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Controlling Grass Weeds on Hard Surfaces: Effect of Time Intervals between Flame Treatments

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An experiment was conducted on a specially designed hard surface to study the impact of time interval between flaming treatments on the regrowth and flower production of two grass weeds. The goal of this experiment was to optimize the control of annual bluegrass and perennial ryegrass, both species that are very difficult to control without herbicides. Aboveground biomass from 72 plants per treatment was harvested and dry weights were recorded at regular intervals to investigate how the plants responded to flaming. Regrowth of the grasses was measured by harvesting aboveground biomass 2 wk after the second flaming treatments that were implemented at different time intervals. Flaming treatments decreased plant biomass of both species and also the ratio of flowering annual bluegrass plants. However, few plants were killed. The first flaming treatment affected aboveground biomass more than the second flaming treatment. A treatment interval of 7 d provided the greatest reduction in regrowth of perennial ryegrass, whereas the effect of treatment interval varied between the first and second repetitions of this experiment for annual bluegrass. In general, short treatment intervals (3 d) should be avoided, as they did not increase the reduction of aboveground biomass compared with the 7-d treatment interval. Knowledge on the regrowth of grass weeds after flaming treatments provided by this study can help improve recommendations given to road keepers and park managers for management on these weeds.

Nomenclature: Annual bluegrass, *Poa annua* L.; perennial ryegrass, *Lolium perenne* L.

Key words: Grasses, perennial weed, gas burners, thermal weed control, nonchemical weed control, pavements, amenity areas.

Se realizó un experimento en una superficie dura especialmente diseñada para estudiar el impacto de los intervalos de tiempo entre los tratamientos de quema con lanzallamas en la regeneración y producción de flores de dos malezas gramíneas. El objetivo de este experimento fue optimizar el control de *Poa annua* y *Lolium perenne,* ambas especies muy difíciles de controlar sin herbicidas. La biomasa aérea de 72 plantas por tratamiento se cosechó y los pesos secos se registraron en intervalos regulares para investigar cómo las plantas respondían a la quema. La regeneración de las malezas fue medida a través de la cosecha de la biomasa aérea dos semanas después del segundo tratamiento con fuego, que a su vez fueron realizados en diferentes intervalos de tiempo. Los tratamientos con fuego disminuyeron la biomasa de ambas especies y también el índice de floración de las plantas de *P. annua.* Sin embargo, solamente murieron unas cuantas plantas. El primer tratamiento afectó la biomasa aérea más que el segundo tratamiento. Un intervalo entre tratamientos de siete días proporcionó la mayor reducción de regeneración de *L. perenne*, mientras que el efecto de la duración del intervalo varió entre la primera y segunda repetición de este experimento para *P. annua*. En general, los intervalos cortos entre tratamientos (tres días) deben de evitarse, debido a que no mejoran la reducción de la biomasa aérea en comparación con el intervalo de 7 días. Los conocimientos obtenidos en este estudio acerca de la regeneración de las malezas gramíneas después de los tratamientos con fuego, pueden ayudar a mejorar las recomendaciones dadas a los encargados del mantenimiento de los caminos y a los administradores de parques para el manejo de estas malezas.

Weeds are unwanted on hard surfaces for several reasons. They can damage surfaces by breaking asphalt, disrupting the edge of road seal, and enlarging cracks, all of which shorten the lifetime of the surfaces (Holgersen 1994; Zwerger et al. 2000). Additionally, weeds can make footpaths slippery, clog water drains, and provide substrate for new weed establishment. At road verges they can impair the visibility of traffic signs and vehicles, and thereby facilitate accidents. Furthermore, weeds make the streets and pavements unsightly and may adversely affect human health by releasing allergenic pollen into the atmosphere (Benvenuti 2004).

