Field sprayer for inter- and intra-row weed control: performance and labor savings

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Abstract

Studies of new tools and methods for weed control have been motivated by increased consumer demand for organic produce, consumer and regulatory demands for a reduction in environmentally harmful herbicide use, and the decreased availability of farm workers willing to perform manual tasks, such as hand weeding. This study describes the performance of a new sprayer system for commercial production that integrates two herbicide applications in a single pass, selective herbicide (SH) application in narrow bands over the crop row, and a non-selective herbicide (NSH) application between crop rows. A real-time kinematic (RTK) global positioning system (GPS) was used for auto-guidance in seeding and spraying operations. Conventional broadcast SHs and experimental treatments were applied at a constant nominal speed of 5.5 km h^{-1} for comparison. Trials in commercial sugar beet fields demonstrated the following: (i) average hand-weeding time can be reduced by 53% (ii) the new sprayer system reduced SH use by 76%, and (iii) sugar beet density did not change significantly during treatment. These results demonstrate the feasibility of using the new RTK-GPS controller sprayer system for differential and efficient herbicide application in inter- and intra-row zones in row crop production.

Additional key words: hooded sprayer; precision farming; herbicide application; site-specific management.

Introduction

Competition from weeds in row crops can cause significant losses in crop yields and impair crop quality, resulting in unnecessary economic loss for the farmer. For example, sugar beet (*Beta vulgaris* L.) yield may be reduced by as much as 95% due to shading and competition for light from weeds (Scott & Wilcockson, 1976), and tomato (*Solanum lycopersicum* L.) yield losses resulting from weed interference can reach 88% (Miyama, 1999). Carrot (*Daucus carota* L.) and lettuce (*Lactuca sativa* L.) yield reductions have been as high as 50% and 54%, respectively (William & Warren, 1975; Morales-Payan *et al.*, 1996).

Overall, the selection of a weed control method is influenced by the type and condition of the crop, the type and size of the weeds, the equipment available, and the time of treatment (Bainer *et al.*, 1963). However, herbicides applied by field sprayers have been used most frequently because of their ability to control a broad spectrum of weed species, their proven efficacy, and their low cost compared to manual labor, such as hand hoeing. Where weeds have evolved resistance or are naturally tolerant to herbicide, a moderate amount of hand hoeing is required to remove intra-row weeds after chemical application. The current objective of precise herbicide application is to make operating input more efficient by minimizing overlap and skip incidents and eliminating application on non-crop areas. As this objective is achieved, fewer herbicides can be used compared to conventional application, resulting in lower cost and risk for the environment (Schroers *et al.*, 2010).

Abbreviations used: AIMCRA (Research Association for the Improvement of Sugar Beet Crop of Spain); BBCH (Biologische Bundesanstalt Bundessortenamt and Chemical industry); CA (conventional application); EA (experimental application); GNSS (global navigation satellite system); GPS (global positioning system); NSH (non-selective herbicide); PPS (pulse per second); NMEA (National Marine Electronics Association); RTK (real-time kinematic); SH (selective herbicide).

The sugar beet (*Beta vulgaris* L.) complex is of particular interest, as it can be found in both crop and weedy forms in western Mediterranean regions (Desplanque *et al*., 1999). The weed beet problem has been a major concern since the 1970s in Europe (Viard *et al*., 2002), as weed beets cannot be chemically weeded and compete vigorously with the crop. Hand hoeing is the primarily control method available. However, hand hoeing is also most expensive method, as it requires intensive labor, it is time consuming, and its speed and accuracy are restricted by the skills and experience of the crew.

