Research Progress on Chemical Ecological Management of Three *Tomicus* Species (Coleoptera: Scolytidae) in Yunnan Province of China[1]

Junhui Wang[2,3,7], Weizhong Gao[2,4], Hongzhen Cai[5,7], and Jun Teng[6,7]

Editorial Department of Academic Journals, Shandong University of Technology, Shandong, Zibo 255000, China.

J. Entomol. Sci. 60(2): 192–204 (April 2025)
DOI: 10.18474/JES24-22

Abstract Bark beetles in the genus *Tomicus* (Latreille) (Coleoptera: Scolytidae) are the most destructive pests of pine trees (Pinaceae) in the Yunnan region of China, causing significant damage to shoots and trunks, leading to extensive pine tree mortality. This has had a negative impact on the sustainabilityequally and healthy development of local forestry. Currently, the primary methods of managing *Tomicus* are through the removal of damaged wood and chemical control, which not only requires significant manpower, materials, and financial resources, but also poses a threat to the ecological stability of the environment and has led to the development of resistance to pesticides by the pests. This article introduces an overview of research in the field of chemical ecological management of *Tomicus minor* (Hartig), *T. yunnanensis* Kirkendall & Faccoli, and *T. brevipilosus* (Eggers) in Yunnan Province. This includes summaries of research on informational chemicals, artificial attractants, and volatiles from both host and nonhost plants. The aim of this review is to provide a comprehensive overview of chemical ecological management methods for these beetles, thus assisting researchers and research institutions in their efforts to provide for sustainability of our environmental resources.

Key Words Yunnan region, *Tomicus*, chemical ecology, control, management

Tomicus minor (Hartig), *T. yunnanensis* Kirkendall & Faccoli, and *T. brevipilosus* (Eggers) (Coleoptera: Scolytidae) have been the most destructive pests of pines (e.g., *Pinus yunnanensis* Franch, *P. massoniana* Lambert, and *P. kesiya* Royle ex Gordon) in Yunnan Province, China over 3 decades (Kirkendall et al. 2008, Langstrom 1983, Langstrom et al. 1990, Langstrom and Hellqvist 1993, Li et al. 2006, Wang et al. 2006, Wood 1982, Ye 2011, Yue and Yang 2011a, Zhao

[1]Received 24 February 2024; accepted for publication 7 April 2024.
[2]These authors contributed equally to this work.
[3]Editorial Department of Academic Journals, Shandong University of Technology, Shandong, Zibo 255000, China.
[4]School of Management, Shandong University of Technology, Shandong, Zibo 255000, China.
[5]Present address: Shandong University of Technology, No. 266 West Xincun Road, Zhangdian District, Zibo City, Shandong Province, China.
[6]Shandong Dacheng Agrochemical Company Limited, No. 222 Changguo Road, Zhangdian District, Zibo City, Shandong Province, China.
[7]Co-corresponding authors (email: lingnanmuzhe2008@163.com; zixiwang0927@163.com; 13705338025@163.com).

et al. 2003). These pests primarily attack the shoots of healthy pine trees, leading to a reduction in chlorophyll, carotenoid content, net photosynthesis, and transpiration. This attack weakens the tree's vigor and reduces its resistance during the shoot-feeding stage (Byers 1992, Duan et al. 2004, Hu et al. 2009, Langstrom et al. 2002, Liu et al. 2019, Ye 1992, Ye and Lieutier 1997). During the trunk-breeding stage, they primarily damage the phloem of weaker pine plants, ultimately leading to the death of the host plant (Lv et al. 2010, Tong et al. 2009, Ye and Dang 1986, Ye and Li 1994, Ye et al. 2004). Serious damage by *Tomicus* has affected the sustainable development of local forestry and caused huge economic losses.

Management practices such as silviculture, cutting down damaged trees, and chemical pesticide control are widely used to manage these pests (Braquehais 1973, El-Sayed et al. 2006, Gitau et al. 2013, Hansen et al. 2006, Lu et al. 2000, Schiebe et al. 2011). Although the bark beetle cleanup method is straightforward, mastering the technical standards for cleanup can be challenging (Chen et al. 2005), and improper handling can facilitate the spread of bark beetles, leading to significant resource consumption in terms of manpower, material resources, and financial resources. Although chemical control can effectively curb beetle damage in a short time, it can easily pollute the environment and repeated use can lead to pest resistance.

Chemecology is the study of chemical information, connections, and mechanisms of action between organisms to reveal the chemical essence of their connections in nature (Yan 2011). Insect chemical ecology focuses on insects as the research object, exploring the chemical connections between insects and other organisms, insects and plants, and insects and their environment. This domain mainly encompasses insect pheromones, the sources and functions of information substances, the interrelationships between insects and plants, and chemical sensing mechanisms (Hao 2018, Yan et al. 2013). Applying chemical ecology methods to prevent and control bark beetle damage is not only simple and effective but also saves manpower, material resources, and financial resources, making it environmentally compatible. Furthermore, because of the small size and strong concealment of bark beetles, the control effect is better and more sustainable. This article provides an overview of recent research on the chemical and ecological management of bark beetles in Yunnan Province in Southwest China. It not only offers effective methods for local bark beetle control but also provides effective references for their control in other regions, promoting the development of related research.

