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A review of history and geographical distribution of grapevine moths in Italian vineyards in light of climate change: Looking backward to face the future

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ABSTRACT

Tortricid and pyralid moths include important pests of vineyards. This review offers a retrospective analysis of the geographic distribution expansion of the European grapevine moth, *Lobesia botrana* (Denis & Schiffermüller) (Lepidoptera: Tortricidae) and the replacement or marginalization of the importance of the previously largely vine-infesting species, i.e., *Sparganothis pilleriana* (Denis & Schiffermüller) and *Eupoecilia ambiguella* (Hübner), because of the combination and interaction between climate change, invasive alien species, and new cultivation techniques. Herein, we have focused on the case study of Italy, which is currently representing the fourth largest country in the world in terms of cultivated wine-growing area, and the biggest producer of wine grapes, as a model to analyze the possible influence of climate change on the occurrence and harmfulness of grapevine moths and what will be the next challenges for their sustainable management. Starting from the retrospective analysis and learned lessons, a research agenda outlining future challenges for IPM of grapevine moth pests in Mediterranean countries is developed.

1. Introduction

Although the ongoing climate change may have started with the industrialization processes in the 1800s, it has progressively intensified in recent decades, and has generated concern in recent years with an increase in the frequency and intensity of extreme events characterized by high temperatures and, conversely, a decrease in episodes marked by low temperatures. Among the serious harms that climate change causes are those related to biological invasions of non-native species, often invading new environments by accidental introductions, which adapt and spread due to the slackening of the ecosystem resilience associated with climate change (Halsch et al., 2021; Kenis et al., 2023).

The number of invasive species has increased exponentially since the 16th century (Roques et al., 2010), because of the increase and speed of trade, but they have been able to expand rapidly to higher latitudes and altitudes because of increases in temperature (Kenis et al., 2023). Increased mean temperature, more than any other abiotic parameter related to climate change, is the main factor that has a direct effect on phytophagous insects. However, an increasing number of studies have also investigated the impact of relative humidity, CO_2 and UVB radiation on different invasive species (Chu et al., 2012; Fisher et al., 2021; Zeni et al., 2022), while direct impacts of precipitation have been largely neglected in current climate change research (Bale et al., 2002).

Rising temperatures can induce changes in the development cycle length, number of generations per year, population density, size of individuals, genetic composition, geographic distribution, and/or host plant range (Bale et al., 2002). In general, under the influence of warming, most insect species tend to shift their geographic distribution northward (Parmesan et al., 1999; Roques et al., 2015; Thiéry and Chuche, 2007). Thus, the effects of climate change on phytophagous insects of agricultural interest can be direct, through the impact on their physiology and behavior, but also indirect, when insects respond to climate-induced changes mediated by other factors, particularly the phenology or the nutritional value of the host plant, including the adaptation of agricultural practices to changing climatic conditions (Iltis et al., 2021).

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However, agriculture has experienced in the past some of these trends. In the decades at the turn of the 20th century, Italian viticulture underwent a major upheaval due to the invasion and rapid spread of the grapevine phylloxera, *Daktulosphaira vitifoliae* (Fitch) (Hemiptera: Phylloxeridae) (Ollat et al., 2014). The use of American rootstocks resulted in an increase in vigor and consequently in a change of the microclimatic conditions within the canopy (Corso and Bonghi, 2014; Thiery, 2005; Thiéry et al., 2011). In addition, towards the end of the 1800s, less frosty years alternated with milder periods were the harbinger of the end of the Little Ice Age and the transition into a period of rising temperatures that lasted throughout the 1900s (Nesje and Dahl, 2003).

In this scenario, the purpose of the present review is to retrospectively analyze the expansion of the geographic distribution of the European grapevine moth, *Lobesia botrana* (Denis & Schiffermüller) (Lepidoptera: Tortricidae) and the replacement or marginalization of the importance of the previously largely vine-infesting species, i.e., *Sparganothis pilleriana* (Denis & Schiffermüller) and especially *Eupoecilia ambiguella* (Hübner) (Fig. 1), because of the combination and interaction between climate change, new invasive species, and modified cropping techniques. From 1800 onwards, a special focus on pest population dynamics and employed pest management methods in grapevine-producing areas of Italy is offered. In the final section, starting from the historical overview and learned lessons, a research agenda outlining future challenges for IPM of grapevine moth pests is formulated.

2. The "worms" in the vineyards: from the bible to ancient Rome

It has been known since ancient times that grapevine can suffer from the attack of moth larvae that compromise the integrity of the bunch and the wine production. Already in the Bible, there are clear references to pest outbreaks that were considered a curse for those who did not observe God's law "*You'll plant and hoe and prune vineyards but won't drink or put up any wine - the worms will devour them*" (Deuteronomy, ch. 28, verse 39).

These kinds of calamities were also a cause of concern for ancient Roman winegrowers. The Latin playwright Plautus (254-184 B.C.) calls "*bestiam et damnificam*" (an harmful beast) the larva (*involvolus*) that twines and entwines itself in the vine shoots (Cistellaria, 727 and 729). Cato the Censor (234-149 B.C.) gives a recipe for preparations of oil sludge, bitumen and sulfur applied to the vine trunk to prevent the vineyard from being infested by worms (De Agricultura Liber, 95). Columella, a prominent writer on agriculture in the Roman time (1st cent. A.C.), calls "*volutra*" the insect "*which has the habit of gnawing off vine shoots and bunches that are still tender*" and suggests other remedies to prevent this from happening (*De Re Rustica*, XV). Pliny the Elder (23–79) in his *Naturalis Historia* (XVII, 264) reports what Cato says about the "*convolvulus*", which is probably the same winged insect indicated by Columella.

3. Moths attacking grapes from 1800 onwards: what happened in Italy?

Some of the earliest historical reports of infestations most likely attributable to grape moths date back to the beginning of the 17th century and refer to vineyards located around the city of Bolzano. Weber wrote in 1849 (in Catoni, 1910) (Fig. 2): "*A disastrous event was that of the grape worm, which brought incalculable damage to the vineyards. According to municipal protocols, these insects or caterpillars first appeared in the year 1624 and till brought devastation to the vineyards on several occasions over a period of about 30 years, rendering the grape harvest null and void in entire districts*". " … *To contrast this scourge (the grape worm) many natural and supernatural means were employed. First, it was forbidden to kill birds, especially those that nest and feed on insects and caterpillars during their broods. A miller who transgressed this order was, as a punishment, locked up in the mad house, so insane did his lightness seem. Eggs and caterpillars were*

