Chapter 5

WEED CONTROL BY SOLARIZATION

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I. INTRODUCTION

Soil solarization or soil tarping was initiated for control of soil pathogens.[1-5] When it was apparent that other organisms were controlled, experimental work was initiated in other pest disciplines. Research has concentrated on major "difficult to control" species such as *Orobanche*[6-10] or *Cyperus*[9-13] for general weed control in high-value crops[14-17] or as a method of broad-spectrum pest control.[18-20] Soil solarization has been utilized to control weeds in crops where there are no registered herbicides, where selective weed control is not satisfactory such as in many minor crops, as a nonpesticide control treatment, in crops where crop safety is marginal or nonexistent with herbicides, and to eliminate the concern with herbicide soil residues.[21]

A principal interest in solarization is to control weed seeds that are not susceptible to selective herbicides in a crop. These weeds include *Malva parviflora, Convolvulus arvensis,* and *Abutilon theophrasti*. Some of these species also are not controlled with soil fumigation.

II. BARRIER MULCHES AND RADIATION FOR WEED CONTROL

Early research on the use of plastics for weed control was primarily on barrier-type methods. Inada[22] reported that black polyethylene was effective in controlling *Digitaria adscendens, Portulaca oleracea,* and *Cyperus serotinus* species. Green polyethylene inhibited 51% of *D. adscendens* dry weight, 90% of *P. oleracea,* and 67% of *C. serotinus,* compared to the clear polyethylene. Maximum soil temperatures were low (~33°C), but were virtually the same under clear and green film. Temperatures were reduced under black film. Hesketh[23] and Standifer et al.[24] found that temperatures under black film were lower than under clear film. Residual weed control under clear film[24] (polyethylene or polyvinylflouride) was greater than under black film. Horowitz[25] and Horowitz et al.[7] observed decreased weed control after black film, compared to clear. Abu-Irmaileh[25a] used black polyethylene to cover beds previously treated with clear polyethylene for solarization or black polyethylene as a barrier mulch to lengthen and increase weed control on beds planted to vegetables.

Herbicides have been combined, coated, or printed onto polyethylene to enhance weed control, enhance accuracy of application, and reduce rate of herbicide application. Nakayama et al.[26] achieved weed control with a 33% reduction of herbicide. The film itself did not contribute to weed control in this study, although the authors did not study the effects of leaving the film on the soil for solarization.

Radiation from solar-enhanced fresnel lenses with a line focus[27] has been effective for the control of seeds of many weeds on the soil surface and, to a lesser extent, of seeds in the surface 10 mm of soil. A 20-s exposure of seed at the surface gave 100% control of five annual weed species. Increased time of exposure and a low soil moisture decreased seedling emergence. The irradiation of soil with microwave radiation has decreased organisms,[28] as the heating and radiation of soil with electromagnetic waves[29] has been effective in controlling weed seeds.

III. WEED SUSCEPTIBILITY

A. PARASITIC WEEDS

The parasitic weeds *Orobanche aegyptiaca, O. ramosa,* or *O. crenata* (broomrape) have been controlled with solarization.[6,8,10,12,13] Although broomrape was not eradicated, yields of carrots[6] or broadbeans[13] were increased. Seeds of *Striga hermonthica* were killed in a greenhouse study where supplemental lighting of 50,000 or 70,000 lx was provided.[8] *S. hermonthica* seeds were more sensitive to solarization than *O. ramosa* in this study.

