Received: 19 June 2021 | Accepted: 23 June 2021

DOI: 10.1111/wre.12496

ORIGINAL ARTICLE

WEED RESEARCH An International Journal of Weed Biology, Ecology and Vegetation Management WILEY

Effects of band steaming on weed control, weed community diversity and composition and yield in organic carrot at three Mediterranean sites

Stefano Carlesi[1] | **Luisa Martelloni**[2] | **Federica Bigongiali**[1] | **Christian Frasconi**[2] | **Marco Fontanelli**[2] | **Paolo Bàrberi**[1]

[1]Group of Agroecology, Institute of Life Sciences, Scuola Superiore Sant'Anna, Pisa, Italy

[2]Department of Agricultural, Food and Agro-Environmental Sciences, Università di Pisa, Pisa, Italy

Correspondence
Stefano Carlesi, Group of Agroecology, Institute of Life Sciences, Scuola Superiore Sant'Anna, Piazza Martiri della Libertà 33, 56127 Pisa, Italy.
Email: s.carlesi@santannapisa.it

Funding information
Ministry of Agricultural, Food & Forestry Policies of the Italian Republic

Subject Editor: Marleen Riemens, Wageningen University and Research Centre, Lelystad, The Netherlands

Abstract

Band steaming is a non-chemical weed control method of increasing interest for highly remunerative, low competitive crops. This study aimed to test the field application of a new prototype of band-steaming machine in three organic fields under contrasting Mediterranean environmental conditions. Trials were conducted in carrot under real-field conditions to investigate the effects of three steaming doses and one control (no steaming) on weed vegetation and crop yield. Soil temperature at steaming application, weed density at species level during carrot crop growth, and weed and carrot biomass at harvest were sampled at each site. Band steaming significantly affected total weed density: when comparing the untreated control with the highest steam dose, weed density reduction ranged from 62% (−492 plants m^{-2}) at site II to 94% (−146 plants m^{-2}) at site III. Generally, diversity of weed communities decreased with increasing steaming dose, indicating a progressive species filtering effect: *Fumaria officinalis* L. and *Sonchus oleraceus* L. were filtered by steaming application at site I, while *Polygonum lapathifolium* L. and *Portulaca oleracea* L. were filtered at sites II and III. Weed community composition was affected by steaming dose at two sites out of three. Small seeded species (seed mass <1.5 mg) were less tolerant of steaming than species with large seeds. Through reduction in weed density, steam application gave carrot a competitive advantage, increasing fresh yield from 47% at site III (+3,646 g m^{-2}) to 92% at site II (+1,866 g m^{-2}), compared with yields at non-steamed plots.

KEYWORDS

alpha-diversity, functional trait, seed size, soil texture, thermal weed control

1 | INTRODUCTION

Soil steaming is an old technology that has been recently rediscovered thanks to the increasing environmental and health concerns associated with use of chemical soil biofumigants. Besides its effect against soil borne pests and diseases (Luvisi et al., 2015), soil steaming is considered a promising method to control weeds, even if, due to the absence of selectivity between weeds and crop, it can be used mainly as a pre-emergence method. Concerns were raised about possible side effects on soil biota like reducing temporarily the presence of nitrifying bacteria, that may strongly affect their community structure (Roux-Michollet et al., 2008), or select heat-tolerant potential pathogen biota (Altenburger et al., 2014). Other concerns were raised about a significant inhibition of enzyme activities and fungal propagules (Elsgaard et al., 2010). Anyway, the same authors stated that those side effects should not disqualify this technique for application in organic farming, and if we consider band application, those side effect should be looked with less concerns (Elsgaard et al., 2010). Steaming can cause a high mortality of weed seeds, including dormant ones (Bàrberi et al., 2009; Melander and Jørgensen, 2005; Peruzzi et al., 2012), which could lead to effective long-term weed control through weed seedbank management.

To increase steam effectiveness on weed seed devitalisation, use of exothermic compounds allowed in organic farming such as calcium oxide (CaO), able to prolong duration of high temperatures (Dahlquist et al., 2007), has been successfully tested. In the case of broadcast soil steaming, an application rate of 4,000 kg ha^{-1} CaO was found optimal (Bàrberi et al., 2009). Use of CaO in conjunction with steaming may also stimulate the availability of nutrients such as K^+, NH_4^+ and NO_3^- (Gelsomino et al., 2010), and may increase soil pH temporarily (Tesi et al., 2007).

Carrot is a crop characterised by low competitive ability against weeds, therefore any method able to reduce weed density in the early crop growth stages is of strategic importance. As such, soil steaming may be a promising method to be applied in carrot production systems. However, high application cost, high fuel consumption and low work capacity are considered the main limits of broadcast soil steaming (Peruzzi et al., 2017). To reduce these drawbacks, band steaming was proposed by Melander and Jørgensen (2005) and by Peruzzi et al. (2012). A dedicated band steaming prototype has been recently designed and built at the University of Pisa, Italy and tested at a single site (Raffaelli et al., 2016). Results showed significant reduction in weed biomass (−74%), in time needed for hand weeding (−30%), and an increase in carrot yield (+313%) when comparing the maximum steam dose (2.78 kg m^{-2}) with the untreated control. Despite a clear reduction in diesel fuel consumption, compared to broadcast soil steaming, heavy dependence on energy input remains a main issue (Raffaelli et al., 2016).

To increase effectiveness, some authors considered the peak temperature reached by steaming to be more important than heat duration (Melander and Jørgensen, 2005; Melander and Kristensen, 2011), while others claimed that a longer duration of high temperatures (between 50 and 60°C) in soil may compensate for a lower peak temperature (Dahlquist et al., 2007). However, variable effects are expected on individual species depending on their sensitivity to heat (Melander and Kristensen, 2011; Peruzzi et al., 2012; Vidotto et al., 2013). This evidence suggests that steaming may select species according to their capacity to escape the effect of steaming application, due e.g. to seed morphological and physiological traits. Vidotto et al. (2013) found that seed mass was inversely correlated with sensitivity to the thermal treatment while Zhang et al. (1998) found that seed mass positively correlated to the maximum depth for seed to emerge. However, only few studies have considered the effect of steaming on weed diversity or composition in field trials (Bàrberi et al., 2009; Peruzzi et al., 2012).

Soil characteristics, like texture, are expected to influence soil steaming effectiveness. According to Melander and Kristensen (2011), sandy soils need more time to reach a given temperature when steam is applied but, in these soils, steam can spread more easily than in fine textured soils, thus increasing the overall effectiveness of the treatment.