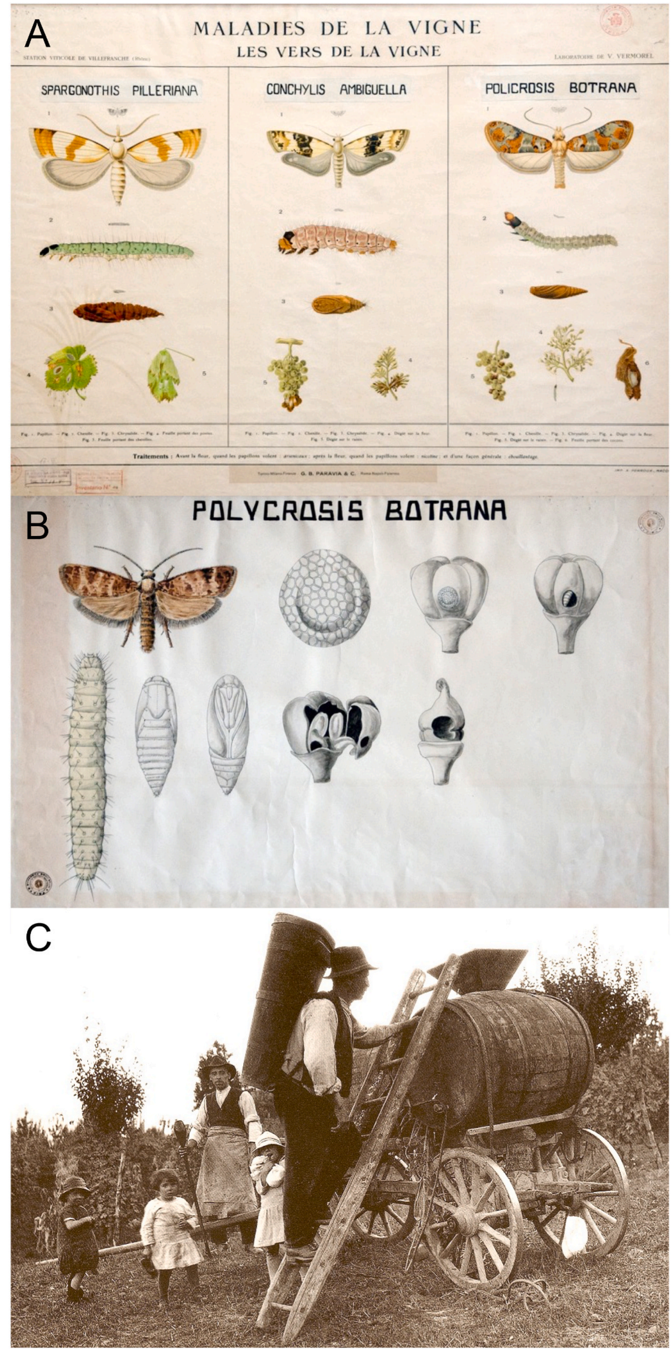

Fig. 1. Vineyard pest management has a long history in the Mediterranean area. **(A–B)** Handmade drawings reporting selected developmental stages of tortricid moths, *Sparganothis pilleriana*, *Eupoecilia ambiguella* (=*Cochylis ambiguella*), and *Lobesia botrana* (=*Polichrosis botrana*), attacking grape (A: V. Vermorel, G.B. Paravia, plate no. 24, DISAAA, University of Pisa, Italy; B: plate no. 318, DISAAA, University of Pisa, Italy). **(C)** Grape harvest conducted in Trentino (Northern Italy) vineyards in earlier '900 (Foundation P. Scheuermeier, Archive of the Roman Studies Seminar, University of Bern, Switzerland).

also sought in all their stages, either on the leaves or on the bark of the vine, crushing them or killing them with sprays and poisonous liquids. Twice the miraculous scepter of St. Magnus was transported from Füssen to bless the threatened vineyards with it. Even papal bulls requested by the city council arrived in Bozen with special curses for the caterpillars. In the years 1739-1744, frequent Gossen-Processionen against the caterpillar took place, with a huge participation of citizens and farmers. They were always staged with the utmost pomp. In 1739, it was the famous Provost Frayer who made

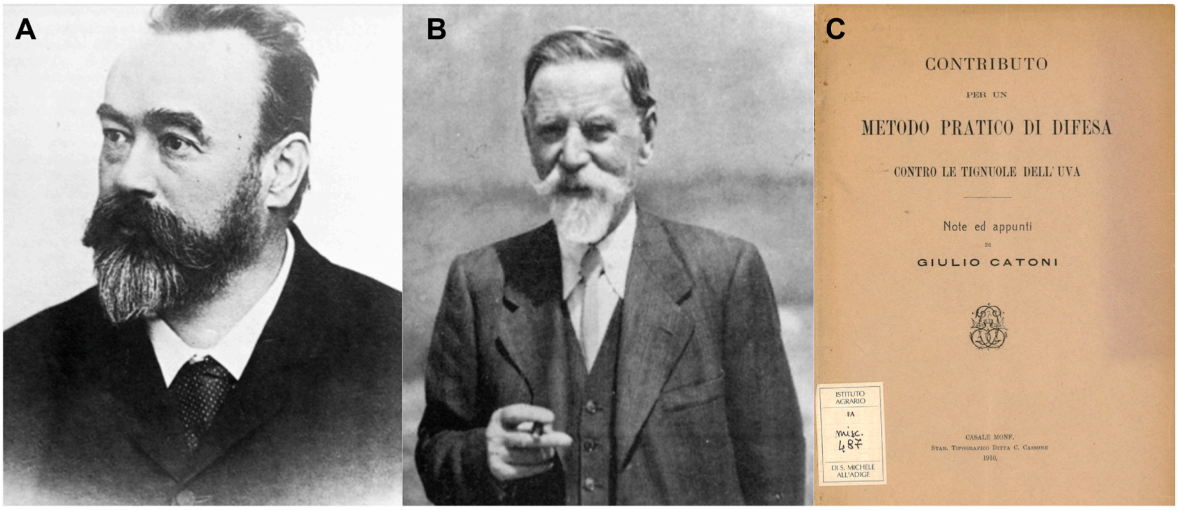

Fig. 2. (A–B) The pioneer research activity of Edmund Mach (Bergamo, 1846 -Vienna, 1901) and Giulio Catoni (Trento, 1869–1950) on moth pests of grapevine represented a milestone in Integrated Pest Management. **(C)** A pioneer study by Giulio Catoni on key moth pests attacking grape in northern Italy; it was published in 1910 (A–C: Archive of the Istituto Agrario San Michele all'Adige).

the great procession to rid the town of grape worm. A Jesuit from Innsbruck took part and sprinkled the vineyards with St Ignatius' holy water. During this procession, four Gospels were read, one at the Holy Sepulchre, one at Reutsch, one at St Ostwald, the last on the banks of the Talfer. In the 1741 procession, a priest from Salorno who lived in the odor of sanctity was called to take part, and he blessed the lustral water with which he himself sprinkled the vines. The procession of 1744 was even more solemn than the previous ones and was crowned with such success that in that year and for many subsequent ones, no damage was caused by the terrible insect" (in Catoni, 1910).

To which species these caterpillars or grape moths belonged is unknown. Vivarelli (1924), describing the grape moth as the '*scourge*' of vines, ascribes the main responsibility to *Cochylis ambiguella* and points out that the first reports of its harmful presence date back to the early 18th century: "*Damages of Cochylis were first reported from the island of Reichenau on Lake Constance from 1711 to 1713, and so heavy was the pest infestation that up to 30 chrysalises were found* per *vine stump"*. Some years later, in 1740, the same species was reported by Charles Bonnet in the vineyards of the canton of Geneva (Switzerland), and in 1771 the abbot Rozier recorded its presence in several French wine-growing areas (Champagne, Burgundy, Lyon, Dauphiné). At the end of that century, Hübner (1796) made a morphological description of the adults (still considered valid today) and gave to that species the name of *Tinea ambiguella*.

During the first half of the 19th century, its presence is reported in Württemberg in Germany, while major devastating invasions affected several wine-growing areas in France (Maĉon, Charriére-Saint-Denis, Bezons, Jonne, Nièvre, Charante) (Vivarelli, 1924). In Italy, the presence and harmfulness of this grape moth pest was confirmed a century later by Lunardoni (1889) who, defining it as the most powerful and widespread enemy of vineyards after phylloxera, stated: " … *This deadly pest first showed to be very harmful to our vineyards only in 1877, and since that time the reports have continued, so much that it can now be said, without fear of error, that it has spread its presence to almost all the wine-growing areas of our peninsula and islands*". According to Lunardoni, *Tortrix ambiguella* had two generations per year in Northern Italy. However, this was not the case in Southern Italy and part of Central Italy. From direct observations carried out in Marino (Rome surroundings), he assumed that most of the second-generation larvae gave rise to a third generation in the fall. Regarding microclimate, while sunny and open vineyards experienced very limited damages by *T. ambiguella*, lowland vineyards, especially those that were humid or close to waterways or irrigated meadows, were the most attacked. Similar observations were later done by Vivarelli, who dated the first report of this species in Italy to 1877 in Piedmont vineyards (Monferrato and Novarese areas), followed by reports of heavy infestations in Tuscany and Lombardy as "… *considerable damage began in 1878-1879 in the plains of Pisa, Florence and in Lombardy*".

