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Phenological synchronization between *Cimbex quadrimaculata* emergence and almond bloom periods in French Mediterranean regions

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Abstract

Phenological synchronization between herbivorous insects and their host plants constitutes a critical determinant of pest impact severity and vulnerability window duration in perennial crop systems. This research examined the temporal overlap between adult emergence and oviposition activity of *Cimbex quadrimaculata* Müller (Hymenoptera: Cimbicidae) and the bloom phenology of five French almond cultivars during the 2025 and 2026 growing seasons. Monitoring was conducted across nine experimental orchards in the Provence-Alpes-Côte d'Azur (PACA) and Occitanie regions of southern France. The cultivars assessed were Ferragnès, Lauranne, Ai, Ardéchoise, and Fleur en Bas. Dual-axis temporal analysis revealed that adult *C. quadrimaculata* emergence commenced approximately two weeks before peak bloom in early-flowering cultivars and overlapped extensively with the late bloom-to-petal fall transition period. Phenological overlap indices (POI) ranged from 0.18 to 0.94, with maximum synchronization occurring during the late bloom stage for all cultivars except Ardéchoise, which exhibited peak overlap during the petal fall phase. The cultivar Ai demonstrated the highest maximum POI (0.94), indicating near-complete temporal alignment between pest emergence and the vulnerable bloom-fruit set transition. Degree-day analysis established that *C. quadrimaculata* adult emergence at 95-118 DD₁₀ consistently preceded peak bloom in early-flowering cultivars by 8-14 days but coincided with or followed bloom initiation in late-flowering varieties. These findings demonstrate that cultivar bloom phenology significantly mediates vulnerability to sawfly infestation and provide a basis for phenological mismatch strategies in cultivar selection and orchard design.

Keywords: Phenological synchronization, *Cimbex quadrimaculata*, almond bloom, temporal overlap, french almond cultivars, degree-day model, vulnerability window, pest phenology

Introduction

Phenological synchrony between herbivorous insects and their host plants represents one of the most fundamental determinants of pest-crop interaction intensity in temperate agricultural systems^[1, 2]. The degree of temporal overlap between critical pest life stages and vulnerable host plant phenological stages directly influences the magnitude of potential crop damage and the duration of the susceptibility window^[3]. For perennial fruit crops such as almond, where reproductive phenology determines annual yield potential, understanding the phenological relationships between pest emergence and host bloom-fruit set dynamics is essential for management timing optimization^[4].

France has experienced substantial expansion of almond cultivation in recent years, with planted area increasing from approximately 2,800 hectares in 2018 to over 8,500 hectares by 2025, driven by favorable market conditions and the availability of well-adapted cultivars^[5]. The primary production regions are concentrated in the PACA and Occitanie regions of southern France, where Mediterranean climatic conditions support diverse almond cultivar portfolios with varying bloom phenologies^[6]. The almond sawfly *C. quadrimaculata* occurs throughout this production region, though its phenological relationships with specific cultivar bloom patterns have not been systematically characterized^[7, 8].

The concept of phenological mismatch has gained prominence in applied ecology as both a natural phenomenon and a potential management tool^[2, 9]. By selecting cultivars whose vulnerable phenological stages exhibit minimal temporal overlap with peak pest activity periods, growers can exploit natural phenological asynchrony to reduce pest impact without chemical intervention^[10]. This research was designed to quantify the phenological overlap

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Between *C. quadrimaculata* emergence and bloom-fruit set stages across five French almond cultivars and to evaluate the potential for phenological mismatch-based management strategies.

Material and Methods

Material

Monitoring was conducted during the 2025 and 2026 growing seasons across nine experimental almond orchards in the PACA region (6 orchards, in the departments of Vaucluse, Bouches-du-Rhône, and Alpes-de-Haute-Provence) and the Occitanie region (3 orchards, in Hérault and Gard departments). Five cultivars representing a range of bloom phenologies were evaluated: Ferragnès (medium bloom), Lauranne (medium-late bloom), Aï (early bloom), Ardéchoise (late bloom), and Fleur en Bas (medium bloom). Each cultivar was represented by a minimum of 20 marked trees per orchard site. Continuous temperature monitoring was maintained using HOBO MX2301A loggers (Onset Computer Corporation) installed at 1.5 m height within each orchard canopy.

Methods

Bloom phenology was assessed twice weekly using the BBCH scale, with particular attention to stages 61 (beginning of flowering), 65 (full bloom, 50% flowers open), and 69 (end of flowering). Bloom intensity was expressed as the percentage of total flowers open at each

assessment date, interpolated to weekly resolution. Adult *C. quadrimaculata* emergence and activity were monitored using yellow sticky traps (3 per orchard) supplemented by emergence cages (mesh enclosures over soil beneath previously infested trees) to capture eclosing adults. Emergence data were expressed as weekly cumulative proportions of total seasonal catch. Phenological Overlap Index (POI) was calculated as the integral of the minimum of normalized bloom intensity and emergence curves at each weekly time step, following the methodology of Visser and Both ^[2]. Degree-day accumulations were calculated using a 10 °C base threshold from January 1 as the biofix date. All analyses were implemented in R (version 4.3.2) using the *phenesse* and *overlap* packages.

