

Mating disruption of the ambrosia beetle *Megaplatypus mutatus* in poplar and hazelnut plantations using reservoir systems for pheromones

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Abstract

Megaplatypus mutatus (Chapuis) (Coleoptera: Curculionidae: Platypodinae) is an ambrosia beetle native to South America, but it has recently been introduced into Italy and represents a serious problem in commercial poplar and fruit tree plantations. Male *M. mutatus* emit a sex pheromone composed of (+)-6-methyl-5-hepten-2-ol [(+)-sulcatol], 6-methyl-5-hepten-2-one (sulcatone), and 3-pentanol. We performed three field trials of mating disruption of *M. mutatus* in hazelnut and poplar plantations in Argentina and Italy. To perform these tests, we made plastic pheromone reservoir-type dispensers for sulcatol, sulcatone, and 3-pentanol with zero-order kinetics that were deployed in the field during the female flight period. The number of galleries where mating took place was significantly higher in control than in treated areas, indicating that pheromone application had interfered with female behavior and male localization. Because damage reduction was >56% in both countries, these results demonstrate the potential for the strategy of pheromone-mediated mating disruption of *M. mutatus* in commercial poplar and hazelnut plantations. Also, our study provides the first evidence for successful pheromone-mediated mating disruption in a forest beetle.

Introduction

Mating disruption is a pest management technique based on the release in the field of large amounts of synthetic sex pheromones with the aim of disrupting the sexual communication between insects. It is frequently used for controlling lepidopteran pests, but it has seldom been exploited for coleopteran species. Trudel et al. (2004) showed that hand deployment of bubblecaps containing the female-produced pheromone, pityol, reduced damage by the cone beetle, *Conophthorus coniperda* (Schwarz), in white pine orchards, and the sex pheromone of oriental beetles (Scarabaeidae) was used for mating disruption in cranberries (Wenninger & Averill, 2006).

Megaplatypus mutatus (= *Platypus mutatus*) (Chapuis) (Coleoptera: Curculionidae: Platypodinae) is an ambrosia beetle native to South America (Wood, 1992, 1993). Unlike most other ambrosia beetles, it attacks healthy young trees, boring galleries into the wood and introducing its symbiont fungus *Raffaelea santoroi* Guerrero (Ophiostomatales) (Bascialli et al., 1996). These galleries subsequently weaken the tree's stem, causing it to break under extreme stress and representing a serious problem in poplar, *Populus deltoides* Marshall (Salicaceae), commercial plantations (Alfaro et al., 2007; Achinelli et al., 2005). Furthermore, the dark staining of the tunnels caused by the decaying ambrosia mycelium reduces the quality of wood for export.

The population dynamics of *M. mutatus* suggests a bivoltine emergence in Argentina (Gatti et al., 2008b), and this pattern is also observed in Italy (H Funes, unpubl.). Although external temperature affects the duration of the various life stages (Santoro, 1963), in central Argentina

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and southern Italy, *M. mutatus* starts to fly in search of new host by the beginning of spring and by the end of summer. This species exhibits protandry (earlier emergence of males than females).

Host colonization by *M. mutatus* is initiated when a male penetrates the bark and excavates a gallery that is a few centimeters long. With the particles of sawdust (frass) it produces, the male beetle builds a crown-like arrangement surrounding the entrance to the gallery, from where it releases volatile emissions that attract females (Santoro, 1963; Milligan & Ytsma, 1988; Gonzalez-Audino et al., 2005; Gatti-Liguori et al., 2008a). This call to females commences 2 days after colonization and ends approximately 10 days later, when pheromone emission ceases altogether (Gatti et al., 2011). If the female detects the calling male (CM), she lands at the entrance hole of the gallery, is accepted by the male, and mating soon takes place. After mating, the couple continues extending the parent gallery inwards perpendicular to the tree surface following the annual rings and depositing sawdust at the gallery entrance. This sawdust is clearly distinguishable from the pre-mating one (Santoro, 1963), as is explained in the materials and methods section. When the gallery becomes long enough, females start to lay their eggs in a staggered manner (Santoro, 1963). Depending on the external temperature, hatched larvae feed on tree xylem and develop into pupae in 2–3 months. Adults fly as soon as they emerge without feeding.

