cotyledon, two-leaf, three-leaf, and four-leaf growth stages, respectively; this variation was accounted for during analysis. Flaming duration was held constant across all $EXP_{FLAME.DISTANCE}$ treatments at 2.0 seconds; this flaming duration was chosen as a 'lethal dose' upon referencing $EXP_{FLAME.INTENSITY}$ results from 2019 and 2020, it was also considered that $FD_{0.0}$ would receive a direct hit by the flame (Fig. 3).

2.5 Data collection

Upon sugar beet harvest in $EXP_{HOE.DISTANCE}$, $EXP_{FLAME.INTENSITY}$, and $EXP_{FLAME.DISTANCE}$, leaves were dissected from the roots at the soil's surface and laid flat, without any overlapping, beneath a transparent vinyl sheet. Digital photos were taken from above the broken-down shoot components and analyzed to determine the final leaf area using Easy Leaf Area software (SciPy Developers 2013, University of California, Los Angeles, California, United States; Easlon &

Bloom, 2014). Soil was rinsed from the roots, then blow- and above-ground components were dried separately for 24 hours at a temperature of 80°C and weighed to acquire dry matter measurements of both root and shoot biomass (g).

In $EXP_{HOE.DISTANCE}$, before implementing each hoeing treatment, soil moisture, as a measure of volumetric water content (%), was measured with a HydroSense II Handheld Soil Moisture Sensor (Campbell Scientific Inc., North Logan, UT, USA). In $EXP_{FLAME.INTENSITY}$ and $EXP_{FLAME.DISTANCE}$, when carrying out flaming treatments, the maximum achieved temperature (°C) at the center of the sugar beet plant was measured using a FLIR ONE™ Gen 2 thermal imaging camera (FLIR® Systems Inc., Wilsonville, OR, United States). Thermal imaging camera temperature approximation was validated by obtaining a reading of the temperature of boiling water (100°C). In $EXP_{FLAME.DISTANCE}$, a non-destructive measure of leaf area (cm^2) was acquired on the day of flaming treatment; digital photos were taken from above each plant and analyzed using Easy Leaf Area software.

2.6 Data analyses

The studies included quantitative independent variables (hoeing distance, flaming intensity, and flaming distance); however, it was not possible to establish clear and unambiguous relationships to describe treatment responses by regression analyses. Hence, it was decided to make use of analyses of variances to test treatment effects.

Data were analyzed using JMP® software (version PRO 16.1.0, SAS Institute, Cary, NC, USA). Across experiments, $\log_{10}$ (x+1) and square root (x+1) transformations were made when necessary to satisfy test assumptions of equality of variance among residuals and the normal distribution of residuals. Where data transformations were performed, both the transformed and back-transformed means are presented in tables. Notably, percent change calculated between treatments and discussed throughout the text were calculated using the back-transformed means. $\mathrm{EXP}_{\mathrm{HOE.DISTANCE}}$ data from 2019 and 2020 were analyzed separately. Because $\mathrm{HD}_{\mathrm{CTRL}}$ was not included in the full factorial design, separate models were used to evaluate main effects and interactions and to perform pre-planned contrasts. With $\mathrm{HD}_{\mathrm{CTRL}}$ excluded from analysis, a two-way analysis of variance (ANOVA) was used to evaluate the main effects and interactions among experimental factors, hoeing distance (HD), and crop stage (CS). Mixed model variables included the random term, block, and fixed terms, CS, HD, and CS*HD. With $\mathrm{HD}_{\mathrm{CTRL}}$ included in the analysis, a one-way ANOVA was used to carry out pre-planned contrasts. Mixed model variables included the random term, block, and one fixed term, treatment, comprised of all 18 unique combinations of HD and CS represented in experiments and the untreated control group, $\mathrm{HD}_{\mathrm{CTRL}}$. Contrasts compared each unique combination of HD and CS to $\mathrm{HD}_{\mathrm{CTRL}}$. Soil moisture at the time of hoeing was assessed for its effect on treatment outcomes. No relationship was observed between the continuous variable, soil volumetric water content (%), and response variables, sugar beet final leaf area, root biomass, shoot biomass, or total biomass; therefore, soil moisture was not included in the model. The same methodology was used to analyze $\mathrm{EXP}_{\mathrm{FLAME.INTENSITY}}$ as was described for $\mathrm{EXP}_{\mathrm{HOE.DISTANCE}}$; however, with the experimental factor, flame intensity (FI) was assessed in place of HD. Notably, soil moisture was not measured when flaming treatments were implemented in $\mathrm{EXP}_{\mathrm{FLAME.INSTENSITY}}$ or $\mathrm{EXP}_{\mathrm{FLAME.DISTANCE}}$; therefore, the relationships between soil volumetric water content and response variables were not evaluated.

In the analysis of $EXP_{FLAME.DISTANCE}$, FD_{CTRL} was included within the full factorial design; therefore, a single model was used to assess treatment effects and to perform pre-planned contrasts. With FD_{CTRL} included in the analysis, a one-way analysis of covariance (ANCOVA) was carried out. Mixed model variables included the random term, block, the fixed term, treatment, comprised of all nine flaming distances (FD) tested, as well as the untreated control group, $HD_{CTRL,}$ and the continuous term, leaf area (cm^2), measured on the day of implementing flaming treatments, as a co-variate assuming a linear relationship between leaf area and the response variable. Contrasts compared each level of FD to HD_{CTRL}.

Oxygen and propane fuel consumption per linear km of crop row (kg km^{-1}) were estimated for the ROBOVATOR flame weeder among all treatments studied in $EXP_{FLAME.INTENSITY}$ and $EXP_{FLAME.DISTANCE}$ (Table 2). Calculations were based on ROBOVATOR specifications; two bars outfitted with 30 flame-emitting nozzles operate together when working within the intra-row zone, and there's a 4 cm distance between nozzles. An intra-row crop spacing of 15 cm between sugar beet plants was also assumed. Measures of ROBOVATOR fuel and oxygen flow were acquired using an AWM5102 Airflow Sensor (Honywell International Inc., Houston, TX, USA). A single flaming nozzle used approximately 1.0 L min^{-1} of propane and 0.87 L min^{-1} of oxygen. In both $EXP_{FLAME.INTENSITY}$ and $EXP_{FLAME.DISTANCE}$, the absolute pressure of propane and oxygen were held constant across treatments at 1.15 and 1.21 bar, respectively.

3. Results

3.1 Hoeing distance

Hoeing distance (HD) had a significant main effect on all dependent variables in both 2019 and 2020, resulting from a strong and consistent response to the direct hit (HD_0) treatment (Fig. 4, Tables 3 and 4). HD interacted with crop growth stage (CS) in 2019, showing that HD_0 was only significantly different from $HD_{1–5}$ at CS_{12} and CS_{14}. When contrasting HD_0 to the untreated control (HD_{CTRL}) in both 2019 and 2020, significant reductions ($P < 0.05$) of final sugar beet leaf area (cm^2), sugar beet root biomass (g), sugar beet shoot biomass (g), and total sugar beet biomass (g) were greater than 50% in all cases (Fig. 4, Tables 3 and 4).

Sugar beet mortality rate was 50% at CS_{10} HD_0 and 25% at CS_{10} HD_1 in 2020 (data not shown). In both years, 50% of sugar beet plants were killed at CS_{12} HD_0, and 100% and 25% were killed at CS_{14} HD_0 in 2019 and 2020, respectively. A 100% survival rate was observed across all other treatments. Although some plants survived being hit directly with the hoeing simulator, resulting in physical damages caused taproot forking in all surviving sugar beets receiving HD_0 (data not shown). No forking of the taproot was observed in any other hoeing distance treatments tested ($HD_{1–5}$).

3.2 Flaming intensity

The average maximum temperatures achieved at the center of the sugar beet plants during treatment for each flaming intensity (FI) studied were 30.6°C (±1.1) at $FI_{0.1}$, 45.2°C (±3.4) at $FI_{0.2}$, 65.6°C (±4.6) at $FI_{0.4}$, 69.2°C (±5.6) at $FI_{0.8}$, 80.0°C (±6.0) at $FI_{1.6}$, 97.1°C (±5.6) at $FI_{3.2}$. In most cases, flaming intensity (FI) had a significant main effect on final sugar beet leaf area (cm^2), sugar beet root biomass (g), sugar beet shoot biomass (g), and total sugar beet biomass (g). For all response variables and in both years, FI interacted significantly with CS (Tables 5 and 6). In general, small-sized sugar beet plants ($CS_{10–12}$) were more vulnerable to increasing flaming intensity than the more developed beet plants ($CS_{14–16}$) (Fig. 5, Tables 5 and 6). Only $FI_{0.1}$ and partly $FI_{0.2}$ could be tolerated at CS_{10} in 2020. Flaming intensities up to $FI_{0.4}$ in 2020 and $FI_{0.8}$ in 2019 were possible at CS_{12} without significant crop injuries (> 50% growth reduction). At CS_{14}, sugar beet plants were not significantly affected by flaming intensities up to $FI_{0.8}$ in 2020 and FI3.2 in 2019; at CS_{16}, sugar beets were not significantly affected by $FI_{0.1–3.2}$.

Sugar beet mortality was 25% at CS_{10} $FI_{0.2}$, 75% at CS_{10} $FI_{0.4}$, and 100% at CS_{10} $FI_{0.8}$, CS_{10} $FI_{1.6}$, and CS_{10} $FI_{3.2}$ in 2020 (data not shown). In 2020, 25% of plants were killed at CS_{12} $FI_{0.8}$, and 50% and 75% were killed at CS_{12} $FI_{1.6}$ in 2019 and 2020, respectively. Across site-years, 100% of plants were killed at CS_{12} $FI_{3.2}$, and 75% of sugar beets were killed at CS_{14} $FI_{3.2}$ in 2020. A 100% survival rate was observed across all other treatments.

3.3 Flaming distance

The average maximum temperatures achieved at the center of the sugar beet plants during treatment for each flaming distance (FD) studied were 132.5°C (±8.8) at $FD_{0.0}$, 118.4°C (±18.0) at $FD_{0.5}$, 130.6°C (±10.1) at $FD_{1.0}$, 116.9°C (±11.8) at $FD_{1.5}$, 120.7°C (±29.3) at $FD_{2.0}$, 97.6°C (±15.3) at $FD_{2.5}$, 42.6°C (±7.6) at $FD_{3.0}$, 33.5°C (±1.7) at $FD_{3.5}$, and 42.5°C (±7.4) at $FD_{4.0}$. Flaming was tolerated for all distances greater than 1.0 cm ($FD_{1.0}$), while flaming closer to the sugar beet plants resulted in significant and marked growth reductions (> 30% reduction for most variables assessed) (Fig. 6, Table 7).

Sugar beet mortality was 88% at $FD_{0.0}$, 25% at $FD_{0.5}$, and 13% at $FD_{1.0}$; a 100% survival rate was observed across all other treatments (data not shown).

4. Discussion

4.1 Hoeing distance

The majority of sugar beets that experienced a direct hit with the hoeing simulator (HD_0) were either killed or significantly damaged. Across affected treatments, total sugar beet biomass at HD_0 was 58 to 95% less than that of the untreated control (HD_{CTRL}). The only instance whereby HD_0 did not significantly reduce total biomass or final leaf area was when hoeing was performed at CS_{10} in 2019. While none of the sugar beets receiving direct cultivation at the cotyledon stage were killed in 2019, forking of the taproot (also known as root bifurcation) was observed among all plants in this category. In fact, across all crop growth stages evaluated, the survival rate of sugar beets receiving a direct hit with the hoe (HD_0) ranged from 0% to 75%, and taproot forking was observed in all surviving plants. Root forking is likely to have resulted from damage imparted to, or decapitation of, the root apical meristem during cultivation. Forked taproots in sugar beet significantly reduce crop quality and value. In addition, forked beets cling readily to the soil and are, therefore, more difficult to clean upon processing; forking in sugar beets may also result in greater soil loss at harvest (Ruysschaert et al., 2004). Melander et al. (2000) also noted the presence of forking among transplanted sugar beets cultivated with weed harrows or torsion weeders, although it is suggested that forking could have been caused by rearing sugar beet seedlings as transplants. In the present study, all sugar beets were grown in containers, but forking was observed only among plants receiving HD_0 in $EXP_{HOE.DISTANCE,}$ suggesting that cultivation damage was responsible.

