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Original article

Damage reduction and performance of mass trapping devices for forest protection against the spruce bark beetle, *Ips typographus* (Coleoptera Curculionidae Scolytinae)

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Abstract –
• The spruce bark beetle, *Ips typographus*, is one of the main European forest pests, and mass trapping is probably the most common strategy applied to reduce its population density. However, the results concerning the effectiveness of this control system are often controversal, and many studies consider only the trapping performance with no attention to the damage reduction.
• During spring-summer 2005, a control program against *I. typographus* outbreaks was set up in NE Italy. Twenty-four spruce forests heavily infested by *I. typographus* were studied: six protected by pheromone slot-traps, six by horizontal trap-logs and six by standing trap-logs; six untreated stands were kept as controls. Trap-logs were baited with a pheromone specific to *I. typographus* and treated with insecticide. Each type of device was tested at high, medium and low density in relation to the number of trees infested during the previous year. New damage occurring in the investigated stands was later monitored for one year.
• Protected forests showed mean damage about 80% lower in 2005 than in 2004, with no statistical difference among traps, trap-logs or standing trap-logs. Instead, unprotected forests (controls) suffered damage to a similar extent in both years. Trapping devices showed no statistical differences among mean captures. Device densities showed similar results in damage reduction and insect trapping.
• The results support the hypothesis that intensive trapping performed at stand level may be useful for protecting forests against *I. typographus*, locally reducing population density and tree mortality.

spruce / bark beetle / outbreak / mass trapping / biological control

Résumé – Réduction des dégâts et efficacité des dispositifs de piégeage de masse pour la protection des forêts contre le typographe, *Ips typographus* (Coleoptera Curculionidae Scolytinae).
• Le coléoptère scolytide, *Ips typographus*, est l'un des principaux ravageurs des forêts européennes d'épicéa, et le piégeage phéromonal est probablement le procédé de lutte le plus utilisé pour réduire la densité de ses populations. Cependant, l'efficacité de ce système de contrôle n'est souvent pas très claire, et beaucoup d'études considèrent seulement les performances du piégeage et non la réduction des dégâts.
• En 2005, un programme de lutte contre *I. typographus* a été appliqué dans le Nord-Ouest de l'Italie. Une étude a été conduite dans 24 forêts d'épicéa lourdement infestées par le typographe : six protégées par pièges à phéromones, six par arbres-pièges abattus, six par arbres-pièges sur pied, et six laissées sans protection (témoins). Les arbres-pièges ont été appâtés avec une phéromone spécifique d' *I. typographus* et traités avec un insecticide. Chaque type de dispositif a été testé à haute, moyenne et basse densité en se basant sur le nombre d'arbres infestés l'année précédente. Les dégâts nouveaux causés par le typographe ont été suivis pendant un an.
• En 2005, toutes les forêts protégées ont montré un niveau moyen de dégâts d'environ 80 % inférieur à celui de 2004, sans différence significative entre les dispositifs, alors que les forêts témoins ont souffert de dégâts similaires les deux années. Le nombre moyen de captures ne différait pas significativement entre les dispositifs de piégeage. La diminution des dégâts et du nombre d'insectes piégés a été comparable à toutes les densités de traitement.
• Ces résultats confortent l'hypothèse selon laquelle le piégeage de masse au niveau du peuplement peut être utile pour la protection des forêts contre le typographe, en diminuant la densité de population du ravageur et ses dégâts.

épicéa / scolytides / pullulation / piégeage de masse / lutte biologique

1. INTRODUCTION

Summer 2003, the warmest summer in Europe in the last 500 years (Luterbacher et al., 2004), caused stress to many European forests. The high temperature and dry weather increased the susceptibility of spruce (*Picea abies* Karsten) to infestations by many pests, including bark beetles. Environmental disturbances or extreme weather conditions usually give rise to subsequent outbreaks of the spruce bark beetle *Ips typographus* (Linneaus, 1758) (Coleoptera Curculionidae Scolytinae), the most destructive pest attacking spruce in Eurasia (Christiansen and Bakke, 1988). In many cases, severe infestations of *I. typographus* began one year later, in 2004. A similar trend was already known in northern Europe, where population density was correlated with the previous year's

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temperatures of May and June (Bakke, 1992). In the last few years, *I. typographus* has also produced severe infestations in the Southern Alps (Frigimelica et al., 2000; Lozzia, 1993; Stergulc et al., 2000). Since 1994, the damage caused by *I. typographus* has been monitored in the spruce forests (covering about 65 000 ha) of the Friuli Venezia Giulia region (FVG), SE Alps, by about 60 foresters working for the Regional Forest Service. From 1994 to 2003, the mean *I. typographus* damage involved a total of about 950 m^3 per year. However, the damage recorded in 2004 was 8 100 m^3. This large amount of damage required the application of specific control programs to reduce the loss expected in the following years.

