RESEARCH PAPER

Fine-tuning of a mowing regime, a method for the management of the invasive plant, *Ambrosia artemisiifolia*, at different population densities

IVANA MILAKOVIC[1]★, KONRAD FIEDLER[2] and GERHARD KARRER[1]

[1]*Institute of Botany, Department of Integrative Biology and Biodiversity Research, University of Natural Resources and Life Sciences and* [2]*Department of Botany and Biodiversity Research, University of Vienna, Vienna, Austria*

Common ragweed (*Ambrosia artemisiifolia*) is an invasive annual plant with highly allergenic pollen. Its spread in introduced and native ranges often occurs on roadsides, where it builds stable and rapidly growing populations. The most sustainable way of controlling the population size of this species is to prevent seed production in order to deplete the soil seed bank. Populations on roadsides are submitted to regular mowing management, which can even exacerbate the situation by inducing resprouting after cutting or by accidentally spreading seeds along the road. The population density in the juvenile stages of development could play an important role in the success of cutting regimes, as it might influence the resprouting capacity of this plant. The influence of the juvenile population density and of seven cutting regimes, differing in the timing and frequency of cuts, on easily measurable reproductive traits was investigated in a glasshouse experiment. The cutting regimes had a strong influence on the reproductive success and on the phenology of the development stages of ragweed. The population density in the juvenile stages did not play a role in further phenological development, but did influence the reproductive traits. The reproduction of ragweed can be lowered by locally adapted combinations of the timing and frequency of mowing. As the optimal management option for the reduction of both the male and female flowers, the authors suggest a first cut just before the start of male flowering, followed by subsequent cuts every 3–4 weeks.

Keywords: annual, common ragweed, neophyte, reproduction, weed.

Ambrosia artemisiifolia L. (common ragweed) is an annual Asteraceae species. This ruderal plant, introduced to Europe from North America, grows on warm and disturbed sites. It shows salt tolerance at the germination stage of growth (DiTommaso 2004). This probably explains its massive occurrence in the vegetation of road shoulders, which are treated with de-icing salt and therefore represent unfavorable habitats for salt-intolerant species. This invasive plant is spreading all over Eurasia (Kazinczi *et al.* 2008); often, the spreading occurs massively along roads (Chauvel *et al.* 2006; Essl *et al.* 2009; Vitalos & Karrer 2009; Joly *et al.* 2011). *Ambrosia* has a high economical impact: its pollen causes allergies and asthma, the treatment of which can be very costly and it causes yield loss in different crops, such as sunflower, soy and pumpkin (Taramarcaz *et al.* 2005; Brandes & Nitzsche 2007; D'Amato *et al.* 2007; Zwerger & Eggers 2008).

The sustainable control of *A. artemisiifolia* is difficult because a single plant can produce ≤62,000 seeds (Dickerson & Sweet 1971). The seeds can persist in a germinable state in the soil for ≤39 years (Toole & Brown 1946). Some seeds become dormant after seed set and accumulate in the soil, forming a soil seed bank,

which provides seeds that can germinate in the following years when abiotic conditions are favorable. The management solutions for the control of this weed species therefore must aim at a continuous depletion of the soil seed bank. Mowing is the most common control measure in roadside vegetation. The vegetation must be mown for visibility and security reasons, as the use of herbicides is often prohibited by law because of environmental concerns. The influence of different mowing practices on the growth and reproduction of *A. artemisiifolia* is quite complex. This annual plant usually reacts to mowing like a perennial plant by resprouting from the basal buds that remain on the main axis below the cutting height (Brandes & Nitzsche 2007; Bohren *et al.* 2008). The timing of the cut can be essential. If done too early, mowing could enhance the production of male flower heads (Beres 2004). If done too late, the seeds might already have ripened before the cut (Bohren *et al.* 2008). Too-frequent mowing can cause this phenomenon as well (Vitalos M. & Karrer G., 2009, unpublished data). The spread of this plant along roadsides is massive and very quick. Vitalos and Karrer (2009) showed that the seeds that stick to the dirt on mowing machines are numerous and they possibly spread for several kilometres. The management of ragweed by mowing has been tested mostly for the effect of cutting, compared to no cutting. In contrast, very little is known as to how mowing regimes with more than one cut during the vegetation period, at various times during plant phenology, can affect ragweed reproduction (Beres 2004; Bohren *et al.* 2008; Patracchini *et al.* 2011; Simard & Benoit 2011). Also, little is known about the variation in the reproductive traits of ragweed in relation to intraspecific competition (Gebben 1965; Simard & Benoit 2011; Leskovšek *et al.* 2012).

