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Chemical control of *Popillia japonica* adults on high-value crops and landscape plants of northern Italy

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A R T I C L E I N F O

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A B S T R A C T

The introduction of the Japanese beetle (*Popillia japonica* Newman) in Italy raised concerns for its control in herbaceous and perennial crops, nurseries and landscape plants. During the early stages of spread of an invasive pest, the availability of effective insecticides is essential to sustain the immediate needs of plant protection. Here, we screened the effects of 20 active ingredients representative of chemical and organic insecticides registered in Europe for adult beetle management on high-value crops (grapevine, peach and corn) and landscape plants (willow and Virginia creeper) by field trials carried out in 2019 and 2020. Plant parts suitable for spraying were sleeved and beetles were caged before the application (contact effect), after the application but on the same day (residual, short-term effect), and 7–8 days after the application (residual, long-term effect). Among the 20 active ingredients tested, only four broad-spectrum (acetamiprid, deltamethrin, lambda-cyhalothrin and phosmet) were effective in killing beetles under all the experimental conditions, while other broad-spectrum and selective ingredients were mainly effective only on contact and as short-term residual. The organic active ingredients were much less effective under any condition. The data provide a valid support to update the European guidelines aimed at controlling *P. japonica* for growers, landscape managers and homeowners. The low selectivity of the most effective insecticides requires the integration into management strategies that envisage their use only whether strictly necessary, and in combination with other containment measures.

1. Introduction

The Japanese beetle (*Popillia japonica* Newman) was detected for the first time in mainland Europe in Italy in 2014 (EPPO, 2014; Pavesi, 2014) and quickly established at both banks of the Ticino river, in the two contiguous regions of Lombardy and Piedmont, spreading over 15, 000 km^2 so far (EPPO Data Sheet, 2020; Mori et al., 2021).

In the recently colonized area in Italy, adults of *P. japonica* were found to feed on grapevine, fruit trees, forest plants, crops, vegetables, ornamental and wild plants. Among agricultural crops, considerable damage was observed in vineyards and corn fields (EFSA et al., 2019; Bosio et al., 2020). Defoliation has been reported on fruit trees and ornamental plants (*e.g.*, linden, birch, wisteria, rose) in private gardens. Flowers and fruits of small fruit crops (*e.g.*, raspberry, blackberry, northern highbush blueberry) were also damaged by adults (EFSA et al., 2019; Bosio et al., 2020). All crops and ornamentals were located near irrigated meadows (EPPO Data Sheet, 2020), which are among the preferred oviposition sites of *P. japonica* (Potter and Held, 2002).

The pest is listed as a priority quarantine organism of delegated regulation (EU) 2019/1702 (EFSA PLH Panel, 2018). Therefore, as per European Regulation 2019/2072, the Italian National Plant Protection Organization activated all the mandatory control measures in order to

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contain and/or limit the spread of Japanese beetle populations (EPPO, 2016). Although control measures were taken immediately (Ministerial Decree, 2018), the extent of the outbreak and the biological and behavioural characteristics of the pest indicated that the species could not be eradicated in Italy.

The appearance of an alien organism requires the integration of agronomic, biological and chemical actions to protect the crops and landscape. In Italy, *P. japonica* management was performed at both regional and local level. At a regional level, hundreds of hectares of heavily infested meadows were treated with entomopathogenic nematodes (*Heterorhabditis bacteriophora* Poinar), resulting in variable extent of control (Paoli et al., 2017; Marianelli et al., 2017). Moreover, adult mass trapping and long-lasting insecticide-treated nets were used against adult beetles with variable results (Marianelli et al., 2018). Pheromone-based lures commonly used in traps attract more adults than those caught in traps or killed by the insecticide, and therefore their use is not recommended in private gardens and sports grounds or near orchards and nurseries. The use of trapping or attract & kill devices should also be avoided near sites with high risks of passive spread of the pest through hitchhiking, *i.e.*, car parks and delivery yards (EPPO, 2016). At a local level, a strategy based on physical protection of host plants with insect-proof nets was suggested, especially for family gardens and orchards. During the early stage of infestation, however, the use of readily effective insecticides is essential to sustain the immediate needs of the crop production system.

In the U.S., the predominant control method of *P. japonica* adults is broad-spectrum insecticides (Potter and Held, 2002; Bethke and Cloyd, 2009; Shanovich et al., 2019) because of their effectiveness and relatively low cost. There are many products labeled for the control of Japanese beetle, *e.g.*, pyrethrins, neem oil, chlorantraniliprole, pyrethroids, carbaryl, imidacloprid, dinotefuran (NPRO website). Because many of the U.S. recommended insecticides were restricted or cancelled in Europe since the 2000s (EU Reg. 1107/2009), there was no information about effective, fast-acting and curative products against *P. japonica* adults available for growers, landscape managers, and homeowners in European countries. The current limitation of registered products against this species requires experimental tests to evaluate the effectiveness of the active ingredients currently available on the market.

In this study, we explored contact and residual (both short and long-term) effectiveness of insecticides registered in Europe in main agricultural crops and landscaping especially for adult beetle management, including *Popillia japonica*. We considered both broad-spectrum (avermectins, carbamates, pyrethroids, neonicotinoids, organophosphates, oxidiazines) and selective active ingredients (anthranilamides, butenolides, organic products, semicarbazones, sulfoximine). Products for both professional and non-professional use were investigated.