Detailed descriptions of the moth presence in Trentino (North-Eastern Italy) also date back to the same period. "*The Tortrix uvana (Cochylis ambiguella) is definitely one of the fiercest enemies of grapevine, and only the appearance of new, devastating enemies such as phylloxera and downy mildew made us forget this unfortunate insect, which, apart from phylloxera, was perhaps the one that has caused the most damage to the vines so far"* (Mach, 1890). This is how Edmund Mach (Fig. 2), the first Director of the Agricultural Institute of San Michele all'Adige (now "Fondazione Edmund Mach"), described the grapevine moth infestations in a report to the Provincial Agricultural Council in Innsbruck in 1890.

At that time, the increased importance of *E. ambiguella* was a fact not only in Trentino, but also in other Italian regions. In the work of Jemina (1891) in Asti as well as in that of Berlese (1894) in Naples, both dedicated to control methods against the grape moths, a reference is mainly made to *Cochylis ambiguella*, while the presence of other species is only passing mentioned.

Considering the bibliographic reports known at the time, Silvestri (1912) confirms the prevalence of *Cochylis*, *'ab antiquo'* at least in the central-northern regions, although he still has doubts on the presence of this species in the Southern regions and Sicily. Therefore, according to these first reports, it seems that, at the time, the prevalent and most feared species was the one now known as *Eupoecilia ambiguella* (Hübner) and by the common Italian name of "*tignola della vite*" (= European grape berry moth). However, a more extensive reading of the literature from that period makes it clear that a change in grape moth populations in Italian vineyards was taking place.

Although limited to certain environments, the other grape moth species, *L. botrana,* to which Silvestri (1912) gave the common, distinctive Italian name of "*tignoletta della vite*" (= European grapevine moth), was also present. The sporadic occurrence of this moth in vineyards of Central-Northern Italy is mentioned in the aforementioned work by Mach: "… *I must also point out that in addition to the common tortrix (Tortrix ambiguella), a second, not dissimilar species must also be found on vines, the Tortrix cruciata (Tortrix botrana) also known as Conchylis religuana. While the caterpillars of the former are flesh-red in color, those of the latter are dirty green …*" (Mach 1890).

The presence of *L. botrana* in Italy was first hypothesized by Dei in 1873 when he noted that he had "*never seen caterpillars and perhaps not* *even butterflies* …“, but, on the basis of the information in his possession concerning repeated infestations attributable to *Conchylis vitisana* (= future *L. botrana*) in vineyards near Vienna, he wondered whether it was not the same insect that had devastated grapes in Trieste and other Italian vineyards in 1868 and 1869.

> At the end of the 19th century, knowledge about what would be called the grape moth was very modest. On this subject, Mach wrote: "… *Even in publications nothing is said, based on observations made, about this species only vaguely* < < *should be* > > *, so this needs further study in any case*".

In his detailed morphological and ecological description of *L. botrana*, Silvestri (1912) attested that it makes three complete generations in Campania (Southern Italy). He also referred to a developing situation and more precisely to an alarming spread of *L. botrana* in many provinces of Southern France (Bordeaux, Alpes Maritimes) and Southern Germany (Bavaria) since the end of the 19th century.

Feytaud (1920) reviewed the extended distribution of *Polychrosis botrana* (= *L. botrana*) in France in the late XIX and early XX century. Although originally the local outbreaks were of minor importance, it has become one of the most serious pests in the vineyards. Wherever *P. botrana* became established, *Clysia ambiguella* apparently disappeared.

Precise information on the presence of the two species in Trentino vineyards and of the ongoing replacement process is provided by the fundamental work of Catoni (1910, 1914). In his studies carried out on the parasitization of overwintering chrysalises of grapevine moths carried out in 1909 on 76,000 cocoons from 8000 vines, he provided a detailed assessment of the situation in a vineyard in the village of Romagnano, in Trento province. In the vineyard under observation, the largely predominant species was *L. botrana*, while *E. ambiguella* was present in insignificant percentages.

Catoni wrote: "*At one time Cochlylis (= Cochylis ambiguella Hübn.) was the only moth prevalent in Trentino, while Eudemis (= Eudemis botrana Schiffm.) was only represented in a very low percentage. In recent years, however, Eudemis has been on the increase, so much that from 76,000 cocoons only 317 Cochylis chrysalis were found, and of these only 94 were alive*".

Based on these unexpected results, Catoni began a more in-depth investigation on the distribution of the two species in the various wine-growing districts of the province, making both first- and second-generation observations. The study began in 1909, continued until 1913 and produced a detailed picture of the presence of the two species. Despite considerable spatio-temporal variability, it was confirmed that the percentage of *L. botrana* pupae never fell below 40% and often exceeded 90% of the total number of collected pupae.

A similar situation emerged from the studies by Voglino (1914) on the distribution and cycle of the two species in the Turin (Piedmont) hillside areas and neighboring wine-growing provinces in 1913–14. According to this author, the two species were coexistent in various vineyards, with one species predominating over the other, depending on the area, although *L. botrana* was considered " … *The most disastrous for the Piedmont wine-growing regions*".

Based on the foregoing, there is reason to believe that, at least in certain wine-growing areas, *L. botrana* had become more widespread and more aggressive than *E. ambiguella* and had gradually replaced it (Dalmasso, 1922).

What caused this reversal in the population ratio between *E. ambiguella* and *L. botrana* is unclear. Catoni, in 1910, having observed a high occurrence of abnormalities and malformations in chrysalides *of E. ambiguella*, hypothesized that the considerable decrease in the population of this species was due to a disease. According to Thiéry (2005), who recalls the similar situation that occurred in France in the early 1900s, the causes are likely to be found in the widespread practice of grafting European vines onto American rootstocks to cope with the phylloxera problem. The vigor and yield of grafted plants, which differed from that of free-standing vines, may have favored *L. botrana* in competing with *E. ambiguella*.

More daring is the hypothesis according to which grafting on American rootstock somehow altered the spectrum of volatiles emitted by the vine, making it more attractive to *L. botrana*, which until then was mainly associated with what is considered its primary host, the spurge flax *Daphne gnidium* L. (Thymelaeaceae). However, this hypothesis would not explain the existence of wine-growing environments that have always been characterized by the absence of *D. gnidium*.

4. Climate change and moth pests of vineyards

Climate change may have played a significant role in favoring one moth species to the detriment of the other. Thermo-hygrometric changes occurred both at the microenvironmental level, because of the aforementioned different vigor of the vines, and as an effect of a generalized rise in temperature and a decrease in relative humidity (Thiéry and Chuche, 2007). The greater climatic aridity would have disadvantaged *E. ambiguella*, the more hygrophilous of the two species, creating the conditions for *L. botrana* to gain the upper hand. Indeed, it is known that the two species have different climatic requirements; *L. botrana* prefers hot and dry areas, while *E. ambiguella* develops better in more temperate and humid zones (Dalmasso, 1922; Stellwag, 1938; Balachowsky, 1966). In Trentino (Northern Italy), this hypothesis would also be confirmed by the fact that, in the last century, the number of generations completed by the two species has risen from two, as reported in detail in Catoni's cited work and confirmed again in 1959 by Zangheri, to three (Zangheri, 1959). Moreover, the start of the second flight of the adults now occurs significantly earlier; it was reported in mid-July at the beginning of the century, changed to the first ten days of July in the 1950s and is now increasingly shifted to late-June (Benelli et al., 2023a).