While the destructive consequences resulting from direct cultivation are not unexpected, results affirm the importance of avoiding collision during intra-row hoeing. Thus, the accuracy of intra-row hoeing machines is critical if attempting to cultivate in close proximity to crop plants. Kunz et al. (2015) identify the need for research into both the optimal operating distance of hoeing blades relative to crop plants and the accuracy of precision cultivation equipment. The present study addresses the former request, and results emphasize the need for additional research pertaining to the latter request. The objective assessment of intelligent intra-row weeding machines capable of operating across early crop growth stages is necessary to define optimal intra-row hoeing distances within direct-seeded crops. Machleb et al. (2020) provide a summary of mean guidance errors for both GNSS-navigation and machine-vision-based cultivation systems; of those reporting intra-row cultivator accuracy during field operation, errors of ± 0.6 to 2.9 cm were reported at forward speeds of 0.79 to 1.87 km h^{-1} (Nørremark et al., 2008; Nørremark et al., 2012; Pérez-Ruiz et al., 2012). Notably, variability in intra-row crop spacing (Nørremark et al., 2012), heightened weed pressure (Fennimore et al., 2017; Lian et al., 2013), increasing intra-row crop density (Nørremark et al., 2008), and increasing forward speed (Nørremark et al., 2008; Pérez-Ruiz et al., 2012) all negatively affect intra-row hoeing accuracy.

The incidence of survival among young sugar beets receiving direct cultivation and their resulting loss of quality also represents important information for practitioners who may wish to employ automated intra-row cultivators with the concurrent goals of removing intra-row weeds and thinning intra-row sugar beet densities. Under these circumstances, results indicate that direct cultivation may not always have the desired effect of crop removal, thus introducing the potential for leaving behind lesser-quality damaged crop plants. However, this issue can likely be resolved via tool adjustment. The present study maintained hoeing depth at 2 cm from the soil's surface across all treatments. Cultivating at a shallower depth may have resulted in higher mortality at HD_0, either by undercutting roots more shallowly or by segmenting roots and shoots completely, in both cases decreasing the survival rate of sugar beet plants.

Across experimental years and crop stages tested, 100% of sugar beets survived hoeing when implemented at distances ≥ 1 cm without reducing sugar beet's final leaf area, root biomass, shoot biomass, or total biomass. This information is highly relevant to manufacturers of automated intra-row cultivators, who, provided these results, may aim to develop tools capable of accurately operating 1 cm from crop plants at CS_{10}, CS_{12}, and CS_{14} without reducing crop stand or yield. The results of Nørremark et al. (2008) indicate that accurate intra-row hoeing 1 cm from crop plants may be possible; hoeing errors, whereby undesired hoeing occurred < 1 cm from crop plants, were reported as occurring in only 18 out of 1224 observations. As intra-row hoes capable of accurately cultivating 1 cm from crop plants become available, it will be necessary to affirm or refute the results of the present study under field conditions. Dependent upon soil conditions and hoe design, soil throw and incidental burial of the crop may be of concern, especially if cultivating very close to the crop while it is small. In the field, heterogeneous soil texture and structure, as well as amplified vibration of hoeing equipment, may also negatively affect accuracy.

Across site-years, conflicting results were observed regarding sugar beet tolerance to hoeing across early growth stages. In 2019, crop stage at the time of hoeing significantly affected root biomass, with sugar beets treated at the cotyledon stage having 12% larger roots on average compared to plants treated at the two- and four-leaf stages. This effect was primarily driven by a high survival rate of cotyledon stage sugar beets receiving a direct hit with the hoe. It was speculated that tolerance to direct hoeing could be attributed to plant flexibility and small crop size at the cotyledon stage; however, results from 2020 refute this notion. In 2020, direct hoeing at CS_{10} and CS_{12} had a more significant adverse effect on crop growth parameters compared to CS_{14}; results are therefore inconclusive.

4.2 Flaming intensity

Flaming should be avoided altogether when sugar beets are at the cotyledon growth stage. Across flaming intensities investigated, final leaf area and total biomass at CS_{10} were reduced by 51% on average compared to other growth stages tested. While no adverse effects on sugar beet growth were observed when cotyledon stage plants were exposed to a propane dose of 0.19 kg km^{-1} (Table 2), weed mortality at this flaming intensity may be too low to justify treatment (Sivesind et al., 2009). At the cotyledon stage, sugar beets are particularly vulnerable to lethal damages resulting from flaming because the above-ground apical meristem is highly exposed. As the crop develops, additional layers of leaves form a rosette, surrounding the apical meristem, further insulating it from damage during flaming.

As expected, increasing flaming intensity corresponded with increasing crop damages, and sugar beets became more tolerant to flaming as they advanced in growth stage. Direct flaming in sugar beet may be permissible at the two-leaf stage and if flame intensity is well controlled. No adverse effects on sugar beet growth were observed when propane dose was $\leq$ 0.74 kg km^{-1} at the two-leaf growth stage, $\leq$ 1.49 kg km^{-1} at the four-leaf growth stage, and $\leq$ 5.95 kg km^{-1} at the six-leaf growth stage (Table 2).

Dose-response curves to flaming intensity for common weed species have been described in experiments by Sivesind et al. (2009) and Ascard (1994; 1995). Due to differences in methodology, experimental design, and equipment, definitive conclusions should not be made by cross-referencing the flaming tolerance of sugar beet, reported by the present study, and weeds' response to flaming, reported by previous works. However, approximating weed control possible across flaming intensities studied is highly relevant. A propane dose of 0.74 kg km^{-1} (tolerated by sugar beet at and above the two-leaf stage) controlled 50% of *Amaranthus retroflexus* L. up to the two-leaf stage, *C. album* L. up to the four-leaf stage, and *Capsella bursa-pastoris* [L.] Medik. at the cotyledon stage (Sivesind et al., 2009). A propane dose of 1.49 kg km^{-1} (tolerated by sugar beet at and above the four-leaf stage) controlled 95% of *A. retroflexus* at the cotyledon stage, *C. album* up to the four-leaf stage, and *C. bursa-pastoris* at the cotyledon stage (Sivesind et al., 2009). Finally, a propane dose of 5.95 kg km^{-1} (tolerated by sugar beet at and above the four-leaf stage) controlled 95% of *A. retroflexus*, *C. album* and *C. bursa-pastoris* up to the four-leaf, six-leaf, and five-leaf stage, respectively (Sivesind et al., 2009). Results suggest that sugar beet may be more tolerant to flaming than some common annual broadleaf weeds; thus, further research on direct flaming at intensities appropriate to the crop's growth stage is warranted. Establishing a false or stale seedbed would also delay weed emergence relative to crop emergence (Mohler, 2001), producing weeds that are delayed developmentally relative to the crop and increasing within-row flaming efficacy.

Further research on intra-row flaming in direct-seeded sugar beet is suggested to determine the level of weed control attainable across early growth stages in the field. However, field environments typically contain more variability than controlled environment experiments. For instance, the susceptibility of crops and weeds to flaming injury increases as the relative water content of plant tissues decreases (Ulloa et al., 2012). Sugar beets were watered uniformly and regularly in $EXP_{FLAME.INTENSITY}$ and $EXP_{FLAME.DISTANCE}$ to limit variability and drought stress; however, within the field environment, it is necessary to consider how water availability may affect sugar beet tolerance to flaming. In addition, heightened crop injury resulting from the re-direction of flames due to uneven soil may be a factor to contend with (Vanhala and Rahkonen, 1998).

4.3 Flaming distance

Adverse effects on crop growth were not observed at flaming distances ≥ 1.5 cm. Results suggest that it is possible to selectively manage annual broadleaf weeds in the intra-row zone via flame weeding without sugar beet injury. Exposure to 2.0 seconds of flaming is equivalent to 3.72 kg km^{-1} of propane consumption (data not shown). Studies by Sivesind et al. (2009) indicate that exposing intra-row weeds to an equivalent flaming treatment may control 95% of *A. retroflexus*, *C. album*, and *C. bursa-pastoris* up to the four-leaf, six-leaf, and five-leaf stage, respectively.

Future investigations should seek to aggregate results from $EXP_{FLAME.INTENSITY}$ and $EXP_{FLAME.DISTANCE}$, exploring whether flaming intensity (propane dose) can be adjusted in the close-to-crop zone extending 1.5 cm to either side of sugar beet plants within the crop row. For example, the information generated by these studies could be applied to develop variable rate intra-row flame weeders capable of adjusting flaming intensity in the close-to-crop zone during operation to maximize efficacy and minimize crop injury according to the growth stage of individual crop plants. Results from $EXP_{FLAME.INTENSITY}$ suggests that flaming dose in the close-to-crop zone should not exceed 0.74 kg km^{-1} at the two-leaf growth stage, 1.49 kg km^{-1} at the four-leaf growth stage, and 5.95 kg km^{-1} at the six-leaf growth stage (Table 2). Combining automated intra-row hoeing at distances as close as 1 cm from sugar beet plants with selective flaming in the close-to-crop zone may also provide positive results.

A 100% mortality rate was expected to result from exposing sugar beet plants to 2.0 seconds of direct flaming at the two-leaf stage. This assumption was based on results from $EXP_{FLAME.INTENSITY}$; however, only an 88% mortality rate was recorded at FD_0. While the present study focuses on the crop's response to post-emergence flaming, pre-emergence flaming is a notable and effective method of intra-row weed control in sugar beet. Following pre-emergence flame weeding, a 30% to 47% reduction in weed density has been reported (Rasmussen, 2003; Rasmussen et al., 2011). Finally, average temperatures measured at the crop's center with a thermal imaging camera did not decline incrementally as flaming distance increased. The thermal camera appears to have better measured thermal energy in front of the flame ($EXP_{FLAME.INTENSITY}$) than the side of the flame ($EXP_{FLAME.DISTANCE}$). In either case, the achieved temperatures reported in the present study should be considered approximate. Vanhala and Rahkonen (1998) describe an improved method for measuring achieved temperatures using thermocouples.

5. Conclusions

Sugar beet tolerance to hoeing and flame weeding across early crop growth stages, tool working distances, and intensities were evaluated. From the cotyledon to the four-leaf stage, hoeing could be performed as close as 1 cm from sugar beet plant centers before adverse crop effects were observed. It is unclear, however, whether sugar beets become more or less sensitive to hoeing as the crop progresses through early growth stages. Direct flaming of sugar beet at the cotyledon stage is not advised at any intensity, though flaming tolerance was observed to increase with crop growth stage. Direct flaming did not affect sugar beets when the propane dose was ≤ 0.74 kg km^{-1} at the two-leaf stage, ≤ 1.49 kg km^{-1} at the four-leaf stage, and ≤ 5.95 kg km^{-1} at the six-leaf stage. Sugar beets at the two-leaf growth stage could withstand flaming at distances ≥ 1.5 cm at a propane dose of 3.72 kg km^{-1} without causing damage. Results from the present study are highly relevant to informing the development and operation of automated intra-row weeding machines in direct-seeded sugar beet. Performing this study within a controlled environment enabled the accurate evaluation of a narrow range of tool settings for their effects on sugar beet growth; however, additional experimentation is necessary to confirm or refute results from this study across various agricultural field settings.

CRediT authorship contribution statement

Margaret R McCollough: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. **Frank Poulsen:** Conceptualization, Investigation, Methodology, Resources, Writing – review and editing. **Bo Melander:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing.

Acknowledgments

We extend a great deal of gratitude to Garth Douston and Eugene Driessen for their assistance in experiment establishment and data collection. We also thank Brian Lading, Per Heinager, Betina Anitta Bendtsen, Christian Appel Schjeldahl Nielsen, and Jakob Sørensen for their technical assistance. This research was funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 727321 (project acronym, IWMPRAISE); we thank the funding body for its financial support.

Conflicts of Interest

Authors Margaret R McCollough and Bo Melander declare no conflicts of interest. Frank Poulsen is the founder and CEO of F. Poulsen Engineering ApS., a manufacturer of intelligent automated intra-row weeding devices.