In this study, it was hypothesized that variation in the timing and frequency of cuts and in population density can influence the plant reproductive traits of ragweed. Furthermore, it was expected that the plants that grow in dense populations in their juvenile stage would have more elongated first internodes and consequently fewer nodes remaining on the staples after mowing, so that resprouting could not be as successful as for the plants that grow in low-density populations. The high-density-grown plants therefore are expected to produce fewer flowers after cutting. The impact of the variation in the timing and frequency of mowing on the reproductive traits of ragweed individuals that originated from high-density, compared to low-density, populations was studied, as those traits serve as a basis for the development and refinement of cutting regime management methods. The hypothesis is that the precisely adapted timing and frequency of management can break the life cycle of ragweed by preventing seed production, progressively depleting the soil seed bank. The authors consider that knowledge about the reproductive traits of individual plants is essential for the successful control of the size of ragweed populations.

The following questions specifically were addressed in this study:

1 How do different mowing regimes affect the number of male inflorescences and female flowers?
2 Does the population density in the juvenile stage play a role in the reproductive success of *Ambrosia*?
3 Do the juvenile population density and cutting regime influence the phenological development of Ambrosia plants?
4 Which recommendations for management practice can be drawn from the results?

MATERIALS AND METHODS

The experiment was conducted in semi-open glasshouse conditions in 2009. The seeds that were used for the experiment were collected from a single ruderal population near Vienna, Austria (Seyring; 48°19′50.8′′N, 16°30′09.8′′E, 164 m a.s.l.) in fall 2008, naturally dried at room temperature for 1 month and then stored in darkness at 4°C. The plants were sown in early April 2009 in two different densities that are representative for natural populations along roadsides (Leitsch-Vitalos M. & Karrer G., 2009, unpublished data); that is, 153 seeds m^{-2} (low density) and 728 seeds m^{-2} (high density). The plants were grown in these densities for 12 weeks and subsequently transplanted into individual pots (17 cm high, 13 cm in diameter). The individually potted plants were positioned equally spaced on tables without further differences in density. After transplanting, seven cutting regimes (varying in the timing and frequency of cutting) and one control (no cutting) were applied to both the high-density and the low-density groups (see Table 1). Each combination of treatment and density consisted of ten *Ambrosia* individuals. The plants were cut at a height of 8 cm above the substrate surface in order to simulate the mowing conditions on roadsides. After the last cut at the end of September, most of the plants had died or no longer grew.

The following response variables were measured for all the individuals in all the groups at three dates, in mid-August, early September and at the end of September, always just before the cutting term:

1 The number of female flowers (regardless of their developmental stage) per individual.

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Table 1. Plan of the cutting treatments

Cutting treatment	Cuts			
	July 9	August 17	September 8	September 29
1 (control; no cut)				
2	x†		x	
3	x			x
4		x	x	
5		x		x
6			x	x
7	x		x	x
8		x	x	x

† Cuts are represented by the letter x.

2 The number of male inflorescences per individual (each consisting of several flower heads arranged as spikes).
3 The phenological stage of the male inflorescences.
4 The phenological stage of the female flowers.

The scale that was used for the male phenology was: 1 = no flower; 2 = flowers are present but not yet in anthesis; 3 = flowering (the anthers are liberating pollen); and 4 = withered. For the female phenology, the scale that was used was: 1 = no visible flower; 2 = flowering; the stigmata are visible and not dry; 3 = seeds are developing (in the ripening process) and the stigmata are dry; and 4 = the seeds are dropping off. As most plants simultaneously possess flowers in different phenological stages, the most advanced phenological stage that was present on each individual was always recorded. The withered female flowers (i.e. "seeds") were considered to be potentially ripened and the "dropping-off seeds" were considered to be ripened.

For simplicity, in this article the term "female flowers" is used consistently, regardless of their phenological stage. At some assessment times, "female flowers" thus can refer to flowers, fruits or seeds, depending on their developmental stage.