Since the identification of the aggregation pheromone for *I. typographus*, control strategies include the use of several types of baited traps or trap-trees. The aim is to catch as many flying beetles as possible, reducing the population density and, therefore, the risk of outbreaks. Several efforts to control scolytids have been based on the mass trapping method. The first major attempt was carried out in California against the western pine beetle, *Dendroctonus brevicomis*. One sticky trap baited with pheromones plus host monoterpenes was placed every 2.6 ha of Ponderosa pine forests growing in four plots of 1.3 km^2 each. The test appeared to be successful, since the number of trees killed by the beetle declined to 10% of the pre-treatment level for several years (Bedard et al., 1979; DeMars et al., 1980). In the late 1970s, a major outbreak of *I. typographus* occurred in southern Scandinavia. In the worst affected provinces of southern Sweden, both pheromone-baited standing trap-trees and drainpipe traps were used from 1978 to 1981. The high number of insects caught (7 400 million in 1979–1980) led to a durable decline in outbreaks (Bakke, 1989). Several other studies have reported successful control of bark beetles with the intensive use of pheromone-baited traps or trap-trees (Jakus, 1998; Niemeyer, 1992; Richter, 1991; Schlyter et al., 2001; Vrkoc, 1989). Preliminary results have also been reported for some Italian populations (Faccoli and Stergulc, 1999; 2004; 2006; Lozzia, 1993; Marchetti et al., 1999). However, in several cases the successful bark beetle reductions achieved by mass trapping have been questioned. Experiments carried out in 1986–1990 in Germany showed that the population density of *I. typographus* could not be substantially influenced by mass trapping with pheromone-baited traps, and forest hygiene was considered to be the most reliable long-term method against scolytid attacks (Dimitri et al., 1992). Even when considering higher trapping performance, Weber, 1987, calculated that enough beetles would remain untrapped to colonize susceptible hosts, quickly replenishing population density due to low intraspecific competition. Similarly, the capture rate of *I. typographus* in pheromone traps in Sweden was estimated to be only about 30% over the 3 years (1978–1981) of an infestation, and although the outbreak collapsed between 1979 and 1982, there is no evidence that the decline was induced by mass trapping (Weslien, 1992a). The same authors reported that only a minor proportion (< 20%) of the beetles caught in pheromone traps originated in the local population, and that, because of immigration, it is difficult to suppress local populations of bark beetles only by trapping (Weslien and Lindelöw, 1989). Moreover, Danish authors reported that during a 2-year-long experiment carried out in areas with windthrown spruces, the densities of new attacks occurring around pheromone traps were not correlated with the number of beetles caught in the traps, and that pheromone traps were not suitable as the only protective measure to prevent further infestation (Wichmann and Ravn, 2001). Nevertheless, the study recorded at least one old attack within 500 m of all new attacks, concluding that the majority of the beetles dispersed over short distances before entering a new host, which disagrees with the results of the previous paper (Weslien and Lindelöw, 1989). Other approaches considered the mass trapping programs as an integrating part of the outbreak management (Bakke, 1991), applied in combination with other forest protection measures (Jakus, 1998; Niemeyer, 1992; Niemeyer et al., 1994; Schlyter et al., 2001).

However, most of the cited papers described how the mass trapping affects insect population density or reported differences among mean catches by varying types of mass trapping devices (Abgrall, 1987; Bakke, 1989; Faccoli and Stergulc, 1999; Lozzia, 1993; Raty et al., 1995), but in general there are few data on damage reduction induced in protected forests. On the other hand, it is essential to know if, and to what extent, high insect catches influence damage reduction, considering that control strategies should focus on forest protection rather than monitoring insect populations. In addition, because many of these studies lacked appropriate non-managed controls, due to the problem of finding control areas within the same general biotope and climatic regime, it was not possible to determine the effect of the treatment, and the role of mass trapping remains unclear, as observed damage reduction may be due to either control efforts or natural decreases in population density (Byers, 2004).

Beyond the effectiveness of trapping devices, the second most important factor concerning mass trapping programs is device density: how many trapping devices are needed for forest protection? In studies on mass trapping, Abgrall and Schvester, 1987, and Lobinger and Skatulla, 1996, set up an extremely different number of pheromone traps per hectare. However, in both cases insect trapping was not enough to protect forests from new infestations. In addition, trap density related to forest area (number of traps per hectare) gives results which do not allow statistical comparisons among stands, because of the differences in tree and pest density occurring in different forests. Bakke, 1989, reported the optimal number of traps as depending on the number of trees killed the previous year within the area, but without indicating in what proportion. Extensive applications of trap-trees have also been carried out in Belgium (Grégoire et al., 1997), testing different densities of trap-trees in relation to the number of spruces killed during the previous year. Nevertheless, also in that case, the study had no control area and each trap-tree density was tested with no replication, making evaluation of any density effect difficult.

