Agrilus mali **Matsumura (Coleoptera: Buprestidae) density and damage in wild apple *Malus sieversii* (Rosales: Rosaceae) forests in Central Eurasia under four different management strategies**

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Abstract

In 1993 the apple buprestid, *Agrilus mali* Matsumura (Coleoptera: Buprestidae) native to northeast Asia*,* invaded the Yili River valley, Xinjiang Uyghur Autonomous Region, China. It is now widespread across 95% of wild apple forests (*Malus sieversii* (Ledeb.) Roem) in the region. This invasive species poses a major threat to wild apple populations serving as the key germplasm refuge for the ancestor of domestic apples across 6 countries in Central Eurasia. We first described the symptoms and damage caused by *A. mali* to wild apple trees, and then assessed abundance of *A. mali* and tree damage under four different management strategies in three consecutive years (2016-2018): release of commercial biocontrol agents, aerial spraying of insecticide, aerial spraying/pruning, and establishment of fenced areas to preserve understory vegetation and enhance natural pest control. The apple buprestid feeds on inner bark and preferentially damages the small branches (1-4 cm in diameter) located in the canopy 4-6 m above ground. The average fruit production declined from 90 kg to 10 kg per tree after the pest invasion. Pest abundance, as measured by damage scars, declined in sprayed areas. Fenced areas had higher pest abundance (damage). Fruit production in biological control and spraying/pruning areas increased slightly, while tree damage ranking declined over the years. Our results suggest that a combination of biological control and spraying/pruning may contribute to pest management of *A. mali* and resilience of wild apple forests in Central Eurasia.

Key words: forest pest management, tree damage, pruning, biocontrol

Introduction

In an era of unprecedented ecological change due to globalization, understanding the effects of exotic species on native species and ecosystems is critical to predicting the consequences on native biodiversity and agroforest production and to develop mitigation strategies for conservation (Brockerhoff et al. 2006, Pejchar & Harold 2009). The emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), originally from Asia and now widespread in North America, has caused the death of hundreds of millions of ash trees since its invasion in the USA (EAB Info 2019). In infested stands, emerald ash borer kills up to 99% of ash trees and it threatens the entire North American ash resource (Klooster et al. 2014, Herms & McCullough 2014). This damage is typical of aggressive invasive species, which can cause massive economic and environmental losses (Gandhi & Herms 2010, Kovacs et al. 2010). In recent years a congeneric species, the apple buprestid (*Agrilus mali* Matsumura), has invaded the wild apple (*Malus sieversii*) forests in Xinjiang Uyghur Autonomous Region, China. Over 95% of the wild apple forests in this region are now infested and 40-50% of infested trees have been killed (Cui et al. 2015). The wild apple species *M. sieversii* is recognized as an important germplasm bank and ancestor of cultivated apples worldwide (Richards et al. 2009, Zhang et al. 2015, Duan et al. 2017). This pest poses a high threat to wild apple forests in neighboring countries and throughout central Eurasia. Therefore, research on *A. mali* damage to wild apple forests and evaluation of potential management strategies is crucial to understanding the impact of this new invasive pest, and to implementing emergency strategies in Central Eurasia for mitigating its economic and environmental damage.

The apple buprestid is native to the Russian Far East, Japan, and the Korean Peninsula, and has been recorded in Heilongjiang, Jilin, and Liaoning provinces of Northeast China since the 1950s. However, in China it was long considered a minor pest of domestic apples because of appropriate orchard management, including pruning and pesticide application to damaged bark (Zhang 2008). In the early 1990s, the species was inadvertently introduced to Xinjiang Uygur Autonomous Region, most likely via the movement of domestic apple seedlings from Northeast China. Because of its small adult body size and the cryptic larval life history beneath bark, detection of *A. mali* was delayed until its outbreak in domestic apple orchards at Gaochao farm in Xinjiang in 1993 (Wang et al. 2013). Soon after it was reported, it was found to be widespread in nearby wild apple forests in the Yili River valley. This invasive pest is of great concern to local farmers and regulatory authorities because it threatens both domestic apple orchards and wild apple forests. Therefore, some land managers rapidly implemented emergency management strategies without any field assessments, in an attempt to mitigate the threat.

Understanding the biology and impacts of invasive pests is fundamental for developing effective management strategies. The life history of *A. mali* has been investigated in wild apple forests (Cui et al. 2019). Larvae of the apple buprestid are the key damaging stage, which feed on the inner bark and tunnel into the phloem (Cui et al. 2019). In response to larval feeding, branches and younger trunks develop inner necroses and longitudinal bark cracks, which are visible as scars. Wild apple in Central Eurasia is a new host record for *A. mali*. Symptoms caused by *A. mali* damage on wild apple have not been well-described, and little is known about insect-host interactions, which hampers development of management options.

Detection and management of *A. mali* are further hampered by its cryptic life history and uneven developmental stages. Larvae are difficult to detect and control with insecticides because they are hidden and protected under the bark. However, the adults of *A. mali* feed and mate on foliage, which suggest that aerial spraying of insecticide at the right time could be a relevant management strategy. However, life history and phenology vary with different temperatures at different latitudes and altitudes in mountainous areas complicating the timing of treatments (Cui et al. 2019). The terrain is also problematic for insecticide application equipment. These issues pose major challenges for timely and efficient suppression of this pest.