The distribution of the phenological stages in the cutting treatments in July before the application of the cutting treatments is shown in Figure 1a.

Statistical analysis

The mean numbers of female flowers and male inflorescences were compared across treatments for August and two dates in September. The number of female flowers was compared only at the beginning and at the end of September. The data were analyzed by general linear model (GLM) procedures in the package, Statistica 10.0 (StatSoft 2011), using Gaussian distribution models for continuous predictors. As independent categorical factors, the treatment and juvenile density were always included in the models. The data for the number of female flowers per plant for early September and for the end of September were log-transformed in order to meet normality assumptions, whereas the data for the number of male inflorescences at the end of September were log $(x + 2)$-transformed. The inspection of residuals (Q:Q plots, frequency distributions) revealed a reasonable fit of the data to the statistical model assumptions in all the GLMs that were tested. The association of male and female phenology with the management treatments was analysed with contingency tables, using Pearson's χ^2-tests.

RESULTS

Male inflorescences

The number of male inflorescences per plant in August was associated with the juvenile population density (Table 2). The plants that were grown at a high population density during their juvenile stage had fewer male inflorescences per plant than the plants that initially were grown in the low-density populations (Table 3). In early September, the number of male inflorescences per plant was related to the cutting treatment (Table 2). The plants in cutting treatments 4, 5 and 8, cut for the first time in August, now had noticeably fewer male inflorescences than those in the other cutting treatments (Fig. 2b). At the end of September, the number of male inflorescences per plant was influenced by the juvenile density and the cutting treatment (Table 2). The plants that issued from the high-density populations had fewer male inflorescences than those from the low-density populations (Table 3). The plants of the uncut treatments 1 and 3 had far more male inflorescences on average than all the others (Fig. 2c).

Female flowers

The number of female flowers per plant in early September was associated with the cutting regime and with the juvenile population density (Table 4). The plants that were grown in the high-density populations during their juvenile stage had fewer female flowers per plant than the plants that initially were grown in the low-density populations (Table 3). The female inflorescence numbers varied across the cutting treatments in a manner
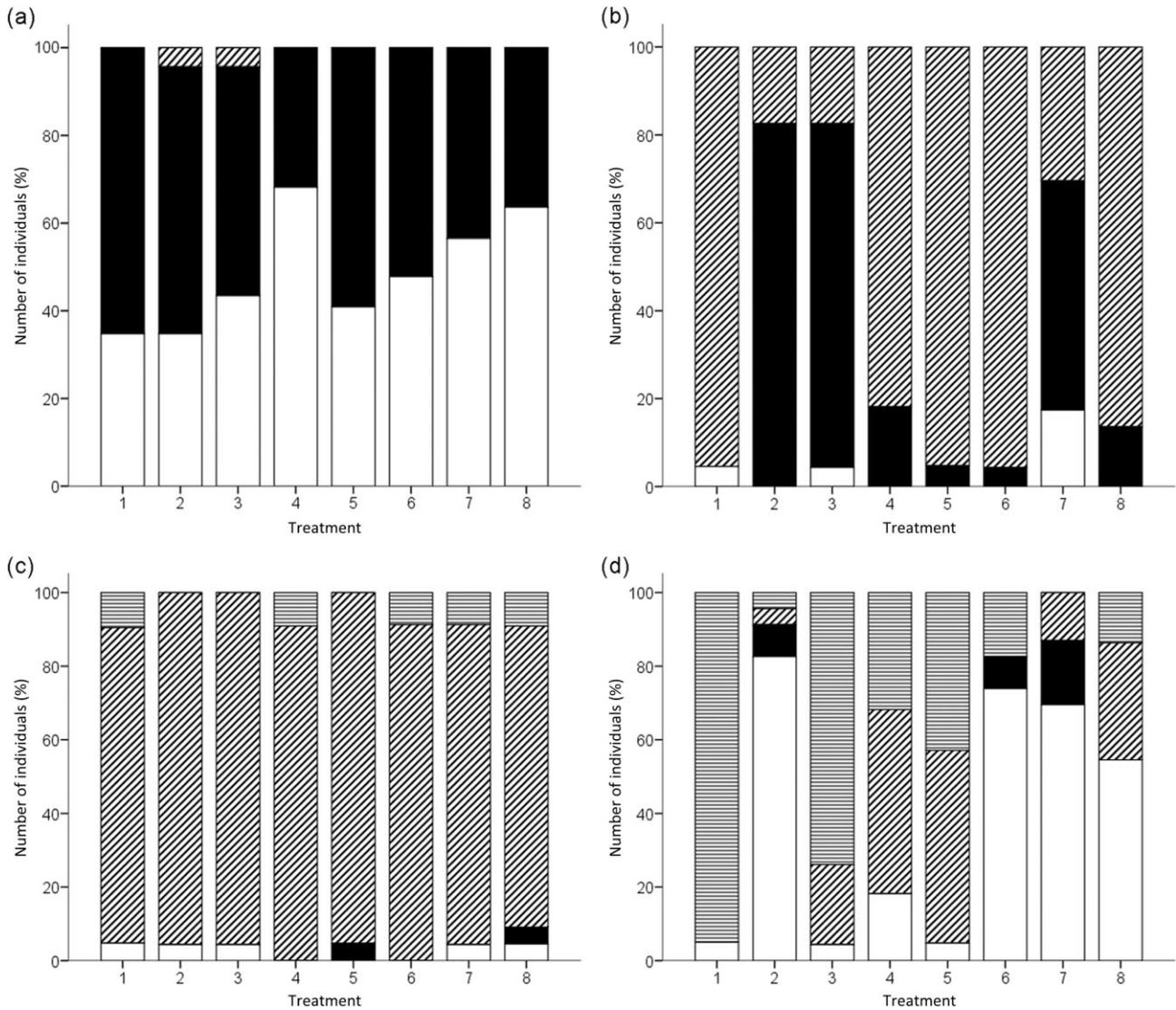
Fig. 1. Percentage of ragweed individuals in the different phenological stages of male inflorescences, according to treatment group: (a) in July, (b) in August, (c) in early September and (d) at the end of September. The vertical bars show the percentage of ragweed individuals. (□), No inflorescence; (■), inflorescences that were not yet flowering; (▨), inflorescences that were flowering; (▤), inflorescences that had withered.