In favor of the climate change hypothesis, the contents of the exchange of correspondence between some Sicilian vineyard owners and the Director of the Entomological Station of Florence, Targioni Tozzetti, is worthy of note. This exchange of correspondence, collected and published by Grassi Patanè (1876), refers to the infestations of "*an insect that chews and wastes the grapes from the time they bloom until the state of maturity* … *A worm so noxious*" whose appearance in the vineyards of the east coast of Sicily had been noted for many years. The identification of *L. botrana* made by Targioni Tozzetti based on the descriptions he received, turned out to be incorrect since it was *Albina wockiana* [now known as *Cryptoblabes gnidiella* (Millière) (Lepidoptera: Pyralidae Phycitinae)] first described by Briosi (1878) two years later.

Nevertheless, at the beginning of the 20th century *Polychrosis botrana* (= *L. botrana*) was widespread in the regions of Mediterranean Europe and Africa, as well as in Austria-Hungary, Switzerland, southern Germany, and southern and south-western France (Silvestri, 1912). This suggests that in warm and dry climatic context, the moth found the ideal environment to be able to proliferate and prevail over the other species even in northern viticulture when, as hypothesized, there was a general rise in temperature and a decrease in relative humidity.

To this regard are noteworthy the Zangheri (1959) observations on the cycle of the two leafrollers in the Trentino environment. A study he conducted in the late 1950s showed a more rapid development of *L. botrana* in comparison with *E. ambiguella* and therefore, in warmer years, only the former could perform a third annual generation.

The impact of climatic conditions on the biotic potential and competitive ability of *E. ambiguella* seems to be particularly relevant, so much that Solinas (1962) stated that "*abiotic factors play a decidedly greater role than biological factors in the development of the insect*". Again, in the same article "… *Clysiana ambiguella occurs in large numbers in those years in which the climatic trend is characterized by a rather cool and fairly humid spring-summer season; while its presence can be reduced almost to zero in those years with a spring-summer period characterized by high maximum temperatures and low relative humidity in the atmosphere*'.

Some years later, Balachowsky (1966) came to the same conclusion as well, attributing to the changing climatic conditions, and in particular, to the combined effect of "temperature-relative humidity", the cause of the prevalence of one or the other species, considering the assertion that: "*L. botrana would drive out E. ambiguella*" "*without any ecological foundation*". This would suggest that long-term observations, in homogenous environments and with appropriate monitoring means would have made it possible, at least in the regions of northern Italy, to detect a periodic alternation of the two species. The apparent replacement of *E. ambiguella* by *L. botrana* documented between the end of the 19th and the beginning of the 20th century would be nothing more than a phase of these alternation periods due to climatic conditions. In this regard, it is worth to remind that, in the early 1950s, following an average drop in temperatures (Fig. 3) and an increase in relative humidity, there was a resurgence of *E. ambiguella* attacks in those same European wine-growing areas in which the species seemed to have been replaced by *L. botrana* (Zangheri, 1959; Balachowsky, 1966; Lucchi, 2017).

Having said this, we must point out that in reality *E. ambiguella* has never completely disappeared from Trentino vineyards (and from regions with similar climatic conditions in Northern Italy), but its presence has been constantly reported in limited areas characterized by higher humidity. *E. ambiguella* returned to the limelight of the crop protection news when the method of mating disruption began to be applied in Trentino to control *L. botrana* on a territorial scale (Ioriatti et al., 2004). This effective but extremely selective method led to the freeing up of an ecological niche into which *E. ambiguella* gradually became more and more frequent.

5. Managing tortricid pests of grapevine: learning from the past

Before the advent of the modern crop protection science, the means of control available to the winegrower were very limited and required a great deal of labor.

Dei (1873), referring to the proposal of *'lighting fires in vineyards at sunset infested by Cochylis roserana Froelich (Tinea ambiguella Hüb.) so that the moths, attracted by the light, could fly to the fire and burn there"* pointed out its ineffectiveness. Mach (1890) was very skeptical about the efficacy of adult control, whether it involved the use of "*lights made of transparent paper coated on the outside with glue*" to be placed in the vineyards at night, or the use of "*fans coated with sticky material*" with which to catch butterflies flying up, after shaking the vegetation with a stick. Nevertheless, he did apply this practice with the help of schoolchildren, and catching "*until mid-May more than* 6000 moths".

More promising appeared the direct control of the larvae. Dei (1873) believed that the most effective strategy was "*... visiting the vines carefully and periodically and crushing all the caterpillars hidden in the vine leaf and flower clusters*". According to Mach (1890), this was an effective strategy that "*has been practiced since ancient times*", but has the drawback of requiring a great deal of manpower and therefore can only be practiced by a "*small landowner .... By himself and with the help of his children and relatives*", but certainly not by large landowners.

> Greater hopes, about both the efficacy and economy of the operation, are nurtured by Mach himself with regard to the harvesting and destruction of the attacked berries; an operation that is recommended to be carried out in August as it is "*... easy to perform, because it happens at a time when there is no shortage of arms*". As well as reducing the damage to the grapes and improving the quality of the wine obtained, with "*... fewer chrysalises under the bark of the vines ...*".

The control of the moth by destroying overwintering individuals was strongly recommended by Targioni Tozzetti in his correspondence with Grassi Patanè (1876); he suggests a series of preventive practices including torching support poles, cleaning vine trunks, applying boiling water to the trunks or "*boiling steam released from a closed pot with a tube bent in the lid to direct it into the trunks themselves ...* ".

At the end of the 19th century, for the destruction of the chrysalises overwintering on the vines, the use of a special iron-mesh glove (Sabatier glove) or simpler leather gloves was a practice strongly suggested both for its effectiveness and for the fact that it could be carried out at a time when there was ample availability of labour. The failures reported by Mach in the application of this practice are attributed by him to the small size of the plots involved in the operation: "*What good could the destruction of the leafroller done in a small plot of vineyard if the adults can fly to a rather great distance?*" Aware of this, he continues: "*with the application of both methods - harvesting the grapes and destroying the chrysalides - one can certainly achieve a result, there is no doubt about that, but only on one condition, namely that the fight is organised, compact and compulsory for entire plots*". Therefore, he calls for the municipalities to apply, albeit with common sense so as not to "*produce agitation and discontent*", the provisions of the provincial law relating to "*the compulsory protection of crops and soil against caterpillars and other harmful insects*".

We do not know how far these suggestions were followed up and whether they really proved to be effective in controlling moths. What is certain, however, is that this vision of concerted pest control on a territorial scale, anticipates by about a century Rabb's (1978) approach to

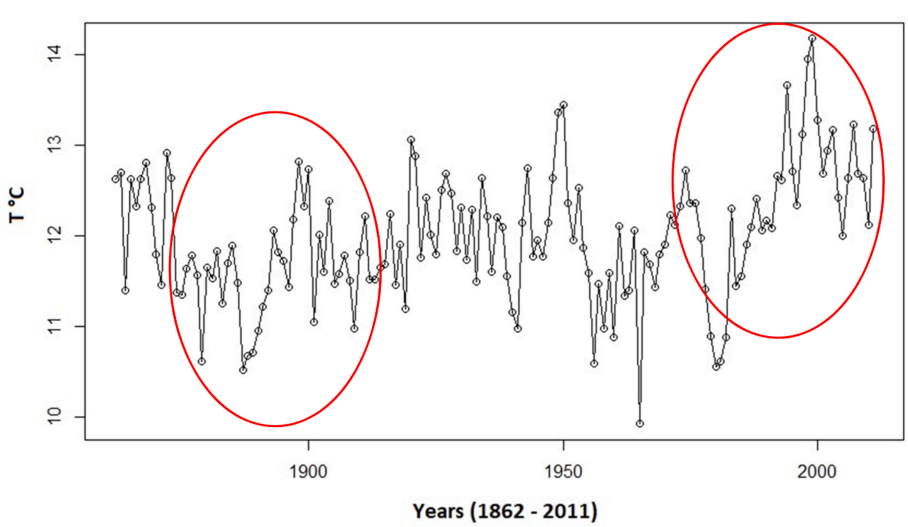

Fig. 3. Yearly average temperature recorded in San Michele all'Adige (Trentino-Alto Adige, Northern Italy) from 1862 to 2011 (data not published, courtesy of Emanuele Eccel). The red circles highlight time frames discussed in the text.

