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The Japanese beetle (*Popillia japonica*), an invasive quarantine pest

Biology, spread, potential impact as well as monitoring and control measures

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Summary

The Japanese beetle (*Popillia japonica*) is a scarab beetle native to Northeast Asia, where it is regarded as a relatively minor pest. It was first recorded in the USA in 1916. In both the EU and Switzerland, it is listed as a **priority quarantine organism** [Art. 4 of the Plant Health Ordinance PGesV SR 0.916.20]. A quarantine organism is a particularly harmful organism which can potentially cause significant economic, social or environmental damage in the endangered area. **Preventive measures** which aim to avert the introduction of quarantine organisms are therefore essential. In addition, the phytosanitary situation must be monitored in the survey of the territory to determine if pests are present [Art. 18 of the PGesV SR 0.916.20]. This risk-based monitoring for early detection is coordinated by the Confederation and implemented by the cantonal plant protection services throughout Switzerland. “Pheromone” traps are used to monitor Japanese beetles. **Any quarantine organism found is subject to official control measures** which aim to eradicate it.

The Japanese beetle was first recorded in Mainland Europe in 2014, in the Milan area. Despite eradication and containment measures, it has since spread rapidly beyond Northern Italy and was first trapped in Switzerland in 2017 in Stabio (TI), close to the Italian border. By the end of 2024 the Japanese beetle had colonised large parts of Ticino and the valley south of the Simplon Pass of the canton of Valais. Small, isolated populations have also been found in Kloten near Zurich, in the Basel region and in the cantons of Solothurn and Schwyz. Despite mandatory reporting and control requirements, it can be assumed that the Japanese beetle will continue to spread in Switzerland due to human activities such as the trade in plant products, and the movement of goods and people. In this publication we summarise the most important information on the biology, ecology and control of the Japanese beetle relevant to practice. We also provide insights into the legal bases for controlling this priority quarantine organism and estimate its damage potential for individual crops.

The Japanese beetle generally produces one generation per year, with females laying 40 to 60 eggs throughout the summer, mainly in moist or irrigated grassland. The larvae hatch and feed on the roots in the soil. They moult twice before winter, then burrow deeper into the soil to protect themselves from the cold. In spring, the larvae return to the root zone, where they complete their development and pupate. The next beetle generation emerges in early summer. Adult Japanese beetles, no bigger than a one-cent coin, have an oval body with metallic golden green thorax and head and iridescent copper-coloured wing cases. They are relatively easy to distinguish from native beetle species on account of **five white tufts of hair on either side of their abdomen and two more at the tip**. Identifying eggs, larvae and pupae is more challenging and requires entomological knowledge.

The host plant range of the Japanese beetle encompasses more than 400 species, with adult beetles and larvae feeding on different species. Adult host plants include agricultural crops such as grapevines, stone fruits, apples, berries, maize, soya, beans and asparagus. Ornamental plants such as roses, wisteria and Virginia creeper and native shrubs are also attacked. The larvae’s preferred host plants include species in the genera of *Festuca*, *Poa* and *Lolium*, although they may feed on the roots of many other grasses and occasionally herbaceous plants as well. Adult Japanese beetles and their larvae cause non-specific feeding damage which cannot be clearly distinguished from that of native plant pests. Holes chewed in leaves are indications of adult Japanese beetle damage and severe infestations can strip all the tissue between the leaf veins, known as skeletonising. Discoloured patches in grass and a patchy sward – both increasing over time – are signs of larval damage. Secondary damage caused by wildlife such as wild boars, badgers and crows foraging for grubs is often more severe than the primary damage caused by the Japanese beetle larvae themselves. **Moist meadows and grassland, irrigated sports grounds and recreational spaces** (e.g. football pitches, golf courses, camp sites, outdoor pools, parks and gardens) and **tree nurseries and turf growing sites are particularly at risk of larval damage.**

Grubs and adult Japanese beetles can cause **significant economic damage to crops and ornamental plants**. The European Union estimates the annual agronomic damage potential without effective control to be around 2.4 billion euros. For Switzerland, experts predict that without control measures annual yield losses will amount to tens or hundreds of millions (CHF), with the risk to individual crops varying significantly.

Damage to frequently irrigated **sports grounds and turfed areas** is caused exclusively by Japanese beetle grubs, which eat the roots of the grass. In the USA, for example, the cost of replacing damaged turf grass runs to over 150

million US dollars a year. Although the damage is mostly aesthetic – apart from the increased risk of accidents on sports grounds – substantial amounts of money are spent on repairing damaged areas.

Japanese beetles can occasionally occur in large numbers in **arable crops** such as soya or maize. The economic damage threshold can be reached or even exceeded if Japanese beetles occur in soya together with other pest insects. The weedy margins around maize crops can also be infested with larvae. In heavily infested areas, adult beetles can also congregate on the cob tips and eat the 'maize beard' (corn silk). However, economic damage is only a concern if consumption of the maize beard coincides with other damage factors such as heat or drought stress.

Since the Japanese beetle is a generalist, its host plant range also includes different **vegetable crops** such as beans, sweetcorn, tomatoes, aubergines, asparagus and rhubarb. Adults eat all or part of the leaves, weakening the plant and reducing the marketability of the harvested crop. Irrigated vegetable growing areas can also make attractive egg-laying sites in dry summers, resulting in direct larval root damage and thinning of the vegetable crop.

The **species of fruit trees** most widely grown in Switzerland are also host plants of the Japanese beetle. Apples, apricots, cherries, plums, peaches and even hazelnuts can be severely affected by adult beetles. The leaves are damaged first, but the fruits can also be eaten when adults are present in very high numbers. In Switzerland, the ripening and harvesting of cherries, apricots and early plum varieties is likely to coincide with the flight period of the Japanese beetle, while the vulnerable ripening phase of apples will probably fall outside of this period. The fruits of apricots, unnetted cherries and early plum varieties are therefore particularly at risk.

Japanese beetles can cause considerable damage to **berry crops.** Adult beetles eat the leaves and fruits of strawberries, raspberries, blackberries and blueberries. This adversely affects the rate of photosynthesis, yield and quality of these plants, and greatly reduces the proportion of marketable fruits. Damage to ripe berries is particularly problematic. Furthermore, it increases the cost of harvesting, as damaged berries must be separated from intact ones.

The grapevine is a favourite host plant of the Japanese beetle. In Italy, over 300 Japanese beetles have been observed on a single vine. The beetles mainly skeletonise the leaves, leaving the still unripe berries largely untouched. While mature grapevines can tolerate a certain degree of leaf damage, young grapevines are particularly vulnerable to defoliation. Overall, it can be assumed that a Japanese beetle infestation will increase operating costs and lead to yield and quality losses.

Across all crop production sectors, vulnerable crops close to larval breeding grounds are most at risk of attack by adult Japanese beetles, with crops whose harvesting time coincides with the beetles' flight period particularly under threat.

Successful management of the Japanese beetle can only be achieved through a combination of different preventive, mechanical, physical, biological, biotechnical and chemical plant protection measures. The first and most important protective measure is to prevent the introduction and spread of the Japanese beetle. Care must therefore be taken when returning from infested areas and when buying plant material that could be at risk. In infested areas, it is also advisable to avoid irrigating lawns and green spaces during the flight period of the Japanese beetle. In addition, the risk of egg-laying in pots and vulnerable areas can be reduced using insect-proof covers (e.g. coconut fibre and other materials). Similarly, insect-proof nets can protect crops and potted plants from leaf damage and egg-laying. It is possible to reduce an infestation mechanically and physically by tilling, modifying the soil substrate, removing adults, using repellents such as kaolin, and adapting the host plant range close to vulnerable crops. However, biological pest control is key to successfully controlling the Japanese beetle. The use of microorganisms is particularly promising. Specifically, these include the bacterium *Bacillus thuringiensis* var. *galleriae*, entomopathogenic fungi in the *Beauveria* and *Metarhizium* genera and highly specialised fungi (microsporidia), which weaken the immune system of the larvae, thereby making them more susceptible to other pathogens. Nematodes (roundworms) have also proved effective at controlling larvae in the soil. Under favourable conditions, they can have an efficacy rate of over 90%. Over the last one hundred years, more than twenty species of exotic parasitoid species have been introduced to the USA to control the beetle, although only three have successfully established. Of these, the parasitoid fly *Istocheta aldrichi* and the parasitoid wasp *Tiphia vernalis* could be of interest for Switzerland. Although native predators such as spiders, birds and mammals are known to feed on juvenile and adult Japanese beetles, their non-specific diet prevents their targeted use. The attractants developed for monitoring the Japanese beetle can also be used as a biotechnological control method, either by mass trapping or in combination with insecticide-treated nets (LLINs). Preliminary results for these control measures are promising, and both can be used within and outside cropping areas. Finally, the use of conventional insecticides is a simple and cost-effective measure for controlling the pest quickly and effectively. Italian trials have shown that the active substances acetamiprid, deltamethrin and phosmet in direct contact and in contact with surfaces treated one week previously are highly effective against adult beetles (for approved substances in Switzerland, please refer to the corresponding internet pages of the Federal Food Safety and Veterinary Office, FSVO).

The accidental introduction of the Japanese beetle and its continuous spread presents the Swiss Federal Plant Protection Service and the cantonal phytosanitary services with one of their greatest challenges of recent years. However, the Japanese beetle poses a threat not just to agriculture, but also to public and private green spaces. Unlike numerous other harmful insects recently introduced into Switzerland, the Japanese beetle has been present in North America for over a century. Accordingly, there is a wealth of knowledge available on its biology, ecology and control. Two special points should be emphasised here: firstly, in addition to the agriculture and horticulture, many public and private recreational spaces, parks and gardens are also affected. Secondly, there is a clear-cut spatial separation between the presence of eggs, larvae and pupae and of adult beetles. This means that plant protection measures taken in adult beetle habitats have little chance of succeeding if the steady supply from the often hard-to-find larval areas is not supressed at the same time. **The development of sustainable protection strategies must therefore extend beyond the confines of cultivated areas and comprise a combination of different measures**, even if individually, these measures are only partially effective. **Integrated pest control strategies must be adapted to suit the crops, the features of the landscape and the available host plant range.**

To summarise, we believe that knowledge gained in the USA and more recently in Italy and Ticino provides a valuable basis for controlling the Japanese beetle. Nonetheless, at this stage it is difficult to identify the endangered crops at local level within Switzerland, to estimate the damage potential of the Japanese beetle at small scale and to calculate the financial cost to the Swiss economy and society. However, we expect that **irrigated turfed areas such as sports grounds, golf courses, turf growing facilities, public parks and private gardens are most susceptible to larval attack.** In addition, **vulnerable crops close to larval breeding grounds are most at risk from adult Japanese beetle damage, especially if the harvesting period coincides with the adults' flight period**.

1 Introduction

Native to Northeast Asia, the Japanese beetle (*Popillia japonica*) was introduced to the USA in the early 20th century. It is now widespread there and has also become locally established in Canada. While the Japanese beetle is a relatively minor pest in its native Japan, in North America it causes damage amounting to several hundred million US dollars a year (USDA, 2015). The first European record of this beetle was in the Azores in the 1970s, where it persists despite eradication measures. In 2014, Italy reported an outbreak near Milan which was not eradicated and from where this quarantine pest continues to spread, despite the implementation of containment measures. As a result, in 2017 Japanese beetles were caught for the first time in Switzerland, in Stabio (TI) close to the Italian border. Since then, the pest has rapidly colonised Southern Ticino. In 2023, beetles were trapped in the canton of Valais south of the Simplon Pass. Also in 2023, a small, isolated population was discovered in Kloten near Zurich, another in the Basel region in 2024, and further outbreaks in the cantons of Solothurn and Schwyz. Moreover, individuals have been trapped along the main transport routes north of the Alps since 2021.

In Switzerland, as in Europe, the Japanese beetle is regulated as a priority quarantine organism. This means that there is an obligation to report and control it (PGesV SR 0.916.20). A confirmed sighting of the Japanese beetle automatically entails eradication or containment measures, depending on the situation. Human activities such as the movement of goods and people and the trade of plant products enable adult beetles, eggs and larvae to be transported over large distances. Furthermore, beetles can spread over several kilometres by active flight.

In the following chapters we delve into the biology and ecology of the Japanese beetle and the legal bases of its regulation. In addition, we estimate the risk posed by the Japanese beetle to different crops and describe the official control measures associated with the mandatory control of this quarantine organism. We also present additional control measures currently used in previously colonised regions.

2 Biology

The Japanese beetle (*Popillia japonica*) was first described by English entomologist Edward Newman in 1841. Within the order of Coleoptera (beetles), this species is a member of the family of Scarabaeidae (scarab beetles, subfamily Rutelinae), which also includes cockchafers, garden chafers and rose chafers (see 2.1.5 Similar native beetle species). The genus *Popillia* comprises more than 300 species, most of which are native to Africa and Asia (EPPO, 2006; EFSA, 2023). To date, the Japanese beetle is the only member of this genus to be found in Central Europe.

2.1 Morphology

Figure 1: Life stages of the Japanese beetle (© Doris Ortner, Spotteron, IPM-Popillia www.popillia.eu).

Adult Japanese beetles can be identified by eye with a little practice. Identifying eggs, larvae and pupae (Figure 1), on the other hand, is more challenging and requires entomological knowledge in addition to optical aids, i.e. a good binocular microscope (EPPO, 2006).

2.1.1 Adults

Figure 2: Adult Japanese beetle and size comparison (© Christian Schweizer & Christian Linder, Agroscope).

Adult Japanese beetles have an oval body, 8–12 mm long (Figure 2) and are no bigger than a one-cent coin. The head and thorax are iridescent, metallic golden green while the wing cases are copper-coloured. The abdomen, antennae and legs of the beetle are black and shiny. **Five white tufts of hair on each side of the abdomen and two more tufts on the last abdominal segment (at the tip of the abdomen when viewed from above) are characteristic features.** The individual tufts are clearly defined and consist of short, bristle-like hairs. They are not to be confused with the sparser, long, fine hairs of the native June beetles and garden chafers or the white spots of cockchafers (also known as May bugs) and rose chafers, which consist of closely overlapping white scales. Females are generally larger than males, and the two sexes can be distinguished by the shape of the tibia and the tarsus on the forelegs (Figure 3). The male tibial spur (Figure 3a) is more sharply pointed with a distinct outward curve and the tarsi are shorter and more powerful than those of the female. The female tibial spur (Figure 3b) is slightly curved to straight with a distinctly rounded tip (EPPO, 2006).