Table 2. General linear model results for the number of male inflorescences per ragweed individual

Effect	August			Early September			End of September		
	d.f.	*F*-value	*P*-value	d.f.	*F*-value	*P*-value	d.f.	*F*-value	*P*-value
Treatment	7	1.49	0.173	7	20.74	**<0.001**†	7	108.12	**<0.001**
Density	1	19.48	**<0.001**	1	1.30	0.256	1	4.81	**0.029**
Treatment × density	7	1.27	0.269	7	1.68	0.118	7	1.40	0.208

† Values in bold represent significant results.

Table 3. Sample sizes, means and standard errors of the measured variables of individually potted *Ambrosia artemisiifolia* plants, according to their initial cultivation density

Inflorescence (time)	Low cultivation density			High cultivation density		
	N	Mean	Standard error	N	Mean	Standard error
Male inflorescences (August)	89	72.5	4.5	90	46.9	4.0
Male inflorescences (early September)	88	49.0	4.4	90	42.3	4.2
Male inflorescences (end of September)	87	19.0	3.4	90	14.1	2.8
Female flowers (early September)	88	281.7	25.9	90	213.9	16.7
Female flowers (end of September)	87	185.4	24.2	90	176.7	19.0

similar to that observed with the male inflorescences. The plants that were from cutting treatments 4, 5 and 8, cut for the first time in August, exhibited much fewer female flowers than those from the other cutting treatments (Fig. 2d). At the end of September, the number of female flowers per plant was significantly related to the cutting treatment and to the interaction of treatment and density (Table 4). The uncut control plants, as well as the cutting treatment 3 plants, showed up to fourfold higher the average number of female flowers than the plants in the other cutting treatments at this census term (Fig. 2e).

Phenology

The male phenology varied significantly across the cutting treatments in August and at the end of September (Table 5). In August, cutting treatment groups 2, 3 and 7, which had been cut in July (3 weeks before the August measurement), had a more delayed phenological development than those in the other cutting treatments: >70% of individuals were not yet in anthesis at this date (Fig. 1b). The plants in cutting treatments 1, 4, 5, 6 and 8 were more advanced in their phenological development of male inflorescences: >80% of individuals were already in anthesis in August (Fig. 1b). In early September, the cutting treatments did not differ significantly in the distribution of their phenological stages (Table 5, Fig. 1c). At the end of September, the plants in cutting treatments 2, 6, 7 and 8 comprised relatively more non-flowering individuals than the plants in the other cutting treatments (between 54 and 91% of individuals in these former treatments were non-flowering; Fig. 1d).