In previous studies, we showed that male volatile emissions are composed of (+)-6-methyl-5-hepten-2-ol [(+)-sulcatol], 6-methyl-5-hepten-2-one (sulcatone) (Gonzalez-Audino et al., 2005), and 3-pentanol (Gatti-Liguori et al., 2008a). These compounds were demonstrated to be attractive to beetles both in the laboratory (Gonzalez-Audino et al., 2005) and in the field (Funes et al., 2009a; González Audino et al., 2011). Racemic sulcatol may be used in replacement of (+)-sulcatol, as the (–)-isomer does not interfere with its attracting capacity (Funes, 2009b).

Megaplatypus mutatus was introduced into Italy in 1998 (EPPO/OEPP, 2004, 2007; Tremblay et al., 2000) causing great concern because poplar plantations are a highly important economic resource. In 2000, it was detected in *Populus canadensis* (Moench) in the Campania region (Caserta province). The risk of dispersal of *M. mutatus* to other regions of Europe and its corresponding potential damage (Alfaro et al., 2007) is of great concern to European regulatory authorities, who added it to the EPPO/OEPP Alert List in 2004, and in 2007 recommended treating it as a quarantine pest (Allegro & Griffio, 2008; EPPO/OEPP, 2004, 2007).

Several factors favor the potential success of pheromone-based management of *M. mutatus*: it is monoga-

mous, relatively immobile because females do not leave the host tree after they mate (Santoro, 1962), and its pheromones are produced at relatively low-cost, stable in-field conditions during the flight period, and can be formulated to be deployed in controlled release devices. Here, we describe the results of three field trials of mating disruption of *M. mutatus* in hazelnut and poplar plantations in South-America and Europe.

Materials and methods

Pheromone dispensers

Analytical grade (98%) sulcatone, (±) sulcatol, and 3-pentanol (Aldrich, Saint Louis, MO, USA) were added to reservoir-type dispensers. In these systems, the pheromone is stored in a reservoir in contact with a rate-controlling polymeric membrane, unlike in monolithic or matrix systems where the pheromone is homogeneously dissolved and/or dispersed in a polymer matrix. For monitoring trials, the baits had low release rates (7–30 mg per day). For sulcatol and 3-pentanol, we used rectangular polyethylene bags, and for sulcatone, we used glass vials with polyethylene semipermeable cap (Funes et al., 2009a) (Table 1). The bags or vials were filled with 0.5–2 ml of pheromone and sealed with heat. In the case of bags, this had to be done carefully, as getting pheromone into the seal prevents its sealing properly. These dispensers had a constant release rate (zero-order kinetics) until total consumption as is usual for diffusion-controlled membrane-moderated reservoir systems (Tojo, 1985) and as we demonstrated in our previous work (Funes et al., 2009a). Baits were hung in the traps.

For mating disruption trials, the baits had high release rates (60–100 mg per day). To obtain the necessary surface, we studied the correlation between pheromone release rate and permeable surface of the dispensers, and performed regression analysis of release rate vs. permeable surface [Microsoft Office 2002 and Microcal-Origin working model (version 6.0) 1999; Microcal Software, Northampton, MA, USA; <http://www.microcal.com>]. To measure the release rate of the dispensers in the laboratory, the weight loss per day in a wind tunnel (27–28 °C, 0.5 m s⁻¹) was monitored until pheromone depletion. Three replicates of each permeable surface and each pheromone were measured for weight loss per day.

