A prototype band-steaming machine: design and field application

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Abstract

Soil steaming is a preventive non-chemical weed control method. We designed and studied a new prototype band-steaming machine. Tests were conducted during the growing cycle of organically cultivated carrot in real-field conditions, in order to study the effect of different steam doses on crops and a natural weed seedbank, throughout the whole growth cycle. The prototype has a 3265 MJ h⁻¹ steam generator, which applies steam in 12 soil bands, 180 mm wide. The steam was mixed with the soil by mean of an apposite rotary cultivator. Four biological steam doses (0, 1.11, 1.59, and 2.78 kg m⁻²) were applied in combination with 4000 kg ha⁻¹ of CaO prior to sowing the crop. Log-logistic models were used to describe the responses of temperatures, weed density, time required for hand weeding, weed dry biomass at harvest, and carrot yield to the band-steaming application. Based on the experimental data, an economic margin was evaluated to find the optimum application dose. Overall responses were influenced by steam dose. The results showed that a maximum temperature of 63 °C at a 25 mm depth was observed with a steam dose of 2.78 kg m⁻². With a 2.78 kg m⁻² dose, the operative time was approximately 14 h ha⁻¹ and total fuel consumption was 768 kg ha⁻¹. An estimated mean steam dose of 2.3 kg m⁻² could be able to provide similar yield and hand weeding times responses to the highest steam dose applied, thus reducing both the operative time and fuel consumption of the machine.

Keywords: steamer, steaming, soil temperature, dose-response curves, weed control, carrot.

1. Introduction

Steam is used in agriculture for soil disinfection of pathogens and for weed seed control. Soil steaming prior to cropping destroys a huge number of weed seeds and provides prolonged weed control in the ground (van Loenen et al., 2003; Melander & Jørgensen, 2005; Samtani et al., 2011).

37 How efficient steam is at heating the soil is strictly related to the steam distribution system used.
38 Sheet steaming consists in blowing steam under a sheet, which is left to penetrate the soil. Mean
39 temperatures of 100 °C in the top 10 cm of soil are kept for up to 6-7 h (Runia, 2000; Minuto,
40 Gilardi, Kejii, Gullino, & Garibaldi, 2005). The negative pressure steaming method consists in
41 introducing the steam under a steaming sheet and forcing it into the soil by negative pressure,
42 created in the soil by a fan, which sucks air out of the soil through buried perforated polypropene
43 tubes. The temperatures in the deeper soil layers achieved with negative pressure steaming are
44 higher than with sheet steaming (Runia, 2000). Runia (2000) used negative pressure steaming, and
45 observed a reduction of up to 50% of fuel consumption compared with sheet steaming, and a mean
46 temperature of 60 °C at a 0.45 m depth after a 4 h application.

47 Improvements in terms of machinery have been achieved by introducing steaming hoods. A
48 steaming hood is a mobile device consisting of corrosion-resistant material connected by a flexible
49 pipe to the steam generator, which is placed onto the area to be steamed. Unlike sheet steaming, it
50 does not involve the cost-intensive working steps such as laying out and weighing the sheets,
51 however, the area steamed per working step is smaller depending on the size of the hood
52 (Echevarría & Rodríguez, 2012). Whole-area treatments using steaming hoods enable temperatures
53 higher than 100°C to be reached in soil layers of 0-100 mm (Roux-Michollet et al., 2008). However,
54 hood steaming makes extensive use of fossil fuel oil ranging from 2550 to 4250 kg ha⁻¹ and the high
55 time consumption of 70-100 h ha⁻¹ (Pinel, Bond, White, & de Courcy Williams, 1999).

56 Steaming hoods can be combined with sub-surface steam injectors (Gay, Piccarolo, Ricauda
57 Aimonino, & Tortia, 2010a). Gay, Piccarolo, Ricauda Aimonino, and Tortia (2010b) developed a
58 custom 2 m x 2.5 m stainless steel hood combined with 99 steam injectors connected to a self-
59 propelled steaming machine powered by a 75 kW engine and carrying a superheated steam
60 generator operating at a relative pressure of 50 kPa with a flow rate of 500 kg h⁻¹. Each injector
61 supplies orthogonal flows of steam via four holes with a diameter of 4 mm buried at a depth of 18
62 mm. During steaming, the border of the hood remains buried at a depth of 30-40 mm in order to
63 prevent steam leakages. This prototype resulted in a fuel consumption of 8160 kg ha⁻¹ of diesel fuel,
64 66% and 18% lower than sheet and hood steaming without steam injectors (23885 and 10030 kg ha⁻¹,
65 respectively). Maximum temperatures ranged from 70 up to 100°C in soil layers of 0-90 mm and
66 decreased at temperatures ranging from 50 up to 70°C in two hours after steam application for 6-10
67 minutes (Gay et al., 2010b).