control phytophagous pests over wide areas (Area Wide Pest Management) and finds fulfilment in the current pest control methods based on the territorial application of mating disruption. Catoni (1910) pointed out that little progress had been made in the fight against the vine moths and identified the "*lack of a pest management governed by modern criteria and made compulsory by law*" as the cause of the failure of the albeit valid instruments suggested. "*Fortunately,*" he wrote, "*while our agrarian institutions are distracted by other occupations, and scholars are searching for a radical remedy, … Nature, in its marvelous manifestations, does not forget to come to the aid of the poor winegrower, placing entire armies of small insects at their disposal, with the task of an all-out hunt for the enemies of his crops*". He alludes to the high level of mortality caused by the predation and parasitization of grape vine chrysalides by spiders, insects, and entomopathogenic fungi, which he categorizes and lists in detail in one of his publications (Catoni, 1914). The importance of natural containment had already been pointed out by Lunardoni (1889), who referred to the role of ichneumonid and calcidoid Hymenoptera, although in his opinion "… *Their help will not be sufficiently effective or such as to dispense us from vigorous intervention*". Jemina (1891) counts among the moth natural enemies hymenopteran parasitoids along with insectivorous birds, whose protection he calls for. In addition to what has already been reported by previous authors, Vivarelli (1924) also mentions the relevant role of earwigs, spiders, and some predatory beetles, although he confirms the need for their supplementation with other means of control.

The late 19th century also saw the birth of the modern crop protection science. More and more frequently we find quotations on experiments with treatments mainly based on tobacco extracts, pyrethrum powder, quassio wood infusion, petroleum derivatives, soap, and others, all of which are believed to possess real or presumed insecticidal activity (Jemina, 1891; Dufour, 1893; Berlese, 1894). Vivarelli (1924, taking his cue from unconfirmed observations on the activity of silkworm mashed potato infected with *Botrytis bassiana* (= *Beauveria bassiana*) when sprayed on clusters for the control of *Cochylis ambiguella*, speculates that bacteriology and in general increased knowledge of insect pathogens, may soon provide some microorganism-based tools to act as a potent parasite of the pest for improving the control efficacy.

Without going into a description of the countless preparations proposed, it seems interesting to mention the conditions to which, according to Berlese (1894), the desired insecticide had to respond.

1) It should not be harmful to the operator or those who eat or ingest, the parts of the vine or its transformation, subjected to the treatment.
2) It should be of truly lethal effect on *Cochylis* larvae, and this in such doses as meet the other conditions.
3) It should be completely harmless to the plant (in the doses necessary to kill the insect) even in its most delicate parts, such as the inflorescence and tender shoots.
4) Its price, when used in the above-mentioned doses, should not exceed in expense (included the cost for the application), the profit to be made by saving part of the product.
5) It should be practical, such that every farmer can use it without too much study or difficulty.
6) It should be ready, affordable for everyone at any time and in any measure

In over a hundred years of history, the modern crop protection science has provided us with countless effective solutions for moth control, so much so that we have the illusion that we can do without the help of nature. Only recently, with the worsening problems induced using plant protection products, it has been realized that the Berlese conditions, while still valid, had to be supplemented. The insecticide potential also had to be required to be harmless to beneficial organisms, the importance of which had long been pointed out, but perhaps too quickly forgotten.

At the end of this historical analysis, it seems appropriate to conclude with the words of the winegrower Grassi Patanè, which, although written in 1876, are still very relevant today: "*and now all that remains for me to do is to recommend that we all take the trouble to implement one or other of the proposed remedies, and communicate to each other the effects obtained, the observations made and the studies undertaken. If we work in this way, it will not be difficult, perhaps, that with our cooperation, with the support of the government, which has been promptly demonstrated, and with the invaluable help of the men of science who have been so kindly granted to us, and who will continue to lend us their support, we may one day have the pleasure of seeing our vineyards cleared of this destructive insect, or at least, the sad consequences that it can produce, diminished sufficiently*".

6. The future: developing a research agenda for sustainable IPM in mediterranean areas

The Mediterranean basin is considered one of the main hot spots of global warming (Lionello and Scarascia, 2018; Cos et al., 2022). This phenomenon is already having direct effects on viticulture in the Mediterranean territories, changing the quantity and quality of production and the suitability of the different areas (Santos et al., 2020). In addition to these aspects, it has been pointed out above that temperature is the abiotic factor that most influences insect biology and ecology (Bale et al., 2002). In this review, we have used the case study of Italy, which is representing in 2022 the fourth largest country in the world in terms of cultivated wine-growing area and the biggest producer of wine grapes (Roca, 2022), as a model to analyze the possible influence of climate change on the occurrence and impact of grapevine moths and what will be the next challenges for their sustainable management.

Given the persistence of the rising temperature trend and the intensified arrival of new invasive alien species, it can be expected that the grapevine phytophagous community will undergo further changes in its composition with the gradual replacement of currently predominant species, differently and gradually with respect to the latitude and altitude of the various Italian wine-growing areas. Furthermore, the constant increase in average temperatures is already affecting the biological cycle of the grapevine moths already present in our vineyards, accelerating their developmental phases and consequently causing an increase in the number of annual generations (Reineke and Thiery, 2016). Indeed, field observations in the Mediterranean vineyards report a significant advance in the phenology of *L. botrana* and consequently can display increased moth voltinism with a partial or entire additional generation (Martín-Vertedor et al., 2010; Benelli et al., 2023a).

On the other hand, the impact of climate change may have different effects on the host-plant/pest system, such that the increased number of generations might not be as severe as expected (Caffarra et al., 2012). The multiple interactions among pests, pathogens, and plants in a context of climate change have been simulated by mean of phenological models to demonstrate how may be altered by warmer climate. While damage risk for *V. vinifera* close to the timing of harvests in northern Europe is expected to increase, in southern Europe, increased asynchrony between the larvae-resistant growth stages of grapevines and *L. botrana* larvae, the adverse impact on the reproductive success, as well as the advance in harvest dates and the increased mortality rates of the fourth generation would limit damages of the pest (Caffarra et al., 2012; Gutierrez et al., 2018; Iltis et al., 2020; Reis et al., 2022; Castex et al., 2023).

The role of the new climate scenarios in changing the relevance of different pests is still under debate. Nevertheless, the change of the pest status of some species, usually not considered of phytosanitary importance, is more and more frequent. This is known for the resident species *C. gnidiella*, *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae), as well as for the new invasive alien species that feed on grape berries (*Drosophila suzukii* Matsumura (Diptera: Drosophilidae); *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) (Nieri et al., 2022). However, it could concern also other potentially destructive species for viticulture which are at the risk of invasion, such as *Lycorma delicatula* (White) (Hemiptera: Fulgoridae) from Korea (Song, 2010) or North America

(Harner et al., 2022). In particular, the impact of *C. gnidiella* in Italian vineyards is increasing and in some areas it has become the most damaging grapevine moth (Lucchi et al., 2019). It is a species adapted to distinctly Mediterranean, hot, and arid climates, its range is expanding northwards due to climate change, in a process similar to that described for *L. botrana*.

Furthermore, in addition to the invasive species already mentioned, climate change and globalization are increasing the risk of invasion in Europe of other moths of great viticultural interest and which are key species in grapevine cultivation in other areas of the world, such as *Paralobesia viteana* (Clemens) and *Lasiothyris luminosa* (Razowski & Becker) (Lepidoptera: Tortricidae), respectively from North America (Isaacs et al., 2012) and South America (da Costa-Lima et al., 2021), at least among those already known and monitored. In the event of an invasion, researchers and practitioners will have to be prepared to provide sustainable and environmentally friendly solutions for the control of these moth species. Fortunately, the experiences already made with the other tortricids and the knowledge of the biology and ecology of these species in their native areas has already shown us possible solutions, such as multiple mating disruption and other multimodal approaches (Lucchi and Benelli, 2018; Nieri et al., 2022).

