Weed suppression by soil steaming in combination with activating compounds

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Summary

The aim of this study was to determine the weed suppression potential of soil steaming plus activating compounds (KOH or CaO) to boost soil temperature. Different combinations between the compounds and rates were tested in experiments carried out in the field and in a controlled environment. Treatment effects were assessed on field weed vegetation and on seedbank and seedling emergence of three winter (*Alopecurus myosuroides*, *Matricaria chamomilla* and *Raphanus raphanistrum*) and four spring annuals (*Amaranthus retroflexus*, *Echinochloa crus-galli*, *Fallopia convolvulus* and *Setaria viridis*), were assessed on field weed vegetation. Neither maximum soil temperature (from 72 to 85°C) nor duration of high temperature in the 3 h following application consistently affected weed suppression. In the field, no significant effects on total weed density were recorded, but there were some significant effects on individual species. The weed seedbank was clearly suppressed by activated steaming: total seedling emergence was inversely related to increasing KOH rates both in the 0–10 and 10–20 cm soil layers, while for CaO the relationship was significant only in the 0–10 cm layer. Winter annuals were more sensitive to KOH than CaO and spring annuals had a more pronounced species-specific response to treatments. There was a strong negative relationship between compound rate and seedling emergence for all species. *Alopecurus myosuroides* was the most sensitive to the steam-alone treatment (77% reduction), whereas *M. chamomilla* and *E. crus-galli* were the least sensitive. Results from this study indicate that the type and rates of activating compounds for soil steaming must be adjusted to the weed community composition.

Keywords: integrated weed management, soil disinfection, methyl bromide substitutes, non-chemical weed control, preventive methods, weed seedbank.

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Introduction

Growing societal attention for environmental protection and food safety and the phasing out of methyl-bromide has stimulated research into alternative methods for soil disinfection. Solarisation is a viable alternative in Mediterranean and tropical areas (Sauerborn *et al.*, 1989; Kumar *et al.*, 1993). However, besides its limited use (just in summer months), soil solarisation subtracts vast areas from production for periods up to 3 months (Ricci *et al.*, 1999). Moreover, radiation intensity and the consequent soil temperature increase to a maximum of 55°C at 5 to 10 cm depth for 40 days (an increase of up to 11°C with respect to the non-solarised soil) (Ahmad *et al.*, 1996; Habeeburrahman & Hosmani, 1996; Arora & Yaduraju, 1998) are often insufficient to guarantee good results.

The limits of soil solarisation can be overcome by the use of hot steam, a common practice in greenhouse horticulture, but not yet adapted to large-scale field application. With soil steaming, temperatures of up to 100°C have been registered for about 10 min at 15 cm depth, after which temperature gradually decreased to 40°C (Raffaelli *et al.*, 2002).

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Although steam does not leave any residues, high temperatures can change the physical and chemical characteristics of the soil, causing the formation of toxic substances, e.g. salt accumulation and ammonia formation (Triolo & D'Errico, 2002). Another disadvantage of soil steaming is its non-selectivity, because steaming can also kill the beneficial soil microflora (e.g. nitrifying bacteria, antagonists of soil pathogens and mycorrhizal fungi), thus upsetting the soil ecosystem equilibrium. Alternatively, steaming can be performed at lower temperatures (*c.* 70°C) by including air in the steam stream. A temperature range from 45 to 75°C for 30 min is considered sufficient to control nematodes, most bacterial and fungal pathogens and weed seeds in a single treatment (Triolo & D'Errico, 2002).

For application in the open field, fixed tubes used for steaming in protected environments must be replaced by a machine that injects steam into the soil. While in the case of the fixed-tube system, temperature and duration of the treatment can easily be controlled, in the open field they are dependent on initial soil temperature, moisture and particle size (Melander & Jørgensen, 2005). Only the forward speed of the machine can regulate steaming duration (Tesi, 2001). Therefore, any technical solution increasing the amount of heat released or maintaining high soil temperatures for a longer period is potentially able to increase the effect of steaming. Activating compounds like soil-incorporated fertilisers or amendments can boost soil temperature through a hydration reaction and prolong its duration. These compounds should have low environmental impact and possibly positive side-effects, e.g. the correction of anomalous soil pH values or the addition of nutrients, thus buffering the negative aspects that steam may cause. The use of a polyethylene soil-mulching film laid down just after steaming can also increase the duration of high soil temperature (Habeeburrahman & Hosmani, 1996; Chase *et al*., 1999).

In this study, the machine used for soil steaming was developed by Celli S.p.A. (Forlì, Italy) in collaboration with DAGA, University of Pisa. All operations (distribution and incorporation in soil of the activating compound, steam injection down to 20 cm depth, and placement of the plastic mulch film) are carried out in just one pass (Bàrberi *et al*., 2002; Peruzzi *et al*., 2002). The effect of two activating compounds, potassium hydroxide (KOH) and calcium oxide (CaO), was tested. Both have a low environmental impact and may positively affect soil nutrient status and pH. Following a preliminary field experiment carried out in the spring of 2000, which showed that steaming with a low dose of activating compound (up to 1000 kg ha^{-1} CaO or KOH), with or without a polyethylene cover, did not significantly decrease weed density in lettuce (A. Peruzzi and M. Raffaelli, unpubl. obs.), a new set of experiments was planned both under field conditions and in controlled environment.

We hypothesised that the weed suppression capacity of a specially developed soil steaming machine (Bioflash System™) increases with increasing doses of activating compounds, with and without soil cover. We then tested the effect of increasing doses of CaO and KOH on suppression of the total weed seedbank and on the emergence of seven weed species common in central Italy.

Materials and methods

Experimental designs and samplings

The field experiment was carried out in the autumn of 2000 on a sandy soil with 91.4% sand, 4.0% silt, 4.6% clay (USDA classification) at the Centro Interdipartimentale di Ricerche Agro-Ambientali (CIRAA) 'E. Avanzi' of the University of Pisa at S. Piero a Grado, central Italy (43°40′N; 10°19′E). Soil steaming was performed on 23 October 2000. Characteristics of soil steaming with the Bioflash System™ can be found in Peruzzi *et al.* (2002, 2007). Initial soil humidity and temperature were 3% and 21°C respectively. Just before treatment, the seedbed was carefully prepared to ensure maximum smoothness of the soil surface to increase the steaming effect. No crop was sown after soil steaming. The 2000–2001 winter was characterised by particularly high autumn precipitation, low spring precipitation and relatively high temperatures. The experimental layout followed a factorial combination (split–split–plot design) between two soil cover treatments (bare soil vs. black polyethylene film laid down on the soil straight after steam injection) in the main plots, two activating compounds (KOH vs. CaO) in the sub-plots and five rates of these compounds (0, 1000, 2000, 3000 and 4000 kg ha^{-1}) in the sub-sub-plots, giving a total of 20 treatments replicated six times in plots of 1.2 m width by 5 m length. Two control treatments were added to the non-steamed plots, one with and the other without the black polyethylene film cover. The day after soil steaming, just after removal of the mulch film, the soil was sampled for weed seedbank analysis. Three soil cores of 20 cm depth were taken in each plot with a 3.5 cm diameter manual steel probe and immediately sub-divided into 0–10 and 10–20 cm sub-samples for the assessment of steaming effect on seeds located at different depths. The weed seedbank was analysed with the seedling emergence technique (Bàrberi & Lo Cascio, 2001) during a 6 month period in a semi-open glasshouse, as described in Moonen and Bàrberi (2004). Emerged weed seedlings were periodically identified, counted and then removed. Seedling identification was based on Hanf (1990) and Viggiani and Angelini (1998). Actual weed infestation in the field was measured by counts in two fixed 1 × 0.5 m quadrats per plot carried out 2, 4, 6, 10, 14 and 19 weeks after steaming (T1 to T6; 10 and 23 November 2000, 8 December 2000, 5 January 2001, 8 February 2001 and 15 March 2001 respectively).