TABLE 1
Susceptibility of Winter Annual Weeds to Soil Solarization

Weed species	Susceptibility	Location	Ref.
Anagalis coerulea	S, S, S, S	Isr, Isr, Isr, Isr	4, 6, 7, 36
Arum italicum	S	Por	33
Avena fatua	S	U.S.	30
Avena sterilis	MS, S	Isr, Isr	4, 6
Brassica niger	S	U.S.	30
Capsella bursa-pastoris	S, S	Por, U.S.	31, 41
Capsella rubella	S	Por	33
Centaurea iberica	S	Isr	36
Chrysanthemum coronarium	S	Por	33
Daucas aureus	S	Isr	36
Emex spinosa	S	Isr	36
Erodium spp.	S	Aust	19
Heliotropium suaveolus	S, S	Isr, Isr	7, 36
Hordeum leporinum	S	Jor	25a
Lactuca scariola	S, S	Isr, Isr	4, 6
Lamium amplexicaule	S, S, S	Isr, Isr, Isr	6, 36, 30
Medicago polymorpha	S	Jor	25a
Mercurialis annua	S, S	Isr, Isr	4, 6
Montia perfoliata	S	Isr	4
Notobasis syrica	S, S	Isr, Isr	1, 4
Papaver dubium	S	Por	33
Phalaris brachystachys	S, S, S, S	Isr, Syr, Syr, Jor	6, 12, 13, 25a
Phalaris paradoxa	S, S	Isr, Isr	36, 37
Poa annua	S, S, S	U.S., Por, Isr	30, 31, 4
Polygonum equisetiforme	S	Isr	36
Raphanus raphanistrum	S, S	Isr, Por	36, 31
Senecio vernalis	S	Isr	36
Senecio vulgaris	S, S	U.S., U.S.	23, 30
Sinapis arvensis	S, S, S	Isr, Ger, Syr	36, 12, 13
Sisymbrium spp.	S, S	Isr, Isr	4, 6
Sonchus oleraceus	S, S, S, S, S	Isr, Isr, U.S., Por, Jor	3, 36, 30, 31, 25a
Stellaria media	S, S	Isr, U.S.	4, 30
Urtica urens	S	Isr	36

Note: S, susceptible; MS, moderately susceptible; Aust, Australia; Ger, Germany; Isr, Israel; Jor, Jordan; Por, Portugal; Syr, Syria; U.S., United States.

B. WINTER ANNUAL WEEDS

Species of weeds that germinate under cool temperatures have been effectively controlled (Table 1, Figure 1). The temperature regime required for germination (with or without short days) makes these species very susceptible to elevated soil temperatures. Control is achieved even though these species are not germinating or growing in the solarization period. Elmore and Van Hausen[30] found that 1 week of solarization would control many susceptible winter annuals (*Poa annua, Montia perfoliata,* and *Senecio vulgaris*) using 2-mil UV-stablized polyethylene in June and July in Davis, California. Silveira et al.[31] studied the control of weeds and the potential for weed flora after two successive periods of solarization. The wind-distributed species *P. annua* and *Conyza bonariensis* were found to be invaders in the solarized areas. None of the weeds studied appeared to have the potential to become a major weed problem after treatment. Horowitz et al.[7] found that the winter annual species *Lamium amplexicaule* was controlled in Israel. Egley[32] found that unspecified "winter annual" species were significantly reduced with 4 weeks of solarization in Mississippi. Other genera of winter annuals that have been controlled[4] include *Anagallis, Avena, Lactuca, Sisymbrium,* and

FIGURE 1. Bedtop solarization for control of weeds in broccoli, Davis, California. (A) Bed solarized for 6 weeks in July and planted in August; (B) Bed unsolarized, shallow cultivated, and planted in August.

Stellaria. Sonchus oleraceus cover was reduced by 87.5% in late-summer experiments in Portugal.[33]

C. SUMMER ANNUAL WEEDS

Weed species growing in the summer months require higher temperatures and/or longer days to germinate. These species should, if temperature is the only mechanism of action of solarization, be much more difficult to control. Many investigators have shown that solarization, when conducted under good experimental conditions, has controlled most summer annual species (Table 2). Egley[32] found that solarization for 1 week in midsummer signif-