In this paper, we report results from an extensive *I. typographus* control program applied in 2005 to many spruce stands growing in the Italian SE Alps. The study involved various types of mass trapping devices, comparing *I. typographus* damage recorded in protected and unprotected stands in relation to the catch performance of each device. The effect of device density on *I. typographus* damage was also investigated.

2. MATERIALS AND METHODS

2.1. Choice of the investigated stands

Trials were performed in 2005 in 24 spruce forests of the SE Italian Alps. The investigated stands were chosen to be as similar as possible among more than 50 infestation spots caused by *I. typographus* outbreaks during spring and summer 2004, and spread over the whole FVG region. The large number of infested sites, of sizes ranging from 10 to 1 320 m^3, gave the possibility of setting up the same experiment in several forests chosen among those having similar silvicultural, ecological and epidemiological characteristics, to minimize the effects of environmental variables, such as composition, age, density, tree size, occurrence of previous infestations and pest voltinism. The chosen stands, growing at altitudes between about 500 and 1200 m a.s.l. (Tab. I), belonged to a homogeneous ecosystem of mountainous conifer forests constituting coetaneous pure spruce stands, managed by a non-intensive silviculture, and reproducing by natural regeneration. The infestations that occurred in 2004 killed 1 185 spruce trees, leading to a loss of 1 466 m^3 of timber, with intensity ranging from 25 to 140 m^3 per stand (Tab. I). However, the year before (2003) the damage was very low (Tab. I) and did not require the application of specific control programs. The mild climatic conditions of the Southern Alps, and the low altitudes where the experiment was set up, make *I. typographus* able to complete two generations per year in all the investigated stands (Faccoli and Stergulc, 2006). The main characteristics of the stands infested in 2004 (altitude, tree diameter, tree age, stand density, and damage observed in 2003 and 2004) were compared by statistical tests, looking for homogeneous stands in which to carry out the trials. In addition, the stands were chosen growing as far apart as possible, in order to avoid data correlations caused by their spatial arrangement, with the closest being not less than 500 m away, and the farthest several dozens of km away. Once 24 similar stands were found, different treatments were assigned randomly. In particular, various types of trapping devices were set up in 18 stands, whereas 6 stands were kept as controls, with no protection against *I. typographus* infestations (Tab. I).

2.2. Mass trapping devices

Three different types of mass trapping devices were tested. Sixteen Theysohn® slot-traps (Salzgitter, Germany), 24 horizontal trap-logs and 16 vertical, standing, trap-logs were set up singly in 18 spruce stands, 6 stands per type of device (Tab. I). Freshly felled trap-logs (25–30 cm in diameter, 1.5 m long) were laid in mesh-covered aluminum boxes, to prevent the trapped insects from being preyed upon by birds. Standing trap-logs, similar in size to the horizontal logs, were fixed to dry wooden poles and placed upon round plastic plant pot-holders (45 cm in diameter) for insect collection. The devices were set up in clear-cut areas infested in 2004, about 15–20 m from the forest edge, and baited with pheromone dispensers specific to *I. typographus* (Superwood® – Serbios, Italy). Both trap-logs and standing trap-logs were treated with an aqueous solution (0.73%) of deltamethrin (K-Othrine® Flow 7.5, Bayer, Germany), to ensure the prompt killing of beetles attracted by the pheromone. The mean volume of insecticide solution applied to each log was about 0.16 L per m^2 of bark. All devices were baited at the end of April and checked weekly until the middle of September. In order to follow the whole spring and summer activity of *I. typographus*, which in Italy lasts for more than 4 months (end of April–mid-September), the dispensers were replaced and insecticide spraying repeated 8 weeks after the beginning of the trial. Trapped beetles were collected, identified and counted weekly, and data reported as mean catches per device.

2.3. Device density

Each type of device (slot-traps, trap-logs and standing trap-logs) was tested at high, medium and low density (Tab. I). These densities were calculated in relation to the degree of infestation recorded during the previous year (2004), reported not as number of trees killed, as suggested by Bakke, 1989, but as volume (m^3) of spruce timber infested by *I. typographus*. The number of infested trees is not a clear damage indicator because of the different sizes, i.e. volume, of different trees. At high density, each device was set up approximately every 15 m^3 of infested timber; at medium density, one device every 30 m^3, and every 45 m^3 at low density. Each density was tested for all types of device, looking for correlation between device density and damage reduction in relation to the applied catching device.

