Biological control of Mediterranean sage \((Salvia aethiopis)\) in Oregon

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Summary

Mediterranean sage, \(Salvia aethiopis\) L., is a serious naturalized invasive plant of rangelands in the sagebrush steppe in the Pacific Northwest area of the United States. Two species of weevils, \(Phrydiuchus\) \(tau\) Warner and \(Phrydiuchus\) \(spilmani\) Warner, were introduced from Europe as classical biological control agents. Only \(P.\) \(tau\) established and was widely redistributed throughout the region. Our observations show that, after the establishment and population increase of the weevil, densities of Mediterranean sage decreased at three of the four initial release sites and subsequently at 17 of 25 weevil release sites where plant densities dropped 2–5 orders of magnitude from \(>1/m^2\). Level of control appears to be associated with a combination of plant community type, disturbance and grazing intensity. The decline in weed density was most apparent in the sagebrush steppe community with light to no grazing. In comparison, salt desert scrub, annual grass dominated and heavily grazed communities showed little change in Mediterranean sage density over 25 years. This is the first report of successful biological control against Mediterranean sage.

Keywords: successful management, range improvement, weevil, \(Phrydiuchus\) \(tau\).

Introduction

Target plant

Mediterranean sage, \(Salvia aethiopis\) L. (Lamiaceae), is a pungent herbaceous monocarpic, biennial weed, naturalized in the United States from its native range in southern and southeastern Europe (Tutin et al., 1972; Mijatovic, 1973; Davis, 1975; Roche and Wilson, 1999). The plant has been observed and studied in xeric ruderal habitats in Yugoslavia, Bulgaria, Greece, Turkey and Iran, and was occasionally observed in similar habitats in France, Italy and Spain (Andres and Drea, 1963).

Mediterranean sage and several of its allies have been imported and cultivated in the United States for use as ornamentals and medicinal herbs (Bailey, 1935). Mediterranean sage was first reported in North America from California in 1892 (Howell, 1942) and was suspected of being introduced as a contaminant in alfalfa seed (Dennis, 1980). It has since spread and become a serious range pest in Oregon, California and Idaho and a minor problem in Washington, Colorado, Texas and Arizona (Wilson et al., 1994; Coombs and Wilson, 2004). The major infestation in the United States occurs in the Goose Lake Basin in southern Lake County, OR, and northern Modoc County, CA (Andres et al., 1995). Overall infestations were estimated at 510,000 ha in seven Oregon counties (Radtke and Davis, 2000), 2800 ha in northeastern California, 1600 ha in northern Idaho (Wilson et al., 1994) and 120 ha in Colorado (Mower, 1996). Infestations have also been recorded in South Dakota, Arizona and Texas.

Mediterranean sage reproduces only by seed, sprouting in the fall or spring after rains provide adequate soil moisture for seedling survival. Young plants overwinter as rosettes and typically bolt in late spring and flower mid-June to early July. Smaller rosettes may overwinter for a second year without flowering (Wilson and McCaffrey, 1993). Mature plants grow to 20–90 cm tall, producing up to 100,000 seeds. Seeds are dispersed during the late summer and fall after the stalks break off and are blown about as tumbleweeds.

In Oregon, the majority of Mediterranean sage occurs in early successional communities in the sagebrush...
vascular tissues of the root crown, which results in the petiole into the root crown. Larval feeding can sever leaves (Andres, 1966; Wilson and McCaffrey, 1993). The midribs and petioles on the undersides of rosette leaves (Andres et al., 1995), followed by an intensive redistribution program in Oregon by the Oregon Department of Agriculture Agricultural Research Service (USDA-ARS) in 1958 (Andres and Drea, 1963). The life history of *P. tau* is as follows: (1) continue monitoring the original four ARS release sites, (2) assess efficacy at early ODA regional release sites, (3) document trends of Mediterranean sage density, (4) document the relationship of *P. tau* numbers to plant density and (5) compare trends of plant density to site characteristics and land use.