The female phenology likewise was significantly affected by the cutting treatment (Table 6). In August, cutting treatments 2, 3 and 7 (first cut in July) comprised mostly non-flowering individuals. Overall, most of the cutting treatments did not have many individuals

bearing seeds at that time, except for control treatment 1 (Fig. 3). In early September, groups 4, 5 and 8 (cut in the preceding month) had the fewest individuals with seeds (Fig. 4). In cutting treatments 2, 3 and 7 (first cut in July), few individuals were already starting to have ripened seeds at this date. In contrast, the uncut cutting treatments 1 (control) and 6 (first cut just after that census) had the highest percentages of seeding individuals (Fig. 4). At the end of September, the cutting treatments with the lowest proportions of individuals bearing ripe seeds were those in which the plants were cut in early September (i.e. cutting treatments 2, 6 and 7). Cutting treatments 4 and 8, in which the plants were cut for the first time in August, had ≤50% of the individuals bearing ripe seeds, whereas cutting treatments 1 (control), 3 and 5 had 80–100% of the individuals bearing ripe seeds (Fig. 5).

At each census term, neither the male nor the female phenology was related to the initial juvenile plant density (Tables 5 and 6).

DISCUSSION

The plants that were grown in the high-density populations in their juvenile phase generally had fewer male inflorescences than those that were grown in the low-density populations. Possibly, the lower amount of available resources, caused by high intraspecific competition in the juvenile life stage, had lasting effects on the fitness of the plants. Indications in this direction have already been published by Patracchini *et al.* (2011), who observed a lower flower biomass at higher ragweed population densities, but these authors did not report on the statistical significance of their findings. An effect of plant spacing on reproductive traits was also suggested by Gebben (1965), who found evidence of higher numbers of staminate heads per plant at lower population densities, but again without indications on statistical
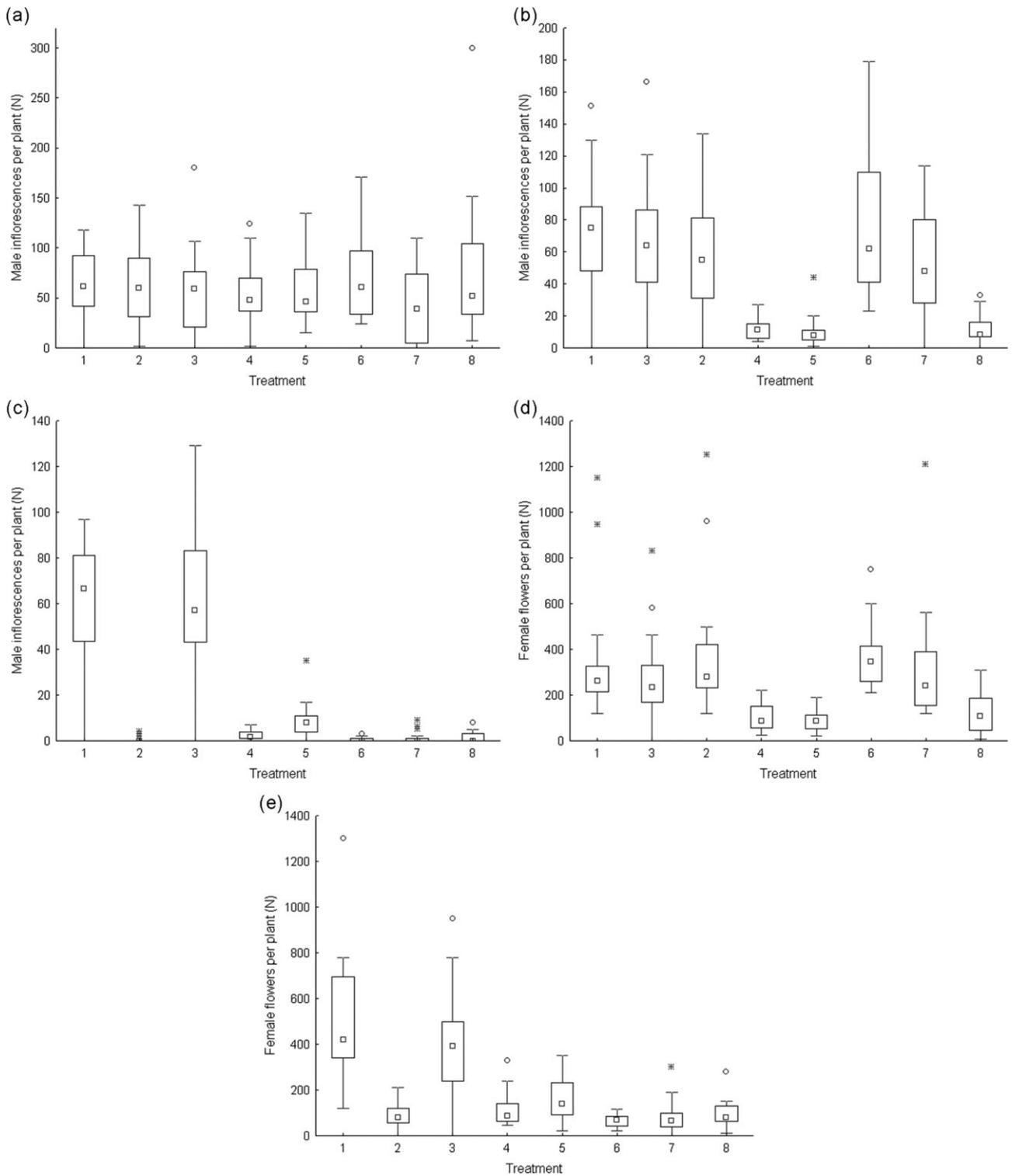
Fig. 2. Boxplots of the number of male inflorescences per ragweed individual in August (a), early September (b), end of September (c) and of the number of female flowers per plant in early September (d) and at the end of September (e) for plants under different cutting treatments. Small square, median; box, 25–75% percentiles; whiskers, area without outliers; circle, outlier; star, extreme.