68 Mobile steaming hoods have the disadvantage of performing a discontinuous application of steam
69 because the hood must stay put in the soil for periods ranging from 6 to 15 minutes (Pinel et al.,
70 1999, Gay et al., 2010). Peruzzi, Raffaelli, Ginanni, Fontanelli, and Frascioni (2011) improved a

71 self-propelled machine able to apply broad-steaming continuously. The steamer (Celli Ecostar SC
72 600) was developed in cooperation with the University of Pisa and Celli (Celli SpA, Forlì, Italy)
73 (Celli, 2015). The Celli Ecostar SC 600 also differs from other steamers due to the possibility of
74 injecting exothermic compounds into the soil, in addition to the steam (Bioflash system). CaO is
75 commonly used as an exothermic compound, providing extra heat to the soil (Bàrberi, Moonen,
76 Peruzzi, Fontanelli, & Raffaelli, 2009). Bàrberi et al. (2009) found that soil temperatures were
77 different and lower when steam was applied alone compared with the application of steam in
78 combination with 4000 kg ha⁻¹ of CaO. The machine can be equipped with three different injection
79 bars and with ridging-mulching equipment in order to cover the soil with a plastic film after the
80 steam application. The driving speed ranges from 60 to 6000 m h⁻¹. At the common treatment speed
81 of 150 m h⁻¹, the operative time was 53 h ha⁻¹ for a total fuel consumption of 2288 kg ha⁻¹ and
82 temperatures remained above 60 °C for 30 min in soil layers of 0-10 cm (Peruzzi et al., 2011).
83 Gelsomino, Petrovičová, Zaffina, and Peruzzi (2010) found that the use of combination of CaO with
84 steam did not cause bacterial eradication or compositional shifts in bacterial community structure,
85 and soil steaming stimulated an increased release of soluble nutrients (K⁺, Mn²⁺, NH⁴⁺-N). The use
86 of combination of CaO with steam is safe and does not cause hygienic-toxicological and
87 environmental issues (Triolo, Materazzi, Luvisi, 2004). Fennimore et al. (2014) evaluated a newly
88 designed mobile steam applicator for the efficient soil disinfestation of weeds and pathogens in
89 raised strawberry beds. The tractor-drawn machine physically mixed the steam with the soil as it
90 passed through the shaped planting beds. The steam was produced by a 74 kW propane-fuelled
91 generator. In the study the target temperature of 70°C was achieved and maintained for 30 min in
92 all the steam treated strawberry beds with an average speed of 161 m h⁻¹. The operative time was 47
93 h ha⁻¹ for a generator fuel consumption of 12,191 kg ha⁻¹.

94 Extremely high fuel consumption and low operative times are major disadvantages of broad soil
95 steaming (Melander & Kristensen, 2011). In order to save the energy consumption and decrease the
96 operative time, steam could be applied only in bands corresponding to the intra-row area, which is
97 where weeds cause the main problems in terms of weed control (Melander & Jørgensen, 2005).
98 Melander, Jørgensen, and Elsgaard (2004) developed a prototype band steamer able to apply steam
99 in soil bandwidths of 80 mm at a depth of 50 mm. Elsgaard, Jørgensen, and Elmholt (2010) applied
100 band-steaming in a field study using a prototype with steaming tines that injected the steam
101 produced by a 200 kW (720 MJ h⁻¹) steam generator at a depth of 50 mm, and found that the
102 temperature decreased from about 75°C to 45°C in 8 min.

103 Hansson and Svensson (2007) used a band-steaming prototype with a 700 kW (2520 MJ h⁻¹) diesel-
104 driven steam generator in order to apply steam in 105 mm wide soil bands at a depth of 50 mm. The

105 quantity of steam applied per unit area and the temperature in the steamed bands varied with the
106 tractor driving speed (from 200 up to 370 m h⁻¹). A mean labour requirement of about 8 h ha⁻¹
107 which allowed a maximum temperature of 86°C at a 40 mm depth was needed to obtain 90% weed
108 control within the steamed bands, with an energy use of 485 kg ha⁻¹ of diesel fuel (Hansson &
109 Svensson, 2007).

110 No experiments however have been conducted to evaluate both weed control and crop yields after
111 the application of different steam doses in soil bands. The aim of this research was to design a new
112 prototype band-steaming machine and to study its field application. Tests were conducted during
113 the growing cycle of organically cultivated carrots in real-field conditions, in order to study the
114 effect of different steam doses on crop and a natural weed seedbank, throughout the whole growth
115 cycle.

116

117 **2. Materials and methods**

118

119 **2.1. Description of band-steaming machine**

120 The main characteristics of the band-steaming machine are detailed in Table 1 and shown in Figs. 1
121 and 2. The machine consisted of a chassis with two pneumatic wheels that supports all the devices
122 and the equipment, a steam generation system, a system for applying steam and an exothermic
123 compound [Bioflash system (Peruzzi et al. 2011)], a hydraulic system, and an electric system. The
124 machine was hitched to the tractor by a drawbar. The rear of the chassis has a three-point linkage
125 with lifting arms in order to attach the steaming device.

126 The steam generation system was created by adopting a rapid steam generator, VAP series
127 (Babcock & Wanson). The burner of the steam generator was fuelled with diesel fuel and was
128 equipped with a pressure nozzle atomisation system. Inside the combustion chamber there was a
129 water pipe that formed a double coaxial coil which was subjected to three passes of hot fumes. In
130 the outer part of the double coil the water was pre-heated (economiser), and the steam was
131 generated in the inner part. There were also two water tanks, a fuel tank and the relative electric
132 pumps, which led to a steam outflow of about 1200 kg h⁻¹. The steam generation was not an
133 instantaneous process, when the steam generator was activated. Initially the steam generator
134 produced hot water and 3 to 5 minutes were needed to reach the suitable steam working pressure. In
135 the initial design of the machine, hot water flowed towards the steamer thus wasting hot water on
136 the soil prior to treatment. In order to overcome this, the original steam generator was equipped
137 with a water-saving system, consisting in a valve, a pump and a bypass pipeline which connected
138 the output steam tube of the boiler with the water tank. Thus whilst the steam was forming, the hot

139 water was recirculated in the water tank. When the right working pressure was reached, and the
140 machine was ready to begin treatment, the valve excluded the bypass and the steam flowed to the
141 application devices.

