

Land snail diversity and reproductive biology of the major pest *Acusta tourannensis* (Souleyet, 1842) (Gastropoda, Camaenidae) in Vietnamese orange (*Citrus sinensis* (L.)) orchards

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Abstract

Land gastropods are increasingly recognised as significant agricultural pests across tropical regions, yet their diversity and biological dynamics within Vietnamese perennial fruit systems remain poorly documented. This study evaluated the species composition of terrestrial gastropods infesting orange (*Citrus sinensis*) orchards across key production provinces in southern (Tien Giang, Hau Giang) and northern (Hung Yen) Vietnam. Surveys conducted from 2023 to 2025 identified 16 species across 14 genera and nine families. The camaenid snail *Acusta tourannensis* (Souleyet, 1842) emerged as the primary pest based on its high occurrence frequency and severe damage to foliage, shoots, and developing fruit. Controlled laboratory experiments demonstrated that ambient temperature and dietary composition significantly dictate developmental trajectories. Rearing at 30°C accelerated shell growth and biomass accumulation relative to 25°C. However, embryonic viability peaked at 25°C (95.9% hatching success) and ceased entirely at 35°C. Nutritional quality strongly influenced adult fecundity; snails receiving a protein-enriched mixed diet yielded a mean fecundity of 240.6 ± 24.85 eggs per adult, representing an eightfold increase over individuals restricted to *Citrus* foliage (30.10 ± 7.03 eggs per adult). Under optimal conditions (25°C, 80% relative humidity), *A. tourannensis* completed its life cycle in 117.3 ± 11.6 days, with a mean cumulative fecundity of 564.6 ± 96.1 eggs per adult. These findings establish essential baseline data on the thermal thresholds and reproductive potential of *A. tourannensis*, providing a scientific foundation for predicting population outbreaks and developing targeted integrated pest management strategies in Southeast Asian citrus agroecosystems.

INTRODUCTION

Land gastropods, encompassing both shelled snails and slugs, are increasingly recognised as significant agricultural pests worldwide. This trend is particularly pronounced across tropical and subtropical regions, where ambient environmental conditions facilitate rapid ontogeny and high fecundity [1–4]. Terrestrial molluscs inflict substantial economic losses through direct herbivory on a broad spectrum of crops and by serving as vectors for various phytopathogens [5–8]. Despite their escalating impact on agricultural production, the pest status of land snails and slugs within perennial fruit systems, particularly citrus orchards, remains insufficiently documented. This knowledge gap is particularly acute in Southeast Asia, where persistent high humidity and mild winters promote the rapid proliferation of gastropod populations [9–12].

In Vietnam, citrus species (*Citrus* spp.) constitute a vital group of fruit crops, with orange (*Citrus sinensis* (L.)) cultivation holding paramount economic importance across both northern and southern agricultural zones. Production areas in the southern agricultural Mekong Delta, including Tien Giang and Hau Giang provinces, alongside northern regions such as Hung Yen, have experienced a rapid expansion in orange production driven by a combination of favourable agroecological factors and rising market demand [13, 14]. However, this agricultural intensification has been accompanied by heightened pest pressure. While insect and fungal pests of citrus have been the focus of extensive research, reports regarding land snails in these cropping systems remain fragmented and taxonomically ambiguous [10]

Recent field observations across Vietnamese citrus orchards indicate that terrestrial snails exert a growing negative impact on tree health by damaging young shoots, foliage, and developing fruits. The cryptic nature, nocturnal foraging behaviour, and high reproductive capacity of these organisms present formidable challenges to conventional management and control strategies [9, 11, 15, 16]. Consequently, effective mitigation requires a deeper understanding of species occurrence and pest biology within these agroecosystems.

To date, no systematic assessment of species composition or the specific pest status of snails within Vietnamese citrus systems has been conducted [10, 17]. The present study was undertaken to address these deficiencies by surveying the diversity and geographical distribution of land snails and slugs infesting orange orchards across key Vietnamese production regions. During these field surveys, *Acusta tourannensis* (Souleyet, 1842) was identified as the predominant pest species due to its high occurrence frequency and the severity of the damage inflicted on host crops. To support the development of effective integrated pest management (IPM) strategies, laboratory evaluations were conducted to elucidate the fundamental biological traits of *A. tourannensis*, focusing on growth dynamics, thermal tolerance, and reproductive performance across varying dietary regimes. These findings establish a scientific foundation for predicting population outbreaks and refining control measures within citrus-based agricultural systems.

MATERIALS AND METHODS

Study sites and environmental characteristics

The investigation was conducted over a two-year period, from January 2023 to January 2025, within three major citrus-producing provinces in Vietnam. The survey locations comprised Tien Giang and Hau Giang in the Mekong Delta of southern Vietnam, and Hung Yen in the Red River Delta of northern Vietnam. These regions were selected to represent the primary agroecological zones of orange (*Citrus sinensis* (L.) production across the country.