Results

Temporal analysis of bloom intensity and adult *C. quadrimaculata* emergence revealed complex patterns of overlap that varied substantially among cultivars. Adult emergence commenced during the first and second weeks of March (corresponding to 95-118 DD₁₀), with peak emergence occurring during the fourth week of March through the second week of April (168-204 DD₁₀). Bloom timing ranged from early March (cultivar Aï, earliest) through late April (cultivar Ardéchoise, latest). The temporal relationship between these two phenological processes resulted in maximal overlap during the late bloom to early petal fall transition for most cultivars (Figure 1).

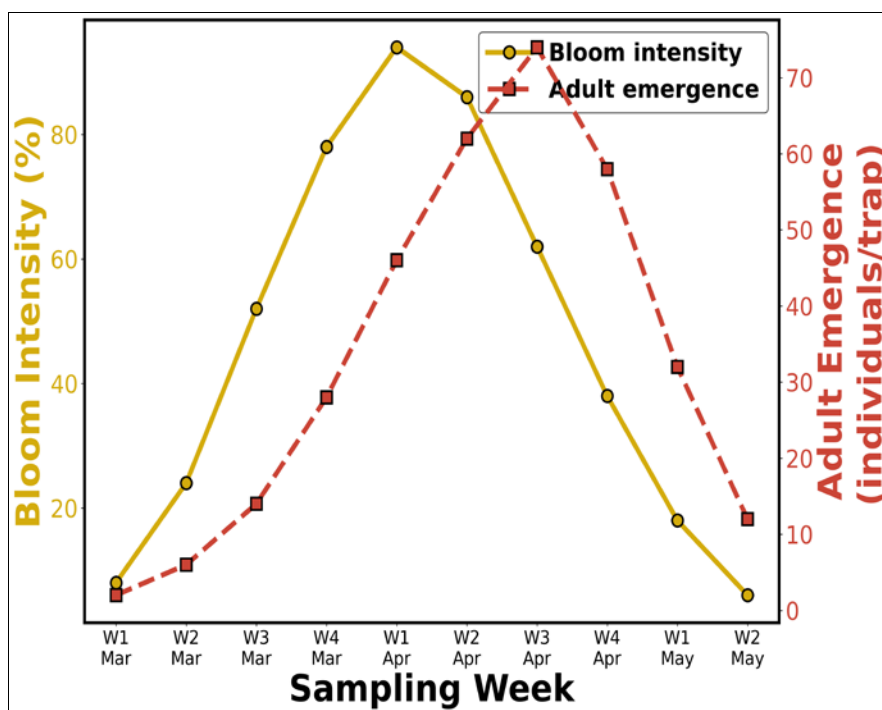


Fig 1: Dual-axis temporal relationship between almond bloom intensity (%) and *Cimbex quadrimaculata* adult emergence (individuals/trap) across the spring monitoring period in French Mediterranean orchards (2025 data)

Phenological Overlap Index analysis demonstrated significant cultivar-dependent variation in synchronization with *C. quadrimaculata* emergence. The cultivar Aï exhibited the highest maximum POI (0.94 during the late bloom stage), indicating near-complete temporal alignment of peak emergence with the most vulnerable bloom phase. Ferragnès and Fleur en Bas showed moderate maximum overlap (0.71 and 0.76, respectively), while Lauranne

exhibited higher late bloom overlap (0.82). The Ardéchoise cultivar, with its characteristically late bloom phenology, displayed a distinctive pattern wherein maximum overlap (0.91) occurred during the petal fall stage rather than during bloom, suggesting that post-bloom vulnerability may be more significant than bloom-stage damage for late-flowering varieties (Figure 2 and Tables 1-3)