2.4. Damage monitoring

New infestations of *I. typographus* occurring in the 24 investigated stands were recorded from field observations carried out from May 1st 2005, at the beginning of the trial, to April 30th 2006. Damage monitoring was prolonged until spring 2006 because spruce trees infested in summer 2005 by the second generation of *I. typographus* became identifiable only the following spring. Observed damage was reported as volume of trees killed over a circular area of about 28 ha, corresponding to a 300-m radius around each trapping device. Previous studies had reported that both the effective attraction radius of a pheromone-baited device and the total catches decrease with increasing distance (Byers et al., 1989). In addition, investigations carried out in Danish lowland forests, having, however, an orography different from alpine stands, showed that all new attacks occurred within 500 m of old attacks, and most of the beetles emerging from an epidemic attack dispersed over short distances (i.e., less than 500 m) (Wichmann and Ravn, 2001).

2.5. Data analysis

Before performing any comparisons among treatments, we needed to estimate the actual number of beetles killed by standing trap-logs, because some of the dead beetles fell outside the round plastic pot placed below the log. For these estimates, we applied the model proposed by Raty et al., 1995, who found a correlation between the number of bark beetles caught in four collectors nailed around the trunk, and the number of bark beetles killed by the whole standing trap-tree holding the collectors. In the experiment of Raty et al., 1995, one round collector was set up in front (where the pheromone dispenser was nailed), two on the sides, and one behind the trunk. The collecting surface of our pot was divided into four similar sections, and the catches observed in each section were corrected in relation to the collector areas described in the above study (Raty et al., 1995). The area

Table I. Investigated spruce stands and their characteristics, damage caused by *I. typographus* in 2003–2005 and type of device set up in each stand. In 2005 three different densities were tested, setting up one device for every 15, 30 or 45 m^3 of spruce trees killed during the previous year (2004). "St. trap-logs" means Standing trap-logs. * Data not available; however, these sites were similar to those where the data were available (for comparison see data concerning mean diameter and age).

Sites	Stand characteristics							Damage (m^3)			Devices tested in 2005		
	Altitude (m a.s.l.)	Soil	Expos.	∅	Age	Density (m^2/ha)	Vol. (m^3/ha)	2003	2004	2005	Type	Density	Number
Comeg. Stali	800	Leptosol	E	36	90	*	*	0	58	53	Control	–	–
Forni Col Maggiore	1 275	Cambisol	N	39	90	24.7	280	0	32	14	Control	–	–
Forni Rigolato	650	Cambisol	NE	36	90	*	*	0	25	22	Control	–	–
Paluz. Mondovana	1 250	Cambisol	W	30	90	15.3	268	0	50	39	Control	–	–
Paluz. Treppo	1 200	Cambisol	S	36	70	33.4	431	0	40	62	Control	–	–
Tolm. Avosacco	750	Leptosol	W	35	70	*	*	0	40	42	Control	–	–
Comeg. Miozza	575	Cambisol	SE	36	90	*	*	0	34	12	Traps	15	2
Forni Slinghin	725	Alisol	SW	32	65	26.1	305	0	61	20	Traps	15	4
Paluz. Chiarandis	1 050	Cambisol	S	33	50	33.1	416	0	73	13	Traps	15	5
Paularo Zermula	1 275	Cambisol	W	35	90	31.8	400	0	58	4	Traps	30	2
Tolm. Rio Maliis	675	Cambisol	W	39	90	25.2	284	0	60	0	Traps	30	2
Paluz. Costasecca	875	Cambisol	SW	38	70	53.4	633	0	50	0	Traps	45	1
Comeg. Runchs	675	Cambisol	SW	36	90	*	*	0	86	0	Trap–logs	15	6
Paluzza Tausia	1 050	Cambisol	SW	38	110	33.8	439	0	140	60	Trap–logs	15	9
Tolm. B.go Radina	625	Cambisol	S	36	80	23.1	242	0	42	0	Trap–logs	15	3
Comeg. Costa Pelosa	450	Leptosol	W	36	90	34.0	321	71	90	18	Trap–logs	30	3
Villa Sant. Raveo	650	Cambisol	E	35	70	*	*	22	58	0	Trap–logs	30	2
Comeg. Punizze	600	Cambisol	E	33	50	*	*	0	50	20	Trap–logs	45	1
Comeg. T. Degano	475	Cambisol	E	33	50	*	*	10	34	0	St. trap–logs	15	2
Forni Campiut	1 125	Alisol	N	40	90	32.9	468	0	75	0	St. trap–logs	15	5
Forni Givigliana	1 075	Alisol	S	32	70	35.9	420	0	100	7	St. trap–logs	30	3
Paluz. Ronchies bassa	775	Leptosol	W	37	90	21.4	273	0	95	50	St. trap–logs	30	3
Paularo Valdajer	1 250	Alisol	SW	36	110	27.0	333	0	67	18	St. trap–logs	30	2
Villa Sant. Enemonzo	450	Leptosol	SW	33	50	*	*	0	48	0	St. trap–logs	45	1
Total/mean	845	–	–	35	79	30.0	367	103	1 466	454	–	–	56

correction was required because both the distance from the trunk and the collector position around the trunk affect the distribution model describing the number of beetles falling around a trap-tree. Then, the total trap-log catches were estimated by multiplying the catches of each pot section by the corresponding correction factor (front, side or rear), and summing the results.