Semiochemicals

All organisms produce chemical signals, and all organisms respond to these signals. The chemicals involved in biological communication are collectively referred to as informational chemicals (Wang and Yan 2023). The category of semiochemicals is further divided into two major groups: pheromones and allelochemicals, depending on whether the interaction is within a species or between species, respectively (Nordlundd and Lewis 1976). Insect pheromones are extremely small amounts of chemical substances secreted and released by insects to regulate population behavior and development. These pheromones are typically categorized as sex pheromones or aggregation pheromones (Jiang et al. 2002, Pitman et al. 1975, Vite et al. 1972, Vite and Pitman 1969, Yan 2006, Yan et al. 2014). Sex pheromones of

Tomicus are chemical substances produced by individuals of a specific gender, detected by receptors in both same- and opposite-sex individuals, and trigger reproductive behaviors like mate seeking and mating. These pheromones are emitted from the hindgut of *Tomicus* and facilitate interactions between individuals. The limited amount of sex pheromones released by *Tomicus*, whether in natural or controlled settings, hinders research progress on these compounds. Additionally, aggregation pheromones released by *Tomicus* within their bodies induce aggregation behavior in individuals of the same species, contributing to the damage caused by beetles in the Yunnan region.

The pheromones secreted by bark beetles regulate their aggregation and harmful behavior (Byers 1989, Byers et al. 1985, Poland et al. 2003). The attraction of *Tomicus* to ethanol was weaker compared with its attraction to a monoterpene mix, (±)-α-pinene, (+)-3-carene, terpinolene. However, a combination of (−)-(*S*)-α-pinene, (+)-(*R*)-α-pinene, (+)-3-carene, and terpinolene, or each alone, was effective in attracting *Tomicus* (Byers 1992). Pinene is not only a volatile compound found in pine trees but also a crucial component of aggregation pheromones in bark beetles. Alongside carene, limonene also plays a significant role in aggregation pheromones.

Verbenol, myrtenal, and myrtenol were detected in the hindguts of male and female adults of *T. yunnanensis*, whereas verbenone was only detected in female adults (Yan et al. 2009, Zhou et al. 1997). During the shoot-feeding stage, β-pinene, *trans*-verbenol, and myrtenol exhibited strong attraction to *T. minor* and *T. brevipilosus*. Additionally, myrtenol was found to have attractive effects on *T. yunnanensis*. During the trunk-breeding phase, α-pinene, 3-carene, *trans*-verbenol, and myrtenol were strongly attractive to *T. minor*. Furthermore, α-pinene, β-pinene, *trans*-verbenol, *cis*-verbenol, and myrtenol were strongly attractive to *T. yunnanensis*. Last, α-pinene, β-pinene, myrcene, 3-carene, *trans*-verbenol, *cis*-verbenol, and myrtenol were strongly attractive to *T. brevipilosus* (Wang 2015). Additional studies have confirmed this conclusion, demonstrating that the effect of verbenol is dose dependent and that verbenone has repellent activity against *Tomicus*. The hindguts of female and male *T. minor* and *T. yunnanensis* adults contained the following amounts of the compounds: 0.19, 0.09, 0.22, and 0.05 ng/individual of (−)-*trans*-verbenol; 0.16, 0.06, 0.03, and 0.05 ng/individual of verbenone; and the most attractive levels of *cis*-verbenol and (−)-*trans*-verbenol for *T. yunnanensis* and *T. minor* were 0.1 and 1.0 ng/μl, respectively. Verbenone was not attractive at any concentration, and its addition to *cis*-verbenol or (−)-*trans*-verbenol reduced the attraction response. Therefore, it can be concluded that (−)-*trans*-verbenol produced by these two pine shoot beetles is attractive at low concentrations and repellent at high concentrations (Wu et al. 2019). Additional research results have confirmed this. During the initial phase, researchers collected volatiles from the hindgut of the beetles in the laboratory. Through detection, analysis, and field trapping experiments, it was determined that verbenol and myrcenol are likely the primary components of the sex pheromones of *Tomicus*.

In recent years, research has clarified the effects of verbenol and verbenone on the control of *Tomicus*. The hindguts of female and male *T. minor* and *T. yunnanensis* adults contained (−)-*trans*-verbenol, and this level increased to 16.74–292.71 ng/individual in *T. minor* females after interactions with other beetles. The levels of *cis*-verbenol and (−)-*trans*-verbenol were most attractive to *T. yunnanensis* and *T. minor* when the content was 0.1 and 1.0 ng/μl, respectively. Verbenone was not attractive at any concentration to these two beetles, but it had a repellent effect when added to verbenol. The research suggests that the presence of aggregation pheromone (−)-*trans*-verbenol in the hindgut of *T. yunnanensis* regulates population behavior (Wu 2019). However, the use of verbenone as an inhibitor to control *Tomicus* damage has not been satisfactory (Frühbrodt et al. 2024). *Tomicus* are small, and the amounts of verbenalenol and verbenalenone detected in their hindgut volatiles are also very small. During the field trapping experiment, the artificial attractant configured according to the test results needs to be continuously adjusted according to the trapping results. This is also one of the reasons why research on the application of artificial attractants in the field to control beetles has been relatively slow. Compared with verbenalenol, verbenalenone has a stronger attracting effect on *Tomicus*.

During the gallery initiation stage, the hindgut extracts of beetles not only contained higher amounts of myrtenol, *cis*-verbenol, *trans*-verbenol, and verbenone, but also exhibited candidate aggregation pheromone compounds in the form of myrtenol and *trans*-verbenol. Furthermore, a blend of these two components with *S*-(−)-α-pinene and *S*-(−)-β-pinene was found to attract more *T. brevipilosus* individuals in a field bioassay (Liu et al. 2019). Therefore, on the basis of previous research results, it can be inferred that verbenol, myrtenol, and pinene are the main pheromone chemical components of *Tomicus*. This provides great support for the future deployment of artificial attractants. These can be combined with indoor bioassays and, through the results of field trapping experiments, used to develop more effective artificial attractants to prevent and manage the damage of bark beetles.

Artificial Attractants

In recent years, researchers have made progress in enhancing the effectiveness of artificial attractants for bark beetles by collecting field samples, conducting indoor chemical composition analysis, and integrating biological measurements. Despite these advancements, the low levels of semiochemicals in bark beetles pose challenges for detection. The composition remains incompletely understood, leading to limited effectiveness of current artificial attractants.