Our objectives were (1): to improve the detection of *A. mali* in wild apple trees, by investigating and precisely describing the damage symptoms. (2): to assess the effectiveness of four different management strategies implemented by local farmers and authorities in the Yili River valley, by comparing damage and fruit production among years. Our study aims to better inform the management practices for this invasive pest of wild apple forests across Central Eurasia.

Methods and materials

1. Survey sites

The remnant patches of wild apple forests in China are found mostly in Gongliu and Xinyuan Counties (Fig 1), accounting for more than 75% of the wild apple trees in Xinjiang. Most of these patches are located on the shady northern slopes of the Tianshan Mountains, between 900 m and 1700 m altitude. We established survey sites at 7 locations with four different management strategies (Fig. 1, Table 1, and Appendix S1), where *M. sieversii* was a dominant species in the experimental forest stands with other tree and shrub species including *Armeniaca vulgaris* L., *Lonicera hispida* Pallas ex Schultes, *Crataegus sanguine* Pallas, and *Berberis nummularia* Bunge (Table 1).
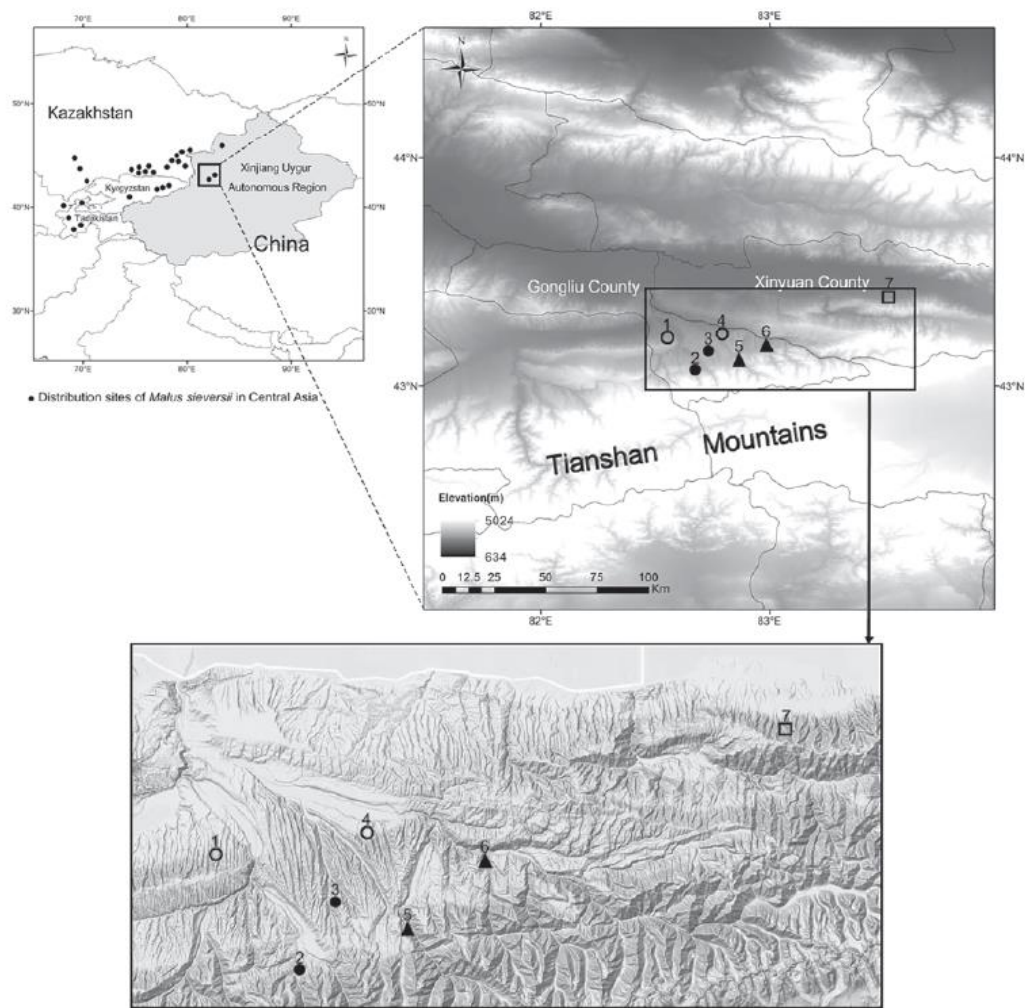
Fig. 1. Location of survey sites in Gongliu and Xinyuan County, Xinjiang Uyghur Autonomous Region, China. The dots in the map on the left indicate the distribution of *Malus sieversii* in Central Asia. The symbols in the enlarged map on the right indicate the 7 survey sites in the Yili River valley: 1: Erxiang; 2: Damohe; 3: Xiaomohe; 4: Balian; 5: Jiaolesai; 6: Saha; 7: Xinyuan; Different symbols represent varying management strategies: hollow circle (fenced area); solid circle (aerial spraying); solid triangle (biocontrol); hollow square (aerial spraying/pruning).