References

Ascard, J., 1994. Dose-response models for flame weeding in relation to plant size and density. Weed Res. 34, 377–385. https://doi.org/10.1111/j.1365-3180.1994.tb02007.x.

Ascard, J., 1996. Mechanical in-row cultivation in row crops. Proceedings of the Second International Weed Control Congress, Copenhagen, Denmark, 1121–1126.

Ascard, J., Hallefä, L.T.F., Olsson, R., 1995. System för ogräsbekämpning i sockerbetor. Proceedings of the Sockernäringens Samarbeits Kommitté Försöksverksamhet i Sockerbetor, Arlöv, Sweden, 1–11.

Bleeker, P., van der Weide, R., Kurstjens, D., 2002. Experiences and experiments with new intra-row weeders. Proceedings of the Fifth European Weed Research Society Workshop on Physical Weed Control, Pisa, Italy, 97–100.

Champagne, R., 2022. Evaluating physical and cultural methods to improve weed management in organic vegetables (Doctoral Dissertation). University of Maine. https://digitalcommons.library.umaine.edu/etd/3589/ (accessed 14 October 2023).

Easlon, H.M., Bloom, A.J., 2014. Easy Leaf Area: Automated digital image analysis for rapid and accurate measurement of leaf area. Appl. Plant Sci. 2, 1–4. http://doi.org/10.3732/apps.1400033

Fennimore, S.A., Slaughter, D.C., Siemens, M.C., Leon, R.G., Saber, M.N., 2016. Technology for automation of weed control in specialty crops. Weed Technol. 30, 823–837. https://dio.org/10.1614/WT-D-16-00070.1.

Gallandt, E.R., Brainard, D., Brown, B., 2018. Developments in physical weed control, in: Zimdahl, R.L. (Eds.), Integrated weed management for sustainable agriculture, Burleigh Dodds Science Publishing, pp. 1–23. http://dx.doi.org/10.19103/AS.2017.0025.15.

Heisel, T., Andreasen, C., Christensen, S., 2002. Sugarbeet yield response to competition from *Sinapis arvensis* or *Lolium perenne* growing at three different distances from the beet and removed at various times during early growth. Weed Res. 42, 406–413. https://doi.org/10.1046/j.1365-3180.2002.00301.x.

Kropff, M.J., 1998. Modeling the effects of weeds on crop production. Weed Res. 28, 465–471. https://doi.org/10.1111/j.1365-3180.1988.tb00829.x.

Kropff, M.J., Spitters, C.J.T., 1991. A simple model of crop loss by weed competition from early observations on relative leaf area of weeds. Weed Res. 31, 97–105. https://doi.org/10.1111/j.1365-3180.1991.tb01748.x.

Kropff, M.J., Spitters, C.J.T., Schnieders, B.J., Joenje, W., De Groot, W., 1992. An eco-physiological model for interspecific competition, applied to the influence of *Chenopodium album* L. on sugar beet. II. Model evaluation. Weed Res. 32, 451–463. https://doi.org/10.1111/j.1365-3180.1992.tb01906.x.

Kunz, C., Webber, J.F., Gerhards, R., 2015. Benefits of precision farming technologies for mechanical weed control in soybean and sugar beet–Comparisons of precision hoeing with conventional mechanical weed control. Agronomy 5, 130–142. https://doi.org/10.3390/agronomy5020130.

Kunz, C., Webber, J.F., Peteinatos, G.G., Sokefeld, M., Gerhards, R., 2018. Camera steered mechanical weed control in sugar beet, maize and soybean. Precis. Agric. 19, 708–720. https://doi.org/10.1007/s11119-017-9551-4.

Lian, H., Xiwen, L., Shan, Z., Zhigang, Z., Xiongfei, C., Chaoxing, L., 2013. Plant recognition and localization for intra-row mechanical weeding device based on machine vision. Trans. Chin. Soc. Ag. Eng. 29, 12–18.

Lati, R.N., Siemens, M.C., Rachuy, J.S., Fennimore, S.A., 2016. Intrarow weed removal in broccoli and transplanted lettuce with an intelligent cultivator. Weed Technol. 30, 655–663. https://dio.org/10.1614/WT-D-15-00179.1.

Machleb, J., Peteinatos, G.G., Kollenda, B.L., Andujar, D., Gerhardds, R., 2020. Sensor-based mechanical weed control: Present state and prospects. Comput. Electron. Agr. 176, 1–12. https://doi.org/10.1016/j.compag.2020.105638.

Meier, U., 2001. Growth stages of mono- and dicotyledonous plants, second ed. Federal Biological Research Centre for Agriculture and Forestry.

Melander, B., 2000. Mechanical weed control in transplanted sugar beet. Proceedings of the Fourth European Weed Research Society Workshop on Physical Weed Control, Elspeet, Netherlands.

Melander, B., McCollough, M.R., 2021. Advances in mechanical weed control technologies. Burleigh Dodds Science Publishing, pp. 1– 27. http://doi.org/10.19103/AS.2021.0098.11.

Melander, B., Cirujeda, A., Jørgensen, M.H., 2003. Effects of inter-row hoeing and fertilizer placement on weed growth and yield of winter wheat. Weed Res. 43, 428–438. https://doi.org/10.1046/j.0043-1737.2003.00359.x.

Melander, B., Lattanzi, B., Pannacci, E., 2015. Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. Crop Prot. 72, 1–8. http://dx.doi.org/10.1016/j.cropro.2015.02.017.

Melander, B., Jabran, K., Notaris, C.D., Znova, L., Green, O., Olesen, J.E., 2018. Inter-row hoeing for weed control in organic spring cereals–Influence of inter-row spacing and nitrogen rate. Eur. J. Agron. 101, 49–56. https://dio.org/10.1016/j.eja.2018.08.005.

Mohler, C.L., 2001. Mechanical management of weeds, in: Liebman, M, Mohler, C.L., Staver, C.P. (Eds.), Ecological Management of Agricultural Weeds. Cambridge University Press, pp. 139–209.

Nørremark, M., Griepentrog, H.W., Nielsen, J., Søgaard, H.T., 2008. The development and assessment of the accuracy of an autonomous GPS-based system for intra-row mechanical weed control in row crops. Biosyst. Eng. 101, 396–410. https://dio.org/10.1016/j.biosystemseng.2008.09.007.

Nørremark, M., Griepentrog, H.W., Nielsen, J., Søgaard, H.T., 2012. Evaluation of an autonomous GPS-based system for intra-row weed control by assessing the tilled area. Precis. Agric. 13, 149–162.

Pérez-Ruiz, M., Slaughter, D.C., Gliever, C.J., Upadhyaya, S.K., 2012. Automatic GPS-based intra-row weed knife control system for transplanted row crops. Comput. Electron. Agr. 80, 41–49. https://dio.org/10.1016/j.compag.2011.10.006.

Rasmussen, J., 2003. Punch planting, flame weeding and stale seedbed for weed control in row crops. Weed Res. 43, 393–403. https://dio.org/10.1046/j.0043-1737.2003.00357.x.

Rasmussen, J., Henriksen, C.B., Griepentrog, H.W., Nielsen, J., 2011. Punch planting, flame weeding and delayed sowing to reduce intra-row weeds in row crops. Weed Res. 51, 489–498. https://dio.org/10.1111/j.1365-3180.2011.00858.x.

Ruysschaert, G., Poesen, J., Verstraeten, G., Govers, G., 2004. Soil loss due to crop harvesting: significance and determining factors. Prog. Phys. Geog. 28, 467–501. https://dio.org/10.1191/0309133304pp421oa.

Sivesind, E.C., Leblanc, M.L., Coulter, D.C., Seguin, P., Stewart, K.A., 2009. Weed response to flame weeding at different developmental stages. Weed Technol. 23, 438–443. https://dio.org/10.1614/WT-08-155.1.

Tillet, N.D., Hauge, T., Miles, S.J., 2002. Inter-row vision guidance for mechanical weed control in sugar beet. Comput. Electron. Agr. 33, 163–177. https://dio.org/10.1016/S0168-1699(02)00005-4.

Ulloa, S.M., Datta, A., Bruening, C., Gogos, G., Arkebauer, T.J., Znezevic, S.Z., 2012. Weed control and crop tolerance to propane flaming as influenced by the time of day. Crop Prot. 31 1–7. https://doi.org/10.1016/j.cropro.2011.09.005.

Vanhala, P., Rahkonen, J., 1998. Laboratory assessment of crop tolerance to selective flaming. Proceedings of the Third European Weed Research Society Workshop on Physical Weed Control, Wye College, United Kingdom, 22.

Table 1

Summary of dates and crop growth stages when critical operations were performed within $EXP_{HOE.DISTANCE}$ and $EXP_{FLAME.INTENSITY}$ trials in 2019 and 2020, and $EXP_{FLAME.DISTANCE}$ in 2021.

Experiment	Year	Experiment operations	Date	Crop growth stage expressed as the number of true leaves unfolded[a]
$EXP_{HOE.DISTANCE}$	2019	Sow sugar beets	15 July	–
		First hoeing treatment	22 July	Cotyledons
		Second hoeing treatment	1 August	2
		Third hoeing treatment	7 August	4
		Harvest experiment	29−30 August	6−18
	2020	Sow sugar beets	16 July	–
		First hoeing treatment	28 July	Cotyledons
		Second hoeing treatment	4 August	2
		Third hoeing treatment	11 August	4
		Harvest experiment	24−27 August	4−11
$EXP_{FLAME.INTENSITY}$	2019	Sow sugar beets	15 July	–
		First flame weeding treatment	30 July	2
		Second flame weeding treatment	8 August	4
		Third flame weeding treatment	13 August	6
		Harvest experiment	30−31 August	6−16
	2020	Sow sugar beets	16 July	–
		First flame weeding treatment	27 July	Cotyledons
		Second flame weeding treatment	3 August	2
		Third flame weeding treatment	10 August	4
		Harvest experiment	21 August	4−10
$EXP_{FLAME.DISTANCE}$	2021	Sow sugar beets	22 April	–
		Flame weeding treatments	20 May	Cotyledons−4
		Harvest experiment	15 June	6−13

[a] "Cotyledons" denotes instances whereby only cotyledons were unfolded at the time of implementing experimental operations, also known as sugar beet (Beta vulgaris L.) growth stage 10 according to Meier et al. (2001) BBCH decimal codes.

Table 2

$EXP_{FLAME.INTENSITY}$ and $EXP_{FLAME.DISTANCE}$ treatments converted from flaming intensity [(FI), at 0.1 ($FI_{0.1}$), 0.2 ($FI_{0.2}$), 0.4 ($FI_{0.4}$), 0.8 ($FI_{0.8}$), 1.6 ($FI_{1.6}$), and 3.2 ($FI_{3.2}$) seconds of exposure to flame when flaming distance relative to the center of sugar beet plants is held constant at 2.0 cm, in addition to an untreated control (FI_{CTRL})] and flaming distance [(FD), at 0.0 ($FD_{0.0}$), 0.5 ($FD_{0.5}$), 1.0 ($FD_{1.0}$), 1.5 ($FD_{1.5}$), 2.0 ($FD_{2.0}$), 2.5 ($FD_{2.5}$), 3.0 ($FD_{3.0}$), 3.5 ($FD_{3.5}$), and 4.0 ($FD_{4.0}$) cm flaming distance relative to the center of sugar beet plants when flaming duration is held constant at 2.0 seconds, in addition to an untreated control (FD_{CTRL})] to oxygen and propane fuel consumption per linear km of crop row (kg km^{-1}) when a 15 cm intra-row crop spacing is assumed.