The bioassay results using the blend of *V*(α-pinene):*V*(β-pinene):*V*(β-phellandrene):*V*(γ-careen) = 20.6:4.7:6.6:1 demonstrated a significant attraction effect on *T. yunnanensis*. However, when tested with individual components, or blends of α-pinene and terpinolene or α-terpinen and γ-careen, no significant attraction was observed (Yin et al. 2002). This shows that, in many information chemical species, not one component works alone, but a variety of chemicals works together. It was further found in the bioassay that the attraction rate of α-pinene, γ-careen, and *trans*-verbenol exceeded 95%, whereas *cis*-verbenol only achieved an 83.4% rate. Additionally, a forest-based bioassay revealed that α-pinene and *trans*-verbenol had superior attraction to *T. yunnanensis* compared with other compounds (Li et al. 1993). The test result is consistent with the previous ones, indicating that α-pinene and *trans*-verbenol attract the beetles, but there should be other unknown chemical substances. Although the content of these substances should not be substantial, they also play an important role, and research on the detection and identification of related substances should be increased in the future. Studies have shown that artificial attractants 1-6 were developed through bioassays to identify the main components as monoterpenes and monoterpenols (Wang 2015). The results showed artificial attractants 1-4 effectively attracted *T. minor* and *T. yunnanensis* in field trapping experiments; however, attractants 5 and 6 trapped only a few *T. brevipilosus* individuals, and the effect was not satisfactory (Wang 2015). The study results reveal that *T. minor*, *T. yunnanensis*, and *T. brevipilosus* are found in the Yunnan region. Although the primary components of artificial attractants are monoterpenes and monoterpenols, their efficacy in attracting the three species of beetles varies. Therefore, it is essential to explore and create distinct types of artificial attractants tailored to the species of *Tomicus*.

The attractant *trans*-verbenol was mixed with α-pinene in a volume ratio of 1:20 to test its attraction on *Tomicus* in the forest. The average number of adults captured by each trap was 96.33 (Zhou et al. 1997). When using the artificial attractants formulated with *S*-α-pinene, myrcene, *R*-α-pinene, *trans*-verbenol, *cis*-verbenol, and myrtenol, the highest number of *T. yunnanensis* was captured in the forest. Additionally, the average insect infestation rate in the forest decreased from 65.25% to 26.88% (Zuo and Huang 2018). In Xiangyun County, Yunnan Province, artificial attractants were prepared using 10 ml of α-pinene, 1 ml of 3-carene, 1 ml of myrtenol, 0.1 ml of ipsenol, and 0.1 ml of verbenol. Forty-five artificial traps were used to trap *T. minor*, and a maximum of 486 individuals was caught in 5 d (Fang et al. 2019). Myrtenol and *trans*-verbenol were identified as candidate aggregation pheromone compounds. Furthermore, a blend of these two components with *S*-(−)-α-pinene and *S*-(−)-β-pinene attracted a greater number of *T. brevipilosus* individuals in a field bioassay. However, there was no significant difference in the number of traps captured by the two attractants (Liu et al. 2019). These research results further demonstrate that, in addition to the predominant chemical components like verbenol, myrtenol, and pinene, there are also myrcene, carene, ipsenol, and other compounds that exhibit significant effects on bark beetles. Ongoing research on artificial attractants is in progress, with a focus on enhancing the ratio of each component and exploring unknown chemical compounds to develop increasingly effective attractants in the future.

Insects commonly utilize multicomponent informational chemicals for intraspecific chemical communication, rather than relying on single compounds alone (Zhao and Zhang 1993). Despite the increasing application of attractants in insect management in recent years, the regulatory effect of a single compound on insect behavior remains limited (Wang and Yan 2023). The chemical components that effectively trap bark beetles for control should be a combination of multiple compounds, rather than a single substance. Further research is needed to determine the optimal ratio of these different components, presenting a key scientific challenge that must be addressed urgently in the chemical ecological management by trapping *Tomicus*.

Host Plant Volatiles

The three species of bark beetles damage host plants at different times, which may be related to the different attracting effects of the host plant's volatiles on the beetles. *Tomicus brevipilosus* breeding attacks in *P. yunnanensis* generally start in early March and end in early June in Anning County, Yunnan. From early March to mid-April, *T. brevipilosus* bred preferentially in the trunks of Yunnan pine trees that were already infested by *T. yunnanensis* and *T. minor*; from about mid-April to early June, when there were no Yunnan pine trees newly infested by *T. yunnanensis* and *T. minor*, *T. brevipilosus* attacked Yunnan pine by itself (Chen et al. 2015). The behavior of the three species should be influenced by the volatilization of the host plant and volatiles of other bark beetles. The application of volatile emissions from host plants in trapping and killing bark beetles has a certain impact on their prevention and control (Wang and Zhang 2019). The aggregation of bark beetles is primarily influenced by the volatile emissions of the host plant, as the volatiles in the phloem of *P. yunnanensis* encourage beetle aggregation. Additionally, trap log bundles are attractive to beetles, and untreated bundles are heavily attacked; verbenone, either alone or in combination with nonhost volatiles (three green leaf C_6 alcohols and one bark C_8 alcohol), significantly reduces attacks on the bundles (Sun et al. 2005). Notably, monoterpenes emitted by pines serve as signaling substances for *Tomicus* host location, and they are a significant component of pheromones produced by certain bark beetles (Yan 2006). The volatiles of the host plant have an attracting effect on the beetles that harms the host first, and the volatiles of this beetle may have an attracting or repelling effect on other beetles. They attract other beetles to harm the host; on the other hand, they avoid them to prevent overpopulation.