Applications of glyphosate have been the main weed control method for hard surfaces in most European cities, usually requiring two applications per year (Augustin et al. 2001). However, in recent years, several countries have restricted the use of herbicides on hard surfaces because of the risk of leaching herbicides into ground and surface waters (Kristoffersen et al. 2008b). In Denmark, local authorities and state institutions signed a voluntary agreement in 1998 for total elimination of herbicides in public areas. Therefore, many public authorities rely on the use of nonchemical weed control methods, primarily flame weeding (Hansen et al. 2004). In contrast to glyphosate, which almost completely kills the plant, most nonchemical methods mainly affect the aboveground plant parts (Rask and Kristoffersen 2007). Effective weed control with nonchemical methods requires repeated treatments, and the effectiveness is strongly related to the susceptibility of the weed species and the stage of development (Ascard et al. 2007; Kristoffersen et al. 2008a). For example, the grass species annual bluegrass and perennial ryegrass have meristems located at the soil surface and are therefore protected against flaming. Consequently, treatment

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frequency highly depends on the weed species composition as well as other factors such as weed cover, weed acceptance level, weed control method, climate, and type of hard surface (Rask and Kristoffersen 2007).

Kristoffersen et al. (2008a) suggested treatment intervals of 2 to 4 wk for flame weeding on traffic islands, and Kreeb and Warnke (1994) concluded that treatment intervals of 2–5 wk should be performed on railway banks to keep weed density at an acceptable level. Hansen et al. (2004) performed experiments with different thermal methods and brushing on pavements. In their experiments 11 to 12 treatments per growing season were necessary to achieve acceptable weed control on areas heavily infested with perennial weeds, irrespective of the method applied. Dutch research on pavements (Vermeulen et al. 2006) showed that fewer treatments were needed: four to six brushings, three to five flamings, or three to five hot water applications per growing season. Because a high treatment frequency increases the costs of weed control, knowledge of tolerant weeds and their response to flaming can provide recommendations on how to reduce the number of treatments and lower the costs of control.

To confirm the impacts of time intervals between flame treatments on regrowth and flower production of grass weeds, an experiment was conducted on a simulated hard surface. The species that were chosen were annual bluegrass and perennial ryegrass, both of which are very difficult to control without herbicides. Annual bluegrass is the most frequent species on hard surfaces in five North European countries (Melander et al. 2009).

The hypotheses tested were that: (1) repeated flaming will reduce plant dry weight and number of flowering plants substantially in comparison with untreated plants, but the interval between treatments is crucial for effectiveness and cost, and (2) increasing time between treatments increases regrowth.

Materials and Methods

Growing of Seedlings in Greenhouse. In April 2008 seeds from annual bluegrass and perennial ryegrass were sown separately in large plastic trays (10 trays per species). Each plastic tray contained 100 planting holes (1 by 1 cm, depth 4 cm) and after germination the seedlings were thinned to ensure that each planting hole contained only one seedling. The soil in the plastic trays was chosen carefully. It was a sandy soil to resemble the harsh conditions found in joints between flagstones and on hard surfaces. The soil was 70% coarse sand and 23% fine sand. Additionally, it had a low content of silt (3%), clay (2%), and humus (2%). After sowing, the plastic trays were placed in a naturally lit greenhouse (mean temperature 17 C). The seedlings were watered daily, but were not fertilized. The seedlings were kept in the greenhouse for 35 d. Perennial ryegrass plants were approximately 11 cm tall and annual bluegrass plants were approximately 8 cm tall at the time of transplanting. Plants were removed easily from the tray without damaging the roots. Only seedlings in good condition were used in the experiment. The experiment was repeated 7 d later to create two identical experiments separated in time.

Figure 1. Concrete flagstone with 12 perennial ryegrass plants. The image was taken on August 10, 2008, 20 d after the first flaming treatment. These plants had received one flaming treatment and were harvested the following day, i.e., 3 wk after the treatment. A color version of this figure is available in the online journal.