Inter-row cultivators have been commonly used in row crops, such as sugar beets and vegetables, for many decades. In many instances, the success of these implements depends on dry weather conditions and workable soil (Rueda-Ayala *et al*., 2010). In-row weeds are more difficult to eliminate than between-row weeds due to their proximity to the crop or seed line. Standard mechanical cultivation methods generally eliminate weeds between the rows; they do not remove weeds between the crop plants within the rows. However, the research community has been working to develop different commercial machines for intra-row weeding with different costs and field capacities, including i) mechanical intra-weed control based on the real-time kinematic (RTK) global positioning system (GPS) weed knife (at 1.6 km h^{-1}) (Pérez-Ruiz *et al*., 2012), ii) intelligent systems using digital cameras to view crops and a spinning disc to remove weeds (guide price $17,000/row and speed limited to 3 km h^{-1}) (Dedousis *et al*., 2007). In some cases, thermal methods, such as flame weeding and soil steaming, can be less costly than hand weeding, but there is a high machine cost ($4,700/row and €27,023 ha^{-1} yr^{-1}, respectively) (Ascard, 1998; Vidotto *et al*., 2011). Ascard (2011) suggests that constraints due to cost, low capacity, low selectivity, and time to perform all of the necessary adjustments have prevented most of these recently developed weed control systems from being widely used in practice.

During the early growth stages, when competition for nutrients, water, and radiation is critical (Slaughter *et al*., 2008), sugar beets require either continued hand labor for weed removal (Tillett *et al*., 2008), banded application of selective herbicides (SHs) on the crop row followed by between row cultivation (Kaya & Buzluk, 2006), or broadcast herbicide application. This last scenario is currently the primary method used for sugar beet cultivation in Spain.

There are three areas within crop rows that can be clearly identified for weeding: between rows, between crop plants within the row, and close to but 3-4 cm below the plant (Griepentrog *et al*., 2003). Hand hoeing can be eliminated with mechanical weeding in the area between crop rows, but intra-row weeds remain problematic (Melander, 1997; Tillett *et al*., 2002).

Typical inter-row cultivators used in sugar beet production in Spain are composed of a parallelogram, which holds a number of rigid or vibrating shanks mounted on sweeps and distributed along the toolbar. Unless an implement positioning control system is used, these cultivators generally cannot work close to the crop plant due to the danger of root pruning. Manual steering, using a second human operator, has been a common guidance method to control the toolbar to increase cultivation accuracy and reduce crop damage. A second operator is often employed to control the toolbar laterally, making adjustments by hand based on the operator's vision. However, three issues remain problematic: increased operation costs, difficulties in recruiting trained workers, and low efficiencies associated with human error, particularly when operating with poor visibility (*e.g.*, at night or in dusty conditions). Hydraulically guided systems based on computer vision and GPS technology, which aim to reduce human error caused by the tractor driver, have been introduced (Melander *et al*., 2005; Griepentrog *et al*., 2007).

A major disadvantage of using the cultivator for weed control is that it causes soil disturbance and stimulates new weed seeds to germinate. In this context, a new method of post-emergence control of in-row weeds was recently successful in a field-tested for both corn and soybeans (Forcella, 2012). This method involves the use of air-propelled abrasive grit. The grit (*i.e.*, "green grits") abrades small weed seedlings within the crop row and leaves the crop plants essentially unscathed.

Typical RTK-GPS technology has a row positioning accuracy of ± 2.5 cm, which is comparable to that of machine vision guidance systems, but it manages to accomplish this accuracy without visual guidance landmarks in the field (Leer & Lowenberg-DeBoer, 2004). Visual targets may not always be possible, such as when the crop has not emerged or too small. A high level of geoposition accuracy in row crops can enhance the precision of chemical placement in narrow bands or cultivation close to the plant line (Abidine *et al*., 2004). However, one disadvantage of the RTK-GPS solution

is the requirement that a base station be located within 10 km at all times. GPS service providers and government institutions are working to mitigate this issue by developing a network of base stations that can provide access to RTK correction signals over a wider geographic region via cellular or radio modems (Leandro *et al.*, 2011). In the future, these networks will provide coverage to all farmers with RTK-GPS receivers, eliminating the need for multiple base stations on each farm.

Under Mediterranean climate conditions, mild winters allow the sugar beet to be sown in autumn and harvested in summer. A longer growing season contributes to higher yields in relation to the spring-sown sugar beet. However, season-long weed control is too expensive because it may require the application of a pre-emergence herbicide at planting, up to three post-emergence herbicides depending on the region and year, and one or several mechanical cultivations coupled with hand hoeing. The Research Association for the Improvement of Sugar Beet Crop of Spain (AIMCRA) has conducted economic studies of labor management and has reported values of 20% and 23% of production costs due to weed control in irrigated and rain-fed sugar beet production, respectively (Bermejo *et al.*, 2008). AIMCRA is concerned with crop conditions, production costs, and crop profitability due to the impending reduction of financial support by the European Union. Accordingly, it has launched a program to improve sugar beet crop competitiveness, which could provide substantial savings in agro-chemicals with associated environmental and economic advantages for more sustainable sugar beet production systems.