The trap log bundles proved to be highly attractive to beetles, with untreated bundles experiencing heavy infestation (Sun et al. 2005). *Tomicus yunnanensis* exhibited a strong attraction response to both *P. yunnanensis* needle and branch material, with a more significant response observed toward branches from which the needles had been removed. α-Pinene, the primary volatile emitted by *P. yunnanensis*, is believed to be the key chemical attractant for *T. yunnanensis*. When exposed to α-pinene, the female adults of *T. yunnanensis* exhibited an increase in both the length of the main tunnel and larval tunnel, indicating that α-pinene serves as a feeding stimulus factor that promotes feeding behavior and leads to an increase in the body length and weight of larvae (Liu 2019).

Tomicus minor, *T. yunnanensis*, and *T. brevipilosus* were found to be attracted to shoot extracts and dynamic headspace volatiles from shoots damaged by the same species and sex. Furthermore, female *T. minor* and male *T. yunnanensis* demonstrated attraction to dynamic headspace volatiles from shoots damaged by both sexes of *T. brevipilosus*. These results suggest that specific semiochemicals induced or produced by *T. brevipilosus* also attract *T. minor* and *T. yunnanensis* (Wang et al. 2015). When the trunks of *P. yunnanensis* are damaged by *T. yunnanensis*, the amount of α-pinene in the phloem decreases, whereas myrcene and 3-carene increase. This promotes the release of terpinolene and 4-allylanisole from Yunnan pine. Healthy pine trees typically contain a higher concentration of 4-allylanisole, which generally inhibits the attraction of host volatiles to beetles, compared with damaged pine trees (Joseph et al. 2001, Nebeker et al. 1995).

Gas chromatography–mass spectrometry (GC-MS) and gas chromatography–electroantennographic detection (GC-EAD) methods can effectively detect semiochemicals that attract and repel bark beetles. To investigate the pine volatiles produced by *P. yunnanensis* infested by *T. yunnanensis*, dynamic headspace and solvent extraction techniques were utilized. GC-MS coupled with GC-EAD and bioassays were conducted to identify the biologically active compounds that attracted *T. yunnanensis* to host pine. The results revealed that pine volatiles from the needles and resins of *P. yunnanensis* consisted of 18 terpenes, and their chemical profiles varied significantly between needles and resins. Mass fraction of needle volatile compounds was primarily monoterpenes (99.98%), with α-pinene (90.82%) being the most abundant, followed by β-pinene (8.78%), D-limonene (4.77%), camphene (2.86%), and β-myrcene (1.42%). In contrast, resin volatiles contained both monoterpenes and diterpenes, with α-pinene (21.38%) being the most prevalent monoterpene, followed by 3-carene (21.42%) and terpinolene (2.78%). The diterpenes present in resin were primarily highly oxidized, with palustric acid accounting for 51.13% of the relative abundance. Electroantennographic responses of *T. yunnanensis* indicated strong attraction to α-pinene, β-pinene, 3-carene, γ-terpinene, and 4-allylanisole. Behavioral choice experiments further demonstrated that α-pinene, γ-terpinene, and 3-carene significantly enhanced the attraction of *T. yunnanensis*, whereas β-pinene and 4-allylanisole displayed repellent effects (Yan et al. 2021). Using GC-MS, the volatile compositions of the phloem from healthy and previously attacked *T. yunnanensis* trees were analyzed. The attraction of these two types of trees to *T. yunnanensis* was determined through trap log experiments. The results showed that the attraction of logs from previously attacked trees was significantly higher than that of healthy trees at the same time. The content of the main volatile components differed significantly between the two types of trees. The phloem of attacked *P. yunnanensis* had higher levels of α-pinene, camphene, β-thujene, and β-ocimene compared with healthy *P. yunnanensis*. Conversely, the levels of β-pinene, β-phellandrene, and myrcene were lower in the attacked trees. The differences in volatile components between healthy and previously attacked pine trees are one of the key factors that influence their attraction to pine shoot beetles (Zhao et al. 2002). The GC-MS analysis of volatiles released from the trunks and branches of *P. yunnanensis* revealed significant differences between the two types of volatile components. The main component in trunk volatiles was α-pinene, accounting for 81.01% of the total. In shoot volatiles, the main components were α-pinene and β-phellandrene, with percentages of 29.20% and 30.52%, respectively. When compared with shoot volatiles, trunk volatiles had higher levels of α-pinene and 3-carene, whereas shoot volatiles had higher levels of camphene, sabinene, limonene, β-phellandrene, terpinolene, and caryophyllene than trunk volatiles. *Tomicus yunnanensis* displayed a positive response to the extract of shoots of *P. yunnanensis*, but a repellent response to the extract of trunks (Yan et al. 2011).

Nonhost Plant Volatiles

The utilization of nonhost plant volatiles primarily serves as a repellent against *Tomicus*. Currently, common nonhost plants include *Cupressus torulosa* D. Don ex Lambert, *Cinnamomum camphora* (L.) J. Presli, *Cyclobalanopsis glaucoides* Schottky, *Alnus ferdinandi-coburgii* C.K. Schneider, and *A. nepalensis* D. Don.

Control effects can be achieved by extracting these volatile compounds into biological agents or through intercropping forests and other methods.

The shoots of *P. yunnanensis* were mixed with those of *C. torulosa*, *Ci. camphora*, and *Cy. glaucoides*, either as single trees, strips, rows, or as groups. The results showed that the single tree mixing method had the greatest effect on the olfactory behavior of *T. yunnanensis*, followed by the row mixing model. The strip and group mixing methods had lesser effects (Yue and Yang 2011a). When essential oil from two nonhost plants (*C. torulosa* and *Cy. glaucoides*) was sprayed on the shoots of *P. yunnanensis* using single tree, strip, row, and group methods, the total number of *T. yunnanensis* on the shoots was lowest and the average was lowest with the single tree method, followed by the row, strip, and group methods. This indicated that nonhost plants disrupted the odor characteristics of the original host plants, making it difficult for *T. yunnanensis* to recognize the host, thereby achieving the goal of protecting the target tree species (Yue et al. 2013). The pine needles of *P. yunnanensis* were mixed with leaves of *C. torulosa*, *Ci. camphora*, and *Cy. glaucoides* in various ratios, including (in grams) 0:6, 1:5, 2:4, 3:3, 4:2, 5:1, and 6:0. These mixtures were placed in the response arm of a Y-tube olfactometer as the odor source to observe the olfactory behavior of *T. yunnanensis*. The impact of nonhost plants on olfactory responses of *T. yunnanensis* was minimal. As the proportion of nonhost leaves gradually increased, the inducement rate of leaf mixtures on *T. yunnanensis* gradually decreased (Yue and Yang 2011b).