Outdoor Planting and Conditions. The experiment was conducted at Taastrup, Denmark (55°40′10N; 12°18′32E). A hard surface area of 24 m^2 was constructed with "Costa" concrete flagstones ("Costa" concrete flagstones, FC Beton, A/S, www.fc-beton.dk). These flagstones are typically used in parking lots or gateways. The size of each concrete flagstone was 40 by 30 cm and the height was 10 cm. Each concrete flagstone had 18 holes of 4 by 4 cm. Twelve of the holes were used as planting holes (Figure 1). Before the concrete flagstones were laid, about 3 cm of gravel (grain size 0 to 4 mm) was placed on top of a large paved area. After compacting and smoothing of the gravel, it was covered with a water-permeable mat (black weed control fabric, WeedSeal®, Fibertex Nonwovens A/S, www.fibertex.com) to prevent root penetration below the concrete flagstones and into the gravel. On this base of pavement, gravel, and water-permeable mat, the concrete flagstones were laid. Each flagstone was separated by about 1 cm of gravel. All the planting holes were filled with the same soil used in the plastic trays described previously. Before planting, the soil was watered and the holes were refilled with soil once. The first run of seedlings was planted on May 20. One seedling was carefully planted in each hole, 12 seedlings per concrete flagstone. The second run of seedlings was planted 7 d later. Seedlings that failed to establish in the flagstones after transplanting were replaced with new seedlings from the greenhouse within the first week of both runs of the experiment.

Treatment Plan. The experiment was set up as a randomized complete block design with three blocks per run. In each block there was one flagstone with 12 plants (subsamples) per treatment/harvest, 13 flagstones per block and per species. For three blocks, two species, and two runs of the experiment there was a total of 156 flagstones with 12 plants in each (1,872 plants). Treatments for the first run of this experiment started on July 21 (approximately 2 mo after transplanting) and treatments for the second run of the experiment started 7 d later. At that time all plants were well established. Before the first treatment each concrete flagstone was marked

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randomly to indicate which treatment the 12 plants should receive. Hence, plants within the same concrete flagstone received the same treatment and were harvested at the same date. With three blocks (replications) and 12 plants (subsamples) in each flagstone per treatment, a total of 36 plants was harvested at each harvest date in each experiment.

Treatments: (1) One flaming treatment with a gas burner (see application details); (2) two flaming treatments with different treatment intervals. The first treatment was applied the same time as the one flaming treatment. At 3, 7, 14, or 21 d after the first treatment 36 plants received a second flaming treatment; (3) undisturbed growth (nontreated control).

Application Details. The first treatment was conducted with a HOAF 75-cm gas burner mounted on a Kerstin self-driven machine. The working width of the flamer was 75 cm, mean gas consumption was 5.25 kg h^{-1}, and the driving speed was 0.9 km h^{-1}. The same dose was applied on all treatments (80 kg gas ha^{-1}). The relatively high dose was chosen to ensure that all leaves were killed.

Plants that were treated twice were treated with a handheld gas burner for the second application, at the same dose. The gas burner was a HOAF Midi handheld gas burner with a gas consumption of 2.1 kg h^{-1}. On the basis of the gas consumption, burner size, and heating value of gas (kWh kg^{-1}) we could calculate the treatment time per stone (2 s). An iron frame (height 20 cm) was constructed and placed around the concrete flagstones before each treatment to ensure that only the 12 plants within the same concrete flagstone were treated, without damaging neighboring plants.

The gas consumption per hour of the two different burners was calculated by weighing the gas bottles before and after three different 10-min treatments, calculating the mean gas use per 10 min, and multiplying this value by 6.