TABLE 2
Susceptibility of Summer Annual Weeds to Soil Solarization

Weed species	Susceptibility	Location	Ref.
Abutilon theophrasti	S, MS, S	U.S., Isr, U.S.	32, 36, 35
Alhagi maurorum	S	Isr	1
Amaranthus albus	S	U.S.	14
Amaranthus blitoides	S, S	Por, Por	31, 33
Amaranthus retroflexus	S, S, S, S, MR	Isr, Isr, It, Por, U.S.	5, 36, 16, 33, 45
Anchusa aggregata	MR	Isr	36
Anoda cristata	S, S, MS	U.S., U.S., U.S.	32, 35, 43
Astragalus boeticus	R, MS, R	Isr, Isr	36, 6, 34
Carthamus syriacum	S	Syr	13
Chenopodium album	S, S, S, S, S, S, S, S,	Egy, Egy, Isr, Por, Aust, It, Ger, U.S.	9, 10, 36, 33, 19, 17, 8, 45
Chenopodium murale	S, S	Isr, Isr	6, 36
Chenopodium pumila	S	Aust	19
Commelina communis	S	U.S.	24
Conyza bonarinsis	S	Por	31
Conyza canadensis	MR	Isr	7
Coronilla scorpiodes	R	Syr	13
Crozophora tinctoria	MR	Isr	36
Cyperus spp.	S	U.S.	24
Datura stromomium	MS, S	Isr, Por	36, 33
Digitaria sanguinalis	S, S, S, MR, S	Isr, Por, Aust, Ger, U.S.	5, 33, 19, 8, 49
Echinchloa crus-galli	S, S, S	U.S., U.S., Aust	41, 24, 19
Eleucine indica	S, S, S	U.S., Isr, Isr	24, 3, 4
Eragrostis magastachys	S	Aust	19
Fumaria judaica	S, S, S	Isr, Isr, Isr	4, 6, 7
Fumaria muralis	S	Por	33
Hyperium crispus	MS	Isr	6
Ipomoea lacunosa	S, MS	U.S., U.S.	32, 45
Lavatera cretica	R	Isr	36
Malva niceaensis	MR, MR, MR	Isr, Isr, Isr	6, 34, 36
Malva parviflora	S, MS, MS	U.S., U.S., Jor	30, 11, 25a
Malva sylvestris	S	It	17
Melilotus sulcatus	R, R, R, MR, R, R, R	Egy, Egy, Isr, Isr, Isr, Isr, Isr	9, 10, 3, 4, 6, 34, 36
Orobanche aegyptica	S, MS	Isr, Syr	25, 13
Orobanche crenata	S, S, MS	Isr, Isr, Syr	7, 25, 13
Orobanche ramosa	MS	Sud	8
Polygonum persicaria	S	Ger	8
Polygonum polyspermum	S	Ger	8
Portulaca oleracea	S, S, MS, S, MR, MS, R	Egy, Isr, Isr, U.S., It, U.S., Jpn	10, 5, 36, 14, 16, 11, 22
Prosopis furcata	S	Isr	1
Scorpiurus muricatus	R, R	Isr, Syr	36, 13
Setaria glauca	S	It	17
Sida spinosa	S, S, S	U.S., U.S., U.S.	32, 35, 43
Solanum luteum	S, MR, S	Isr, Isr, Isr	3, 36, 34
Solanum nigrum	S, S, MR, S, S, S, S, S	Egy, Egy, Isr, Por, Aust, It, Isr, U.S.	9, 10, 36, 31, 19, 16, 44, 48
Striga hermonthica	S	Ger	8
Trianthema portulacastrum	S	U.S.	32
Tribulus terrestris	S	Isr	36
Xanthium pensylvanicum	S, S	U.S., U.S.	32, 35
Xanthium spinosum	S	Isr	5
Xanthium strumarium	MR, MS	Isr	36, 45

Note: S, susceptible; MS, moderately susceptible; R, resistant; MR, moderately resistant; Aust, Australia; Egy, Egypt; Ger, Germany, Isr, Israel; It, Italy; Jor, Jordan; Jpn, Japan; Por, Portugal; Sud, Sudan; Syr, Syria; U.S., United States.