The controlled environment experiment was carried out in May 2003 at CIRAA and DAGA, University of Pisa. Treatments were applied in 30 cm square plastic containers with parallelepiped shape and height of 50 cm, in which steam was injected at a depth of 15 cm by means of a specific dispenser. The amount of steam injected was the same as that used for field treatments (Peruzzi *et al.*, 2002, 2004). Effects of steaming were evaluated on weed seeds of three winter annuals (*Alopecurus myosuroides* Hudson, *Matricaria chamomilla* L. and *Raphanus raphanistrum* L.) and four spring annuals [*Amaranthus retroflexus* L., *Echinochloa crus-galli* (L.) P. Beauv., *Fallopia convolvulus* L. and *Setaria viridis* L.]. The experimental layout consisted of a factorial combination (two-way completely randomised design) of two activating compounds (KOH vs. CaO) and four compound rates (1000, 2000, 3000 and 4000 kg ha^{-1}), compared with the steam-only and an untreated control and replicated four times. The activating compounds were mixed with sandy soil to 15 cm depth, while weed seeds were put in permeable small plastic bags (100 seeds 250 cm^{-3} soil) resistant to high temperature and chemical damage, that were placed at 7.5 cm depth. After steaming, the soil and seeds present in the bags was put in plastic tubs (14 × 10.5 × 4.5 cm) in an open glasshouse. Tubs were watered and monitored daily, until (after 40 days) no further seedling emergence occurred.

Soil temperature was monitored at 15 cm depth in the field trial and at 7.5 cm depth in the controlled environment trial by means of PT100 sensors (CEAM control equipment, Empoli, Italy) 4 cm long that sent a voltage signal to data loggers. Temperatures were measured just at the end of the soil steaming treatments and throughout the next 180 min. Values were then allocated to four temperature intervals ($<40°C$; $40 \leq$ temperature $< 60°C$; $60 \leq$ temperature $< 80°C$; $\geq 80°C$). Persistence of soil temperature in each of the four intervals and the highest and final (after 180 min) temperature values were calculated to compare the effects of different treatments.

Data analysis

The parameters used for statistical analyses were: (a) weed density, species richness and percentage density reduction with respect to the 'true' control plots at each of the six sampling dates in the field experiment; (b) total weed seedling density emerged from the seedbank at 0–10 and 10–20 cm depths in the field seedbank experiment; and (c) total seedling density by weed species and per cent density reduction with respect to the control in the controlled environment experiment. Seedbank and field weed density and weed biomass subsamples taken in each plot were aggregated and thus considered as replicates. These data and species richness were expressed per square metre. Total and individual weed species densities in the seedbank and field and per cent reduction with respect to the 'true' control plots were square-root-transformed to obtain homogeneous error variances.

Analysis of variance for split–split–plot designs was performed with CoStat (COHORT Software, 2002), on transformed data when necessary. Analysis of variance for a split–plot design was performed on square-root-transformed field weed density data and on non-transformed seedbank densities of the 0–10 and 10–20 cm layers (field experiment) to test the effect of the control treatments without activating compound but with or without soil cover and steam.

In the controlled environment experiment, weed density by species was expressed as percentage of initial seeds that germinated and analysed by two different series of ANOVA: (i) a completely randomised design to compare the nine different treatments with the untreated control, and (ii) a two-way completely randomised design to evaluate the effect of the two different activating compounds at the four rates. Differences between treatment mean values were compared using an LSD test at the 5% significance level, as derived from the appropriate SEDs (Gomez & Gomez, 1984). In the case of data transformation, SEDs and LSDs were calculated on transformed data and back-transformed data are presented in parentheses. Linear regression analysis was performed on total weed seedling emergence from the two soil layers (field experiment) and on individual species emergence (controlled environment experiment) as related to increasing rates of activating compounds.

Results

Soil temperature

In the field experiment, the maximum soil temperature was 75°C in the steam-alone treatment and always $>80°C$ in all other treatments (Table 1). Application of CaO at the highest rate (4000 kg ha^{-1}) resulted in the highest peak and final temperature (85 and 42°C respectively) and in higher duration at high values, always $>40°C$ in the 3 h following soil steaming. These

Table 1 Maximum soil temperature, temperature after 180 min. and average duration of soil temperature in different intervals after treatment with steam alone or in combination with an activating compound (KOH or CaO) applied at 1000 or 4000 kg ha^{-1} in the field experiment (steaming date: 23 October 2000) and in the controlled environment experiment (steaming date: 21 May 2003)

Soil temperature (T)	Treatment				
	Steam alone	Steam + KOH 1000	Steam + KOH 4000	Steam + CaO 1000	Steam + CaO 4000
Field experiment (15 cm depth)					
T max (°C)	75	80	81	80	85
T after 180 min (°C)	37	41	40	39	42
T <40 (min)	58	0	0	19	0
T 40–60 (min)	103	159	151	137	148
T 60–80 (min)	19	17	24	19	25
T >80 (min)	0	4	5	5	7
Controlled environment experiment (7.5 cm depth)					
T max (°C)	46	50	57	57	72
T after 180 min (°C)	44	45	48	45	47
T <40 (min)	10	0	0	0	0
T 40–60 (min)	170	180	178	177	130
T 60–80 (min)	0	0	2	3	50
T >80 (min)	0	0	0	0	0

differences were even more pronounced in the controlled environment experiment, where maximum soil temperature (at 7.5 cm depth) ranged between 46 and 72°C, whereas final temperature ranged between 44 and 48°C. CaO at 4000 kg ha^{-1} was the best treatment to boost the exothermic reaction in soil, as soil temperature remained in the 60 to 80°C interval for 28% of the time in the 3 h following application (Table 1).