Harvest Procedures. At each harvest date different sets of plants were harvested. Plants that were flamed once were harvested at six different times: 3, 7, 14, 21, 28, or 35 d after flaming (36 plants per harvest and a total of 216 plants per species and per run). Plants that were flamed a second time at 3, 7, 14, or 21 d after the initial flaming were harvested at four different times (36 plants per harvest and a total of 144 plants per species and per run). These plants were harvested 2 wk after the second treatment to measure the plants' regrowth capacity. Nontreated control plants were harvested at three different times: 0, 14, or 35 d after the experiment was started (36 plants per harvest and a total of 108 plants per species and per run). Plants within the same flagstone were numbered from 1 to 12 and aboveground biomass was harvested just above the soil surface. Harvested plants were washed and dried at 80 C for 24 h and then weighed. Withered leaves were not removed and were therefore included in the total dry weight of the plants. The number of plants with flowers was determined for annual bluegrass. Perennial ryegrass did not set flowers as it was sown and harvested the same year, and a vernalization period is needed for it to flower.

Statistical Analysis. Data from the two species were analyzed separately. A mixed model (SAS version 9.2, SAS Institute Inc., Cary, NC) was used to take account of random effects. All systematic factors were tested against variation among the three blocks (replications) and between the two runs of the experiment, which were considered random effects. To adjust for the time span between harvest dates, day numbers since the first treatment were used. The following factors were considered as fixed factors in the systematic part of the model: treatment, number of days since first treatment, and their interaction. Harvest data before the first treatment were given the value 0 d. P-values below 0.05 were considered significant.

Homogeneity of variance was assessed on the basis of plots of standardized residuals against predicted values by use of residual plots and QQ normal plots of raw residuals. To achieve homogeneity of variance, plant dry weight was subjected to a log transformation. For presentation of results, means and measures of variability were back-transformed by the delta method (Weisberg 2005).

Difference between time intervals was compared by least-square means (R version 2.11.1, R Development Core Team. 2010. R: A language and environment for statistical computing. R Foundation for Statistical computing, Vienna, Austria. ISBN 3-900051-07-0, URL http:/www.R-project.org). To test whether there were significant differences between plant dry weight after one and two treatments at the same harvest date, the differences between plant dry weights (log transformed) after one or two treatments were calculated. The four groups (3, 7, 14, or 21-d intervals) were then compared by least-square means.

Results and Discussion

General Treatment Effects. Flaming once or twice reduced aboveground biomass of both perennial ryegrass and annual bluegrass substantially compared with the nontreated control plants (Figure 2). Aboveground biomass of the nontreated control plants continued to increase during the experiment; however, aboveground biomass of flame-treated plants was relatively constant. The effect of flaming was obtained after only one treatment. In general, flaming twice reduced aboveground biomass even further for perennial ryegrass (Figures 2a and 2b) and annual bluegrass in the second run of the experiment (Figure 2d) ($P < 0.0001$). At 35 d after the first flaming treatment, aboveground biomass of perennial ryegrass was 42% (run 1, Figure 2a) and 54% (run 2, Figure 2b) of control plants. In contrast, aboveground biomass of perennial ryegrass plants flamed twice was 17% (run 1, Figure 2a) and 16% (run 2, not significant at this stage, Figure 2b) lower than plants flamed once. Aboveground biomass 35 d after the first treatment for annual bluegrass plants flamed once was reduced 45% (run 1, Figure 2c) or 50% (run 2, Figure 2d), whereas that of plants flamed twice was reduced a further 40% (run 1, Figure 2c) or 16% (run 2, a significant decrease at this stage, Figure 2d).

Even though flaming reduced aboveground biomass of the two grass species, only very few plants were actually killed. Most of the leaves withered after the treatment but soon new green leaves appeared. Grass weeds are very difficult to control with nonchemical methods because of strong ability to regrow (Ascard 1995b; Rask and Kristoffersen 2007; Ulloa et al. 2010a, 2010b). In a dose–response study by Ascard (1995a) annual bluegrass could not be killed completely with a single