Recorded catches, corresponding damage in 2005 and stand characteristics (altitude, tree diameter, tree age, stand density and volume, and damage observed in 2003 and 2004) were compared by ANOVA testing for differences among the four treatments. Homogeneity of variance was tested by Cochran's test (test C), and normality by Kolmogorov-Smirnow's test (test D); when necessary, data were log- ($X' = \log(x + 1)$) or arcsin- ($X' = \arcsin \sqrt{x}$) transformed to obtain homogeneous data and normal variance. Wherever significant differences occurred, Tukey's Honest Significant Difference (HSD) multiple comparison test was applied for mean separation (Zar, 1999). Differences at a 0.05 level of confidence were considered significant. Analyses were performed by STATISTICA® 3.1 for WINDOWS® software (Statistica®, Tulsa, OK, USA).

3. RESULTS

3.1. Stand characteristics

The 24 investigated stands were selected to have similar ecological and epidemiological characteristics. In this respect, the four groups of six forests included in the study did not show statistical differences concerning the main silvicultural parameters. In particular, they were located at a mean altitude of about 850 m a.s.l. (ANOVA, $F_{(3,20)} = 1.29, p = 0.30$), with similar average diameters (35 cm d.h.b.) (ANOVA, $F_{(3,20)} = 0.03, p = 0.98$), tree age (about 80 years) (ANOVA, $F_{(3,20)} = 1.23, p = 0.87$), tree density (30 m^2 per ha) (ANOVA, $F_{(3,11)} = 1.15, p = 0.36$), and wood volume of the stand (370 m^3 per ha) (ANOVA, $F_{(3,11)} = 1.07, p = 0.39$). Most of the stands were growing on cambisol, with S-SW exposure (Tab. I). Damage recorded in 2003 and 2004, before the beginning of the study, was similar among treatments (ANOVA, $F_{(3,20)} = 1.62, p = 0.21$, and $F_{(3,20)} = 2.24, p = 0.11$, respectively). In 2003 the damage caused by *I. typographus* was very low in almost all the stands, indicating a non-epidemic phase of the pest population . By contrast, following the dry and warm summer of the previous year, the damage of 2004 increased strongly everywhere with a similar intensity (Tab. I), passing from a total of 103 to 1 466 m^3 and requiring the application of a protection program.

3.2. Trapped beetles and trapping efficiency

During the whole trapping period (May–September) traps, standing trap-logs and trap-logs captured mean numbers of beetles of 12 970, 11 010 and 18 400, respectively (Fig. 1). The lowest capture (2 178) was recorded in a standing trap-log, whereas the highest (32 218) was in a horizontal trap-log. However, although there was an apparently high diversity in insect catches, no statistical differences occurred among the trapping performances of the tested devices (ANOVA, $F_{(2,15)} = 1.66, p = 0.23$) (Fig. 2). In this respect, it is an interesting finding that traps caught as effectively as trap-logs, although the small size of the logs (1.5 m long) may partially explain this result (see Discussion).

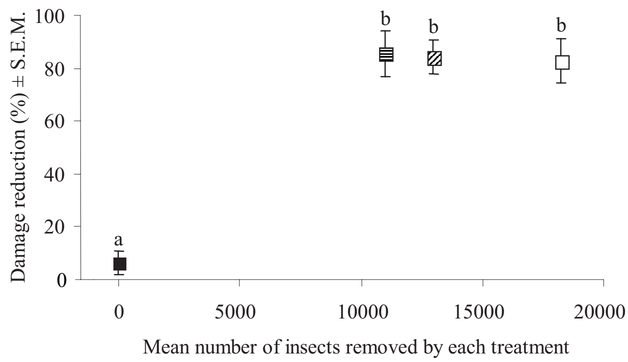

Figure 1. Reduction of *Ips typographus* damage from 2004 to 2005, in relation to the mean number of adults removed according to different treatments applied in 2005. There is no significant difference among trapping devices either in the number of caught insects or in damage reduction. Differences occur only between treated and untreated (control) stands. Different letters indicate statistical differences (Tukey test, $P < 0.05$). For symbol legend, see Figs. 2 and 3; black square means control.