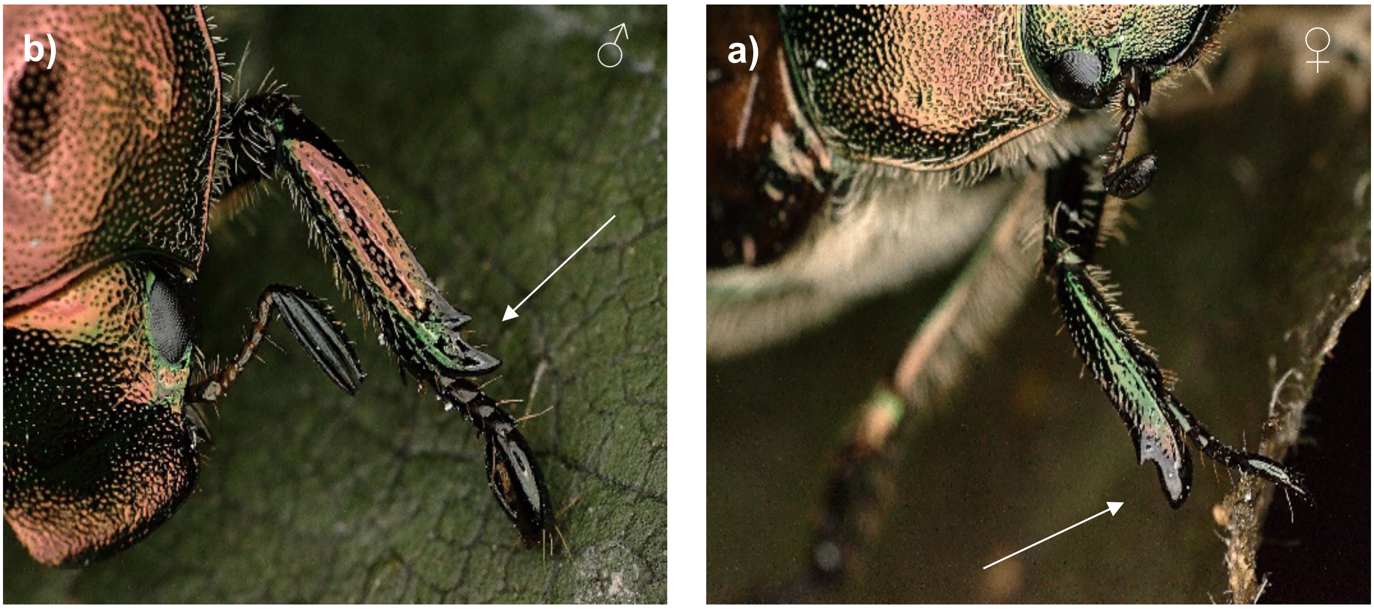

Figure 3: Tibial spur of a) a male and b) a female Japanese beetle. In males (♂) the tip is sharply pointed with a distinct outward curve, while in females (♀) it is rounder and less curved (© Giselher Grabenweger, Agroscope).

2.1.2 Eggs

Figure 4: Eggs of the Japanese beetle (© Giselher Grabenweger, Agroscope).

Newly deposited eggs may be quite variable in size and shape. They may be round with a diameter of 1.5 mm to elliptical (1.5 mm long by 1.0 mm wide) or nearly cylindrical (Figure 4). Colour may range from translucent to creamy white and the external surface is marked with a hexagonal pattern. The eggs enlarge to double their initial size and become more spherical as the embryo develops (EPPO, 2006). The eggs cannot be clearly attributed to the species *P. japonica* by their morphological features alone.

2.1.3 Larvae

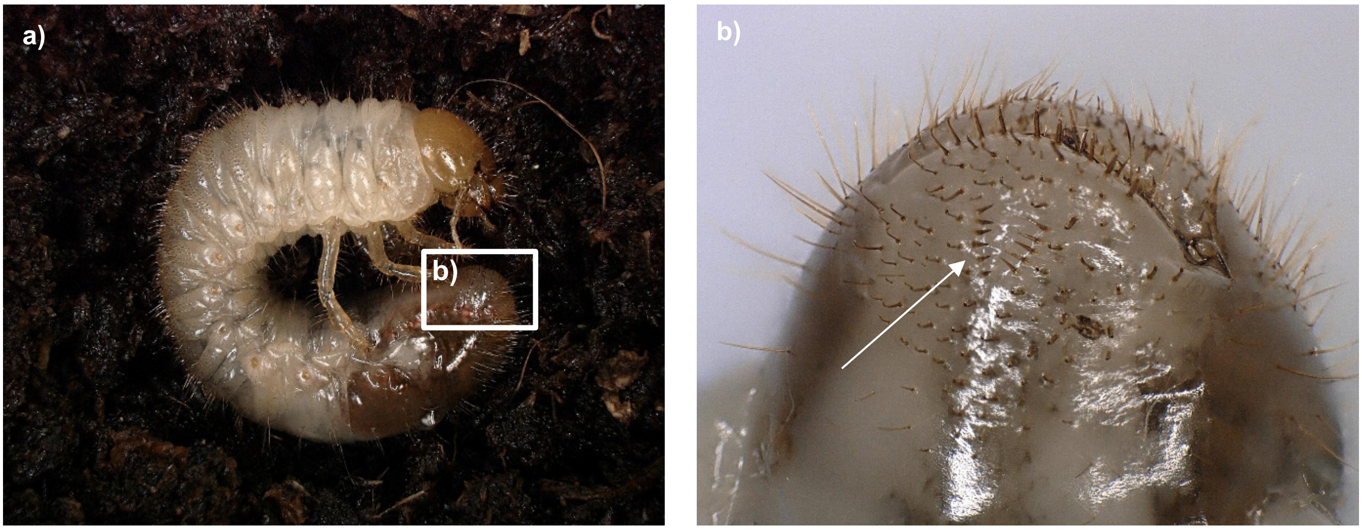

Figure 5: a) C-shaped third-instar Japanese beetle larva and b) close-up of its characteristic V-shaped arrangement of spines, which is unique to this species (© Giselher Grabenweger, Agroscope).

The larvae of scarab beetles are also known as grubs. The larval body is typically C-shaped and white. While the grubs are still feeding, the contents of the intestine are visible through the thin skin at the tip of the abdomen, making this region appear greyish to black in colour. Grubs also have a clearly defined, hardened brown head capsule with clearly visible mouthparts. The three pairs of brown thoracic legs are also clearly visible, well segmented and fully functional. Japanese beetle grubs (Figure 5a) go through three development stages, known as larval instars. The first instar is pale in colour and only 1.5 mm long. The second instar is 1–2 cm long and the third instar 2–3 cm.

Grubs can be clearly identified to species based on the characteristic arrangement of spines on the ventral side of the last abdominal segment (the ‘raster’). The raster is only visible with a powerful magnifying glass or binocular microscope. The raster of *P. japonica* consists of **5–7 spines on each side arranged in a V-shaped pattern** (Figure 5b). It lies directly below the anal split which runs in a straight line across the tip of the abdomen. This unique raster pattern can be used to distinguish Japanese beetle larvae from native grubs (EPPO, 2006).

2.1.4 Pupae

Figure 6: Pupa of the Japanese beetle (© Giselher Grabenweger, Agroscope).

A prepupal stage and the pupa mark the end of development. A prepupa is a fully developed larva which has stopped feeding and reduced its activity as internal physiological changes take place. The only difference between the prepupa and the third larval instar is that its intestine is empty and so the abdominal tip appears whitish – like the rest of the body. Pupae of Japanese beetles (Figure 6) are on average 14 mm long and 7 mm wide. They resemble adult beetles, but with wings, legs and antennae held close to the body and functionless. The colour changes from cream to brown and eventually to metallic green. Males, unlike females, have a three-lobed protrusion covering the developing genitalia on the posterior ventral abdominal segments. This characteristic can be used to distinguish between the two sexes in the pupal stage (EPPO, 2006).

2.1.5 Similar native beetle species

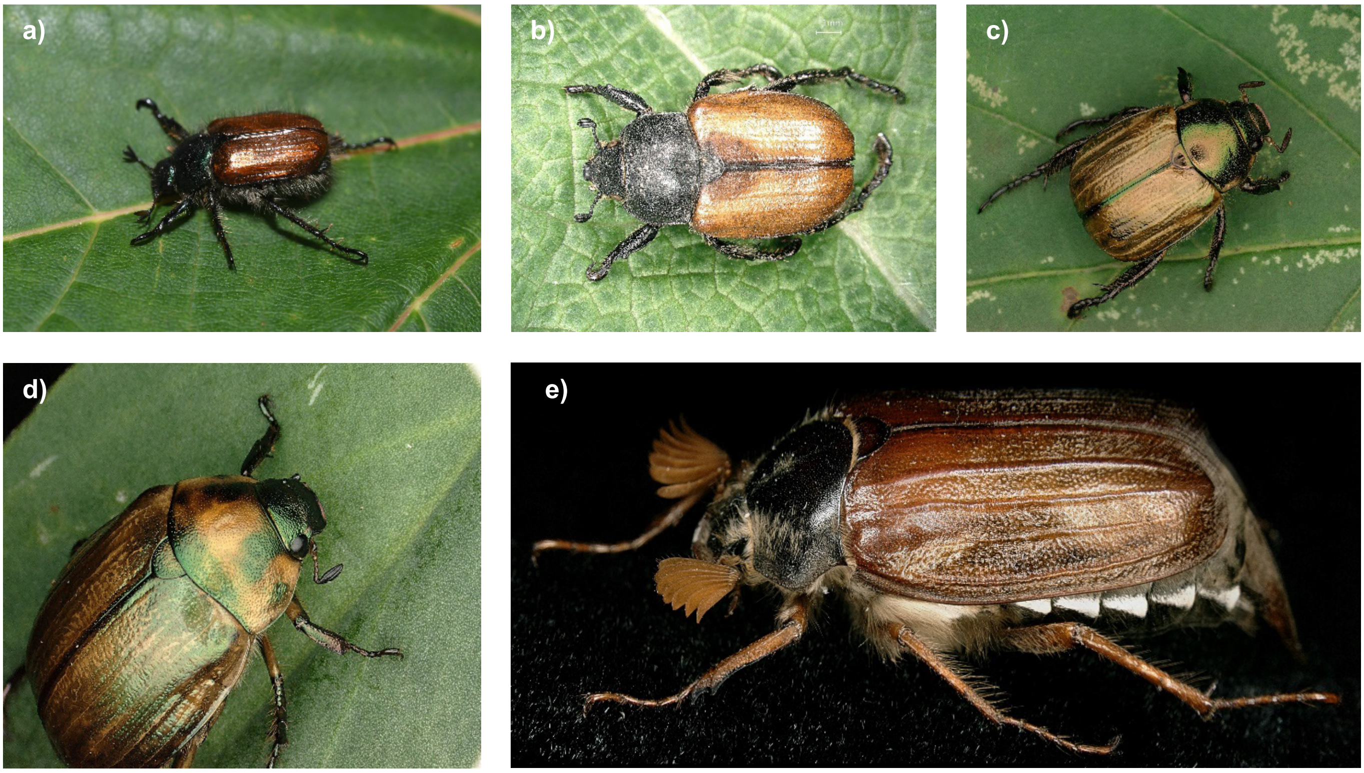

*Figure 7: Different native chafer beetles: a) garden chafer (*Phyllopertha horticola*), b)* Anisoplia villosa*, c) Mediterranean June beetle (*Mimela junii*), d) dune chafer (*Anomala dubia*) and e) cockchafer (*Melolontha melolontha*) (© Giselher Grabenweger, Agroscope).*

Adult Japanese beetles are relatively easy to distinguish from most native scarab beetles (Figure 7). In terms of shape, colour and size, the Japanese beetle most closely resembles the widespread garden chafer (*Phyllopertha horticola*), *Anisoplia villosa* and the rare 'Mediterranean June beetle' (*Mimela junii*). However, unlike these species, (Fig. 6a-c), *P. japonica* has the characteristic **five white tufts of hair on either side of the abdomen and two additional tufts on the last abdominal segment.** A further distinguishing feature is the distinctive alarm behaviour of the Japanese beetle; **when threatened, adults freeze and hold one pair of legs out to the side** (Figure 8). Similar native beetle species do not respond to threats in this way.

Figure 8: Alarm behaviour of the adult Japanese beetle with splayed hind legs (© Christian Schweizer, Agroscope).

2.2 Life cycle and reproduction

Figure 9: Life cycle of the Japanese beetle (© Magdalena Wey, Agroscope).

Like all cold-blooded insects, the survival, development, life cycle and reproduction of individual Japanese beetles as well as the phenology, population dynamics and spread of the species are determined by ambient temperature patterns (Régnière et al., 2012). In most of its native and invasive range, *P. japonica* produces one generation a year (Figure 9), although in cooler regions and years the reproductive cycle can last two years (EPPO, 2016). In Switzerland, the Japanese beetle is likely to complete its life cycle within one year in most lowland sites.

Female Japanese beetles mate repeatedly, laying 40 to 60 eggs in total throughout the summer. **Eggs are usually laid in moist or irrigated grassland.** Moist to very damp soils are the preferred egg-laying sites, and eggs are laid singly or in small clusters. Females may form a burrow in the upper 10 cm of the soil to deposit their eggs (Potter & Held, 2002). The larvae hatch after around two weeks and begin to feed on the surrounding roots, altering the soil structure though their activity (MacLeod et al., 2024). Most grubs moult twice before burrowing deeper into the soil (up to a depth of 30cm) to overwinter, protected from the cold. When springtime temperatures exceed 12.8 °C, the larvae come out of hibernation (Gilioli et al., 2022) and return to the root zone to complete their development. The prepupa makes a cocoon-like structure from soil material where pupation subsequently takes place. Pupae are well-camouflaged inside this cocoon, which makes them difficult to find in the soil. Adult beetles emerge after one to two weeks. The males emerge from the soil first, followed by the females, already carrying mature eggs (Régnière et al., 1981). Shortly after emerging, the beetles begin to feed on the leaves, shoots and fruits of a wide range of host plants, and to reproduce (EPPO, 2016).

Japanese beetles produce one generation a year in the areas of Switzerland where they are currently established. Adult individuals usually have a life span of 4 to 6 weeks. In May and June, the adult beetles begin to fly and mate. The flight period lasts from mid-May to September, peaking in July. The beetles are at their most active at temperatures between 20 and 35 °C with light winds and over 60% relative humidity. The phenology of *P. japonica* can be predicted using models (e.g. Régnière et al., 1981; Ebbenga et al., 2022b; Gilioli et al., 2022). The time when adults begin flying is often calculated by adding up the mean degree-days from 1 January using lower and upper thresholds of 15 °C and 21.7 °C (Ebbenga et al., 2022b). According to this model, the first 10% of adult beetles will be caught in the traps when the cumulative degree-day reaches 257 °C. These calculations also indicate that larval development will last two years in regions where the annual cumulative degree-day above 10 °C is lower than 1422 °C. In contrast, one generation a year will be produced in warmer regions.

Mathematical models for Northern Italy indicate that the population growth of *P. japonica* follows a logistic distribution and therefore produces a sigmoid (S-shaped) curve. This means that the Japanese beetle population remains relatively small in the two to three years following establishment, hampering early detection of the pest. Thereafter, the population increases rapidly in suitable habitats, so that four to five years after the first incursion, over two hundred adult beetles can be trapped each day. According to these modelled predictions, the maximum population density of *P. japonica* is reached 7–8 years after establishment without control measures (Gotta et al., 2023).

2.3 Host plants and symptoms of damage

The host range of the Japanese beetle includes **over 400 plant species from at least 79 plant families** (EPPO, 2016; Tayeh et al., 2023; EPPO, 2024). It is worth noting, however, that adult beetles and larvae feed on different host plant species. We will start by examining the dietary spectrum of adult beetles and their feeding damage, and then describe the larval host plants and symptoms of damage.

2.3.1 Preferred host plants of adults

Adult Japanese beetles feed on a wide range of hosts including agricultural crops, ornamental plants and wild plants. Grapevines (*Vitis* spp.), stone fruits (*Prunus* spp.), apples (*Malus* spp.), hazel (*Corylus avellana*), blackberries and raspberries (*Rubus* spp.), blueberries (*Vaccinium* spp.), maize (*Zea mays*), soya (*Glycine max*), hops (*Humulus lupulus*), lucerne (*Medicago sativa*), beans (*Phaseolus vulgaris*) and asparagus (*Asparagus officinalis*) are the most severely affected crops. However, adult beetles also feed on many widely grown ornamental plants, such as roses (*Rosa* spp.), wisteria (*Wisteria* spp.) and Virginia creeper (*Parthenocissus* spp.). In addition, adult beetles feed on the foliage of native trees, especially maple (*Acer* spp.), lime (*Tilia* spp.), poplar (*Populus spp.*), oak (*Quercus spp.*), elm (*Ulmus* spp.), willow (*Salix* spp.) and blackthorn (*Prunus spinosa*). In infested areas of Europe, feeding damage has also been reported in many herbaceous plants such as nettles (*Urtica* spp.), evening primrose (*Oenothera* sp.) and cinquefoil (*Potentilla* sp.) (EPPO, 2016).