2. Materials and methods

2.1. Investigated crops

The trials were carried out in the Lombardy Region near the eastern bank of the Ticino River in the following five high economic value contexts. 1) Vineyard (*Vitis vinifera* L.) in Solbiate Arno (45° 43′ N, 8° 50′ E) on 12-year-old Merlot cultivar grapevine trained by Sylvoz system (row spacing: 3.0 m, plant spacing within the row: 1.0 m). 2) Peach (*Prunus persica* (L.) Batsch) orchard in Galliate Lombardo (45° 47′ N, 8° 46′ E) on 7 year old Redhaven cultivar plants, trained by delayed open centre tree (row spacing: 6.0 m, plant spacing within the row: 4.0 m). 3) Corn (*Zea mais* L.) field in Galliate Lombardo (45° 47′ N, 8° 46′ E) on FAO 600 P1470 hybrid sowed on April 16, 2020. 4) Willow (*Salix caprea* L.) ornamental plant nursery in Mornago (45° 44′ N, 8° 45′ E) on 2-year-old plants (row spacing: 5.0 m, plant spacing within the row: 2.5 m). 5) Virginia creeper (*Parthenocissus quinquefolia* (L.) Planch.) ornamental plant nursery in Bodio Lomnago (45° 47′ N, 8° 45' E) on 1-year-old potted plants about 0.5 m high, cultivated on 25 cm diameter black plastic containers with peat potting soil. Peach orchard and Virginia creeper plant nursery were covered with anti-hail nets.

In the experimental sites, the population density of *P. japonica* was very high since 2015. The climate of the region is mainly temperate, with a high seasonal temperature variation: the average daily temperature is 2.5 °C in January and 24 °C in July. The total annual rainfall is on average 827 mm.

2.2. Insecticide effect evaluation

Twenty active ingredients available in 21 commercial formulations were studied on different crops in the field (Table 1). For each crop, the whole plant or parts of them were covered with insect-proof net cages (sleeve of 70 × 100 cm, mesh xx mm). This method allowed to apply the insecticides in the same way as growers and landscape managers (Macfadyen et al., 2014). To test the contact effect, *P. japonica* beetles were introduced before the insecticide spraying. To test the residual effect, the beetles were introduced on the same day of the application (short-term) or 7–8 days after the spraying (long-term).

The treatments (insecticides plus untreated control) were tested with four replicates each. A replicate consisted of one cage with 25 *P. japonica* adults, placed on a separate treatment plant.

A single branch of the plant was confined in one cage on grapevine, peach and willow. One plant with two cobs was confined in one cage on corn, after removing the apical stalk. One potted plant was entirely confined in the cage on Virginia creeper. The size of the branches/cobs/plants confined in the cages secured sufficient food for the insects throughout the trial period.

Therefore, in each crop and for each insecticide, 100 insects (*i.e.*, four cages) were subjected to a contact application and 100 insects (*i.e.*, four cages) to a short-term residual exposure. In each crop, 100 insects (*i.e.*, four cages) were left untreated. The long-term residual effect was tested on peach, willow and corn (on separate plants) with another 100 insects (*i.e.*, four cages) per treatment, and another 100 insects (*i.e.*, four cages) were left untreated.

A completely randomized design was chosen since site and plant characteristics were fairly homogeneous (Davison, 2003). The insects were collected on wild plants growing at the border of the sites by sweep entomological nets immediately before each experiment.

The mortality was determined by scoring the number of dead insects in each cage. The beetles observed as immobile were stimulated by poking to confirm death (Wise et al., 2014). Sampling mortality was done 1, 3, 8 days after treatment (DAT) on grapevine, 1, 3, 7, 10, 14, 21 DAT on peach, 1, 3, 8 DAT on corn, 1, 3, 8, 15, 23 DAT on willow, and 2, 8, 13, 21 DAT on Virginia creeper. The trial was interrupted 8 DAT on grapevine to allow the owner to perform a proper control on the whole field due to heavy infestation, and on corn due to the limited amount of silk in the caged cobs. The long-term residual effect was scored seven days after the caging.

2.3. Insecticide applications

Insecticide applications were performed by spraying the entire canopy of the plants until runoff on July 9, 2019 in vineyard and willow nursery, and on June 30, 2020 in peach orchard, corn field and Virginia creeper nursery. Tap water (pH 7.2) was sprayed as control. The mesh of the sleeves ensured permeability to insecticide applications and it was evaluated with water-sensitive papers of 76 × 25 mm (Quantifoil Instruments Gmbh, Jena, Germany) as artificial targets.

At the time of insecticide application, the canopy size of the plants was 1.6 × 1.2 × 0.6 m for grapevine; 3.5 × 3.2 × 3.0 m for peach; 0.6 × 0.6 × 2.5 m for corn; 1.2 × 0.9 × 1.4 m for willow; 0.2 × 0.2 × 0.5 m for Virginia creeper. The phenological stages of agricultural crops, identified through the BBCH-scale, was 77 for grapevine, berries beginning (Lorenz et al., 1994), 65 for corn, with upper and lower parts of tassel in flower, stigmata fully emerged (Lancashire et al., 1991), and 81 for

Table 1
Characteristics and application rate of the insecticides used, with the indication of the crops on which they were tested. (*) product for non-professional use.