Soil steaming may also stimulate weed germination of certain species, thanks to increased nutrient availability. Sub-lethal steaming doses may favour dormancy breaking, as suggested by Vidotto et al. (2013). Despite the indirect evidence that soil steaming can affect weed diversity and community composition, few experiments have been conducted to evaluate these effects under band steaming.

The aim of this study was to evaluate the effects of band steaming applied with a new prototype (Raffaelli et al., 2016) in three commercial farms with different soil and climate conditions. Tests were conducted in organically cultivated carrot fields, where weed management follows the usual farmer practices, to investigate the effect of applying steaming at different doses on the dynamics of weed communities and on crop biomass. The research hypotheses were:

(i) By reducing weed density, band steaming application will determine a competitive advantage for carrot and hence higher yield. This effect should be proportional to the steaming dose applied.
(ii) By acting as species filter, band steaming will reduce weed community alpha diversity (plot level) and gamma diversity (field level).
(iii) Band steaming affects weed species differently depending on biological and ecological traits related to their persistence in the agroecosystems, seed dimension and maximum depth of emergence. In particular, we hypothesised that large seeded species are less sensitive to steam application than small seeded ones.

2 | MATERIALS AND METHODS

2.1 | Setup of the band-steaming machine

The band-steaming machine used in this study is a prototype designed and built at the University of Pisa, whose technical details are thoroughly explained in Raffaelli et al. (2016). Briefly, the prototype consists of (a) a chassis with two pneumatic wheels that supports devices and equipment, (b) an industrial steam generator, and (c) a system for application of steam and of an associated exothermic compound ('Bioflash system', Peruzzi et al., 2011). The steam application system consists of 12 power take off-driven small rotary hoe implements each 0.18 m wide, placed on three foldable sections at a distance of 0.14 m, working at a depth of 0.10 m. Each section includes four small rotary hoe implements for a total working width of 4.58 m (Figure 1). The machine was coupled with a four-wheel drive tractor with a nominal output of 110 kW. The steam generator (200 kW of nominal output) energy consumption applied at band was lowered by 43.8% compared to the theoretical full rate application.

2.2 | Study sites and experimental setup

Experiments were conducted in 2012 at three sites located in Central Italy (sites I and II) and North Italy (site III). Sites I and II were located at Torre in Pietra (41°53′N, 12°13′E) and Maccarese (41°49′N, 12°14′E), respectively, while site III was located at Comacchio (44°43′N, 12°12′E).

At site I the soil was loamy (50% sand, 30% silt, 20% clay, 2.5% organic matter, pH 7.5), and carrot F1 hybrid 'Laguna' was used. At site II the soil was sandy (89% sand, 6% silt, 5% clay, 0.7% organic matter, pH 8.1), and carrot F1 hybrid 'Maestro' was used. At both sites I and II, soil tillage included chiselling at 0.50 m depth followed by one pass of rotary tiller. Fertilisation at sites I and II consisted in pre-chiselling application of 50 t ha^{-1} of organic manure (80% organic matter, 125 Kg N, 87.5 P_2O_5), 150 kg ha^{-1} of K, 50 kg ha^{-1} of Mg and 210 kg ha^{-1} of S.

At site III the soil was also sandy (90% sand, 6% silt, 4% clay, 1.2% organic matter, pH 8.0). Soil tillage included mouldboard ploughing at 0.40 m depth followed by one pass of a grubber. Fertilisation consisted in pre-ploughing application of 30 t/ha of organic fertiliser

FIGURE 1 Band-steaming machine performing steam application at site I on 4 April 2012

pellet (Prodigy BIOGARD, CBC Europe S.r.l.). Carrot F1 hybrid 'Dordogne' was used.

Band steaming was applied on 4 April 2012, 31 July 2012 and 20 July 2012 at sites I, II and III respectively. Sowing was done on the day after band steaming using a four-row planter with a distance of 0.32 m and a density of 2,000,000 seeds/ha. The sowing line was at the centre of the 0.18 cm wide steamed band. Flame weeding was applied pre-emergence of the crop to devitalise weeds emerged after sowing. Inter-row cultivation and intra-row hand weeding were conducted at 8, 31, 45 and 59 days after band-steaming application (DAS) at site I, 17 and 34 DAS at site II, and 8, 20 and 41 DAS at site III, as standard farmer weed management. Crop water requirement was met by rainfall and sprinkler irrigation. Carrot was harvested on 26 June 2012, 6 December 2012 and 5 December 2012 at sites I, II and III respectively.

2.3 | Experimental design, treatments and data collection

The trials were arranged in a one-way completely randomised blocks design with four treatments and three replicates (blocks). The four treatments were a non-steamed control (representing the standard farmer weed management), and band-steaming application at the three different doses (1.11, 1.59 and 2.78 kg m^{-2}), applied in 0.18 m wide soil bands. Steam consumption, considering the actual field area treated (bands + inter bands), was 0, 5.2, 7.5 and 13.1 Mg ha^{-2} of steam, respectively, corresponding to a diesel fuel consumption of 0, 225, 361 and 592 kg ha^{-1}, respectively, for steam generation. CaO (exothermic compound) was equally distributed to all steamed thesis at a dose of 4,000 kg ha^{-1} in the intra-row space disturbed by the machine, leading to a consumption of 1,886 kg ha^{-1} considering the dose applied at field scale. Plots were 15 m long and 4.5 m wide and comprised 12 carrot rows each.

Soil temperature was measured at 2.5 cm depth, according to Elsgaard et al. (2010) findings, at 60 s. intervals for the 3 hr period following steam application, using four type K thermocouples (PCE-T 390, PCE Inst.) in each plot. At site I temperature data were not recorded to malfunctioning of the thermocouples.

Weed seedlings by species were recorded in nine 0.18 × 0.30 m sampling frames/plot randomly placed over the steamed band (18 cm wide), keeping the 0.30 m of carrot row in the centre of the frame. Weeds were counted before each weeding treatment, whose timing was decided by farmers. Since weed sampling followed an uneven time pattern (8, 31, 45 and 59 DAS at site I, 17 and 34 DAS at site II, and 8, 20 and 41 DAS at site III), and time (DAS) did not explain significantly the weed seedling dynamics, data on weed seedling density, collected at different times, were summed in each sampling plot.

Weed seedling densities were also used to calculate three different weed community diversity indices: species richness (S), Shannon diversity (H′) and Pielou's equitability (J).