Field experiment: effect on actual weed vegetation

The total number of weed species recorded at the six sampling dates (T1 to T6; 2, 4, 6, 10, 14 and 19 weeks after steaming respectively) increased from 10 to 21, and mean species richness increased from 2.7 m^{-2} at T1 to 5.2 m^{-2} at T6. Overall, four species contributed more than 96% to total weed density at all sampling dates: *Veronica hederifolia* L. (46%), *Capsella bursa-pastoris* (L.) Medicus (27%), *Lamium purpureum* L. (24%) and *Lilium* spp. (3%). Of these, only *L. purpureum* was absent at T1.

No significant treatment effects on species richness, other than an activating compound by mulch interaction at T2 and an application rate effect at T3, were found. However, these effects were inconsistent. No significant differences in weed density between the control and steam-alone treatments, with or without black plastic mulch were found. Mean weed density per plot doubled from T1 to T2 (74 to 148 plants m^{-2}) and then fluctuated slightly from T2 to T6. None of the sampling date treatment combinations resulted in a significant decrease in total weed density with respect to the control plots. Mean reductions in weed density for the six sampling dates were: 36% and 29% with and without black plastic mulch film; and 37% and 31% using CaO and KOH; and 24%, 39%, 35%, 29% and 32% using 0, 1000, 2000, 3000 and 4000 kg ha^{-1} of activating compounds respectively.

Treatments never had an effect on *Lilium* spp. density. *C. bursa-pastoris* density was reduced significantly with increasing activating compound rate at T4 (stronger effect of CaO) and an application rate by cover interaction at T6 was found (data not shown). At T2, activating compound and application rate showed a significant effect on *L. purpureum* density and from T3 to T6 there was an interaction between activating compound and application rate for which density of this species decreased using CaO at 1000 and 2000 kg ha^{-1} and increased with respect to the control treatment at the higher compound rates, while it increased with increasing KOH rates (Table 2). For *V. hederifolia* there was a significant effect of application rate from T1 to T5, of activating compound at T5 and of the activating compound by application rate interaction at T6 (stronger effect of KOH, data not shown). At T1, the highest application rate (4000 kg ha^{-1}) reduced *V. hederifolia* density by 60%, while from T2 to T6 all rates (averaged over activating compounds) reduced *V. hederifolia* density with respect to the steam-alone treatment (on average, by 35%, 36%, 45%, 40% and 31% respectively) (Table 3).

Field experiment: effect on the weed seedbank

The total density of weed seedlings emerging from the 0–10 cm soil layer was not affected by any of the four control treatments without activating compound. The mean number of total seedlings emerging from the plots without or with steam treatment was 4417 and

Table 2 Effect of activating compound × rate interaction on square-root transformed field density of *Lamium purpureum* (back-transformed mean values are shown in parentheses) across five sampling dates

Compound	Rate (kg ha^{-1})	Weeks after steaming 4	6	10	14	19
L. purpureum density (plants m^{-2})						
CaO	0	4.1 (16)	5.5 (31)	5.3 (28)	5.4 (29)	4.4 (20)
	1000	3.4 (11)	4.9 (24)	4.3 (19)	4.6 (21)	3.8 (14)
	2000	3.2 (10)	4.4 (19)	4.0 (16)	4.4 (19)	3.9 (16)
	3000	4.3 (18)	5.6 (32)	5.1 (26)	5.4 (29)	4.7 (22)
	4000	4.5 (20)	6.7 (45)	5.8 (34)	6.2 (38)	4.8 (23)
KOH	0	4.1 (16)	5.5 (31)	5.3 (28)	5.4 (29)	4.4 (20)
	1000	5.4 (29)	7.2 (52)	6.5 (42)	6.9 (47)	5.7 (32)
	2000	5.9 (35)	8.3 (69)	8.3 (68)	7.9 (62)	7.3 (53)
	3000	6.4 (41)	9.2 (84)	8.6 (73)	8.7 (75)	7.3 (51)
	4000	6.4 (41)	8.6 (73)	7.9 (63)	8.4 (71)	7.3 (53)
	SED (d.f. = 80)	NS	0.97*	0.88*	0.87*	0.71*

NS, not significant.
*Significant at $P < 0.05$ (*F*-test).

Table 3 Effect of application rate (averaged over two activating compounds) on square-root transformed field density of *Veronica hederifolia* (back-transformed mean values are shown in parentheses) across six sampling dates

Rate (kg ha^{-1})	Weeks after steaming 2	4	6	10	14	19
V. hederifolia density (plants m^{-2})						
0	4.4 (20)	8.4 (71)	9.6 (92)	10.8 (116)	11.5 (133)	9.6 (91)
1000	3.8 (15)	7.0 (49)	8.1 (65)	8.0 (64)	9.2 (84)	7.9 (63)
2000	3.9 (15)	6.8 (46)	7.5 (56)	7.7 (60)	8.7 (76)	7.8 (61)
3000	4.0 (16)	6.9 (47)	7.7 (59)	8.3 (68)	9.1 (83)	8.1 (66)
4000	2.9 (8)	6.5 (43)	7.4 (55)	7.9 (62)	9.0 (81)	7.8 (61)
SED (d.f. = 80)	0.36**	0.52*	0.58*	0.68**	0.64*	0.47*

* and **Significant at $P < 0.05$ and 0.01 respectively (*F*-test).

3840 seedlings m^{-2} respectively. However, seedlings emerging from the 10–20 cm layer were significantly higher in the control plots without steam treatment (7305 seedlings m^{-2}) than in the steam-treated plots (4215 seedlings m^{-2}).

The cumulative number of seedlings per square metre emerging from the 0–10 cm layer showed no effect of soil mulch treatment, but an interaction ($P < 0.01$) between activating compound and application rate (Table 4). Addition of CaO resulted in a decrease in seedling density with respect to the steam-alone treatment only when applied at the highest rate (4000 kg ha^{-1}), while KOH reached this effect at 2000 kg ha^{-1}. In the 10–20 cm layer, the use of activating compounds at any rate reduced ($P < 0.001$) seedling density with respect to the steam-only treatment, up to 30% at 4000 kg ha^{-1} (on average 1917 seedlings m^{-2}).