Active ingredient (AI) and formulation	Trade name	IRAC MoA group	Manufacturer	Crop/Application rate				
				Vineyard kg AI ha^{-1}	Peach orchard kg AI ha^{-1}	Corn field kg AI ha^{-1}	Willow nursery kg AI ha^{-1}	Virginia creeper nursery mL $plant^{-1}$
Abamectin 18 g L^{-1} EC	Vertimec® EC	Avermectins (6)	Syngenta		0.018			
Acetamiprid 50 g L^{-1} SL	Epik® SL	Neonicotinoids (4A)	Sipcam Oxon Italia	0.100	0.100		0.100	
Acetamiprid 0.05 g L^{-1} AL	Polysect Ultra (*)	Neonicotinoids (4A)	Scotts France					25
Azadirachtin 26 g L^{-1} EC	Oikos®	Limonoids (UN)	Sipcam Oxon Italia	0.039			0.039	
Beauveria bassiana ATCC 74040 0.185 g kg^{-1} OD	Naturalis®	Fungal entomopathogens	CBC (Europe)					25 (0.185 kg AI ha^{-1})
Chlorantraniliprole 200 g L^{-1} SC	Coragen®	Anthranilamides (28)	Du Pont de Nemours	0.032		0.032	0.040	
Chlorpyrifos-methyl 225 g L^{-1} EC	ReldanTM LO	Organophosphates (1B)	Dow AgroSciences	0.450			0.450	
Deltamethrin 25 g L^{-1} EW	Decis® EVO	Pyrethroids (3A)	Bayer Crop Science	0.013	0.013	0.013	0.013	
Deltamethrin 0.0075 g L^{-1} AL	Decis® Giardino (*)	Pyrethroids (3A)	Bayer Crop Science					25
Etofenprox 287.5 g L^{-1} SC	Trebon® UP	Pyrethroids (3A)	Sipcam Oxon Italia			0.144		
Flupyradifurone 0.08 g L^{-1} AL	Sanium® (*)	Butenolides (4D)	SBM Life Science					25
Indoxacarb 300 g kg^{-1} WG	Steward®	Oxidiazines (22A)	Du Pont de Nemours			0.125		
Lambda-Cyhalothrin 94.8 g kg^{-1} SC	Karate Zeon®	Pyrethroids (3A)	Syngenta			0.024		
Metaflumizone 240 g L^{-1} SC	Alverde®	Semicarbazones (22B)	BASF				0.060	
Paraffinic mineral oil 8.0 g L^{-1} AL Cypermethrin 0.05 g L^{-1} AL	Oleosan Plus (*)	Mineral oils (UN) Pyrethroids (3A)	Arysta					25
Pirimicarb 50 g L^{-1} WG	Pirimor 50	Carbamates (1A)	ADAMA Italia			0.020		
Phosmet 200 g L^{-1} EC	Spada® 200 EC	Organophosphates (1B)	Gowan		0.750			
Pyrethrins 2 g L^{-1} AL	Piretro Garden (*)	Pyrethrum extracts (3A)	Copyr					25
Rapeseed oil 17 g L^{-1} AL	Biopolysect (*)	Vegetal oils (UN)	Scotts France					25
Spinosad 480 g L^{-1} SC	Laser™	Spinosoids (5)	Dow AgroSciences			0.096		
Sulfoxaflor 120 g L^{-1} SC	Closer™	Sulfoximines (4C)	Dow AgroSciences		0.048			

peach, with fruit about 90% of final size and at beginning of fruit coloring (Meier et al., 1994).

For willow and Virginia creeper, the individual plants were treated. For grapevine, peach, and corn, additional plants on each side of the caged plants were treated (for a total of 5 plants in a row in grapevine and peach and 10 plants in corn) in order to achieve a satisfactory coverage of the caged plants.

For corn and perennial plants, a motorized sprayer with a disc core nozzle (Albuz, ATR 80 yellow) and 12 bars of pressure was used for the foliar applications with a water volume equal to 400 and 1000 L/ha, respectively. For the Virginia creeper, 25 mL/potted plant were applied using the commercial sprinkler bottle provided by the manufacturer for ready-to-use products for non-professional use.

The mean daily temperature recorded during the trials was 23.8 °C (SD = ± 2.7 °C) in 2019 (9 July – 1 August) and 22.6 °C (SD = ± 2.0 °C) in 2020 (30 June – 23 July). Two rain events occurred during the experiment in both years (15 and July 16, 2019, 5.6 and 25.6 mm, respectively; 2 and July 10, 2020, 13.8 and 5.2 mm, respectively). Weather data were collected from the nearest meteorological station, in Castronno (province of Varese; 45° 45′ N, 8° 48’ E).

2.4. Statistical analyses

The effectiveness of the insecticide treatments was assessed through a survival analysis. Survival curves were estimated by the Kaplan-Meier method (Klein and Moeschberger, 2006). To account for possible insect intra-cluster dependence due to net-cages, a marginal Cox proportional-hazards model was applied where robust standard errors were obtained to adjust for such dependence (Therneau and Grambsch, 2000; Martinussen and Scheike, 2007). The Cox model was validated by checking the proportional hazards assumptions with a Schoenfeld residual analysis (Klein and Moeschberger, 2006). Ten Cox models (5 crops and 2 effects, *i.e.*, contact and short-term residual), were built to compare insect survival between treatments. The dependent variable was the lifetime of each insect; the categorical explanatory variable was the treatment, composed by 5–7 insecticide products depending on the crop (Table 1) and the untreated control; the cluster factor was the cage identity. Further 30 Cox models were built to compare contact and short-term residual effects of each insecticide for each crop (Table 1). The dependent variable was the lifetime of each insect; the categorical explanatory variable was the effect, *i.e.*, contact or short-term residual; the cluster factor was the cage identity.