Pinus armandii Franch, *Celtis kunmingensis* C.C. Cheng & D.Y. Hong, *C. torulosa*, and *A. ferdinandi-coburgii* all had an impact on the host search of *T. yunnanensis*, with *A. ferdinandi-coburgii* exhibiting the most significant effect. This species, including its volatile compounds 4-ethylacetophenone, *trans*-2-hexen-1-ol, (*Z*)-hexen-4-en-1-ol, and 4-ethylacetophenone, significantly interfered with the post-embryonic development of *T. yunnanensis*. In particular, the two green leaf volatiles, *trans*-2-hexen-1-ol and (*Z*)-hexen-4-en-1-ol, directly reduced the body size and weight of pupae and newly emerged adults (Qian et al. 2023). The β-pinene, *trans*-2-hexen-1-ol, (*Z*)-hexen-4-en-1-ol, 4-ethylacetophenone, and 4-ethylacetophenone of *A. ferdinandi-coburgii* exhibited significant repellent action against *T. yunnanensis*. Among them, 4-ethylacetophenone exhibited the most effective repellent action (Liu 2019).

As nonhost plants for *T. yunnanensis*, *Ce. kunmingensis* and *A. nepalensis* have the potential to interfere with its infestation of *P. yunnanensis*. Forest surveys have also observed relatively low populations of *T. yunnanensis* in mixed forests in Yunnan Province (Yue and Yang 2011a). The leaves of *Ce. kunmingensis* and *A. nepalensis* emit volatile compounds such as 2-hexenal, 2-hexenol, and 3-hexenol, which can significantly reduce the olfactory behavior and fecundity of *T. yunnanensis* (D. Wang et al. 2013, 2015). Laboratory olfactory tests using a Y-tube olfactometer showed that the volatiles of *P. yunnanensis* have an attractive effect on *T. yunnanensis*, whereas the volatiles of *A. nepalensis* have a repellent effect (Wang et al. 2016). Nonhost volatiles from *Ce. kunmingensis* and *A. nepalensis* can also reduce egg production in *T. yunnanensis* by regulating the expression of its vitellogenin and vitellogenin receptor genes (Wang et al. 2023). These nonhost plants also decrease the fecundity of *T. yunnanensis* by reducing the transcription levels of vitellogenin and vitellogenin receptor genes in its leaves (Zhao 2015).

It was concluded that *C. torulosa*, *Michelia alba* Figlar, *Ce. kunmingensis*, and *A. nepalensis* possess promising taxis effects on *T. yunnanensis*, making them suitable candidates for mixed planting in *P. yunnanensis* plantations (Zhou et al. 2012). The repellent activity of essential oils from various plants, including *Mentha canadensis* L., *Artemisia carvifolia* Besser, *Perilla frutescens* (L.) Britton, *Eucalyptus globulus* Labillardiere, *Ci. camphora*, *Citrus reticulata* Blanco, *Agastache rugosa* Fischer & von Meyer) Kuntze, and *Acorus gramineus* Alton, was evaluated. The bioassay results indicated that the essential oil from *Me. canadensis* exhibited the strongest repellent activity and the longest repellent duration. When diluted with acetone at ratios of 10, 40, and 160 times, the repellent rates against adult *T. yunnanensis* were 100, 100, and 96.55%, respectively. However, when diluted at a ratio of 320 times, the repellent rate decreased to 54.57% (Yang et al. 2003).

Volatiles from nonhost plants are used to prevent bark beetle host location behavior. In laboratory analysis of the chemical composition of volatiles collected from nonhost plants, combined with the bioassay results, we see that it is helpful to plant nonhost plants to prevent and control the damage caused by the beetles. Y-tube olfactometer bioassays revealed that the host location behavior of *T. yunnanensis* was significantly repelled by the three most abundant green leaf volatiles: (*E*)-2-hexenal, (*E*)-2-hexenol, and (*Z*)-3-hexen-1-ol, which are emitted by nonhost trees. Furthermore, these green leaf volatiles have a negative impact on the feeding behavior of *T. yunnanensis* in the field, ultimately reducing damage to Yunnan pines (D. Wang et al. 2015). Verbenone, either alone or in combination with nonhost volatiles (three green leaf C_6 alcohols and one bark C_8 alcohol), significantly reduced attacks on the bundles. However, the nonhost volatiles alone did not inhibit attacks (Sun et al. 2005).

Prospects

Research on chemical and ecological management of *Tomicus* in Yunnan Province is continuously delving into the potential of new chemical components and artificial attractants to gradually improve ecological and environmental protection. This may offer a green and sustainable management method for effectively preventing and controlling the harm caused by bark beetles. The research on chemical and ecological management of *Tomicus* in Yunnan Province is also helping to avoid the human, material, and financial resources required for cleaning up damaged trees, chemical control of environmental pollution, and the development of pest resistance. In future research, chemical ecology research methods will be further developed and improved, artificial attractant technology will continue to mature, and the trapping effect will gradually improve. This also provides an effective reference for the management of *Tomicus* and other pests in other regions.