Table 4. General linear model results for the number of female flowers per ragweed individual

Effect	Early September			End of September		
	d.f.	F-value	P-value	d.f.	F-value	P-value
Treatment	7	16.97	**<0.001†**	7	16.27	**<0.001**
Density	1	8.50	**0.004**	1	0.35	0.554
Treatment × density	7	1.12	0.355	7	2.70	**0.011**

† Values in bold represent significant results.

Table 5. Results of the contingency table analyses for the frequency distribution of the male phenological stages, according to the initial ragweed density and cutting treatment

Time	Density			Treatment		
	χ^2-value	d.f.	P-value	χ^2-value	d.f.	P-value
August	0.81	2	0.668	106.98	14	**<0.001†**
Early September	2.63	3	0.452	15.75	21	0.783
End of September	0.97	3	0.808	144.34	21	**<0.001**

† Values in bold represent significant results.

Table 6. Results of the contingency table analyses for the frequency distribution of the female phenological stages, according to the initial plant density and cutting treatment

Time	Density			Treatment		
	χ^2-value	d.f.	P-value	χ^2-value	d.f.	P-value
August	1.53	2	0.465	95.83	14	**<0.001†**
Early September	1.89	3	0.595	67.70	21	**<0.001**
End of September	2.04	3	0.564	99.69	21	**<0.001**

† Values in bold represent significant results.

significance. Also, Leskovšek *et al.* (2012) observed a decrease in male inflorescence biomass with increasing plant density in uncut ragweed populations; however, they did not state its significance level. In this study, the density did not play a role in male flowering phenology. The results of this study confirm the findings of Deen *et al.* (1998) and of Simard and Benoit (2011), who also did not observe any effect of density on phenological traits.