Orchards were selected based on cultivation scale, a documented history of terrestrial gastropod infestation, and logistical accessibility for longitudinal monitoring. At each site, geographic elevation, total plantation area, cultivated cultivars, tree age, and planting density were recorded to ensure methodological reproducibility (Table 1).

Table 1 Summary of horticultural and environmental characteristics of the surveyed orange (*Citrus sinensis*) orchards in northern and southern Vietnam.

Locations (Commune, District, Province)	Elevation (m)	Area (ha)	Orange variety	Tree age (years)	Density (trees/ acre)
Tien Giang Province					
My Loi A, Cai Be	1–2	5.06	<i>Citrus nobilis</i> , <i>Citrus sinensis</i>	7–10	290–350
My Loi B, Cai Be	1–2	4.86	<i>C. nobilis</i>	7–9	300–350
My Tan, Cai Be	1–2	4.65	<i>C. nobilis</i>	7–9	280–360
An Thai Trung, Cai Be	2–3	5.26	<i>C. nobilis</i> <i>C. sinensis</i>	6–9	270–350
My Luong, Cai Be	1–2	4.86	<i>C. nobilis</i>	7–10	290–350
Hau Giang Province					
Dong Thach, Chau Thanh	1–2	4.65	<i>C. nobilis</i> <i>C. sinensis</i>	7–9	280–350
Thach Xuan, Chau Thanh	1–2	3.84	<i>C. nobilis</i> <i>C. sinensis</i>	7–9	280–360
Hung Yen Province					
Quang Chau, Hung Yen	4–6	16.31	<i>Citrus myrtifolia</i> , <i>Citrus sinensis</i>	5–7	270–320
Tam Đa, Phu Cu	4–5	18.94	<i>C. myrtifolia</i> , <i>C. sinensis</i>	7–8	300–380
Dai Dong, Van Lam	6–7	9.11	<i>C. myrtifolia</i>	6–9	280–380

Species composition survey and sampling design

Field sampling was conducted at monthly intervals from 2023 to 2025 to establish the species composition of terrestrial gastropods associated with orange orchards. The survey scope extended beyond primary citrus plantations to include adjacent boundary habitats, including fence rows, fallow land, and garden margins, which potentially serve as environmental refugia. A combined quantitative and qualitative sampling framework was implemented to sample diverse microhabitats.

Quantitative sampling was performed by establishing 1 m² quadrats at the base of selected citrus trees. Within each quadrat, all snails and slugs present on tree trunks, the soil surface, and within the leaf litter to a depth of 5 cm were systematically collected. To

complement quantitative quadrats, qualitative manual searches across diverse microhabitats surrounding the sampled trees, specifically targeting cryptic species.

To account for diurnal and nocturnal variations in gastropod activity, sampling was conducted across multiple daily time intervals, specifically early morning, midday, late afternoon, and night. Sampling was intensified during and immediately following rainfall events to capture peak emergence periods.

Assessment of the primary pest species

Population dynamics of the predominant pest species, *Acusta tourannensis* (Souleyet, 1842), were monitored in accordance with the Vietnamese national standard TCVN 13268-4 (2021) [18]. Assessments within the orange orchards were performed at 10-day intervals to record fine-scale temporal variations in population density.

A systematic sampling design was employed, establishing ten distinct sampling points were established within each orchard. At each point, a single tree was randomly selected for detailed examination. Arboreal abundance of *A. tourannensis* was quantified by recording the total number of individuals present on ten randomly selected branches per tree, focusing on foliage and developing fruits.

Ground-level assessments were conducted simultaneously at the base of each sampled tree using a 0.2 m² quadrat frame. Snails present on the soil surface and within the immediate leaf litter were recorded. Counts were subsequently converted to individuals per square metre (ind./m²) for statistical standardisation.

Specimen collection, preservation, and taxonomic identification

Specimens were collected manually using soft-tipped forceps to prevent structural damage to the periostracum or aperture margin. Live individuals were placed in ventilated plastic containers at densities of 10 to 20 individuals per container to minimise overcrowding during transport.

In the laboratory, live specimens were maintained under controlled conditions at 25°C–30°C in terraria containing autoclaved moist soil and supplied with fresh citrus foliage *ad libitum*. Selected specimens were relaxed in water before preservation in 70% ethanol for long-term archival storage and tissue preservation suitable for anatomical dissection. Shells were cleaned gently using deionised water to remove organic debris.