2.3.2 Symptoms of damage caused by adults

Figure 10: Damage to different host plants (© Mauro Jermini & Patrik Kehrli, Agroscope).

Feeding damage caused by adult Japanese beetles are easy to spot, but non-specific, since other insects with biting mouthparts (e.g. other chafers, leaf beetles (Chrysomelidae), caterpillars...), or snails, can cause similar symptoms. **Holes chewed in the leaves of host plants** are indications of adult Japanese beetles (Figure 10). When population densities are high, all the tissue between the leaf veins can be stripped out, leading to complete skeletonisation of the foliage, with only the veins left intact. Severely damaged leaves soon turn brown and eventually drop. The beetles can consume entire irregularly shaped sections of flower petals or host plants with thin leaves and fine venation. Fruits also show signs of irregular feeding damage.

The **beetles often congregate in groups and begin by feeding on fresh foliage at the top of the plant**, then gradually work downwards (EPPO, 2016). They sometimes strip an individual plant completely bare, while leaving adjacent plants virtually untouched. Defoliation weakens the plant and can reduce the quantity and quality of the harvest, whereas damage to fruits and flowers can directly impact the marketability of the harvested crop.

2.3.3 Preferred host plants of larvae

The host range of Japanese beetle larvae is less well known; since they develop underground, there is considerable uncertainty about the exact number of plant species on which the larvae can complete their life cycle. Which roots the grubs feed on depends primarily on which plant species are growing close to the egg-laying site. **The most important grassland species** are in the genera **fescue** (*Festuca* spp.), **meadow grass** (*Poa* spp.) and **rye grass** (*Lolium* spp.) (EPPO, 2016). However, it is likely that the larvae also feed on the roots of many other grass species and occasionally herbaceous plants as well. Furthermore, females prefer to lay their eggs in moist, but not wet, undisturbed soil. Moist meadows and pastures, irrigated turf grass and humid areas therefore make ideal egg-laying sites.

2.3.4 Symptoms of damage caused by larvae

Figure 11: Japanese beetle larvae damage to a lawn, leading to discolouration and patchy appearance of the sward (© Servizio fitosanitario cantonale, Sezione dell'agricoltura, canton of Ticino).

The grubs of Japanese beetles damage the roots of their host plants, and as with the adults, feeding symptoms are non-specific. They are similar to the feeding damage caused by cockchafers (*Melolontha* spp.). Discoloured patches of grass, increasing in size over time, indicate the presence of Japanese beetle grubs in the soil (Figure 11). At first the grass sward becomes thinner, accompanied by discolouration or wilting. Affected lawns and grassed areas may die off completely when suffering from water stress in later summer and early autumn. A severe infestation of *P. japonica* grubs can cause the roots to completely detach from the above-ground plant parts, enabling the turf to be lifted and rolled back with ease. Visible signs of damage to vulnerable plant species are evident at densities of as little as 15-20 larvae /m^2 (Crutchfield et al., 1995). In contrast, some other plant species show no signs of damage even at larval densities of 600 larvae/m$^{2.}$ Less visible damage generally occurs with sufficient irrigation and fertilisation, and lower temperatures (Crutchfield et al., 1995).

When larval densities are high, wildlife such as wild boars, badgers and crows foraging for grubs in grassland cause highly visible, indirect damage (EPPO, 2016). This secondary damage is often more serious than that caused by the grubs. Moist meadows and pastures, irrigated sports grounds and recreational areas (e.g. football pitches, golf courses, racecourses, camp sites, outdoor pools, parks and gardens) and tree nurseries, turf production sites and irrigated pastures are particularly at risk.

2.4 Natural enemies

In the 1920, the fauna of natural enemies of the Japanese beetle was studied in detail in the Asiatic range to identify species which could be imported into the USA for use as classical biological control agents. In total, seven parasitoid species which attack *P. japonica* were found in Japan, including five species of flies (Tachinidae) which parasitise adult beetles only, as well as two larval parasitoids in the Tachinidae (Diptera) and Scoliidae (Hymenoptera) families, which attack larvae. Among these parasitoids, three tachinid species were relatively common, namely *Istocheta aldrichi*, *Hamaxia incogrua* and *Prosena siberita*, with the first having the highest rate of parasitisation (Clausen et al., 1927; Clausen et al., 1933). Other known predators include ants (Formicidae) and ground beetles (Carabidae), which have been observed feeding on eggs and larvae (Terry et al., 1993; Zenger & Gibb, 2001). In addition, adult beetles and grubs are predated by various bird species such as crows (*Corvus* spp.), starlings (Sturnidae) and gulls (Laridae). Moles (Talpidae) and wild boar (Suidae) as well as presumably badgers and foxes also feed on grubs in the soil (Sim, 1934). Furthermore, beetles and larvae are susceptible to entomopathogenic microorganisms, e.g. fungi in the genera *Metarhizium, Beauveria* and *Ovavesicula,* and bacteria in the genera *Paenibacillus* and *Rickettsia*. Grubs are also parasitised by entomopathogenic nematodes (roundworms) in the genera *Steinernema*, *Heterorhabditis* and *Hexamermis* (Figure 12) (CABI, 2022).

Figure 12: Japanese beetle grub parasitised by a nematode in the genus Hexamermis *(© Giselher Grabenweger, Agroscope).*

2.5 Occurrence and spread

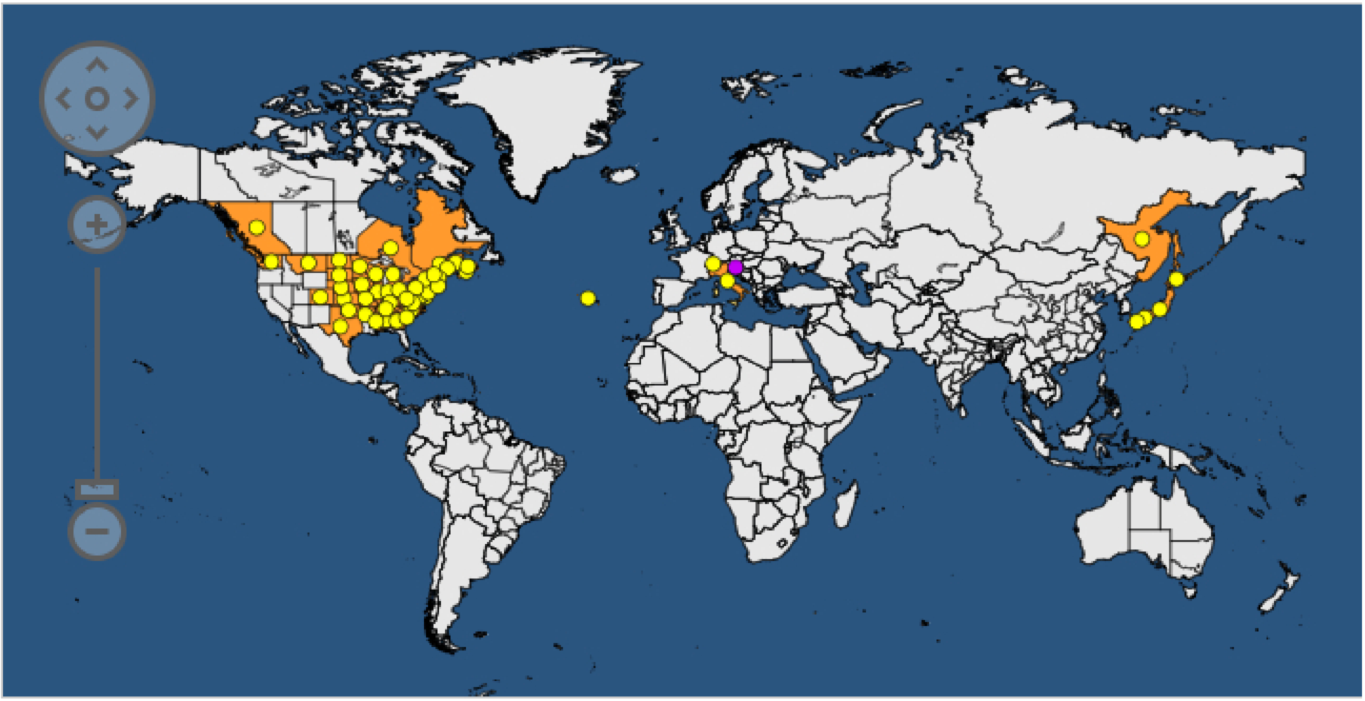

Figure 13: Global distribution map of the Japanese beetle; the regional resolution is imprecise as individual countries and federal states are not differentiated (© EPPO Global Database, last updated 7.11.2024, https://gd.eppo.int/taxon/POPIJA/distribution).

The Japanese beetle is **native to Northern Japan and the Russian Kuril Islands**. As a result of anthropogenic introduction, the Japanese beetle has become established in North America, the Azores, and more recently in Northern Italy, from where it has colonised Southern Switzerland (Figure 13) (EPPO, 2024). There are also unconfirmed reports of *P. japonica* sightings in Vietnam (2011), Bhutan (2015), China and Taiwan (2020), and South Korea (2020) (Streito & Chartois, 2022) – and despite a comprehensive survey, the Korean report has not yet been confirmed. It seems likely that it may have been confused with the closely related species *Popillia quadriguttata*. Records of the Japanese beetle in China are also regarded as invalid or unreliable (EPPO, 2016). Overall, it is assumed that *P. japonica* can occur in all regions where the mean soil temperature at a depth of 0.5 to 1 m lies between 17.5 and 27.5 °C in summer and does not fall below -9.4 °C in winter (CABI, 2022). Central Europe thus appears to be particularly suitable, while Northern European countries have a lower risk of infestation (Borner et al., 2023).

***P. japonica* was first recorded in the USA in 1916** in a nursery in New Jersey. The Japanese beetle is now widespread throughout the eastern States apart from Florida. In Canada, however, its range is restricted to the southern parts of Ontario and Quebec. First identified on the Portuguese island of Terceira in the Azores in the early 1970s, today the Japanese beetle is found on eight of the nine islands of the Azores. **In 2014, the Japanese beetle was recorded on the European mainland for the first time** when an outbreak was reported in the Ticino Valley Natural Park in Northern Italy. Around 180 adult beetles were collected along a 2-km stretch near Turbigo. Although the entry pathway is unknown, it seems likely that these beetles may have entered by plane since Milan's Malpensa Airport and an American airbase are located close to the infested area (EPPO, 2016). This population has since spread throughout Northern Italy, arriving in Switzerland three years later.

In 2017, Japanese beetles were trapped in Switzerland for the first time in the border municipality of Stabio in Ticino. Captures have since risen rapidly and the population has spread northward, reaching parts of the Magadino Plain for the first time in 2024. In addition, in 2023 several thousand beetles were trapped for the first time in the canton of Valais south of the Simplon Pass. It is assumed that this population migrated from Northern Italy by natural means. Also in 2023, a small, isolated population was discovered in Kloten near Zurich. Further small, isolated populations were also found in the Basel region and in the cantons of Solothurn and Schwyz in 2024. Additionally, a small population was also discovered in the canton of Valais in the Brig-Visp area. Since 2021, traps set up for the survey of the territory North of the Alps have been repeatedly catching individual beetles, thought to be ‘hitchhikers’. By the end of the 2024 season, subsequent investigations indicated that these were only one-off findings.

Although analysis of the genetic origins of the Japanese beetle invasion in the USA is inconclusive, evidence suggests that individual invasions can be traced back to Central or Northern Japan. Several Japanese lineages have been introduced into the United States over the last one hundred years (Nardi et al., 2024). Furthermore, genetic data suggests that the invasive beetles in the Azores came from the south-eastern region of North America, whereas individuals from north-eastern North America have been introduced to Italy (Strangi et al., 2024). Thus the **populations in the Azores and Northern Italy most likely originate from two separate** *P. japonica* **introductions** (Nardi et al., 2024).

2.6 Natural spread

Adult *P. japonica* mostly fly over short distances of less than one kilometre (EFSA, 2023). There are notable exceptions: in the USA a few marked beetles have been recaptured up to 3.2 km away from their original release site (Fleming, 1972), while in Italy marked individuals covered a distance of 12 km in a single day (Lessio et al., 2022). However, most adult Japanese beetles in the Italian study were recaptured within a radius of 1 to 7 km of the original site after a week, which concurs with studies from the USA (Hamilton, 2003). In the USA, it is estimated that the pest spreads from the point of introduction at a rate of 3.2 to 24 km per year, while infested area in the Azores initially expanded by around 2 km a year. (EPPO, 2016). **The rate of spread in Italy is estimated to be 4.5 to 13.8 km per year**, and increasing with habitat suitability (Gilioli et al., 2024).

2.7 Human-assisted spread

The Japanese beetle can cover long distances over a short time through human activities (Borner et al., 2024). **People travelling back from infested areas and goods imported from infested areas pose a particularly high risk for the accidental introduction of adult beetles as ‘stowaways’** (=‘hitchhikers’) (Hamilton, 2003; USDA, 2015; EPPO, 2016). This explains why initial sightings of *P. japonica* are often reported close to airports, railway stations, motorway service stations, container handling facilities, ports, campsites and distribution centres (Borner et al., 2024). Individuals have also occasionally entered with harvested crop, e.g. through imported fruits. On the other hand, the transportation of topsoil and the trade of turf and plant material are the only pathway for the entry of eggs and grubs.

3 Aspects linked to Plant Health Ordinances

The International Plant Protection Convention (IPPC) SR 0.916.20 established in 1951 forms the basis for international "cooperation in controlling pests of plants and plant products and in preventing their international spread." The Convention has been signed and ratified by 185 countries worldwide. The IPPC is recognised by the World Trade Organisation (WTO) as the international organisation responsible for developing plant protection standards and harmonising phytosanitary measures relating to trade. In addition to the IPPC, plant health is also governed by the Agreement on Trade in Agricultural Products between the Swiss Confederation and the European Community SR 0.916.026.81. Among other topics, it establishes a common plant health area which aims to break down trade barriers while maintaining phytosanitary safety. This means that many provisions and legal bases relating to plant health are very similar in Switzerland and the EU.

The Japanese beetle is listed as a priority quarantine organism in both the EU (EFSA, 2018, 2023) and Switzerland (Art. 4 of the Plant Health Ordinance of 31 October 2018, PGesV, SR 0.916.20). A quarantine organism is a particularly harmful pest that can potentially cause significant economic, social or environmental damage in the endangered area where it is not yet present, or present but not widely distributed. Preventive measures such as goods inspections at borders are therefore essential to prevent the entry of these organisms. Monitoring the phytosanitary situation, by means of the survey of the territory for example (Art. 18 of PGesV SR 0.916.20), is a key measure for the early detection of outbreaks of quarantine organisms. Any quarantine organism found is then subject to official control measures. Some quarantine organisms are designated as priority quarantine organisms because they can potentially cause major harm. In addition, all quarantine organisms are subject to reporting and control requirements.

Two strategies are generally used to control quarantine organisms:

- If a pest is discovered at a time when eradication is still possible, the **eradication strategy** is pursued (Art. 13 of PGesV SR 0.916.20).
- Once it has been established and eradication is no longer feasible, the **containment strategy** is pursued. The aim of containment is to prevent or at least slow down the spread of the organism. It should also reduce damage caused by the pest (Art. 16 of PGesV SR 0.916.20).

Official control measures must be taken if the presence of a quarantine organism in Switzerland is confirmed by a laboratory certified by the Swiss Federal Plant Protection Service (SPPS) (Art. 11 of PGesV SR 0.916.20). In this case, the responsible federal office in consultation with the cantonal agencies decides on the appropriate strategy and measures.