Experiment	Treatment	Propane consumption	Oxygen consumption
		kg km^{-1}	
$EXP_{FLAME.INTENSITY}$	$FI_{0.1}$	0.19	0.12
	$FI_{0.2}$	0.37	0.25
	$FI_{0.4}$	0.74	0.49
	$FI_{0.8}$	1.49	0.99
	$FI_{1.6}$	2.97	1.98
	$FI_{3.2}$	5.95	3.95
	FI_{CTRL}	0.00	0.00
$EXP_{FLAME.DISTANCE}$	$FD_{0.0}$	5.07	3.37
	$FD_{0.5}$	4.73	3.14
	$FD_{1.0}$	4.39	2.92
	$FD_{1.5}$	4.06	2.69
	$FD_{2.0}$	3.72	2.47
	$FD_{2.5}$	3.38	2.25
	$FD_{3.0}$	3.04	2.02
	$FD_{3.5}$	2.70	1.80
	$FD_{4.0}$	2.37	1.57
	FD_{CTRL}	0.00	0.00

Table 3

In 2019, sugar beet (*Beta vulgaris* L.) response to hoeing distance [(HD), at 0 (HD_0), 1 (HD_1), 2 (HD_2), 3 (HD_3), 4 (HD_4), and 5 (HD_5) cm] across early crop growth stages [(CS), at cotyledons unfolded (CS_{10}), two leaves unfolded (CS_{12}), and four leaves unfolded (CS_{14})]. Treatment effects on sugar beet final leaf area, root biomass, shoot biomass, and total biomass are shown. Least square means are presented. P-values associated with each mean result from contrasts made with an untreated control (HD_{CTRL}), * (P = 0.0500−0.0100) ** (P = 0.0100−0.0010), and *** (P = 0.0010−0.0001). Significant main effects (P < 0.05) are highlighted in bold text.

Treatment		Final leaf area			Root biomass[a]				Shoot biomass[b]				Total biomass[a]			
					Trans.	Back-trans.			Trans.	Back-trans.			Trans.	Back-trans.		
		cm²			g											
CS_{10}	HD_0	203.4	0.9702		2.26	4.10	0.1344		0.77	4.83	0.2717		3.16	9.00	0.1405	
CS_{10}	HD_1	220.7	0.7393		2.65	6.00	0.7626		0.78	5.06	0.3371		3.48	11.09	0.4239	
CS_{10}	HD_2	190.8	0.7577		2.80	6.86	0.8494		0.77	4.90	0.2894		3.59	11.89	0.5796	
CS_{10}	HD_3	180.5	0.5961		2.67	6.13	0.8215		0.85	6.03	0.6753		3.67	12.50	0.7114	
CS_{10}	HD_4	197.1	0.8626		2.99	7.91	0.4522		0.90	6.90	0.9955		3.99	14.89	0.7557	
CS_{10}	HD_5	144.5	0.1964		2.31	4.33	0.1799		0.64	3.37	**0.0337**	*	2.95	7.73	0.0560	
CS_{12}	HD_0	97.1	**0.0236**	*	1.16	0.34	**<0.0001**	***	0.22	0.64	**<0.0001**	***	1.42	1.00	**<0.0001**	***
CS_{12}	HD_1	176.0	0.5320		2.41	4.83	0.3077		0.72	4.26	0.1408		3.21	9.30	0.1689	
CS_{12}	HD_2	135.4	0.1379		2.55	5.50	0.5475		0.74	4.46	0.1813		3.39	10.52	0.3272	
CS_{12}	HD_3	176.6	0.5400		2.65	6.03	0.7748		0.85	6.08	0.6943		3.63	12.16	0.6368	
CS_{12}	HD_4	194.0	0.8112		2.29	4.22	0.1582		0.82	5.53	0.4912		3.34	10.14	0.2712	
CS_{12}	HD_5	239.6	0.4612		2.79	6.76	0.8959		0.90	6.87	0.9954		3.87	13.95	0.9588	
CS_{14}	HD_0	0.0	**<0.0001**	***	1.00	0.00	**<0.0001**	***	0.22	0.68	**<0.0001**	***	1.30	0.69	**<0.0001**	***
CS_{14}	HD_1	171.6	0.4721		2.87	7.26	0.6823		0.85	6.05	0.6829		3.82	13.63	0.9670	
CS_{14}	HD_2	212.3	0.8781		2.73	6.45	0.9675		0.88	6.66	0.9157		3.77	13.21	0.8723	
CS_{14}	HD_3	168.0	0.4628		2.49	5.22	0.4384		0.74	4.48	0.1862		3.28	9.76	0.2214	
CS_{14}	HD_4	167.8	0.4240		2.48	5.17	0.4203		0.83	5.83	0.5990		3.52	11.38	0.4788	
CS_{14}	HD_5	195.7	0.8388		2.41	4.81	0.3020		0.87	6.39	0.8125		3.53	11.47	0.4954	
	HD_{CTRL}	205.2			2.74	6.52			0.90	6.88			3.84	13.77		
ANOVA									P-values							
HD		**0.0099**				**<0.0001**				**<0.0001**				**<0.0001**		
CS		0.1657				**0.0369**				0.2613				0.1611		
HD*CS		**0.0192**				**0.0237**				**0.0010**				**0.0070**		

[a] Data underwent a square root (x+1) transformation before analysis. Transformed means (Trans.) are presented along with back-transformed means (Back-trans.). Percent change calculated between treatments and discussed throughout the text of the present article are calculated from back-transformed means.

[b] Data underwent a $\log_{10}$ (x+1) transformation before analysis. Transformed means (Trans.) are presented along with back-transformed means (Back-trans.). Percent change calculated between treatments and discussed throughout the text of the present article are calculated from back-transformed means.

Table 4

In 2020, sugar beet (*Beta vulgaris* L.) response to hoeing distance [(HD), at 0 (HD_0), 1 (HD_1), 2 (HD_2), 3 (HD_3), 4 (HD_4), and 5 (HD_5) cm] across early crop growth stages [(CS), at cotyledons unfolded (CS_{10}), two leaves unfolded (CS_{12}), and four leaves unfolded (CS_{14})]. Treatment effects on sugar beet final leaf area, root biomass, shoot biomass, and total biomass are shown. Least square means are presented. P-values associated with each mean result from contrasts made with an untreated control (HD_{CTRL}), * (P = 0.0500−0.0100) ** (P = 0.0100−0.0010), and *** (P = 0.0010−0.0001). Significant main effects (P < 0.05) are highlighted in bold text.

Treatment		Final leaf area		Root biomass		Shoot biomass[a]			Total biomass[b]		
						Trans.	Back-trans.		Trans.	Back-trans.	
		cm^2		g							
CS_{10}	HD_0	23	**0.0005** ***	0.17	**0.0061** **	0.05	0.12	**0.0003** ***	1.14	0.29	**0.0007** ***
CS_{10}	HD_1	78	0.3260	0.41	0.2970	0.21	0.63	0.5015	1.43	1.04	0.4020
CS_{10}	HD_2	98	0.9764	0.48	0.6541	0.25	0.79	0.9080	1.51	1.27	.9232
CS_{10}	HD_3	113	0.4325	0.77	0.0984	0.34	1.20	0.0629	1.73	1.98	0.0551
CS_{10}	HD_4	78	0.3426	0.46	0.5193	0.22	0.67	0.6213	1.46	1.12	0.5723
CS_{10}	HD_5	113	0.4276	0.51	0.7809	0.27	0.87	0.6192	1.54	1.38	0.8127
CS_{12}	HD_0	17	**0.0002** ***	0.04	**0.0004** ***	0.04	0.09	**0.0001** ***	1.07	0.13	**0.0001** ***
CS_{12}	HD_1	79	0.3517	0.41	0.3164	0.20	0.59	0.3731	1.41	1.00	0.3368
CS_{12}	HD_2	132	0.0924	0.60	0.6965	0.30	1.00	0.2816	1.61	1.60	0.3745
CS_{12}	HD_3	102	0.8077	0.57	0.8261	0.23	0.68	0.6735	1.50	1.26	0.8948
CS_{12}	HD_4	83	0.4628	0.44	0.4162	0.21	0.63	0.4848	1.44	1.06	0.4452
CS_{12}	HD_5	100	0.9098	0.53	0.8946	0.25	0.76	0.9911	1.51	1.29	0.9769
CS_{14}	HD_0	39	**0.0054** **	0.19	**0.0104** *	0.13	0.35	**0.0258** *	1.24	0.54	**0.0125** *
CS_{14}	HD_1	102	0.8127	0.60	0.6624	0.27	0.86	0.6705	1.57	1.45	0.6486
CS_{14}	HD_2	94	0.8567	0.53	0.9108	0.24	0.72	0.8257	1.50	1.25	0.8571
CS_{14}	HD_3	89	0.6905	0.57	0.8613	0.25	0.77	0.9970	1.53	1.33	0.9307
CS_{14}	HD_4	93	0.8337	0.57	0.8219	0.23	0.71	0.8001	1.51	1.29	0.9571
CS_{14}	HD_5	87	0.6028	0.43	0.3724	0.21	0.62	0.4792	1.43	1.05	0.4234
	HD_{CTRL}	97		0.54		0.25	0.77		1.52	1.30	
ANOVA						P-values					
HD			**<0.0001**		**<0.0001**			**<0.0001**			**<0.0001**
CS			0.9834		0.6102			0.5488			0.5512
HD*CS			0.3690		0.4920			0.1775			0.2453

[a] Data underwent a $\log_{10}$ (x+1) transformation before analysis. Transformed means (Trans.) are presented along with back-transformed means (Back-trans.). Percent change calculated between

treatments and discussed throughout the text of the present article are calculated from back-transformed means.

[b] Data underwent a square root (x+1) transformation before analysis. Transformed means (Trans.) are presented along with back-transformed means (Back-trans.). Percent change calculated between treatments and discussed throughout the text of the present article are calculated from back-transformed means.

Table 5

In 2019, sugar beet (*Beta vulgaris* L.) response to flaming intensities [(FI), at 0.1 ($FI_{0.1}$), 0.2 ($FI_{0.2}$), 0.4 ($FI_{0.4}$), 0.8 ($FI_{0.8}$), 1.6 ($FI_{1.6}$), and 3.2 ($FI_{3.2}$) seconds] across early crop growth stages [(CS), at two leaves unfolded (CS_{12}), four leaves unfolded (CS_{14}), and six leaves unfolded (CS_{16})] when flaming distance is held constant at 2.0 cm. Treatment effects on final sugar beet leaf area, root biomass, shoot biomass, and total biomass are shown. Least square means are presented. P-values associated with each mean result from contrasts made with an untreated control (FI_{CTRL}), * (P = 0.0500−0.0100) ** (P = 0.0100−0.0010), and *** (P = 0.0010−0.0001). Significant main effects (P < 0.05) are highlighted in bold text.

Treatment		Final leaf area			Root biomass			Shoot biomass			Total biomass		
		cm^2			g								
CS_{12}	$FI_{0.1}$	163.1	0.1676		6.15	0.3392		5.75	0.1559		11.9	0.2093	
CS_{12}	$FI_{0.2}$	143.6	0.5063		4.74	0.9272		3.09	0.2663		7.8	0.5557	
CS_{12}	$FI_{0.4}$	146.8	0.4345		5.14	0.8361		4.09	0.8675		9.2	0.9627	
CS_{12}	$FI_{0.8}$	134.1	0.7544		6.09	0.3620		4.88	0.5534		11.0	0.4007	
CS_{12}	$FI_{1.6}$	56.0	**0.0119**	*	1.26	**0.0093**	**	1.62	**0.0145**	*	2.9	**0.0061**	**
CS_{12}	$FI_{3.2}$	0.0	**<0.0001**	***	1.77	**0.0245**	*	0.04	**0.0002**	***	1.8	**0.0015**	**
CS_{14}	$FI_{0.1}$	107.7	0.5046		4.13	0.5830		3.68	0.5774		7.8	0.5473	
CS_{14}	$FI_{0.2}$	139.4	0.6114		6.26	0.3016		5.45	0.2593		11.7	0.2422	
CS_{14}	$FI_{0.4}$	137.7	0.6547		5.74	0.5150		4.10	0.8858		8.8	0.8841	
CS_{14}	$FI_{0.8}$	146.0	0.4520		6.54	0.2157		5.32	0.3144		11.9	0.2163	
CS_{14}	$FI_{1.6}$	109.8	0.5559		4.37	0.7150		3.81	0.6698		8.2	0.6694	
CS_{14}	$FI_{3.2}$	131.7	0.8233		5.41	0.6847		4.40	0.8919		9.8	0.7541	
CS_{16}	$FI_{0.1}$	96.7	0.2845		5.48	0.6482		5.03	0.4667		10.5	0.5309	
CS_{16}	$FI_{0.2}$	140.3	0.5872		6.35	0.2694		5.28	0.3328		11.6	0.2555	
CS_{16}	$FI_{0.4}$	120.9	0.8587		2.74	0.1177		3.77	0.6423		6.5	0.2373	
CS_{16}	$FI_{0.8}$	139.6	0.6061		5.44	0.6671		4.66	0.7030		10.1	0.6562	
CS_{16}	$FI_{1.6}$	136.5	0.6882		6.99	0.1165		5.62	0.1997		12.6	0.1164	
CS_{16}	$FI_{3.2}$	146.9	0.4321		5.71	0.5282		3.92	0.7459		9.6	0.8171	
	FI_{CTRL}	125.7			4.86			4.26			9.1		
ANOVA		P-values											
FI		**0.0068**			0.0946			**0.0065**			**0.0165**		
CS		0.0719			**0.0433**			**0.0028**			**0.0084**		
FI*CS		**<0.0001**			**0.0029**			**0.0027**			**0.0011**		