**Biological control agent**

Foreign exploration to search for natural enemies of Mediterranean sage was conducted in Turkey and Iran. A weevil, later described as *Phrydichus tau* Warner (Coleoptera: Curculionidae), was found (Andres and Drea, 1963; Andres and Riza, 1965; Andres, 1966; Warner, 1969). A second species, *P. spilmani* Warner (Warner, 1969), was found feeding on *Salvia verbenacea* L. in Italy. During feeding trials, *P. spilmani* also accepted *S. aethiopis* as a host.

Both species of weevils were introduced in the United States as classical biological control agents for Mediterranean sage (Andres et al., 1995). A total of 631 adult *P. spilmani* were collected in Italy and released in Oregon from 1969 to 1970. Although several recoveries of adults were made, the weevil failed to establish (Andres et al., 1995). A total of 1650 adult *P. tau* were introduced from Yugoslavia and released in Oregon from 1971 to 1973 (Andres et al., 1995). *P. tau* readily established, and the sites provided surplus weevils that were shipped to California in 1972 (Andres et al., 1995), Idaho in 1979 (Wilson and McCaffrey, 1993) and Colorado in 1992 (Mowrer, 1996). A limited local redistribution began in Oregon and California in 1976 (Andres et al., 1995), followed by an intensive redistribution program in Oregon by the Oregon Department of Agriculture (ODA) from 1979–1983 (Coombs et al., 1996; Turner and Coombs, 1996).

The life history of *P. tau* was studied as part of the process of assessing its efficacy as a biological control agent. The weevil is univoltine, producing one generation per year. In the fall, females oviposit along the midribs and petioles on the undersides of rosette leaves (Andres, 1966; Wilson and McCaffrey, 1993; Coombs and Wilson, 2004). The newly hatched larvae penetrate the plant epidermis and tunnel down the leaf petiole into the root crown. Larval feeding can sever vascular tissues of the root crown, which results in the suppression of flowering and seed production. Severe larval feeding can result in plant death (Andres, 1966).

In the spring (June), the mature larvae exit the rosette and construct a spherical chamber of soil particles in which they pupate. Adults emerge after several weeks and feed on the foliage and flowers before entering a period of summer dormancy (aestivation) until fall rains stimulate plant growth. In the fall, adults feed, mate and deposit eggs on rosettes (Andres, 1966; Wilson and McCaffrey, 1993).

Biological control has come under some scrutiny because of the lack of monitoring efficacy and non-target effects (McEvoy and Coombs, 2000). To document the overall efficacy of the Mediterranean sage biological control project, we determined that there was a need to conduct additional evaluation beyond the original release site studies. Our project objectives were to: (1) continue monitoring the original four ARS release sites, (2) assess efficacy at early ODA regional release sites, (3) document trends of Mediterranean sage density, (4) document the relationship of *P. tau* numbers to plant density and (5) compare trends of plant density to site characteristics and land use.

**Methods and materials**

**Original release sites**

Initial observations of plant and insect interactions were conducted by Andres and cooperators in southern Lake County, OR, near the town of Lakeview. The climate is characterized by wet winters and dry summers. The average annual precipitation in the Lakeview area is 36 cm. Four sites served as the original release sites for *P. tau*. The criteria for selection were heavy infestations of Mediterranean sage (>1 m²), and representative of the variety of plant communities and land use in the area. Three sites: (1) Geyser, about 1.5 km north of Lakeview; (2) Cottonwood, 13 km west of Lakeview and (3) Killer Hill, 6.5 km south of Lakeview, were classified as sagebrush steppe, encompassing dense to open grassland intermixed with dense to open shrub. The fourth site, Dick’s Creek, 24 km north of Lakeview, is in a yellow pine-shrub forest that was logged 10 years before the release of *P. tau*. Unfortunately, several years of data from the ARS studies were lost during a relocation of the USDA-ARS offices at the Albany, CA facility. Furthermore, the Killer Hill site was infrequently visited because it was difficult to relocate.

Periodic visits were made to the four original release sites, usually in early November to (1) estimate the density of rosettes per square metre, (2) conduct a timed count of the number of adult weevils observed per observer hour and (3) estimate percent ground cover by rosettes. No data were taken between 1980 and 1991. Plant density and percent cover were determined by using a 1/4-m² quadrat frame placed on the ground every 4 m along established transects. Twelve readings...
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were made along each cardinal direction for a total of 48 plots per site per visit. Weevil counts were obtained by counting the number of adults observed per minute in each transect to determine number of weevils per observer hour.