Shell dimensions were measured in millimetres (mm) using digital calipers with a precision of 0.1 mm. Measured parameters included shell height (SH), defined as the distance from the apex to the most basal point of the aperture, and shell width (SW), measured at the maximum diameter perpendicular to the coiling axis. Whorls was counted to an accuracy of 0.25 whorls following Kerney & Cameron (1979) [19]. Digital imaging was performed using a Nikon® Z6 II camera equipped with a macro lens; depth of field was optimised by focus-stacking multiple focal planes in Adobe Photoshop.

Taxonomic identification was accomplished using diagnostic keys and original descriptions provided by Souleyet (1842) [20], Crosse & Fischer (1863) [21], Stoliczka (1873), Morelet (1875) [22], and Morlet (1886) [23], alongside contemporary taxonomic revisions and regional malacological studies [2, 6, 24–36]. Diagnostic determinations were validated by direct comparison with high-resolution digital photographs of type specimens curated in the Muséum National d'Histoire Naturelle (MNHN), Paris, and the Natural History Museum, London (NHMUK). Classification followed the database MolluscaBase (accessed 28 May 2025). Representative voucher specimens were deposited in the Zoological Collection at the Biological Museum, VNU University of Science (ZVNU), and the Specimen Collection of the Plant Protection Research Institute (PPRI) in Hanoi, Vietnam.

Species frequency classification

Species frequency was determined by calculating the proportion of sampling units in which a specific taxon was recorded, enabling the characterisation of community structure and spatial distribution patterns [37, 38]. Five frequency categories were established based on the percentage of occurrence across total samples:

1. **Very rare:** recorded in fewer than 5% of the total samples (assigned symbol: -);
2. **Rare:** recorded in 5% to 20% of samples (symbol: +);

3. **Moderately common:** recorded in 21% to 50% of samples (symbol: ++);
4. **Common:** recorded in 51% to 70% of samples (symbol: +++);
5. **Very common:** recorded in more than 70% of samples (symbol: ++++).

Frequency values were calculated by dividing the number of sampling sites where a species was recorded by the total number of sites surveyed.

Laboratory experiments on *Acusta tourannensis*

Following the field identification of *A. tourannensis* as the primary agricultural pest, controlled laboratory experiments were conducted at the Plant Protection Research Institute, Vietnam Academy of Agricultural Sciences, to determine its biological and reproductive traits.

Growth under different temperature and dietary regimes

Newly hatched *A. tourannensis* individuals with 1.25 whorls were isolated into 150 ml plastic containers lined with sterile paper and fitted with ventilated lids. A factorial experimental design was implemented, combining two constant temperature regimes (25°C and 30°C) with two dietary treatments: The first dietary treatment consisted of *Citrus* foliage exclusively. The second treatment provided *Citrus* foliage supplemented with chicken starter feed (C210; containing 21% crude protein). Containers were supplied with a standardized substrate consisting of soil sterilised at 121°C for two hours, amended with 10% microbial fertiliser and 3% calcium carbonate to support shell development. Morphometric parameters were recorded at 15-day intervals, quantifying shell width (SW), shell height (SH), aperture height (AH), aperture width (AW), number of shell whorls, and total body mass (g).

Egg incubation experiment

To determine thermal tolerance thresholds for embryonic development, freshly laid eggs were incubated in 150 ml plastic containers lined with sterile paper moistened regularly with deionised water. Environmental conditions were maintained at 80% relative humidity, a 12:12 h light: dark photoperiod, and an illumination intensity of 1000 lux.

Four constant temperature regimes were tested: 20°C, 25°C, 30°C, and 35°C. Each treatment comprised 150 eggs, divided into five replicates of 30 eggs each. Incubation duration (days to hatching) and hatching success rate (%) were evaluated for each temperature regime.

Reproductive performance under varying dietary regimes

Upon attaining five whorls, mature mating pairs were established in plastic containers measuring 33 × 25 × 17 cm maintained at 30°C and 80% relative humidity. Pairs were assigned to one of two dietary treatments (individuals per treatment):

The first treatment (T1) consisted of *Citrus* foliage supplemented with chicken layer feed (C145; containing 16% crude protein), while the second treatment (T2) involved the provision of *Citrus* foliage exclusively.

Cumulative egg production per adult was monitored throughout the reproductive period. Substrate moisture was regulated by manual irrigation every two days, and the soil substrate was replaced every 15 days to maintain hygienic conditions and prevent metabolic waste accumulation.

Life cycle duration

The complete life cycle of *A. tourannensis* was accumulated under controlled conditions at 25°C and 80% relative humidity. A cohort of 100 newly hatched individuals was monitored continuously from hatching to natural biological senescence. Key parameters included egg incubation period, juvenile development duration, age at first oviposition, and lifetime cumulative fecundity.