Total above ground weed biomass was measured at carrot harvest in three randomly chosen 0.18 × 5 m strips/plot. Only the areas within the steamed bands were considered for weed sampling. Weed biomass was oven-dried at 105°C until constant weight. Carrot total fresh biomass, leaf biomass and root yield were determined at harvest time by collecting samples from three randomly chosen 3.2 m^2 areas/plot (0.32 × 10 m). Biomass data were then averaged at plot level to obtain a single value for each block in each treatment.

2.4 | Statistical analysis

The temporal dynamics of soil temperature were assessed by means of dose-response curves. Non-linear least squares were used to fit the following four-parameter log-logistic model:

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

where Y is the soil temperature (°C), C is the lower asymptote (i.e. the limit temperature when time approaches infinity), D is the temperature at 0 min, B is the slope of the curve at the inflection point, X is time (min), and E is the time needed to yield a 50% response between C and D (also known as the abscissa of the inflection point or ED_{50}) (Knezevic et al., 2007). For each location, Equation 1 was fitted to the observed data for each steam dose, and the fitted curves were used to derive the time required for temperature to reach 60 or 50°C. Model fitting was performed by using the *drc* package (dose-response curves) (Ritz and Streibig, 2005) for R (R Core Team, 2015).

For each parameters of Equation 1 and the time spans, pairwise ratios between the different steam doses and locations were calculated and tested for their difference from one, by using the Wald test, as available in the *comParm*() function in *drc* package (Ritz and Streibig, 2012).

The effect of band steaming on weed community structure was tested by means of a permutational analysis of variance (PERMANOVA; Anderson, 2001) using a matrix dissimilarity based on the Bray-Curtis index. The significance of steam dose, for each site, was tested by means of *F*-tests based on sequential sums of squares from permutations of the raw data (9,999 tries). If in the same location more than two samples had no species, a 'zero-adjusted Bray-Curtis' measure was applied, by adding a dummy species to the every sample unit in that location, prior to calculation of the dissimilarity matrix (Clarke et al., 2006). Sampled permutations were constrained to each block in each location. The diversity matrix was also used to create a multivariate ordination through Non-metric Multi-Dimensional Scaling (NMDS) (1,000 traces, 20 tries). A biplot was produced representing the effect of steaming dose application on weed community structure; sampling areas with no species were removed from the analysis. Species accumulation curves (SAC) were calculated from 100 random permutations of the data for each dose and site (Gotelli and Colwell, 2001). SAC and multivariate analyses were conducted using the *vegan* package for R (Oksanen et al., 2009).

Weed community composition was also analysed through a functional approach (Bàrberi et al., 2018), i.e. weed species were aggregated according to biological and ecological response traits, which could potentially be affected by steam application. For each weed species, the corresponding seed mass and maximum depth of emergence were retrieved using a dedicated weed trait database (Armengot et al., 2016; Bàrberi et al., 2018) and different sources (Appendix S5). Two species (accounting for 21% of total weed seedling density) could not be identified and therefore were excluded from the trait-based analysis.

Three groups of species based on seed mass were selected according to three seed mass clusters: from 0.20 to 0.56 mg (n = 9), from 0.80 to 1.20 mg (n = 5), and from 1.95 to 15.4 mg (n = 8). Two groups were determined according to the maximum depth of emergence: one (n = 5) including species that can emerge from a soil layer deeper than steaming application (>100 mm) and one including species that can only emerge from the shallowest layer, i.e. 0 to 100 mm (n = 17). For each group of species, the ratio (%) of seedlings on the total number of seedlings in each plot was then calculated.

The effect of band steaming on outcome variables, i.e. weed seedling density, weed diversity index, weed biomass at harvest, carrot above ground biomass (leaf biomass), carrot root biomass, carrot number and mean carrot root biomass (the mean weight of each single carrot root) were analysed using linear mixed models. For count data, a generalised linear mixed model was used, adopting Poisson distributions and a log link function, while for continuous variables a linear mixed effect model, assuming Gaussian distribution and an identity link function, was used. A random slope model was adopted for total weed seedling density, while a random intercept model was adopted for species richness, Shannon index and equitability. In all cases, sites and blocks within sites were added as random effects to the models. The observed data were fitted to the following mixed models:

$$Y = b_0 + b_1 X \quad (2)$$

$$Y = b_0 + b_1 X + b_2 X^2 \quad (3)$$

$$Y = b_0 + b_1 \log(1 + X) \quad (4)$$

$$Y = b_0 + b_1 1/(1 + X) \quad (5)$$

where Y is the dependent variable, X is the steam dose, b_0 is the intercept and b_1 is the slope. Random effects were added to all models, as detailed before. For each variable, the models were compared based on the Akaike Selection Criteria.

To calculate the effect of band steaming on the probability of encountering a species belonging to the trait groups studied (i.e. seed mass and maximum germination depth), a generalised linear mixed model (Equation 2) was used, with a binomial distribution and a logit link function. A random intercept model was adopted; sites and blocks within sites were added as random effects to the models.

To study the effect of weed density on yield biomass and the interaction effect between steam dose and seed density, the observed data were fitted to the following mixed model:

$$Y = b_0 + b_1 \log(1+X) + b_2 1/(1+Z) + b_3 XZ \quad (6)$$

where Y is the yield, X is the steam dose, Z is the weed density, b_0 is the intercept, b_1 is the slope for steam dose, b_2 is the slope for weed density, and b_3 the parameter for 'steam dose × weed density' interaction. A random intercept model was adopted, sites and blocks within sites were added as random effects to the models.

The package used was *lme4* (Bates et al., 2014). All analysis were performed using the software R.

3 | RESULTS

3.1 | Soil temperature

Soil temperatures at sites II and III decreased over time for each steaming dose applied (Figure 2). Within each dose, maximum soil temperatures reached were similar between sites (Table 1). When the maximum steaming dose was applied, the time elapsed between maximum T and 60°C was similar at both sites and ranged from 12 to 19 min at site II and from 11 to 20 min at site III. In contrast, when the intermediate and lower steaming doses were applied, the temperature drop from maximum to 60°C was faster at site III than at site II (Table 1). On average, soil temperatures remained in the 50 to 60°C range for 34, 33 and 36 min for the 2.78, 1.59 and 1.11 kg m^{-2} steaming doses, respectively, at site II, and for 27, 17 and 15 min at site III. Soil moisture at steaming application was similar in all three sites (10.2, 9.7 and 12.3% respectively).