Acknowledgments

The authors thank Zhang Zhen, Wang Hongxun, Jia Liping, and Yang Yunbo for their assistance during the work, in addition to the Forest Pest Control Stations of Yuxi City. We thank the Foundation for the University–Industry Collaborative Education Program (230804092051354) for the support of the research.

References Cited

Braquehais, F. 1973. Trap-trees as an integral part of the control of beetle pests. Bol. Estacion Central Ecol. 2: 65–70.

Byers, J.A. 1989. Chemical ecology of bark beetle. Experientia 45: 271–283.

Byers, J.A. 1992. Attraction of bark beetles, *Tomicus piniperda*, *Hylurgops palliatus*, and *Trypodendron domesticum* and other insects to short-chain alcohols and monoterpenes. J. Chem. Ecol. 18: 2385–2402.

Byers, J.A., B.S. Lanne, J. Lofqvist, F. Schlyter and G. Bergstrom. 1985. Olfactory recognition of host-tree susceptibility by pine shoot beetles. Naturwissenschaften 72: 324–326.

Chen, P., J. Lu, R.A. Haack and H. Ye. 2015. Attack pattern and reproductive ecology of *Tomicus brevipilosus* (Coleoptera: Curculionidae) on *Pinus yunnanensis* in Southwestern China. J. Insect Sci. 15: 43.

Chen, P., N. Zhou, T. Zhao, L. Li, H. Li, S. Ze and H. Liu. 2005. Cleaning technical standards and controlling methods for *Tomicus* damaged woods in *Pinus yunnanensis*. Pract. For. Tech. 10: 29–30.

Duan, Y., C. Kerdelhue, H. Ye and F. Lieutier. 2004. Genetic study of the forest pest *Tomicus piniperda* (Col., Scolytinae) in Yunnan province (China) compared to Europe: New insights for the systematics and evolution of the genus *Tomicus*. Heredity 93: 416–422.

El-Sayed, A.M., D.M. Suckling, C.H. Wearing and J.A. Byers. 2006. Potential of mass trapping for long-term pest management and eradication of invasive species. J. Econ. Entomol. 99: 1550–1564.

Fang, J., C. Wu, W. Lu, F. Liu, S. Zhang, Z. Zhang and X. Kong. 2019. Correlation analysis between the shoot damages and trap catches of *Tomicus minor* in the *Pinus yunnanensis* forest. Sci. Silvae. Sin. 55: 129–135.

Frühbrodt, T., M. Schebeck, M.N. Andersson, G. Holighaus, J. Kreuzwieser, T. Burzlaff, H. Delb and P. H.W. Biedermann. 2024. Verbenone—The universal bark beetle repellent? Its origin, effects, and ecological roles. J. Pest. Sci. 97: 35–71.

Gitau, C.W., R. Bashford, A.J. Carnegie and G.M. Gurr. 2013. A review of semiochemicals associated with bark beetle (Coleoptera: Curculionidae:Scolytinae) pests of coniferous trees: A focus on beetle interactions with other pests and their associates. For. Ecol. Manag. 297: 1–14.

Hansen, E.M., B.J. Bentz, A.S. Munson, J.C. Vandygriff and D.L. Turner. 2006. Evaluation of funnel traps for estimating tree mortality and associated population phase of spruce beetle in Utah. Can. J. For. Res. 36: 2574–2584.

Hao, H. 2018. Application of insect chemical ecology on the prevention and control of public health pests. Chin. J. Vector Biol. Control. 29: 313–316.

Hu, S., Z. Li and H. Ye. 2009. Species and occurrence of important stem borers in *Pinus kesiya var. langbianensis* in Yunnan Province. For. Pest Dis. 28: 27–30.

Jiang, Y., C. Lei and Z. Zhang. 2002. The aggregation pheromones of insects. Acta Entomol. Sin. 45: 822–832.

Joseph, G., R.G. Kelsey, R.W. Peck and C.G. Niwa. 2001. Response of some scolytids and their predators to ethanol and 4-allylanisole in pine forests of central Oregon. J. Chem. Ecol. 27: 697–715.

Kirkendall, L.R., M. Faccoli and H. Ye. 2008. Description of the Yunnan shoot borer, *Tomicus yunnanesis* Kirkendall & Faccoli.Sp.n (Curculidae, Scolytidae), an unusually aggressive pine shoot beetle from southern China, with a key to the species of *Tomicus*. Zootaxa 1819: 25–39.

Langstrom, B. 1983. Life cycles and shoot-feeding of the pine shoot beetles. Stud. For. Suec. 163: 1–29.

Langstrom, B. and C. Hellqvist. 1993. Induced and spontaneous attacks by pine shoot beetles on young Scots pine trees: Tree mortality and beetle performance. J. Appl. Entomol. 115: 25–36.

Langstrom, B., L. Li, H. Liu, P. Chen, C. Hellqvist and F. Lieutier. 2002. Shoot feeding ecology of *Tomicus piniperda* and *T. minor* (Col., Scolytidae) in southern China. J. Appl. Entomol. 126: 333–342.

Langstrom, B., O. Tenow, A. Ericsson, C. Hellqvist and S. Larsson. 1990. Effects of shoot pruning on stem growth, needle biomass, and dynamics of carbohydrates and nitrogen in Scots pine as related to season and tree age. Can. J. For. Res. 20: 514–523.

Li, L., H. Liu, P. Chen, H. Li, B. Langstrom and L. Francoies. 2006. Comparison study on ecological characteristics of *Tomicus piniperda* and *T. minor*. J. West Chin. For. Sci. 35: 1–5.

Li, L., N. Shu, K. Huai, X. Zhu and H. Jin. 1993. Inducing experiments of several compounds on *Tomicus piniperda*. Entomol. Knowl. 30: 159–161.