Figure 1 shows the relationships between KOH and CaO application rate and total weed seedling emergence from the two soil layers. In the 0–10 cm layer, the relationship was significant for both compounds ($r^2 = 0.98$ and 0.89 for KOH and CaO respectively), while in the 10–20 cm layer it was significant only for KOH and not for CaO ($r^2 = 0.87$ and 0.31 respectively). In the 0–10 cm layer, application of the highest rate of KOH resulted in a 76% reduction in total weed seedling density compared with the steam-alone treatment, while the maximum reduction achieved with the highest rate of CaO was 20% (> 3000 seedlings m^{-2} still emerged). The regression equations show that for any additional 100 kg ha^{-1} of activating compound used, KOH caused a reduction of 58 seedlings m^{-2} more than CaO. In the 10–20 cm layer, the highest rate of KOH was able to reduce total weed emergence by 55%

Table 4 Effect of activating compound × rate interaction on square-root transformed total weed emergence from the 0–10 cm soil layer (back-transformed mean values, as seedlings m^{-2}, are shown in parentheses)

Compound	Total seedbank – rate (kg ha^{-1}) 0	1000	2000	3000	4000
CaO	60.8 (3694)	58.4 (3412)	59.3 (3515)	57.9 (3358)	53.9 (2904)
KOH	60.8 (3694)	57.8 (3344)	48.6 (2358)	41.3 (1708)	27.0 (728)
SED (d.f. = 80)	4.72***				

***Significant at $P < 0.001$ (*F*-test).

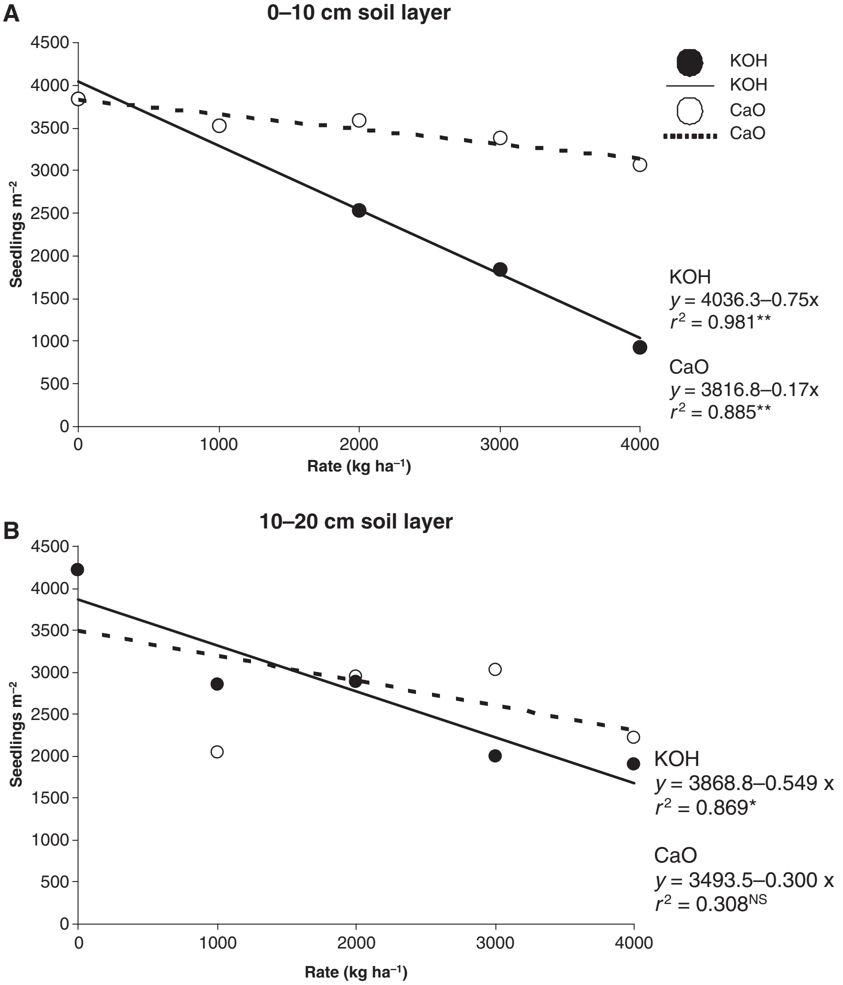

Fig. 1 Regression lines of total weed seedlings emergence from the 0–10 cm (A) and 10–20 cm (B) soil layers on activating compound (KOH or CaO) rate, and corresponding equations and r^2 values. NS, not significant; * and **significant at $P < 0.05$ and 0.01 respectively.

compared with the steam-alone treatment, whereas CaO rates had inconsistent effects on emergence.

A total of 19 and 15 weed species were recorded in the 0–10 and 10–20 cm layers respectively. Seven species, each with a relative abundance >1%, accounted for at least 96% of the total weed seedbank in the two layers: *C. bursa-pastoris* (60% and 59%), *L. purpureum* (12% and 14%), *V. hederifolia* (9% and 11%), *P. oleracea* (8% in each layer), *Sonchus* spp. (3% and 1%), *C. album* (1% in each layer) and *Poa* spp. (1% and 2%).

In the 0–10 cm layer, seedling densities showed a compound by application rate interaction for *C. bursa-pastoris* and a significant compound effect on *V. hederifolia* (32% reduction for CaO vs. 80% reduction for KOH with respect to the steam alone treatment), whereas *L. purpureum* and *P. oleracea* (on average, 191 and 99 seedlings m^{-2} respectively) were not influenced by any of the treatments. Increasing rates of CaO had no effect on seedling density of *C. bursa-pastoris*, while an application rate of 2000 kg ha^{-1} KOH already significantly reduced seedling density with respect to the steam-alone treatment. This effect was stronger with increasing application rates (87% reduction at 4000 kg KOH ha^{-1}). In the 10–20 cm layer, seedling density of *C. bursa-pastoris*, *L. purpureum* and *V. hederifolia* was lower where an activating compound was used, independent of the type of compound, and it was almost significant ($P < 0.10$) for *P. oleracea* (data not shown). Any compound rate significantly decreased seedling densities of all four species with respect to the steam-alone treatment, except for the 2000 kg ha^{-1} rate in the case of *C. bursa-pastoris*.

Controlled environment experiment

Compared with the control, the steam-alone treatment reduced ($P < 0.05$) seedling emergence of *A. myosuroides*, *F. convolvulus* and *S. viridis* (by 77%, 44% and 39% respectively), whereas it was not effective on *M. chamomilla*, *R. raphanistrum*, *A. retroflexus* and *E. crus-galli* (Table 5). Addition of an activating compound decreased weed seedling emergence in all species, with the only exception of *E. crus-galli* when both compounds were used at the lowest rate.

In general, winter annuals showed a higher sensitivity to KOH than to CaO, with emergence reductions from

Table 5 Final percentage seedling emergence of the seven weed species after soil steaming with addition of two activating compounds (KOH and CaO) at four rates (1000 to 4000 kg ha^{-1}) as compared to the steam-alone treatment and the untreated control in the controlled environment experiment

Treatment	ALOMY (d.f. = 24)	MATCH (d.f. = 24)	RAPRA (d.f. = 24)	AMARE (d.f. = 27)	ECHCG (d.f. = 27)	POLCO (d.f. = 27)	SETVI (d.f. = 27)
Control	77.0	82.0	87.0	69.8	89.5	83.0	80.3
Steam alone	17.5	91.0	90.3	59.8	78.0	46.5	49.3
KOH 1000	10.8	37.0	24.0	50.0	74.0	26.8	39.5
KOH 2000	8.8	23.0	10.5	27.0	56.0	22.8	34.0
KOH 3000	5.5	11.0	8.8	25.0	49.8	18.8	28.8
KOH 4000	4.0	3.3	6.0	22.5	17.5	14.5	21.8
CaO 1000	15.8	49.3	41.3	23.5	73.3	26.5	42.8
CaO 2000	12.3	44.5	18.0	17.0	56.0	23.5	29.0
CaO 3000	7.8	36.0	9.5	12.5	46.8	15.3	28.5
CaO 4000	7.0	20.3	7.8	11.8	30.5	7.8	17.8
SED	4.00***	14.21***	7.94***	6.83***	10.59***	4.15***	7.43***

ALOMY, *Alopecurus myosuroides*; MATCH, *Matricaria chamomilla*; RAPRA, *Raphanus raphanistrum*; AMARE, *Amaranthus retroflexus*; ECHCG, *Echinochloa crus-galli*; POLCO, *Fallopia convolvulus*; SETVI, *Setaria viridis*.
***Significant at $P < 0.001$ (*F*-test).