2.1 Experiment: Symptoms of damaged trees, characteristics of larval galleries, and emergence holes

Branches from wild apple trees were cut and debarked to investigate the symptoms and characteristics of larval galleries and emergence holes of *A. mali*. We randomly selected 200 branches from 100 trees at the Xinyuan field site during May and June in 2014. This site was selected because the management strategy implemented in Xinyuan included pruning of infested branches; therefore, branch sampling did not interfere with management activities. Insecticide applications at the site were not initiated until 2016 and so did not affect the *A. mali* infestation pattern. Scars that develop over *A. mali* galleries have a distinctive appearance and can be clearly distinguished from surrounding bark (see Appendix S1). We peeled off the bark over each scar to reveal galleries made by the pest. Parchment paper and a pencil were used to trace each gallery. Tracings were overlaid onto 1 mm^2 gridded graph paper to calculate the area for each scar. The length of each gallery was estimated using a string which was bent to "trace"

along the gallery, then straightened and measured. The perimeter and maximum width of scars, the length and depth of pupal chambers, and the width of emergence holes were measured *in-situ* using a ruler and a caliper.

2.2 Experiment: Within-tree distribution of *A. mali* larvae

To estimate the vertical distribution of *A. mali* infesting individual trees, ten single stem trees (9 cm to 20 cm in DBH, 6.5 m to 9.1 m in height) were randomly selected in the area where *A. mali* was first reported in Xinjiang Uyghur Autonomous Region, our site 7 in Xinyuan County. Each tree was cut at ground level and the main trunk was cut into 2 m bolts. For all branches in each 2 m segment, all signs of damage (damage scars and new emergence holes) were counted and recorded.

2.3 Experiment: Assessment of four management strategies on *A. mali*

Since 2013, four different management strategies were implemented by the local government aiming to reduce the damage caused by *A. mali* in this area as follows:

1. Biological control (two sites: Jiaolesai and Saha), was started in 2014 using the native parasitoid *Sclerodermus pupariae* Yang et Yao (Hymenoptera: Bethylidae). This larval ectoparasitoid was produced commercially by the Chinese Academy of Sciences and its partner companies, and this species was found to be able to utilize novel hosts including *A. planipennis* (Wei et al. 2013). This parasitoid was augmentatively released in mid-May during three consecutive years (2014, 2015, and 2016). One tube containing 100 individual parasitoids was placed on each tree. Overall 6100 tubes were released in Saha and 8050 tubes in Jiaolesai across 60-80 ha at each site.

2. Exclusion fences (two sites: Balian and Erxiang), which were constructed in 2013 enclosing 100-150 ha to protect the woodlot from grazing by cows and sheep, thus preserving the understory vegetation. Cutting and mowing grass were also forbidden in the fenced areas. As a result, natural biocontrol services were expected to be improved, because refuge and supplementary nectar were available for native natural enemies, including five species of braconid parasitoids recently recorded to attack *A. mali* (Heimpel and Jervis 2005; Cao et al. 2019).

3. Aerial spraying of insecticide (two sites: Damohe and Xiaomohe), was conducted in early-July, mid-July and early-August of each growing season for three consecutive years (2016, 2017, and 2018). Thiacloprid, a systemic neonicotinoid insecticide (2%, active ingredient; 48 kg pesticide with 200 kg water applied per 40 ha forest) was applied by aerial spraying. The areas sprayed ranged from 1000ha to 2000 ha each year. GPS was used to delimit the sprayed area.

4. Aerial spraying/pruning (one site: Xinyuan), which were implemented in an area of 100-200 ha. Old damaged branches were pruned by the local forest staffs each year from 2013 to 2018. The spaying protocols were the same as the "Aerial spraying of insecticide" strategy.

Table 1. Details of the location of each transect used to assess *Agrilus mali* damage and effectiveness of various management strategies in wild apple forests in Xinjiang, China, 2016-2018.

Transect site	Management strategies	Location (°)	Altitude (m)*	Density of wild apple trees per ha	Plot number	Mean basal diameter (cm)	Mean DBH (cm)
Jiaolesai	Biological control[1]	43.232N, 82.778E	1350	152	J1	33.47	16.48
					J2	31.45	19.44
					J3	38.41	15.18
Saha	Biological control[1]	43.261N, 82.857E	1300	103	S1	61	36.26
					S2	51.33	43.14
					S3	57.72	41.83
Balian	Exclusion fence[2]	43.235N, 82.766E	1350	196	B1	34.97	27.21
					B2	39.28	30.81
					B3	52.05	40.14
Xiaomohe	Aerial spraying[3]	43.178N, 82.734E	1200	154	X1	34.25	23.85
					X2	31.41	23.93
					X3	31.59	22.59
Damohe	Aerial spraying[3]	43.224N, 82.754E	1200	161	D1	43.12	31.62
					D2	61.92	32.73
					D3	51.77	41.55
Xinyuan	Aerial spraying/pruning[4]	43.377N, 83.605E	1400	360	Y1	39.38	29.19
					Y2	29.86	23.11
					Y3	29.54	21.23
Erxiang	Exclusion fence[2]	43.203N, 82.601E	1450	223	E1	40.15	23.54
					E2	27.32	20.86
					E3	35.72	22.24

* Altitude at the initial point of the transect through the middle of each sample site.