Another aspect to be carefully considered for the future is the impact that climate change may have on the presence and role of natural enemies of grapevine moths, being they microorganisms or other arthropods, and consequently on the biological control strategies to be adopted (Reineke and Thiery, 2016; Benelli et al., 2023b). In this respect, the evidence so far available is conflicting and depends on the individual species and context. Some biocontrol agents may be favored and spread by milder winters and higher average temperatures. At the same time, sudden and catastrophic weather events, which are increasingly common in the current scenario, could adversely affect their populations. In addition, higher temperatures can also impact the insect immune system (Mandriolo, 2012). All these factors will have to be studied with particular attention in the near future.

Another potential change that could affect the future vineyard is the modification of the varietal asset in favor of varieties resistant to the main diseases (downy and powdery mildew) and/or more adapted to global warming. Breeding programs are currently active, tackling the complex issue from different perspectives either using traditional approaches or through new breeding technologies (Bavaresco, 2019; Delrot et al., 2020; Marín et al., 2021; Vezzulli et al., 2022). The new grape varieties are more and more meeting the interest of the wine-consumer who pays great attention to the reduction in agrochemicals and to environmentally friendly production practices (Mian et al., 2023). The expected expansion of the cultivation of this new germplasm could alter the sensory profile perceived by the pest currently infesting vineyards, favoring some to the detriment of others as was hypothesized with the advent of phylloxera-resistant rootstocks. This process involving insect-plant interactions could be a challenge to be managed in retrospect or an opportunity to be considered within grape breeding programs (Salvagnin et al., 2018). In addition, all the species mentioned can contribute to altering the multiple interactions between pests and grapevines. Insects that feed on grape bunches can play an important role in promoting fungal infections, some of which produce toxic secondary metabolites. In the Mediterranean area, *L. botrana* has been reported to be linked to the accumulation and spread of ochratoxin (OTA), a metabolite classified as a possible human carcinogen. Although there is currently no evidence of the involvement of other neither old nor new berry-feeding insects in OTA contamination, considering similar feeding behavior, their potential role in the spread of OTA needs to be investigated (Mondani et al., 2020).

In conclusion, we have seen how grapevine moths are rapidly adapting to the extraordinary environmental changes underway. It can be seen from the present work that researchers and operators in the wine sector will also have to make an equally extraordinary and rapid effort to adapt pest monitoring and control systems to these changes. To achieve this goal, it will be necessary to increase collaboration between institutions and districts to share the practical experiences already faced in places that were gradually subjected to new climatic and biotic conditions (Daane et al., 2018). It remains essential to continue investigating the biology and ecology of these species and the complex multitrophic relationships with host plants and their antagonists, which in turn are rapidly changing, as well as developing effective and sustainable tortricid management methods tailored to warmer Mediterranean agricultural settings (Lucchi and Benelli, 2018).

CRediT authorship contribution statement

Claudio Ioriatti: Conceptualization, Data curation, Writing – original draft. **Gianfranco Anfora:** Conceptualization, Data curation, Visualization, Writing – review & editing. **Bruno Bagnoli:** Conceptualization, Data curation, Visualization, Writing – review & editing. **Giovanni Benelli:** Conceptualization, Data curation, Writing – original draft. **Andrea Lucchi:** Conceptualization, Data curation, Writing – original draft.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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References

Balachowsky, A.S., 1966. Lepidopteres, Entomologie appliquées à l'agriculture. Masson et Cie, Paris, pp. 859–887.

Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., Whittaker, J.B., 2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Global Change Biol. 8 (1), 1–16. https://doi.org/10.1046/j.1365-2486.2002.00451.x.

Bavaresco, L., 2019. Impact of grapevine breeding for disease resistance on the global wine industry. Acta Hortic. 1248, 7–14. https://doi.org/10.17660/ActaHortic.2019.1248.2.

Benelli, G., Lucchi, A., Anfora, G., Bagnoli, B., Botton, M., Campos-Herrera, R., Carlos, C., Daugherty, M.P., Gemeno, C., Harari, A.R., Hoffmann, C., Ioriatti, C., López Plantey, R.J., Reineke, A., Ricciardi, R., Roditakis, E., Simmons, G.S., Tay, W.T., Torres-Vila, L.M., Vontas, J., Thiery, D., 2023a. European grapevine moth, *Lobesia botrana*: part I, Biology and ecology. Entomol. Gen. 43 (2), 261–280. https://doi.org/10.1127/entomologia/2023/1837.

Benelli, G., Lucchi, A., Anfora, G., Bagnoli, B., Botton, M., Campos-Herrera, R., Carlos, C., Daugherty, M.P., Gemeno, C., Harari, A.R., Hoffmann, C., Ioriatti, C., López Plantey, R.J., Reineke, A., Ricciardi, R., Roditakis, E., Simmons, G.S., Tay, W.T., Torres-Vila, L.M., Vontas, J., Thiery, D., 2023b. European grapevine moth, *Lobesia botrana*: part II, Prevention and management. Entomol. Gen. 43 (2), 281–304. https://doi.org/10.1127/entomologia/2023/1947.

Berlese, A., 1894. Le tignuole della vite (*Cochylis ambiguella* Hübn. ed *Eudemis botrana* Schiffm.) e modo di combatterle. Bollettino della Regia Scuola Superiore d'Agricoltura in Portici 17, 1–15.

Briosi, G., 1878. Il Marciume Od Il Bruco Dell'uva *Albinia wockiana* Briosi. Tipografia Artero e Comp., Roma, p. 31.

Caffarra, A., Rinaldi, M., Eccel, E., Rossi, V., Pertot, I., 2012. Modelling the impact of climate change on the interaction between grapevine and its pests and pathogens: European grapevine moth and powdery mildew. Agric. Ecosyst. Environ. 148, 89–101. https://doi.org/10.1016/j.agee.2011.11.017.

Castex, V., de Cortázar-Atauri, I.G., Beniston, M., Moreau, J., Semenov, M., Stoffel, M., Calanca, P., 2023. Exploring future changes in synchrony between grapevine (*Vitis* *vinifera*) and its major insect pest, *Lobesia botrana*. OENO One 57 (1), 161–174. https://doi.org/10.20870/oeno-one.2023.57.1.7250.

Catoni, G., 1910. Contributo per un metodo pratico di difesa contro le tignuole dell'uva. Casale Monferrato: Stabilimento Tipografico ditta C. Cassone, p. 27.

Catoni, G., 1914. Die Traubenwickler (*Polychrosis botrana* Schiff. und *Conchylis ambiguella* Hübn.) und ihre natürlichen Feinde in Südtyrol. Z. Angew. Entomol. 1 (2), 249–258.

Chu, D., Tao, Y.L., Zhang, Y.J., Wan, F.H., Brown, J.K., 2012. Effects of host, temperature and relative humidity on competitive displacement of two invasive *Bemisia tabaci* biotypes [Q and B]. Insect Sci. 19 (5), 595–603.

Corso, M., Bonghi, C., 2014. Grapevine rootstock effects on abiotic stress tollerance. Plant Science Today 1 (3), 108–113.

Cos, J., Doblas–Reyes, F., Jury, M., Marcos, R., Bretonnière, P.A., Samsó, M., 2022. The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. Earth Syst. Dynam. 13, 321–340. https://doi.org/10.5194/esd-13-321-2022.

da Costa-Lima, T.C., de Araújo, A.T.P., Torris, A.F., 2021. Biology and population dynamics of the American vine moth and the potential biocontrol with *Trichogramma pretiosum*. Neotrop. Entomol. 50 (3), 470–475. https://doi.org/10.1007/s13744-021-00850-w.