4 Prevention, early detection and monitoring

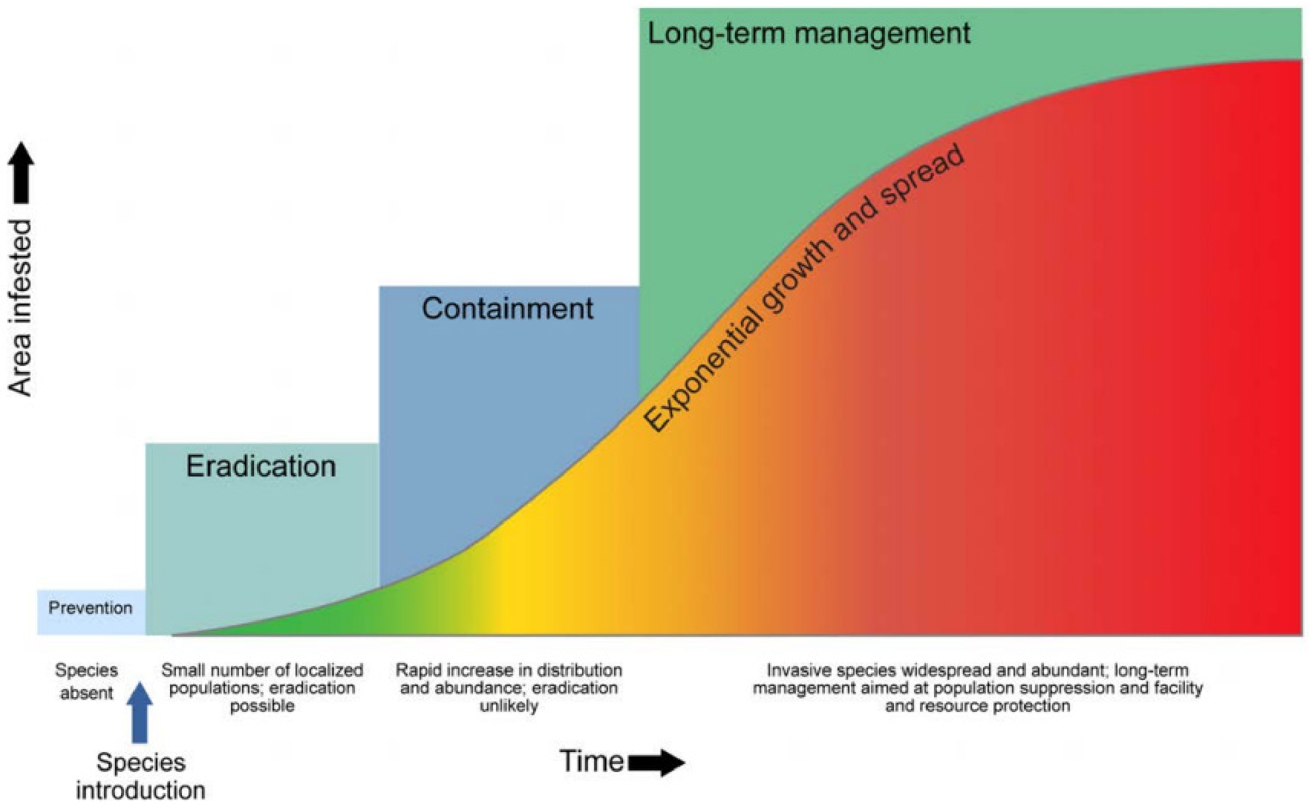

Figure 14: Invasion curve for an invasive pest showing population dynamics and control options (© United States Government Accountability Office (GAO) 2015. AQUATIC INVASIVE SPECIES Additional Steps Could Help Measure Federal Progress in Achieving Strategic Goals. GAO-16-49. https://www.gao.gov/products/gao-16-49).

The legal bases enable public funds to be made available for implementing control measures against *P. japonica.* These measures are effective at different stages of invasion. Typically, the sooner measures are taken, the more cost-effective they are (Figure14).

- Absent: prevent introduction and conduct monitoring for early detection
- Small number of individuals and localised populations: conduct delimiting and monitoring surveys, prevent spread, introduce eradication measures
- Population growth: conduct monitoring survey, prevent spread, introduce containment measures
- Widespread in high densities: long-term management

International standards provide the basis for surveillance and monitoring (i.e. monitoring an area in which the pest has been detected) in the respective situations (EPPO, 2016; EFSA, 2020; IPPC, 2021, 2024). These standards describe the international state of knowledge and consensus regarding the optimal methodology for monitoring and diagnostics. This ensures effective monitoring and renders findings comparable at international level.

Prevention of introduction focuses on entry pathways through natural spread and human activities and in particular, likely first points of entry of *P. japonica* into Switzerland (see 2.6 Natural spread, 2.7 Human-assisted spread and 6.1 Preventive measures). This has resulted in the following risk-based measures and activities:

- Commercial trade: legislation with requirements for certain products.
- Import controls: systematic control of goods from third countries which pose a risk for introducing *P. japonica.*
- Information for private individuals: private individuals have a legal obligation to prevent the spread, so the general public must be kept regularly informed.

The monitoring for early detection (survey of the territory) is a Swiss-wide coordinated and risk-based surveillance method using pheromone traps (see 4.1 ‘Pheromone' traps). It is conducted during the flight period of the adults and only in areas considered to be free from *P. japonica*. The Swiss Federal Plant Protection Service works in partnership with the cantons to perform the survey in accordance with the principles of the EPPO (2016) and EFSA (2023). Surveys are conducted at sites deemed at high risk of Japanese beetle infestation due to their natural spread or their introduction through human activities (risk sites). Since the movement of goods and people is one of the main drivers of spread, risk sites include motorway service stations and suitable habitats for Japanese beetles close to railway stations, airports, truck stops, distribution centres, freight transfer depots and shopping centres (Borner et al., 2024). In 2024, more than 250 traps were set up in pest-free areas of Switzerland and regularly inspected as part of this early detection strategy. Conversely, visual inspections (see 4.2 Visual inspections) and soil sampling (see 4.3 Soil sampling) are not used for the purpose of early detection, since the probability of spotting small beetle populations is very low, making it disproportionate to the enormous effort involved.

Early detection is key to the rapid and effective control of *P. japonica*. The probability of successful eradication is considerably increased if the Japanese beetle is discovered before it has become widespread.

The **delimiting survey** aims to record the extent of a Japanese beetle infestation as fast as possible once the presence of one or several beetles has been confirmed. It forms the data basis for establishing the boundaries of the area where appropriate control measures will subsequently be implemented. These measures involve the use of pheromone traps, visual inspections and soil samples, depending on the period in the Japanese beetle’s life cycle and the estimated population size. The surrounding area up to six kilometres from the place of discovery is considered when selecting suitable sites for these control measures. It is possible to conduct an effective, risk-based survey by identifying risk sites, transport routes and highly suitable habitats in this area and taking into account the typical behaviour of the Japanese beetle.

The **monitoring survey** provides the basis for

- making any necessary adjustments to the delimited area
- monitoring the number of beetles in the infested zone and their population dynamics
- checking the efficacy of the measures
- checking the pest-free status of the buffer zone immediately adjacent to the infested area.

The monitoring survey uses all available surveillance methods to monitor the Japanese beetle. Adult Japanese beetles can be located aboveground by visually inspecting host plants or using traps. The larvae, on the other hand, live underground, so they need to be located by soil sampling.

4.1 'Pheromone' traps

Figure 15: 'Pheromone' trap for monitoring adult Japanese beetles (© Joana Weibel, Agroscope).

'Pheromone' traps (Figure 15) **can attract Japanese beetles from a distance of several hundred meters, making it easier to detect them** (EPPO, 2016). They contain a lure based on a combination of the **female sex pheromone** ('Japonilure' [(R,Z)-5-(1-decencyl)-dihydro-2(3H)-furanone]) **and floral attractants** (kairomone; phenethyl propionate + eugenol + geraniol in a ratio of 3:7:3). **The traps attract both male and female beetles.** The beetles fly towards the attractants and fall through a funnel into a container from which they cannot escape. Although the lure is highly effective, the traps never attract and catch all beetles in the surrounding area. Traps are set up at selected sites with different aims, depending on the situation (monitoring for early detection, delimiting survey, mass trapping). They enable individual beetles and small populations to be located and provide information about established populations, such as flight period and population growth year on year. Due to their high attractiveness, 'pheromone' traps increase the risk of spreading Japanese beetle, so they can only be set up by order of the responsible cantonal or federal services. The beetles caught in traps are representative for the incidence and sex ratio of the population (Legault et al., 2024). This makes the traps a reliable tool for monitoring the Japanese beetle.

The general criteria to be considered when setting up a 'pheromone' trap are described below. These criteria are based on the recommendations of EPPO (2016) and EFSA (2023).

4.1.1 Positioning of the traps

The placement in the landscape and the distance between the traps are adapted to the given situation. A **distance below 200 m** is generally assumed to be **unsuitable** and not practical for conducting a spatially differentiated monitoring (EPPO, 2016). Furthermore, traps should be placed at a distance of 3–7.5 m away from host plants to prevent the landing of attracted beetles on the plants. Ideally, traps should be placed in a sunny position since direct solar radiation favours diffusion of the lure, thereby increasing its attractiveness and efficacy. The ideal funnel height for optimal accessibility by the beetles is between 30–60 cm above the ground for turf and tall trees, and at host plant level for species such as roses and grapevines.

4.1.2 Management and inspection of traps

The lure lasts for up to three months. If traps are to remain in place longer, the lure should be replaced – preferably just before the main flying period in July – to ensure maximum efficacy. The inspection interval depends on the type and purpose of the survey and how quickly further information is needed for any measures. Trap inspections **generally take place during the flying period of the Japanese beetle (e.g. mid-May to September**. Traps are usually checked every two weeks. For early detection, the inspection interval is shortened during the main flying period in July. Similarly, the inspection interval is shorter for delimiting surveys since additional information about the spread of this quarantine pest is urgently needed. The responsible cantonal services regularly provide the Swiss Federal Plant Protection Service with information about inspection periods and numbers of captures in line with their reporting requirements.

4.1.3 Unsuitable trap sites

Wooded areas are not suitable for trap placement as woodland is not an optimal habitat for the Japanese beetle. Larval development in forest soil is suboptimal, and the range of host plants is limited (Langford et al., 1940; Tayeh et al., 2023). Furthermore, the dense vegetation reduces the lure's effectiveness.
Humid areas are high-risk sites as they tend to provide suitable conditions for larval development and only limited control measures can be taken. For this reason, pheromone traps are generally not placed in humid areas to avoid attracting beetles from the surroundings. The exception is when there are strong reasons to suspect that Japanese beetles are already present in the moist area.

4.2 Visual inspections

The visual examination is a selective, risk-based inspection based on the recommendations of EPPO (2016) and EFSA (2023). In general, the area in question is not searched in full; instead, specific areas where the Japanese beetle is most likely to be found are inspected. This is because Japanese beetles can only be detected by visual examination when their population density reaches a certain level. A disproportionate amount of time is spent on visual inspections if the density is too low.

Preferred host plants in the immediate vicinity of a location, ideal egg-laying sites and risk sites are places where Japanese beetles are likely to be detected by visual examination. Sites where no traps have been set up or no soil samples have been taken are also visually examined. The interior of wooded areas can be ignored as no Japanese beetles have been found in these habitats yet.

It is important to take account of environmental conditions which can influence the activity of the Japanese beetle when conducting a visual inspection. The inspection should generally take place in calm and sunny conditions when the beetles are unlikely to be sheltering in the undergrowth. Flight activity is reduced at temperatures below 21 °C, so the beetles are more likely to be found on the host plants (Kreuger & Potter, 2001).

Leaf damage is a good indication to take a closer look to check whether Japanese beetles are on the plant or in the immediate vicinity (see 2.3.2 Symptoms of damage caused by adults). **Feeding symptoms alone are not enough to indicate the presence of *P. japonica* as some native herbivores cause similar symptoms of damage.** Definitive conclusions about the presence of *P. japonica* can only be drawn if adult beetles are observed on the actual plant.

4.3 Soil sampling

Figure 16: Soil sampling for Japanese beetle larvae (© Giselher Grabenweger, Agroscope).

Since adult Japanese beetle and their larvae generally colonise different habitats, larval infestation sites must also be identified to enable specific measures to be taken to control the larvae. However, the hidden lifestyle of the grubs in grassland soil makes it very difficult to detect Japanese beetles in their larval stages. Furthermore, this can only be done by collecting and carefully sorting soil samples, which is a labour-intensive and time-consuming process. At present, there are no reliable alternatives to soil sampling. However, research is currently being conducted on the use of detection dogs which can locate Japanese beetle grubs, and molecular biological approaches based on the detection of genetic material in the environment (eDNA) (Milián-García et al., 2023).

Conventional soil sampling (Figure 16) is only worthwhile if an area is already suspected of having a large grub population. Unfortunately, visible damage aboveground is not a helpful indicator, since damage to the grass sward of moist grassland only becomes apparent when around one hundred larvae per square metre are present. However, visible signs of larval infestation or secondary damage such as digging by wild boars or areas where crows have torn the turf (see 2.3.4 Symptoms of damage caused by larvae) are a good indication to search specifically for grubs and take soil samples. Large groups of adult beetles on host plants can also indicate a nearby larval breeding site.

Samples can be taken randomly across the area or along transects. It is important to note that marginal areas (e.g. close to hedges which may be attractive to adults) and moist (not waterlogged!) patches of grassland should be prioritised as the probability of finding larvae are greatest in these areas.

Since freshly hatched larvae are hard to find, sampling should coincide with the anticipated period when larvae have reached at least the second instar, or better still the third. Larvae can be found in the upper soil layer provided that the soil has not cooled down due to the onset of winter. In the spring, it is best to collect soil samples before the pupal stage as pupae in their earth cocoon are very hard to distinguish from the surrounding substrate. To summarise, the ideal period is before winter from around mid-September to the onset of cold weather, and in the following spring between March and April.

The methodology of soil sampling is very simple: a spade is used to extract ‘squares’ of soil (approximately 20 cm x 20 cm x 20 cm) which are then placed on a plastic sheet. The grass sward is removed by hand and the soil is carefully examined. Any grubs found are collected and placed in boiling water for around 10 minutes (camping stove). This step prevents the larvae turning black after death, thus ensuring that the characteristic raster with the V-shaped arrangement of spines (Figure 5b) remains visible. The larvae are then preserved in 70% alcohol to their identification.

It is theoretically possible to use statistical methods to determine the number of soil samples that needs to be taken per unit area to detect a larval population (IPPC, 2008). However, these recommendations are often impractical, as they would entail several hundred or thousand samples, depending on the area. As a rule of thumb, around 50 samples on an area the size of a football pitch is sufficient to find larvae in a moderately infested area (approx. 5% of the area shows signs of larval damage). In contrast, a very small infestation (0.1%) would require thousands of samples to be taken. For this reason – as mentioned at the beginning – it makes no sense to search for grubs when infestation levels are expected to be low, in the case of small populations shortly after introduction, for example. 250-500 larvae/m^2 is regarded as a severe infestation level, i.e. a sample measuring 20x20x20 cm yields 10-20 larvae.

4.4 Public awareness

Adult Japanese beetles can be distinguished from other native beetle species relatively easily by well-informed stakeholders such as farmers and naturalists (see 2.1.5 Similar native beetle species). For example, the first outbreak in Continental Europe, namely in the Ticino Valley Natural Park in Northern Italy, was discovered by an amateur naturalist (EPPO, 2016). This highlights the importance of raising public awareness among these groups to ensure early detection of a potential outbreak of the Japanese beetle. Experiences in the USA confirm that the development and implementation of a public awareness campaign can be critical to the success of eradication programmes (USDA, 2015). Awareness-raising activities (Figure 17) should specifically target those involved in the trading of plants and plant products, agencies and stakeholders working in high-risk areas or habitats, e.g. tree nurseries, sports grounds, golf courses, parks as well as entry and departure/exit points. Awareness can be raised through articles in technical journals, the internet and mobile apps as well as through workshops involving farmers, landowners, gardeners, amateur entomologists, etc. Factsheets with photos and text can also be provided to help with the detection and identification of the Japanese beetle.