Dispensers that were used in the field were selected based on the release rates obtained for different surfaces. For sulcatone and 3-pentanol, we used rectangular bags made with a non-permeable side (high-density polyethylene of 80 µm; PBB Polisur, Buenos Aires, Argentina) and a semipermeable side (low-density polyethylene of 40 µm). For sulcatol, we built bags with two semipermeable sides

Table 1 Mean release rate (mg per day \pm SE) of pheromone lures containing sulcatone, 3-pentanol, or sulcatol, at 27–28 °C and 0.5 m s⁻¹ in a laboratory wind tunnel

Compound	Type of dispenser	Effective release area (cm ²)	Release rate (mg per day)	Initial pheromone load (ml)	Field trial
Sulcatone (6-methyl-5-hepten-2-one)	Glass vials with polyethylene semipermeable cap	0.2	6.68 \pm 0.63	0.5	M
	Polyethylene bags	12	63.20 \pm 0.07	1.5	MD
3-Pentanol	Polyethylene bags	20	29.84 \pm 1.8	1	M
	Polyethylene bags	64	91.20 \pm 0.18	2	MD
(\pm) Sulcatol [(\pm)-6-methyl-5-hepten-2-ol]	Polyethylene bags	16	11.27 \pm 0.51	0.5	M
	Polyethylene bags	128	79.40 \pm 0.23	2	MD

M, monitoring; MD, mating disruption.

(low-density polyethylene of 40 μ m). The pheromone dispensers were attached to trees 1.6 m above the ground in sets of three, one for each component and adjacent to each other and distributed uniformly throughout each treatment plot at a density of 20 sets per ha. This resulted in release rates of about 1.26, 1.82, and 1.58 g per ha per day for sulcatone, 3-pentanol, and sulcatol, respectively. Devices were checked weekly and replaced before total depletion.

Field trial locations

Junín, Buenos Aires, Argentina. Dispensers were deployed between November 19, 2007 and January 24, 2008 (67 days) in a commercial poplar (*P. deltoides*, Australiano clone I29/60) plantation located in Morse, Junín, Province of Buenos Aires, Argentina (34°43'56.3"S, 60°51'11.5"W) at an elevation of 59 m a.s.l. The experimental area consisted of 12 ha of a 10-year-old plantation with a density of 625 trees per ha (4 \times 4 m spacing) and a mean (\pm SE) diameter at breast height (dbh) of 30.8 \pm 0.49 cm. Treatment and control plots were each 1 ha in area, located at the extremes of the diagonal line crossing the plantation with a distance of 1 400 m between them.

Caserta, Campania, Italy. Field trials were performed during the 2008 summer season in Caserta, Campania Region, Italy, in a poplar plantation and a hazelnut plantation. The plantations were located in Falciano del Massico (41°09'07"N, 13°57'54.3"E, and 38 m a.s.l.). In the poplar plantation, dispensers were deployed from 26 May to 19 June. In the hazelnut plantation, dispensers were deployed from 12 May to 16 June.

The poplar field [*Populus* \times *euroamericana* (Dode) Guinier Louisa Avanzo clone] consisted of 0.8 ha of an 11-year-old plantation with a density of 494 trees ha⁻¹ (4.5 \times 4.5 m spacing) and a mean dbh of 26.6 \pm 0.95 cm. Treat-

ment and control plots were 0.3 ha in size and separated by at least 100 m (Sower et al., 1982). Although the test plots were relatively small, this limitation was difficult to avoid, as plantations in Italy are typically very small. Fortunately, there is no risk of dispersal of mated females because they do not leave the host tree after mating and remain in the gallery until death (Santoro, 1962), thereby making the infestation of nearby plantations unlikely.

The hazelnut field [*Corylus avellana* L. San Giovanni clone (Betulaceae)] consisted of 4.8 ha of a 16-year-old plantation, with a density of 444 trees ha⁻¹ (4.5 \times 5 m spacing). Treatment and control plots were of 0.5 ha in size and 300 m apart. The percentages of mating disruption obtained in the three experimental areas were not averaged because each test relates to a different location with different site conditions and population levels.