Seeking to increase sugar beet competitiveness in weed control operations, AIMCRA and the University of Seville have collaborated in the development and evaluation of the performance of a RTK-GPS-guided tractor and an implement suitable for commercial production that integrates two herbicide applications in a single pass. These applications use a SH in narrow bands over the crop row and a non-selective herbicide (NSH) between crop rows. The specific objectives of this paper were as follows: (i) to develop and assess a field sprayer that combines the under-hood application of NSHs between rows and the application of SHs within crop rows; (ii) to demonstrate that a significant reduction in the current reliance on hand labor in conventional production systems can be achieved by using such combined herbicide applications.

Material and methods

Equipment design and fabrication

A field prototype sprayer for inter- and intra-row herbicide application was designed and built for precise weed control operation in sugar beet fields. This equipment enables a one-pass SH treatment over the seed line (band width 14 cm) and NSH treatment between crop rows (band width 36 cm). Two 100-L herbicide tanks were mounted on the implement's main frame, with one tank for each type of herbicide. At the bottom of each tank, a 12 V electric pump (model 5800, Develan Pumps, Inc. Minneapolis, MN, USA) was installed to create flow. Each tank also included an agitation system to keep the chemical mixed, a pressure regulator valve to control flow rate, a pressure gauge with the appropriate scale, and miscellaneous components, such as fittings and strainers. For the inter-row weed control application, seven hood units protected adjacent row crop foliage from NSH. NSH was then applied to six rows. The five center metal spray-hood units had a fixed spray width of 36 cm and a height of 32 cm. The two end spray-hood units had the same height but with spray widths of 26 cm. All hoods were designed to travel 1.5 cm below the soil surface and were controlled by a set of mechanical guide wheels attached to the main frame.