3.2 | Total weed seedling density

Nearly all the weed species sampled were annuals; the rare perennial species sampled were individuals originated from seeds.

Soil steaming significantly affected weed seedling density (Table 2). A logarithmic function was the model that better explained steaming dose effect. In sandy soils (sites II and III) weed seedling density was lower than in the loamy soil (site I), with an average total weed seedling density of 55 and 44 plants m^{-2} at sites II and III, respectively, and 674 plants m^{-2} at site I. Weed seedling density decreased significantly already with the lowest steaming dose applied, with a reduction of 60.9 and 82.8% compared to the control at sites II and III respectively. At these sites, weed seedling density reached a plateau also at the lower steam dose (Appendix S1). On the loamy soil (site I), where weeds were much more abundant, the higher steaming dose was necessary to obtain a similar weed seedling density reduction (69.6%).

3.3 | Weed community diversity

Despite a general low weed diversity, 18, 7 and 10 species were found at sites I, II and III, respectively. Overall, weed community alpha diversity (H′, J and S) showed a linear negative trend with steaming dose (Table 2; Appendix S2). Similarly, a dose-dependent filtering effect of

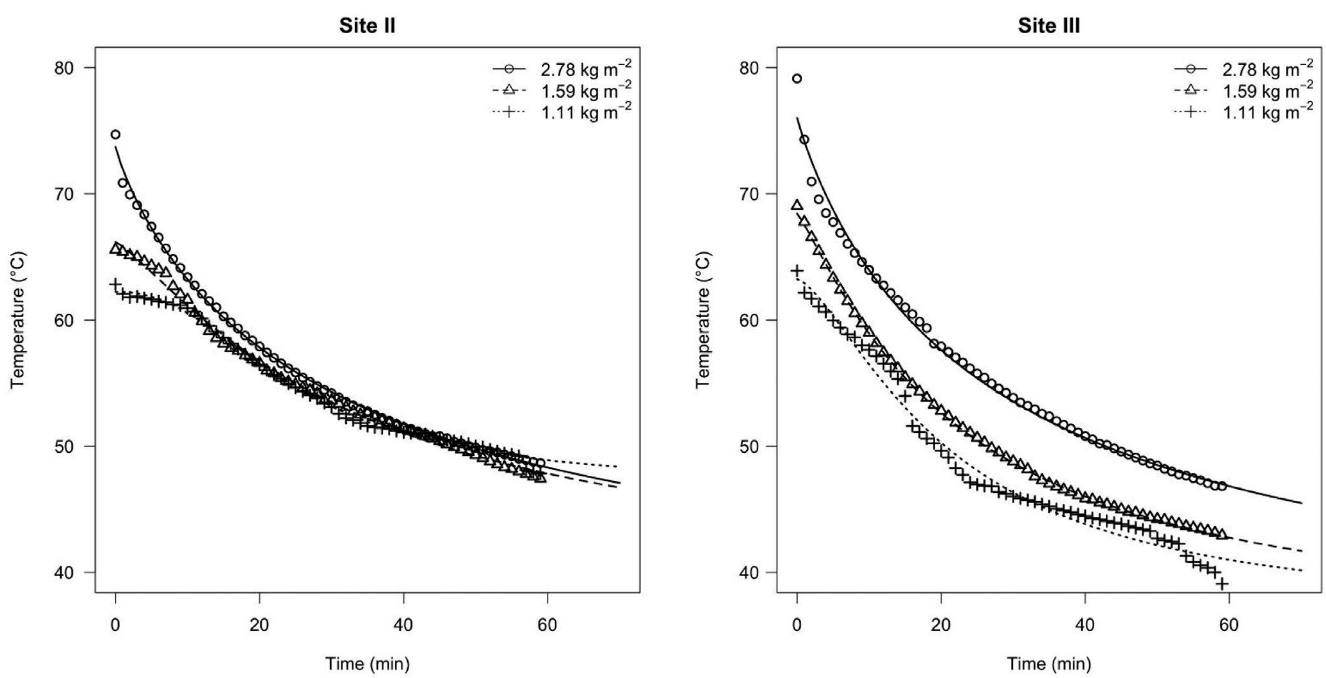

FIGURE 2 Influence of band steaming on soil temperature (°C) at 2.5 cm depth as affected by steam dose (1.11, 1.59 and 2.78 kg m^{-2}) and time after steaming (min) at sites II and III. A CaO dose of 4,000 kg/ha was combined with all steam doses. Temperature of the non-steamed soil was ca. 38°C. Regression lines are plotted using Equation 1 (see text), and their parameters are shown in Table 1

TABLE 1 Regression parameters for soil temperature (°C) as affected by time (min) after steaming for the three steam doses applied (1.11, 1.59 and 2.78 kg m^{-2}) at sites II and III. A CaO dose of 4,000 kg ha^{-1} was combined with all steam doses. Temperature of the non-steamed soil was ca. 38°C. Standard error is shown in brackets

		Regression parameters				Time span (min)	
Site	Steam dose (kg m^{-2})	B[a]	C[b]	D[c]	E[d]	Peak to 60°C	Peak to 50°C
II	2.78	0.9 (0.07)	34.2 (2.92)	73.7 (0.48)	31.2 (4.86)	15.4 (1.68)	49.0 (9.22)
	1.59	1.2 (0.10)	38.7 (2.20)	66.2 (0.31)	33.9 (4.42)	12.4 (0.86)	45.5 (6.87)
	1.11	2.2 (0.17)	47.0 (0.61)	62.2 (0.21)	25.2 (1.05)	11.4 (0.50)	47.1 (3.90)
III	2.78	0.9 (0.14)	32.5 (4.31)	76.0 (1.89)	27.9 (5.19)	15.6 (2.32)	42.6 (9.82)
	1.59	1.2 (0.18)	34.6 (3.18)	68.4 (1.36)	22.4 (3.21)	8.7 (0.95)	26.1 (4.22)
	1.11	1.5 (0.22)	36.1 (2.17)	63.2 (0.95)	21.3 (2.21)	5.5 (0.83)	20.5 (2.06)

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

[b]C = lower limit. The value of C is soil temperature when times approaches infinity.