The number of male inflorescences was strongly related to the cutting treatment in this study. In August, all the cutting regimes had rather high numbers of male inflorescences, but cutting treatments 2, 3 and 7 were more successful than the others as they had a delay in phenology: 60–80% of the plants in those cutting treat-ments were not releasing pollen yet. Thus, if manage-ment aims at the reduction of pollen production, then a first cut in August is too late, as ≥80% of the plants that had not been cut before August now already were releasing pollen. In early September, the plants that were cut in August had five–eightfold less inflorescences than those in the other cutting treatments. In late September, the plants that were cut 3 weeks before had practically no male inflorescences, suggesting that within 3 weeks they could not develop new male inflorescences. As some of the cutting treatments were most effective in August and others were shown to be more effective in early September, it was concluded that the most effec-tive regime for reducing the number of male inflores-cences should combine the tested treatments. The plants
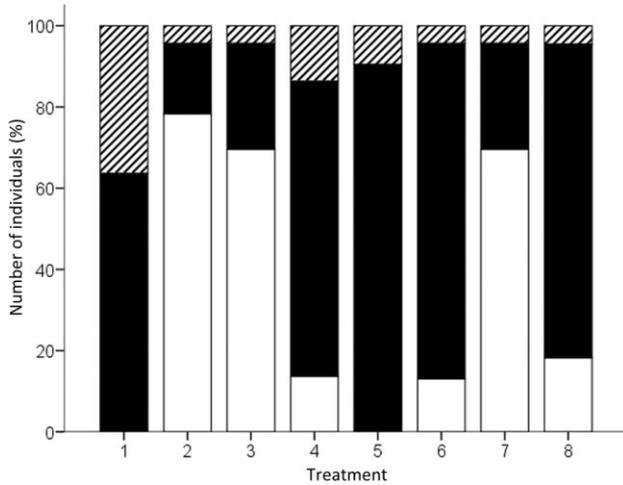
Fig. 3. Percentage of ragweed individuals in the different phenological stages of female flowers, according to the treatment group, in August. (□), No visible flower; (■), flowering; (▨), seeds.
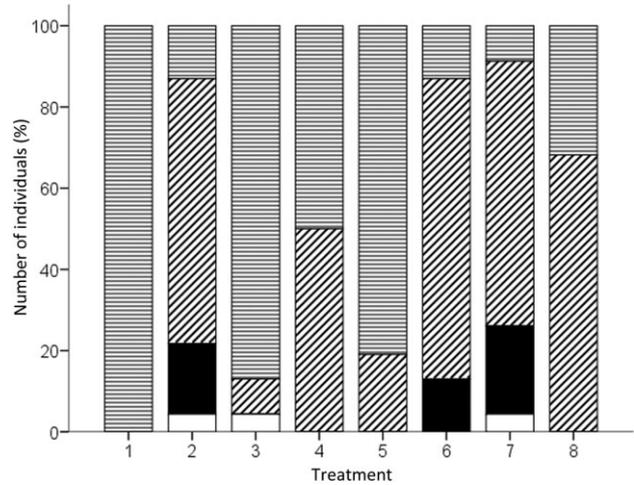

Fig. 5. Percentage of ragweed individuals in the different phenological stages of female flowers, according to the treatment group, at the end of September. (□), No visible flower; (■), flowering; (▨), seeds; (▤), seeds falling out.
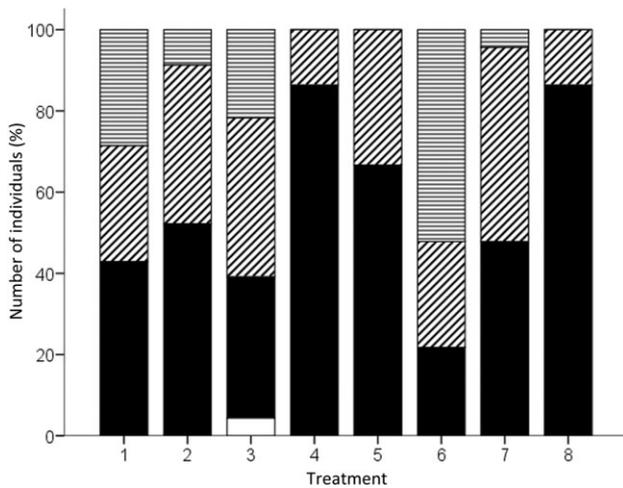

Fig. 4. Percentage of ragweed individuals in the different phenological stages of female flowers, according to the treatment group, in early September. (□), No visible flower; (■), flowering; (▨), seeds; (▤), seeds falling out.

should be cut in July just before the male flowering and then the cuts should be repeated every 3–4 weeks in order to prevent new male inflorescences from reaching anthesis.