Fig. 1 presents the sprayer in three possible configurations: conventional broadcast SH application (Fig. 1a), a narrow band NSH intra-row application (Fig. 1b), and NSH inter-row and SH intra-row application (Fig. 1c). The configurations in Figs. 1a and 1c were employed for this study. In the broadcast application, the supply tank one fed the spray boom while six ISO110025 standard (ALBUZ, Evreux Cedex, France) flat-fan nozzles were positioned at a height of 50 cm above the crop (height adjustment) and separated by 50 cm with a spray angle of 110°. This scheme is the conventional practice of local sugar beet producers. In the experimental application, the angle of the spray pattern and the mounting height of the nozzle were critical to controlling band width. For this study, the optimal nozzle height, located at the center of the hoods, was 21 cm for a spray angle of 80° and a band width of 36 cm. Seven even ISO standard flat-fan nozzles were used to apply the inter-row NSH to provide a uniform distribution of the spray throughout the fan pattern. The six even flat-fan nozzles (angle of 80°) over the crop rows were regulated to a height of 9 cm
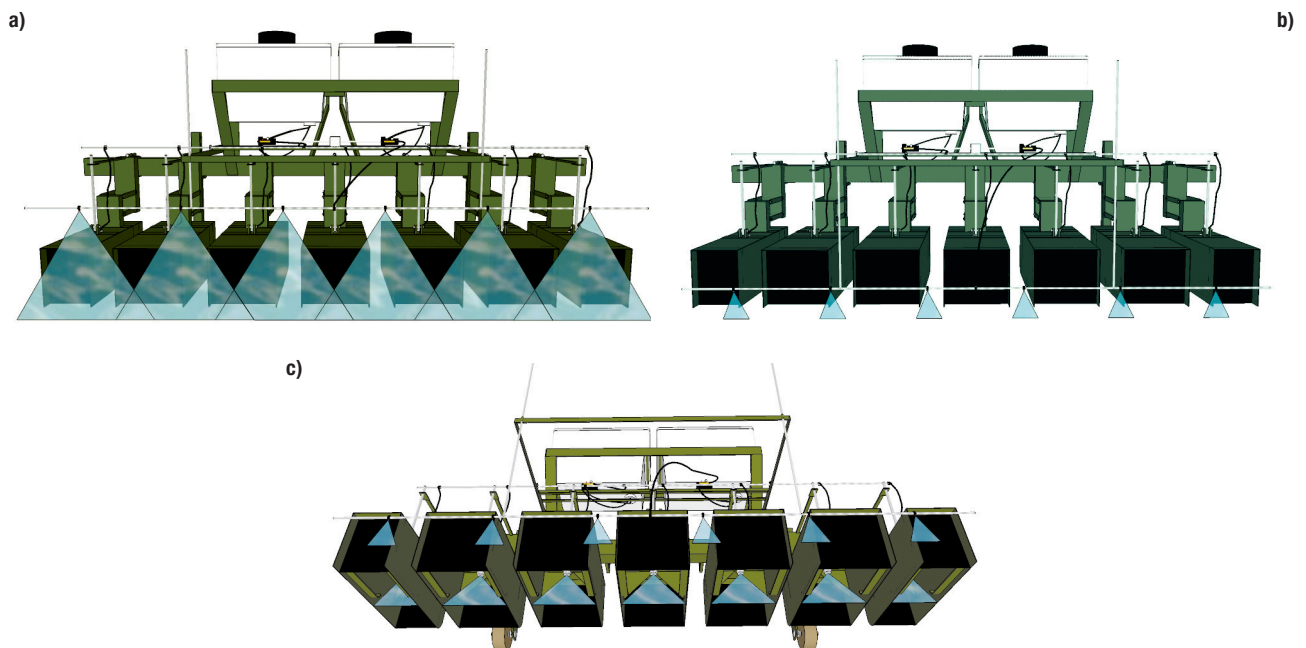
Figure 1. Field sprayer prototype and three possible configurations: a) for conventional broadcast HA (flat-fan nozzle), b) for narrow band seed line application (even flat-fan nozzle), c) for NSH spray nozzles in the hoods and SH boom spray nozzles over the crop (even flat-fan nozzle). Configurations (a) and (c) were tested.

to achieve a band width of 14 cm. There are certain disadvantages of using NSHs; for instance, they are less effective on some weeds, and thus, there is a lack of soil residual activity due to their application. However, if the farmer's most problematic weeds are not among the most resistant species, then NSHs could be adequate for the weed control issues between the sugar beet crop rows.

An initial test of the system was conducted to characterize the lateral implement movement with a forward speed of 5.5 km h⁻¹. The anti-drift hood units create a small furrow to demarcate the hood patch as it passes across the field. A hand ruler was used to characterize the lateral implement movement by measuring the ground distances between this furrow and the crop rows; a similar procedure was described and used by Griepentrog *et al*. (2006).

Global positioning system (GPS)

Precision guidance was required in this system to ensure reliable centering of the intra-row SH application about the crop stem. RTK provides the highest degree of accuracy (2.5 cm) for global navigation satellite system (GNSS) applications. An RTK system requires two receivers, a radio link, and an embedded navigation controller that integrates rover sensors and GPS data to compute the final position of the rover receiver (Misra & Enge, 2006). In this study, an RTK-GPS automatic guidance system (AgGPS Autopilot, Trimble Navigation Ltd., Sunnyvale, CA, USA) was used to pilot the tractor (model TS90, New Holland with category 2, three-point hitch) for all seeding operations and field trials. The GPS system included: (i) a rover RTK-GPS receiver (Trimble EZ Guide 500) with the GPS antenna mounted on top of the tractor's cabin (~3 m above the soil surface); (ii) a user interface capable of displaying cross-track error information and receiving user input, such as the desired pass spacing and the location of the first guidance line; (iii) path-planning algorithms capable of calculating cross track error relative to the desired guidance path; (iv) vehicle steering actuators; (v) manual override sensors; (vi) steering angle sensors; (vii) controller calculating steering correction algorithms; and (viii) terrain compensation sensing (*i.e.*, pitch, roll and yaw).