RESULTS

Species composition and major pest species

The malacological survey across Vietnamese orange (*Citrus sinensis*) orchards revealed a gastropod fauna comprising 16 species across 14 genera and nine families. In the southern region (Tien Giang and Hau Giang provinces), 14 species were recorded, consisting of ten land snail species and four slug species representing the orders Stylommatophora and Systellommatophora (Table 2; Figs 1, 2) These taxa represented a broad range of families within the orders Stylommatophora and Systellommatophora. *Acusta tourannensis* (Souleyet, 1842) maintained a common frequency of occurrence (+++) during both the dry and rainy seasons, producing very high perceived economic damage (Table 2). Other prevalent southern species included *Lissachatina fulica* (Bowdich, 1822), which increased from rare (+) in the dry season to common (+++) in the rainy season, and *Subulina octona* (Bruguière, 1789), which shifted from rare (+) to moderately common (++) (Table 2).

Table 2Species composition, seasonal frequency, and perceived economic impact of terrestrial gastropods in orange orchards within Tien Giang and Hau Giang provinces, southern Vietnam.

No.	Taxonomic Group and Species	Seasonal Frequency		Economic Damage (Farmer's Perception)
		Dry Season	Rainy Season	
	Phylum Mollusca			
	Class Gastropoda			
	Subclass Heterobranchia			
	Order Stylommatophora			
	Achatinidae Swainson, 1840			
1	<i>Allopeas gracile</i> (Hutton, 1834)	+	+	Low
2	<i>Lissachatina fulica</i> (Bowdich, 1822)	+	+++	Low
3	<i>Subulina octona</i> (Bruguière, 1789)	+	++	Low
	Agriolimacidae Wagner, 1935			
4	<i>Deroceras laeve</i> (Müller, 1774)	+	+	Low
	Ariophantidae Godwin-Austen, 1883			
5	<i>Sarika resplendens</i> (Philippi, 1847)	–	–	Very low
	Camaenidae Pilsbry, 1895			
6	<i>Acusta tourannensis</i> (Souleyet, 1842)	+++	+++	Very high
7	<i>Amphidromus inversus</i> (Müller, 1774)			
8	<i>Bradybaena jourdyi</i> (Morlet, 1886)	++	++	High
9	<i>Bradybaena similaris</i> (Férussac, 1822)	+	++	Low
	Dyakiidae Gude & Woodward, 1921			
10	<i>Quantula weinkauffiana</i> (Crosse & Fischer, 1863)	–	–	Low
	Philomycidae Gray, 1847			
11	<i>Meghimatium bilineatum</i> (Benson, 1842)	+	++	High
	Succineidae Beck, 1837			
12	<i>Succinea tenella</i> Morelet, 1875	+	+	Low
	Order Systellommatophora			
	Veronicellidae Gray, 1840			
13	<i>Laevicaulis alte</i> (Férussac, 1822)	+	+	Low
14	<i>Valiguna siamensis</i> (von Martens, 1867)	+	++	High

Notes: Frequency categories were determined by the percentage of occurrence across total sampling units: –, very rare (<5%); +, rare (5–20%); ++, moderately common (21–50%); +++, common (51–70%); and +++, very common (>70%).

In the northern region (Hung Yen Province), 11 species were documented, comprising eight land snail species and three slug species (Table 3; Figs 1, 2). *Acusta tourannensis* emerged as the most dominant taxon, shifting from common (+++) in the dry season to very common (++++) in the rainy season, corresponding to very high economic damage (Table 3). High seasonal frequencies and substantial crop damage were also recorded for the camaenid snail *Bradybaena jourdyi* (Morlet, 1886) (moderately common [++] to common [+++]) and the philomycid slug *Meghimatium bilineatum* (Benson, 1842) (rare [+] to moderately common [++]) (Table 3).

Table 3 Species composition, seasonal frequency, and perceived economic impact of terrestrial gastropods in orange orchards within Hung Yen province, northern Vietnam.

No.	Taxonomic Group and Species	Seasonal Frequency		Economic Damage (Farmer's Perception)
		Dry Season	Rainy Season	
	Phylum Mollusca			
	Class Gastropoda			
	Subclass Heterobranchia			
	Order Stylommatophora			
	Achatinidae Swainson, 1840			
1	<i>Allopeas gracile</i> (Hutton, 1834)	+	+	Low
2	<i>Lissachatina fulica</i> (Bowdich, 1822)	+	++	Low
	Ariophantidae Godwin-Austen, 1883			
3	<i>Sarika resplendens</i> (Philippi, 1847)	–	–	Very low
	Camaenidae Pilsbry, 1895			
4	<i>Acusta tourannensis</i> (Souleyet, 1842)	+++	++++	Very high
5	<i>Bradybaena jourdyi</i> (Morlet, 1886)	++	+++	High
6	<i>Bradybaena similaris</i> (Férussac, 1822)	+	++	Low
	Philomycidae Gray, 1847			
7	<i>Meghimatium bilineatum</i> (Benson, 1842)	+	++	High
	Streptaxidae Gray, 1860			
8	<i>Gulella bicolor</i> (Hutton, 1834)	+	+	Low
	Succineidae Beck, 1837			
9	<i>Succinea</i> sp.	+	+	Low
	Order Systellommatophora			
	Veronicellidae Gray, 1840			
10	<i>Laevicaulis alte</i> (Férussac, 1822)	+	+	Low
11	<i>Valiguna siamensis</i> (von Martens, 1867)	+	++	High