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

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

TABLE 2 Results of a linear mixed model for seedling density, measuring the effect of steaming dose (Steam) as kg m^{-2} on total weed seedling density (sum of all seedling at m^2 sampled during crop growth), species richness (S), Shannon index (H′), Pielou's equitability (J), carrot fresh biomass, leaf fresh biomass and root number. For each dependent variable, the minimum adequate model selected based on Akaike information criterion is reported as one of the equations presented in materials and methods. Distribution used is reported in square brackets, link function in round brackets

Outcome	Model [distribution] (link function)	Parameters	Estimate	SE	*p*
Total weed seedling density	Eq.4	b_0	8.3305	1.7327	***
	[Poisson]	b_1	2.0349	0.1111	***
	(log)				
Species richness	Eq.2	b_0	1.60345	0.26814	***
(S)	[Poisson] (log)	b_1	−0.29205	0.08832	***
Shannon index	Eq.2	b_0	1.17616	0.25031	*
(H′)	[Gaussian]	b_1	−0.18790	0.25031	**
	(identity)				
Equitability (J)	Eq.2	b_0	4.2716	1.5501	**
	[Gaussian]	b_1	−1.3536	0.6723	*
	(identity)				
Carrot fresh biomass	Eq.4 [Gaussian]	b_0	4201.33	1728.69	
(g m^{-2})	(Identity)	b_1	1958.00	420.80	*
Leaf fresh biomass (g m^{-2})	Eq.4 [Gaussian]	b_0	1219.71	475.00	
	(Identity)	b_1	663.49	184.08	*
Root number	Eq.2	b_0	3.239	0.073	***
(n m^{-2})	[Poisson]	b_1	0.161	0.037	***
	(log)				

Note: A random slope model was adopted for total weed seedling density leaf fresh biomass and carrot fresh biomass, for Root number, S, H′, and J a random intercept model was adopted. In all cases, the sites and blocks within sites were added as random effects to the models; $n = 36$.

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

steaming on weed community gamma diversity, as depicted by Species Accumulation Curves (SAC), was observed (Figure 3). SAC showed that at sites I and II only the highest steaming dose was different from the other treatments. Instead, at site III all steaming doses clearly diverged from the untreated control. Use of the maximum steaming dose resulted in the elimination of the following widespread species: *Fumaria officinalis* L. and *Sonchus oleraceus* L. at site I, *Polygonum lapathifolium* L. and *Portulaca oleracea* L. at sites II and III (Table 3).

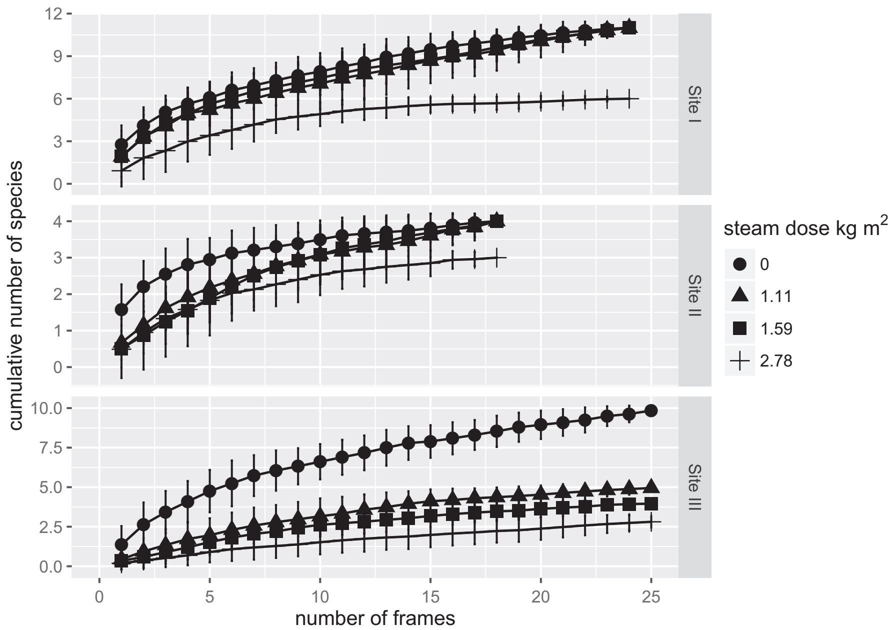

FIGURE 3 Weed species accumulation curves produced by 100 random permutation of sampling areas at sites I, II and III

3.4 | Weed community composition

Results of PERMANOVA (Table 4) showed that at sites II and III weed community composition was affected by steaming dose, unlike site I.

Bi-dimensional NMDS analysis (stress = 0.140, n = 34, two empty samples at site III were removed) confirmed the trend of communities to cluster by site. However, steaming dose also determined a stratification of samples and weed composition (Figure 4). Application of the lower steaming dose resulted in a less characteristic weed composition (as indicated by the proximity to the axes origin), while increasing steaming doses determined a more site-specific weed community assemblage. *P. lapathifolium*, *P. oleracea* and *Solanum nigrum* L. appeared as the species more likely to be present with lower steaming doses.

The analysis of weed community traits showed that the probability to find small-seeded species (seed mass <0.56 mg) decreased at increasing levels of steam application (Equation 2, $b_0 = -0.1635$ SE = 0.340 $p = 0.631$; $b_1 = -0.1230$, SE = 0.0260, $p < 0.001$, estimate on log odds scale, distribution = binomial, link function = logit). Maximum depth of seedling emergence was strongly positively correlated with seed mass (Adjusted $R^2 = 0.76$, $p < 0.001$, df = 20), and species with a maximum emergence depth <80 mm were disfavoured by steaming application dose (Equation 2, $b_0 = 1.79215$, SE = 0.66459, $p = 0.007$, $b_1 = -0.30195$, SE = 0.02968, $p < 0.001$, estimate on log odds scale, distribution = binomial, link function = logit).

3.5 | Crop yield and weed biomass

Steaming doses increased total crop fresh biomass curvilinearly (Equation 4) with increased steaming dose, upon a logarithmic model (Table 2; Appendix S3). Carrot yield was increased by the highest steaming dose by 70.3, 92.2 and 47.7% at sites I, II and III respectively. Carrot leaf biomass (Table 2) increased similarly with steam dose reaching a value 72.4% higher than the control with application of the maximum dose. The number of carrot plants reaching maturity was increased linearly by steam dose; in particular, the highest dose increased values by 64.3, 23.3 and 106.9% at sites I, II and III, respectively, compared to the control. In contrast, mean carrot root biomass (on average 59.5 g carrot^{-1}) was not significantly affected by steaming dose.

Yield data were used to parameterise the effect of weed density steam dose and their interaction on yield (Equation 6). At first, only the effect of weed density was added to the model (i.e. b1 = b3 = 0), which proved to be significant ($p = 0.021$; $b_0 = 5482.78$ and $b_2 = 2419.97$), see also Appendix S4.