To test the long-term residual effect, as only one check was carried out, a generalized linear model was built and validated for each crop (peach, corn, and willow). Models were fitted with a binomial distribution, or quasi-binomial distribution whether data were overdispersed, using a logit link-function. The response variable was the proportion of survivors per cage; the categorical explanatory variable was the treatment, composed by 5–7 insecticide products (Table 1) and the untreated control.

Pairwise comparisons between treatments were performed using adjusted p-values (Bonferroni correction). All analyses were run in R (R Core Team, 2020). Cox models were developed and validated using the 'survival' package (Therneau and Lumley, 2020). Pairwise comparisons were run using the 'emmeans' package (Lenth et al., 2020). Kaplan-Meier curves were plotted using the 'survminer' package (Kassambara et al., 2020). In Section 3, statistical differences with untreated control were indicated when $p < 0.05$.

3. Results

3.1. Contact and short-term residual effects

In the vineyard, acetamiprid and deltamethrin showed good effectiveness against *P. japonica* adults, killing a large proportion of insects (over 70%) in 3 days with contact effect and in less than 8 days with residual effect ($p < 0.001$ in all cases). Chlorantraniliprole reduced the number of the insects after longer times, mainly between 3 and 8 days with both contact and residual effects (both $p < 0.001$). Chlorpyrifos-methyl and azadirachtin were not different from the untreated control (Fig. 1). Mean mortality in untreated control after 8 days was 30%.

In the peach orchard, acetamiprid, deltamethrin, phosmet and abamectin had a very high effectiveness leading to death all caged adults in 1–3 days with contact effect and in 7–10 days with residual effect ($p < 0.001$ in all cases). Sulfoxaflor showed limited effectiveness only through contact effect after 10–14 days ($p < 0.001$) (Fig. 2). Mean mortality in untreated control after 21 days was 55%. This high mortality was probably due to the high temperatures (Kreuger and Potter, 2001) reached under the anti-hail cover nets.

In the corn field, deltamethrin and lambda-cyhalothrin showed good effectiveness in the shortest time (1–3 days) with both contact and residual effects ($p < 0.001$ in all cases). Chlorantraniliprole, etofenprox and indoxacarb caused almost total mortality (over 85%) in adults 3–8 days with both contact and residual effects ($p < 0.001$ in all cases). Pirimicarb was also effective, with both contact ($p < 0.001$) and residual ($p = 0.009$) effects. Spinosad did not differ from the untreated control (Fig. 3). Mean mortality in untreated control after 8 days was 30%.

In the willow nursery, acetamiprid and deltamethrin killed almost all the insects (over 75%) in 3 days with contact effect and in less than 8 days with residual effect ($p < 0.001$ in all cases). Chlorantraniliprole caused the mortality of *P. japonica* (over 40%) mainly between 2 and 8 days with both contact and residual effects (both $p < 0.001$). Chlorpyrifos-methyl showed effectiveness only contactly ($p < 0.001$). Metaflumizone caused around 85% and 10% mortality with contact and residual effects, respectively (both $p < 0.001$), whereas azadirachtin did not differ from the untreated control (Fig. 4). Mean mortality in untreated control after 23 days was 5%.

In the Virginia creeper nursery, acetamiprid and deltamethrin killed most of the adults (over 70%) in 2 days with contact effect ($p < 0.001$) and in 8–13 days with residual effect ($p < 0.001$ and $p = 0.001$). The mixture of paraffinic mineral oil and cypermethrin showed some effectiveness only with contact effect ($p < 0.001$). Flupyradifurone caused around 50% mortality after 13 days with both contact ($p = 0.018$) and residual effects ($p = 0.002$). Pyrethrins, rapeseed oil and entomopatogenic fungi *Beauveria bassiana* (Bals.-Criv.) Vuill. did not differ from the untreated control (Fig. 5). Mean mortality in untreated control after 21 days was 60%. This high mortality was probably due to the high temperatures (Kreuger and Potter, 2001) reached under the anti-hail cover nets.

According to "Rainfastness rating chart" reported for fruit trees (Wise, 2019), the rain events occurred during the experiment in both years (listed in Subsection 2.3) had no impact on the insecticide residues in the short-term.

3.2. Long-term residual effect

In the peach orchard, deltamethrin, sulfoxaflor and phosmet showed good effectiveness in killing insects in the long-term ($p = 0.001$, $p = 0.004$ and $p = 0.035$, respectively). Acetamiprid reduced the number of insects caged without significant differences with untreated control (mean mortality: 21%). Abamectin did not differ from the untreated control (Fig. 6A).

In the corn field, deltamethrin and lambda-cyhalothrin showed good effectiveness in long-term causing around 70% and 40% adult mortality, respectively ($p < 0.001$ and $p = 0.008$). Other active ingredients (chlorantraniliprole, etofenprox, indoxacarb, pirimicarb and spinosad) did not differ from the untreated control (mean mortality: 18%) (Fig. 6B).

According to "Rainfastness rating chart" reported for fruit trees (Wise, 2019), the rain events occurred before caging, 2 DAT, and after caging, 10 DAT, had no impact on peach and corn.