The system utilized an RTK-GPS correction signal from a local (~1 km from the test site) GPS base station (Trimble Model 4700) to obtain RTK fixed quality accuracy. An 8 µs clock reference pulse per second (PPS) signal was produced by the autopilot receiver to synchronize the geoposition data with external events. The autopilot receiver was set to output the "NMEA-

0183 GPGGA" string containing the geographic coordinates (latitude and longitude) every second via an RS-232 serial connection.

The AB line used for seeding was stored internally in the tractor navigation system for future use during the weed control trials. Near the location of this study, RTK-GPS quality guidance systems are increasingly being used by commercial farming operations for automatic guidance of tractors and other types of field equipment despite the significant financial investment required.

Field experiments

Field tests were conducted during the 2011/2012 sugar beet season in southern Spain within the Seville region (36.99760754°N, 6.03544936°W). A total of approximately 14 ha were planted with a 12-row pneumatic drill seeder in a commercial sugar beet field. These hectares were divided into three separate sections: A (4 ha), B (6 ha), and C (4 ha). The local farmer allowed our study team to use a 1-ha area per section for our field tests. A weed control treatment was selected for each 1-ha area. The tractor used for the seeding operation was guided by an automatic steering system with cm-level precision to ensure straight seed lines and generate an AB line for use during the trials. The field trials were carried out at a constant nominal speed of 5.5 km h^{-1}. The nominal forward travel speed was controlled by the auto-guidance tractor.

A completely randomized design used 10 zones for field test "A" (30/11/11) to determine the time per square meter required for a skilled worker to hand weed. Two weed control systems, hand hoeing and herbicide application with the experimental setup, had five experimental units for each treatment. The objective of this test was to compare the cost of weed control in sugar beet fields using hand-weeding versus the hooded sprayer for intra-row SH and inter-row NSH applications. Herbicide application was performed at a rate of 225 L ha^{-1}, a pressure of 4×10^5 Pa, and a nominal tractor speed of 5.5 km h^{-1}. One post-emergence herbicide application was carried out during this test, and the banded spray over the crop row used six nozzles located 5 cm from the top of the crop. The nozzles were separated by 50 cm with a spray angle of 110°. The wetted surface using SH (Phenmedipham 9.1%+Desmedipham 7.1%+Ethofumesate11.2%) was 84 cm (six rows with a 14 cm band per row). The wetted surface width with the banded application between crop rows using NSH (glufosinate-ammonium) was 232 cm (five middle hooded spray units of 35 cm each, two end spray units of 52 cm each). In both treatments, a follow-up hand weeding operation was conducted by a volunteer worker to remove the remaining weeds in the central 14 cm band along the row centerline and the 36 cm band between rows. For this test, initial weed density, the worker's hand weeding rate, and sugar beet plant counts along the row were recorded. In this field, 90% of the weeds were wild beet (*Beta vulgaris* ssp. *maritime*, a perennial species form the Mediterranean and European Atlantic coasts), which meant that SH would not kill the weeds. The only options for post-emergence control were our prototype hooded sprayer for inter-row NSH application and hand hoeing. Sugar beet growers typically use hand hoeing, as it is currently the only viable option.

One pre-emergence (16/11/11) and one post-emergence (27/12/11) herbicide application were carried out in field test "B" to include the complete sugar beet spraying cycle in this atypical, weed-scarce year. This test was performed with a completely randomized, unbalanced design factor (weed control) and three types of treatment: (i) conventional or broadcast application (CA); (ii) experimental sprayer application (EA), in which the pre- and post-emergence treatments were applied on the crop line, leaving the remaining plot untreated, whereas a post-emergence treatment involves treating the entire surface with the experimental herbicide application; and (iii) control, without any herbicide application. Conventional broadcast herbicide applications were conducted on six experimental plots, applied uniformly on the ground (pre-emergence) or over the crop canopy (post-emergence). The experimental applications, as described earlier, were also conducted on six experimental plots. Eighteen untreated control plots of 18 m^2 each remained between the experimental plots. Each experimental plot was comprised of 2 m of crop line, which is equivalent to 1 m^2. Weeds and crop plants were then counted and recorded to compare the weed control system efficacy and crop plant phytotoxicity (dependent variables).