Liu, F., C. Wu, S. Zhang, X. Kong, Z. Zhang and P. Wang. 2019. Initial location preference together with aggregation pheromones regulate the attack pattern of *Tomicus brevipilosus* (Coleoptera: Curculionidae) on *Pinus kesiya*. Forests 10: 156–169.

Liu, J. 2019. Effects and evaluation of plant volatiles of *Alnus ferdinandi-coburgii* on ovary and post-embryonic development of *Tomicus yunnanensis* (Coleoptera: olytidae). MS thesis. Southwest Forest Univ., Kunming, China.

Liu, J., H. Chen, J. Wang, X. Chen, Z. Yang and J. Liang. 2019. Photosynthetic traits and antioxidative defense responses of *Pinus yunnanensis* after joint attack by bark beetles *Tomicus yunnanensis* and *T. minor*. J. For. Res. 30: 2031–2038.

Lu, N., X. Zhang, L. Li and H. Liu. 2000. Techniques of clearing *Tomicus piniperda* damaged woods in *Pinus yunnanensis* stands. Yunnan For. Sci. Technol. 2: 43–45.

Lv, J., H. Ye, Y. Duan, Z. Liao and Q. Mu. 2010. On trunk attacks and the killing mechanism of *Tomicus yunnanensis* (Coleoptera: Scolytinae) on *Pinus yunnanensis* trees. Acta Ecol. Sin. 30: 2100–2104.

Nebeker, T.E., R.A. Tisdale, R.F. Schmitz and K.R. Hobson. 1995. Chemical and nutritional status of dwarf mistletoe, Armillaria root rot, and Comandra blister rust infected trees which may influence tree susceptibility to bark beetle attack. Can. J. Bot. 73: 360–369.

Nordlundd, A. and W.J. Lewis. 1976. Terminology of chemical releasing stimuli in intraspecific and interspecific interactions. J. Chem. Ecol. 2: 211–220.

Pitman, G.B., R.L. Hedden and R.I. Gara. 1975. Synergistic effects of ethyl alcohol on the aggregation of *Dendroctonus pseudotsugae* (Col., Scolytidae) in response to pheromones. J. Appl. Entomol. 78: 203–208.

Poland, T.M., P.D. Groot, S. Burke, D. Wakarchuk, R.A. Haack, R. Nott and T. Scarr. 2003. Development of an improved attractive lure for the pine shoot beetle, *Tomicus piniperda* (Coleoptera: Scolytidae). Agric. For. Entomol. 5: 293–300.

Qian, L., M. Zhang, J. Liu and Z. Li. 2023. Effects of 4 kinds of odor-active compounds of non-host *Alnus ferdinandi-coburgii* on the post-embryonic development of *Tomicus yunnanensis* (Coleoptera: Curculionidae: Scolytinae). J. Southwest For. Univ. 43: 96–102.

Schiebe, C., M. Blazenec, R. Jakus, C.R. Unelius and F. Schlyter. 2011. Semiochemical diversity diverts bark beetle attacks from Norway spruce edges. J. Appl. Entomol. 135: 726–737.

Sun, J., S. Clarke, L. Kang and H. Wang. 2005. Field trials of potential attractants and inhibitors for pine shoot beetles in the Yunnan province, China. Ann. Sci. For. 62: 9–12.

Tong, Q., P. Zhang and J. He. 2009. A study on the species and damage of *Tomicus* in *Pinus kesiya*. Pract. For. Technol. 9: 35–37.

Vite, J.P., A. Bakke and J.A. Renwick. 1972. Pheromones in *Ips* (Coleoptera:Scolytiae): Occurrence and production. Can. Entomol. 104: 1967–1975.

Vite, J.P. and G.B. Pitman. 1969. Insect and host odors in the aggregation of the western pine beetle. Can. Entomol. 101: 113–117.

Wang, C. and F. Yan. 2023. Information chemicals and their applications in pest control. Chin. J. Appl. Entomol. 60: 313–314.

Wang, D., L. Hu, B. Yang, M. Ji, N. Zhao and S. Yang. 2016. Influence analysis of *Alnus nepalensis* leaves extracts on behavior of pine shoot beetle *Tomicus yunnanesis*. J. Green Sci. Technol. 14: 42–45.

Wang, D., N. Zhao, S. Ze and B. Yang. 2013. Interruption of host-location behavior in the Yunnan pine shoot beetle, *Tomicus yunnanesis* (Coleoptera: Scolytidae), with three green leaf volatiles. Acta Entomol. Sin. 56: 570–574.

Wang, D., N. Zhao, S. Ze, J. Zhu and B. Yang. 2015. Interruption effects of green leaf volatiles to a forest pest pine shoot beetle, *Tomicus yunnanesis* (Coleoptera, Scolytidae). J. Zhejiang Univ. Agric. Life Sci. 41: 269–276.

Wang, H., Y. Zhang and L. Li. 2006. Bionomics of *Tomicus piniperda* in Yunnan. For. Pest Dis. 25: 21–24.

Wang, J. 2015. Chemical ecological relationships of three *Tomicus* species. PhD Dissertation. Chin. Acad. For., Beijing, China.

Wang, J. and X. Zhang. 2019. Advances on occurrence, damage and control of *Tomicus* spp. in Yunnan Province. J. Zhejiang For. Sci. Technol. 39: 117–121.

Wang, J., Z. Zhang, X. Kong, H. Wang and S. Zhang. 2015. Intraspecific and interspecific attraction of three *Tomicus* beetle species during the shoot-feeding phase. Bull. Entomol. Res. 105: 225–233.

Wang, Y., Y. Zhao, X. Zhang, N. Zhao, J. Zhu and B. Yang. 2023. Influence of volatiles from leaves of *Celtis kunmingensis* and *Alnus nepalensis* on gene expression of vitellogenin and its receptor of *Tomicus yunnanensis*. J. Southwest For. Univ. 43: 62–68.