In the willow nursery, acetamiprid and deltamethrin showed good

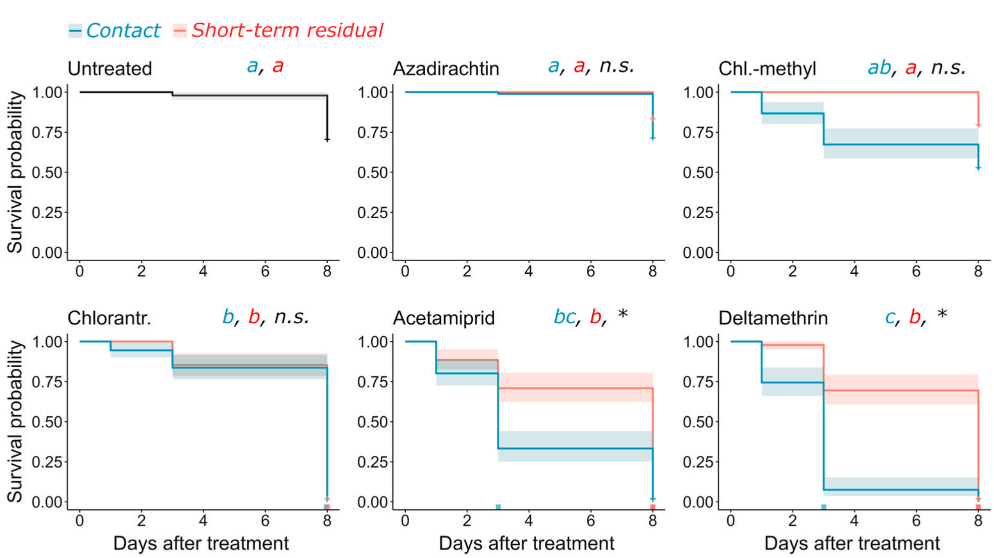

Fig. 1. Kaplan-Meier survival curves for contact (green) and short-term residual (red) effects on grapevine. 95% confidence intervals are reported. Censored data (*i.e.*, surviving insects) are marked with a plus (+). Green and red letters indicate significant differences ($p < 0.05$) in the pairwise comparisons between treatments for contact and short-term residual effects, respectively. Within each treatment, significant differences ($p < 0.05$) between contact and short-term residual effects are marked with an asterisk (*), otherwise with *n.s.* Green and red squares on x-axis indicate median survival time (*i.e.*, time when 50% of the insects are alive) for contact and short-term residual effects, respectively. Names of active ingredients are abbreviated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

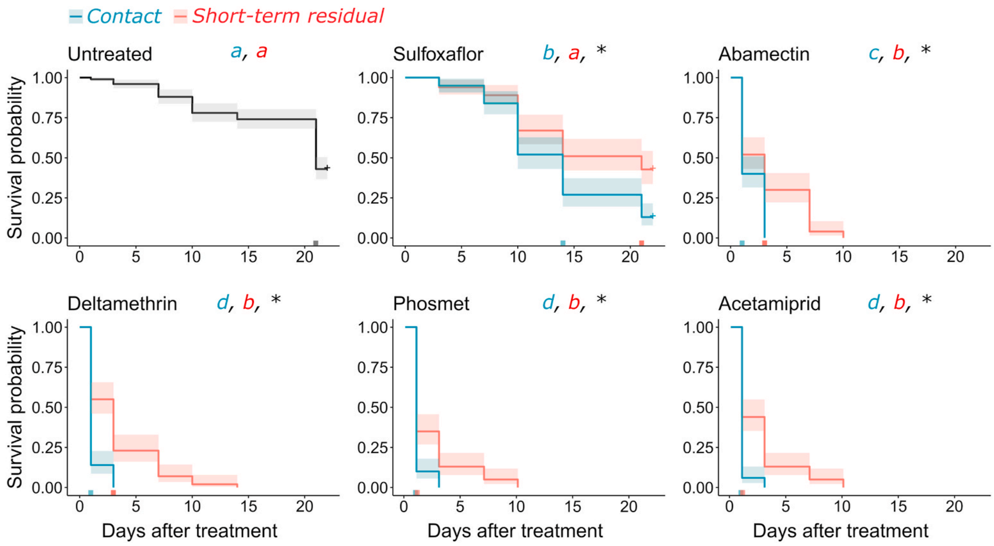

Fig. 2. Kaplan-Meier survival curves for contact (green) and short-term residual (red) effects on peach. 95% confidence intervals are reported. Censored data (*i.e.*, surviving insects) are marked with a plus (+). Green and red letters indicate significant differences ($p < 0.05$) in the pairwise comparisons between treatments for contact and short-term residual effects, respectively. Within each treatment, significant differences ($p < 0.05$) between contact and short-term residual effects are marked with an asterisk (*), otherwise with *n.s.* Grey, green and red squares on x-axis indicate median survival time (*i.e.*, time when 50% of the insects are alive) for control, contact and short-term residual effects, respectively. Names of active ingredients are abbreviated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