93% to 96% when treated with steam + 4000 kg ha^{-1} KOH vs. 75% to 91% for the corresponding rate of CaO (Table 5). Spring annuals showed a more pronounced species-specific response to treatments: at the highest application rate, *A. retroflexus*, *F. convolvulus* and *S. viridis* were better controlled by CaO than KOH (emergence reduction of 83% vs. 68%, 91% vs. 83% and 78% vs. 73% respectively), whereas *E. crus-galli* showed the opposite behaviour (66% vs. 80%).

These results were largely confirmed by the two-way (compound × rate) analysis of variance, which showed a stronger effect of KOH than CaO on winter annuals (Table 6), whereas for spring annuals the compound effect was significant only for *A. retroflexus* (CaO > KOH). The application rate effect was significant for all the seven weed species, with the two higher rates (3000 and 4000 kg ha^{-1}) that always reduced ($P < 0.05$) seedling emergence compared with the 1000 kg ha^{-1} rate (on average by 42% and 63% respectively). A compound × rate interaction ($P < 0.05$) was found only for *R. raphanistrum*.

Linear regression analyses (Figs 2 and 3) showed a strong negative relationship between compound rate and seedling emergence, which was stronger for KOH in *A. retroflexus* and *S. viridis*, for CaO in *R. raphanistrum*, *E. crus-galli* and *F. convolvulus*, and comparable between the two compounds in *A. myosuroides* and *M. chamomilla*. Regression equations show that for any additional 100 kg of activating compound, seedling emergence was reduced by a quantity ranging between 0.3% and 2%,

Table 6 Final percentage seedling emergence of the seven weed species after soil steaming with addition of two activating compounds (KOH and CaO) at four rates (1000 to 4000 kg ha^{-1}) in the controlled environment experiment. Compound and rate mean effects and two-way ANOVA results

Factor	ALOMY	MATCH	RAPRA	AMARE	ECHCG	POLCO	SETVI
Compound (C)							
KOH	7.3	18.6	12.3	31.1	49.3	20.7	31.0
CaO	10.7	37.5	19.1	16.2	51.6	18.3	29.5
SED (d.f. = 24)	0.84***	3.72***	1.93**	2.89***	6.03 NS	2.17 NS	3.82 NS
Rate (R, kg ha^{-1})							
1000	13.3	43.1	32.6	36.8	73.6	26.6	41.1
2000	10.5	33.8	14.3	22.0	56.0	23.1	31.5
3000	6.6	23.5	9.1	18.8	48.3	17.0	28.6
4000	5.5	11.8	6.9	17.1	24.0	11.1	19.8
SED (d.f. = 24)	1.19***	5.25***	2.74***	4.09***	8.53***	3.06***	5.30**
C × R	NS	NS	3.868*	NS	NS	NS	NS

ALOMY, *Alopecurus myosuroides*; MATCH, *Matricaria chamomilla*; RAPRA, *Raphanus raphanistrum*; AMARE, *Amaranthus retroflexus*; ECHCG, *Echinochloa crus-galli*; POLCO, *Fallopia convolvulus*; SETVI, *Setaria viridis*; NS, not significant.
*,** and ***Significant at $P < 0.05$, 0.01 and 0.001 respectively (*F*-test).