Flight period detection

To determine the beginning of the female flight period to time pheromone deployment, we monitored the population using pheromone-baited traps (Funes et al., 2009a). The temporal monitoring was performed in a plantation adjacent to the experimental one with the same clones at Junin and Campania. In the Argentine trials, 30 self-made CIPEIN-F-type cross-vane traps were deployed, made of two acrylic panels in a cross-arrangement above a funnel (as used in Funes et al., 2009a), and in Italy 20 Mastrap® (Isagro, Milan, Italy) cross-vane traps. All traps were checked every 3 days.

Damage assessment

Two parameters were used to evaluate damage by *M. mutatus*: mated galleries (MG) and active galleries (AG). MG are galleries where a male initiated attack, lured a female, mating took place, and both male and female extend the gallery length inwards. These galleries ranged from 5 to 10 cm long in a straight line with no twists and with the

female in the lead position (Santoro, 1962). In case of doubt, the presence of the female was confirmed. After a couple of months, MG become AG. Then, AG are the entrance holes where a male initiated attack, lured a female, mating took place, females laid their eggs, offspring were produced, and feeding larvae expelled the sawdust outside. The characteristic gallery frass is composed of disaggregated particles of irregular shape and flourish aspect (0.13–0.15 mm) (Santoro, 1963) (Figure 1), and the length of the gallery is more than 6 cm. In each case, the length of the gallery was measured with a small calibrated wire.

Both AG and MG still contain the male and the female and represent galleries that achieved successful mating. To survey AG, it is necessary to wait for about 2 months until the larval development is achieved. In some cases (trials in Italy), we could not access the experimental zone for that long, so we surveyed only MG after treatment instead of AG + MG.

Megaplatypus mutatus damage in control and pheromone-treated plots was assessed before placing the pheromone devices and from 10 to 35 days after the end of the experiment. The prior assessment is necessary so that relative differences in damage between pre- and post-treatment may be compared between control and treated plots. Damage assessment was carefully carried out before the

trial by examining tree trunks, identifying AG, and numbering them individually. In each experimental area, in both treated and control plots, we randomly sampled 30% of the trees (Sower et al., 1982). We assigned every tree a number, and afterward we picked random numbers until reaching 30% of the individuals. The surveillance of galleries was performed up to 2 m high for each tree. Old galleries (dry) from previous seasons were also marked to avoid confusion when the galleries were quantified later on.

To test the possibility of introducing another damage assessment parameter, in the Campania field trial, we also quantified the new galleries with a calling live male inside that exhibited the characteristic crown arrangement of sawdust (Figure 1). In this case, the sawdust particles were needle shaped, 2–3 mm long, and 0.13–0.15 mm wide (Santoro, 1963). This response variable allowed us to test whether male behavior at host location was affected by the presence of high amounts of male pheromone in the environment. Calling males are only detectable in poplar trees as in the case of hazelnuts, the crown arrangement of sawdust is not formed on the surface of the tree. Therefore, CM was only evaluated in poplar plantations.

Damage was expressed as mean number of MG, AG, and/or CM per tree, and the means of treated and control areas were compared by a t-test after the trial (STATISTICA 5.0; StatSoft, Tulsa, OK, USA). To standardize the