3. Transect and survey design

One sampling transect was established in every abovementioned experimental site to monitor pest abundance, tree damage and tree characteristics over three consecutive years (2016, 2017, and 2018). Due to time constraints and labor costs, one 2-6 km transect was established at each site (Table 1) to represent typical forest and damage conditions for the entire site. Each transect ran on grade across the sloping terrain at a fixed altitude. Three plots with 20-m radius were established within each transect, one in the middle of the transect and the other two plots were placed 1000-3000 m on either side of the middle plot (depending on the size of the site). Diameter at breast height (DBH), and basal diameter were recorded for all wild apple trees within each plot. At the same time, the level of pest damage was recorded for each tree, and the potential yield was also calculated. Methods for determining levels of pest damage and potential fruit production are described in the next section.

4. Abundance of *A. mali* and tree damage in wild apple forests under different management strategies

Tree damage by *A. mali* is difficult to quantify because the larval stage was concealed in the phloem tissue under the bark and lasts for several months depending on local temperature. Moreover, tree damage accumulates over time (often years). We estimated *A. mali* abundance and tree damage by sampling branches from wild apple trees at each site, under the four different management strategies.

We randomly selected and cut four branches from each tree, which were 2-6 cm in diameter located at 4-6 m in height on the southern and northern sides of all wild apple trees, at all plots in each transect. The length of each cut branch and the diameter (cm) at the base of the branches were recorded. We counted the number of new emergence holes as well as scars (new emergence holes were distinguished from old ones based on the lighter color of surrounding bark), then converted to density by length (per meter). At the same time, the damage ranking and the potential fruit production per tree (in kg) were estimated. We used a visual damage ranking with five classes based on the proportion of damaged branches (0-10% branches damaged ranked as Class 1, 11-25% as Class 2; 26-50% as Class 3; 51-75% as Class 4; more than 76% as Class 5). The potential fruit production was estimated by local forestry staffs with over 20 years of experience in wild apple agronomy. The number of new emergence holes and scars indicated pest abundance in the current year. All indices were summarized for each plot to reflect the forest health status based on all sampled trees.

5. Data analyses

In order to test the relative effectiveness of different management strategies over three years, data for each plot and each transect were categorized according to the management strategy employed (Table 1). Density of *A. mali* for each tree was estimated based on the number of scars and new emergence holes per meter of branch length. In addition, the damage ranking and the potential fruit production per tree were analyzed among years for each management strategies. All data were pooled from all sites and management strategies, and then analyzed using two-way ANOVA (SPSS, IBM Company, Version 20) to compare *A. mali* density, damage ranking, and the potential fruit production for each management strategy among years. Additionally, a paired t-Test was then employed to compare the differences in density of scars, density of emergence holes, tree damage ranking, and fruit production from null hypothesis for each management strategy between 2016 to 2017, 2017 to 2018, and finally between 2016 to 2018, to identify whether a management strategy has a significant effect on damage reduction consistently in the three consecutive years.

Results

1. Symptoms of damaged trees, characteristics of larval galleries, and emergence holes

Wild apple trees produced brown liquid which exuded from branches after pest infestation in spring and autumn, and congealed after exposure to the air (Appendix S1). A total of 81 exudations and 54 emergence holes were checked. We found 1-3 young larvae (1.57 ± 0.08, mean $\pm$ SE) feeding on the cambium beneath each area of congealed exudate. Feeding damage from *A. mali* larvae resulted in subcortical necrosis and longitudinal bark cracking visible as scars (Appendix S1) that ranged from 0.6 to 6.8 cm in width (2.89 ± 0.11), and 1.94 to 45.92 cm^2 in area (10.39 ± 0.66). Galleries ranged from 3.6 to 25.9 cm in length (11.7 ± 0.37), and usually did not cross over other galleries. Mature larvae chew into the xylem and form pupal chambers, which averaged 0.83 ± 0.02 cm in length. Successful adult emergence leaves a distinctive D-shaped exit hole on the branch (Appendix S1). The width of emergence holes ranged from 0.11 to 0.28 cm (0.19 cm ± 0.01).