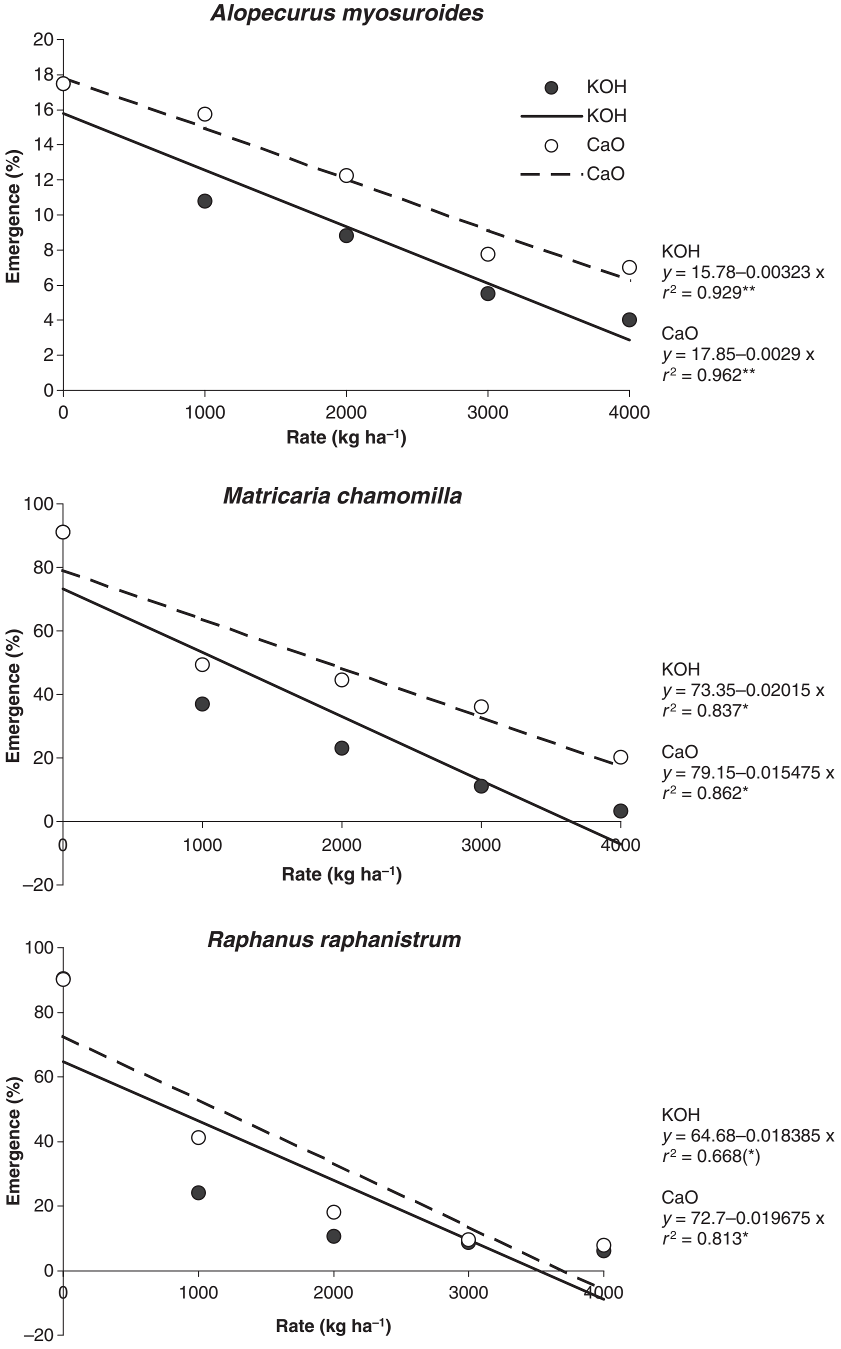

Fig. 2 Regression lines of per cent seedling emergence of the three winter annuals on activating compound (KOH or CaO) rate, and corresponding equations and r^2 values. (*),* and **Significant at $P < 0.1$, 0.05 and 0.01 respectively.

A. myosuroides being the least sensitive species (−0.3% for both compounds) and *R. raphanistrum* the most sensitive one (−1.8% with KOH and −2% with CaO).

Discussion

Soil temperature

The use of activating compounds (especially CaO) at high rates considerably increased the duration of high soil temperatures in both field and controlled environment experiments. Little is known about the effect of maximum soil temperature and duration of heating on seed germination capacity. Horowitz *et al.* (1983) found that temperature varying from 45 to 65°C for 8–10 h day^{-1} during a 2 to 5 week period was sufficient to significantly decrease weed seed germination. Other studies, which focused on the effects of heat from composting and mulching, demonstrated that weed seed germination decreased after 1 to 3 weeks with $T > 46°C$ and that it was almost completely inhibited if temperature exceeded *c.* 60°C (Grundy *et al.*, 1998; Nishida

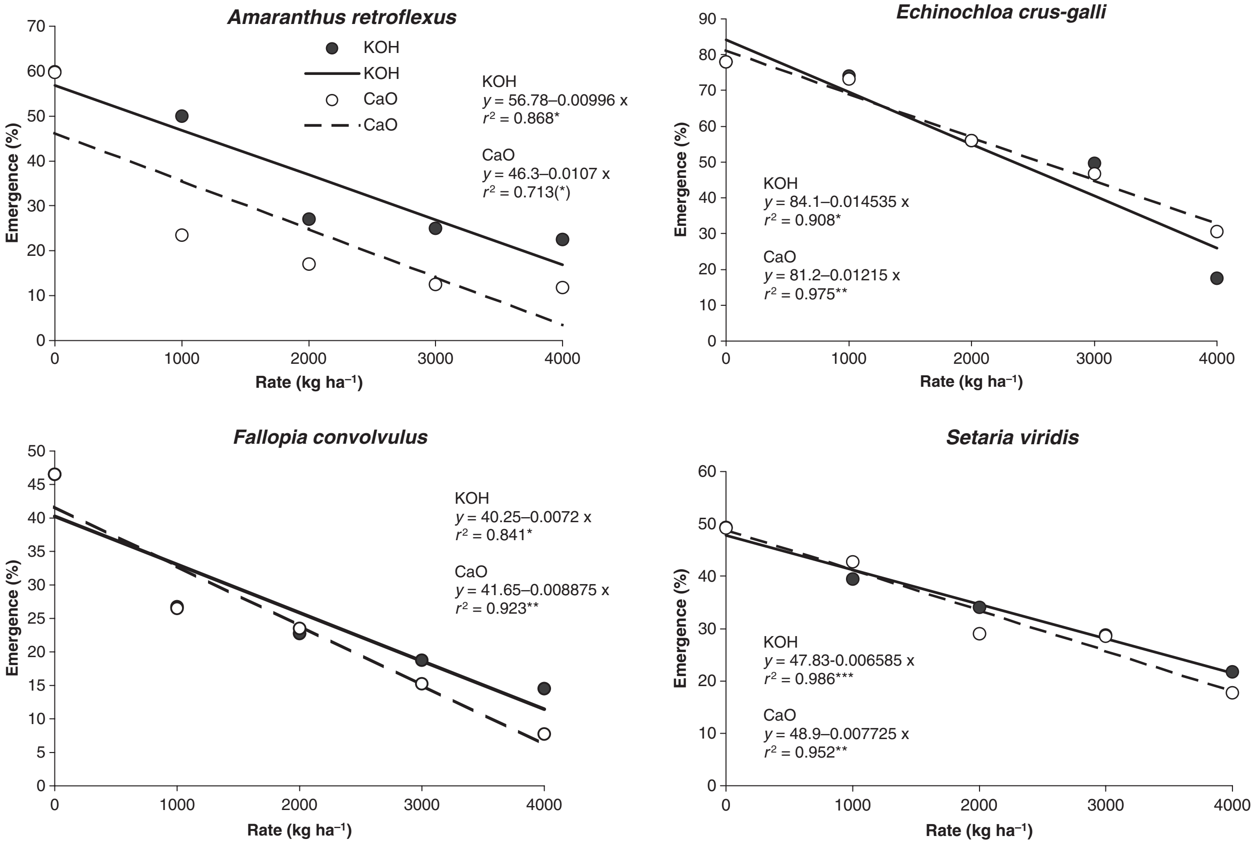

Fig. 3 Regression lines of per cent seedling emergence of the four spring annuals on activating compound (KOH or CaO) rate, and corresponding equations and r^2 values. (*),*,** and ***Significant at $P < 0.1$, 0.05, 0.01 and 0.001 respectively.

et al., 1998; Davis & Liebman, 2003). In the case of soil steaming, the maximum soil temperature reached was found to be more important than the duration in order to decrease seed viability and it differs between species (Thompson *et al.*, 1997). For *C. bursa-pastoris*, a minimum of 70°C is needed, while for *Polygonum* spp. 60°C is sufficient (Melander *et al.*, 2002). *Senecio vulgaris*, *Stellaria media* and *P. annua* could be almost completely controlled by one steaming treatment with a maximum soil temperature > 70°C for a duration of 6 to 9 min at a depth of at least 2.5 cm (Bødker & Noyé, 1994). These data indicate that all steaming treatments performed in October 2000 in this study were sufficient to cause a control effect on at least *C. bursa-pastoris* and most probably also on the other species.