When the steam dose was added to the model as fixed effect ($b_3 = 0$), it resulted as the main driver of crop yield (b0 = 4194.98; $b_1 = 1788.47$, $p < 0.001$); in the model with steam dose, weed seedling density still affected yield significantly ($p = 0.027$, $b_2 = 1569.26$). No significant interaction between steam dose and weed seedling density was observed ($p > 0.05$).

Due to intense hand weeding, total weed biomass at harvest was unaffected by the steam dose ($p = 0.633$).

4 | DISCUSSION

As hypothesised (hypothesis 1), steam application gave carrot a competitive advantage over weeds, that led to higher yields. According to van Loenen et al. (2003), steaming treatments reaching soil temperatures of 50 to 60°C for a period of 11 min can kill

TABLE 3 Presence/absence of each weed species found at the three sites in four steam doses

	Site I				Site II				Site III			
	Steam dose (kg m^{-2})				Steam dose (kg m^{-2})				Steam dose (kg m^{-2})			
Species	**0**	**1.11**	**1.59**	**2.78**	**0**	**1.11**	**1.59**	**2.78**	**0**	**1.11**	**1.59**	**2.78**
Amaranthus retroflexus	1	1	1	1	1	1	1	1	1	1	0	0
Anagallis arvensis	0	1	1	1								
Beta vulgaris									1	0	0	0
Brassica oleracea	1	0	0	0								
Chenopodium album					1	1	1	1	1	0	0	0
Convolvulus arvensis					0	0	0	1				
Crepis biennis	0	1	0	0								
Datura stramonium	0	0	1	0					1	0	0	1
Digitaria sanguinalis									1	1	0	1
Fumaria officinalis	1	1	1	0								
Lycopersicon esculentum									1	1	1	1
Lolium spp.	0	0	1	0								
Poa pratensis	0	0	1	0								
Polygonum lapathifolium	1	1	0	0					1	0	0	0
Portulaca oleracea	1	1	1	1	1	1	0	0	1	1	1	0
Senecio vulgaris	1	0	0	0								
Solanum nigrum	1	1	1	1	1	0	1	0	1	1	1	0
Sonchus oleraceus	1	1	0	0								
Spergula arvensis	1	1	0	1								
Stellaria media	0	0	1	0								
Trifolium spp.	0	1	0	0								
Veronica persica	1	0	1	0								
Unknown monocotyledon	1	1	1	1	0	0	1	0	1	0	1	0
Unknown dicotyledon					0	1	0	0				

most seeds. In our experiment, soil temperatures remained in that range from a minimum of 15 min (lowest dose at site III) to a maximum of >30 min (higher doses at sites III and all doses at site II), and all treatments reached the 60°C indicated by Melander and Jørgensen (2005) as the T threshold to obtain 90% weed control. However, only at site III weed seedling density reduction (94%) was comparable to that observed by Melander and Jørgensen (2005). At site II, weed seedling density reduction was only 72%: Our data cannot distinguish which of the two mechanisms (duration of period above 60°C or peak soil temperature) is more important for controlling weed seedling density, since the thresholds of satisfactory weed control for both mechanisms (Loenen et al., 2003; Melander and Jørgensen, 2005) were reached in any treated plot.

Usually, higher weed density is associated with higher weed community diversity (see e.g. site I vs. III in this study, with 18 and 10 species recorded respectively). Higher weed community diversity likely results in a wider range of sensitivity to steaming of component species, which increases the probability of survival for individuals of a larger share of species under lower steaming doses.

Regarding soil texture, higher weed control in sandy soil was also observed by Melander and Kristensen (2011) despite the fact that in such soil high temperatures are retained less. Compared to Elsgaard et al. (2010), in our experiments temperature decay times were longer, and the soil cooled down to 40°C only after 60 min. This is likely due to the addition of CaO (Bàrberi et al., 2009).

Band steaming was able to reduce weed seedling density in the steam-treated plots hence giving a competitive advantage to carrot over weeds. This advantage was given during the critical period for weed control, comprised between 3 and 6 weeks after crop emergence (Swanton et al., 2010). A reduction in weed seedling in steamed plot, reducing the effort for hand weeding (Raffaelli et al., 2016), may also further reduce weed emergence due to lower soil disturbance.

Although other side effects of steaming, like pathogens reduction (Luvisi et al., 2015) or increased nutrient availability

WEED RESEARCH An International Journal of Weed Biology, Ecology and Vegetation Management — WILEY

TABLE 4 Results of permutation multivariate analysis of variance (PERMANOVA) of weed community composition as influenced by steam dose based on 9,999 permutations, stratified by blocks (3) at each site (I, II and III)

Site	Effect	df	R^2	*F*	P (Perm)
Site I	Steam dose	1	0.100	1.114	0.335
	Residuals	10	0.900		
Site II	Steam dose	1	0.179	2.178	0.085
	Residuals	10	0.821		
Site III	Steam dose	1	0.200	2.494	0.025
	Residuals	10	0.800		