2. Within-tree distribution of *A. mali* larval feeding galleries

Larvae of apple buprestid were found in younger branches; 0.5 to 8.5 cm diameter (3.84 ± 0.26, mean $\pm$ SE, n = 739), and mostly (78%) in branches from 1-4 cm in diameter (Fig. 2a). Furthermore, larvae mostly occurred in branches in the central part of the canopy, and more than 44% of scars were found in branches at 4-6 m height in the canopy (Fig. 2b). No larva of *A. mali* was found in the trunk of mature trees.
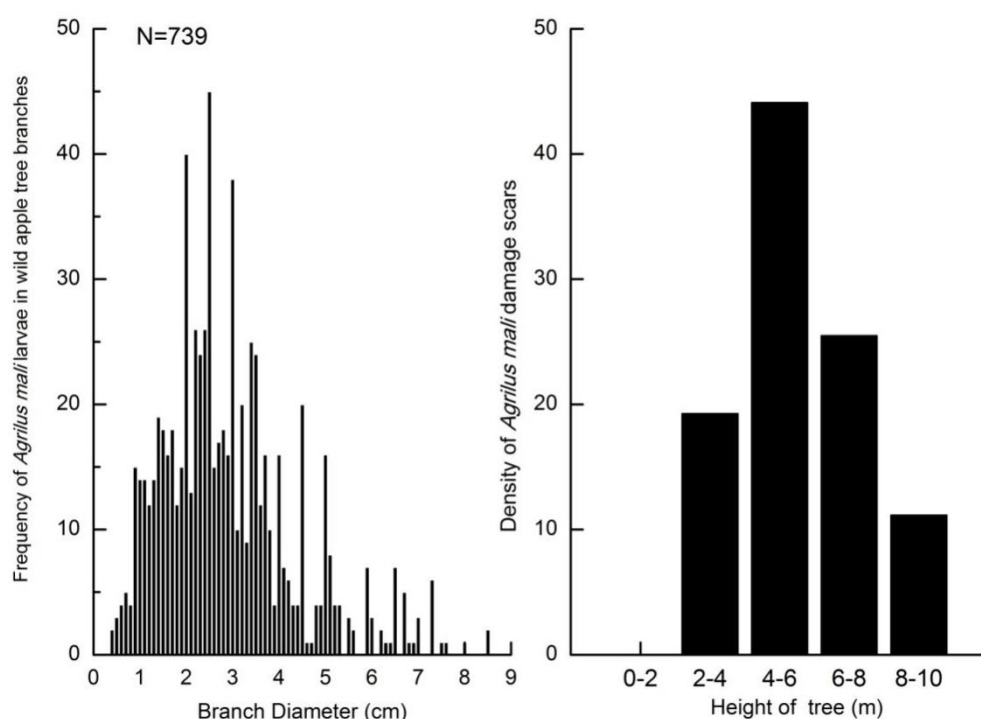

Fig. 2. Infestation pattern of *A. mali* on wild apple trees (N=10, Xinyuan County). (a) Density of *A. mali* larvae in branches with different diameters; (b) Density of *A. mali* damage scars in different tree heights.

3. Abundance of *A. mali* and tree damage in wild apple forests under different management strategies

The density of scars was significantly different among the three years ($F = 29.28$, df = 2, $P < 0.001$). Under four management strategies, significant differences were detected (aerial spraying between 2016 to 2017: $t = -3.29$, df = 5, $P = 0.022$; exclusion fence between 2017 and 2018: $t = 8.82$, df = 5, $P < 0.001$), but no management strategy showed a significant effect of the density of scars between 2016 to 2018 (all $P > 0.05$) (Fig. 3A). Similarly, the density of new emergence holes varied over years ($F = 8.4$, df = 2, $P < 0.001$). However, the densities were not impacted by the management strategies (all $P > 0.05$) (Fig. 3B).
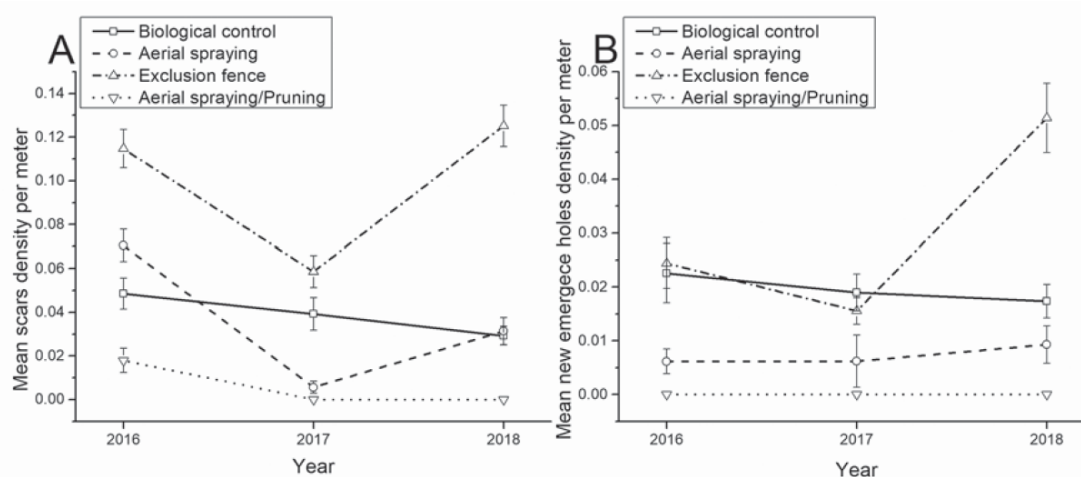

Fig. 3. The abundance of *A. mali* under different management strategies in 2016-2018 in Xinjiang Uyghur Autonomous Region, China. (A) the density of *A. mali* damage scars (mean ± SE) per meter of branch; (B) the density of new emergence holes (mean ± SE) per meter of branch. Square with solid line indicates biological control strategy, circle with dash line indicates aerial spraying strategy, up triangle with dash dot line indicates exclusion fence strategy, and down triangle with dot line indicates aerial spraying/pruning strategy.