Field test C was performed with the experimental sprayer over twelve 1-m^2 zones on January 24, 2012. Six zones were randomly selected to obtain a weed count, and six were selected to determine crop plant density. Three observations were made on each plot before treatment on July 2, 2012. This test was aimed at validating the proper functioning of the newly designed sprayer.

Data analysis

Field test A used the non-parametric Wilcoxon-Mann-Whitney test to compare the independent samples (one-sided). The relationship between the weed count and hand-weeding time was calculated using least-trimmed-squares regression (Rousseeuw, 1984). Robust elliptic plot (Relplot) was used to detect and study outliers (Goldberg & Iglewicz, 1992).

In field test B, univariate analysis of variance (ANOVA) was used to establish the effects of the weed treatment factor on the dependent variable (sugar beet density). This factor had three levels: conventional application, experimental application, and control. Normality was tested using the Shapiro-Wilk test, and the homogeneity of variance was tested using the Levene test. The absence of data normality motivated the use of a robust model for this condition. Therefore, the null hypothesis was used to compare the equality of 0.2-trimmed means.

In addition, a comparison of weed density (weeds m^{-2}) was performed to determine the effectiveness of CA and EA treatments; weeds were counted 10 days after the applications. The analysis was performed using a robust Wilcoxon-Mann-Whitney test (Mee, 1990), and the null hypothesis was tested at $p = 0.5$.

Finally, regarding field test C, the comparison before and after performing a treatment using the experimental application setup in terms of the number of beet plants per unit area, as well as weed density (weed m^{-2}), was performed using the percentile bootstrap confidence interval method, with 2,000 simulated replicates to determine the difference between medians on paired data ($\alpha = 0.05$).

Analyses were performed using R software (R Development Core Team, 2011).

Results and discussion

In this study, an experimental implement that combines two herbicide applications in a single pass, allows for SH application in narrow bands over the crop row, and allows for NSH application between crop rows was successfully developed and operated for sugar beet crops (Fig. 2).

All measurements of lateral hood movements, *i.e.*, the ground distances between the mark left by an anti-drift hood and the crop rows, were located within the intra-row bandwidth, which for this study was defined as ±70 mm from the row center line. This result is in agreement with the findings reported by Abidine *et al.* (2002), in which an implement operating 50-75 mm from the crop center line produced no crop damage, confirming that the RTK-GPS-based autoguidance system did not cause transverse damage interaction between anti-drift hood units and sugar beet plants. Applying this technology can eliminate the need for a second human operator that is employed in some implements to control the toolbar by laterally making adjustments by hand based on the operator's vision. In addition, during the trials, although a thorough evaluation was not performed, it appeared that the aim of the electronic guidance system was to reduce the concentration needed from the tractor driver, a result that was also observed by Melander *et al.* (2005).

Labor savings in follow-up hand weeding was documented by measuring the time required for experienced laborers to hoe the remaining weeds after the experimental application and compared with the time required to hand hoe the control rows. In field test A, the median hand-weeding times in the zone with post-emergence experimental herbicide application (45 ± 6.3 s
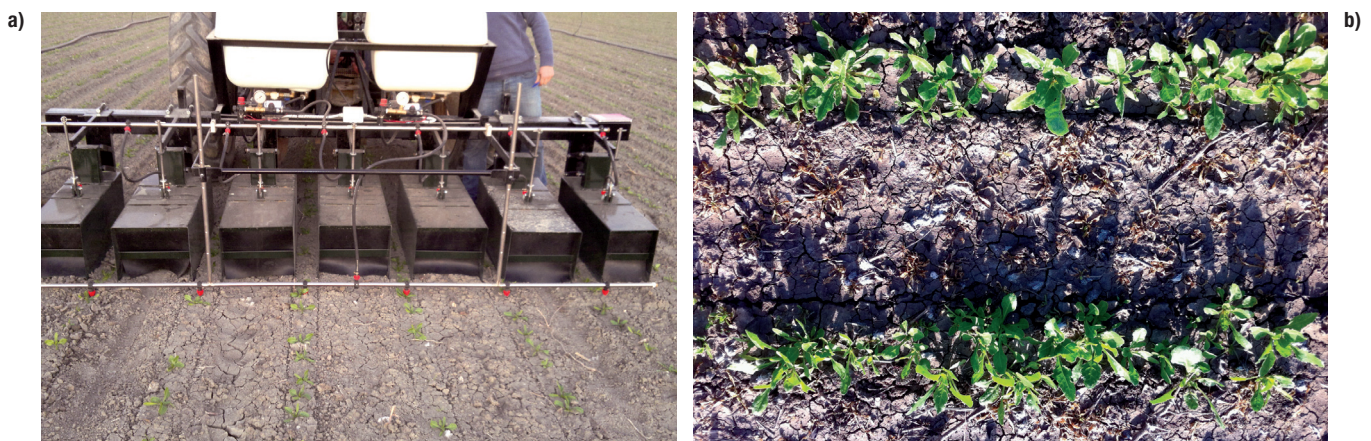
Figure 2. Hooded sprayer design for inter- and intra-row HA (a) and weed control effect between row crops after NSH application (b).