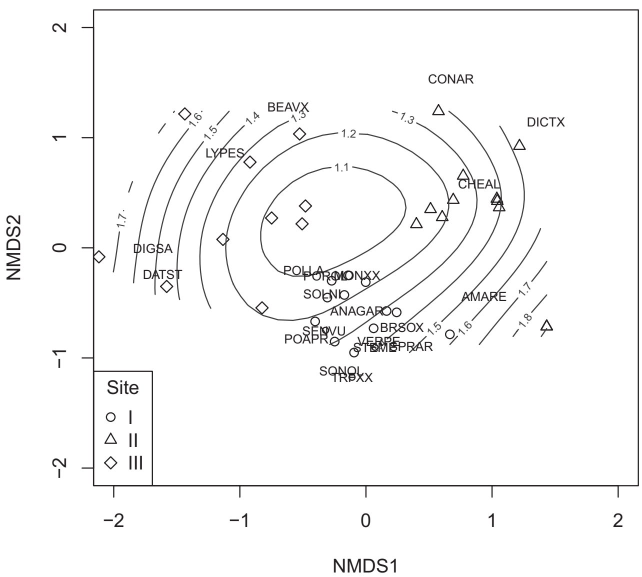

FIGURE 4 Non-metric multidimensional scaling (NMDS) ordination of weed community structure at the three sites. Markers represent sampling areas. Species are presented with their EPPO-Bayer codes (EPPO, 2016) : AMARE, *Amaranthus retroflexus*; ANGAR, *Anagallis arvensis*; BEAVX, *Beta vulgaris* ; BRSOX, *Brassica oleracea*; CHEAL, *Chenopodium album*; CONAR, *Convolvulus arvensis*; CVPBI, *Crepis biennis*; DATST, *Datura stramonium*; DIGSA, *Digitaria sanguinalis*; FUMOF, *Fumaria officinalis*; LYPES, *Lycopersicum esculentum*; LOLXX, *Lolium* spp.; POAPR, *Poa pratensis*; POLLA, *Polygonum lapathifolium*; POROL, *Portulaca oleracea*; SENVU, *Senecio vulgaris*; SOLNI, *Solanum nigrum*; SONOL, *Sonchus oleraceus*; SPRAR, *Spergula arvensis*; STEME, *Stellaria media*; TRFXX, *Trifolium* spp.; VERPE, *Veronica persica*; MONXX, Unknown monocotyledon; DICTX, Unknown dicotyledon. Steam dose values are represented as smooth surfaces (contours). Stress = 0.140; $n = 34$

(Gelsomino et al., 2010) consequent to altered soil micro biota composition (Roux-Michollet et al., 2008) may have contributed to affect carrot yields, no significant interaction between steaming application and weed seedling density on carrot yield was found, suggesting that the reduction of weed seedling density caused by steaming was the main driver of carrot yield. As hypothesised (hypothesis 2), we found a species filtering effect on the expression of actual flora connected with steam application. Since weed seed survival was not studied, the 'filtering effect' is referred to the actual vegetation emerged during crop growth. In particular, we found a significant reduction in alpha and gamma diversity, upon a site-specific pattern. At site I, where the species pool was larger, weed density higher and the soil less sandy, only the higher steaming dose caused a significant filtering effect. At sites II and III, which had similar soil characteristics and weed density, a different effect of steaming on diversity was observed. At site III a clear reduction in both alpha and gamma diversity was found already with the lower steaming dose, whereas at site II, which was quite poor in species, only gamma diversity was reduced and only by the highest steaming dose. Our data support the hypothesis that increasing steaming doses lead to a clear species selection (filtering effect): higher steam doses lead to a reduction of species richness, and to an increase of the relative importance of the surviving species.

Upon hypothesis 3, we expected that steaming would select weed flora based on traits that respond to that type of disturbance. Seed mass was the most important trait related to weed sensitivity to steaming. Two main mechanisms may explain why species with larger seeds have more chance of escaping the effect of steaming: (a) the relationship between seed mass and maximum soil depth for emergence, as large-seeded species are capable of emerging from deeper soil layers (Zhang et al., 1998), that cannot easily be reached by steam-induced heat; (b) smaller seeds need less energy to be devitalised (Vidotto et al., 2013).

Among the 19 species identified, two species represent an exception to the described mechanisms: *P. lapathifolium* and *F. officinalis*. These two species, despite a seed mass higher than the mean of species found (respectively 2.2 and 3 mg) resulted anyway very sensitive to steaming application. The reason for this behaviour is unclear, since seed traits of both species (e.g. coat thickness) should ensure good persistence in soil (Gardarin et al., 2010).

Our work showed the potential of band steaming for in-field weed control and increased crop yield under different soil and climate conditions. Band steaming can be considered an effective technology for reducing weed density in high value organic crops, especially those that are poor competitors against weeds. Despite the reduction of fuel consumption due to band application, the high energy input needed remains a major issue that may limit the spread of this technique. As discussed in Raffaelli et al. (2016), further work is needed on the optimisation of energy used. Another aspect that requires attention is the effect on weed community diversity and composition, since – as shown in the present paper – there are some risks of species selection. On top of this, band steaming effectiveness is clearly dependent on soil texture. In synthesis, where the local species pool is expected to be less sensitive to steaming (e.g. due to higher presence of large seeded species) and the soil texture is heavier, higher steaming doses may be needed to reach acceptable weed control levels. In any case, it is advisable to avoid exerting a strong selection pressure on the weed community, e.g. by alternating and combining the use of band steaming with other suitable techniques as stale seedbed, flaming, pre- and post-emergence mechanical weeding operation.

Future research focusing on the effect of soil steaming should tackle issues like seed dormancy levels and seed traits or attributes linked to survival (e.g. seed coat thickness or ratio of endosperm to total seed mass): this would allow better predictions of weed seed sensitivity to steaming.

ACKNOWLEDGEMENTS

The authors would like to thank the financial support for the COFICO project, funded by the Ministry of Agricultural, Food & Forestry Policies of the Italian Republic, and the farmers Claudio Caramadre and Fabrizio e Giuliano Naldi for their participation in the field experiments, and Dr Gionata Bocci (Scuola Superiore Sant'Anna, Pisa) for statistical advice.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/wre.12496.

ORCID

Stefano Carlesi https://orcid.org/0000-0002-9712-3474
Luisa Martelloni https://orcid.org/0000-0001-6721-0027
Christian Frasconi https://orcid.org/0000-0001-6339-341X
Paolo Bàrberi https://orcid.org/0000-0003-1266-7024

REFERENCES

Altenburger, A., Bender, M., Ekelund, F., Elmholt, S. & Jacobsen, C.S. (2014) Steam-treatment-based soil remediation promotes heat-tolerant, potentially pathogenic microbiota. *Environmental Technology*, 35(6), 773–780.

Anderson, M.J. (2001) A new method for non-parametric multivariate analysis of variance. *Austral Ecology*, 26, 32–46.

Armengot, L., Blanco-Moreno, J.M., Bàrberi, P., Bocci, G., Carlesi, S., Aendekerk, R. et al. (2016) Tillage as a driver of change in weed communities: a functional perspective. *Agriculture, Ecosystems & Environment*, 222, 276–285.

Bàrberi, P., Bocci, G., Carlesi, S., Armengot, L., Blanco-Moreno, J.M. & Sans, F.X. (2018) Linking species traits to agroecosystem services: a functional analysis of weed communities. *Weed Research*, 58, 76–88.

Bàrberi, P., Moonen, A.C., Peruzzi, A., Fontanelli, M. & Raffaelli, M. (2009) Weed suppression by soil steaming in combination with activating compounds. *Weed Research*, 49, 55–66.

Bates, D., Maechler, M., Bolker, B. & Walker, S. (2014) lme4: linear mixed-effects models using Eigen and S4. Available at: http://CRAN.R-project.org/package=lme4 [Accessed 1 August 2018].