142 The system for applying steam and the exothermic compound was achieved by modifying a 12 unit
143 PTO-driven rotary cultivator. Each unit was 0.18 m wide and had a driven rotary cultivator covered
144 by a carter (Fig. 2). A steam injection bar was placed on the carter. The steam was mixed with the
145 tilled soil by mean of the rotary cultivator. The tilled soil was thus exposed to the action of steam
146 heat. The bars were drilled and threaded to enable interchangeable nozzles to be used for flow
147 regulation and for maintenance and replacement. The steam flow on the units was fed with hoses
148 connected to a rail for accumulating and distributing steam. For each carter bar, the steam flow
149 could be controlled by a manual valve placed on the common rail. The rotary cultivator was
150 motorised by a hydraulic motor powered by the hydraulic system of the operative machines. The
151 rotary cultivator was divided into three folding parts. The folding system was controlled by two
152 hydraulic pistons powered by the hydraulic system of the tractor. Each of the three parts was
153 equipped with four units and a hopper for the exothermic compound. Each hopper was equipped
154 with a dispenser equipped with an adjustable metering device and four discharge tubes (Fig. 3).
155 This system was powered by an electric motor, thus the correct dose of the exothermic compound
156 was applied on the soil surface in front of each rotary cultivator unit. Since the machine is a
157 prototype, the dispenser has not a distribution mechanism proportional to forward speed. For the
158 purpose of the experimental tests a manual calibration of CaO dose based on machine forward
159 speed was conducted before each band-steaming application. The angular speed of the rotary
160 cultivator varied from 3.14 to 6.28 rad s⁻¹ (30-60 rpm). The function of the multiple rotary cultivator
161 was to incorporate and to mix the steam and the exothermic compound into the tilled soil.

162 The hydraulic system of the operative machine for band steaming consisted in a hydraulic pump
163 powered by the PTO of the tractor, an oil tank, pressure regulators, pressure gauges and the hoses
164 for high-pressure oil, which connected the utilities. An electric generator driven by the PTO of the
165 tractor powered the electric system of the machines. The generator provided electric power for all
166 the auxiliary systems of the steam generator, and for the electric motors of the system for the
167 exothermic compound application.

168

169 **2.2. Machine set up for field application**

170 The machine was coupled to a four-wheel drive tractor with a nominal output of 99 kW. Band-
171 steaming was applied in a 0.18 m wide soil band, corresponding to the intra-row space where, one
172 day after the application of steam, the crop was sown in the middle. The machine was used with 12

173 0.18 m wide units, four units on each of 3 ridges, for a total working width of 4.58 m. Each ridge
174 was 1.28 m wide. The space between ridges was 0.37 m wide, and the space between steamed
175 bands was 0.14 m (Fig. 2). The experiment was carried out using three forward speeds (200, 350
176 and 500 m h⁻¹) which were chosen, based on previous experience (Peruzzi et al., 2011), to obtain
177 responses that could be then analysed and comparable data. Four steam doses (0, 1.11, 1.59, and
178 2.78 kg m⁻²) were applied by combining the constant flow of the steam generator (1200 kg h⁻¹) with
179 the three working speeds (200, 350 and 500 m h⁻¹). The steam doses were calculated as intra-row
180 biological doses applied into the band. The actual doses, computed on the full width of the machine
181 were 0, 0.52, 0.75, and 1.31 kg m⁻², respectively. A CaO intra-band biological dose of 4000 kg ha⁻¹
182 was applied combined with all the intra-row biological steam doses. The actual dose, computed on
183 the full width of the machine was 1886 kg ha⁻¹. The CaO dose was chosen based on previous
184 experience (Peruzzi et al., 2012) such as that which combined with steam gave the highest soil
185 temperatures and weed control values. Lenzi, Lombardi, and Tesi (2004) indicated that CaO can be
186 used in association with steam without production risks, provided that the application dose not
187 exceeds 4000 kg ha⁻¹. In order to exclude problems due to repeated applications and to reduce the
188 cost of the treatment, doses of 1000-2000 kg ha⁻¹ are recommended Lenzi et al. (2004). Mazzoncini,
189 Risaliti, Ginanni, and Mainardi (2002) found that the little variations in soil pH, active calcium
190 carbonate, and conductivity disappear in 15 days after treatment when a CaO dose of 4000 kg ha⁻¹
191 was used in combination with steam.

192

193 **2.3. Experiment set up**

194 The field experiment was carried out in the 2012 carrot-growing season at the experimental farm of
195 the University of Pisa (43°40'N, 10°20'E) located in San Piero a Grado, close to Pisa, in central
196 Italy. The soil type was sandy (ISSS) (75% sand, 13% silt, 12% clay, 2% organic matter, and pH of
197 6.21). The soil water content was 10.3%, expressed as a percentage of wet soil weight. The soil had
198 not been cultivated in the previous five years. Soil tillage included a shallow ploughing (0.25 m
199 deep) and two passes of a rotary harrow. Fertilisation consisted in the application of 40,000 kg ha⁻¹
200 of manure before ploughing. Maestro carrot hybrid F1 was used.

201 Band-steaming was applied on July 2, 2012. Sowing was conducted on July 3, 2012 using a four-
202 row planter with a distance of 0.32 m at a density of 2,000,000 seeds ha⁻¹. The sowing line was at
203 the center of the 0.18 steamed band. Hand weeding was performed 45 days after the band-steaming
204 application (45 DAT) in order to control the emerging weeds in the steamed bands. In order to
205 guarantee the crop yield, hand weeding was necessary because during the crop cycle, carrot is not
206 competitive against weeds. Cultivation was performed in order to control weeds in the inter-band

spaces. Carrot was harvested on October 10, 2012. The crop water requirement was 15 mm of water per week provided by rainfall and/or sprinkling irrigation for the whole growing season.