Table 6

In 2020, sugar beet (*Beta vulgaris* L.) response to flaming intensities [(FI), at 0.1 ($FI_{0.1}$), 0.2 ($FI_{0.2}$), 0.4 ($FI_{0.4}$), 0.8 ($FI_{0.8}$), 1.6 ($FI_{1.6}$), and 3.2 ($FI_{3.2}$) seconds] across early crop growth stages [(CS), at cotyledons unfolded (CS_{10}), two leaves unfolded (CS_{12}), and four leaves unfolded (CS_{14})] when flaming distance is held constant at 2.0 cm. Treatment effects on final sugar beet leaf area, root biomass, shoot biomass, and total biomass are shown. Least square means are presented. P-values associated with each mean result from contrasts made with an untreated control (FI_{CTRL}), * (P = 0.0500−0.0100) ** (P = 0.0100−0.0010), and *** (P = 0.0010−0.0001). Significant main effects (P < 0.05) are highlighted in bold text.

Treatment		Final leaf area			Root biomass[a]				Shoot biomass			Total biomass		
					Trans.	Back-trans.								
		cm^2							g					
CS_{10}	$FI_{0.1}$	105.90	0.4820		0.177	0.502	0.7771		0.891	0.8260		1.395	0.9816	
CS_{10}	$FI_{0.2}$	60.82	**0.0254**	*	0.113	0.297	0.1181		0.629	0.0666		0.941	0.0769	
CS_{10}	$FI_{0.4}$	0.47	**<0.0001**	***	0.001	0.003	**<0.0001**	***	0.019	**<0.0001**	***	0.022	**<0.0001**	***
CS_{10}	$FI_{0.8}$	0.00	**<0.0001**	***	0.000	0.000	**<0.0001**	***	0.005	**<0.0001**	***	0.005	**<0.0001**	***
CS_{10}	$FI_{1.6}$	0.00	**<0.0001**	***	0.000	0.000	**<0.0001**	***	0.001	**<0.0001**	***	0.001	**<0.0001**	***
CS_{10}	$FI_{3.2}$	0.00	**<0.0001**	***	0.000	0.000	**<0.0001**	***	0.004	**<0.0001**	***	0.004	**<0.0001**	***
CS_{12}	$FI_{0.1}$	80.47	0.3275		0.140	0.382	0.4396		0.684	0.1340		1.075	0.2073	
CS_{12}	$FI_{0.2}$	92.85	0.8717		0.118	0.313	0.1584		0.726	0.2144		1.053	0.1787	
CS_{12}	$FI_{0.4}$	84.28	0.4664		0.151	0.415	0.6343		0.783	0.3724		1.204	0.4435	
CS_{12}	$FI_{0.8}$	41.91	**0.0008**	***	0.067	0.168	**0.0051**	**	0.393	**0.0014**	**	0.569	**0.0019**	**
CS_{12}	$FI_{1.6}$	6.85	**<0.0001**	***	0.009	0.021	**<0.0001**	***	0.139	**<0.0001**	***	0.161	**<0.0001**	***
CS_{12}	$FI_{3.2}$	0.00	**<0.0001**	***	0.005	0.012	**<0.0001**	***	0.009	**<0.0001**	***	0.022	**<0.0001**	***
CS_{14}	$FI_{0.1}$	80.41	0.3258		0.129	0.345	0.2654		0.740	0.2479		1.097	0.2389	
CS_{14}	$FI_{0.2}$	99.75	0.7670		0.170	0.480	0.9255		0.891	0.8276		1.384	0.9469	
CS_{14}	$FI_{0.4}$	86.48	0.5596		0.154	0.427	0.7128		0.699	0.1591		1.143	0.3163	
CS_{14}	$FI_{0.8}$	78.90	0.2794		0.136	0.368	0.3696		0.651	0.0890		1.027	0.1483	
CS_{14}	$FI_{1.6}$	32.53	**0.0001**	***	0.071	0.176	**0.0065**	**	0.472	**0.0060**	**	0.657	**0.0052**	**
CS_{14}	$FI_{3.2}$	0.00	**<0.0001**	***	0.017	0.040	**0.0001**	***	0.329	**0.0004**	***	0.369	**0.0002**	***
	FI_{CTRL}	95.29			0.167	0.469			0.926			1.401		
ANOVA							P-values							
FI			**<0.0001**				**0.0001**			**<0.0001**			**<0.0001**	
CS			**<0.0001**				**<0.0001**			**<0.0001**			**<0.0001**	
FI*CS			**<0.0001**				**0.0031**			**0.0044**			**0.0050**	

[a] Data underwent a $\log_{10}(x+1)$ transformation before analysis. Transformed means (Trans.) are presented along with back-transformed means (Back-trans.). Percent change calculated between treatments and discussed throughout the text of the present article are calculated from back-transformed means.

Table 7

In 2021, sugar beet (*Beta vulgaris* L.) response to flaming distance [(FD), at 0.0 ($FD_{0.0}$), 0.5 ($FD_{0.5}$), 1.0 ($FD_{1.0}$), 1.5 ($FD_{1.5}$), 2.0 ($FD_{2.0}$), 2.5 ($FD_{2.5}$), 3.0 ($FD_{3.0}$), 3.5 ($FD_{3.5}$), and 4.0 ($FD_{4.0}$) cm] when crop growth stage and flaming duration are held constant at two leaves unfolded and 2.0 seconds, respectively. Treatment effects on final sugar beet leaf area, root biomass, shoot biomass, and total biomass are shown. Least square means are presented. P-values associated with each mean result from contrasts made with an untreated control (FD_{CTRL}), * (P = 0.0500−0.0100) ** (P = 0.0100−0.0010), and *** (P = 0.0010−0.0001). Significant main effects (P < 0.05) are highlighted in bold text.

Treatment	Final leaf area			Root biomass			Shoot biomass			Total biomass		
	cm^2						g					
$FD_{0.0}$	5.1	**< 0.0001**	***	- 0.015	**< 0.0001**	***	0.181	**< 0.0001**	***	0.17	**< 0.0001**	***
$FD_{0.5}$	75.9	0.2582		0.343	**0.0423**	*	0.478	0.3603		0.82	0.0915	
$FD_{1.0}$	54.7	**0.0208**	*	0.281	**0.0109**	*	0.457	0.2408		0.74	**0.0332**	*
$FD_{1.5}$	157.8	**0.0006**	***	0.856	**0.0174**	*	0.891	**0.0001**	***	1.75	**0.0012**	**
$FD_{2.0}$	127.2	0.0748		0.710	0.2618		0.728	**0.0381**	*	1.43	0.1051	
$FD_{2.5}$	152.3	**0.0022**	**	0.734	0.1936		0.838	**0.0012**	**	1.57	**0.0219**	*
$FD_{3.0}$	112.3	0.3329		0.632	0.6428		0.656	0.2083		1.29	0.3914	
$FD_{3.5}$	144.2	**0.0064**	**	0.830	**0.0310**	*	0.799	**0.0036**	**	1.63	**0.0080**	**
$FD_{4.0}$	129.7	0.0542		0.743	0.1594		0.756	**0.0162**	*	1.50	**0.0485**	*
FD_{CTRL}	95.5			0.579			0.553			1.13		
ANCOVA							P-values					
FD		**< 0.0001**			**< 0.0001**			**< 0.0001**			**< 0.0001**	
Leaf area (cm^2)[a]		**< 0.0001**			**< 0.0001**			**< 0.0001**			**< 0.0001**	

[a] Leaf area (cm^2) on the day of implementing flaming treatments.

Fig. 1

A visual description of implementing hoeing distance ($EXP_{HOE.DISTANCE}$) treatments, including (a) an overhead illustration of a sugar beet (*Beta vulgaris* L.) seedling at the center of a growing container. The striped gray rectangles represent the path of the side knife through the container at the minimum and maximum hoeing distances evaluated, 0 and 5 cm relative to the center of the plant, respectively. A total of six hoeing distances were evaluated [0 (HD_0), 1 (HD_1), 2 (HD_2), 3 (HD_3), 4 (HD_4), and 5 cm (HD_5)] across three sugar beet growth stages [cotyledons unfolded (CS_{10}), first pair of true leaves unfolded (CS_{12}), and second pair of true leaves unfolded (CS_{14})], in addition, an untreated control treatment (HD_{CTRL}) was included. Within each container, four passes were made in sequence with the side knife (b−e); hoeing passes were performed one at a time, rotating the growing container 90° between passes.

Fig. 2

A visual description of implementing flaming intensity ($EXP_{FLAME.INTENSITY}$) treatments, including (a) the side view of a sugar beet (*Beta vulgaris* L.) seedling at the center of a growing container. The dotted triangle represents the flame pointed at the sugar beet plant, and the gray circle shows the point at which the flame contacts the soil's surface. Flaming distance was held constant at 2 cm from the center of the plant across treatments. A total of six intensities were evaluated, ranging from 0.1−3.4 seconds of exposure to flaming [0.1 ($FI_{0.1}$), 0.2 ($FI_{0.2}$), 0.4 ($FI_{0.4}$), 0.8 ($FI_{0.8}$), 1.6 ($FI_{1.6}$), and 3.4 ($FI_{3.4}$)] across three sugar beet growth stages [first pair of true leaves unfolded (CS_{12}), second pair of true leaves unfolded (CS_{14}), and third pair of true leaves unfolded (CS_{16}) in 2019, and cotyledons unfolded (CS_{10}), CS_{12}, and CS_{14} in 2020], in addition, an untreated control treatment (FI_{CTRL}) was included. Within each container, flaming treatments were implemented twice, in sequence, on opposite sides, with the flame aimed directly at the plant (b–c); therefore, growing containers were rotated 180° between the two flaming events.

Fig. 3

A visual description of implementing flaming distance ($EXP_{FLAME.DISTANCE}$) treatments, including (a) an overhead illustration of a sugar beet (*Beta vulgaris* L.) seedling at the center of a growing container. The dotted triangles represent the position of the flame at the minimum and maximum distances evaluated, 0 and 4 cm relative to the center of the plant, respectively; gray circles show the point at which the flame contacts the soil's surface. A total of nine flaming distances were evaluated [0.0 ($FD_{0.0}$), 0.5 ($FD_{0.5}$), 1.0 ($FD_{1.0}$), 1.5 ($FD_{1.5}$), 2.0 ($FD_{2.0}$), 2.5 ($FD_{2.5}$), 3.0 ($FD_{3.0}$), 3.5 ($FD_{3.5}$), and 4.0 cm ($FD_{4.0}$)] in addition to an untreated control treatment (FD_{CTRL}). At $FD_{0.0}$, the flame's contact point with the soil's surface was centered on the crop plant, and flaming distance increased perpendicular to the theoretical crop row. Across treatments, sugar beets were treated when the first pair of true leaves unfolded, and flaming intensity was held constant at 2 seconds of exposure. Within each container, flaming treatments were implemented twice, in sequence, on opposite sides of the plant (b–c); therefore, growing containers were adjusted laterally between the two flaming events.