These awareness activities should also explain how to report potential findings. Anyone who discovers beetles outside an infested area should report their **findings to the relevant** cantonal **phytosanitary service immediately including photographic evidence if possible**.

Figure 17: *Flyer published by the Federal Office for Agriculture FOAG warning of the Japanese beetle*

5 Economic impact and crops at risk

Figure 18: Rose infested with Japanese beetles (© Tanja Graf, Agroscope).

Grubs and adult Japanese beetles can cause significant economic damage to crops and ornamental plants. The EU ranks the Japanese beetle as the second most harmful quarantine organism for native crops after *Xylella fastidiosa* (Sanchez et al., 2019). Adult beetles cause primary damage by feeding on leaves, flowers and fruits. Grapevines, stone fruits, pome fruits, berries, maize, soya, hops, beans and asparagus are thought to be the most threatened agricultural crops grown in Switzerland. However, adult beetles also feed on ornamental plants, such as roses (Figure 18), wisteria and Virginia creeper.

Since the grubs feed on grass roots in moist grassland and irrigated lawns, the Japanese beetle is the most wide-spread turf pest in the USA today. However, the roots of maize, soya and strawberries can also be affected, leading to harvest losses or even plant dieback.

In the USA, annual costs for controlling grubs and adults across all crops are estimated to be over 460 million US dollars. Losses attributable to grubs alone are estimated at 234 million US dollars per year, around one third of which is spent on controlling the pest and the rest on replacing damaged turf (USDA, 2015). Without effective control measures, the potential annual agronomic damage caused by an EU-wide infestation is estimated at up to 2.4 billion euros by Sanchez et al. (2019), while Straubinger et al. (2022) suggest a figure ranging from 30 million to 7.8 billion euros based on worst- and best-case scenarios for crops such as maize, soya, apples, peaches, cherries and grapes. Wine-producing nations such as France and Italy are particularly affected by economic damage. In 2019 the Federal Office for Agriculture estimated that annual yield losses caused by the Japanese beetle in Switzerland could amount to tens or hundreds of millions (CHF), based on a rough expert assessment.

We will examine the potential impact on individual production branches in detail below, emphasising that **crops close to larval breeding grounds are most at risk of damage by adult Japanese beetles.**

5.1 Sports grounds and other turfed areas

Figure 19: Sports ground a) infested with Japanese beetle grubs and b) emerging adults (© Servizio fitosanitario cantonale, Sezione dell'agricoltura, canton of Ticino).

Damage to turf (Figure 19) is caused exclusively by the larvae of the Japanese beetle, which feed on grass roots. Female Japanese beetles prefer to lay their eggs in moist soil as it gives the larvae a higher chance of survival (Potter et al., 1996). For this reason, the irrigated turf of sports grounds, golf courses, recreational areas and parks, as well as private gardens, can host large populations of larvae. Damage to these areas is by no means a side issue; indeed, it constitutes a significant economic burden. In the USA alone, the expenses for replacing damaged turf runs to over 150 million US dollars a year (USDA, 2015).

The damage occurs in two different ways. Firstly, Japanese beetle grubs damage the turf directly by feeding on the roots. When population densities are high, yellow patches appear, followed by entire swathes of dead, brown grass (Potter, 1998). In our latitudes, the garden chafer causes similar damage to golf courses (Strasser et al., 2005). Secondly, crows, wild boars, badgers and foxes dig up the turf in search of grubs. Even one hundred years ago it was observed that the **secondary damage caused by the digging of insectivorous predators can be considerably more harmful than the primary damage caused by the grubs themselves** (Sim, 1934).

Although turf damage is primarily aesthetic, the costs of replacing damaged areas are high. In addition, uneven ground and an unstable grass sward increase the risk of accident on sports grounds (Potter, 2003). Furthermore, it is important not to underestimate that infested turf might be important breeding grounds for the invasive insect during eradication and containment campaigns.

5.2 Arable production

Figure 20: Japanese beetle infestation in a) maize and b) soya (© Giselher Grabenweger and Tanja Graf, Agroscope).

Japanese beetles can sometimes be found in large numbers in arable crops (Figure 20) such as maize or soya. Maize can be attacked by Japanese beetle larvae, with large numbers found mostly in the weedy margins of maize fields (Figure 20a). In individual cases that are not economically relevant, root damage causes stems to develop a characteristic 'gooseneck' bend. In heavily infested areas, when flowering coincides with the flight period, adult beetles have also been observed congregating at the cob tips and devouring the 'maize beard', which can impair cob pollination (Fleming, 1972; Edwards, 1999). **However, more recent studies suggest that the earlier studies overestimated the impact and that economic damage is generally only a concern** when consumption of the maize beard **coincides with other damage factors** such as heat or drought stress(Edwards, 1999).

Soya is one of the most important crops in the USA, and the Japanese beetle can often be found there (Hammond, 1994). As with maize, it is now assumed that the damage to soya caused by the Japanese beetle was overestimated in earlier sources. The economic damage threshold is only reached, if at all, when Japanese beetles are present at the same time as other insect pests (Ribeiro et al., 2022). The economic threshold can also be reached in individual cases when severe feeding damage occurs shortly before the soya bean harvest (Shanovich et al., 2019).

5.3 Vegetable production

Figure 21: Japanese beetles on an aubergine leaf (© Luca Jelmini, Servizio fitosanitario cantonale, canton of Ticino).

The host range of the Japanese beetle also includes various vegetable crops (Fleming, 1972; EFSA, 2023). The main hosts are beans, sweet corn, tomatoes, aubergines (Figure 21), asparagus and rhubarb (Regione Piemonte, 2019; Tayeh et al., 2023; EPPO, 2024). According to Tayeh et al. (2023), different kinds of brassicas, peas, carrots, melons, pumpkins, cucumbers, celery and endives are also at risk when adult beetle populations are high. **The diversity of vegetable crops and their small-scale cultivation in a wide range of landscape types makes it particularly difficult for this sector to accurately estimate the potential impact of Japanese beetles.**

Leaf damage caused by adult beetles impacts the crop in two ways: it weakens the plants and inhibits growth on the one hand and renders the damaged crop unmarketable on the other. If the effort for sorting the harvest is not worthwhile, whole fields can be lost with major financial losses. Moreover, retailers and consumers are unwilling to accept the presence of adult beetles on the product. Residues of animal organisms are a major problem, especially in processed vegetables such as spinach or peas since the beetles are not detected and removed by the harvesting machines or during the downstream processing stages.

Although females prefer to lay their eggs in moist, sunny grassland (Potter & Held, 2002), irrigated vegetable fields with a loose soil structure may also prove attractive in dry summer months (Fleming, 1972). Since the chosen egg-laying site determines the immobile larvae’s food source, vegetable roots can also be damaged. Root damage can lead to crop failure and thinning of the canopy. Due to the hidden lifestyle of the grubs, there is a risk that they remain undiscovered until the crop has been severely damaged, at which point control measures will be ineffective (Fleming, 1972). Signs of feeding damage on root vegetables impairs their quality and makes the crop unsaleable.

5.4 Fruit production

Figure 22: Plums infested with Japanese beetles (© a) Tanja Graf, Agroscope, b) Giovanni Dal Zotto, University of Verona).

Most tree fruits crops grown in Switzerland are host plants of *P. japonica*. Apples, apricots, cherries, plums (Figure 22), peaches and hazelnuts can suffer very severe adult beetle infestations (Fleming, 1972; Regione Piemonte, 2019; Shanovich et al., 2021). In addition, *P. japonica* may also feed on quinces and chestnuts (Fleming et al., 1934). Pears, on the other hand, are only sporadically attacked by adult *P. japonica*, which suggests that they are less attractive to the beetles (Fleming, 1972). A very severe attack can reduce the leaf area of trees by up to 50%, leading to impaired shoot growth the following year (Fleming, 1972). The Japanese beetle targets the leaves of fruit crops first but can also devour the fruit when population densities are very high (Fleming et al., 1934; Hawley & Metzger, 1940). A study involving the apple variety SweeTango by Pires and Koch (2020) showed that the skin of intact apples is not damaged by the beetles' feeding activity, although damage to individual apples has been observed in the USA (Fleming et al., 1934; Hawley & Metzger, 1940). Adult Japanese beetles generally prefer ripe or injured fruit (Smith, 1923; Fleming et al., 1934).

The EFSA estimates the pest's potential economic impact on stone fruit to be up to 20% harvest losses when the following conditions are met: high population density, long flight period, limited use of insect-proof nets and limited availability of effective pesticides (EFSA, 2023). However, based on experiences from the USA and Italy, and taking into account agricultural practices (early harvest), a harvest loss of 5% is considered more realistic in European stone fruit-growing regions (Korycinska & Baker, 2017; EFSA, 2023). Another study estimates the potential annual impact of *P. japonica* in the absence of control measures to be 2.3 million CHF for Swiss apple growers and 140,000 CHF for cherry growers (Straubinger et al., 2022). According to our assessment, it is however quite possible that the potential damage has been underestimated for cherries and overestimated for apples, as we judge the different ripening times for the threatened fruit crops and the main flight period of the Japanese beetle differently to Straubinger et al. (2022). In Switzerland the ripening and harvesting of cherries, apricots and early plum varieties is generally assumed to coincide with the flight period of the Japanese beetle, which makes them particularly vulnerable. On the other hand, the vulnerable ripening phase of apples in Switzerland is likely to fall outside the main flight period of adult Japanese beetles. It can therefore be assumed that apricots, unnetted cherries and early plums are at risk of infestation and of fruit damage. According to our estimates, direct fruit damage to apples, pears, hazelnuts, quinces and chestnuts is likely to be rare. However, the foliage of these crops can be severely affected in individual cases.

To date, no indications can be found in the scientific literature to suggest that large numbers of Japanese beetle grubs are present in the undergrowth of orchards, where they can cause direct damage to trees. We assume that orchards which are not close to the larval breeding grounds of *P. japonica* are at low risk.

5.5 Berry production

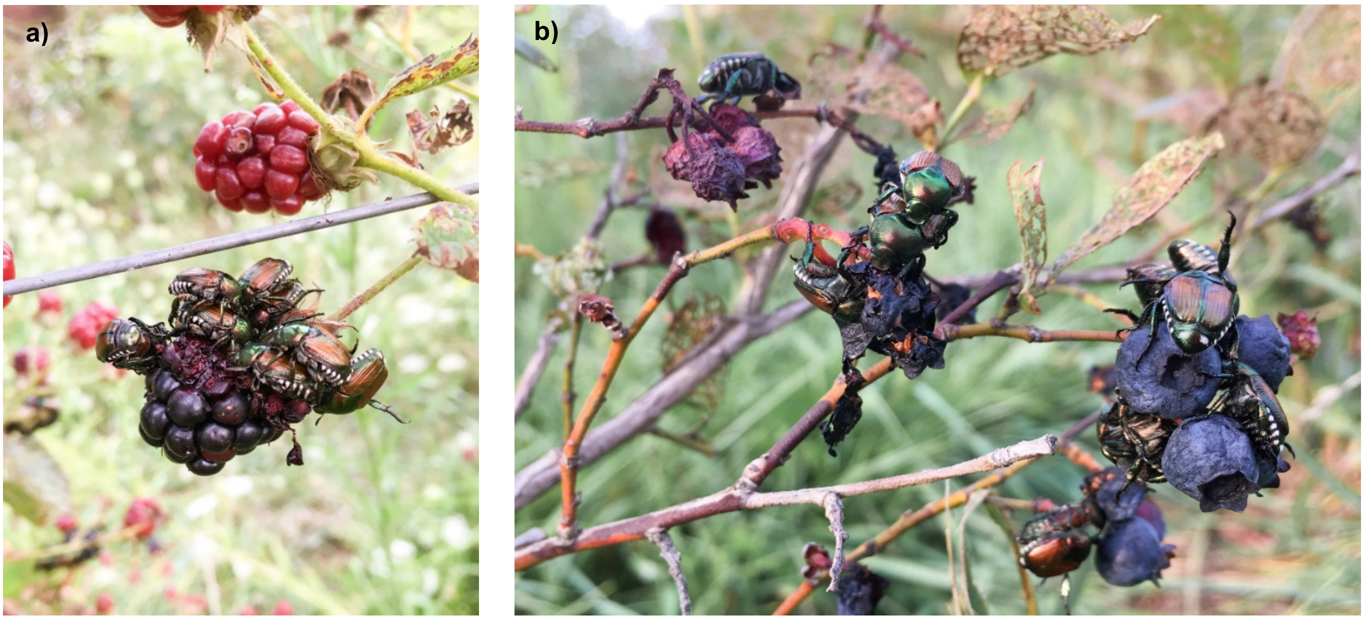

Figure 23: a) Blackberries and b) blueberries infested by Japanese beetles (© Tanja Graf, Agroscope).

Japanese beetles can cause significant damage to berry crops such as strawberries, raspberries, blackberries and blueberries (Figure 23). Adult beetles devour the leaves and fruits, which can disrupt photosynthesis and greatly reduce the proportion of marketable fruits. The consumption of ripe berries is particularly problematic as it considerably reduces not only the yield, but also the quality, which can result in market losses. In heavily infested fields, the entire crop is often unusable as the damaged berries are no longer fit for sale (Burkness et al., 2022). This damage can be economically disastrous for growers in regions with high berry production and high levels of infestation, as the crop is often marketed to high quality standards and losses are difficult to compensate. In addition, the effort required to separate damaged berries from intact ones adds to the harvesting costs. Mechanical removal of the beetles combined with time-consuming control measures place an additional burden on operational structures, leading to higher production costs.

The flight period of the Japanese beetle coincides with the harvest time of many berry species (Bushway et al., 2008; Burkness et al., 2020). **During this period, adult beetles may be present in vast numbers and cause substantial damage to berry crops.** The potential harvest loss in berry production is estimated to be 15% when protective measures such as netting or pesticide treatments are considered (Santoiemma et al., 2021; EFSA, 2023).

5.6 Grape production

Figure 24: Grapevines infested with Japanese beetles (© Tanja Graf and Joana Weibel, Agroscope).

The grapevine (*Vitis vinifera* L.) is one of the Japanese beetle's favourite host plants (Klein, 2022). Large numbers of adult beetles can be observed in infested Italian vineyards between June and July (Figure 24). As many as 200–300 Japanese beetles per vine have been recorded in Piedmont, with peaks of over 1000 adults (Bosio et al., 2022). The potential damage to the Italian wine-growing sector is estimated to be around 50 million euros per year, corresponding to roughly 75% of the total damage caused by *P. japonica* in Italy (Straubinger et al., 2022). A socio-economic survey of Italian wine producers revealed that they anticipated increased management costs and believed a further spread of the beetle would lead to at least moderate yield and quality losses for the majority of vineyards (Straubinger et al., 2023). The authors estimate that a Japanese beetle infestation would result in an average annual decrease in net income of around €2,727 per hectare. Additional labour costs account for €1,715 of this figure, with the rest attributable to yield losses (€966) and additional control costs (€47). While the wine producers surveyed do not expect grapevine cultivation to stop in the majority of vineyards, affected growers believe it is likely that more than a quarter of the plots will be abandoned on economic grounds. However, the survey also found that affected producers rated the resilience of their grapevines more highly than unaffected producers (Straubinger et al., 2023).