2.4. Experimental design, treatments, and data collection

The experimental plot size was $15 \times 4.5 \text{ m}^2$. The treatments were arranged in a randomised complete block design with three replications. The treatments consisted of non-steamed bands (control), and band-steaming applied with three different biological doses (1.11, 1.59, and 2.78 kg m^{-2}), resulting in a total of four treatments. The highest dose was chosen to be similar to the dose which led to a satisfactory weed control level in previous studies with a self-propelled machine (Peruzzi, Raffaelli, Frascioni, Fontanelli, & Bàrberi, 2012). The other doses were chosen to ensure a reasonable spread in the abscissa values to ensure that the curve of regression analysis can be determined from the data (Ritz, Kniss, & Streibig, 2015). Moreover, the total fuel consumption when the doses of 1.11 and 1.59 kg m^{-2} were applied were similar to consumptions of Ascard, Hatcher, Melander and Upadhyaya (2007) and Hansson and Svensson (2007) band-steaming machines, respectively.

The use of only four doses was related to the choice of maximise the space available for the study in order to reduce the operation variability of the machine, which has a large working width. Because the machine was a prototype, and its function was tested in a real crop production management, it was more notable to focus on the precision of the treatment along the plots space, instead of considering an additional working speed.

Soil temperatures were measured using type K thermocouples connected to four channel thermometers with a data logger. During the experiments, soil temperatures were recorded at regular intervals of 60 s, during the 3 h following band-steaming. Sensors were placed at a depth of 25 mm, taking care not to interfere with the temperature measurements. Weed density samples were collected 30 days after band-steaming (30 DAT) from a 0.054 m^2 ($0.18 \text{ m} \times 0.30 \text{ m}$) area in nine randomly selected sampling points per plot. The time required for hand weeding was measured for the whole area of the steamed bands (and controls). Weed dry biomass at harvest was measured after collecting weeds from a 0.9 m^2 ($0.18 \text{ m} \times 5 \text{ m}$) area within the middle two steamed bands (and control) of each plot in three randomly selected points. Weeds were cut without roots and dried at 105°C to a constant weight. Carrot yield was determined by collecting samples from a 1.8 m^2 area ($0.18 \text{ m} \times 10 \text{ m}$) within the middle two steamed bands (and controls) of each plot in three randomly selected points.

2.5. Statistical analysis and economic estimate

241

242 Initial testing of the effect of time and replications on the basis of temperatures, and of dose and
243 replications on the basis of weed density, time required for hand weeding, weed density, weed dry
244 biomass at harvest, and carrot yield were analysed for significance by computing the mixed
245 ANOVA by using the R statistical software (R Core Team, 2013) with the extension package
246 *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2014). A significant effect of the steam dose on
247 each dependent variable was observed.

248 The responses of temperature, weeds, time required for hand weeding, and carrot yield to band-
249 steaming were analysed using nonlinear regression analysis of dose-response curves which were
250 fitted using three observations (replicates) per dose. The extension package *drc* (dose-response
251 curves) (Ritz & Streibig, 2005) of R (R Core Team, 2013) was chosen to fit nonlinear regressions,
252 estimate their parameter values, effective doses, and predicted values, and also to plot the
253 distribution of data and regression lines. Akaike Information Criterion (AIC) was used to find the
254 better fit model to the data. The four parameter log-logistic model (Knezevic, Streibig, & Ritz,
255 2007; Seefeldt, Jensen, & Fuerst, 1995) (Eq. 1) resulted in smaller values of AIC compared with the
256 three parameter model for all the dependent variables.

257 Temperatures, weed density, time required for hand weeding, weed dry biomass at harvest, and
258 carrot yield were thus analysed using Eq. 1:

$$Y = C + \frac{(D - C)}{\{1 + \exp[B(\log X - \log E)]\}} \quad (1)$$

260 where (Y) is the response, (C) is the lower limit, (D) is the upper limit, (B) is the slope of the line at
261 the inflection point, (X) is the independent variable, and (E) is the amount of the independent
262 variable giving a 50% response between the upper and the lower limits (also known as the
263 inflection point or ED₅₀) (Seefeldt et al., 1995). For the weed density model, the type=Poisson was
264 set. Although from a biological point of view it would have been better to have not less than 5
265 points, the lower AIC value compared with a three parameter log-logistic model and positive
266 degrees of freedom for the four parameter curve fitting which resulted from variation in the
267 replicates, led to fit the four parameter log-logistic model. All condition for regression were met and
268 a test of lack-of-fit at a 95% level was not significant for any of the dose-response curves tested,
269 which means that the non-linear regression model provides an acceptable description of the data
270 (Ritz & Streibig, 2005).

271 Predicted response values for models were estimated by using the “predict.drc” function in *drc*
272 (Ritz & Streibig, 2005). The ED-levels with the steam dose producing 70%, 80% and 90% weed
273 control in terms of weed density, 10%, 20% and 30% reduction in time required for hand weeding,

274 60%, 70% and 80% weed control in terms of weed dry biomass at harvest, and 2.5%, 5% and 10%
275 yield losses were calculated from fitted dose-response curves (Ritz, Cedergreen, Jensen, Streibig,
276 2006).