Fig. 4

Sugar beet (*Beta vulgaris* L.) response to hoeing distance [(HD), at 0 (HD_0), 1 (HD_1), 2 (HD_2), 3 (HD_3), 4 (HD_4), and 5 (HD_5) cm] across early crop growth stages [(CS), at cotyledons unfolded (CS_{10}), two leaves unfolded (CS_{12}), and four leaves unfolded (CS_{14})]. Treatment effects on final sugar beet leaf area in 2019 (a) and 2020 (b) are shown, as well as treatment effects on total sugar beet biomass in 2019 (c) and 2020 (d). Final leaf area figures (a, b) present the least square means and standard errors. Total biomass figures (c, d) present back-transformed least square means; data underwent a square root (x+1) transformation prior to analysis. Results that differ significantly from the untreated control (HD_{CTRL}) are denoted with * (P = 0.0500−0.0100), ** (P = 0.0100−0.0010), or *** (P = 0.0010−0.0001).

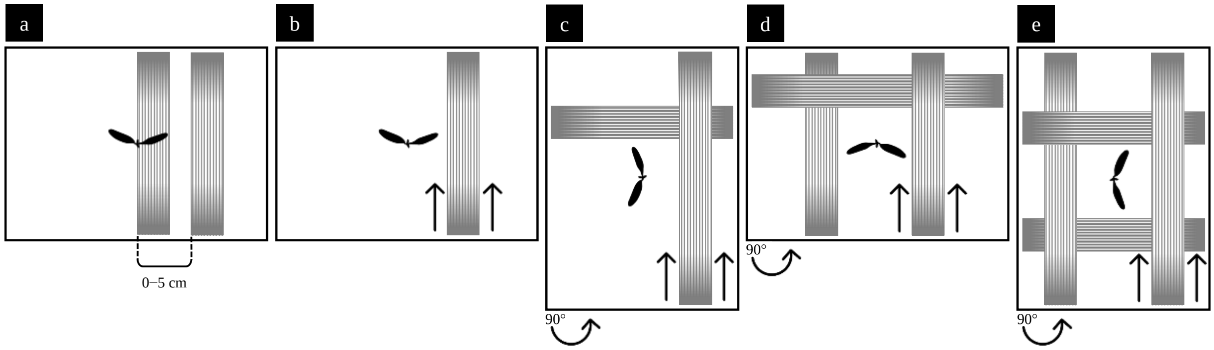
Fig. 5

Sugar beet (*Beta vulgaris* L.) response to flaming intensity [(FI), at 0.1 ($FI_{0.1}$), 0.2 ($FI_{0.2}$), 0.4 ($FI_{0.4}$), 0.8 ($FI_{0.8}$), 1.6 ($FI_{1.6}$), and 3.2 ($FI_{3.2}$) seconds] across early crop growth stages [(CS), at cotyledons unfolded (CS_{10}), two leaves unfolded (CS_{12}), four leaves unfolded (CS_{14}), and six leaves unfolded (CS_{16})] when flaming distance is held constant at 2.0 cm. Treatment effects on final sugar beet leaf area in 2019 (a) and 2020 (b) are shown, as well as treatment effects on total sugar beet biomass in 2019 (c) and 2020 (d). Least square means and standard errors are presented. Results that differ significantly from the untreated control (FI_{CTRL}) are denoted with * (P = 0.0500−0.0100), ** (P = 0.0100−0.0010), or *** (P = 0.0010−0.0001).

Fig. 6

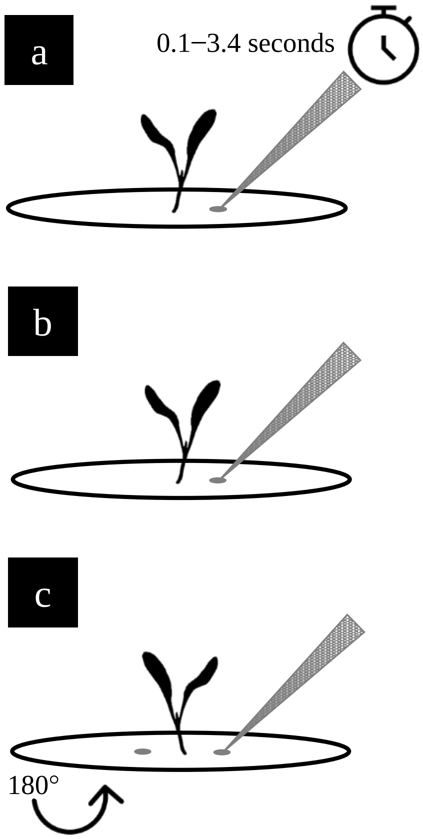
Sugar beet (*Beta vulgaris* L.) response to flaming distance [(FD), at 0.0 ($FD_{0.0}$), 0.5 ($FD_{0.5}$), 1.0 ($FD_{1.0}$), 1.5 ($FD_{1.5}$), 2.0 ($FD_{2.0}$), 2.5 ($FD_{2.5}$), 3.0 ($FD_{3.0}$), 3.5 ($FD_{3.5}$), and 4.0 ($FD_{4.0}$) cm] when crop growth stage and flaming duration are held constant at two leaves unfolded (CS_{12}) and 2.0 seconds, respectively. Treatment effects on final sugar beet leaf area (a) and treatment effects on total sugar beet biomass (b) are shown. Least square means and standard errors are presented.

Results that differ significantly from the untreated control (FD_{CTRL}) are denoted with * (P = 0.0500−0.0100), ** (P = 0.0100−0.0010), or *** (P = 0.0010−0.0001).