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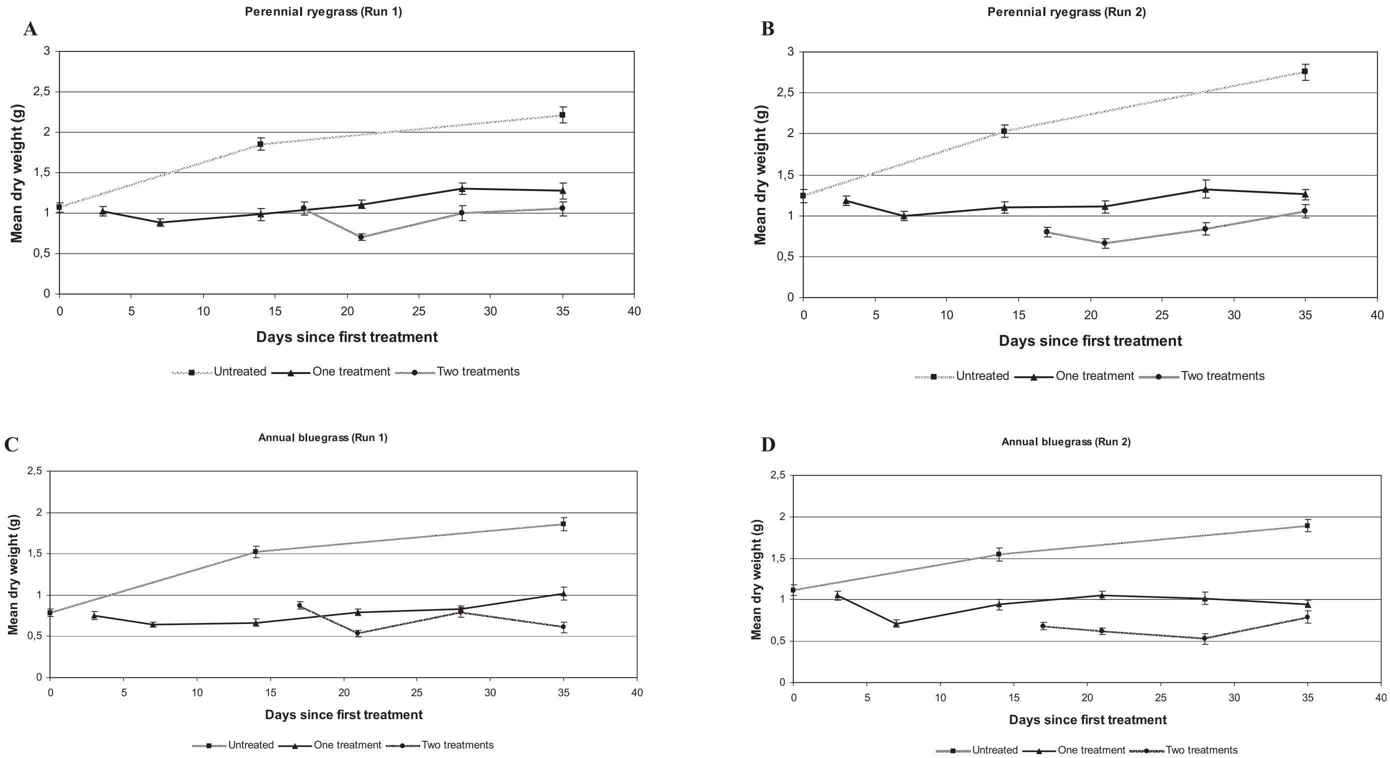

Figure 2. Mean leaf dry weight of perennial ryegrass (a = run 1, b = run 2) or annual bluegrass (c = run 1, d = run 2). Each dot represents the mean dry weight of 36 plants. Control plants were harvested on days 0, 14, and 35 after the experiment was started. All the other plants were treated with a gas burner on day 0. After 3, 7, 14, 21, 28, and 35 d half of the plants were harvested. The other half of the plants was treated a second time with a gas burner 3, 7, 14, or 21 d after the first treatment. These plants were harvested 14 d later to measure regrowth capacity. Bars indicate mean standard errors.