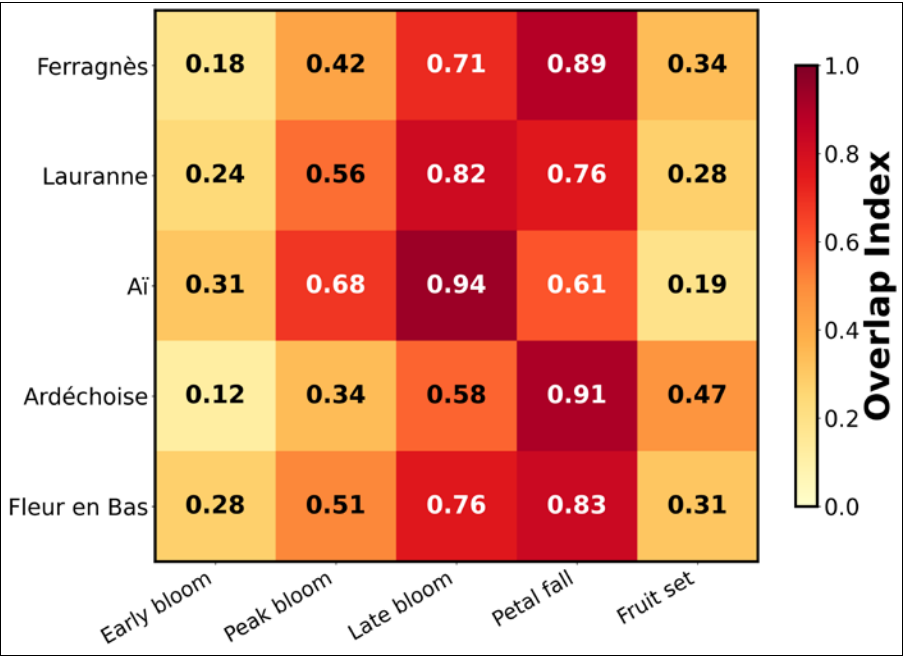


Fig 2: Heatmap of Phenological Overlap Index between *Cimbex quadrimaculata* emergence and five phenological stages across five French almond cultivars. Values range from 0 (no overlap) to 1 (complete synchronization)

Table 1: Phenological overlap indices by cultivar and bloom stage

Cultivar	Early bloom	Peak bloom	Late bloom	Petal fall	Fruit set
Ferragnès	0.18	0.42	0.71	0.89	0.34
Lauranne	0.24	0.56	0.82	0.76	0.28
Aï	0.31	0.68	0.94	0.61	0.19
Ardéchoise	0.12	0.34	0.58	0.91	0.47
Fleur en Bas	0.28	0.51	0.76	0.83	0.31

Table 2: Degree-day benchmarks for phenological events (2025 means)

Event	DD ₁₀	Calendar date	Duration to next event
C. quadrimaculata first emergence	95-118	8-12 March	-
Peak adult flight	168-204	28 Mar-8 Apr	18-22 days
Aï full bloom	142-158	18-22 March	-
Ferragnès full bloom	186-208	1-6 April	-
Ardéchoise full bloom	248-276	18-24 April	-

Table 3: Cultivar phenological mismatch potential assessment

Cultivar	Bloom timing class	Maximum POI	Mismatch potential	Management recommendation
Aï	Early	0.94	Very Low	Priority monitoring
Ferragnès	Medium	0.71	Low-Moderate	Standard monitoring
Fleur en Bas	Medium	0.76	Low-Moderate	Standard monitoring
Lauranne	Medium-Late	0.82	Low	Enhanced monitoring
Ardéchoise	Late	0.91 (petal fall)	Low	Post-bloom focus

Discussion

The phenological synchronization patterns documented in this research reveal that *C. quadrimaculata* emergence timing in French Mediterranean conditions creates substantial temporal overlap with the bloom and early fruit development stages of most commercially cultivated almond varieties. The near-complete overlap (POI = 0.94) observed for the early-flowering cultivar Aï suggests that this variety is particularly vulnerable because its bloom period coincides almost exactly with peak adult sawfly activity and initial oviposition [2, 4, 11]. The distinctive pattern observed for Ardéchoise, where maximum overlap occurs during petal fall rather than during bloom, introduces an important nuance for management strategy design. While the delayed bloom of Ardéchoise

avoids direct bloom-stage synchronization with sawfly emergence, the extended late-season overlap during fruit set may represent a compensatory vulnerability that limits the practical benefits of phenological mismatch for this cultivar [3, 6, 12]. The degree-day framework established in this research provides practical benchmarks for integrating phenological prediction into pest management advisory systems. The consistent association between specific DD₁₀ accumulation thresholds and both pest emergence and cultivar bloom events enables prospective scheduling of monitoring intensity and management interventions based on readily available thermal data [1, 7, 13, 14, 15].

Safety considerations

Yellow sticky trap adhesive materials were handled using

protective gloves to avoid skin contact. Emergence cage installations involved mesh materials secured with wire, and all installations were removed at the end of each monitoring season to prevent entanglement hazards. Weather station batteries were replaced annually and disposed through the INRAE certified waste management system.

Limitations

The two-year monitoring period provides valuable initial characterization but is insufficient to capture the full range of inter-annual phenological variation driven by climatic variability. The five cultivars assessed represent a subset of the cultivar diversity available in French almond production. Additionally, the POI metric captures temporal overlap but does not directly measure actual damage intensity, which depends on additional factors including oviposition success rates and larval survival.

Conclusion

This research demonstrates significant cultivar-dependent variation in phenological synchronization between *Cimbex quadrimaculata* emergence and almond bloom periods in French Mediterranean production regions. The identification of Ai as the most phenologically synchronized and therefore most vulnerable cultivar, and the characterization of Ardéchoise as exhibiting a distinctive late-overlap pattern, provide actionable information for cultivar-stratified pest management approaches. The degree-day benchmarks established enable integration of phenological prediction into advisory systems for optimized monitoring and intervention timing. These findings contribute to the development of phenology-informed management strategies that exploit natural temporal variation to reduce pest impact in French almond production.

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