**Regional release sites**

After the establishment of *P. tau* at the original release sites, a programme of collection, redistribution and monitoring was conducted by ODA. By November of 1976, populations of *P. tau* at the Cottonwood site reached >100 adults collected per hour. Weevils from that site were redistributed throughout infestations in Oregon and California. In the following years (1979 to 1983), ODA and cooperators made releases of *P. tau* throughout the region. The objective was to release weevils at all heavily infested townships and in each major drainage system. Some collection and redistribution efforts were made by ODA during later years at new and isolated infestations and for releases in other states (Coombs and Wilson, 2004).

The collections of *P. tau* adults for redistribution were primarily conducted during the mating period in November. Weevils were sorted into groups of 100 adults and placed into containers provisioned with tissue paper and host plant foliage. Releases occurred within several days of collection at Mediterranean sage infestations ≥0.5 ha and a minimum density of 1.0 m$^2$.

In the summer of 1995, a field survey was conducted at 25 sites where *P. tau* had been previously released by ODA from 1979 to 1983. Only sites that could be positively located from maps on the original release forms were selected. Each site was inventoried for (1) estimating plant density by using 1 m$^2$ quadrats or actual counts at low densities within 1000 m$^2$, (2) determining the number of adult *P. tau* observed per minute, (3) assessing present land use and degree of grazing, rated as none, light (<50% use) and heavy (>50% use) and (4) documenting plant community type. The apparent degree of control of Mediterranean sage based on density of plants square metre was categorized as: poor, ≥1.0; fair, 0.99–0.1; good, 0.09–0.01; and excellent, <0.009. The sites were periodically sampled from 1999 to 2006 to determine the stability of control and to assess variability within plant populations.

**Results**

The weevil, *P. tau*, established at all four of the original ARS release sites. Weevils from these sites were later collected and released at numerous infestations in the region. Since the inception of the project, density and percent cover of Mediterranean sage has declined by several orders of magnitude at most sites in the Goose Lake Basin but not in the lower and drier Abert Lake Basin. The following are some of the early results that depict the interaction of weevil-plant dynamics through time at the original release sites and regional release sites. Plant community types and land use interactions will be analyzed in future works.

**Original release sites**

Original plant density at the release sites varied from 3.2 to 12.4 m$^2$ at the time of weevil release (Fig. 1).

![Figure 1. Density changes log$_{10}$ of Mediterranean sage at the four original USDA-ARS study sites. Triangles: Killer Hill site, a heavily over-grazed site that has changed little since the release of *Phrydiuchus tau*. Zero data were entered as 0.0001.](image-url)
Subsequent monitoring of the Mediterranean sage density showed a slight downward trend during the first 5 years among the four sites (Fig. 1). By 1992, plant densities had decreased to less than 1 m\(^2\). From year 2000 on, plant densities remained less than 0.01 m\(^2\) at all sites, except Killer Hill, which was heavily grazed each winter by livestock.

We measured plant density, cover and weevil numbers at the Geyser site and found cover and weevils correlated with plant density (Fig. 2). The weevil population increased to more than 100 per observer hour at two of the sites from 1976 to 1978. After this peak, weevil numbers dropped to 1.3 per observer hour by 1993. By 1993, plant density had dropped to 0.02 m\(^2\). No plants or weevils were found at the Geyser site during the July 1995 visit (Fig. 2). In 1999 and in 2000, several plants with adult feeding were observed but none in 2001 samples, as the site had been recently mowed and sprayed with herbicides to control other species of weeds. The Geyser site was representative of the trends that we observed in Dick’s Creek and Cottonwood sites, in that weevil numbers increased and later decreased as plant density decreased. However, the heavily grazed Killer Hill site changed little in 25 years (Fig. 1).