flame treatment, regardless of developmental stage or propane dose. In our experiments a fixed dose of 80 kg gas ha^{-1} was used. Ulloa et al. (2010a, 2010b) found that about 85 and 86 kg ha^{-1} were needed for 90% dry matter reduction in five-leaf green foxtail (*Setaria viridis* [L.] Beauv.) and four-leaf yellow foxtail (*Setaria glauca* [L.] Beauv.). None of the doses they tested (up to 87 kg ha^{-1}) could provide 90% dry matter reduction in foxtail species at flowering stage, and the grasses started regrowing 2 to 3 wk after flaming. In another study (Ulloa et al. 2010b), 76 kg ha^{-1} of propane was necessary to obtain 90% reduction for seven-leaf barnyardgrass (*Echinochloa crus-galli* Beauv.), but a 90% reduction at the flowering stage was not possible within the selected propane dose interval of up to 87 kg ha^{-1}.

In the present study, assessment of flaming was done by weighing the plants after harvest. However, nondestructive methods like image analysis (counting number of green pixels) or measuring light reflectance from the green parts of the canopy could have been useful to measure the living plant material. Plants that seemed to be affected by flaming (smaller and with many withered leaves but still alive) weighed almost the same as plants that were less affected. The main reason was that the base of the grass leaves weighed much more than the leaves, so even removal of the withered leaves before weighing may not have changed dry weights much. Differences in treatment effects may have been larger if another assessment method was used, but nontreated plants always weighed substantially more, which indicated that dry weights did reveal the effects of the treatments.

Effects of Second Treatment. Generally, a second flaming treatment reduced biomass of perennial ryegrass in comparison with plants that were only flamed once (Figures 3a and 3b). The greatest reduction in aboveground biomass from two flaming treatments in comparison with one flaming treatment was observed when the treatment interval was 7 d (37% biomass reduction in run 1, and 41% biomass reduction in run 2). However, this decrease was not significantly lower when plants were treated at 14-d intervals ($P = 0.09$) or 21-d intervals in run 1, or 3- or 14-d intervals in run 2.

Generally, regrowth of annual bluegrass was not lower after a second flaming treatment in run 1 (Figure 3c). When the plants had received a second treatment within 3 d, regrowth was actually higher after the second flaming treatment in comparison with plants that had been flamed only once. Treatment intervals of 7 or 21 d reduced biomass by 32% or 40%, respectively, in comparison with plants that had been flamed once. In run 2, there was a decrease in biomass when annual bluegrass was flamed twice, regardless of treatment interval (Figure 3d). Treatment intervals of 7 or 14 d resulted in the greatest effect of flaming. The smallest effect of the second flaming treatment was observed when the treatment interval was 21 d, although not significantly lower than after a 3-d treatment interval.

Effect of Time Intervals. In both experiments, 7-d treatment intervals resulted in the lowest regrowth of perennial ryegrass (Figures 3a and 3b). In run 1, there was no difference among flaming intervals of 3, 14, or 21 days. In run 2, perennial