277 A ratio test was used to detect differences between the regression parameters and predicted
278 response values of interest (Wheeler, Park, Bailer, 2005). The 95% confidence interval for the
279 means of interest can be calculated as (Eq. 2):

$$280 \quad CI(ratio) = \left(\frac{num}{den}\right) \pm 1.96 \sqrt{\left(\frac{SE(num)}{num}\right)^2 + \left(\frac{SE(den)}{den}\right)^2} \quad (2)$$

281 where *CI* is the confidence interval for the ratio, *num* is the numerator, *den* is the denominator, *SE* is
282 the standard error of the numerator and denominator, respectively, and 1.96 is the critical t-value. If
283 the resulting 95% confidence interval (CI) for the ratio did not cross the value 1, the null hypothesis
284 that compared means were equal was rejected, meaning that the means were different (Ritz &
285 Streibig, 2012). The decision to use a ratio test instead of a CI overlap test was due to the
286 conservative nature of the CI overlap test which would have reduced the ability of the test to detect
287 differences when, in fact, they did occur. The power of the ratio test is greater than that of the CI
288 overlap test (Wheeler et al., 2005).

289 Total prototype estimated cost per use was calculated by taking into account the standard
290 methodology suggested by Hunt (2001) and ASAE (2001). Steaming application costs were
291 calculated by summing the fixed cost to variable costs at different steam doses. The Gross
292 marketable productions (GMP) were obtained multiplying the estimated yields by the carrot
293 saleable value (0.40 € kg⁻¹). Based on the experimental data, an economic margin (EM) was
294 evaluated to find the optimum application dose. Different economic margins were calculated by
295 subtracting the steaming and hand weeding costs from the GMP. The labour costs were a total of 28
296 € h⁻¹ for the two skilled operators performing the steaming application, and 12 € h⁻¹ for hand
297 weeding.

298

299 3. Results

300

301 3.1. Operational characteristics

302 The operating characteristics measured in the field test are shown in Table 2. The operative time
303 required for band steaming was 14.0, 7.9 and 5.8 h ha⁻¹ at the working speed of 200, 350 and 500 m
304 h⁻¹, respectively. The work chain efficiency for all band-steaming applications was always about
305 78% which is good for this kind of application. This was possible thanks to the efficient
306 management of the additional time on the part of two skilled operators and a rational organisation.
307 The effective time was 10.9, 6.2 and 4.4 h ha⁻¹ and the steam boiler fuel consumption was 562, 321

308 and 225 kg ha⁻¹ when the biological steam doses of 2.78, 1.59 and 1.11 kg m⁻² were applied,
309 respectively. Total fuel consumption was 768, 437 and 310 kg ha⁻¹ with a band-steaming machine
310 working productivity of 0.07, 0.13 and 0.17 ha h⁻¹, respectively.

311

312 3.2. Temperature

313 It was found that the log-logistic model explained the temperature in the soil as affected by the time
314 and the different steam doses applied (lack of fit p-value=1.0). The initial temperature of the soil
315 was about 37°C. Generally, the temperature decreased over time at each doses applied (Fig. 4).
316 Maximum ground temperatures were 63 °C, 50 °C and 46 °C when steam doses of 2.78 kg m⁻², 1.59
317 kg m⁻² and 1.11 kg m⁻² were applied, respectively (upper limit of the curve) (Table 3). These
318 temperatures were 1.7-fold, 1.4-fold and 1.3-fold larger than the temperatures of the non-steamed
319 ground, respectively (95% CIs 1.69, 1.73; 1.34, 1.38, 1.24, 1.30, respectively). Minimum
320 temperatures (lower limit of the curve) (Table 3) were similar to temperatures of the non-steamed
321 bands (95% CIs 0.91, 1.48; 0.87, 1.42; 0.84, 1.38). A similar time of about 17 min (95% CI 0.96,
322 1.14) was necessary to reach mean temperatures of 50°C and 42°C, when the steam doses of 2.78
323 kg m⁻² and 1.59 kg m⁻² were applied, respectively (Table 3). With a dose of 1.11 kg m⁻², the time
324 required to reach a mean temperature of 40 °C was 11 min (Table 3), 1.6-fold and 1.5-fold shorter
325 (95% CIs 1.36, 1.87; 1.27, 1.80) than the time required to reach the mean temperatures with doses
326 of 2.78 kg m⁻² and 1.59 kg m⁻², respectively.

327

328 3.3. Weed density, hand weeding, weed dry biomass and yields

329 Weed composition observed in steamed bands 30 DAT comprised 50% graminaceous species, 40%
330 *Verbena officinalis* L. and 10% other species (*Galium verum* L., *Portulaca oleracea* L., *Picris*
331 *hieracioides* L.). On the same date, weed composition in non-steamed bands comprised 25%
332 *Portulaca oleracea* L., 22% *Verbena officinalis* L., 15% *Chenopodium album* L., 13%
333 graminaceous species, 10% *Trifolium* spp. L. and 15% other species. Weed density decreased with
334 increasing steam doses (Fig. 5). 30 DAT, weed density in the non-steamed bands was 73 plants m⁻²
335 (upper limit of the curve) (Table 4). A weed density of 0 plants m⁻² (a p-value of 0.25 suggested that
336 the value -2.79 was not statistically different from 0) was observed in bands steamed with the
337 highest dose (e.g. 2.78 kg m⁻²) (lower limit of the curve) (Table 4). Table 4 shows the estimated
338 steam doses at ED-levels needed to obtain 70%, 80% and 90% weed control in terms of weed
339 density observed 30 DAT. A weed control level of 100% was obtained with a dose of 2.78 kg m⁻².
340 A weed control level of 100% observed 30 DAT did not mean that the seed-bank was completely
341 depleted, indeed, at 45 DAT, hand weeding was also necessary in bands steamed with the highest