Notes: Frequency categories were determined by the percentage of occurrence across total sampling units: –, very rare (<5%); +, rare (5–20%); ++, moderately common (21–50%); +++, common (51–70%); and +++++, very common (>70%).

Across all surveyed agroecosystems, 14 species (87.5% of total recorded taxa) were classified within the range of rare (+) to moderately common (++), whereas two species, *Sarika resplendens* (Philippi, 1847) and *Quantula weinkauffiana* (Crosse & Fischer, 1863), were categorized as very rare (–) (Tables 2, 3). Although southern orchards displayed higher overall species richness, *A. tourannensis* represented the primary pest species across both geographic zones regardless of seasonal shifts (Tables 2, 3; Fig. 3).

Feeding behaviour and damage characteristics

Field evaluations demonstrated that *A. tourannensis* is a phytophagous pest with a marked preference for young, actively growing plant tissues. Feeding activity escalated during the rainy season from May to October, coinciding with peak population densities and the young tissue availability. The snails damaged host plants by rasping the epidermal layers of young citrus leaves, tender shoots,

and developing fruit rinds (Fig. 4A–F). Damaged leaves displayed characteristic crescent-shaped lesions and skeletal feeding scars (Fig. 4A–C). Wounds inflicted on young shoots and developing fruit caused structural dieback or fruit abortion (Fig. 4D–F), while open feeding scars served as infection courts for secondary fungal and bacterial pathogens.

Morphometric growth under varying temperature conditions

Thermal regimes significantly influenced the developmental rate and physical dimensions of *A. tourannensis* over the 150-day monitoring period (Table 4). Hatchling baseline measurements were identical at 1.82 ± 0.13 mm shell width (SW), 1.62 ± 0.26 mm shell height (SH), 1.44 ± 0.21 mm aperture height (AH), 1.16 ± 0.17 mm aperture width (AW), 1.25 whorls, and 0.002 g body mass.

Divergence in developmental rates between temperature regimes became evident at 45 days post-hatching. At 45 days, individuals reared at 30 °C achieved an average SW of 8.86 ± 1.27 mm, SH of 6.98 ± 1.17 mm, AH of 5.92 ± 0.96 mm, AW of 4.93 ± 0.71 mm, 4.5 whorls, and a mass of 0.253 ± 0.03 g. In contrast, individuals maintained at 25 °C reached an SW of 6.83 ± 0.62 mm, SH of 5.12 ± 0.42 mm, AH of 4.62 ± 0.50 mm, AW of 3.96 ± 0.44 mm, 4.0 whorls, and a mass of 0.127 ± 0.04 g (Table 4).

By 90 days snails maintained at 30°C attained a body mass of 1.326 ± 0.14 g and an SW of 16.89 ± 0.65 mm (>5.5 whorls), compared to 0.993 ± 0.29 g and 14.72 ± 1.24 mm (5.5 whorls) at 25 °C (Table 4). At the conclusion of the 150-day observation period, snails kept at 30 °C reached a mean SW of 17.52 ± 0.82 mm, SH of 14.41 ± 0.86 mm, AH of 10.18 ± 0.74 mm, AW of 9.99 ± 0.51 mm, >5.75 whorls, and a total body mass of 1.925 ± 0.21 g. Snails kept at 25 °C attained an SW of 16.61 ± 0.75 mm, SH of 13.12 ± 0.72 mm, AH of 10.12 ± 0.39 mm, AW of 9.76 ± 0.54 mm, >5.75 whorls, and a mass of 1.890 ± 0.18 g (Table 4).

Table 4 Morphometric growth parameters and body mass accumulation of *Acusta tourannensis* (Souleyet, 1842) reared under two temperature regimes (25°C and 30°C) over a 150-day period.