In the USA, the main flight period of the Japanese beetle coincides with the ripening of grapes (BBCH 83). In particularly vulnerable vineyards, leaf area can be reduced by up to 50% (Hammons et al., 2010a). Minor defoliation of up to 6.5% has no direct impact on shoot growth, yield or bunch quality (Boucher & Pfeiffer, 1989). However, severe defoliation on potted young (non-fruiting) grapevines in cages reduced subsequent carbon assimilation in the plant and soluble solids in the grapes and at the same time increased the titratable acid content of the pressed must (Boucher & Pfeiffer, 1989; Mercader & Isaacs, 2003b). In addition, leaf damage was found to reduce the cold hardiness of newly planted grapevines (Hammons et al., 2010b). Varietal differences also determine the susceptibility of young grapevines to Japanese beetle defoliation (Gu & Pomper, 2008; Hammons et al., 2010a). Gu & Pomper (2008) tested 32 cultivars of different *Vitis* species and found that European and French hybrid varieties had more severe leaf damage than American varieties with *V. labrusca* heritage. The study by Hammons et al. (2010a) also found that young vines of some varieties experienced reduced growth, accompanied by fewer bunches with fewer berries per bunch and delayed increase in sugar and pH. Conversely, other varieties of young grapevines showed little if any response to leaf damage by the Japanese beetle. Overall, young grapevines of all varieties tested were able to tolerate up to 20% defoliation (Hammons et al., 2010a). Mercader & Isaacs (2003a) also concluded that young *V. labrusca* var. Niagara grapevines could withstand forty Japanese beetles over two weeks. In the vineyard, leaf damage on mature grapevines increases with increasing Japanese beetle numbers. This can adversely affect the sugar content, pH, titratable acid content and phenol levels (Ebbenga et al., 2022a). However, it is worth pointing out that in this experiment, in which netted 6- to 7-year-old grapevines of the variety ‘Frontenac’ were infested with varying densities of Japanese beetles from BBCH 75 (pea-size berries) until harvesting, berry quality in the open vineyard was no different from the netted variants without captive beetles. Thus the natural rate of infestation never reached the levels of the tested variants; however, with eleven beetles per grapevine it was already considerable (Ebbenga et al., 2022a). Another study (Henden & Guédot, 2022) conducted in Wisconsin showed that vineyards close to pastures have higher beetle densities than those surrounded by arable land. Furthermore, the edges of vineyards were found to host more adult Japanese beetles and more severe leaf damage than the centre.

Japanese beetles reduce leaves to a lace-like skeleton and may even devour the entire leaf of some species. They rarely attack unripe berries (Pfeiffer, 2012), but when they do, the injured grapes may attract other pests (e.g. wasps), which then feed on them (Hammons et al., 2009). Adult Japanese beetles typically start by feeding on young leaves at the tip of the vine. Consequently, the upper parts of the foliage sustain the most leaf damage (Gu & Pomper, 2008; Pfeiffer, 2012). While mature grapevines can tolerate a certain degree of leaf damage, young vines are at risk of complete defoliation and should therefore be protected, e.g. with plastic cylinders (Pfeiffer, 2012). Overall, in Switzerland it is assumed that **vineyards – and young grapevines in particular – close to Japanese beetle larval breeding grounds** such as irrigated sports grounds and golf courses and moist grassland **are most at risk** and that *P. japonica* will cause the greatest damage in these areas. However, no indications have yet been found in the scientific literature that Japanese beetle grubs are also developing in the understory of vineyards.

6 Control measures

This part of our review deals with control measures that are applied in the mandatory control of the Japanese beetle. To provide a comprehensive overview, we have also included control measures which are used to limit damage caused by *P. japonica* in other regions of the world where the pest is established. These measures are largely based on literature references and experiences from abroad, especially the USA. We have supplemented these with findings from more recent European studies, which were obtained in infested zones in Northern Italy or Southern Switzerland, as well as in quarantine laboratories (e.g. IPM-Popillia, www.popillia.eu).

Successful eradication or containment of the Japanese beetle and its regular control is only possible through a combination of different mechanical, physical, biological, biotechnical and chemical crop protection measures. Since Japanese beetles frequently breed in non-agricultural habitats which are not agricultural, especially public parks and gardens, sports grounds, woodland margins, wetlands and residential areas with private gardens, an integrated approach to control is essential. A control strategy that is acceptable to society, the economy and the environment must comprise a combination of measures appropriate to the situation. An integrated control strategy is paramount, because all known individual measures have only limited efficacy and are never 100% effective.

To avoid any misunderstandings, it is important to stress once again that official regulations for the eradication or containment of the Japanese beetle must be executed. Many of the measures described below are used in official eradication and containment programmes, especially those that have proved effective in the long-term. However, other control methods are not suitable for use within the scope of the Plant Health Ordinance and/or are still in development. Nonetheless, we wish to present them here, since they form part of integrated pest management strategies in other countries and may be of interest in Switzerland in the future.

6.1 Preventive measures

The first and most important preventive measure is to avert the introduction and spread of the Japanese beetle. Adult beetles can 'hitchhike' with people and goods travelling from infested areas. Eggs and grubs can only be spread from one region to another through the transportation of topsoil or the trade in turf, potted plants and soil containing plant material (Gotta et al., 2023). This highlights the importance of complying with mandatory requirements (see 3. Aspects linked to the Plant Health Ordinance and 4. Prevention, early detection and monitoring), following federal and cantonal recommendations and being vigilant when returning from infested areas and when buying plant material that could be at risk. One effective measure is to avoid buying and transporting plant material from infected regions all together, or at least to import only plant material that has a valid plant passport. The general ruling to prevent the spread of *P. japonica* (BBl 2024 2951) applies in Switzerland. This ruling contains measures relating to the handling of compost, plant material from garden maintenance, vehicles and equipment for earthwork, topsoil to a depth of 30 cm, plants rooted in substrate or soil, and turf grass.

Figure 25: Potted plants with mulch covers to prevent Japanese beetles laying their eggs (© Servizio fitosanitario cantonale, Sezione dell'agricoltura, canton of Ticino).

If not already ordered by the relevant authorities, it is advisable to **avoid irrigating lawns and turf grass in contaminated areas during the flight period of the Japanese beetle**. As female Japanese beetles prefer to lay their eggs in moist grass (Allsopp et al., 1992), for example regularly irrigated turf grass in gardens, parks and sports grounds, this simple measure makes grassed areas less attractive, thereby reducing larval densities in the soil. Targeted irrigation and fertilising after the beetles' flight period (Crutchfield et al., 1995) can fully, or at least partially, offset turf grass damage brought on by the summer drought. In infested areas, the **risk of egg-laying in pots and vulnerable areas can also be reduced by using insect-proof mulch covers** (e.g. coconut fibre and other materials) (Figure 25) (Mori et al., 2022; Gotta et al., 2023). **Fine-meshed nets** placed over pot plants can considerably reduce egg-laying and leaf damage (Anselmi, 2022). For delicate crops like cherries, apricots and berries, which are already protected from above with hail nets and rain covers, it is worth considering whether protective lateral nets would also be worthwhile. Crops which are already covered with insect-proof nets to protect them from pests such as the spotted-wing drosophila (*Drosophila suzukii)* or some tortrix moth species are also protected from the Japanese beetle.

6.2 Physical and mechanical control

Preventive measures such as avoiding irrigation or using mulches not only help to reduce the suitability of sites for egg-laying; they can also hinder the development of Japanese beetle grubs or the emergence of adults. Other measures available are mechanical tillage, the removal of adults and the use of repellents. The aim of these measures is to kill grubs and adults or at least keep the adults away.

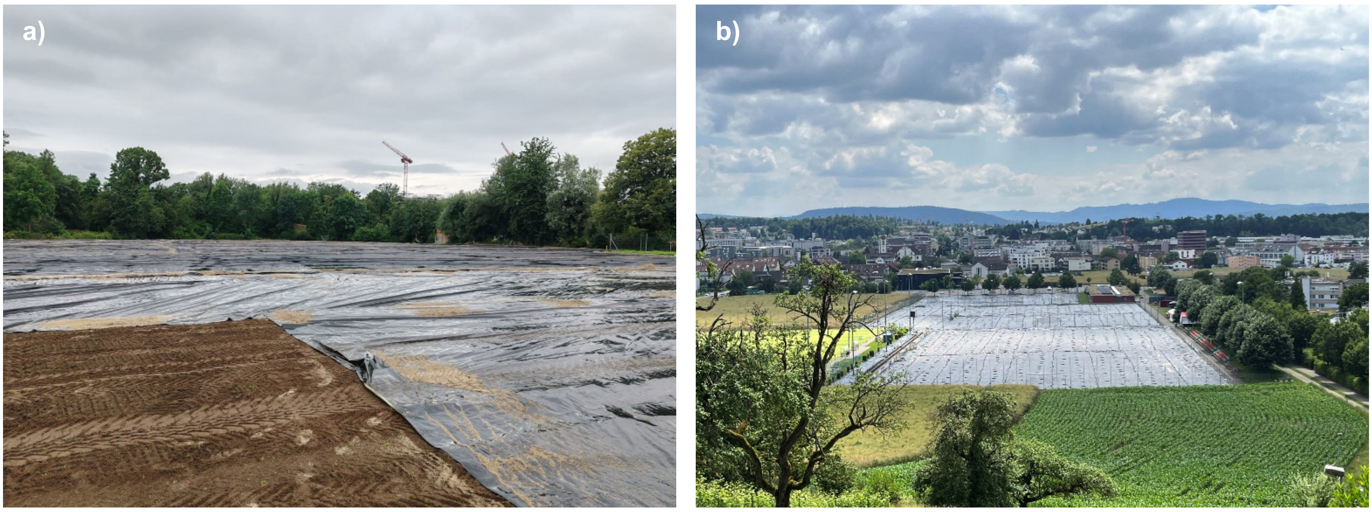

Figure 26: Sports grounds covered to reduce egg-laying and/or emergence of adult Japanese beetles (© a) Eleonor Fiechter, Ebenrain Centre for Agriculture, Nature and Food, canton of Baselland, b) Fiona Eyer, Strickhof, canton of ZH).

Grubs in the soil rely on a certain root mass and soil moisture content. This means that dry topsoil with few living roots does not support larval growth (Pavasini, 2021) and a dry regime from autumn to spring reduces the emergence of Japanese beetles in early summer. Furthermore, Renkema & Parent (2021) found that not all soil substrates used for blueberry growing are equally suitable for the development of Japanese beetle larvae. Specifically, a mulch layer comprising compost, wood chip and sawdust significantly increased grub mortality. Covers placed on the soil of irrigated turf grass such as sports grounds before the start of the flight period (Figure 26) can also reduce the number of emerging adults. This prevents emerging Japanese beetles from reaching the soil surface and flying away. As a result, they die of starvation underneath the covering.

Figure 27: Tilling the grass sward to control Japanese beetle grubs (© Eleonor Fiechter, Ebenrain Centre for Agriculture, Nature and Food, canton of Baselland).

Directly controlling the grubs by mechanical tillage (Figure 27) is an option in individual plots with clear signs of infestation. It is important to till at a time when the grubs are present in the grass sward or the topsoil. Motorised rotavating to a depth of at least 15 cm in dry conditions kills most of the grubs. Some larvae are damaged directly by the mechanical rotavator, while others starve, deprived of their food source due to the destruction of the host plant. Early autumn is the most suitable time for tillage, because the main flight period of the beetles is over, and the larvae have emerged. To ensure that this intervention is effective, it must however be conducted before the grubs withdraw to deeper soil layers to hibernate (EPPO, 2016).

Figure 28: Collecting individual beetles in the vineyard (© Servizio fitosanitario cantonale, Sezione dell'agricoltura, canton of Ticino).

If a small number of adult Japanese beetles are present in a closely defined area, it may be worth picking them off by hand (Figure 28) to reduce the population at local level and prevent further damage (Switzer & Cumming, 2014). However, since the measure is very time-consuming, it is not generally cost-effective or practical to extend its application.

In a broader sense, the use of repellents to protect crops also falls under the category of physical control. In long-term studies in the USA and in Piedmont, the use of **kaolin proved effective** (Lalancette et al., 2005; Bosio et al., 2022). The greyish-white coating of this mineral powder based on aluminium silicate reduces grapevine leaf damage when applied at the start of the flight period. Repellent substances such as neem extract und zeolites are ineffective (Bosio et al., 2022). However, a saponin solution extracted from lucerne (*Medicago sativa*) appears to reduce grapevine damage by adult *P. japonica* (Iovinella et al., 2023). Phytoecdysteroids (secondary plant metabolites which protect against insects) also had a repellent effect on the Japanese beetle in cage trials (Jurenka et al., 2017).

6.3 Habitat management

In the long-term, controlling the host plant range may be another means of regulating Japanese beetle populations. For instance, attractive host plants can be removed locally. However, there are few situations where this is practically feasible. At the same time, other studies showed that **Bermuda grass hybrids** (*Cynodon dactylon* x *C. transvaalensis*) reduce egg-laying, thereby **limiting the level of larval infestation in turf grass mixed with Bermuda grass** (Wood et al., 2009). Japanese beetles also moved around more slowly in soya fields planted with strips of sorghum (*Sorghum bicolor*) than in soya monocultures (Bohlen & Barrett, 1990). The use of pelargoniums (*Pelargonium × hortorum*) as companion plants to protect against Japanese beetles has also been studied, as these plants are toxic to adults and temporarily paralyse them (Fleming, 1972; Potter & Held, 1999). Their flowers are very attractive to adult beetles, and this preference does not diminish, despite repeated consumption with subsequent bouts of paralysis. However, their attraction is relative. Although Japanese beetles are more attracted to pelargonium flowers than linden leaves (*Tilia cordata*), which they also like to feed on, they are even more attracted to raspberry leaves (Maxey et al., 2009). Finally, peonies (*Paeonia lactiflora)* planted closed to turf grass appear to favour parasitoids, thereby increasing the parasitisation of Japanese beetle grubs in the soil (Rogers & Potter, 2004b).

6.4 Biological control

Biological pest control plays a key role in the development of successful control strategies against Japanese beetles. There are two reasons for this: firstly, the invasive pest is by no means limited to agricultural cropping areas. It can also be found in residential and recreational areas, woodland margins, alongside rivers and in nature reserves. For reasons of health and environmental safety, the use of many pesticides is severely restricted or even prohibited in these habitats. Secondly, the only way to reduce Japanese beetle populations sustainably is to control not just the adult beetles, but the larvae in the soil of meadows, pastures and turf grass. Conventional insecticides are generally unsuitable for use in soils.

Research into natural enemies of the Japanese beetle has a long tradition, especially in the USA, and the potential use of specific beneficial insects as biocontrol agents against invasive pests has been thoroughly investigated. Researchers in the USA have been studying the biological control of the Japanese beetle since the 1920s. Initially, exotic predators were released as part of a classical biological pest control programme, but the focus subsequently shifted to native microorganisms (Potter & Held, 2002).

6.4.1 Microorganisms

The term microorganism refers to microscopic life forms such as bacteria, fungi or microsporidia. Individually, they are invisible to the naked eye as they consist of a single cell or a small colony of cells.

6.4.1.1 Bacteria

Figure 29: Japanese beetle grub infected with Bacillus thuringiensis *var.* galleriae *(BTG) (© Giselher Grabenweger, Agroscope).*

Paenibacillus popilliae and *Paenibacillus lentimorbus* are bacteria which cause ‘milky disease’ in Japanese beetle grubs. The bacteria multiply inside the larvae, causing the bodily fluids in the abdominal cavity to take on a cloudy appearance which is visible to the naked eye. The normally transparent abdomen thus appears milky white.

These bacteria were used in the 1940s as biological control agents against the Japanese beetle (Fleming, 1972). In fact, a commercial product was available in the USA until a few years ago. Applications of the bacteria lead to a slowly increasing rate of infection within a population, thus this control method is slow to take effect. Nonetheless, larval populations were significantly and sustainably reduced for several years (Hutton & Burbutis, 1974). According to reports from the USA, its virulence appears to have diminished over the years and its efficacy against *P. japonica* is now in doubt (Dunbar & Beard, 1975; Redmond & Potter, 1995). At present, products containing *Paenibacillus* as a biocontrol agent are not available in Europe.