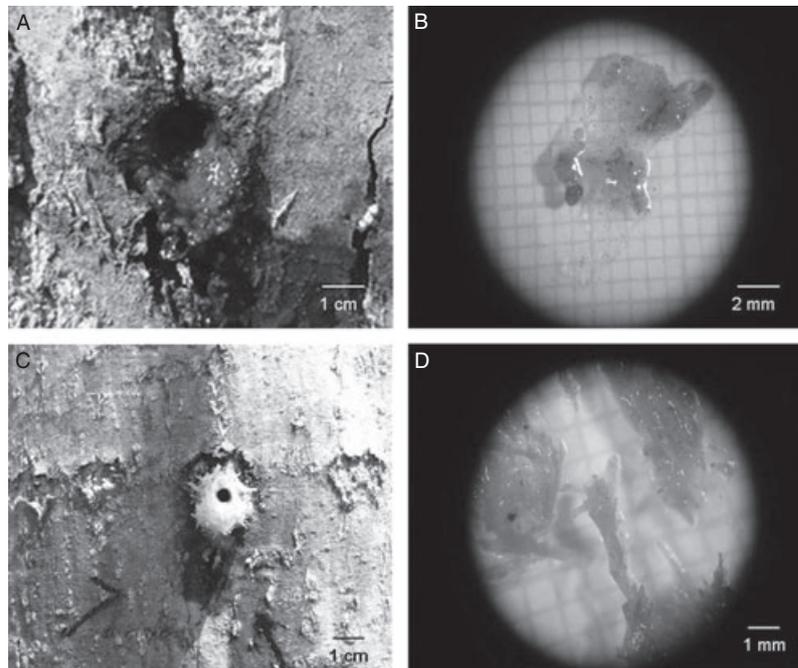


Figure 1 (A) Characteristic gallery frass of active galleries composed of disaggregated particles of irregular shape and flourish aspect. (B) Microscopic view. (C) Characteristic frass crown arrangement of the calling male composed of needle-shaped frass particles. (D) Microscopic view.

post-treatment data for MG and correct for the slightly higher density of AG (and presumably slightly higher population of *M. mutatus*) in the control plots, for each sample tree, we calculated the percentage of total AG that appeared after treatment as: % post-treatment mating (PTM) = [(no. new MG per tree / (no. new MG + no. pre-treatment AG)) × 100. PTM values were compared by Student's t-test.

Results

Pheromone dispensers

For each compound and surface, release rates were constant in time until pheromone depletion and increased linearly with surface effective area over the whole range studied, i.e., up to 20 cm² (Figure 2). We calculated the respective slopes from the lines obtained and their coefficients of determina-

tion (R^2). Then we used the regression line equations (Figure 2) to calculate the effective areas that correspond with the desired release rates. The release rates for monitoring traps were selected according to our previous results (Funes et al., 2009a). The release rates for mating disruption were higher: for sulcatol and sulcatone approximately 10 ×, and for 3-pentanol – whose release rate for monitoring was already high – 3 × higher. Table 1 shows the selected release rates of sulcatol, sulcatone, and 3-pentanol.

Flight period

Flight periods were monitored to start mating disruption experiments at the time when females started to fly. Figures 3 and 4 show the time pattern of the females caught daily in traps in poplar plantations of Junín and Campaña. The dispensers for mating disruption were placed when we detected a rise in the number of females caught in