Wood, S.L. 1982. The role of pheromones, kairomones, and allomones in the host selection and colonization behavior of bark beetles. Annu. Rev. Entomol. 27: 411–446.

Wu, C. 2019. Chemical ecological mechanism of coexistence among three *Tomicus* species. PhD Dissertation. Chin. Acad. For., Beijing, China.

Wu, C., F. Liu, S. Zhang, X. Kong and Z. Zhang. 2019. Semiochemical regulation of the intraspecific and interspecific behavior of *Tomicus yunnanensis* and *Tomicus minor* during the shoot-feeding phase. J. Chem. Ecol. 45: 227–240.

Yan, F. 2011. Chemecology. 2nd ed. Science Press, Beijing, China.

Yan, F., J. Chen and Q. Tang. 2013. Advances and perspectives in insect chemical ecology. Plant Protect. 39: 9–15.

Yan, F., J. Chen, Y. Zhang, Q. Tang and H. Zhou. 2014. Research on the development of insect chemical ecology. P. 90. In China Association for Science and Technology, China Society of Plant Protection. 2012–2013 Report on Advances in Plant Protection. Science and Technology of China Press, Beijing, China.

Yan, G., M. Zhang, L. Qian, S. Ze, B. Yang and Z. Li. 2021. Electrophysiological and behavioral responses of *Tomicus yunnanensis* to plant volatiles from primarily infected *Pinus yunnanensis* in Yunnan, Southwest China. J. Environ. Entomol. 43: 1389–1397.

Yan, Z. 2006. Entomological semiochemical of Scolytidae and effects on attack behavior to host. J. West Chin. For. Sci. 35: 22–33.

Yan, Z., H. Ma and S. Ze. 2011. Difference of taxis responses of *Tomicus yunnanensis* to volatile extracts from trunks and branches of *Pinus yunnanensis*. J. Environ. Entomol. 33: 191–194.

Yan, Z., S. Ze, H. Ma, G. Hu and Y. Liu. 2009. Comparison of volatile chemicals from healthy and bark beetle-attacked trunk of *Pinus yunnanensis* and from hindguts of *Tomicus yunnanensis*. J. West Chin. For. Sci. 38: 70–73.

Yang, Q., Z. Zhou and Q. Li. 2003. Studies on the repellent activity of plant essential oils against *Tomicus piniperda*. J. Southwest Agric. Univ. Nat. Sci. 25: 357–359.

Ye, H. 1992. Approach to the reasons of *Tomicus piniperda* (L.) population epidemics. J. Yunnan Agric. Univ. Nat. Sci. Ed. 14: 211–216.

Ye, H. 2011. *Tomicus yunnanesis*. Yunnan Science and Technology Publishing House, Kunming, China.

Ye, H. and C. Dang. 1986. The study on the feature of the bark beetle (*Blastophagus piniperda* L.) injuring the pine tree (*Pinus yunnanensis*). J. Yunnan Agric. Univ. 8: 218–221.

Ye, H. and F. Lieutier. 1997. Shoot aggregation by *Tomicus piniperda* L. (Col., Scolytidae) in Yunnan, southwestern China. Ann. For. Sci. 54: 635–641.

Ye, H. and L. Li. 1994. The distribution of *Tomicus piniperda* (L.) population in the crown of Yunnan pine during the shoot feeding period. Acta. Entomol. Sin. 37: 311–316.

Ye, H., J. Lv and L. Francois. 2004. On the bionomics of *Tomicus minor* (Hartig) (Coleoptera: Scolytidae) in Yunnan Province. Acta. Entomol. Sin. 47: 223–228.

Yin, C., J. Lv, Z. Gao, H. Ye and F. Liu. 2002. Analysis of chemical composition from hindguts of *Tomicus piniperda* and measurement of taxis. J. Yunnan Agric. Univ. Nat. Sci. Ed. 24: 50–52.

Yue, F. and B. Yang. 2011a. Effects of 3 non-host plants on olfactory behavior of *Tomicus piniperda*. Acta Agric. Boreali-Occident. Sin. 20: 190–193.

Yue, F. and B. Yang. 2011b. Olfactory responses of *Tomicus yunnanensis* to different non-host plants. Plant Dis. Pests. 2: 27–30.

Yue, F., B. Yang and Q. Zhou. 2013. Effects of 2 kinds of non-host essential oil on olfactory behavior of *Tomicus yunnanensis*. Southwest Chin. J. Agric. Sci. 26: 1050–1053.

Zhao, B. and S. Zhang. 1993. Introduction to foreign researches on insect aggregation pheromones. J. Nanjing For. Univ. 17: 84–90.

Zhao, T., L. Li and N. Zhou. 2002. The attraction of Yunnan Pine to pine shoot beetle and tree volatile compositions. J. Northeast For. Univ. 30: 47–49.

Zhao, T., N. Zhou and L. Li. 2003. The reproductive biology of *Tomcus piniperda* in the bole of living Yunnan Pine. J. Northeast For. Univ. 18: 47–49.

Zhao, Y. 2015. Effects of the extracts from *Celtis kunmingensis* and *Alnus nepalensis* on transcriptional level of vetellogenin and its receptor in *Tomicus yunnanensis*. MS thesis. Southwest Forest Univ., Kunming, China.

Zhou, N., L. Li, S. Jiang, H. Liu, K. Wei and N. Shu. 1997. Study on effect of chemical attractants to *Tomicus piniperda*. Yunnan For. Sci. Technol. 79: 20–38.

Zhou, X., N. Zhao, S. Ze and B. Yang. 2012. Study on seeking behavior of *Tomicus yunnanensis* to leaves of *Pinus yunnanensis* and some other non-host tree species. J. West Chin. For. Sci. 41: 93–97.

Zuo, T. and G. Huang. 2018. Test effect of semiochemicals on trapping of *Tomicus yunnanensis*. For. Inv. Plan. 43: 64–69.