TABLE 3
Susceptibility of Perennial Weed Species to Soil Solarization

Weed species	Susceptibility	Location	Ref.
Chloris gayana	S	Aust	19
Convolvulus althaeoides	MS	Por	33
Convolvulus arvensis (seed)	MS	U.S.	39
Convolvulus arvensis (plant)	S, MS, MS, S, MS	Isr, Por, In, U.S., Isr	20, 33, 18, 39, 7
Cynodon dactylon (seed)	S, S	Isr, Isr	34, 37
Cynodon dactylon (plant)	MR, MS, MS, S, S, MS, S	Isr, Isr, Isr, U.S., Isr, In, Jor	20, 36, 37, 39, 5, 18, 25a
Cyperus esculentus	MR	U.S.	11
Cyperus rotundus	R, R, MR, R, S, MR, R, MS, MS, R, R	Egy, Egy, Isr, U.S., Isr, Isr, Por, Isr, In, Sud, U.S.	10, 36, 1, 32, 34, 37, 33, 36, 18, 8, 38
Equisetum arvense	S	Por	33
Equisetum ramosissimum	S	Por	33
Oxalis corniculata	S	Por	33
Plantago spp.	MS	Isr	6
Sorghum halepense (seed)	S, S, S, S	Isr, Isr, U.S., U.S.	37, 34, 25, 45
Sorghum halepense (plant)	MR, MS, MS	Isr, Isr, U.S.	36, 37, 38

Note: S, susceptible; MS, moderately susceptible; R, resistant; MR, moderately resistant; Aust, Australia; Egy, Egypt; In, India; Isr, Israel; Jor, Jordan; Por, Portugal; Sud, Sudan; U.S., United States.

icantly reduced numbers of *Sida spinosa, Xanthium pensylvanicum,* and *Anoda cristata.* Species where inconsistent results have been reported include *Malva niceaensis,*[6,7,36] *Fumaria judaica,*[6,7] *Portulaca oleracea,*[4,5,7,9-11,16,17,19,20,22,27,32] *Solanum luteum,*[3,36] *S. nigrum,*[10,16,17,27,31,36] and *Astragalus boeticus.*[6,36] Factors that could affect the sensitivity of the species in different tests include soil moisture, the care in placing the film, duration of solarization, depth of the seeds in the soil, and weather conditions during the tests. This has been one of the difficulties in evaluating the studies to determine the susceptibility of summer species. Braun et al.,[8] under moderate conditions, reported *Digitaria sanguinalis* to be very tolerant in Germany.

The species that consistently is described as resistant is *Melilotus sulcatus.*[3,10,13,20,36] Jacobsohn et al.[6] reported good control of this species. Sauerborn et al.[13] also found the leguminous species *Coronilla scorpiurus* and *Scorpiurus muricatus* to be tolerant. This knowledge could be capitalized upon to establish legume cover crops for nitrogen fixation in vegetables.

Standifer[24] has shown that some summer annual species are also very sensitive to solarization. Clear and black film controlled annual sedge in the 0- to 2-cm depth during a 2-week treatment interval. However, with clear film, there was increased control, to the 3- to 4-cm depth at 4 weeks or more. There was a trend of increased control at the 4- to 5-cm depth at 4 weeks as well.[24] In the same study, *Commelina communis* was controlled to a depth of 10 to 11 cm with clear film.

The solarization studies of short duration (1 to 2 weeks) have indicated the sensitivity of many weed species; however, the common length of film coverage of 4 to 6 weeks has given the most consistent control of summer annual species.

D. PERENNIAL WEEDS

Differential responses have been achieved with solarization for perennial weed control (Table 3). Unfortunately, the condition of the species at the time of solarization has not always been given to inform the reader about the potential for control.

The difficult to control weeds, *Cyperus esculentus* and *C. rotundus,* have both been evaluated. Hejazi et al.[11] evaluated solarization for the control of *C. esculentus* in the field and at three temperature regimes under polyethylene-covered flats in the growth chamber. Tubers were harvested at intervals and tested with tetrazolium red dye for viability. Tarping the soil with clear polyethylene reduced the tuber viability by 26% after 6 weeks. Tuber mortality at a 60°C temperature for 6 d was 100%. A temperature of 50°C only reduced viability by 60% after 32 d of treatment.