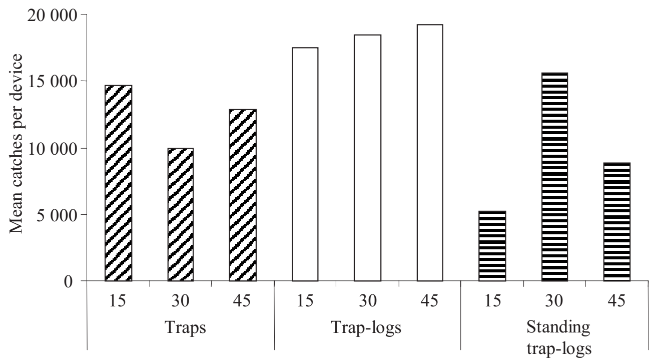

Figure 2. Mean catches of *Ips typographus* performed in 2005 by different devices and densities. The number of trapped beetles was not affected by device (ANOVA, $F_{(2,15)} = 1.66, p = 0.23$) (Fig. 1), or device density (ANOVA, $F_{(2,15)} = 0.10, p = 0.90$), and there was no significant interaction among devices or densities (ANOVA, $F_{(4,12)} = 1.53, p = 0.25$). 15 is the highest density and 45 is the lowest.

Concerning the device density, the number of trapped beetles was similar among the three tested densities (ANOVA, $F_{(2,15)} = 0.10, p = 0.90$), with mean captures of 12 480, 14 660 and 13 640 for the densities 15, 30 and 45, respectively (data pooled from the different treatments) (Fig. 2). In addition, no significant interaction occurred among devices and densities (ANOVA, $F_{(4,12)} = 1.53, p = 0.25$) (Fig. 2), with the highest captures (19 230) recorded on the lowest density (45) of trap-logs and the lowest catches (5 230) in stands protected by the highest density (15) of standing trap-logs (Fig. 2).

Pooling the capture data obtained from the three different devices, there was a mean of about 14 300 insects per device,

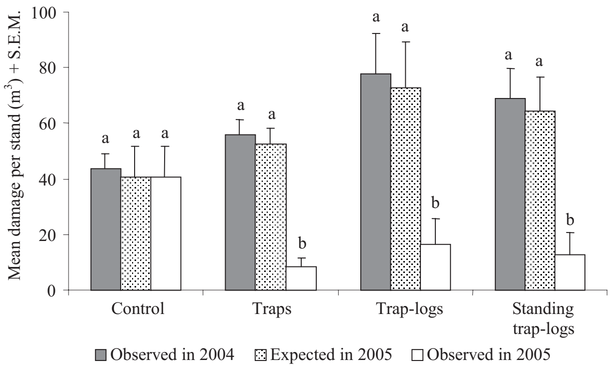

Figure 3. Comparison between mean damage recorded in 2004 and 2005 (expected and observed) in relation to different treatments applied in 2005. Expected damage for 2005 was calculated by reducing the damage in 2004 by the reduction percentage observed in control stands (6.5%). Different letters indicate statistical differences (Tukey test, $P < 0.05$). In control sites expected and observed damage have the same value.

which, compared with other data from the same region, is a very high value, indicating outbreaking populations (Faccoli and Stergulc, 2004).

3.3. Trapping devices and damage reduction

In 2005, following the application of the control program, treated and untreated forests showed significant differences in damage levels (ANOVA, $F_{(3,20)} = 2.12, p < 0.05$) (Fig. 1), with the highest damage being found in control forests (Tukey test, $p < 0.05$) (Fig. 3), indicating that mass trapping may be useful for reducing *I. typographus* damage. In general, damage caused by *I. typographus* was lower in 2005 than in 2004 (ANOVA, $F_{(1,46)} = 30.82, p < 0.005$). In this two-year study, damage was reduced in forests protected by traps (ANOVA, $F_{(1,10)} = 25.59, p < 0.001$), trap-logs (ANOVA, $F_{(1,10)} = 22.66, p < 0.001$) and standing trap-logs (ANOVA, $F_{(1,10)} = 11.99, p < 0.005$), but not in unprotected forests (ANOVA, $F_{(1,10)} = 1.19, p = 0.29$) (Figs. 1 and 3). Although in control forests, where no mass trapping devices were installed, damage decreased only slightly from 2004 to 2005 (about 6.5%) (Fig. 1), damage reduction was considerably higher – more than 80% – in protected forests (ANOVA, $F_{(1,22)} = 12.17, p < 0.01$) (Fig. 1). From 2004 to 2005, traps reduced damage by 84.4%, trap-logs by 82.8% and standing trap-logs by 85.5%, with statistical differences only between treated and untreated forests, but not among devices (ANOVA, $F_{(2,15)} = 0.18, p = 0.83$) (Figs. 1 and 3).