Daane, K.M., Vincent, C., Isaacs, R., Ioriatti, C., 2018. Entomological opportunities and challenges of sustainable viticulture in a global market. Annu. Rev. Entomol. 63, 193–214. https://doi.org/10.1146/annurev-ento-010715-023547.

Dalmasso, G., 1922. La lotta contro le tignuole dell'uva. Casale Monferrato, p. 86.

Dei, A., 1873. Insetti nocivi alle viti in Italia. Estratto dal Giornale Annali di viticoltura ed enologia italiana. Edizioni F. Anselmi e comp., Milano, pp. 36–40.

Delrot, S., Grimplet, J., Carbonell-Bejerano, P., Schwandner, A., Bert, P.-F., Bavaresco, L., Dalla Costa, L., Gaspero, G., Duchêne, E., Hausmann, L., Malnoy, M., Morgante, M., Ollat, N., Pecile, M., Vezzulli, S., 2020. Genetic and genomic approaches for adaptation of grapevine to climate change. In: Kole, C. (Ed.), Genomic Designing of Climate-Smart Fruit Crops, pp. 157–270. https://doi.org/10.1007/978-3-319-97946-5_7.

Dufour, J., 1893. Destruction du ver de la vigne. Extrait de la chronique agricole di canton Vaud. Imprimerie G. Bridel & C., Lausanne, p. 48.

Feytaud, J., 1920. The spread of *Polychrosis botrana* (*Lobesia botrana*) in France. Le Progres- Agric, et Vitic. 38, 281–284.

Fisher, J.J., Rijal, J.P., Zalom, F.G., 2021. Temperature and humidity interact to influence brown marmorated stink bug (Hemiptera: Pentatomidae), survival. Environ. Entomol. 50 (2), 390–398.

Grassi Patanè, A., 1876. Insetti Nocivi Alle Viti. Tipografia Francesco Castorina, Catania, p. 29.

Gutierrez, A.P., Ponti, L., Gilioli, G., Baumgärtner, J., 2018. Climate warming effects on grape and grapevine moth *(Lobesia botrana*) in the Palearctic region. Agric. For. Entomol. 20 (2), 255–271. https://doi.org/10.1111/afe.12256.

Halsch, C.A., Shapiro, A.M., Fordyce, J.A., Nice, C.C., Thorne, J.H., Waetjen, D.P., Forister, M.L., 2021. Insects and recent climate change. Proc. Natl. Acad. Sci. USA 118 (2), e2002543117. https://doi.org/10.1073/pnas.2002543117.

Harner, A.D., Leach, H.L., Briggs, L., Centinari, M., 2022. Prolonged phloem feeding by the spotted lanternfly, an invasive planthopper, alters resource allocation and inhibits gas exchange in grapevines. Plant Direct 6 (10), e452. https://doi.org/10.1002/pld3.452.

Iltis, C., Louâpre, P., Vogelweith, F., Thiéry, D., Moreau, J., 2021. How to stand the heat? Post-stress nutrition and developmental stage determine insect response to a heat wave. Journal of Insect Physiology 131, 104214.

Iltis, C., Moreau, J., Pecharová, K., Thiéry, D., Louâpre, P., 2020. Reproductive performance of the European grapevine moth *Lobesia botrana* (Tortricidae) is adversely affected by warming scenario. J. Pest. Sci. 93, 679–689. https://doi.org/10.1007/s10340-020-01201-1Iltis, C.

Ioriatti, C., Bagnoli, B., Lucchi, A., Veronelli, V., 2004. Vine moths control by mating disruption in Italy: results and future prospects. Redia 87, 117–128.

Isaacs, R., Teixeira, L.A.F., Jenkins, P.E., Neerdaels, N.B., Loeb, G.M., Saunders, M.C., 2012. Biology and management of grape berry moth in North American vineyard ecosystems. In: Bostanian, N., Vincent, C., Isaacs, R. (Eds.), Arthropod Management in Vineyards. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-4032-7_15.

Jemina, A., 1891. Cochylis e pirale della vite. Relazione al Congresso di Asti. Tipografia L.Roux e C., Torino, p. 34.

Kenis, M., Benelli, G., Biondi, A., Calatayud, P.A., Day, R., Desneux, N., Harrison, R.D., Kriticos, D., Rwomushana, I., van den Berg, J., Verheggen, F., Zhang, Y.J., Agboyi, L. K., Ahissou, R.B., Ba, M.N., Bernal, J., de Freitas, B.A., Carrière, Y., Carvalho, G.A., Chen, X.X., Cicero, L., du Plessis, H., Early, R., Fallet, P., Fiaboe, K.K.M., Firake, D. M., Goergen, G., Groot, A.T., Guedes, R.N.C., Gupta, A., Hu, G., Huang, F.N., Jaber, L.R., Malo, E.A., McCarthy, C.B., Meagher Jr., R.L., Mohamed, S., Mota Sanchez, D., Nagoshi, R.N., Nègre, N., Niassy, S., Ota, N., Nyamukondiwa, C., Omoto, C., Reddy Palli, S., Pavela, R., Ramirez-Romero, R., Rojas, J.C., Subramanian, S., Tabashnik, B.E., Tay, W.T., Virla, E.G., Wang, S., Williams, T., Zang, L.S., Zhang, L., Wu, K., 2023. Invasiveness, Biology, Ecology, and Management of the Fall Armyworm, *Spodoptera frugiperda*. Entomol. Gen. https://10.1127/entomologia/2022/1659.

Lionello, P., Scarascia, L., 2018. The relation between climate change in the Mediterranean region and global warming. Reg. Environ. Change 18, 1481–1493. https://doi.org/10.1007/s10113-018-1290-1.

Lucchi, A., 2017. Note di entomologia viticola. Pisa University Press, pp. 1–223.

Lucchi, A., Benelli, G., 2018. Towards pesticide-free farming? Sharing needs and knowledge promotes Integrated Pest Management. Environ. Sci. Pollut. Res. 25 (14), 13439–13445. https://doi.org/10.1007/s11356-018-1919-0.

Lucchi, A., Ricciardi, R., Benelli, G., Bagnoli, B., 2019. What do we really know on the harmfulness of *Cryptoblabes gnidiella* (Millière) to grapevine? From ecology to pest management. Phytoparasitica 47, 1–15. https://doi.org/10.1007/s12600-018-0705-3.

Lunardoni, A., 1889. Gli insetti nocivi alla vite. Loro vita, danni e modi per combatterli. Tipografia Eredi Botta, Roma, pp. 36–47.

Mach, E., 1890. Misure per combattere la Tortrice. Tipografia G.B. Monauni, Trento, p. 10.

Mandriolo, M., 2012. Someone like it hot? Effects of global warming on insect immunity and microbiota. Invertebr. Surviv. J. 9 (1), 58–63.

Marín, D., Armengol, J., Carbonell-Bejerano, P., Escalona, J.M., Gramaje, D., Hernández-Montes, E., Intrigliolo, D.S., Martínez-Zapater, J.M., Medrano, H., Mirás-Avalos, J. M., Palomares-Rius, J.E., Romero-Azorín, P., Savé, R., Santesteban, L.G., de Herralde, F., 2021. Challenges of viticulture adaptation to global change: tackling the issue from the roots. Aust. J. Grape Wine Res. 27 (1), 8–25. https://doi.org/10.1111/ajgw.12463.

Martín-Vertedor, D., Ferrero-García, J.J., Torres-Vila, L.M., 2010. Global warming affects phenology and voltinism of *Lobesia botrana* in Spain. Agric. For. Entomol. 12 (2), 169–176. https://doi.org/10.1111/j.1461-9563.2009.00465.x.