C. rotundus has been generally resistant to control by solarization.[1,2,5,9,21,37] Reduction of tubers has usually been less than 40%, compared to an untreated area. Rubin and Benjamin[37] and Egley[32] reported enhanced germination of *C. rotundus*. This result was confirmed by Miles and Nishimoto[38] in Hawaii, where bud sprouting was increased. Under solarization treatment, the percent of sprouting was increased significantly over untreated tubers. This uniform sprouting could allow for a postemergence herbicide treatment to increase *C. rotundus* control. Maximum temperatures were only recorded to 31°C. Rubin and Benjamin[37] found that temperatures of 70°C for 30 min were required to significantly reduce tuber germination in soil. It is feasible that longer durations of temperature at 55 to 60°C would also reduce *C. rotundus,* but it is apparent that solarization alone will not give adequate control. Rubin and Benjamin[37] evaluated the emergence capability of *C. rotundus* in soil for 60 d after planting. They found that there was no significant difference in emergence between 2 and 10 cm. Although there was reduced emergence at lower depths, 5% of the tubers emerged from 30 cm. This would help explain why *C. rotundus* is not controlled well with solarization.

Seed of the perennial weeds *Cynodon dactylon,*[5,34] *Sorghum halepense,*[5,34,45] and *Convolvulus arvensis*[38] is sensitive to solarization. Egley[45] found *S. halepense* survival to be unaffected by heating dry soil. Germination increased in dry soil heated to 60°C for 7 d. Viable seeds of *S. halepense* decreased when treated for 2 d at 50°C in moist, heated soil or 0.5 d at 60°C. No viable seeds were found after 2 d at 70°C in moist soil. Seeds of *C. arvensis* buried at depths of 4, 8, and 16 cm in the field did not germinate at the 4- and 8-cm depths after 6 weeks of solarization in July and August.[39] Rubin and Benjamin[37] found that when buried rhizomes of *C. dactylon* or *S. halepense* were subjected to 0.5 h of 40°C temperature, there was a reduction of 90 to 95% emergence with no emergence after 0.5 h of 50°C. They also found that rhizomes could emerge from a depth of 20 cm. It is necessary to heat the soil to the depth of the rhizomes to achieve control. In studies in California,[39] this depth for *C. dactylon* and *S. halepense* varies according to the cultural management of the field. If the rhizomes are not buried by plowing, control can be achieved with solarization.

The control of established *C. arvensis* has varied between studies. Horowitz[25] reported that many shoots of *C. arvensis* appeared after the removal of black plastic; none emerged after the removal of transparent plastic. Silveira et al.[33] found a 5% cover of *C. arvensis* in a solarized area 40 d after removal vs. a 20% cover in untreated areas, thus indicating a significant reduction of the established plant. Chauhan et al.[18] indicated an initial reduction in *C. arvensis,* but it gradually recovered. This result has been observed in California, with recovery occurring 2 to 3 weeks after film removal.[39] Since *C. arvensis* frequently is found on heavy, deep soils and the root stocks are keep in the soil, control of established populations with solarization alone will probably not be satisfactory.

The shallow-rooted perennial, *Plantago* sp., regrew after solarization; however, the number of plants were greatly reduced.[6]

IV. FACTORS TO ENHANCE WEED CONTROL

A. BEDS — BED WIDTH AND DIRECTION

When the soil has been solarized flat and followed by planting,[1,4] it has been principally for soil pathogen control. Many researchers have evaluated this method.

For control of weeds where vegetables are planted on beds, the beds must be preformed and solarized. Studies on beds[2,6,7,25] have shown excellent weed control, whether irrigated after bedding and before tarping,[6,7,25] from natural rainfall before tarping,[24,32] or with drip irrigation under the tarps.[3,6,7] Mahrer and Katan[40] measured soil temperatures in different locations under sheets of polyethylene ranging from 10 to 200 cm in width. From their data, the relative efficiency of transparent polyethylene mulch to approximate the center temperature (higher) increased dramatically from the 10- to 20- to 40-cm width. Temperatures were well below the more efficient 80-cm cover width (minimum acceptable) or greater widths. They found that there is usually a 2 to 4°C lower temperature at the edge of the mulch than at the center, at the same soil depth. Horowitz et al.[7] measured the band width of polyethylene as related to maximum soil temperature and irrigation, prior to or during solarization. Although there was no weed emergence from a 20- to 140-cm band width, the temperatures at the 5-cm depth were comparable; temperatures were generally 1 to 2°C higher at the 15-cm depth with the wider band width and irrigation during the solarization period. It has also been observed by the author that beds running in a north-south direction are preferable to an east-west direction, to avoid a lower temperature on one side of the bed.