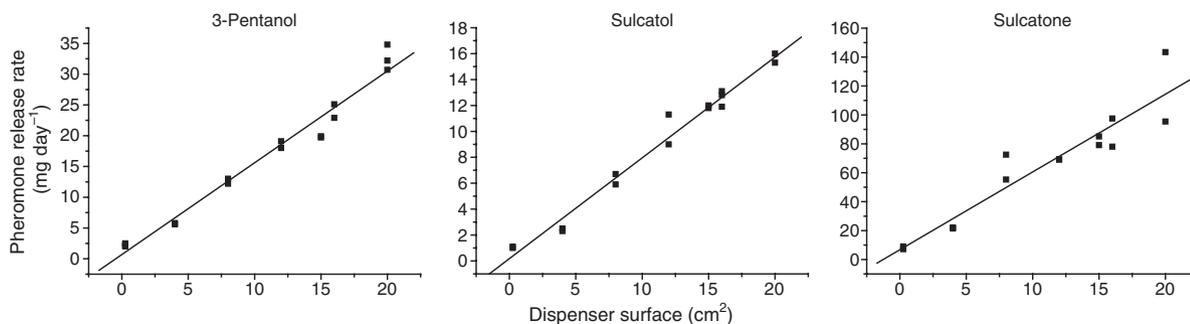


Figure 2 Regression between pheromone release rate (mg per day) and permeable surface of dispensers of plastic pheromone lures (semi-permeable membrane) containing 3-pentanol, sulcatol, or sulcatone, in a laboratory wind tunnel at 27–28 °C and 0.5 m s⁻¹. Release rates are the averages of three replicates for each permeable surface of dispenser. Regression lines: $Y = aX + b$; for 3-pentanol: $a = 1.49$, $b = 0.69$; for sulcatol: $a = 0.78$, $b = 0.18$; and for sulcatone: $a = 5.38$, $b = 0.77$ ($R^2 = 0.97, 0.98, \text{ and } 0.90$, respectively; all three $P < 0.0001$).

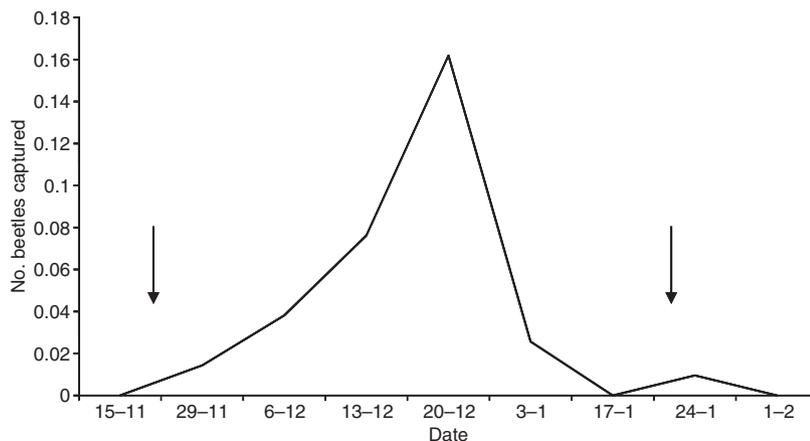


Figure 3 Number of female *Megaplatypus mutatus* captured per trap per day during the 2007–2008 season in Junín, Buenos Aires, using pheromone-baited traps. Arrows indicate the start and finish of the mating disruption trial.

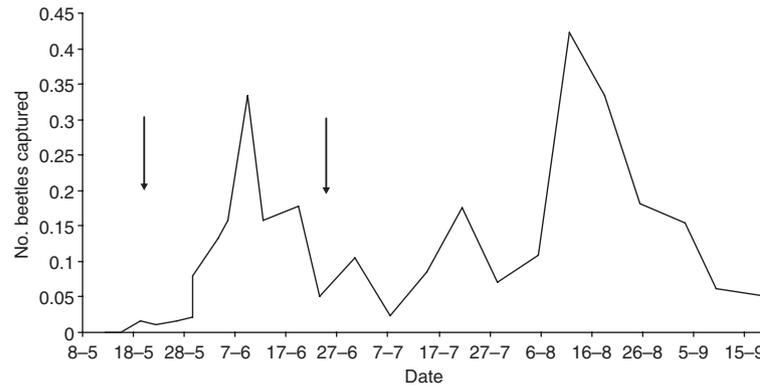


Figure 4 Number of female *Megaplatypus mutatus* captured per trap per day during the 2008 season in Campania, Italy, using pheromone-baited traps. Arrows indicate the start and finish of the mating disruption trial.

traps each day and withdrawn when the number decreased: the trial in Junín was launched on 19 November and finished on 24 January and in the poplar plantation in Campania; it started on May 26 and ended on 19 June. In the hazelnut plantation, located in the vicinity of the poplar plantation in Campania, it began on 12 May and ended on 16 June.