Assuming the damage reduction recorded in control forests (about 6.5%) as occurring in all studied forests, for each stand an "expected damage" was estimated by reducing the damage recorded in 2004 by 6.5%. However, in protected forests, the observed damage was always lower than that expected (ANOVA, $F_{(1,34)} = 59.39, p < 0.001$) (Fig. 3), with reductions of observed vs. expected damage similar among different trapping devices (ANOVA, $F_{(2,15)} = 0.02, p = 0.97$), and ranging between 84.8% and 87.2%.

3.4. Device density and damage reduction

As there were no differences among devices in trapping efficiency and damage reduction, data from traps and trap-logs (both types) were pooled and analyzed together for differences in device densities. The results showed no density effect on forest protection, with low (one device every 45 m^3 of dead trees), medium (30 m^3) and high densities (15 m^3) showing similar damage reduction from year to year (86.6%, 83.6% and 83.9%, respectively) (ANOVA, $F_{(5,15)} = 0.028, p = 0.97$). In 2005 many treated stands showed no infested trees with a damage reduction of 100% (Tab. I), with no apparent density effect. In contrast, except for control stands, the lowest protection from new infestations was achieved by trap-logs set up at the lowest density, with a mean damage reduction of only 60%. However, there was no significant interaction among types of device and their densities in the reduction of damage caused by *I. typographus* (ANOVA, $F_{(4,9)} = 2.43, p = 0.12$). In conclusion, device density seems not to influence damage reduction. The results imply that the lowest device density (45 m^3) protects the trees by *I. typographus* infestations in a way similar to that observed in stands protected by higher densities of trapping devices.

4. DISCUSSION

The main aim of a control program against bark beetle outbreaks is an appreciable reduction of damage occurring in infested stands, and insect trapping has often been believed to be an effective way to reach this goal. In the present study, the tested devices provided a reduction of the amount of timber infested by the spruce bark beetle of about 85%, with no significant differences among traps, trap-logs and standing trap-logs. However, a small amount of damage (about 15%) occurs independently of increasing trapping, as part of the insect population always escapes capture. The strong attraction of pheromones and the sudden death of captured beetles seem to be the main factors affecting device performance. All mass trapping devices tested in the present study acted in the same way once they were baited with pheromones and sprayed with insecticide, although captures ranged between about 11 000 and 18 000 insects per device in standing and normal trap-logs, respectively. The levels of captures recorded during the present study (14 300 insects per trap) indicate outbreaking populations largely exceeding the risk threshold, which for the investigated stand is about 7000–8000 beetles per trap per year (Faccoli and Stergulc, 2004; 2006). In the monitored areas Faccoli and Stergulc found that once the captures overcome this risk threshold, damage increases in an exponential way (Faccoli and Stergulc, 2004; 2006). By comparison, Weslien, 1992b, reported a threshold of 10 000 insects/trap for Sweden, whereas, for the same country, Lindelöw and Schröeder, 2001, suggested 15 000 *I. typographus* per trap.

In this respect, northern and central European spruce plantations, following different silviculture and orography, might tolerate higher densities of *I. typographus* populations, indicating a capture threshold higher than in the Alps (Faccoli and Stergulc, 2004; 2006).

With regard to standing trap-trees, some of the insects landing on the log and killed by the insecticide probably fall outside the collector pot, leading to an underestimation of the real number of insects killed. This could partially explain the numerical difference existing between captures of standing and horizontal trap-trees, although no statistical difference was found. Similar experiments carried out in Belgium also showed no differences in catches between standing and horizontal trap-trees (Grégoire et al., 1997). However, the lack of statistical differences between traps and trap-trees is a little surprising. In previous studies, trap-trees proved to be 3.5-3.6 (Abgrall and Schvester, 1987) to 14 times (Drumont et al., 1992) more efficient than traps at capturing beetles, whereas standing (living) trap-trees baited with pheromones and treated with insecticide caught up to 30 times more beetles than Theysohn traps (Raty et al., 1995). However, the trap-trees tested in previous investigations, with sizes ranging between 6 (Drumont et al., 1992; Raty et al., 1995) and 20 m (Abgrall and Schvester, 1987), were much longer than the trees tested in this experiment, which were of a size allowing them to fit into the collectors. In this respect, our results are supported by a study carried out by Niemeyer et al., 1990, who found the same trapping efficiency of slot-traps compared with trap-trees similar in size to ours (1–3 m long and 20–30 cm in diameter). Because the effectiveness of trap-trees is correlated with bark volatiles, which include many compounds active in *I. typographus* attraction (Jakus and Blazenec, 2003), the use of short logs greatly reduced the treated bark surface and consequently their natural attractiveness. Therefore, the shorter the trap-tree, the smaller the amount of host volatiles released, making trap-trees effective in a way similar to traps, where the pheromone is the only active lure.