B. SOIL MOISTURE AND IRRIGATION

There is general agreement that "good" moisture is required at the beginning of solarization. Many studies with favorable weed control have started with a single heavy sprinkler irrigation,[2,6,7,12,13,31,33] rainfall,[24,32] or furrow[10] irrigation. Weed control also has been effective when the soil was drip irrigated initially and followed with wetting every 3 to 6 d,[1] weekly,[7] or at longer intervals.[10] Differences were measured by number of disease-infected plants, or Orobanche-parasitized carrot plants in drip or sprinkler irrigated studies. Horowitz et al.[7] did show a slight increase in soil temperature at the 15-cm depth with drip irrigation initially plus weekly compared to a single heavy sprinkler irrigation before tarping. These differences are probably not significant on the "difficult-to-control" species or marginal sites for solarization.

C. TIMING AND DURATION OF SOLARIZATION

Consistently excellent weed control occurs during the period of high radiation in the middle of the summer. When solarization was conducted by Mahrer and Katan,[40] for approximately 2-week periods in October and July, the average daily maximum temperatures under polyethylene were lower in October (maximum of 44°C at 5 cm) than in July (maximum of about 48°C). In experiments in May, September, and January, Horowitz et al.[7] found that the average maximum temperatures at 5 cm in solarized plots were 45.3, 41.9, and 27.7°C, respectively. In the summer experiment, weeds did not develop under the plastic and the residual effects were apparent 1 year later. No weeds grew under the tarps in the September experiment. Although good weed control was observed after 4, 6, or 8 weeks of solarization, there was no residual control the following year. Weeds grew under the plastic during the winter treatment and no residual control was observed. Powles et al.[51] has observed residual weed control from a 21-d solarization treatment for 1 year.

Egley[32] compared the control of seeds with 1 or 4 weeks of solarization. Only 1 week of treatment significantly reduced the number of viable seeds of *Sida spinosa, Xanthium pensylvanicum, Abutilon theophrasti,* and *Anoda cristata.* With the duration increased to 2 weeks, additional species were controlled. In one experiment, no significant decrease in weed emergence occurred after 2 vs. 4 weeks (10 to 2%) of solarization.

In California, when solarization was conducted for 4 weeks per treatment starting in May and ending in September,[41] effective weed control was observed in June, July, and August, with reduced effectiveness in May and September.

D. CAUSES OF SEED DEATH

Weed seeds and propagules are controlled in various ways, including heat, contact burning of the germinating seedling or plant shoot, germination promotion at lower depths and control in the higher-temperature surface area, and possibly the imbalance of gaseous compounds in the soil.

Weed seeds in general have a lower germination rate when stored at greater soil depths.[42] This decrease in germination seems to be light-mediated, but can be overcome by increased oxygen. In selective germination studies, Taylorson[43] found that supplying ethylene promoted germination of many species, the most prevalent being *Portulaca oleracea, Chenopodium album,* and several Amaranths. Some species that should be controlled by solarization, such as *Setaria faberi,* however, were not responsive to ethylene in this system.

Horowitz et al.[7] also measured other gases to determine possible control mechanisms. Concentrations of O_2 and CO_2 were measured at depths of 5, 15, and 25 cm in the soil atmosphere. They found that there was no clear differential in CO_2 concentration by depth. Concentrations ranged from about 1 to 2% in tarped areas and was increased over untarped areas. The O_2 content was slightly depressed; however, there was adequate (18 to 20.5% at 5 cm) O_2 for seed germination. Induced dormancy can occur with decreased oxygen[42] or high temperature; however, other volatile compounds should not be ruled out as possible enhancers of soil solarization killing. Katan[20] indicated that volatile compounds (although unspecified) may have an influence on control. Rubin and Benjamin[34] reported that CO_2 concentration levels in the soil air increased to a high of 5.3% within 4 d, but then declined gradually to 2.1%. They also suggested that acetaldehyde and ethylene may be involved in the solarization process. In a later study, Rubin and Benjamin[37] reexamined CO_2 and O_2 levels in the soil atmosphere. They basically confirmed the earlier work of Horowitz et al.,[7] but also indicated they did not find carbon monoxide or methane from solarization.