Mian, G., Nassivera, F., Sillani, S., Iseppi, L., 2023. Grapevine resistant cultivars: a story review and the importance on the related wine consumption inclination. Sustainability 15 (1), 390. https://doi.org/10.3390/su15010390.

Mondani, L., Palumbo, R., Tsitsigiannis, D., Perdikis, D., Mazzoni, E., Battilani, P., 2020. Pest management and ochratoxin A contamination in grapes: a review. Toxins 12 (5), 303. https://doi.org/10.3390/toxins12050303.

Nesje, A., Dahl, S.O., 2003. The 'little ice age' – only temperature? Holocene 13 (1), 139–145.

Nieri, R., Anfora, G., Mazzoni, V., Rossi Stacconi, M.V., 2022. Semiochemicals, semiophysicals and their integration for the development of innovative multi-modal systems for agricultural pests' monitoring and control. Entomol. Gen. 42 (2), 167–183. https://doi.org/10.1127/ENTOMOLOGIA/2021/1236.

Ollat, N., Bordenave, L., Tandonnet, J.P., Boursiquot, J.M., Marguerit, E., 2014. Grapevine rootstocks: origins and perspectives. I International Symposium on Grapevine Roots 1136, 11–22.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. Nat. Cell Biol. 399, 579–583. https://doi.org/10.1038/21181.

Rabb, R.L., 1978. A Sharp focus on insect populations and pest management from a wide-area view. ESA Bull. 24 (1), 55–61.

Reineke, A., Thiery, D., 2016. Grapevine insect pests and their natural enemies in the age of global warming. J. Pest. Sci. 89, 313–328. https://doi.org/10.1007/s10340-016-0761-8.

Reis, S., Martins, J., Gonçalves, F., Carlos, C., Santos, J.A., 2022. European grapevine moth and *Vitis vinifera* L. phenology in the Douro region:(a) synchrony and climate scenarios. Agronomy 12 (1), 98. https://doi.org/10.3390/agronomy12010098.

Roca, P., 2022. State of the World Vine and Wine Sector. OIV Press Conference, International Organization of Vine and Wine. https://doi.org/10.1787/9789264244047-44-en. April 27th 2022.

Roques, A., Rousselet, J., Avcı, M., Avtzis, D., Basso, A., Battisti, A., Ben Jamaa, M., Bensidi, A., Berardi, L., Berretima, W., Branco, M., Chakali, G., Çota, E., Dautbašić, M., Delb, H., El Alaoui El Fels, M., El Mercht, S., El Mokhefi, M., Forster, B., Garcia, J., Georgiev, G., Glavendekić, M., Goussard, F., Halbig, P., Henke, L., Hernańdez, R., Hódar, J., İpekdal, K., Jurc, M., Klimetzek, D., Laparie, M., Larsson, S., Mateus, E., Matošević, D., Meier, F., Mendel, Z., Meurisse, N., Mihajlović, L., Mirchev, P., Nasceski, S., Nussbaumer, C., Paiva, M.-R., Papazova, I., Pino, J., Podlesnik, J., Poirot, J., Protasov, A., Rahim, N., Sańchez Peña, G., Santos, H., Sauvard, D., Schopf, A., Simonato, M., Tsankov, G., Wagenhoff, E., Yart, A., Zamora, R., Zamoum, M., Robinet, C., 2015. Climate warming and past and present distribution of the processionary moths (*Thaumetopoea* spp.) in Europe, Asia Minor and North Africa. In: Roques, A. (Ed.), Processionary Moths and Climate Change: an Update. Springer, Dordrecht, pp. 81–161. https://doi.org/10.1007/978-94-017-9340-7_3.

Roques, A., Kenis, M., Lees, D., Lopez-Vaamonde, C., Rabitsch, W., Rasplus, J. Y., Roy, D. B., 2010. Alien terrestrial arthropods of Europe *BIORISK-Biodiversity and Ecosystem Risk Assessment* 4 (1). special issue.

Salvagnin, U., Malnoy, M., Thöming, G., Tasin, M., Carlin, S., Martens, S., Vrhovsek, U., Angeli, S., Anfora, G., 2018. Adjusting the scent ratio: using genetically modified *Vitis vinifera* plants to manipulate European grapevine moth behaviour. Plant Biotechnol. J. 16, 264–271. https://doi.org/10.1111/pbi.12767.

Santos, J.A., Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Dinis, L.T., Correia, C., Schultz, H.R., 2020. A review of the potential climate change impacts and adaptation options for European viticulture. Appl. Sci. 10 (9), 3092. https://doi.org/10.3390/app10093092.

Silvestri, F., 1912. Contribuzioni alla conoscenza degli insetti dannosi e dei loro simbionti. Bollettino del Laboratorio di Zoologia Generale e Agraria della R. Scuola Superiore d'Agricoltura in Portici 6, pp. 246–307.

Solinas, M., 1962. Studio morfo-biologico sulla *Clysiana ambiguella* Hb. Annali della Facoltà di Agraria di Milano 3, 86–97.

Song, M.K., 2010. Damage by *Lycorma delicatula* and Chemical Control in Vineyards. Agricultural Biology and Applied Entomology. Chunbuk National University, Korea, p. 39.

Stellwag, F., 1938. Untersuchungen zum Ersatz arsenhaltiger Bekämpfungsmittel im Wein-bau. III. Das Verhalten des Traubenwicklers *Clysia ambiguella* bei der Wahl des Winterverpuppungsplatzes und die Möglichkeiten für die Bekämpfung. Ztschr. Pflanzenkrankh. u. Pflanzenschutz 48, 128–144.

Thiery, D., 2005. Vers de la grappe. Les connaître pour s'en protéger. Vigne & Vin Pubblications Internationales, Bordeaux, p. 60.

Thiéry, D., Chuche, J., 2007. Réflexion sur le devenir d'insectes du vignoble dans le contexte d'un réchauffement climatique global. Acte de la 8e Journée Technique du CIVB 13 (3). Bordeaux.

Thiéry, D., Carton, Y., Vidal, C., Gauthier, N., Derridj, S., Vercambre, B., Goebel, F.-R., Grégoire, J.-C., Lieutier, F., 2011. Histoire de l'installation de quelques ravageurs. Interactions Insectes plantes. Quae-ird Publication, pp. 623–673.

Vezzulli, S., Gramaje, D., Tello, J., Gambino, G., Bettinelli, P., Pirrello, C., Schwandner, A., Barba, P., Angelini, E., Anfora, G., 2022. Genomic designing for biotic stress resistant grapevine. In: Genomic Designing for Biotic Stress Resistant Fruit Crops. Springer, Berlin/Heidelberg, Germany, pp. 87–255. https://doi.org/10.1007/978-3-030-91802-6_4.

Vivarelli, L., 1924. Insetti nocivi alla vite. In: Entomologia Agraria Vol I. Casale Monferrato, Fratelli Ottavi, pp. 134–145.

Voglino, P., 1914. Osservazioni sulla biologica delle tignole della vite e sui mezzi di cura. Bollettino del Ministero di Agricoltura Industria e Commercio. Anno XII, serie B, fasc. Luglio-Agosto.

Zangheri, S., 1959. Le "Tignole dell'uva", (*Clysia ambiguella* Hb e *Polychrosis botrana* Shiff.) nel Veneto e nel Trentino. Rivista di Viticoltura e di Enologia di Conegliano 12 (2), 3–39.

Zeni, V., Grassi, A., Santin, M., Ricciardi, R., Pieracci, Y., Flamini, G., Di Giovanni, F., Marmugi, M., Agnolucci, M., Avio, L., Turrini, A., Giovannetti, M., Castiglione, M.R., Ranieri, A., Canale, A., Lucchi, A., Agathokleous, E., Benelli, G., 2022. Leaf UV-B irradiation and mycorrhizal symbionts affect lettuce VOC emissions and defence mechanisms, but not aphid feeding preferences. Insects 14 (1), 20. https://doi.org/10.3390/insects14010020.