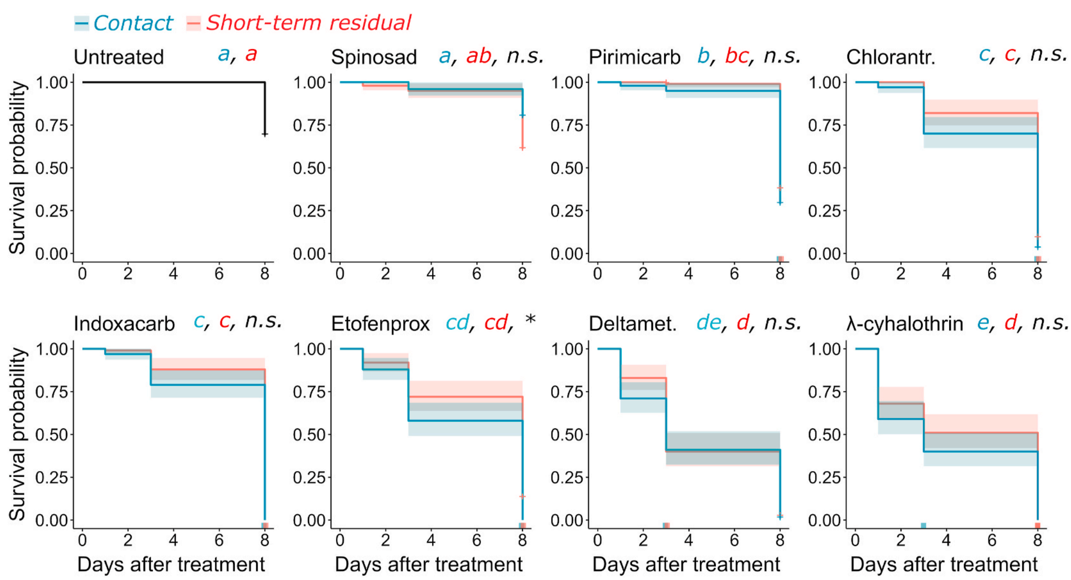

Fig. 3. Kaplan-Meier survival curves for contact (green) and short-term residual (red) effects on corn. 95% confidence intervals are reported. Censored data (*i.e.*, surviving insects) are marked with a plus (+). Green and red letters indicate significant differences ($p < 0.05$) in the pairwise comparisons between treatments for contact and short-term residual effects, respectively. Within each treatment, significant differences ($p < 0.05$) between contact and short-term residual effects are marked with an asterisk (*), otherwise with *n.s.* Green and red squares on x-axis indicate median survival time (*i.e.*, time when 50% of the insects are alive) for contact and short-term residual effects, respectively. Names of active ingredients are abbreviated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

effectiveness killing around 90% and 70% of the adults caged, respectively ($p = 0.002$ and $p = 0.010$). Chlorantraniliprole reduced the number of insects caged without significant differences with the untreated control (mean mortality: 1%). Azadirachtin, chlorpyrifos-methyl and metaflumizone did not differ from the untreated control (Fig. 6C).

According to "Rainfastness rating chart" reported for fruit trees (Wise, 2019), a large amount of insecticides residue on willow leaves was probably wash-off from the two rain events occurred in 2019 before caging, 6 and 7 DAT.

4. Discussion

The Japanese beetle is an economically important pest to growers, landscape managers, and homeowners, who often rely on insecticides to reduce the beetle pressure on crops, especially in emergency situations.

Among the tested compounds, the neonicotinoid acetamiprid, the pyrethroids deltamethrin and lambda-cyhalothrin, and the organophosphate phosmet were effective in killing beetles, with similar contact, short- and long-term residual effectiveness. These results confirm those obtained in the U.S. against *P. japonica* on ornamentals plants, grapevine and soft fruits with the two pyrethroids, imidacloprid and phosmet (Pettis et al., 2005; Baumler and Potter, 2007; Hulbert et al., 2011; Van Timmeren and Isaac, 2013). For lambda-cyhalothrin and phosmet, these are the first data on the effectiveness against Japanese beetle adults in Europe. The anthranilamide chlorantraniliprole showed good contact and short-term residual effectiveness against beetles as reported on lime tree (Tilia cordata Mill.) and grapevine (Redmond and Potter, 2017; Bosio et al., 2020). The pyrethroid etofenprox had a good short-term residual effect as reported in grapevine (Bosio et al., 2020). The same effect was observed for the oxidiazine indoxacarb, which is