Mating disruption of *Megaplatypus mutatus* in field trials

Prior to pheromone deployment, the mean number of AG per tree did not differ significantly between the treated and control plots in the poplar plantations at Junín ($t = -0.73$, d.f. = 332, $P = 0.44$) or Campania ($t = 1.11$, d.f. = 58, $P = 0.27$), or in the hazelnut plantation at Campania ($t = -0.42$, d.f. = 46, $P = 0.68$) (Table 2). The

mean numbers of post-treatment CM per tree did not differ in treated vs. control plots at Campania, in either the poplar ($t = 1.11$, d.f. = 58, $P = 0.27$) or hazelnut plantations ($t = -1.21$, d.f. = 46, $P = 0.23$) (Table 2). However, the mean number of MG per tree was significantly lower in the pheromone-treated plot than in the control plots at all three sites: Junín ($t = -7.13$, d.f. = 347, $P \ll 0.001$), Campania poplar ($t = -2.26$, d.f. = 58, $P = 0.027$), and Campania hazelnut ($t = 2.51$, d.f. = 46, $P = 0.015$) (Table 2).

Post-treatment mating values also show that pheromone treatment significantly decreased the relative number of mating galleries both in poplars in Buenos Aires ($P \ll 0.001$), poplars in Campania ($P = 0.045$), and in hazelnuts in Campania Caserta ($P = 0.0014$).

Table 2 Mean (\pm SE) number of *Megaplatypus mutatus* active galleries (AG), live calling males (CM), and mating galleries (MG) per tree in infested control and pheromone-treated plots of poplar and hazelnut plantations before and after the trial at three locations

Crop (location)	AG per tree		CM per tree	MG per tree	Post-treatment mating (%)
	Before trial	After trial	After trial	After trial	
Poplar (Buenos Aires, Argentina)					
Control	0.50 \pm 0.05a	0.37 \pm 0.027a	–	0.41 \pm 0.05a	21 \pm 6a
Treated	0.45 \pm 0.05a	0.079 \pm 0.004b	–	0.096 \pm 0.020b	8 \pm 4b
Poplar (Caserta, Italy)					
Control	1.96 \pm 0.36a	–	1.60 \pm 0.28a	0.66 \pm 0.17a	34 \pm 3a
Treated	1.53 \pm 0.27a	–	2.06 \pm 0.31a	0.23 \pm 0.07b	11 \pm 2b
Hazelnut (Caserta, Italy)					
Control	4.54 \pm 0.89a	–	2.45 \pm 0.67a	2.08 \pm 0.35a	29 \pm 5a
Treated	4.08 \pm 0.65a	–	1.58 \pm 0.31a	0.92 \pm 0.31b	9 \pm 3b

Means within a column and locality followed by the same letter are not significantly different (t -tests: $P > 0.05$).

MG: galleries where male initiated attack, lured female, mating took place, both male and female are extending the gallery length inwards. AG: entrance holes where male initiated attack, lured female, mating took place, female laid eggs, offspring were produced and feeding larvae are expelling the sawdust outside. % post-treatment mating = [no. new MG per tree / (no. new MG + no. pre-treatment AG)] \times 100.

Discussion

Efficient controlled-release systems are essential to deliver behaviorally relevant aerial concentrations of sex pheromones for both monitoring and mating disruption purposes in the field. Here we made polymeric dispensers that act as reservoir systems and deliver to the environment a constant high amount of pheromone during the female flight period. Release rates were constant (zero-order kinetic), as it would be expected for diffusion-controlled releases.

We deployed these dispensers in the field in three independent trials in Argentina and Italy and found that the number of mating and/or AG after the experiment was significantly higher in control than in treated areas, indicating that the strategy of mating disruption using the pheromone delivery doses reported here is a potential tool for management of hazelnut and poplar plantations. However, the number of CM was not significantly different between treated and control areas. This result was expected as male behavior of host localization should not be affected by the presence of male sex pheromones. Although the number of initial galleries is the same in control and treated plots, the final damage was not the same. This is because pioneer males only build short galleries (5–6 cm) as nuptial chambers to wait for the female, and these galleries do not weaken the tree (Santoro, 1963). Thus, if the female does not arrive in time, the male dies and the damage to the xylem is soon overshadowed by new tree growth.