Age (Days)	T°C	SW (mm)	SH (mm)	AH (mm)	AW (mm)	Whorls	Weight (g)
Hatching	25°C	1.82 ± 0.13	1.62 ± 0.26	1.44 ± 0.21	1.16 ± 0.17	1 ^{1/4}	0.002
	30°C	1.82 ± 0.13	1.62 ± 0.26	1.44 ± 0.21	1.16 ± 0.17	1 ^{1/4}	0.002
15 days	25°C	3.22 ± 0.45	2.40 ± 0.35	2.07 ± 0.26	1.68 ± 0.27	>2 ^{1/4}	0.008
	30°C	3.31 ± 0.24	2.55 ± 0.28	2.14 ± 0.16	1.72 ± 0.19	2 ^{1/4}	0.009
30 days	25°C	5.04 ± 1.09	3.80 ± 0.79	3.28 ± 0.75	2.55 ± 0.86	>3	0.040 ± 0.02
	30°C	5.19 ± 0.68	4.03 ± 0.56	3.33 ± 0.40	2.84 ± 0.33	3 ^{1/2}	0.043 ± 0.015
45 days	25°C	6.83 ± 0.62	5.12 ± 0.42	4.62 ± 0.50	3.96 ± 0.44	4	0.127 ± 0.04
	30°C	8.86 ± 1.27	6.98 ± 1.17	5.92 ± 0.96	4.93 ± 0.71	4 ^{1/2}	0.253 ± 0.03
60 days	25°C	8.70 ± 1.06	6.62 ± 0.80	5.77 ± 0.72	5.18 ± 0.68	4 ^{1/2}	0.357 ± 0.06
	30°C	8.92 ± 1.87	7.12 ± 1.52	6.06 ± 1.15	4.91 ± 1.05	4 ^{3/4}	0.492 ± 0.09
75 days	25°C	11.79 ± 1.89	8.84 ± 1.47	7.58 ± 1.21	7.11 ± 1.28	5	0.754 ± 0.21
	30°C	15.16 ± 0.99	11.56 ± 0.76	9.34 ± 0.36	8.57 ± 0.45	5 ^{1/2}	1.063 ± 0.20
90 days	25°C	14.72 ± 1.24	11.30 ± 1.02	9.16 ± 1.05	8.77 ± 1.09	5 ^{1/2}	0.993 ± 0.29
	30°C	16.89 ± 0.65	12.91 ± 0.31	9.87 ± 0.21	9.49 ± 0.61	>5 ^{1/2}	1.326 ± 0.14
105 days	25°C	15.16 ± 1.16	11.38 ± 1.08	9.34 ± 1.02	8.78 ± 1.04	>5 ^{1/2}	1.021 ± 0.16
	30°C	17.21 ± 0.64	13.55 ± 0.73	9.90 ± 0.22	9.71 ± 0.40	5 ^{3/4}	1.595 ± 0.11
120 days	25°C	15.74 ± 1.09	11.94 ± 1.71	9.40 ± 1.19	9.13 ± 1.47	5 ^{3/4}	1.493 ± 0.31
	30°C	17.47 ± 0.74	13.68 ± 0.96	9.99 ± 0.47	9.80 ± 0.49	5 ^{3/4}	1.808 ± 0.30
135 days	25°C	16.02 ± 1.10	12.48 ± 0.79	9.57 ± 0.76	9.34 ± 0.92	5 ^{3/4}	1.554 ± 0.23
	30°C	17.50 ± 0.56	13.77 ± 0.88	10.05 ± 0.52	9.88 ± 0.64	>5 ^{3/4}	1.853 ± 0.19
150 days	25°C	16.61 ± 0.75	13.12 ± 0.72	10.12 ± 0.39	9.76 ± 0.54	>5 ^{3/4}	1.890 ± 0.18
	30°C	17.52 ± 0.82	14.41 ± 0.86	10.18 ± 0.74	9.99 ± 0.51	>5 ^{3/4}	1.925 ± 0.21

Notes: Abbreviations: AH, aperture height; AW, aperture width; SH, shell height; SW, shell width; Weight, total body mass in grams; Whorls, number of shell whorls.

Influence of dietary composition on morphometric growth

Dietary composition exercised a major effect on shell growth and body mass accumulation (Table 5). Snails receiving a high-protein supplement (chicken starter feed C210) alongside *Citrus* foliage consistently outperformed individuals restricted to foliage alone across all measured time intervals.

Divergence in growth was observable as early as 15 days post-hatching. At 15 days, the supplemented group reached an SW of 3.31 ± 0.24 mm and a body mass of 0.009 g (2.25 whorls), whereas the foliage-only group measured 2.07 ± 0.11 mm SW and 0.002 g mass (1.25 whorls) (Table 5). At 75 days, supplemented snails reached an SW of 15.16 ± 0.99 mm and a body mass of 1.063 ± 0.20 g (5.5 whorls), whereas foliage-restricted snails measured 9.05 ± 0.44 mm SW and 0.288 ± 0.069 g mass (4.5 whorls) (Table 5).