dose. Generally, the time required for hand weeding decreased with an increase in steam dose (Fig. 5). Hand weeding in non-steamed bands was on average 47 h ha⁻¹ (upper limit of the curve) and 33 h ha⁻¹ in bands steamed with the highest dose (e.g. 2.78 kg m⁻²) (lower limit of the curve) (Table 4). This suggests that, compared with non-steamed bands, the weed seed-bank of bands where the highest steam dose was applied was reduced. A maximum hand weeding time decrease of 30% was observed when a steam dose of 2.78 kg m⁻² was applied. Table 4 shows the estimated steam doses at the ED-levels needed to obtain 30%, 20% and 10% decreases in hand weeding time. After hand weeding, the weed density observed in both steamed and non-steamed bands was 0 plants m⁻². To take the sequence of weed emergence after hand weeding into account, weed dry biomass at harvest was studied. Carrots were harvested 60 days after hand weeding. Results showed that steam doses influenced weed response to band-steaming (Fig. 5, Table 4). Weed dry biomass at harvest of non-steamed bands was on average 326 g m⁻² (upper limit of the curve), however, this amount was reduced by increasing the steam dose. Weed dry biomass at harvest was 61 g m⁻² (lower limit of the curve) when weeds were steamed with the highest steam dose (e.g. 2.78 kg m⁻²) (Table 4), suggesting again that the weed seed-bank was smaller in bands where the highest dose was applied. Table 4 shows the estimated steam doses at ED-levels needed to obtain 80%, 70% and 60% decreases in hand weeding time. The carrot yield generally increased with an increase in the steam dose (Fig. 5). Yield in non-steamed bands was 10 t ha⁻¹ (lower limit of the curve) (Table 4). Yield in plots steamed with the highest steam dose (e.g. 2.78 kg m⁻²) was 30 t ha⁻¹ (upper limit of the curve) (Table 4). Table 4 reports the estimated steam doses at ED-levels needed to obtain 2.5%, 5% and 10% yield losses. The economic estimate showed that the highest economic margin could be obtained by applying a steam dose of 1.9 kg m⁻², which gave similar estimated yields and hand weeding times compared with the application of a steam dose of 2.78 kg m⁻² (95% CIs 0.99, 1.02 and 0.96, 1.00, respectively) (Table 5).

367

368 4. Discussion

369 Our machine requires less energy and a lower operative time compared with mobile broad-steaming
370 machines (Gay et al. 2010b; Peruzzi et al. 2011). However, the biological results obtained with our
371 band-steaming machine are not directly comparable with that obtained by Gay et al. (2010b) and
372 Peruzzi et al. (2012). Gay et al. (2010b) used a broad steam machine equipped with hoods
373 combined with sub-surface steam injectors. They applied steam for 6, 8 and 10 min on the whole
374 field area using a hood, buried at a depth of 30-40 mm, combined with sub-surface steam injectors.
375 Treatments were carried out five and seven days before transplanting tomato and lettuce,

376 respectively. Weed density collected at the end of the crop cycle was non affected by the duration
377 of steaming and ranged from 0 to 50 plants m⁻² (Gay et al., 2010b). Peruzzi et al. (2012) used the
378 machine improved by Peruzzi et al. (2011) in order to test the effect of broad-steaming on the
379 natural weed seedbank. They found a weed emergence ranging from 0 to 360 plants m⁻² when a
380 steam dose of 2.5 kg m⁻² was added at 4000 kg ha⁻¹ of CaO and applied in soil layers of 0-70 mm.
381 Fennimore et al. (2014) used a mobile steam applicator that physically mixed the steam with the
382 soil as it passed through the shaped planting beds. They found that weed dry biomass collected at
383 the end of the crop cycle ranged from 0.1 to 0.5 g m⁻² with a soil temperature of 70°C maintained
384 for 30 min.

385 In our experiment, a maximum temperature of 63 °C, observed when the highest steam dose (2.78
386 kg m⁻²) was applied, did not deplete the weed seed-bank. However, a significant decrease in weed
387 emergence was observed in bands where band-steaming was applied. This decrease was greater by
388 increasing the steam dose. Steam treatments at 50-60°C for 11 minutes destroy most weed seeds
389 and reduce problems of phytotoxicity and re-infestation which may persist after steaming at higher
390 temperatures (van Loenen et al., 2003). In our experiment an estimated soil temperature of 55°C
391 (± 0.17) was observed 11 min after the application of the dose of 2.78 kg m⁻².

392 Melander and Jørgensen (2005) applied steaming in the laboratory on a limited soil volume
393 collected from the top 100 mm of the soil, and studied the relationship between maximum soil
394 temperature and effects on weed seedling emergence. They found that maximum temperatures
395 slightly above 60°C were necessary to reduce the emergence of natural weed seedlings by at least
396 90% compared with non-steamed soil samples (Melander & Jørgensen, 2005). However, Melander
397 and Jørgensen (2005) state that whether applying steam to bands in the field situation will change
398 the cooling-down periods to an extent where the maximum soil temperature that gives a 90%
399 reduction in seedling emergence should either be increased or lowered to obtain the same kill rate
400 as those estimated in their study.

401 Melander and Kristensen (2011) observed in the laboratory that in sandy soil a maximum
402 temperature of 65.8°C ($\pm 1.11^\circ\text{C}$) needed 7.6 min to cool to 40°C after steaming application. In our
403 experiment a similar maximum temperature of 62.7°C ($\pm 0.34^\circ\text{C}$) needed an estimated time of 48.7
404 min ($\pm 1.16^\circ\text{C}$) to cool to 40°C post steaming. This was probably because the addition of 4000 kg
405 ha⁻¹ CaO extended the cooling-down period by 84% compared with the cooling-down period found
406 by Melander and Kristensen (2011). Elsgaard et al. (2010) applied band-steaming in a field study
407 using a prototype with steaming tines that injected the steam produced by a 200 kW (720 MJ h⁻¹)
408 steam generator at a depth of 50 mm. They found that the temperature decreased from about 75°C
409 to 45°C in 8 min.