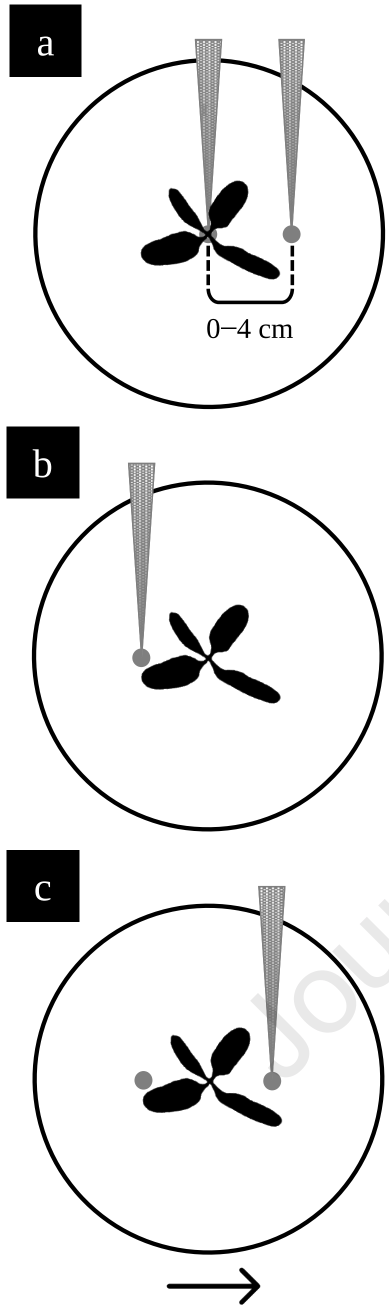
798

799 **Figure 1**



800

801 **Figure 2**



802

803 **Figure 3**

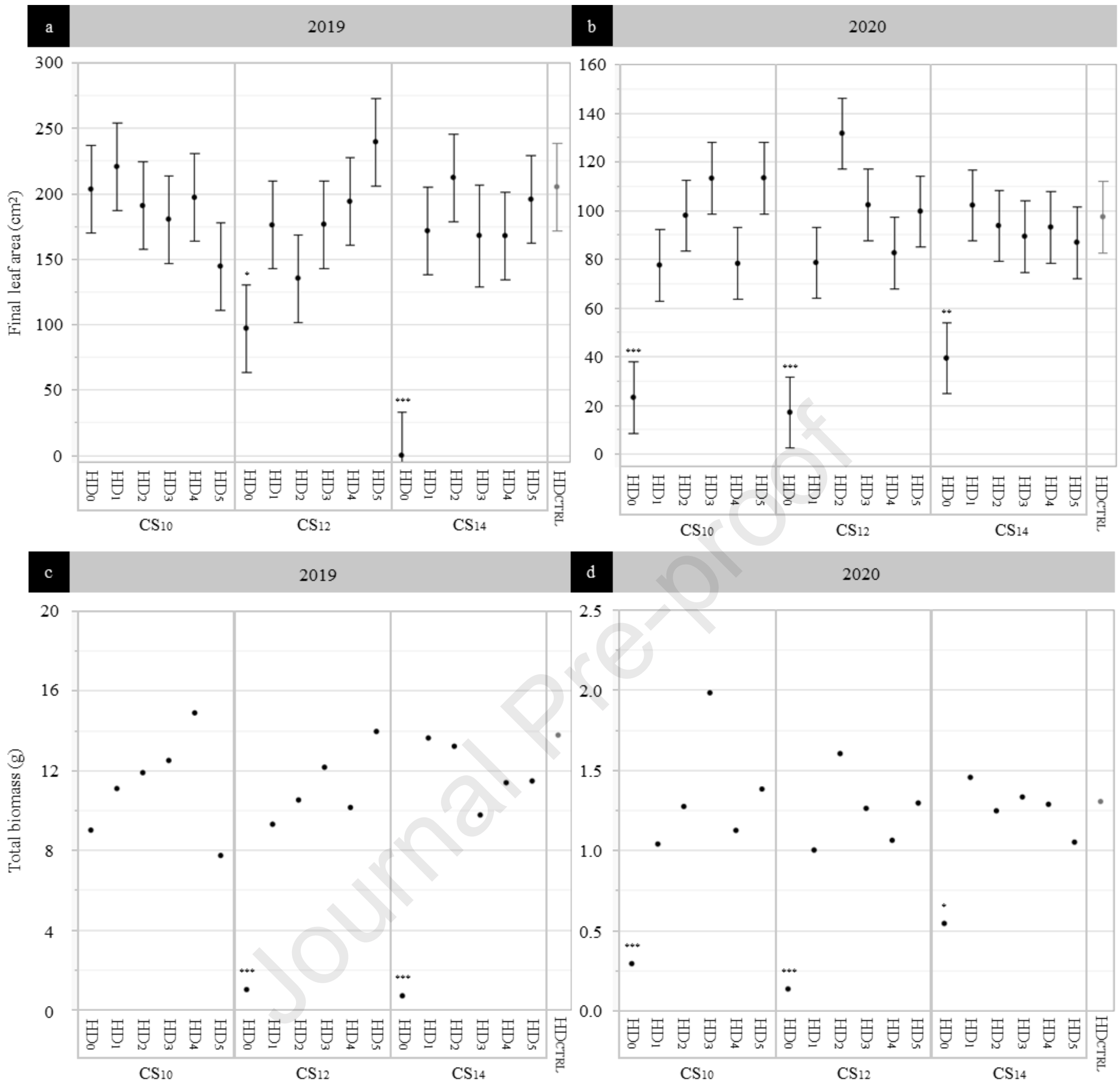
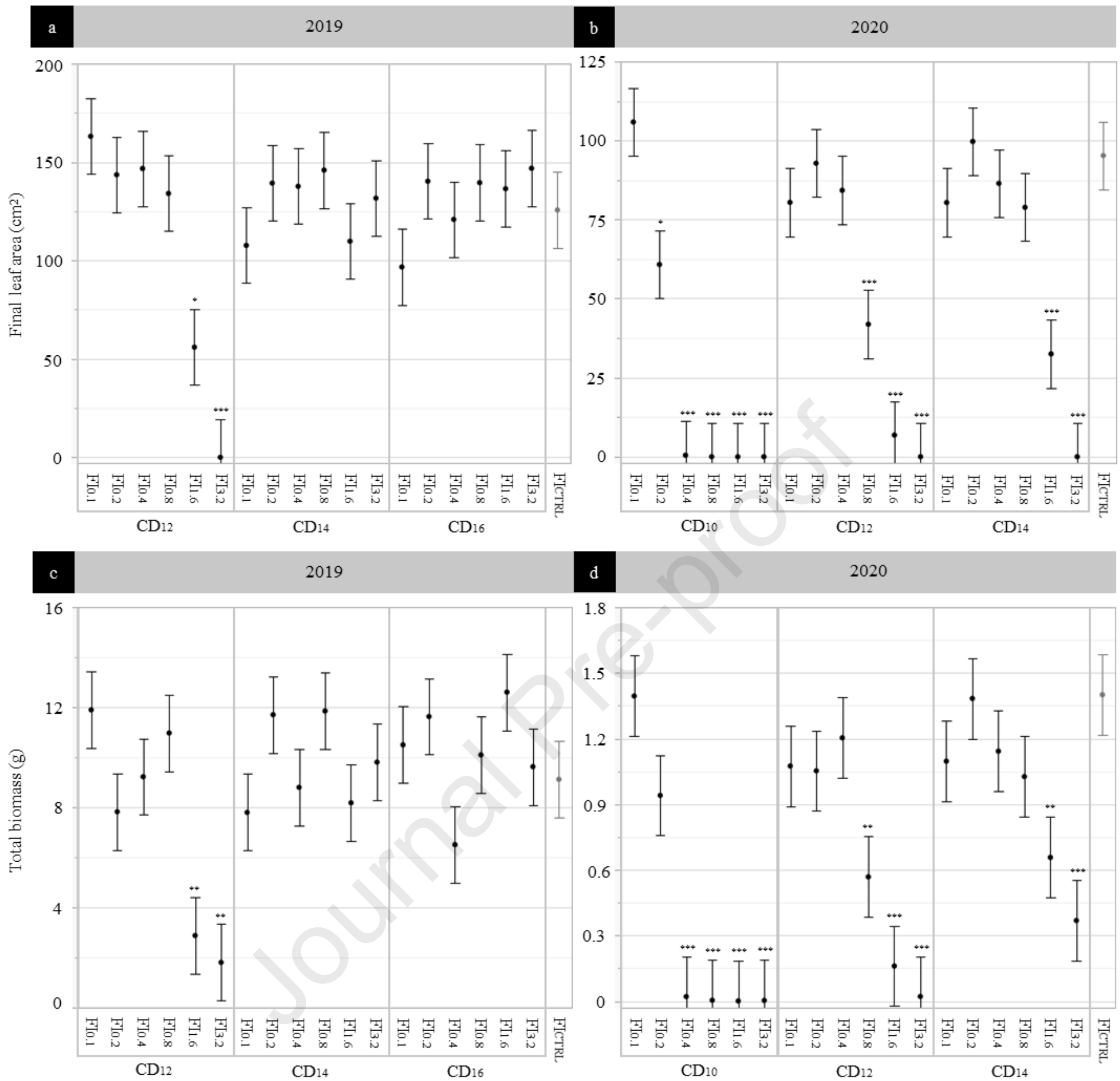
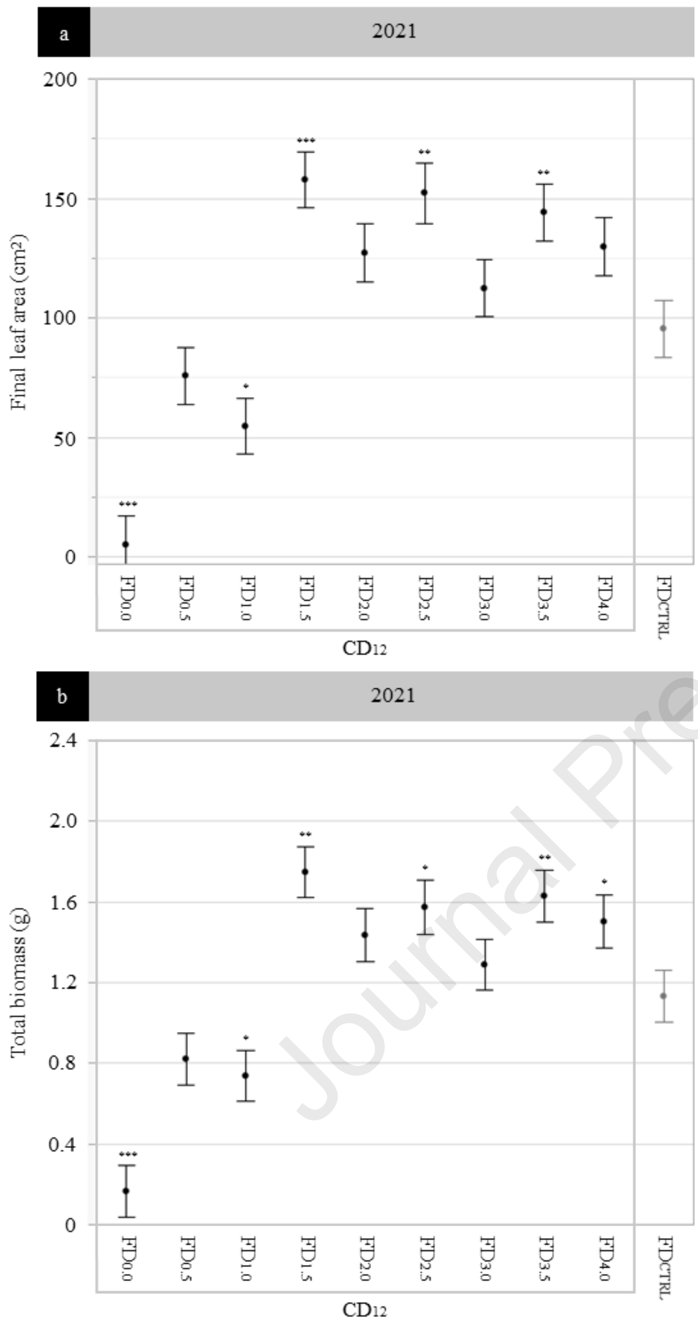

a
2019
b
2020
Final leaf area (cm²)
HD0
HD1
HD2
HD3
HD4
HD5
HDCTRL
CS10
CS12
CS14
c
2019
d
2020
Total biomass (g)

Figure 4



806

807 **Figure 5**



a
2021
Final leaf area (cm²)
200
150
100
50
0
FD0.0
FD0.5
FD1.0
FD1.5
FD2.0
FD2.5
FD3.0
FD3.5
FD4.0
FDCTRL
CD12
b
2021
Total biomass (g)
2.4
2.0
1.6
1.2
0.8
0.4
0
FD0.0
FD0.5
FD1.0
FD1.5
FD2.0
FD2.5
FD3.0
FD3.5
FD4.0
FDCTRL
CD12

Figure 6

6.4.1 Supplementary Materials

Supplementary Video 1. A depiction of the experimental set-up employed to implement hoeing treatments in $EXP_{HOE.DISTANCE}$, including the hoeing simulator.

Supplementary Video 2. A depiction of the experimental set-up employed to implement flaming treatments in $EXP_{FLAME.INTENSITY}$, including the flaming simulator and thermal imaging camera.

Table 1

Experiment	Year	Experiment operations	Date	Crop growth stage expressed as the number of true leaves unfolded[a]
$EXP_{HOE.DISTANCE}$	2019	Sow sugar beets	15 July	–
		First hoeing treatment	22 July	Cotyledons
		Second hoeing treatment	1 August	2
		Third hoeing treatment	7 August	4
		Harvest experiment	29−30 August	6−18
	2020	Sow sugar beets	16 July	–
		First hoeing treatment	28 July	Cotyledons
		Second hoeing treatment	4 August	2
		Third hoeing treatment	11 August	4
		Harvest experiment	24−27 August	4−11
$EXP_{FLAME.INTENSITY}$	2019	Sow sugar beets	15 July	–
		First flame weeding treatment	30 July	2
		Second flame weeding treatment	8 August	4
		Third flame weeding treatment	13 August	6
		Harvest experiment	30−31 August	6−16
	2020	Sow sugar beets	16 July	–
		First flame weeding treatment	27 July	Cotyledons
		Second flame weeding treatment	3 August	2
		Third flame weeding treatment	10 August	4
		Harvest experiment	21 August	4−10
$EXP_{FLAME.DISTANCE}$	2021	Sow sugar beets	22 April	–
		Flame weeding treatments	20 May	Cotyledons−4
		Harvest experiment	15 June	6−13

Table 2

Experiment	Treatment	Propane consumption	Oxygen consumption
		kg km^{-1}	
$EXP_{FLAME.INTENSITY}$	$FI_{0.1}$	0.19	0.12
	$FI_{0.2}$	0.37	0.25
	$FI_{0.4}$	0.74	0.49
	$FI_{0.8}$	1.49	0.99
	$FI_{1.6}$	2.97	1.98
	$FI_{3.2}$	5.95	3.95
	FI_{CTRL}	0.00	0.00
$EXP_{FLAME.DISTANCE}$	$FD_{0.0}$	5.07	3.37
	$FD_{0.5}$	4.73	3.14
	$FD_{1.0}$	4.39	2.92
	$FD_{1.5}$	4.06	2.69
	$FD_{2.0}$	3.72	2.47
	$FD_{2.5}$	3.38	2.25
	$FD_{3.0}$	3.04	2.02
	$FD_{3.5}$	2.70	1.80
	$FD_{4.0}$	2.37	1.57
	FD_{CTRL}	0.00	0.00

Table 3

Treatment		Final leaf area			Root biomass[a]				Shoot biomass[b]				Total biomass[a]			
					Trans.	Back-trans.			Trans.	Back-trans.			Trans.	Back-trans.		
		cm^2			g											
CS_{10}	HD_0	203.4	0.9702		2.26	4.10	0.1344		0.77	4.83	0.2717		3.16	9.00	0.1405	
CS_{10}	HD_1	220.7	0.7393		2.65	6.00	0.7626		0.78	5.06	0.3371		3.48	11.09	0.4239	
CS_{10}	HD_2	190.8	0.7577		2.80	6.86	0.8494		0.77	4.90	0.2894		3.59	11.89	0.5796	
CS_{10}	HD_3	180.5	0.5961		2.67	6.13	0.8215		0.85	6.03	0.6753		3.67	12.50	0.7114	
CS_{10}	HD_4	197.1	0.8626		2.99	7.91	0.4522		0.90	6.90	0.9955		3.99	14.89	0.7557	
CS_{10}	HD_5	144.5	0.1964		2.31	4.33	0.1799		0.64	3.37	**0.0337**	*	2.95	7.73	0.0560	
CS_{12}	HD_0	97.1	**0.0236**	*	1.16	0.34	**<0.0001**	***	0.22	0.64	**<0.0001**	***	1.42	1.00	**<0.0001**	***
CS_{12}	HD_1	176.0	0.5320		2.41	4.83	0.3077		0.72	4.26	0.1408		3.21	9.30	0.1689	
CS_{12}	HD_2	135.4	0.1379		2.55	5.50	0.5475		0.74	4.46	0.1813		3.39	10.52	0.3272	
CS_{12}	HD_3	176.6	0.5400		2.65	6.03	0.7748		0.85	6.08	0.6943		3.63	12.16	0.6368	
CS_{12}	HD_4	194.0	0.8112		2.29	4.22	0.1582		0.82	5.53	0.4912		3.34	10.14	0.2712	
CS_{12}	HD_5	239.6	0.4612		2.79	6.76	0.8959		0.90	6.87	0.9954		3.87	13.95	0.9588	
CS_{14}	HD_0	0.0	**<0.0001**	***	1.00	0.00	**<0.0001**	***	0.22	0.68	**<0.0001**	***	1.30	0.69	**<0.0001**	***
CS_{14}	HD_1	171.6	0.4721		2.87	7.26	0.6823		0.85	6.05	0.6829		3.82	13.63	0.9670	
CS_{14}	HD_2	212.3	0.8781		2.73	6.45	0.9675		0.88	6.66	0.9157		3.77	13.21	0.8723	
CS_{14}	HD_3	168.0	0.4628		2.49	5.22	0.4384		0.74	4.48	0.1862		3.28	9.76	0.2214	
CS_{14}	HD_4	167.8	0.4240		2.48	5.17	0.4203		0.83	5.83	0.5990		3.52	11.38	0.4788	
CS_{14}	HD_5	195.7	0.8388		2.41	4.81	0.3020		0.87	6.39	0.8125		3.53	11.47	0.4954	
	HD_{CTRL}	205.2			2.74	6.52			0.90	6.88			3.84	13.77		
ANOVA									P-values							
HD			**0.0099**				**<0.0001**				**<0.0001**				**<0.0001**	
CS			0.1657				**0.0369**				0.2613				0.1611	
HD*CS			**0.0192**				**0.0237**				**0.0010**				**0.0070**	