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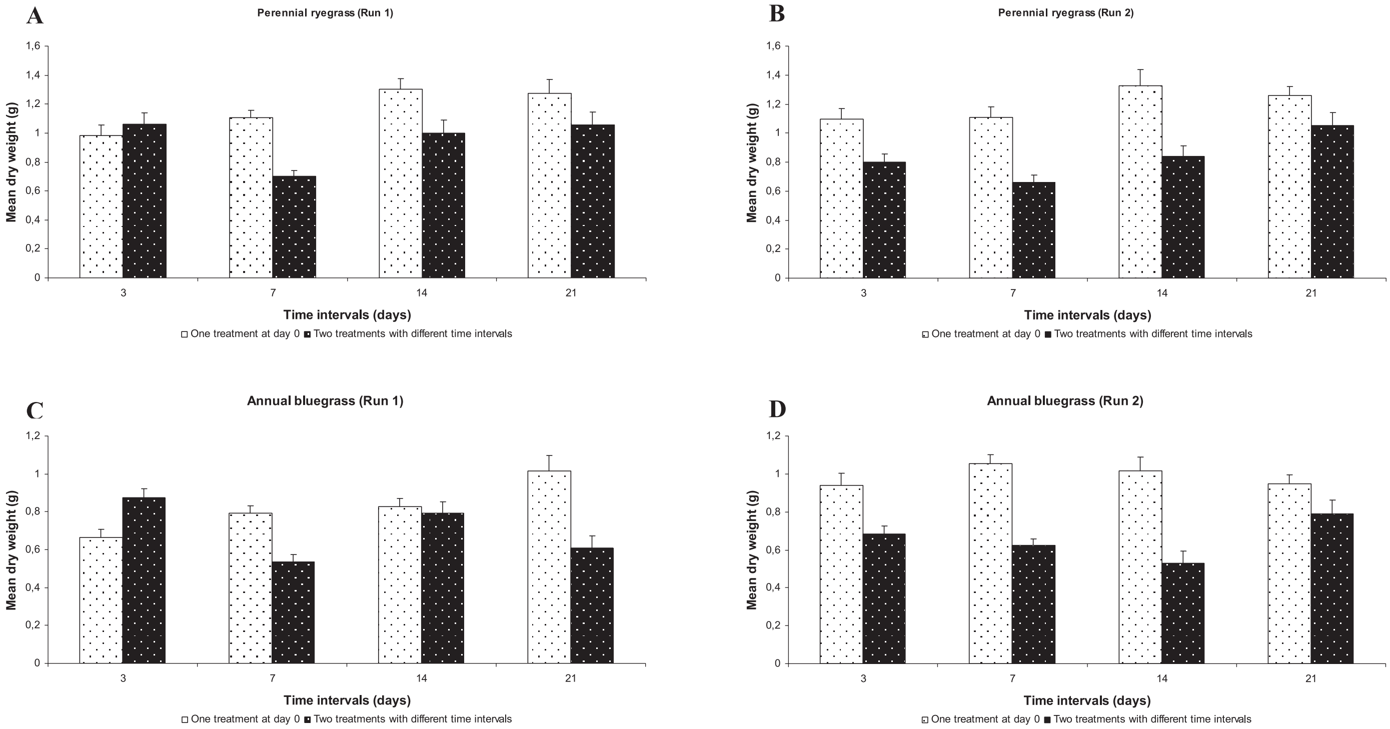

Figure 3. Effect of second treatment on two flaming treatments compared with plants that have only been flamed once. The light dotted bars show the biomass in g dry weight of plants that have been flamed once. The dark bars show the biomass in g dry weight of plants that have been flamed either 3, 7, 14, or 21 d apart. (a) Perennial ryegrass, run 1; (b) perennial ryegrass, run 2; (c) annual bluegrass, run 1; (d) annual bluegrass, run 2. Bars indicate mean standard errors.

ryegrass plants had the highest regrowth capacity after a 21-d treatment interval.

The effect of treatment intervals on regrowth of annual bluegrass was less conclusive (Figures 3c and 3d). In run 1, treatment intervals of 7 and 21 d resulted in the lowest regrowth of annual bluegrass. There was no difference between flaming at a 3- or 14-d interval. In run 2, regrowth of annual bluegrass was highest when plants had been flamed with treatment intervals of 3 and 21 d. However, there was no difference between treatments with 3- or 7-d intervals.

The effect of short time intervals was smaller than expected. A second treatment generally reduced biomass of both species (except annual bluegrass in run 1); however, regrowth was expected to increase more than it actually did, with increasing time between treatments (Figures 2a–d). Generally, however, this was not observed in the experiments, perhaps because of the time of the year. The experiments were performed late in the season (end of July to mid-September), and whether the results would be the same in spring remains to be investigated. How treatment intervals longer than 21 d affect biomass production both in spring and late in the season should be explored.