Damage reduction for field trials in both countries was >56%, and the duration of the trial was adjusted according to the female flight period in each area. In Junín, Argentina, where the trial lasted 2 months, the reduction was 77%. On the other hand in Caserta, where the field trial lasted 24–35 days, the reduction was 65% in the poplar plantation and 56% in the hazelnut plantation. The lower effectiveness observed in Italy could be attributed not only to the shorter duration of the experiment but also to the higher initial population density in Italy compared to Argentina. Insect density is a major limiting factor that can affect mating disruption (Howell et al., 1992). In the case of *Cydia pomonella* (L.), the efficacy of different types of pheromone formulations is highly dependent on codling moth density (Stelinski et al., 2008; Vickers & Rothschild, 1991; Trimble, 1995). Also, mating disruption of *Lobesia botrana* Denis & Schiffmüller was less effective with aggregated populations because of the increased chance of a male entering the active space of a calling female (Schmitz et al., 1995).

Inhibiting female orientation may produce delays in the process of finding a male; furthermore, this delay could

prove to be fatal as females soon begin to suffer from dehydration under the hot summer conditions (P Gatti, unpubl.). Even if the pheromone does not prevent mating and only delays finding males, a definitive effect is produced on the population as males very frequently die while waiting for a female to arrive (Santoro, 1963). Also, protandry minimizes pre-reproductive death of females and restricts the mating success of late-emerging females at low population density (Calabrese & Fagan, 2004; Rhainds, 2010); so, if females fly in search of males for more time because of the confusion generated by the high releases of male pheromones, this effect could be increased.

The success of the mating disruption strategy may also be influenced by mating system (Rhainds, 2010). Mating disruption is generally regarded to be more practical than mass trapping for species that use female-produced sex attractants, as they are generally monogamous (e.g., Lepidoptera), whereas species that use male-produced pheromones are polygamous (e.g., many beetles). Although *M. mutatus* uses a male producing pheromone, it is monogamous, thereby making its management by mating disruption feasible.

Several aspects of the biology of *M. mutatus* contribute to the promising success of mating disruption for controlling this species. First, the treated area is not re-invaded by gravid females, because the adults are relatively immobile and mated females do not leave the host tree after they have mated. In fact, parent insects die inside the gallery before emergence of the offspring (Santoro, 1962). Second, *M. mutatus* has a cryptic lifestyle that protects it against treatments with conventional insecticides (Jutsum & Gordon, 1989), and systemic treatments are very expensive to apply in commercial poplar plantations. Third, *M. mutatus* does not feed on host phloem or xylem before or after emergency (Santoro, 1962; P Gatti, unpubl.), and this may enhance the influence of pheromones more than in species that spend time on foraging (Hasewaga et al., 1993). Fourth, the sex ratio is 1:1 (Santoro, 1963), making the location of males by females less likely than in cases where there is a bias towards females. In that case, timing of emergence is expected to mediate female mating success through its effect on the operational sex ratio (Bessa-Gomes et al., 2004). Fifth, *M. mutatus* is monogamous (Santoro, 1962). Also, the non-destructive nature of damage assessment is positive in the sense that it does not affect the next generation, allowing replication of field trials in the same plantation.

Although synthetic pheromones of *M. mutatus* are not expensive to produce, the application process is labor intensive. Also, it is critical to have an effective monitoring schedule to detect the beginning of the flying period with pheromone-baited traps to maximize the benefit/cost

ratio of the control treatment. The costs of mating disruption treatments are affordable in Italy where poplar and hazelnuts have high market prices, but not yet in Argentina, where the market of poplar timber is still growing.

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