In the controlled environment experiment, KOH reduced seedling emergence of the winter annuals *A. myosuroides*, *M. chamomilla* and *R. raphanistrum* to a greater extent than CaO, despite the fact that soil temperature did not exceed 57°C. In the field experiment, KOH had a stimulating effect on *L. purpureum*, while it suppressed *V. hederifolia*. In contrast, CaO had no effect on *L. purpureum* and suppressed *V. hederifolia*. In the upper seedbank layer, germination of *C. bursa-pastoris* was more inhibited by KOH than by CaO. Although there is basically no information available on this issue, we can hypothesise that site- and species-specific interactions between soil and seed biological characteristics (such as thickness and hardness of the seed coat and seed size) may modulate the weed control effect exerted by increasing soil temperature and activating compounds. The activating compounds can either have a fertilisation effect and thus stimulate germination, or they can have a caustic effect, resulting in an even stronger inhibition of germination. Therefore, maximum soil temperature does not seem to be the only useful parameter for the evaluation of effectiveness of soil steaming. These results are partly in contrast with those of Melander & Jørgensen (2005), who observed that seedling emergence decreased with maximum soil temperature according to a sigmoidal relationship.

Field and controlled environment experiments

During the sampling period (from 2 to 19 weeks after soil steaming), total field weed density did not respond to any of the treatment combinations between activating compound, application rate, and presence or absence of black polyethylene mulch film. This is probably the result of the opposite responses of the most abundant weed species to the activating compounds. These findings indicate that, as effects are species-specific, the choice of activating compound to be used for soil steaming has to be based on major weed species expected in the next crop. Data acquired in the controlled environment experiment, in which type and rate of the two activating compounds were tested on individual weed species, can be used to generate such guidelines.

Total per cent weed density reduction caused by the treatments with respect to the control plots varied from 11% to 48% and decreased in time. From T1 to T2 weed density doubled in all plots, but in treated plots it was on average 40% less than that in the control plots. After 4 weeks, this gap was reduced to about 20%. In the first 4 weeks, the lowest reduction caused by the treatments was 16% and the highest was 63%. Even though there were no significant treatment effects, even a weed density reduction of 16% in the first month after steaming could favour crop early growth and competitiveness, especially in large-seeded crops that have a higher absolute growth rate and a lower relative growth rate (RGR) than the small-seeded weed species. If weed seed germination is retarded, the crop has a better chance of shading out weeds before they can take advantage of their higher RGR (Liebman *et al.*, 2001).

Unlike the 0–10 cm layer, a significant effect of the steam-alone treatment on seedbank density in the 10–20 cm layer was observed. This depended on the fact that the 'true' control had an extremely high seedbank density (> 7300 seedlings m^{-2} in the 10–20 cm layer), while the maximum number of seedlings emerging from the 0–10 cm layer was 4417 m^{-2}. The number of seedlings emerging from the 10–20 cm layer (4215 seedlings m^{-2}) was almost similar to that in the 0–10 cm layer (3800 seedling m^{-2}). Laboratory trials showed a 90% seedling emergence reduction on natural weed flora present in soil samples when maximum soil temperature was 61°C, and a 99% reduction with a further 10°C temperature rise (Melander & Jørgensen, 2005).

Activating compound effects on weed seedling densities in the two layers were similar, but were mitigated by depth. In the upper layer there was a significant compound and application rate effect and a significant interaction between the two factors. In the 10–20 cm layer only the application rate effect was significant. In both layers, weed seedling density decreased with increasing rates of activating compound. Responses of individual species were less consistent between the two layers. Heterogeneity in spatial weed seed distribution in the field increased the variability and partially masked treatment effects. However, data on the weed seedbank are clearer than those on field weed vegetation, an effect probably due to the fact that weed seedlings emergence occurred in controlled environment conditions. In contrast, higher variability in field weed emergence was likely due to additional sources of heterogeneity such as unusual rainfall pattern, seed predation, differences in soil compaction and other soil-mediated factors that cannot be controlled in a field experiment.

Results of the controlled environment experiment gave good indications about sensitivity to soil steaming of seven weed species common in the study area. *A. myosuroides* was the most sensitive species to the steam-alone treatment (77% reduction). The only other two species, the emergence of which was significantly reduced by the steam-alone treatment were *F. convolvulus* and *S. viridis*. Swedish field trials did not show a significant control effect of steaming on *F. convolvulus*, although soil temperature reached 70 to 80°C (Hansson & Svensson, 2004). Species sensitivity to the steam-alone treatment does not seem related to seasonality of weed emergence (winter vs. spring annuals). However, when steam was coupled with use of activating compounds, it seemed that KOH was more effective on winter annuals than on spring annuals. *A. retroflexus* was the only species for which the control effect of CaO was higher, as also shown by the linear regression analysis.

In general, *M. chamomilla* and *E. crus-galli* were the two species that responded less to the different treatment combinations. This is in accordance with Melander and Jørgensen (2005), who also observed a high tolerance of *E. crus-galli* to heat. Data from Table 5 indicate that the highest control effect (in terms of statistical significance) can be achieved even with the application of 2000 kg ha^{-1} of activating compound in the case of *R. raphanistrum* (KOH), *S. viridis* (KOH) and *A. retroflexus* (both compounds) and even 1000 kg ha^{-1} for *A. myosuroides* (KOH). For *F. convolvulus*, at least 3000 kg ha^{-1} of CaO is needed to attain the highest suppression, whereas in the case of *M. chamomilla* (KOH) and *E. crus-galli* (both compounds) this can be attained only when applying the highest rate. Information on species-specific sensitivity to soil steaming treatments is the key to the success of this type of intervention in real farm situations. This is true not only for weeds but also for crops, some of which, e.g. sugar beet, maize, leek, onion and partly carrot, are tolerant to heat (Melander & Jørgensen, 2004). However, simultaneous drilling and steaming is in practice a difficult operation to carry out, because the lethal temperature gap between weeds and crop is often small and the steaming effect can differ depending on soil thermodynamic properties.

The action of the Bioflash System™ can be explained by the combined effect of steam and activating compounds, although soil heating is the main factor. KOH gave better results on weed control and slightly lower soil temperature values with respect to CaO. Thus, a direct herbicidal effect of KOH can be supposed, but only in association with steam. In fact, steam is required to promote the hydration reaction of the activating compounds. No significant weed control effect is expected with the only application of CaO or KOH, that are normally adopted in agriculture as fertilisers or amendments. Finally, it is important to note that the Bioflash System™ is also effective against soil-borne pests and diseases and that treatments are characterised by a unit application cost (*c.* 4000 € ha^{-1}) lower than methyl-bromide (Peruzzi *et al.*, 2007).

Future perspectives

Despite the fact that treatments were not always effective, especially when applied in the field, results from this study show that there are possibilities for weed control by soil steaming (especially in the first 4 weeks after treatment) when applying intermediate to high rates of activating compounds. Individual weed species exhibited different responses to type and rate of activating compound. As such, farmers will have to choose the best compound by rate combination based on the expected weeds in their crop. This study has shown that high compound rates are superfluous when more sensitive weed species are present. Little is known on the effects of activating compounds and maximum soil temperature on the beneficial soil fauna and soil chemical and physical characteristics. Companion trials are needed to investigate these effects, especially in the case of repeated applications of steaming, to generate data that could help fine-tune more environmentally sound crop production systems.