**Regional survey**

More than 120 releases of *P. tau* occurred from 1979 to 1983, which were collected at the original ARS release sites. After these releases, casual inspections by various cooperators revealed that the weevil was widespread throughout the Mediterranean sage infested area. In 1995, we determined that 25 release sites were amenable to quantitative monitoring to document changes over time (Table 1). Variations in Mediterranean sage densities appear to be associated with plant community type and community disturbance history (grazing intensity, fire, road construction and agriculture). The lowest Mediterranean sage densities observed were at sites that consisted of perennial grass/shrubs with no-to-light grazing. Conversely, we observed higher densities of Mediterranean sage at sites characterized by salt desert scrub and annual grasses. At sites with heavier grazing pressure (\(\geq 50\%)\) biomass removal of perennial grasses), control of Mediterranean sage (0.5–0.05 mature plants/m\(^2\)) was better in communities with a strong perennial grass component. The poor control of Mediterranean sage in the ungrazed areas was due partly to historic heavy grazing, having reduced the perennial grasses, and more to recent fires, which allowed the invasion of annual grasses. Again, the lack of competition and resetting the successional clock were likely factors.

In the 1995 survey, 12 sites were not grazed, five were lightly grazed and nine were heavily grazed (Table 1). It appears that heavy grazing reduces the amount of plant competition against Mediterranean sage plants weakened by the biological control agent. Caution should be used when comparing these sites, as our inventory was not designed to cover an equal number of sites in each category.
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Of the regional release sites, 12 were dominated by perennial grasses and shrubs and 13 had a large component of annual grasses (Table 1). Four of the sites had no detectable level of Mediterranean sage (three were shrub/perennial grass communities and one was in agricultural production). In contrast, the highest density of Mediterranean sage (>1.0/m²) remained in salt desert scrub and shrub/annual grass communities, irrespective of grazing. When compared to the original minimum density estimate 1.0 mature plant per square metre, 68% of the survey sites showed reductions of Mediterranean sage of one to three orders of magnitude. We are more concerned about the numbers of mature plants at sites because they produce seed and contribute to rising generations.

Among the 25 sites visited in 1995, 16 sites were periodically re-inventoried through 2006. We observed two distinct patterns in Mediterranean sage density through time based on plant community type (Fig. 3). One pattern was a precipitous drop in Mediterranean sage from the initial estimated plant density (>1 m²; Fig. 3). The second pattern exhibited a stable trend of Mediterranean sage density over time in plant communities that had high components of annual grasses, mostly due to recent disturbances (fire and heavy grazing). From 1995 through 2006, Mediterranean sage con-

Table 1. Comparison of the level of biological control of Mediterranean sage, plant community type and grazing levels at 25 Phrydichus tau regional release sites in Oregon in 1995.

<table>
<thead>
<tr>
<th>Control level</th>
<th>Number of sites</th>
<th>Community type</th>
<th>Grazing intensity</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Shrub/perennial grass</td>
<td>Heavy</td>
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<tr>
<td>Excellent</td>
<td>6</td>
<td>Shrub/perennial grass</td>
<td>0</td>
</tr>
<tr>
<td>Good</td>
<td>4</td>
<td>Shrub/perennial grass</td>
<td>1</td>
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<tr>
<td>Fair</td>
<td>4</td>
<td>Shrub/annual</td>
<td>3</td>
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<tr>
<td>Poor</td>
<td>3</td>
<td>Salt scrub/annual grass</td>
<td>2</td>
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<tr>
<td></td>
<td>2</td>
<td>Shrub/perennial grass</td>
<td>1</td>
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<td>4</td>
<td>Shrub/annual</td>
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<td></td>
<td>2</td>
<td>Salt scrub/annual grass</td>
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<tr>
<td>Total</td>
<td>25</td>
<td></td>
<td>9</td>
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* Control level = average mature plants per square metre; poor, ≥1; fair, 0.99–0.1; good, 0.009–0.01; excellent, ≤0.009.
* Community type – based on dominant species: shrub = Artemisia tridentata, Purshia tridentata; salt scrub = Sarcobatus vermiculatus, Atriplex confertifolia; perennial grass = Agropyron cristatum, Festuca idahoensis; annual grass = Bromus tectorum, Taeniatherum caput-medusae.
* Grazing intensity – utilization of above ground biomass: heavy, ≥50%; light, ≤50%.