Mean damage rankings were significantly different among the three years ($F = 4.76$, df = 2, $P = 0.012$). Under four management strategies, significant differences were detected between 2016 to 2017 (exclusion fence: $t = -4.41$, df = 5, $P = 0.0069$), but not between 2017 to 2018 (all $P > 0.05$). Between 2016 to 2018, significant differences were found (biological control: $t = -2.82$, df = 5, $P = 0.037$; aerial spraying/pruning: $t = -17.73$, df = 2, $P = 0.0032$). (Fig. 4A).

Fruit production was estimated to be less than 10 kg per tree in all surveyed areas. Estimated fruit production showed a slightly increasing trend from 2016 to 2018, except in the aerial spraying and exclusion fence area, which had the highest fruit production in 2017. Fruit productions were significantly different over the three years ($F = 8.34$, df = 2, $P < 0.001$). Under four management strategies, significant differences were detected between 2016 to 2017 (aerial spraying: $t = 4.02$, df = 5, $P = 0.010$; exclusion fence: $t = 5.29$, df = 5, $P = 0.0032$), but not between 2017 to 2018 (all $P > 0.05$). Between 2016 to 2018, significant differences were found for aerial spraying areas ($t = 3.07$, df = 5, $P = 0.028$) (Fig. 4B).
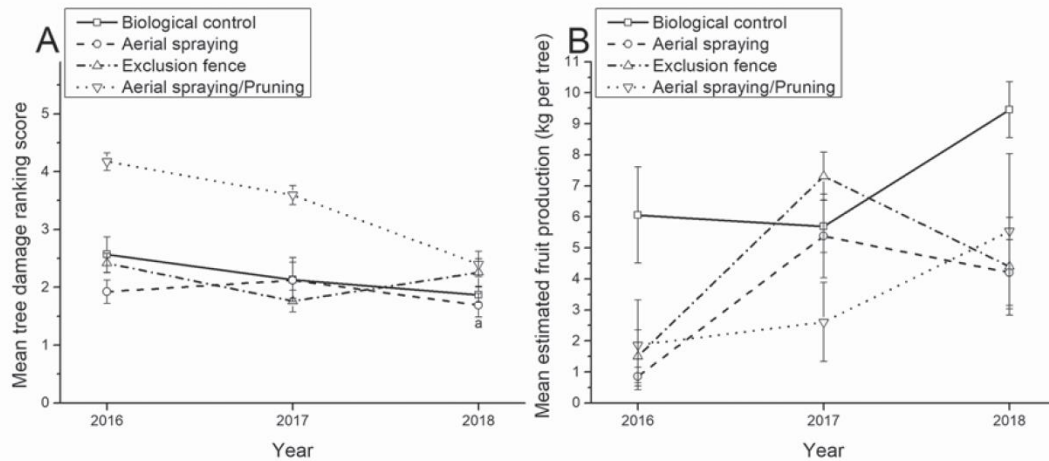
Fig. 4. Accumulated damage in areas under different management strategies after infestation of *A. mali*. (A) the mean damage ranking (mean ± SE) of wild apple trees; (B) the mean estimated fruit production (mean ± SE) (in kg per tree). Square with solid line indicates biological control strategy, circle with dash line indicates aerial spraying strategy, up triangle with dash dot line indicates exclusion fence strategy, and down triangle with dot line indicates aerial spraying/pruning strategy.

Discussion

Identification of plant damage and symptoms is important for the early detection of invasive pest infestations, and can be used for monitoring and management in the field. Nine *Agrilus* species were recorded to associate with *Malus* trees, and *A. mali* was the only species that attack *M. sieversii* (Jendek and Poláková 2014). Another species of wood boring beetle *Tetrops praeusta* was recorded to be a pest of *M. sieversii*, but it mostly damages the very young twigs or shoots and does not leave obvious scars (Dušanka et al. 2012; Jashenko and Tanabekova 2019). As a result, the symptoms caused by *A. mali* on *M. sieversii* branches are unique in our study area. Although the eggs of *A. mali* are minute in size and very difficult to detect, symptoms caused by larval feeding are visible and distinctive. After hatching, young larvae feed on the inner bark and phloem resulting in the rapid appearance of characteristic damage scars and brown liquid exuded from branches (see Appendix S1). In addition, distinctive D-shaped exit holes were found on branches when adults emerged and such symptoms can be used to quantify cumulative damage on trees. Our results indicate that symptoms and damage were highest in young branches that are 1-4 cm in diameter and 4-6 m high in the tree canopy; therefore, surveys targeting these portions of trees would be most efficient for detecting infestations. This finding is similar to results found by Cui et al. (2019). The amount of damage caused to wild apple trees by *A. mali* was variable across sites in the Yili River valley. Overall, the average damage ranking at all sites surveyed was approximately Class 2 (53.7%) (Fig. 4A), except for the aerial spraying/pruning area, where the damage ranking was initially approximately class 4 (38.8%) (site 7, Xinyuan County) but declined over time. The estimated fruit production per tree has experienced a dramatic decline to less than 10 kg per tree from the historical 90 kg per tree before the pest invaded (Dzhangaliev 2010). The rapid decline in fruit production not only has devastating economic impacts, but has implications for the wild apple seed bank and the possibility of *M. sieversii* regeneration. These impacts are similar to the effects of *A. planipennis* in North America where ash species did not form a persistent and viable seed bank (Burr & McCullough 2014; Klooster et al. 2014).