Probably the greatest factor in seed and seedling control is thermal killing. Rubin and Benjamin[37] evaluated five weed seeds treated in soil in pots under constant temperature regimes of 30 to 90°C at 10° increments for 30 min. *Sinapsis arvensis* germination was reduced about 70% at 50°C, with total control at 70°C, while that of *Amaranthus retroflexus* and *Datura stramonium* was decreased at different rates and temperatures as intermediate susceptible species. *Astragalus boeticus* was more resistant than the previous species. *Melilotus sulcatus* was not significantly affected with temperatures up to 90°C for 30 min.

Horowitz[44] indicated that *Solanum nigrum* germination in covered containers of soil was not affected by a temperature of 45°C, but 55°C for 6, 24, or 48 h reduced germination by 30, 60, and 93%, respectively. Hesketh[23] developed temperature-germination curves by time of treatment and found that a lethal death designation (LD_{90}, lethal death for 90% of population) for *S. nigrum* was greater than 60°C for 1 h or 58°C for 8 h. Additional data were presented for *Poa annua* seed and *Senecio vulgaris,* both heat-sensitive species. Repeated short-term thermal treatments (which simulate daily summer maxima) had a similar or stronger inhibition of germination than a single, prolonged application.[45] Egley[45] did an extensive study on eight weed species. The seeds were heated at different temperatures in wet or dry soil for up to 7 d, then germinated. Germination and viability of the seeds was affected most in wet soil. In dry soil, seeds were not killed at 60°C for up to 7 d.

Some of the sublethal levels of heating increased the germination of *Abutilon theophrasti, Sida spinosa, Anoda cristata,* and *Ipomoea lucunosa.*[45]

Horowitz and Taylorson,[46] working with the hard-seed species *Abutilon theophrasti,* found that water imbibition and germination varied between the hard seeds and soft seeds within the same seed batch. Seeds with low water content required higher temperatures to control than wetter seeds. Germination was significantly reduced after 7 h at 43°C, 4 h at 45°C, 2 h at 50°C, and 1 h at 55°C. Complete germination inhibition occurred after 15 h at 45°C, 8 h at 50°C, and 6 h at 55°C. They also found that a heat stress of 1 h at 52°C applied twice within a 24-h period produced greater germination inhibition of soft seeds than a single 2-h, 52°C initial treatment. The latter type of experiment would more closely duplicate daily temperature fluctuations and control practices in the field.

V. PERSISTENCE OF HERBICIDES

The effect of solarization in combination with herbicides, or the residual of herbicides, has varied greatly. When the volatile herbicides *S*-ethyldipropylthiocarbamate (EPTC) and *S*-propyl dipropylthiocarbamate (vernolate) were incorporated mechanically into the soil and solarized, the loss was more rapid than when they were incorporated alone.[36] Neither herbicide increased the weed control over solarization. Solarization of soil did decrease the disappearance of 1-methyl-3-phenyl-5-[3-(triflurometh yl)phenyl]-4(^{1}H)-pyridione(fluridone). No difference was noted in the residual of 5-bromo-3-*sec*-butyl-6-methyl-uracil(bromacil). In a second study, Avidov et al.[47] found that by pretreating soil with methyl bromide or solarization, then treating with either 2-(*tert*-butylamino)-4-(ethylamino)-6-(isopropylamino)-*s*-triazine(terbutryn) or 2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-triazine (atrazine), the degradation of both herbicides was slowed. Loss of the herbicides was faster after solarization than with methyl bromide. Atrazine degradation was not as affected by soil solarization as was terbutryn.

VI. APPLIED SUMMARIES OF SOLARIZATION

Soil solarization has been described for the user in several publications to enhance its public awareness. In weed control, Elmore[48] prepared a summary of weeds controlled and practical applications. Other broader descriptive publications[18,49,50] have been presented through extension services. Additional practical guides of this type are needed to promote the use of solarization in weed science.

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