Bacillus thuringiensis var. *galleriae* (BTG) has also been successfully tested in the USA to control adult Japanese beetles, although granular BTG failed to control larvae (Redmond et al., 2020). Laboratory trials have shown that direct application of BTG is effective against Japanese beetle larvae (Figure 29, Agroscope, unpublished data). However, since BTG can only be effective when it is actively consumed by the host insects and granular formulations are seldom eaten by grubs, no suitable application method for BTG has yet been developed.

6.4.1.2 Entomopathogenic fungi

Figure 30: Japanese beetles infected with Metarhizium brunneum *(© Hanna Neuenschwander, Agroscope).*

Entomopathogenic fungi from the genera *Beauveria* and *Metarhizium* are used in Europe to successfully control close relatives of the Japanese beetle, for example common cockchafers, June beetles and garden chafers (Keller et al., 1997; Keller & Schweizer, 2008). In most cases, a seed drill is used to sow cereal overgrown with fungal mycelia and spores ('fungal barley') into the soil of grassland and turf grass heavily infested with grubs. Test results from the USA (Behle et al., 2015) gave reason to hope that a similar control strategy could also be effective against Japanese beetle grubs. However, follow-up studies in the Swiss quarantine laboratory and in the infected area in Northen Italy were unsuccessful. Graf et al. (2023) notably discovered that the grubs of *P. japonica* are highly resistant to infection by both *B. brongniartii* and *M. brunneum*, whereas adult beetles (Figure 30) were highly susceptible to the same fungal strains. In short, although entomopathogenic fungi are unlikely to successfully control Japanese beetle larvae in the soil, they may be effective in controlling adult beetles. New methods of applying entomopathogenic fungi to control adult Japanese beetles are currently being investigated (Wey et al., submitted).

6.4.1.3 Microsporidia

Microsporidia are a group of highly specialised fungi which are yet to be studied as a potential biological control agent against Japanese beetles in Europe. One species from this group, *Ovavesicula popilliae*, has been used successfully in the USA, to control *P. japonica* locally. *Ovavesicula popilliae* infects the excretory organ (namely the Malpighian tubules) of Japanese beetle grubs in the third instar, causing them to swell and lose their function. Although the disease does not kill the larvae, it weakens their immune system and makes them more susceptible to other pathogens. Piombino et al. (2020) showed that the winter mortality of Japanese beetle grubs infected with *O. vesicula* was three times higher than that of healthy grubs. Smitley et al. (2022) linked a significant reduction in Japanese beetle populations on golf courses in Michigan to the establishment of *O. vesicula* and the ensuing rise in infections rates. Microsporidia are obligate parasitic organisms (i.e. that require a host to reproduce), which means that they cannot be cultured on artificial growth media. This is a major obstacle for the production and marketing of insecticides based on microsporidia. However, in some parts of the USA, this pathogen appears to play an important role in the natural control of Japanese beetles. To date, no microsporidia have been detected on Japanese beetles in Europe. However, a closer investigation of their occurrence in the grubs of closely related native chafer beetles has to take place.

6.4.2 Macroorganisms

Macroorganisms are multi-cellular organisms, most of which are visible to the naked eye. They include small creatures such as nematodes, insects, spiders and mites. They are used for biological control because they feed on or infect pest organisms.

6.4.2.1 Nematodes

Figure 31: Japanese beetle grub infected with the nematode Heterorhabditis bacteriophora *(BTG) (© Giselher Grabenweger, Agroscope).*

The use of nematodes (roundworms) has proved effective in controlling larvae in the soil. A few products containing nematodes as biocontrol agents are already available on the European market for controlling Japanese beetle grubs. Species from the genera *Heterorhabditis* and *Steinernema* are the most well-studied. In both the USA and Europe, it has been shown that the use of *H. bacteriophora* against Japanese beetle grubs (Figure 31) can have efficacy of over 90% under favourable environmental conditions (Villani & Wright, 1988; Klein & Georgis, 1992; Marianelli et al., 2017; Torrini et al., 2020; Sciandra et al., 2024). Strains of these genera occurring naturally in the infested areas have been tested alongside commercially available strains. In some cases, these locally adapted strains proved more effective than commercial strains (Simões et al., 1993; Torrini et al., 2020). The success of nematode treatments depends largely on careful application; they are best applied in the evening when there is as little direct sunlight as possible. In addition, the nematodes must be injected directly into the soil with sufficient water (the CULTAN method) or applied to the soil surface and 'watered in'. The soil temperature also plays an important role; as soon as it starts to drop in autumn, nematodes become less active. Furthermore, the first and second larval instars of the Japanese beetle are more susceptible to nematodes than the third. For these reasons, it is advisable to apply nematode treatments in late summer (from the end of August) when the grubs are still young and the soil temperature is above 12–15 °C.

6.4.2.2 Parasitoids

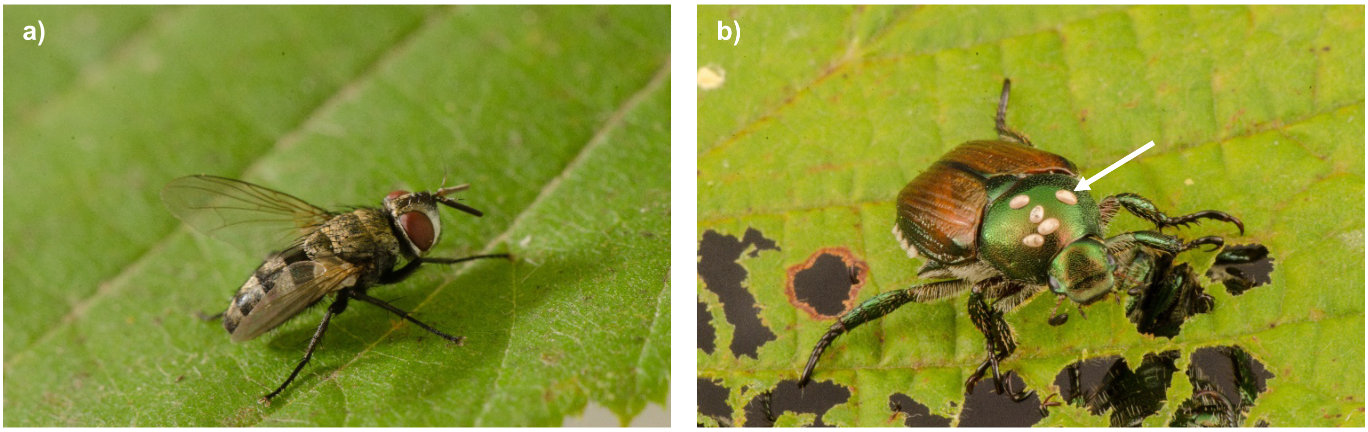

Figure 32: The fly a) Istocheta aldrichi *is a parasitoid which b) lays its eggs on the thorax of adult Japanese beetles (© Tim Haye, CABI).*

Over twenty species of exotic parasitoids have been released in the USA, but only three have successfully established: *Istocheta aldrichi*, *Tiphia vernalis* and *Tiphia popilliavora* (Potter & Held, 2002).

Istocheta aldrichi (the winsome fly) (Figure 32a) is a parasitoid fly (Diptera, Tachinidae). Females of this tachinid fly lay their eggs on the thorax of mainly adult females of the Japanese beetle (Figure 32b). The fly larvae emerge a few days later and bore through the beetle's exoskeleton to consume its inside. Over the following days the parasitoid completely hollows out the beetle, leading to the death of the host. There are several reasons why *I. aldrichi* is a promising candidate for classical biological control in Europe. In Northern Japan, parasitisation rates of up to 90% have been recorded, resulting in widespread control of local *P. japonica* populations (Clausen et al., 1927; Fleming, 1968). However, parasitisation rates vary from 1-70% in North America (Cappaert & Smitley, 2002; McDonald & Klein, 2007; O'Hara, 2014; Shanovich et al., 2019). Large parts of Europe have similar climate conditions (Kottek et al., 2006) to the known distribution ranges of *I. aldrichi* in Northern Japan (Clausen et al., 1927) and North America (Fleming, 1968; Cappaert & Smitley, 2002; Shanovich et al., 2019; Shanovich et al., 2021) . This suggests that European climate conditions would be suitable for the establishment of this species. Although no host-specificity testing was done before its introduction to the USA, *I. aldrichi* seems to be host-specific (King, 1931; Shanovich et al., 2019), which reduces the risk to non-target organisms. Nevertheless, host-specificity testing with European non-target species is essential to ensure its biological safety. For this reason, the climatic suitability and host specificity of *I. aldrichi* for Switzerland are currently investigated in a quarantine laboratory (CABI, 2023).

Tiphia vernalis (the spring Tiphia) is a parasitoid wasp (Hymenoptera, Tiphiidae), which parasitises Japanese beetle grubs when they emerge from hibernation. In spring, the wasps track down their hosts in the soil using scents emitted by the grubs themselves or their droppings, paralyse them and lay a single egg on them. The larvae of *Tiphia vernalis* feed ectoparasitically (from the outside), initially on body fluids and then on the tissue, leading to the death of the host. This makes *Tiphia vernalis* another promising candidate for classical biological control of the Japanese beetle. The species demonstrates high parasitisation rates and significant population control in the USA (Balock, 1934; Gardner, 1938; King & Parker, 1950; Rogers & Potter, 2003; McDonald & Klein, 2007; McDonald et al., 2020). The known distribution range of the parasitoid wasp indicates its compatibility with the European climate (Clausen et al., 1927; Clausen et al., 1933; Krombein, 1948; Fleming, 1968; Reding & Klein, 2001; Rogers & Potter, 2004a; Ramoutar & Legrand, 2007; McDonald et al., 2020). It also shows consistent host-parasitoid synchronicity across a range of latitudes in the USA (King, 1931; Rogers & Potter, 2004b). However, it is not known whether *T. vernalis* parasitises *P. japonica* in its original Japanese distribution range. The species was introduced to the USA from Korea after laboratory tests indicated that the Japanese beetle was a suitable host (Fleming, 1968). *Tiphia vernalis* can kill other chafer beetles in addition to species from the genus *Popillia* (Clausen et al., 1932; Reding & Klein, 2001). However, the North American *T. vernalis* exhibits specific behaviour in seeking Japanese beetle grubs as hosts and has a strong ability to differentiate hosts, which suggests a limited host range (Rogers & Potter, 2002). In view of its potential for biological control, the biological safety of *T. vernalis* for European non-target species should be verified under quarantine conditions. In Switzerland, comprehensive evaluation of biological safety forms the basis for the approval of potential candidates for classical biological control in accordance with the Ordinance on the Handling of Organisms in the Environment.

For *T. popilliavora* – the last of the three potential parasitoid species mentioned – there is little information available to determine whether the species would be suitable for biological control in Europe. For this reason, we will not describe this species in detail.

6.4.2.3 Predators

Figure 33: Zebra spider that has caught two adult Japanese beetles in its web (© Tanja Graf, Agroscope).

In Switzerland, several predators are known to feed on adult Japanese beetles and their grubs. However, they all have a wide prey spectrum, and Japanese beetles are by no means their only food source. Spiders, for instance, eat adult beetles (Figure 33); and as already mentioned, various birds and mammals also predate grubs in the soil (see 2.4 Natural enemies) (Sim, 1934). In some cases, predators appear to have a measurable impact on *P. japonica* populations (Potter & Held, 2002; EPPO, 2016). However, it is not possible to use native predators in a targeted way to control invasive pests due to their large prey spectra.

6.5 Biotechnical control

Biotechnical methods involve mass trapping using 'pheromone' traps and baited net traps. Chemical lures based on the female sex pheromone and a floral attractant (see 4.1 'Pheromone' traps) draw the beetles to a specific location, where they are then caught in traps or poisoned on nets treated with insecticide. These two biotechnical control measures can be used both within and outside agricultural cropping areas.

Most mass traps are equipped with a large container capable of retaining a substantial number of attracted beetles. **The use of mass traps can locally reduce isolated populations in a spatially confined infested areas** (Potter & Held, 2002; Switzer et al., 2009; EPPO, 2016). In the USA, mass traps were set up close to elderberry and blueberry plantations to protect the crops against *P. japonica.* Several million adult Japanese beetles were caught within a three-year period; very few adults were observed in the crops during this time and foliar damage was low (Piñero & Dudenhoeffer, 2018). Mass trapping to control the closely related *Popillia quadriguttata* has also been investigated in China. Here, mass trapping reduced the number of adult beetles by 93% and the number of grubs in the soil by 90% (Chen et al., 2014a). A follow-up study found a direct positive correlation between the number of *P. quadriguttata* adults caught and the protection of maize, soya and cabbage (Chen et al., 2014a; Chen et al., 2014b).

The downside of using lures is that they risk attracting more beetles than the traps can hold (Wawrzynski & Ascerno, 1998) or enticing them to areas that were previously free from infestation. It is important to empty the traps at regular intervals, because the smell of their decaying conspecifics repels any Japanese beetles remaining in the area (Giovanni Bosio, pers. communication). The use of mass traps for eradication and containment purposes therefore requires good regional planning and coordination. The unregulated use of mass traps baited with chemical lures in private gardens and allotments must be discouraged as it may accelerate the spread of the invasive pest (EPPO, 2016).

Figure 34: Japanese beetles lured to an insecticide-treated net (LLIN) (© Giselher Grabenweger, Agroscope).

Long-lasting insecticide-treated nets (LLINs) were originally developed to protect people from mosquitos, which transmit diseases such as malaria and yellow fever. The use of these nets has since been extended to agriculture for the targeted control of pests (Gotta et al., 2023). Nets treated with the pyrethroids α-cypermethrin and deltamethrin have now been tested against Japanese beetles. Adult Japanese beetles are attracted by lures to the nets (Figure34), where they come into contact with the insecticide, are poisoned and die. **Preliminary results from Italy are promising** and there appears to be some degree of flexibility in the configuration of the LLINs. A larger, horizontal net was found to increase the probability of landing and also extend the beetles' residence time. The LLINs remain effective in the field for around one month (Paoli et al., 2023). Furthermore, a few LLINs per hectare appear to be enough to provide an effective control (Paoli et al., 2024). Preliminary results from Switzerland are also promising. In a pilot study conducted in 2024, the number of adult Japanese beetles in the LLIN-treated trial areas was reduced by around one half compared to the untreated control areas (Agroscope, unpublished data).

Unlike the large-scale application of insecticides, the advantage of mass traps and LLINs is that the lures specifically target Japanese beetles, thereby reducing the risk to non-target organisms and to the environment. Lannan & Guédot (2024) tested a similar strategy to control Japanese beetles in the USA. In a two-year study in commercial vineyards, chemical lures were hung from grapevines at the edge of the plots. This peripheral area was subsequently treated with a broad-spectrum insecticide (spot spraying). The efficacy of this approach was similar to the winegrowers' standard management practices in terms of number of adult beetles in the vineyard and leaf damage. However, it succeeded in reducing insecticide applications by 96% (Lannan & Guédot, 2024). The downside of spot spraying is that it also attracts larger numbers of beetles to plots with potentially low levels of infestation. The effectiveness of this measure depends largely on the attractiveness of the crop and the presence of other host plants immediately surrounding the crop to be protected.

6.6 Insecticidal control

Figure 35: Use of insecticides to eradicate Japanese beetles (© Fiona Eyer, Strickhof, canton of ZH).

The use of conventional biological or synthetic insecticides is often a simple and cost-effective measure to control pests quickly and effectively (Figure 35). In the last century, the use of broad-spectrum insecticides to control Japanese beetle populations was widespread in the USA due to their high efficacy and relatively low cost (Gotta et al., 2023). However, side-effects on non-target organisms and negative effects on people and the environment have led to restrictions on their use and modifications to the application methods (Althoff & Rice, 2022). Today, insecticides containing the active ingredients bifenthrin, carbaryl, cyfluthrin, deltamethrin and permethrin are used in the USA to control adult Japanese beetles (USDA, 2015).