The experiments were carried out on plants in their first year of growth. Therefore perennial ryegrass had not built up much root biomass yet and may have behaved more like an annual weed than a perennial weed. Further studies are currently being carried out on older plants of perennial ryegrass to investigate the long-term effect of flaming on this species.

Effect on Flower Production. Flaming resulted in a substantial reduction in number of flowering annual bluegrass plants (Figure 4). All control plants set flowers 14 d after the first treatment, whereas about 50% of the plants that were flamed once set flowers. After two flaming treatments only few plants set flowers during the 4-wk period. The effect on flower production of annual bluegrass is important, as it reproduces quickly by seeds. The seeds can germinate and grow at low temperatures, which enables many generations per year (Warwick 1979). Reducing seed production by flaming thereby can decrease the spread of this weed markedly.

In summary, flaming reduced biomass substantially, but only few plants were killed. There was relatively more effect of the first flaming treatment than of the second. A flaming interval of 7 d reduced regrowth of perennial ryegrass the most, whereas the effect of treatment intervals on annual bluegrass varied between the two runs of this experiment. Very short treatment intervals (3 d) should be avoided, as these did not reduce weed biomass in comparison with 7-d treatment intervals.

Treatment intervals of 3 or 7 d rarely would be used in practice. Hansen et al. (2004) found that 11 to 12 treatments per growing season were necessary to achieve acceptable weed control on areas heavily infested with perennial weeds, resulting in treatment intervals of about 1 to 2 wk. Usually treatment intervals of 2 to 5 wk are suggested (Kreeb and Warnke 1994; Rask and Kristoffersen 2007; Kristoffersen et al. 2008a). However, as a 7-d interval between the first and second treatment led to the lowest regrowth of perennial ryegrass in the present study, this interval may be desirable to increase control of this grass weed. Thus, the number of treatments during the rest of the growing season possibly

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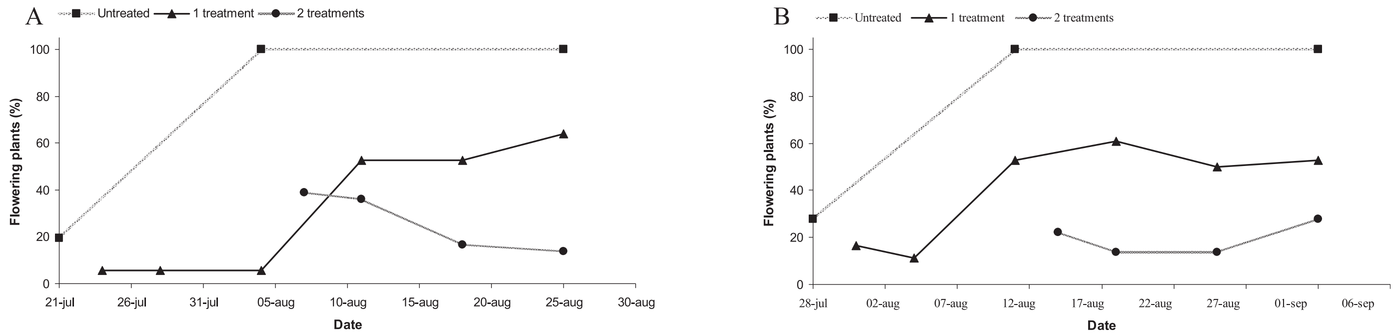

Figure 4. Percentage annual bluegrass plants with flowers at each harvest date. Plants were nontreated control, flamed once with a gas burner, or flamed twice at different time intervals with a gas burner. (a) Run 1; (b) run 2.

could be reduced. Nevertheless, differences in effect between time intervals were relatively small in this study. Therefore, it should be investigated further whether a 7-d interval between the first two treatments actually would reduce the number of required treatments during the rest of the season. Additional research is required to address the effect of several repeated flame treatments on the grass species.

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