Our experimental design had limitations as the four management strategies were implemented at only one (aerial spraying/pruning) or two (biocontrol, aerial spraying,

exclusion fences) sites by local farmers or local governments, and the four treatments did not initiate from the same year. Moreover, the four treatments were not randomly assigned to standardized sites and not control sites (without any management) were included in this study. All of these limitations allowed us to merely compare how the damage level and fruit production varied over years for each management option, not to compare the management efficacy among different options. Nevertheless, changes in *A. mali* damage levels and estimated fruit production over time serve as an indication of the effectiveness of particular strategies at each site. At the two sites where biocontrol was implemented, there was a decrease in damage ranking (Fig. 4A), but no consistent increase in estimated fruit production (Fig. 4B) over the 3 years of the study; however, there was a slight decrease in the density of damage scars (Fig. 3A) and new emergence holes (Fig. 3B). The biocontrol agent *Sclerodermus pupariae* released in the two sites caused an overall parasitism rate from 0.08 to 0.15 in three years, and with an upward tendency (Zhang, unpublished data). Biocontrol strategy showed a significant effect on damage ranking reduction during 2016 to 2018, this may be the initial effect of biocontrol agents, as it usually take several years for introduced or released natural enemies to build stable populations that achieve higher parasitism rates and for biocontrol to have a decisive impact on *Agrilus* spp. population (Duan et al. 2015). Recently eight species of native parasitoids in this region have been reported to attack *A. mali*, including *Atanycolus denigrator* (L.) (Hymenoptera: Braconidae) which showed a high rate of parasitism on *A. mali*(Cui et al. 2019); however, their efficacy at a broader spatial-temporal scale has yet to be evaluated.

Our results were not consistent with those in previous studies showing the high efficacy of aerial spraying in reducing pest density and damage. For the two sites treated with aerial spraying of insecticide, the density of damage scars decreased (Fig. 3A) and estimated fruit production increased, but the trends were inconsistent between 2016 to 2017 and 2017 to 2018 (Fig. 4B); the density of new emergence holes (Fig. 3B) and damage ranking (Fig. 4A) remained similar over the 3 years of the study. Aerial spraying of Thiacloprid was effective for the suppression of *A. mali* and larval density declined by at least 65% in the second season after treatment in Xinyuan County (Liu et al. 2016). Similarly, aerial spraying with Thiacloprid has also been used to control destructive wood borer species including *Monochamus* spp. (Coleoptera: Cerambycidae) (Ugawa & Fukuda 2008). Although aerial spraying seems to be an available option to control wood boring pests, non-target insects, including pollinators and other ecologically important groups, could be negatively affected (Sandrock et al. 2014). Environmental impacts of aerial spraying must be considered in the sensitive and diverse Yili River valley.

Only one site was treated with aerial spraying/pruning; therefore, it is not possible to determine if differences in damage rankings compared to other sites were related to management strategy or other site factors. Nevertheless, estimated fruit production tended to increase from 2016 to 2018 (Fig. 4B) while the damage ranking tended to decrease over the same time period (Fig. 4A), suggesting that aerial spraying/pruning may reduce damage and improve overall health of wild apple trees. However, pruning is a labor-consuming practice. Development of more efficient pruning guidelines along with implementation of subsidies would encourage local farmers to implement this option.

Our results showed that exclusion fences have inconsistent effects on the damage caused by *A. mali* among three years. The damage ranking and fruit production in the fenced sites were improving during 2016 to 2017, but deteriorated during 2017 to

2018. Exclusion fences that prevent mowing and grazing allow seedlings to survive and provide an opportunity for regeneration of wild apples as well as other trees (Canham et al. 1994). Fences can also protect understory vegetation that harbors diverse natural enemies, as an important source to enhance parasitism rates of herbivorous pests (Cappuccino et al. 1999). Mowing and grazing have been shown to suppress the understory as well as decrease woody plant seedlings, thus significantly hindering natural regeneration of forests including wild apple trees (Canham et al. 1994). Animal husbandry is the second most important source of revenue after agriculture in the Yili River valley, and local farmers traditionally rely on mowing to obtain overwinter forage for livestock (Zhang & Yang 2009). Although currently fencing does not show a convincing effect in reducing the pest damage, careful planning to implement fenced areas across the landscape could optimize conservation and regeneration of wild apple forests while allowing for regional economic development in agriculture and animal husbandry.