Table 1. Times required to hand weed for post-emergence experimental herbicide application and using no experimental herbicide application (Control)

Post-emergence experimental application		No post-emergence experimental application (Control)	
Experimental plot	Hand weeding time (s)	Experimental plot	Hand weeding time (s)
1	47.2	6	91.0
2	42.5	7	131.0
3	34.2	8	95.0
4	64.0	9	96.0
5	45.0	10	97.0
Median	45.0	Median	96.0

plot^{-1}) and the zone without post-emergence experimental herbicide application (96 ± 2.9 s plot^{-1}) were significantly different ($p = 0.004$) (Table 1). Each experimental plot was 0.5×10 m (5 m^2). The new experimental spraying system reduced hand-weeding times by 53%. Moreover, the variability in the number of weeds was much higher in the control zone (SD = 25.9 weed m^{-2}) than that in the zone for which the experimental unit had been used (SD = 12.8 weed m^{-2}).

Slaughter *et al*. (2012) also achieved a 52% reduction in man hours per hectare required by using a GPS-based intra-row weeding machine for a similar weed load. Assuming a hand-weeding labor cost of €7.70 h^{-1} in the study area, this level of labor reduction represents a potentially significant savings in the cost of manual labor for hand hoeing.

Fig. 3 shows a linear relationship between hand-weeding time and weed density ($R^2 = 0.93$, $p < 10^{-4}$). The straight-line least-trimmed squares exhibited the following relationship:

$$t = 28 + 0.27 \, wd$$

where *t* is the hand weeding time (s) and *wd* is the weed density (weed m^{-2}).

There are few studies on the relationship between hand-weeding time and weed density because most studies focus on comparisons between weed management techniques (Gopinath *et al*., 2009) and their economic results (Harunur *et al*., 2012). However, the data from Shrestha *et al*. (2008), who compare hand-weeding times for woody crops, can be estimated similar to our study. A linear relationship was observed between the total hand-weeding time per hectare and the total number of weeds throughout the test period. The weed density was between 4 and 365 plants m^{-2}. This is a range similar to that of this study (43 and 423

plants m^{-2}). Most of the weeds were wild beet (*Beta vulgaris* ssp. *maritima*) and *Chenopodium album*. The former were in the four-leaf stage (BBCH 14), a cotyledon stage, and the latter were in a cotyledon stage of development. According to Wellmann (1999), the critical period of sugar beet competition is never before the four-leaf stage.

Field test B examined sugar beet densities as influenced by the control, EA, and CA treatments. Mean ($\pm$ SE) sugar beet densities in these treatments were 12.7 ± 0.21 (control), 12.4 ± 0.32 (EA), and 12.1 ± 0.34 (CA), respectively, and were not significantly different from one another (ANOVA, $p = 0.28$). The equality of these means across treatments indicated that the new spraying system did not affect sugar beet populations adversely and that the new system could likely be used at the field level, even at times when the sugar beet is
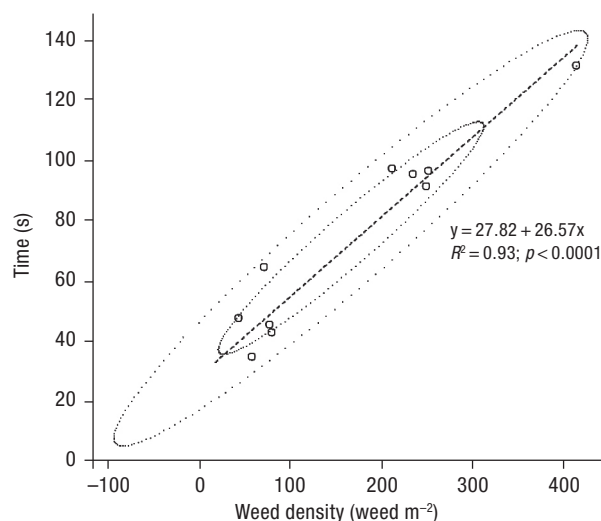
Figure 3. Relationship between hand-weeding time and weed density.