For the female flowers, the cutting treatments were found to be effective at both relevant measuring terms (the beginning and end of September). The patterns were the same as for the male inflorescences. In early September, cutting treatments 4, 5 and 8 (all plants cut for the first time in mid-August) had the fewest numbers of female flowers per plant. Although the average number of female flowers per plant was not negligible in those cutting treatments, their phenology was not yet very advanced: in cutting treatments 4 and 8, only ~15% of the plants had seeds by early September. Therefore, the authors still consider that these cutting treatments are quite successful in controlling the number of seeds being produced.

At the end of September in all the cutting treatments (except 1 and 3), the number of female flowers was lowered. But, when taking into account the phenological stage of the flowers, cutting treatments 2, 6 and 7 were the most successful. They were associated with the lowest numbers of plants (~10–15%) bearing seeds that might have ripened. The authors suggest that this amount could be lowered even further by cutting plants 1 or 2 weeks earlier in September.

In none of the cutting treatments could the level of flower production be reduced to zero, most probably because of the height of the cut, which allowed regenerative shoot growth and a certain number of seeds to be produced below the cutting height. The phenological development, however, of the regrown organs was influenced by the cutting regime. Cutting treatments 2, 4, 7 and 8 were the most successful for sustainable ragweed control, but always at only one of the measurement dates. Cutting treatments 4 and 8, with a late first cut in August, could be improved by later successive mowing every 3 weeks, as the ragweed plants were able to mature the remaining seeds quickly after this cut.

Probably, the plant stubs and roots that were developed by the time of this first cut were already relatively rich in stored resources and allowed for the quick recovery and development during the following month, unless interrupted by a subsequent mowing.

In searching for the best management solution (aiming at a combination of reduced pollen release and prevention of seed production), the authors conclude that the most effective cutting regime under the climatic conditions of eastern Austria should be a combination of the herein-tested cutting regimes. Ragweed plants should be cut first in July, just before the anthesis of the first male flowers, and then cut twice subsequently (every 4 weeks) after this first cut. The total prevention of seed production by cutting will never be possible in natural ragweed populations as a cutting height below the cotyledonar node cannot be implemented in management practice.

In habitats with dense vegetation that is competing with ragweed, it can be assumed that the intraspecific competitive effect of a high population density can be extrapolated to the interspecific competition with the surrounding vegetation (Milakovic & Karrer 2011). Hence, the frequent practice of early spring mowing should be avoided; rather, the first cut should be delayed as far as possible towards male anthesis, ideally until the end of July in eastern central Europe. This method also could decrease the mowing costs in spring and at the same time it would help to minimize the number of male inflorescences on the plants in the critical flowering period.

The phenological status of ragweed plays a very important role in the improvement of management strategies. The results of this study show that the phenological stage of ragweed can be modulated by cutting, but this is not related to the juvenile population density. The cutting dates that were used in this experiment were developed as a compromise between biological optimization and the practical aspects of applicability in the field. For efficient management, the phenological development of the target populations must be monitored to set the cutting dates correctly. For instance, the date of the first cut (to prevent male flowering) might vary across regions by 4 weeks and across years within one region by 3 weeks.

As the plants in roadside populations grow with limited resources in comparison to glasshouse conditions, it can be supposed that their recovery after mowing would not be as vigorous and that their growth and phenological development would not be as fast. Also, the cutting height in field populations might vary, depending on the regularity of the soil surface and the machines that are used. These factors can strongly influence the success of ragweed control by cutting under field conditions (Milakovic et al. 2014).

In order to find the most effective and sustainable management solution, a compromise between several aspects must be found. Reducing the number of flowering male inflorescences and preventing seed production simultaneously might result in contradicting solutions. Optimal results can be achieved by setting the first cut just before the start of male anthesis, followed by subsequent cuts every 3–4 weeks, depending on the favorability of the habitat. This joins the basic idea of Bohren et al. (2008) of one late mowing. However, a very late first cut, for instance in September, is not a reasonable solution for roadside populations, as it will induce the spread of already-ripened seeds or the post-harvest ripening of seeds (Karrer et al. 2012); that is, if the biomass is not removed after the cut. Besides, in many countries, the vegetation along roads must be maintained below a certain height for traffic security reasons.

ACKNOWLEDGMENTS

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