Changes in tree health and estimated fruit production were observed at each site under different management strategies over time. Flowers on wild apple trees were abundant throughout the Yili River valley in the spring of 2018, more than in any of the previous years since initial *A. mali* infestation in 1993, especially in the area with aerial spraying/pruning. Mitigation in *A. mali* damage may be attributable in part to the management activities, although it is difficult to quantify treatment effects directly due to variation among limited sites (low replications, the lack of unmanaged control sites and non-random implementation), and the lack of direct data on the efficacy of management activities such as parasitism rates and insecticide induced pest mortality. Even so, pest monitoring via the assessment of tree damage and laborious physical sampling of larvae in branches is indeed helpful for implementing appropriate management practices.

In conclusion, our data clearly demonstrated that the combination of biological control and spraying/pruning may contribute to pest management of *A. mali* and resilience of wild apple forests in Central Eurasia. Sustaining the health of the wild apple forest ecosystem is more critical than merely reducing pest density in the short term. Rebuilding and enhancing ecosystem resilience at various levels, from the individual tree, populations of *M. sieversii*, to the forest ecosystem, should be considered in the management. In our study, *A. mali* infested the younger branches and not tree trunks. In the long-term, innundative release of the parasitoid, pruning of infested branches, built-up of enclosing areas with fences to exclude mowing and grazing may improve the wild apple forest regeneration and ecosystem health.

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The authors declare that they have no conflict of interest.

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Author contribution

ZL designed research. XZ, YZ, JC, HL, PZ and ZG conducted experiments. ZL and PH contributed analytical tools. XZ, ZL and JC analyzed data. XZ, ZL, TP, MZ and PH wrote the manuscript. All authors read and approved the manuscript.

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This paper includes a Supplement with figures S1 and S2.

S1-1. Four management strategies implemented by local government to reduce *Agrilus mali* damage: (**A**) Biocontrol by releasing the wasp *Sclerodermus pupariae* Yang et Yao, (**B**) Aerial spraying, (**C**) Aerial spraying and pruning of damaged branches, and (**D**) Establishing exclusion fences around areas to prevent human activities and browsing of seedlings by animals.
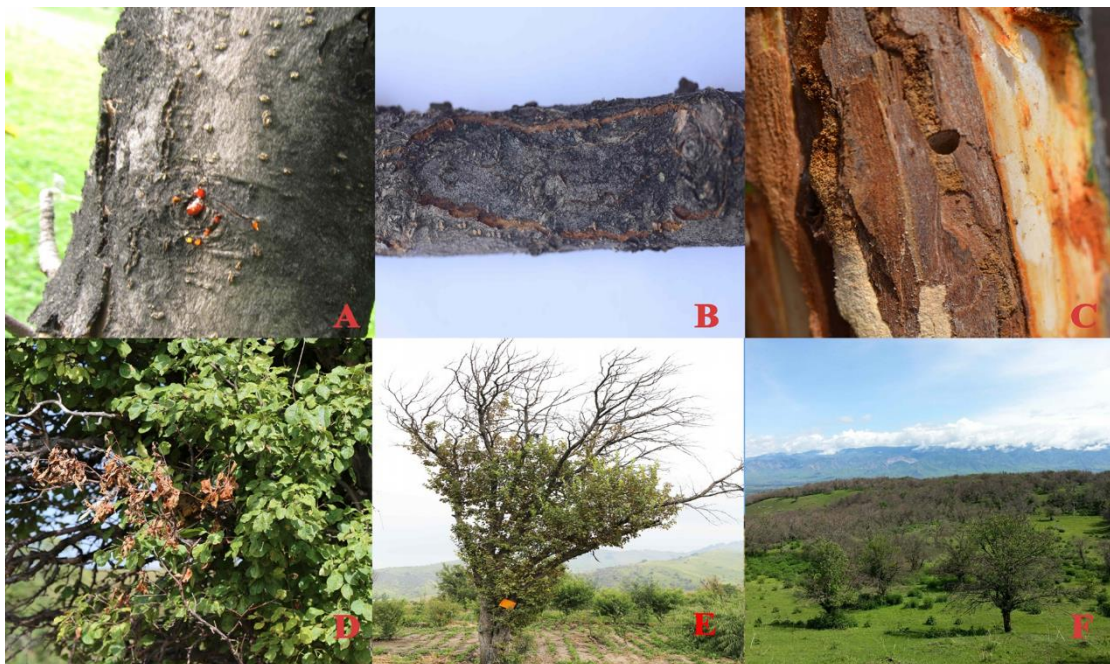
S1-2. Symptoms of wild apple trees damaged by *A. mali* and a landscape view. (A) brown liquid exudates after pest damage; (B) scaring occurs from mid-June to mid-August; (C) D-shape emergence hole; (D) withering of small damaged branches and associated leaves in mid-July; (E) individual tree damage by *A. mali*; (F) Landscape view of dead and dying trees.