highly sensitive to broad-spectrum herbicides that could be useful when broadcasted.

Bermejo *et al*. (2008) conducted an economic study on labor management in this region and reported that an average of 21.5% of production costs were due to weed control practices. The use of this new implement reduces the equipment cost penalty for weed control operations, which could make it economically viable for conventional production systems, even with the reduction of financial support by the European Union.

In relation to the weed population, the count performed on January 17, 2012 indicated that there were no differences between CA and EA after December 27, 2011, with a confidence level of 95% with $p = 0.19$-0.57, thus including the value $p = 0.5$. This result is very important because: (i) this stage is the time when weeds can achieve development that significantly reduces sugar beet production and (ii) the new implement reduced the use of SH, which is considerably more expensive than NSHs containing the active ingredient glyphosate by 76%. This reduction saves approximately €54 ha^{-1} in treatment costs for crop producers (AIMCRA published the 2012 prices of SHs in the sugar beet sector in Spain, and these were used to determine operation costs and savings (Morillo-Velarde, 2012).

Finally, in field test C, an experimental application with the new implement was conducted to assess its proper operation and the crop and weed densities were checked before and after herbicide application. The median density of the sugar beets in the experimental plots was 7 plants m^{-2} (before application) and 6 plants m^{-2} (after application) (Table 2). The 95% confidence interval of the difference before and after treatment for beet density was [0, 1]. Given this interval, there was no significant difference between the data obtained on the earlier and later dates. The median density of weeds in the experimental plots decreased from 43.5 weeds m^{-2} (before application) to 12 weeds m^{-2} (after application). The 95% confidence interval was [17.5, 80]. This interval does not contain zero, indicating that there are significant differences in the weed density due to the effectiveness of the treatment. The combined treatment of SHs and NSHs reduced the median weed population by 73%.

As conclusions, an experimental sprayer combining SH and NSH applications was developed in this study for weed control over six rows. Seven sprayer hoods protected the crops from the NSH, and six narrow band sprayers applied SHs within 7 cm of the seed line using RTK-GPS technology. Field tests demonstrated that the machine adapted to working conditions required for this technique. The potential integration of NSH and SH applications in a new sprayer implement was demonstrated for agronomic management in accordance with the treatment sequence. The beet population was not adversely affected compared to conventional broadcast SH application. There were no significant differences in weed densities between the CA and EA with the new sprayer. Using both the NSH application for inter-row weeding and the SH application for intra-row weeding with band spraying along the crop row reduced the amount of SH by replacing it with NSH. In this study, the method reduced the SH treatment area, and thus the SH input, by more than 76%. The treatment area reduction accorded local producers a savings of €54 ha^{-1} for herbicide application because SH was more expensive than NSH and the labor cost for hand hoeing was reduced. This method may be valuable when a farmer needs to use several applications of an expensive herbicide or when the field is infested with wild beets (*Beta vulgaris* ssp. *maritima*). The adoption of new technologies that optimize farm operations will assist the Spanish sugar beet industry to remain competitive in the global economy.

Acknowledgements

Table 2. Crop and weed density (plants m^{-2}) before and after herbicide application in field test C

Experimental plot	Before application		After application	
	Sugar beet	Weed	Sugar beet	Weed
1	7	19	6	9
2	7	86	6	21
3	8	34	8	6
4	4	36	4	6
5	6	51	6	15
6	7	144	7	49
Median	7	43.5	6	12

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