BIOGARD®, Europe S.r.lhttp://www.intrachem.it/index.php/it/home-ita/prodotti-nutrizione/nutrizione-concimi-organici/98-prodigy-plant [Accessed 1 August 2018].

Clarke, K.R., Somerfield, P.J. & Chapman, M.G. (2006) On resemblance measures for ecological studies, including taxonomic dissimilarities and a zero-adjusted Bray-Curtis coefficient for denuded assemblages. *Journal of Experimental Marine Biology and Ecology*, 330, 55–80.

Dahlquist, R.M., Prather, T.S. & Stapleton, J.J. (2007) Time and temperature requirements for weed seed thermal death. *Weed Science*, 55(6), 619–625.

Elsgaard, L., Jørgensen, M.H. & Elmholt, S. (2010) Effects of band-steaming on microbial activity and abundance in organic farming soil. *Agriculture, Ecosystems and Environment*, 137, 223–230.

EPPO. (2016) EPPO Global Database. https://gd.eppo.int [Accessed 1 September 2016].

Gardarin, A., Dürr, C., Mannino, M.R., Busset, H. & Colbach, N. (2010) Seed mortality in the soil is related to seed coat thickness. *Seed Science Research*, 20, 243–256.

Gelsomino, A., Petrovičová, B., Zaffina, F. & Peruzzi, A. (2010) Chemical and microbial properties in a greenhouse loamy soil after steam disinfestation alone or combined with CaO addition. *Soil Biology and Biochemistry*, 42(7), 1091–1100.

Gotellli, N.J. & Colwell, R.K. (2001) Quantifying biodiversity: procedures and pitfalls in measurement and comparison of species richness. *Ecology Letters*, 4, 379–391.

Knezevic, S.Z., Streibig, J.C. & Ritz, C. (2007) Utilizing R software package for dose-response studies: the concept and data analysis. *Weed Technology*, 21, 840–848.

Luvisi, A., Panattoni, A. & Materazzi, A. (2015) Heat treatments for sustainable control of soil viruses. *Agronomy for Sustainable Development*, 35(2), 657–666.

Melander, B. & Jørgensen, M.H. (2005) Soil steaming to reduce intrarow weed seedling emergence. *Weed Research*, 45, 202–211.

Melander, B. & Kristensen, J.K. (2011) Soil steaming on weed seedling emergence under the influence of soil type, soil moisture, soil structure and heat duration. *Annals of Applied Biology*, 158, 194–203.

Oksanen, J., Kindt, R., Legendre, P., O'Hara, B., Simpson, G.L., Solymos, P. et al. (2009) *Vegan: Community Ecology Package*. R package version 1.15-4. Vienna: R Foundation for Statistical Computing. Available at: http://CRAN.R-project.org/package=vegan [Accessed 1 August 2018].

PCE-T 390, PCE Inst., Lucca, Italy. Available at: http://www.pce-italia.it/html/dati-tecnici-1/termometro-a-contatto-a-vari-canali-tl-309.htm [Accessed 1 August 2018].

Peruzzi, A., Martelloni, L., Frasconi, C., Fontanelli, M., Pirchio, M. & Raffaelli, M. (2017) Machines for non-chemical intra-row weed control in narrow and wide-row crops: a review. *Journal of Agricultural Engineering*, 48(2), 57–70.

Peruzzi, A., Raffaelli, M., Frasconi, C., Fontanelli, M. & Bàrberi, P. (2012) Influence of an injection system on the effect of activated soil steaming on *Brassica juncea* and the natural weed seedbank. *Weed Research*, 52, 140–152.

Peruzzi, A., Raffaelli, M., Ginanni, M., Fontanelli, M. & Frasconi, C. (2011) An innovative self-propelled machine for soil disinfection using steam and chemicals in an exothermic reaction. *Biosystems Engineering*, 110, 434–442.

R Core Team. (2015) *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. http://www.R-project.org/

Raffaelli, M., Martelloni, L., Frasconi, C., Fontanelli, M., Carlesi, S. & Peruzzi, A. (2016) A prototype band-steaming machine: design and field application. *Biosystems Engineering*, 144, 61–71.

Ritz, C. & Streibig, J.C. (2005) Bioassay analysis using R. *Journal of Statistical Software*, 12, 1–22.

Ritz, C. & Streibig, J.C. (2012) Dose response curves and other nonlinear curves in Weed Science and Ecotoxicology with the add-on package drc in R. Available at: https://www.researchgate.net/file.PostFileLoader.html?id=57ebcf0793553b39505bc8c1&assetKey=AS%3A411294889988097%401475071751844 [Accessed 1 August 2018].

Roux-Michollet, D., Czarnes, S., Adam, B., Berry, D., Commeaux, C., Guillaumaud, N. et al. (2008) Effects of steam disinfestation on community structure, abundance and activity of heterotrophic, denitrifying and nitrifying bacteria in an organic farming soil. *Soil Biology and Biochemistry*, 40(7), 1836–1845.

Swanton, C.J., O'Sullivan, J. & Robinson, D.E. (2010) The critical weed-free period in carrot. *Weed Science*, 58, 229–233.

Tesi, R., Gelsomino, A., Baldi, A., Lenzi, A. & Peruzzi, A. (2007) Soil disinfection with steam alone or combined with CaO in a greenhouse radish crop. *Advances in Horticultural Science*, 21(2), 75–82.

van Loenen, M.C.A., Turbett, Y., Mullins, C.E., Feilden, N.E.H., Wilson, M.J., Leifert, C. et al. (2003) Low temperature-short duration steaming of soil kills soil-borne pathogens, nematode pests and weeds. *European Journal of Plant Pathology*, 109, 993–1002.

Vidotto, F., De Palo, F. & Ferrero, A. (2013) Effect of short-duration high temperatures on weed seed germination. *Annals of Applied Biology*, 163(3), 454–465.

Zhang, J., Hamill, A.S., Gardiner, I.O. & Weaver, S.E. (1998) Dependence of weed flora on the active soil seedbank. *Weed Research*, 8, 143–152.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Carlesi, S., Martelloni, L., Bigongiali, F., Frasconi, C., Fontanelli, M. & Bàrberi, P. (2021) Effects of band steaming on weed control, weed community diversity and composition and yield in organic carrot at three Mediterranean sites. *Weed Research*, 61, 385–395. https://doi.org/10.1111/wre.12496