By day 150, individuals provided with the protein-enriched diet attained a mean body mass of 1.925 ± 0.21 g, an SW of 17.52 ± 0.82 mm, an SH of 14.41 ± 0.86 mm, an AH of 10.18 ± 0.74 mm, an AW of 9.99 ± 0.51 mm, and >5.75 shell whorls. Conversely, individuals restricted to vegetative foliage reached a mean body mass of 0.433 ± 0.10 g, an SW of 10.95 ± 0.75 mm, an SH of 9.44 ± 0.95 mm, an AH of 7.79 ± 0.62 mm, an AW of 6.84 ± 0.68 mm, and >5.25 whorls (Table 5).

Table 5 Influence of dietary composition on the shell dimensions and body weight of *Acusta tourannensis* over a 150-day developmental period under laboratory conditions.

Age (days)	Dietary composition	SW (mm)	SH (mm)	AH (mm)	AW (mm)	Whorls	Weight (g)
Hatching	Bran + Vegetative Material	1.82 ± 0.13	1.62 ± 0.26	1.44 ± 0.21	1.16 ± 0.17	1 ^{1/4}	0.002
	Vegetative Material Only	1.82 ± 0.13	1.62 ± 0.26	1.44 ± 0.21	1.16 ± 0.17	1 ^{1/4}	0.002
15	Bran + Vegetative Material	3.31 ± 0.24	2.55 ± 0.28	2.14 ± 0.16	1.72 ± 0.19	2 ^{1/4}	0.009
	Vegetative Material Only	2.07 ± 0.11	1.67 ± 0.09	1.44 ± 0.05	1.15 ± 0.09	1 ^{1/4}	0.002
30	Bran + Vegetative Material	5.19 ± 0.68	4.03 ± 0.56	3.33 ± 0.40	2.84 ± 0.33	3 ^{1/2}	0.043 ± 0.015
	Vegetative Material Only	2.82 ± 0.20	2.13 ± 0.18	1.82 ± 0.17	1.35 ± 0.15	2 ^{1/4}	0.008 ± 0.002
45	Bran + Vegetative Material	8.86 ± 1.27	6.98 ± 1.17	5.92 ± 0.96	4.93 ± 0.71	4 ^{1/2}	0.253 ± 0.03
	Vegetative Material Only	4.38 ± 0.38	3.47 ± 0.36	2.95 ± 0.29	2.55 ± 0.26	3 ^{1/4}	0.037 ± 0.01
60	Bran + Vegetative Material	8.92 ± 1.87	7.12 ± 1.52	6.06 ± 1.15	4.91 ± 1.05	4 ^{3/4}	0.492 ± 0.09
	Vegetative Material Only	6.86 ± 0.60	5.53 ± 0.44	4.41 ± 0.41	3.85 ± 0.23	4	0.178 ± 0.067
75	Bran + Vegetative Material	15.16 ± 0.99	11.56 ± 0.76	9.34 ± 0.36	8.57 ± 0.45	5 ^{1/2}	1.063 ± 0.20
	Vegetative Material Only	9.05 ± 0.44	6.97 ± 0.83	5.67 ± 0.48	4.93 ± 0.62	4 ^{1/2}	0.288 ± 0.069
90	Bran + Vegetative Material	16.89 ± 0.65	12.91 ± 0.31	9.87 ± 0.21	9.49 ± 0.61	>5 ^{1/2}	1.326 ± 0.14
	Vegetative Material Only	9.48 ± 1.19	8.12 ± 1.06	6.39 ± 0.77	5.62 ± 0.89	>4 ^{1/2}	0.300 ± 0.092
105	Bran + Vegetative Material	17.21 ± 0.64	13.55 ± 0.73	9.90 ± 0.22	9.71 ± 0.40	5 ^{3/4}	1.595 ± 0.11
	Vegetative Material Only	10.36 ± 1.09	8.29 ± 0.98	7.01 ± 0.87	6.45 ± 0.52	4 ^{3/4}	0.310 ± 0.093
120	Bran + Vegetative Material	17.47 ± 0.74	13.68 ± 0.96	9.99 ± 0.47	9.80 ± 0.49	5 ^{3/4}	1.808 ± 0.30
	Vegetative Material Only	10.41 ± 1.08	8.41 ± 0.97	7.15 ± 0.74	6.59 ± 0.38	5	0.370 ± 0.08
135	Bran + Vegetative Material	17.50 ± 0.56	13.77 ± 0.88	10.05 ± 0.52	9.88 ± 0.64	>5 ^{3/4}	1.853 ± 0.19
	Vegetative Material Only	10.65 ± 0.84	8.78 ± 0.75	7.72 ± 0.47	6.67 ± 0.45	>5	0.385 ± 0.089
150	Bran + Vegetative Material	17.52 ± 0.82	14.41 ± 0.86	10.18 ± 0.74	9.99 ± 0.51	>5 ^{3/4}	1.925 ± 0.21
	Vegetative Material Only	10.95 ± 0.75	9.44 ± 0.95	7.79 ± 0.62	6.84 ± 0.68	>5 ^{1/4}	0.433 ± 0.10

Notes: Abbreviations: AH, aperture height; AW, aperture width; SH, shell height; SW, shell width; Weight, total body mass in grams; Whorls, number of shell whorls.