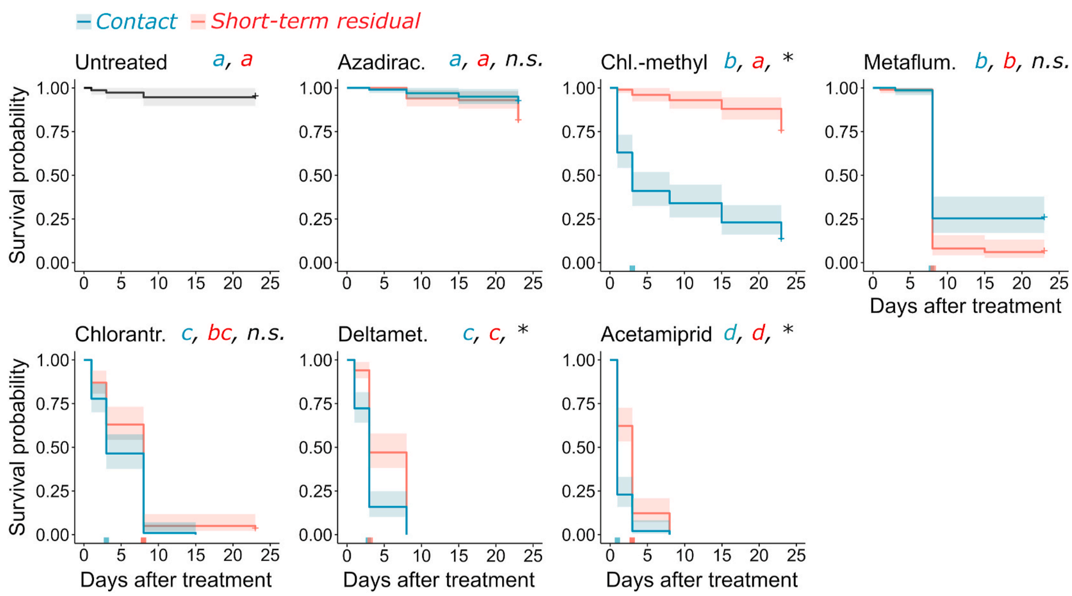

Fig. 4. Kaplan-Meier survival curves for contact (green) and short-term residual (red) effects on willow. 95% confidence intervals are reported. Censored data (*i.e.*, surviving insects) are marked with a plus (+). Green and red letters indicate significant differences ($p < 0.05$) in the pairwise comparisons between treatments for contact and short-term residual effects, respectively. Within each treatment, significant differences ($p < 0.05$) between contact and short-term residual effects are marked with an asterisk (*), otherwise with *n.s.* Green and red squares on x-axis indicate median survival time (*i.e.*, time when 50% of the insects are alive) for contact and short-term residual effects, respectively. Names of active ingredients are abbreviated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

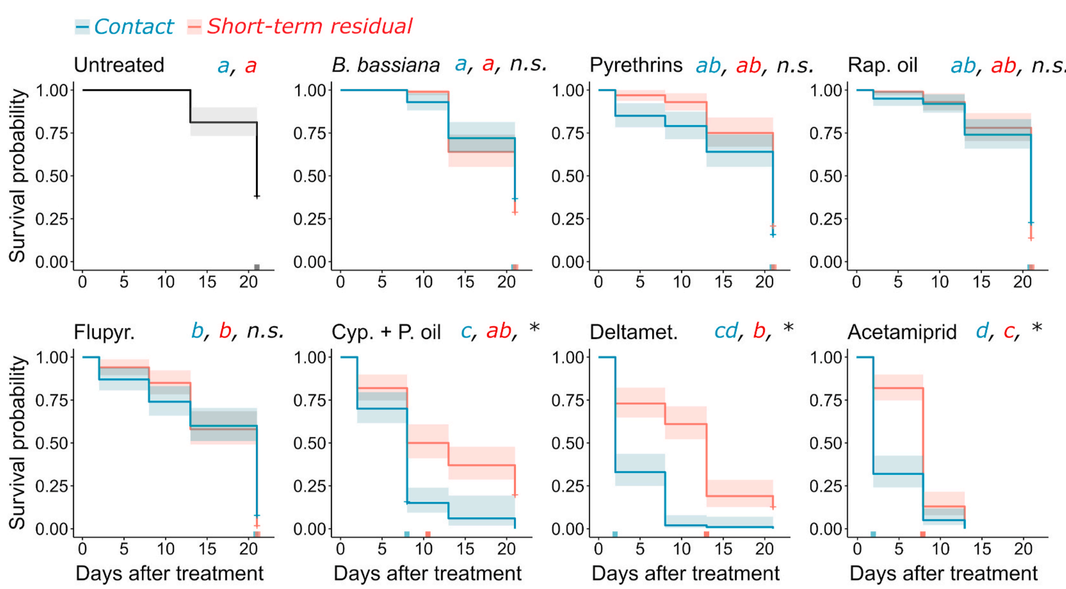

Fig. 5. Kaplan-Meier survival curves for contact (green) and short-term residual (red) effects on Virginia creeper. 95% confidence intervals are reported. Censored data (*i.e.*, surviving insects) are marked with a plus (+). Green and red letters indicate significant differences ($p < 0.05$) in the pairwise comparisons between treatments for contact and short-term residual effects, respectively. Within each treatment, significant differences ($p < 0.05$) between contact and short-term residual effects are marked with an asterisk (*), otherwise with *n.s.* Grey, green and red squares on x-axis indicate median survival time (*i.e.*, time when 50% of the insects are alive) for control, contact and short-term residual effects, respectively. Names of active ingredients are abbreviated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

registered in Europe only for leaf beetles (Chrysomelidae) control. A different response was observed for the organophosphate chlorpyrifos-methyl, no longer allowed in Europe since January 2020 (EU Pesticides Database), which was ineffective. The organic active ingredients azadirachtin and spinosad, registered in Europe only on leaf beetles, were ineffective. These outcomes confirm the results obtained in the U.S. on hybrid tea rose (Rosa x hybrida L.), Lagerstroemia indica (L.) Pers. and Hydrangea quercifolia Bartram (Gupta and Krischik, 2007; Mmbaga and Oliver, 2007). Nevertheless, Baumler and Potter (2007) showed that azadirachtin had a good antifeedant activity. This plant protection effect could be useful to limit the defoliation, without the need to reduce insect populations. Pyrethrin was ineffective, as reported by Baumler and Potter on lime tree (Baumler and Potter, 2007). The active ingredient resulted effective in hybrid tea rose only in formulation with piperonyl butoxide (Gupta and Krischik, 2007). The foliar application of the entomopathogenic fungus B. bassiana and rapeseed oil was