Figure 3. Changes in plant density (log₁₀) of ODA regional release sites (n = 25) over time. The large rectangle represents a conservative estimate of density of Mediterranean sage at release of Phrydichus tau and during the 5 or 6 years after release of P. tau. Circles represent salt desert scrub sites in the Abert Lake Basin with high annual grass component and triangles represent Goose Lake Basin sites with high perennial shrub/grass components. Zero data were entered as 0.0001.
tinued to decline to the point that, by 2006, nine sites exhibited excellent control (≤0.009 mature plants/m²). Most severe infestations typically have two to five mature plants and five to 15 rosettes per square metre. As original mature plant density estimates were ≥1.0/m², our conservative appraisal of control may underestimate the effectiveness of *P. tau*. By 2006, 17 of the 25 ODA regional release sites inventoried showed a reduction in Mediterranean sage density of more than 90%, with nine sites near 99%. One mature plant per square metre was considered as the economic threshold level to justify control measures.

In 2005, after a period of heavy late spring rains, Mediterranean sage populations in the annual grass dominated salt desert scrub community in the Abert Lake basin flourished (1.5/m²), and we expected to see a large increase of Mediterranean sage the following year. However, outbreak-level populations of *P. tau* severely defoliated rosettes and flowering plants (50–90% defoliation). Monitoring in 2006 showed an average reduction of mature plants to 0.1 m², which we attributed to the heavy impact by the weevils.

Discussion

Smith and DeBach (1942) identified three criteria essential for evidence of successful biological control. The Mediterranean sage biological control project meets two of those criterions. First, the densities of Mediterranean sage declined after the introduction, establishment and increase of *P. tau*. In fact, two sites used by ODA personnel to collect *P. tau* in the late 1980s were no longer viable in 1994 because the host plants were nearly eliminated. Second, the levels of Mediterranean sage for the most part have remained at low levels after the establishment and increase of *P. tau*. The third criterion, to show that the target weed would return to its original density when the weevils are removed, remains to be experimentally tested.

Populations of *P. tau* established and increased at the four original study sites, later followed by a decrease in the density of Mediterranean sage and eventually a decrease on *P. tau*. Following a lag time of 10 to 20 years after redistribution of the weevils, reductions of Mediterranean sage density occurred throughout much of the Lakeview area. The majority of landowners, managers and county extension agents we consulted agreed that the overall density of Mediterranean sage in the Lakeview Valley was much lower than before *P. tau* was released.

Our studies suggest that larval destruction and weakening of Mediterranean sage rosettes, supplemented with the stress of competing perennial vegetation, were the main causes of control. Plant competition appears to play an important role in enhancing Mediterranean sage control. Best control occurred in those communities with a strong perennial grass component. Conversely, despite weevil presence, wherever recent fires and heavy grazing had reduced the vigour of competing grasses, the level of Mediterranean sage remained troublesome or decreased slightly. Mediterranean sage sites in some salt desert shrub and annual grass communities (dominated by *Bromus tectorum* L. and *T. caput-medusae* L.) showed little change from their original densities. Plant competition and other environmental stress factors, including limited rainfall that can impact Mediterranean sage (Wilson et al., 1994), contributed little to control before introduction of *P. tau*. Some fluctuation in the density of Mediterranean sage is to be expected, but most sites under good to excellent control have not returned to initial pre-*P. tau* levels. We estimate that 68% of the original release sites were controlled, inverting an annual forage loss of about $0.8 M over 508,000 ha.

Despite successful biological control at many sites in south central Oregon, Mediterranean sage continues to flourish and infest new and isolated areas in northern Oregon and several western states. Although many of those smaller infestations have been targeted for intensive control, *P. tau* has been released and recovered at some. Impacts of *P. tau* in those areas should be monitored. The ability for Mediterranean sage to spread and prosper at disturbed sites suggests that additional natural enemies should be sought to improve control. Mediterranean sage is seed limited; therefore, seed destroying biological control agents may prove more effective in areas where *P. tau* is insufficient.

Without long-term monitoring, the biological control of Mediterranean sage may have been forgotten and its efficacy never demonstrated. This can be a difficult task when old biological control projects span across the careers of multiple scientists, agency priorities and funding commitments.

Acknowledgments

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