Preliminary studies between 2017 and 2019 on the chemical control of adult Japanese beetles in Italian vineyards found that the pyrethroids deltamethrin, lambda-cyhalothrin and acrinathrin are most effective, followed by acetamiprid and chlorantraniliprol (Bosio et al., 2022; Gotta et al., 2023). In contrast, azadirachtin, pyrethrum, a soap preparation, chlorpyrifos-methyl, thiamethoxam, tau-fluvalinate, etofenprox and sulphur had low to no effect (Bosio et al., 2022). In 2021, the trials were extended to other crops such as peaches, maize and two species of ornamental plants, with twenty different active ingredients tested overall. Data showed that acetamiprid, deltamethrin, phosmet, pirimicarb, lambda-cyhalothrin, etofenprox, indoxacarb and abamectin were highly effective at killing adult beetles both through direct exposure to the insecticide and by contact with recently treated surfaces (Santoiemma et al., 2021; Gotta et al., 2023). In contrast, chlorantraniliprole was not effective in all the tests conducted, while sulfoxaflor and metaflumizone showed limited effectiveness and only through direct contact. Azadirachtin, chlorpyrifos-methyl, pyrethrine, rapeseed oil, flupyradifurone, spinosad, a mixture of paraffin oil and cypermethrin as well as the fungus *Beauveria bassiana* were found to have no or only very limited effect. One week after application, however, only the active ingredients acetamiprid, deltamethrin, sulfoxaflor and phosmet retained a long-term residual effect (Santoiemma et al., 2021). Overall, only some of these active ingredients are approved for agricultural use in Switzerland and at the time of writing in January 2025, no insecticide has a regulatory approval for the control of the Japanese beetle. Some insecticides have been granted temporary 'emergency approvals' for the control of *P. japonica*. However, their use is strictly governed by the cantonal phytosanitary services (the relevant 'General Rulings' can be found on the Federal Food Safety and Veterinary Office, FSVO website).

It is difficult to control *P. japonica* grubs by applying conventional insecticides to the soil and this method is rarely considered nowadays due to safety and environmental concerns. That said, we have outlined some findings on the control of larvae in the soil below for the sake of completeness. In the USA, various insecticides from the classes of organophosphates, carbamates, neonicotinoides, dacylhydrazines and pyrethroids were tested on larvae in the soil between the 1970s and the 1990s. Due to lack of efficacy and/or high toxicity to non-target organisms, the use of many of these active ingredients was banned at the end of the 20th century (Potter & Held, 2002). Nonetheless, the active ingredients imidacloprid, halofenzide, trichlorfon and chlorantraniliprol are still used in the USA in tree nurseries and turf grass to control larvae in the soil (USDA, 2015), with the first two instars being more susceptible to the insecticides than the third (Oliver et al., 2009). However, Switzerland no longer permits the use of conventional soil insecticides. Instead, entomopathogenic nematodes are mainly used to control Japanese beetle grubs in the soil (see 6.4.2.1 Nematodes).

In future, gene silencing using RNA molecules could be a highly promising method for controlling the Japanese beetle. This process involves the ingestion of species-specific RNA molecules by the target organism, leading to the disruption of its vital functions and ultimately to its death. Preliminary findings from a laboratory study on the efficacy of this method in controlling adult *P. japonica* are very encouraging (Carroll et al., 2023).

Lastly, we would like to point out that Japanese beetles in the USA have already developed resistance to soil insecticides (Niemczyk & Lawrence, 1973). Furthermore, the harvest period for several crops such as cherries, apricots and various types of berries coincides with adult Japanese beetle attacks, which greatly limits the use of chemical treatments due to the mandatory waiting period between insecticide applications and harvesting. And finally, insecticides approved for use in organic production (namely products based on the active ingredients azadirachtin (neem), rapeseed oil, spinosad or the fungus *Beauveria bassiana*) are often only poorly or partially effective in controlling adult Japanese beetles (Piñero & Dudenhoeffer, 2018).

6.7 Protection of crops

Nowadays numerous control measures are used to eradicate and contain the Japanese beetle. Local eradication strategies targeting individual infestations and regional containment strategies to prevent the further spread of this quarantine pest rely on various measures implemented at large scale and across crops. These measures are listed and described in the national emergency plan for the monitoring and control of the Japanese beetle. For this reason, we do not intend to discuss these control measures in more detail in this article. Instead, we would like to develop long-term prospects and consider which phytosanitary measures could be used in the abovementioned crops if the Japanese beetle becomes widely established in future.

It is already clear that vulnerable crops can only be protected in future through an integrated, multi-crop control approach. It is imperative that phytosanitary strategies include a range of measures that are implemented at regional level by different cooperating stakeholders. This is vital, as there is a clear-cut spatial separation between the presence of eggs, larvae and pupae on the one hand and adult Japanese beetles on the other and because individually, all known measures are effective only to a limited extent. Effective and sustainable phytosanitary strategies must therefore be composed of a combination of different preventive, mechanical, biological, biotechnical and chemical control measures.

It is worth mentioning that **very few crops are harmed by grubs and adult Japanese beetles at the same time.** However, this might nonetheless occur in irrigated vegetable or berry crops, as eggs may be laid in and between crops close to grasses. In orchards, trees are unlikely to sustain direct damage when Japanese beetle grubs are developing on the roots of the understory. We believe that the mostly unirrigated and shallow soils of vineyards are unlikely to provide a suitable habitat for grubs to develop in large numbers in the grassy understory. Furthermore, we can assume that direct control of grubs in arable crops is seldom cost-effective, even when maize roots are locally infested with Japanese beetle larvae (Figure 20a).

We believe that direct control of grubs is economically viable only in specific irrigated turfed areas. The **use of nematodes will play a key role in this areas** (Table 1), **as this is currently the only effective measure to control Japanese beetle larvae in the soil** without damaging the sward. To prevent the spread of the pest, turf producers should take care to ensure that grubs are not inadvertently transferred in the turf grass. Adapted watering strategies can reduce egg laying and larval development wherever grubs develop directly in the crops. Nevertheless, it is important to provide sufficient water to ensure that crops are not damaged by this measure and that the required quality standards for the harvested crop are maintained (Table 1). Covering the soils with plastic sheeting or mulches or modifying the soil substrate can reduce egg laying in turf grass as well as in vegetable and berry crops. Selective tillage in annual and perennial crops can also reduce the host plant spectrum for egg laying and the food supply for grubs, as well as directly killing grubs in the soil. In grassed areas, sowing Bermuda grass hybrids, which reduce egg laying, can reduce primary and secondary grub damage. Potentially, intercropping might also reduce economically unsustainable feeding damage caused by adult beetles in certain crops. In future, it might also be worth growing vulnerable annual crops away from larval breeding grounds. **Nets provide particularly effective protection against feeding damage by adult Japanese beetles.** The number of netted crops will continue to rise, especially close to larval breeding grounds (Table 1). Currently, it is difficult to imagine vineyards completely protected by nets, but their foliage can be treated with the mineral powder kaolin to protect them from adult damage. On the other hand, in other crops the widespread use of kaolin to protect the foliage is problematic, as the crop is often marketed immediately after harvesting and is not allowed to have any visible spray residue. In small plots with particularly profitable crops, it may be possible to collect adult beetles by hand. However, under the existing general conditions we do not believe that this measure is economically viable at large scale. It is unlikely that the use of conventional insecticides to control adult Japanese beetles will be completely avoidable, but spot spraying can strongly reduce the amount applied and the spray residues on the harvested crop. The use of attractants to lure adults to specific areas which are then treated with conventional insecticides is therefore a promising measure to protect very attractive crops. This measure can be used in all crop groups and significantly reduce the amount of pesticide needed. Attractants can also be used to lure adult Japanese beetles into traps or on insecticide-treated nets (LLINs). Mass trapping and LLINs can be used at large scale both within and outside of agricultural crops (Table 1).

Future phytosanitary control strategies against the Japanese beetle will most likely consist of a combination of different options from this list of possible control measures (Table 1). It remains to be seen what role repellents, biological control agents or even gene silencing will play in the future control of the Japanese beetle as further development is still needed and there are also legal hurdles to overcome. Furthermore, it is still unclear how potential larval breeding grounds such as moist meadows and pastures are actively protected against Japanese beetles, and by whom. However, individual control measures such as avoiding transportation, controlling irrigation, covering the soil, netting plants, mass trapping and using nematodes and insecticides are certainly feasible, including in horticulture and plant nurseries.

Table 1: Assessment of the importance of the proposed measures for the future control of the Japanese beetle in different agricultural production sectors. X denotes a promising measure that is likely to be implemented in the corresponding crop sector, (X) denotes a partially promising measure that may be used in this production sector, and empty cells indicate less-promising measures that are unlikely to be implemented in this crop sector.

Control measures	Turf grass	Arable crops	Vegetables	Tree fruits	Berries	Grapes
Preventive measures						
Prevention of introduction	X					
Site selection		(X)	X		(X)	
Adapted irrigation	X		(X)	(X)	(X)	
Soil covering	(X)		(X)		(X)	
Nets			X	X	X	(X)
Mechanical control						
Adaptation of soil substrate	(X)				(X)	
Tillage		X	X		(X)	
Manual collection			(X)		(X)	
Mineral powders (kaolin...)		(X)		(X)	(X)	X
Other repellents	Future localised use to control adults not ruled out					
Control of host plant range	X	(X)	(X)	(X)	(X)	(X)
Biological control						
Bacteria (Bt...)	Future localised use to control larvae conceivable					
Fungi		Future localised use to control adults conceivable				
Microsporidia	Future localised use to control larvae conceivable					
Nematodes	X		X		(X)	
Parasitoids	Future use to control regional populations conceivable					
Predators	Targeted use difficult to imagine even in future					
Biotechnical control						
Mass trapping	X	(X)	(X)	X	X	X
LLINS (insecticide-treated nets)	X	(X)	(X)	X	X	X
Attractants and spot spraying		X	X	X	X	X
Insecticide control						
Conventional insecticides		X	X	X	X	X
Gene silencing	Future localised use conceivable					

7 Conclusions and perspectives

The accidental introduction of the Japanese beetle to Mainland Europe and its continuous spread from Italy to Switzerland **presents the Swiss Federal Plant Protection Service and the cantonal phytosanitary services with one of the greatest challenges of recent years**. This harmful pest is **not only a threat to agriculture, but to public and private parks as well as recreational areas**. Since the Japanese beetle is listed as a priority quarantine organism, eradication and containment measures to control the Japanese beetle have been implemented in accordance with international phytosanitary legislation and the Swiss Plant Health Ordinance. However, the gradual spread of the beetle as well as mathematical models (Borner et al., 2023) on the suitability of habitats indicate that the Japanese beetle will become established throughout Switzerland and in large parts of Europe in the long term. This article covers the official eradication and containment measures, and presents pest control measures that are not yet fully developed or approved but could be applied in future.

Unlike other invasive insect pests such as the spotted wing drosophila (*Drosophila suzukii*) or the brown marmorated stink bug (*Halyomorpha halys*), which were suddenly and somewhat unexpectedly introduced to Switzerland from theirnative Southeast Asia over the last few years, the Japanese beetle has been present in North America for over a century. As a result, there is a correspondingly large body of knowledge available about its biology and ecology. Furthermore, we can draw on decades of experience regarding the efficacy of different control measures. However, this knowledge is only partially applicable to Switzerland due to the large range of host plants, limited effectiveness of individual phytosanitary measures and the impact of regional factors on the success of any such measures.

No serious economic damage has resulted from Japanese beetle infestations in Switzerland so far. This is partly because Japanese beetle populations are still building up, and partly because less susceptible crops are grown in many of the highly infested areas, e.g. Southern Ticino or the alpine Simplon region. In Southern Ticino, grapevines – one of the Japanese beetle's favourite host plants in the region – sustain leaf damage during the flight period of the beetle. However, given the current level of infestation, this can be largely offset and does not yet have a serious impact on grape berry ripening. Damage that severely impairs the quality and quantity of the harvest is expected to arise in regions where outdoor vegetables, fruits and berries are cultivated.

In contrast to many other agricultural pests, there are two aspects of the Japanese beetle which must be accounted for in the design of control strategies. **Firstly, many public and private recreational areas, parks and gardens are also affected in addition to agriculture and market gardening.** At present there is little collaboration and exchange between these two sectors, although this will be of utmost importance in the future to reduce and control Japanese beetles sustainably at regional level. **Secondly, there is a clear-cut spatial separation between the habitat of eggs, larvae and pupae on the one hand, and of adult beetles on the other**. This means that plant protection measures in adult beetle habitats are less likely to be successful in the long term if the steady supply from the often hard-to-find larval areas is not supressed at the same time. Furthermore, **opportunities for intervention are often limited in larval habitats** (e.g. along riverbanks, in water reserves or in leisure and recreational areas).

One thing is certain: an integrated, multi-crop approach at landscape level is the only way to protect crops. Control strategies must therefore consist of different measures which may be only partially effective on their own. In addition, these integrated control strategies must be adapted in respect of the landscape and the available host plants. In the USA, synthetic chemical insecticides play a key role in controlling the Japanese beetle – and their use in Switzerland cannot be entirely ruled out. However, their application can be reduced to a minimum by combining them with other control measures.

The use of entomopathogenic nematodes has proved promising in controlling the larvae of *P. japonica* in grassland and lawns. A nematode application can be over 90% effective, but its efficacy depends largely on careful application and the prevailing environmental conditions in the treated areas. Another interesting and promising approach is the use of lures combined with traps or insecticide-treated nets. Although these nets rely on synthetic chemical pesticides, this novel application method has minimal side-effects on non-target organisms and the environment.

Other biological control methods are still in development. For example, entomopathogenic fungi have been shown to be unsuitable for soil applications due to the low susceptibility of the larvae. However, adult Japanese beetles are highly susceptible to fungal infections. So entomopathogenic fungi combined with attractants could also play a role in controlling the Japanese beetle. The Japanese beetle has no known natural enemies in the newly populated regions, including Switzerland. For this reason, various natural enemies native to the Japanese beetle's place of origin were released in the USA (classical biological control). Some of them have become established following their release and now help to control pest populations. However, the release of non-native natural enemies requires extensive preliminary studies, which are already underway for two possible candidates in Switzerland. The procedure for authorising a non-native beneficial organism in Switzerland is very complex and can take several years.

The knowledge gained in the USA and more recently in Italy and Ticino provides a valuable basis for a successful control of the Japanese beetle. Nonetheless, **at this stage it is difficult to identify the endangered crops at local level within Switzerland, to estimate the damage potential of the Japanese beetle at small scale and to calculate the potential financial cost to the Swiss economy and society.** However, we assume that **irrigated turfed areas such as sports grounds, golf courses, turf growing facilities, public parks and private gardens are most susceptible to larval attack,** and that moist meadows and pastures could be infested to a lesser extent. In addition, **vulnerable crops close to previously mentioned larval breeding grounds are most at risk from being attacked by adult Japanese beetles. Crops whose ripening and harvest period coincides with the flight period of the beetle are also at particular risk**. In-depth research focussing on two main scientific areas will be needed in the coming years to counter these risks. Firstly, to better understand the population and spread dynamics of this invasive pest and this also at small spatial scale. And secondly, to further develop the biological and biotechnical control methods which have proved promising in recent years. **The spatial separation of larvae and adults, often in non-agricultural habitats, requires close collaboration between all stakeholders at regional scale.** This is vital not only for mandatory eradication and containment according to the Plant Health Ordinance, but also for possible future control strategies in the case that the Japanese beetle should lose its quarantine status. Drawing on the current knowledge base and ongoing research, it should be possible to develop and implement effective, efficient and sustainable strategies to control the Japanese beetle in Switzerland.

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10 List of illustrations

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