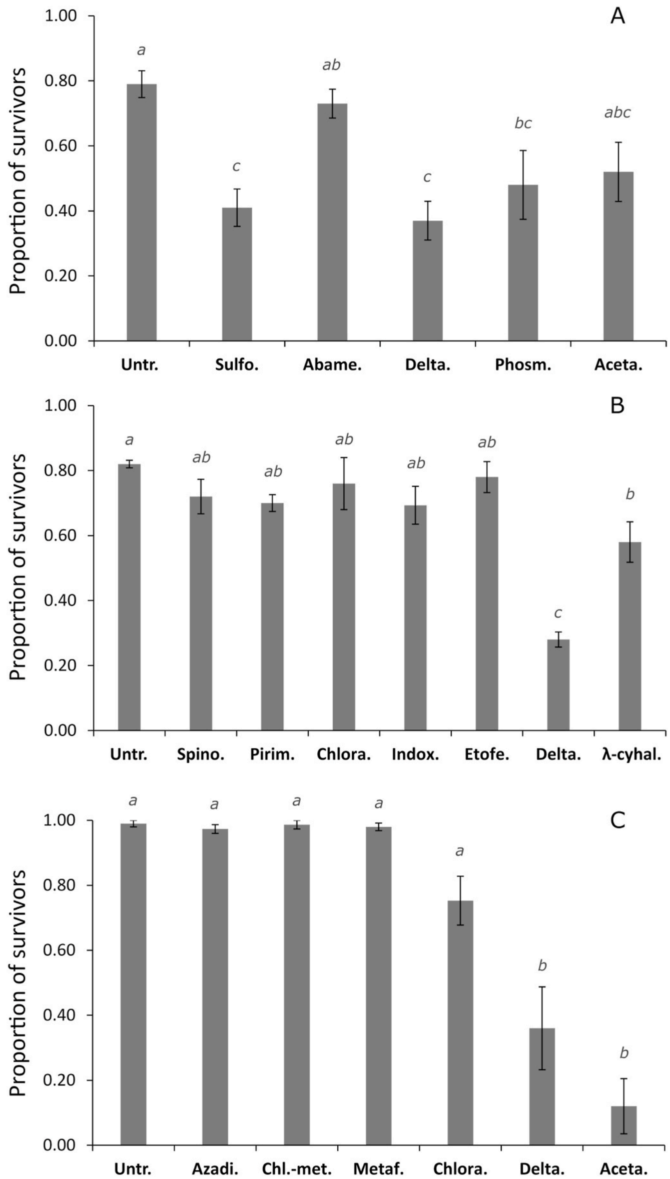

Fig. 6. Mean (±standard error) proportion of survivors for long-term residual effect on (A) peach, (B) corn and (C) willow. Letters indicate significant differences ($p < 0.05$) in the pairwise comparisons between treatments. Names of active ingredients are abbreviated.

ineffective. Similarly, the entomopathogenic fungus Metarhizium brunneum Petch was not effective in grapevine (Bosio et al., 2020) as well as sunflower and canola oil in ornamental plants (Mmbaga and Oliver, 2007). Paraffinic mineral oil showed good contact effectiveness combined with pyrethroid cypermethrin, which proved to be highly toxic for the insect (Hulbert et al., 2012). For this insecticide, there is no history of published studies on Japanese beetle in Europe.

The present survey showed original data for the contact and short-term residual effectiveness of abamectin, pirimicarb and metaflumizone, and it provided evidence of long-term residual effectiveness of sulfoxaflor, while flupyradifurone resulted to be less effective. A robust insecticide effectiveness evaluation on *P. japonica*, however, would include defoliation in addition to adult mortality, so as to capture plant protection resulting from repellency or antifeedant action.

Suitability of a chemical or organic insecticide for managing P. japonica adults will depend on the management objectives of the user. For homeowners, such products do not necessarily need to kill the beetles as long as priority plants are protected. Indeed, homeowners may prefer to reapply a short-term residual every few days to avoid using more toxic products (Baumler and Potter, 2007). Professionals tend to favor long-term residual products that minimize the number of applications needed to protect plants throughout the beetle's activity period, typically 8–10 weeks (Baumler and Potter, 2007). Products that kill may be desirable for sites where grubs are a concern because females tend to lay eggs in turfgrass near adult host plants (Dalthorp et al., 2000). Slow-acting insecticides are not suited, because they allow too much damage, and because additional beetles are attracted to volatiles emitted by damaged leaves (Loughrin et al., 1996).

5. Conclusions

This study compared an array of insecticides marketed to growers, landscape managers and homeowners for contact and residual effectiveness against *P. japonica*, giving a valid support to update the European guidelines aimed at controlling the beetle.

Due to the long flight period of adult beetles (usually >8 weeks), multiple foliar applications of persistent insecticides are typically used to attain satisfactory control of adult beetles on blooms and foliage (Potter and Held, 2002). Therefore, target-selective insecticides for managing insect pests on flowering woody ornamentals that may be visited by non-target organisms are needed. Pesticides used to protect woody ornamentals and turf in urban landscapes need to have a low mammalian and avian toxicity, stability of performance across different conditions, and minimal impact on pollinators, natural enemies, earthworms, and other beneficial invertebrates. Residual activity on foliage is particularly useful for products used to manage leaf-chewing pests, such as Japanese beetles, that have a relatively long seasonal flight and mobile adults (Baumler and Potter, 2007). The client should consider the relative toxicity and the residual profile of the insecticide as a part of their integrated pest management (IPM) decision-making (Hulbert et al., 2011, 2012).

In conclusion, most of the tested active ingredients revealed to be useful to effectively limit *P. japonica* outbreaks on high-value crops. The low selectivity of the more effective active substances requires the need to integrate these chemical agents into a general management plan that envisages their use only where strictly necessary. This should be done in combination with the use of natural enemies and cultural techniques addressed to contain the population growth of the beetle (Altieri and Letourneau, 1982).

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Author contribution

NM, GSa and AB conceived and designed research. GSa, NM, GGu, GSp and LT conducted experiments. GSa and GC performed data analysis. NM, GSa, AB and GC wrote the manuscript. MC, BC and GGi provided supervision. All authors read and approved the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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