410 The function of the machine was regular along the plots space and results showed how the
411 increasing of steam dose was related with the reduction of weeds and time for hand weeding, and
412 with the increasing of yield related probably with a lower presence of weeds during the critical
413 period for weed control. Yields increased by increasing steam doses probably because higher doses
414 reduced the emerging weeds during the first 45 days of the crop cycle (until hand weeding), thus
415 decreasing weed/crop competition. With a mean steam dose of 2.3 kg m^{-2} , resulting in 90% weed
416 control in terms of weed density observed 30 DAT and 70% weed control at harvest, the estimated
417 carrot yields ranged from 29.7 to 30.5 t ha^{-1} and were similar (95% CI 0.99, 1.02) to the highest
418 yields (from 29.7 to 30.6 t ha^{-1}) observed when a steam dose of 2.78 kg m^{-2} was applied. The same
419 steam dose of 2.3 kg m^{-2} reduced hand weeding times by 30% because the estimated time for hand
420 weeding (from 32.2 to 33.2 h ha^{-1}) at a mean dose of 2.3 kg m^{-2} was similar (95% CI 0.98, 1.03) to
421 the observed time for hand weeding (from 31.9 to 33.1 h ha^{-1}) when a dose of 2.78 kg m^{-2} was
422 applied. Hansson and Svensson (2007) found a 65% decrease in the times required for hand
423 weeding compared with non-steamed plots, when a maximum temperature of 86°C was measured
424 in the steamed bands. Fennimore et al. (2014) observed a decrease in time for hand weeding
425 ranging from 25% to 93%, when a temperature of 70°C was maintained for 30 min in the steamed
426 raised beds.

427 From the log-logistic model used for the analysis of data the maximum biological responses derived
428 from using the band-steaming machine, in soils with similar characteristics to those of this study,
429 could be obtained by calibrating the biological steam dose at 2.3 kg m^{-2} . This means regulating the
430 working speed of the machine at 240 m h^{-1} , for 8.6 h ha^{-1} and steam boiler consumption of 442 kg
431 ha^{-1} . These values are similar to those reported by Hansson and Svensson (2007) who used 485 kg
432 ha^{-1} of diesel fuel and 8 h ha^{-1} of labour in order to obtain a 90% weed control within the steamed
433 bands. The estimated steam doses have a little variation due to the estimated confidence intervals,
434 and the upper limit of the estimated dose of 2.3 kg m^{-2} is close or similar to the maximum steam
435 dose applied (2.78 kg m^{-2}). Fitting a four-parameter model with four points and three replicates for
436 each point is correct from a statistical point of view because the degrees of freedom are positive.
437 Focusing on three driving speeds to ensure the optimal functioning of the prototype in a real field
438 condition, and losing in part the accuracy that would have had a regression with five points, the
439 interpretation of the predicted values from the model used in this study can be still considered
440 reliable from a biological point of view. However, in the weed literature authors who studied the
441 effects of herbicides or thermal means used five or more doses to fit a four-parameter log-logistic
442 model (Ascard, 1994; Hansson & Ascard, 2002; Odero, 2012; Ulloa et al., 2011; Wehtje, Gilliam &
443 Marble, 2010). Thus, for biologically related reasons it is always better to consider a minimum of

444 five doses for modelling four-parameters regressions. In our study the application of five doses was
445 not planned because we focused mainly on the functioning of the prototype, which worked
446 continuously at constant speed for a long time, and the surface for the test was a limitation due to
447 the wide area worked with the prototype.

448 Concerning the economic estimate, the dose giving the highest estimated economic margin (1.9 kg m^{-2})
449 m^{-2}), the estimated weed control 30 DAT was 85%, 6% lower than the estimated weed control at the
450 dose of 2.3 kg m^{-2} . Considering the importance of reducing progressively the seed-bank of the soil,
451 authors suggest an application dose not less than 2.3 kg m^{-2} , which however resulted in an
452 economic margin reduction of only 0.9% compared with the application of a steam dose of 1.9 kg m^{-2} .
453 m^{-2} .

454

455 **5. Conclusions**

456 Band-steaming uses less energy and is quicker than broad-steaming techniques. Lower energy
457 consumption is attractive for organic as well as conventional farming systems. Applying steam in
458 bands reduces laborious intra-row hand weeding where herbicides are not used, meeting not only
459 the organic requirements but also making the technique feasible for conventional growers. The high
460 fuel consumption is a critical point of the prototype. Future researches are necessary in order to
461 improve the steam generation system and the efficiency in steam distribution and incorporation into
462 the soil in order to achieve higher temperatures and smaller fuel consumptions. Future and specific
463 studies are also needed to validate our biological results by using more than five doses, once the
464 steaming system will be optimised. The prototype band-steaming machine was powered by fossil
465 fuel, however it would be possible to convert the engine for alternative fuels (e.g. biofuel,
466 ammonia), thus improving energy consumption and lowering the environmental impact.

467

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Figure captions

Fig. 1 - Band-steaming machine.

Fig. 2 - Rear view of the band-steaming machine.

Fig. 3 - Distribution and incorporation of the exothermic compound into the soil.

Fig. 4 - Influence of band-steaming on soil temperature ($^{\circ}\text{C}$) as affected by steam dose (0, 1.11, 1.59 and 2.78 kg m^{-2}) and time. A CaO dose of 4000 kg ha^{-1} was applied combined with the steam doses of 1.11, 1.59, and 2.78 kg m^{-2} . The regression lines are plotted using Eq. (1), and the parameters are presented in Table 3.