Literature data concerning the efficiency of mass trapping devices in relation to their density are scant and in many cases provide poorly comparable results. During one mass trapping experiment, 24 traps per hectare caught only about 3% of the insect population (Lobinger and Skatulla, 1996), but no information was reported concerning stand characteristics, population density or mean damage due to *I. typographus*. Testing standing and lying trap-trees with a density depending on insect damage and ranging between 0.12 and 0.63 trap-trees per attacked spruce, Grégoire et al., 1997, found percentages of newly attacked spruces varying, respectively, between 72% and 30% of the trees infested during the previous year. A similar density (0.4 traps per infested spruce) was applied in large windthrow areas occurring in the French Alps, where traps and trap-trees were not enough to avoid new damage, but strongly reduced its intensity compared with unprotected stands (Abgrall and Schvester, 1987). Also, in other previous investigations trap efficiency was affected by trap density, with fewer beetles trapped in higher than lower density (Sauerwein, 1981). Nevertheless, the density effect on trap captures was observed mainly in isolated traps, set up more than 45 m from the others, but not in closer traps (Sauerwein, 1981). The device densities tested in the present study were low (0.02, 0.03 and 0.06 devices per m^3 of infested tree), especially in comparison with other studies, and the high reduction in damage may appear surprising. However, during a control program set up in China against *I. duplicatus* (Schlyter et al., 2001), a trap density similar to ours (0.035–0.04) produced a similar reduction in tree mortality (see below).

In the present study, untreated forests suffered slightly less damage (6.5%) in 2005 than in 2004, indicating a possible decrease in pest aggressiveness due to local natural factors. However, in all treated forests, observed damage was much lower than damage expected according to the natural population trend, indicating a clear effect of the trapping devices. Wherever a pheromone-baited device was set up, *I. typographus* damage was reduced by more than 80%. The high drop in tree mortality observed in protected forests is difficult to explain by natural factors, as the large silvicultural, epidemiological and ecological homogeneity of the investigated stands did not support any influence of the local conditions, and the only main difference among control and other stands was the occurrence of the trapping devices. In addition, the possible variation over space of climatic factors, which may locally decrease or increase tree resistance and insect breeding success (Guérard et al., 2007), was balanced by the random distribution of the stands. A possible explanation may be found considering the role of natural enemy populations, which could have different density among stands. Small differences in stand compositions and/or stand characteristics may largely affect the predator/prey ratios, and consequently the host population status (Warzée et al., 2006), although the differences observed between protected and unprotected forests were probably too large to be explained by the activity of antagonists.

However, the role of mass trapping in reducing bark beetle damage is still controversial. During a strong outbreak which occurred in 1995 and 1996 in Slovakia and Poland, tree mortality did not significantly decrease despite the use of intensive pest management measures. The forest protection based on the large use of pheromone traps and trap-trees led to an increase in attractiveness of forest edges to bark beetles, which could disperse to these areas from locations where no control measures were practiced (Grodzki et al., 2006). On the other hand, studies three years long (1983–1985) performed in French stands heavily infested by *I. typographus* (Abgrall and Schvester, 1987), showed a damage increase of only about 37% in forests protected by traps and trap-trees, whereas in two unprotected forests kept as control, the damage increased much more – with values ranging between 870% and 4,268% – indicating a clear positive effect of mass trapping in forest protection. Results similar to ours were also obtained in China when, during an experiment carried out to reduce the damage caused in the last 20 years by severe infestations of *I. duplicatus*, three years of mass trapping (1999–2001) decreased tree mortality by 79%, 82% and 84%, respectively (Schlyter et al., 2001). Also, in this case, neither natural population cycles nor weather conditions could explain the mortality drop observed during the three years. As in our experiment, all mass trapping units were positioned in close vicinity to attacked trees, within the sampling range of the devices, showing that intensive trapping performed at stand level may locally reduce population density and tree mortality, as already reported in other papers (Jakus, 1998; Niemeyer et al., 1994; Schlyter et al., 2001), and that in many cases the success of a control program may depend on the geographic scale of its application. In this respect, small control experiments cannot be compared with larger trapping campaigns, which could give different results.

Among the various strategies for minimizing spruce losses due to *I. typographus*, traps and trap-trees are just one component of integrated control programs (Bakke, 1989; 1991; Wermelinger, 2004). The choice concerning traps or trap-trees is always difficult (Raty et al., 1995). Considering the two types of device as giving the same trapping performance, many other factors must be considered. On one hand, traps have purchase costs, they must be checked periodically to empty the collecting jars, and they need space for winter storage. Traps are useful not only for protecting susceptible stands but also for monitoring, giving a measurement of the abundance, phenology and voltinism of *I. typographus* (Wermelinger, 2004). On the other hand, baited and sprayed trap-trees do not have purchase costs, as they can be obtained from harvested timber, and do not need periodical checking or space for winter storage. However, trap-trees do not give information about population density, and the impact of insecticides on the forest ecosystem must still be more thoroughly evaluated.

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