References

Ahmad Y, Hameed A & Aslam M (1996) Effect of soil solarization on corn stalk rot. *Plant and Soil* **179,** 17–24.

Arora A & Yaduraju NT (1998) High-temperature effects on germination and viability of weed seeds in soil. *Journal of Agronomy and Crop Science Zeitschrift Fur Acker Und Pflanzenbau* **181,** 35–43.

Bàrberi P & Lo Cascio B (2001) Long-term tillage and crop rotation effects on weed seedbank size and composition. *Weed Research* **41,** 325–340.

Bàrberi P, Moonen AC, Raffaelli M, Peruzzi A, Belloni P & Mainardi M (2002) Soil steaming with an innovative machine – effects on actual weed flora. In: *Proceedings 2002 5th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Pisa, Italy, 238–241.

Bødker L & Noyé G (1994) Effekten af varmebehandling af overfladejord i nåletræssåbede over for ukrudt og rodpatogene svampe [Effect of heat treatment of surface-soil in raised seedbeds with conifers against weeds and root pathogens (with English summary)]. In: *Proceedings 1994 11th Danish Plant Protection Conference/Pests and Diseases*, Nyborg, Denmark, 239–248.

Chase CA, Sinclair TR & Locascio SJ (1999) Effects of soil temperature and tuber depth on *Cyperus* spp. control. *Weed Science* **47,** 467–472.

COHORT Software (2002) *CoStat*. COHORT Software, Monterey, CA, USA (available at: http://www.cohort.com; last accessed 16 June 2008).

Davis AS & Liebman M (2003) Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. Green manure and tillage timing. *Weed Science* **51,** 919–929.

Gomez K & Gomez A (1984) *Statistical Procedures for Agricultural Research*. John Wiley, New York, USA.

Grundy AC, Green JM & Lennartsson M (1998) The effect of temperature on the viability of weed weeds in compost. *Compost Science and Utilization* **6,** 26–33.

Habeeburrahman PV & Hosmani MM (1996) Effect of soil solarization in summer on weed growth and yield of succeeding rainy-season sorghum (*Sorghum bicolor*). *Indian Journal of Agronomy* **41,** 54–57.

Hanf M (1990) *Le infestanti d'*Europa, le loro plantule, i loro semi. Edizioni Agricole BASF, Bologna, Italy.

Hansson D & Svensson SE (2004) Steaming soil in narrow strips for intra-row weed control in sugar beet. In: *Proceedings 2004 6th EWRS Workshop on Physical and Cultural Weed Control*, Øyer, Norway, 152.

Horowitz M, Regev Y & Herzlinger G (1983) Solarization for weed control. *Weed Science* **31,** 170–179.

Kumar B, Yaduraju NT, Ahuja KN & Prasad D (1993) Effect of soil solarization on weeds and nematodes under tropical Indian conditions. *Weed Research* **33,** 423–429.

Liebman M, Mohler CL & Staver CP (2001) *Ecological Management of Agricultural Weeds*. Cambridge University Press, Cambridge, UK.

Melander B & Jørgensen MH (2004) Recent results in the development of band steaming for intra-row weed control. In: *Proceedings 2004 6th EWRS Workshop on Physical and Cultural Weed Control*, Øyer, Norway, 154.

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

Melander B, Heisel T & Jørgensen MH (2002) Band-steaming for intra-row weed control. In: *Proceedings 2002 5th EWRS Workshop on Physical and Cultural Weed Control*, Pisa, Italy, 216–219.

Moonen AC & Bàrberi P (2004) Size and composition of the weed seedbank after 7 years of different cover-crop-maize management systems. *Weed Research* **44,** 163–177.

Nishida T, Shimizu N, Ishida M, Onoue T & Harishima N (1998) Effect of cattle digestion and of composting heat on weed seeds. *Japan Agricultural Research Quarterly* **32,** 55–60.

Peruzzi A, Raffaelli M, Ginanni M & Mainardi M (2002) Development of innovative machines for soil disinfection by means of steam and substances in exothermic reaction. In: *Proceedings 2002 5th EWRS Workshop on Physical and Cultural Weed Control*, Pisa, Italy, 220–229.

Peruzzi A, Borelli M, Mazzoncini M, Raffaelli M, Ginanni M & Bàrberi P (2004) Weed seeds control by steam and substances in exothermic reaction. In: *Proceedings*

2004 6th EWRS Workshop on Physical and Cultural Weed Control, Øyer, Norway, 155–165.

Peruzzi A, Raffaelli M, Ginanni M, Lulli L, Fontanelli M & Frasconi C (2007) Una operatrice semovente innovativa per la disinfezione del terreno con vapore e sostanze a reazione esotermica. In: *Proceedings 2007 of the Conference: ''Vapore d*'acqua e sostanze a reazione esotermica per la geodisinfezione a basso impatto ambientale: una possibile alternativa all'impiego del bromuro di metile'', Pisa, Italy, 31–48.

Raffaelli M, Peruzzi A, Del Sarto R, Mainardi M, Pulga L & Pannocchia A (2002) Effetto del vapore e di sostanze a reazione esotermiche sul riscaldamento del terreno: risultati di un quadriennio di sperimentazione. In: *Vapor d*'acqua e sostanze a reazione esothermica: una combinazione a risotto impatto ambientale per la disifezioen e la disinfestazione del terreno, Forlì, Italy, 45–52.

Ricci MSF, De Almeida DL, Ribeiro RDD *et al.* (1999) *Cyperus rotundus* control by solarization. *Biological Agriculture and Horticulture* **17,** 151–157.

Sauerborn J, Linke KH, Saxena MC & Koch W (1989) Solarization – a physical control method for weeds and parasitic plants (*Orobanche* spp.) in Mediterranean agriculture. *Weed Research* **29,** 391–397.

Tesi R (2001) *Colture protette: ortoflorovivaismo*. Calderini Edagricole, Bologna, Italy.

Thompson AJ, Jones NE & Blair AM (1997) The effect of temperature on viability of imbibed weed seeds. *Annals of Applied Biology* **130,** 123–134.

Triolo E & D'errico FP (2002) Il vapor d'acqua: un secolo di esperienza per un sistema fitoiatrico attuale. In: *Proceedings 2002 of the Conference ''Vapor d*'acqua e sostanze a reazione esotermica: una combinazione a ridotto impatto ambientale per la disinfezione e la disinfestazione del terreno'', Forlì, Italy, 11–17.

Viggiani P & Angelini R (1998) *Erbe spontanee e infestanti: tecniche di riconoscimento (Graminaceae)*. Bayer, Milan, Italy.