Fig. 5 - Influence of band-steaming on weed density (plants m^{-2}) observed 30 DAT, hand weeding time (h ha^{-1}) performed 45 DAT, weed dry biomass (g m^{-2}) at harvest and yield (t ha^{-1}) as affected by steam dose. The regression lines are plotted using Eq. (1), and the parameters are presented in Table 4.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Tables

Table 1 - Main characteristics of band-steaming machine

Characteristics	Unit	Value
Length	m	5.0
Width max	m	5.1
Height	m	2.7
Weight	kg	3000
Band width	m	0.18
Number of steaming units		12
Capacity reaction hoppers	m ³	0.27
Capacity water tanks	m ³	1.60
<i>STEAM GENERATOR:</i>		
Effective flow	kg h ⁻¹	1200
Power	MJ h ⁻¹	3265
Fuel consumption	kg h ⁻¹	51.5
Max. pressure	MPa	1.18

Table 2 - Performance of band steaming machine

Operational characteristics	Unit	Values		
Working depth	m	0.10		
Working width	m	4.58		
Driving speed	m h ⁻¹	200	350	500
Effective time	h ha ⁻¹	10.9	6.2	4.4
Additional time	h ha ⁻¹	3.1	1.7	1.4
Operative time	h ha ⁻¹	14.0	7.9	5.8
Work chain efficiency	%	78	78	76
Working productivity	ha h ⁻¹	0.07	0.13	0.17
Tractor fuel consumption	kg ha ⁻¹	206	116	85
Steam boiler consumption	kg ha ⁻¹	562	321	225
Total fuel consumption	kg ha ⁻¹	768	437	310

Table 3 - Regression parameters for temperature (°C) as affected by time (min) at four steam doses applied (0, 1.11, 1.59 and 2.78 kg m⁻²). A CaO dose of 4000 kg ha⁻¹ was applied combined with the steam doses of 1.11, 1.59, and 2.78 kg m⁻².

Dose of steam (kg m ⁻²)	Regression parameters (±SE)			
	B ^[a]	C ^[b]	D ^[c]	E ^[d]
2.78	1.9 (0.05)	36.7 (0.10)	62.7 (0.34)	17.6 (0.35)
1.59	1.9 (0.10)	35.3 (0.10)	49.6 (0.35)	16.7 (0.64)
1.11	1.5 (0.13)	34.3 (0.12)	46.4 (0.55)	10.9 (0.85)
0	2.7 (0.74)	30.8 (3.77)	36.6 (0.10)	194.4 (83.0)

^[a] B = slope of the curve at the inflection point.

^[b] C = lower limit. The value of C is the temperature at 180 min.

^[c] D = upper limit. The value of D is the temperature at 0 min.

^[d] E = time (min) resulting in a 50% response between the upper and the lower limit.

Table 4 - Regression parameters for weed density observed 30 DAT, hand weeding, weed dry biomass observed at harvest and yield as affected by steam dose; steam doses (kg m^{-2}) needed to obtain 70%, 80% and 90% weed control expressed as weed density, 10%, 20% and 30% reduction in hand weeding, 60%, 70% and 80% weed control expressed as weed dry biomass, and 2.5%, 5% and 10% losses in carrot yield.

Variable	Regression parameters ($\pm\text{SE}$)				Steam dose ($\pm\text{SE}$)		
	B ^[a]	C ^[b]	D ^[c]	E ^[d]	(kg m ⁻²)		
Weed density (plants m ⁻²)	2.6 (0.52)	-2.8 (2.43)	72.5 (2.84)	1.0 (0.05)	70% weed control 1.4 (0.08)	80% weed control 1.7 (0.16)	90% weed control 2.3 (0.34)
Hand weeding time (h ha ⁻¹)	6.1 (0.65)	32.5 (0.28)	46.6 (0.26)	1.2 (0.02)	10% reduction 1.0 (0.02)	20% reduction 1.3 (0.03)	30% reduction 2.5 (0.21)
Weed dry biomass (g m ⁻²)	2.5 (0.13)	60.8 (4.18)	325.5 (1.17)	1.1 (0.01)	60% weed control 1.7 (0.05)	70% weed control 2.3 (0.11)	80% weed control 5.8 (0.57)
Yield (Mg ha ⁻¹)	-5.4 (0.83)	9.6 (0.20)	30.2 (0.23)	0.9 (0.02)	2.5% loss 1.7 (0.12)	5% loss 1.5 (0.07)	10% loss 1.3 (0.04)

^[a] B = slope of the curve at the inflection point.

^[b] C = lower limit.

^[c] D = upper limit.

^[d] E = dose of steam resulting in a 50% response between the upper and the lower limits.

Table 5 – Yields, hand weeding time and economic margin (EM) calculated by subtracting from the Gross marketable production (GMP) the costs of steaming and hand weeding at different steam doses.

Steam dose (kg m ⁻²)	Yield (t ha ⁻¹)	Hand weeding (h ha ⁻¹)	GMP (€ ha ⁻¹)	Steaming (€ ha ⁻¹)	Hand weeding (€ ha ⁻¹)	EM (€ ha ⁻¹)
0.00	9.62	46.65	3848	0	560	3288
1.11	24.68	40.34	9873	1107	484	8283
1.59	29.17	34.21	11667	1321	411	9936
1.90	29.80	33.10	11920	1454	397	10069
2.30	30.10	32.70	12040	1666	392	9981
2.78	30.16	32.53	12063	1896	390	9976