Table 4

Treatment		Final leaf area			Root biomass			Shoot biomass[a]				Total biomass[b]			
								Trans.	Back-trans.			Trans.	Back-trans.		
		cm^2			g										
CS_{10}	HD_0	23	**0.0005**	***	0.17	**0.0061**	**	0.05	0.12	**0.0003**	***	1.14	0.29	**0.0007**	***
CS_{10}	HD_1	78	0.3260		0.41	0.2970		0.21	0.63	0.5015		1.43	1.04	0.4020	
CS_{10}	HD_2	98	0.9764		0.48	0.6541		0.25	0.79	0.9080		1.51	1.27	.9232	
CS_{10}	HD_3	113	0.4325		0.77	0.0984		0.34	1.20	0.0629		1.73	1.98	0.0551	
CS_{10}	HD_4	78	0.3426		0.46	0.5193		0.22	0.67	0.6213		1.46	1.12	0.5723	
CS_{10}	HD_5	113	0.4276		0.51	0.7809		0.27	0.87	0.6192		1.54	1.38	0.8127	
CS_{12}	HD_0	17	**0.0002**	***	0.04	**0.0004**	***	0.04	0.09	**0.0001**	***	1.07	0.13	**0.0001**	***
CS_{12}	HD_1	79	0.3517		0.41	0.3164		0.20	0.59	0.3731		1.41	1.00	0.3368	
CS_{12}	HD_2	132	0.0924		0.60	0.6965		0.30	1.00	0.2816		1.61	1.60	0.3745	
CS_{12}	HD_3	102	0.8077		0.57	0.8261		0.23	0.68	0.6735		1.50	1.26	0.8948	
CS_{12}	HD_4	83	0.4628		0.44	0.4162		0.21	0.63	0.4848		1.44	1.06	0.4452	
CS_{12}	HD_5	100	0.9098		0.53	0.8946		0.25	0.76	0.9911		1.51	1.29	0.9769	
CS_{14}	HD_0	39	**0.0054**	**	0.19	**0.0104**	*	0.13	0.35	**0.0258**	*	1.24	0.54	**0.0125**	*
CS_{14}	HD_1	102	0.8127		0.60	0.6624		0.27	0.86	0.6705		1.57	1.45	0.6486	
CS_{14}	HD_2	94	0.8567		0.53	0.9108		0.24	0.72	0.8257		1.50	1.25	0.8571	
CS_{14}	HD_3	89	0.6905		0.57	0.8613		0.25	0.77	0.9970		1.53	1.33	0.9307	
CS_{14}	HD_4	93	0.8337		0.57	0.8219		0.23	0.71	0.8001		1.51	1.29	0.9571	
CS_{14}	HD_5	87	0.6028		0.43	0.3724		0.21	0.62	0.4792		1.43	1.05	0.4234	
	HD_{CTRL}	97			0.54			0.25	0.77			1.52	1.30		
ANOVA		P-values													
HD		**<0.0001**			**<0.0001**			**<0.0001**				**<0.0001**			
CS		0.9834			0.6102			0.5488				0.5512			
HD*CS		0.3690			0.4920			0.1775				0.2453			

Table 5

Treatment		Final leaf area			Root biomass			Shoot biomass			Total biomass		
		cm^2						g					
CS_{12}	$FI_{0.1}$	163.1	0.1676		6.15	0.3392		5.75	0.1559		11.9	0.2093	
CS_{12}	$FI_{0.2}$	143.6	0.5063		4.74	0.9272		3.09	0.2663		7.8	0.5557	
CS_{12}	$FI_{0.4}$	146.8	0.4345		5.14	0.8361		4.09	0.8675		9.2	0.9627	
CS_{12}	$FI_{0.8}$	134.1	0.7544		6.09	0.3620		4.88	0.5534		11.0	0.4007	
CS_{12}	$FI_{1.6}$	56.0	**0.0119**	*	1.26	**0.0093**	**	1.62	**0.0145**	*	2.9	**0.0061**	**
CS_{12}	$FI_{3.2}$	0.0	**<0.0001**	***	1.77	**0.0245**	*	0.04	**0.0002**	***	1.8	**0.0015**	**
CS_{14}	$FI_{0.1}$	107.7	0.5046		4.13	0.5830		3.68	0.5774		7.8	0.5473	
CS_{14}	$FI_{0.2}$	139.4	0.6114		6.26	0.3016		5.45	0.2593		11.7	0.2422	
CS_{14}	$FI_{0.4}$	137.7	0.6547		5.74	0.5150		4.10	0.8858		8.8	0.8841	
CS_{14}	$FI_{0.8}$	146.0	0.4520		6.54	0.2157		5.32	0.3144		11.9	0.2163	
CS_{14}	$FI_{1.6}$	109.8	0.5559		4.37	0.7150		3.81	0.6698		8.2	0.6694	
CS_{14}	$FI_{3.2}$	131.7	0.8233		5.41	0.6847		4.40	0.8919		9.8	0.7541	
CS_{16}	$FI_{0.1}$	96.7	0.2845		5.48	0.6482		5.03	0.4667		10.5	0.5309	
CS_{16}	$FI_{0.2}$	140.3	0.5872		6.35	0.2694		5.28	0.3328		11.6	0.2555	
CS_{16}	$FI_{0.4}$	120.9	0.8587		2.74	0.1177		3.77	0.6423		6.5	0.2373	
CS_{16}	$FI_{0.8}$	139.6	0.6061		5.44	0.6671		4.66	0.7030		10.1	0.6562	
CS_{16}	$FI_{1.6}$	136.5	0.6882		6.99	0.1165		5.62	0.1997		12.6	0.1164	
CS_{16}	$FI_{3.2}$	146.9	0.4321		5.71	0.5282		3.92	0.7459		9.6	0.8171	
	FI_{CTRL}	125.7			4.86			4.26			9.1		
ANOVA							P-values						
FI			**0.0068**			0.0946			**0.0065**			**0.0165**	
CS			0.0719			**0.0433**			**0.0028**			**0.0084**	
FI*CS			**<0.0001**			**0.0029**			**0.0027**			**0.0011**	

Table 6

Treatment		Final leaf area			Root biomass[a]				Shoot biomass			Total biomass		
					Trans.	Back-trans.								
		cm^2							g					
CS_{10}	$FI_{0.1}$	105.90	0.4820		0.177	0.502	0.7771		0.891	0.8260		1.395	0.9816	
CS_{10}	$FI_{0.2}$	60.82	**0.0254**	*	0.113	0.297	0.1181		0.629	0.0666		0.941	0.0769	
CS_{10}	$FI_{0.4}$	0.47	**<0.0001**	***	0.001	0.003	**<0.0001**	***	0.019	**<0.0001**	***	0.022	**<0.0001**	***
CS_{10}	$FI_{0.8}$	0.00	**<0.0001**	***	0.000	0.000	**<0.0001**	***	0.005	**<0.0001**	***	0.005	**<0.0001**	***
CS_{10}	$FI_{1.6}$	0.00	**<0.0001**	***	0.000	0.000	**<0.0001**	***	0.001	**<0.0001**	***	0.001	**<0.0001**	***
CS_{10}	$FI_{3.2}$	0.00	**<0.0001**	***	0.000	0.000	**<0.0001**	***	0.004	**<0.0001**	***	0.004	**<0.0001**	***
CS_{12}	$FI_{0.1}$	80.47	0.3275		0.140	0.382	0.4396		0.684	0.1340		1.075	0.2073	
CS_{12}	$FI_{0.2}$	92.85	0.8717		0.118	0.313	0.1584		0.726	0.2144		1.053	0.1787	
CS_{12}	$FI_{0.4}$	84.28	0.4664		0.151	0.415	0.6343		0.783	0.3724		1.204	0.4435	
CS_{12}	$FI_{0.8}$	41.91	**0.0008**	***	0.067	0.168	**0.0051**	**	0.393	**0.0014**	**	0.569	**0.0019**	**
CS_{12}	$FI_{1.6}$	6.85	**<0.0001**	***	0.009	0.021	**<0.0001**	***	0.139	**<0.0001**	***	0.161	**<0.0001**	***
CS_{12}	$FI_{3.2}$	0.00	**<0.0001**	***	0.005	0.012	**<0.0001**	***	0.009	**<0.0001**	***	0.022	**<0.0001**	***
CS_{14}	$FI_{0.1}$	80.41	0.3258		0.129	0.345	0.2654		0.740	0.2479		1.097	0.2389	
CS_{14}	$FI_{0.2}$	99.75	0.7670		0.170	0.480	0.9255		0.891	0.8276		1.384	0.9469	
CS_{14}	$FI_{0.4}$	86.48	0.5596		0.154	0.427	0.7128		0.699	0.1591		1.143	0.3163	
CS_{14}	$FI_{0.8}$	78.90	0.2794		0.136	0.368	0.3696		0.651	0.0890		1.027	0.1483	
CS_{14}	$FI_{1.6}$	32.53	**0.0001**	***	0.071	0.176	**0.0065**	**	0.472	**0.0060**	**	0.657	**0.0052**	**
CS_{14}	$FI_{3.2}$	0.00	**<0.0001**	***	0.017	0.040	**0.0001**	***	0.329	**0.0004**	***	0.369	**0.0002**	***
	FI_{CTRL}	95.29			0.167	0.469			0.926			1.401		
ANOVA						P-values								
FI			**<0.0001**				**0.0001**			**<0.0001**			**<0.0001**	
CS			**<0.0001**				**<0.0001**			**<0.0001**			**<0.0001**	
FI*CS			**<0.0001**				**0.0031**			**0.0044**			**0.0050**	

Table 7

Treatment	Final leaf area			Root biomass			Shoot biomass			Total biomass		
	cm^2						g					
$FD_{0.0}$	5.1	**< 0.0001**	***	- 0.015	**< 0.0001**	***	0.181	**< 0.0001**	***	0.17	**< 0.0001**	***
$FD_{0.5}$	75.9	0.2582		0.343	**0.0423**	*	0.478	0.3603		0.82	0.0915	
$FD_{1.0}$	54.7	**0.0208**	*	0.281	**0.0109**	*	0.457	0.2408		0.74	**0.0332**	*
$FD_{1.5}$	157.8	**0.0006**	***	0.856	**0.0174**	*	0.891	**0.0001**	***	1.75	**0.0012**	**
$FD_{2.0}$	127.2	0.0748		0.710	0.2618		0.728	**0.0381**	*	1.43	0.1051	
$FD_{2.5}$	152.3	**0.0022**	**	0.734	0.1936		0.838	**0.0012**	**	1.57	**0.0219**	*
$FD_{3.0}$	112.3	0.3329		0.632	0.6428		0.656	0.2083		1.29	0.3914	
$FD_{3.5}$	144.2	**0.0064**	**	0.830	**0.0310**	*	0.799	**0.0036**	**	1.63	**0.0080**	**
$FD_{4.0}$	129.7	0.0542		0.743	0.1594		0.756	**0.0162**	*	1.50	**0.0485**	*
FD_{CTRL}	95.5			0.579			0.553			1.13		
ANCOVA						P-values						
FD		**< 0.0001**			**< 0.0001**			**< 0.0001**			**< 0.0001**	
Leaf area (cm^2)[a]		**< 0.0001**			**< 0.0001**			**< 0.0001**			**< 0.0001**	

CROPRO-D-23-00708

Highlights

- Across early growth stages, sugar beets can tolerate hoeing at distances ≥ 1 cm.
- Flame weeding sugar beets directly at the cotyledon stage is not recommended.
- Sugar beets become more tolerant to direct flame weeding as they grow and develop.

Conflicts of Interest

Authors Margaret R McCollough and Bo Melander declare no conflicts of interest. Frank Poulsen is the founder and CEO of F. Poulsen Engineering ApS., a manufacturer of intelligent automated intra-row weeding devices.

Bo Melander

Bo Melander

Journal Pre-proof