Effects of temperature on embryonic development and hatching success

Incubation trials demonstrated that ambient temperature significantly dictated embryonic development duration and hatching viability in *A. tourannensis* (Table 6). Embryonic development duration was inversely related to temperature within the functional thermal range. The shortest mean incubation period occurred at 30 °C (11.15 ± 1.41 days; range 9–14 days), followed by 25 °C (13.07 ± 2.03 days; range 9–16 days), and 20 °C (15.63 ± 2.29 days; range 11–19 days) (Table 6). The coefficient of variation (CV) for the incubation duration across functional temperatures was 1.40%.

Embryonic viability peaked at 25 °C, yielding a mean hatching success rate of 95.91 ± 4.69 per cent (range 85–100%). Raising the temperature to 30 °C slightly reduced mean hatching success to 93.51 ± 5.76 per cent (range 83–100%), while lowering the temperature to 20 °C reduced hatching success to 90.66 ± 3.17 per cent (range 81–95%). The overall coefficient of variation for hatching rate was 0.32%. At an incubation temperature of 35 °C, complete embryonic mortality was recorded, establishing 35 °C as above the upper thermal tolerance limit for egg viability in this species (Table 6).

Table 6 Effects of constant incubation temperatures (20°C, 25°C, 30°C, and 35°C) on the embryonic development duration and hatching success of *Acusta tourannensis* eggs under laboratory conditions.

Observation indicators		Temperature (°C)			
		20	25	30	35
Incubation period	Min (days)	11	9	9	-
	Max (days)	19	16	14	-
	Average (days)	$15.63^a \pm 2.29$	$13.07^b \pm 2.03$	$11.15^c \pm 1.41$	-
	(Av $\pm$ SD)				
CV (%)	1.40				
Hatching rate	Min (%)	81	85	83	-
	Max (%)	95	100	100	-
	Average(%)	$90.66^c \pm 3.17$	$95.91^a \pm 4.69$	$93.51^b \pm 5.76$	-
	(Av $\pm$ SD)				
CV (%)	0.32				

Notes: Abbreviation: SD, standard deviation. Values of zero at 35°C indicate a complete lack of embryonic development or survival.

Influence of dietary composition on reproductive performance

Dietary quality exerted a substantial impact on adult fecundity and offspring development parameters (Table 7). Mating pairs provided with protein-enriched layer feed (C145) alongside *Citrus* foliage produced a mean cumulative output of 240.6 ± 24.85 eggs per adult. In contrast, pairs restricted to *Citrus* foliage produced 30.10 ± 7.03 eggs per adult, representing an approximate eightfold difference in reproductive output.

Dietary composition also influenced egg incubation times and hatching success. Eggs produced by adults fed the supplemented diet exhibited a shorter mean incubation duration (11.16 ± 1.64 days) and a higher mean hatching success rate (93.51 ± 5.47 per cent) compared to eggs from adults restricted to foliage (incubation duration: 13.42 ± 1.39 days; hatching success: 92.57 ± 3.08 per cent) (Table 7).

Table 7 Comparison of reproductive performance and egg viability in *Acusta tourannensis* subjected to varying nutritional regimes under laboratory conditions (30°C; 80% relative humidity).

Diet	Incubation period (days)			Hatching rate (%)			Total number of eggs (eggs/adult)		
	Min (days)	Max (days)	Average (days) (Av± SD)	Min (%)	Max (%)	Average (%) (Av± SD)	Min (eggs)	Max (eggs)	Average (eggs) (Av± SD)
Bran + Vegetative Material	9	14	11.16 ^b ±1.64	83	100	93.51 ^a ±5.47	170	271	240.6 ^a ±24.85
Vegetative Material Only	11	15	13.42 ^a ±1.39	84	96	92.57 ^b ±3.08	9	41	30.10 ^b ±7.03
CV(%)	2.1			0.29			3.88		

Notes: Abbreviation: SE, standard error. Vegetative material refers to Citrus leaves and young shoots.

Life cycle duration and overall fecundity

Under controlled laboratory conditions (25°C, 80% relative humidity), *A. tourannensis* completed its full life cycle from egg deposition to adult biological maturity in a mean duration of 117.3 ± 11.6 days (range 107–130 days). The embryonic incubation phase averaged 13.2 ± 1.4 days, achieving a mean hatching success rate of 98.1 ± 3.34 per cent. Lifetime cumulative egg production averaged 564.6 ± 96.1 eggs per adult, with a maximum recorded output of 647 eggs per individual (Table 8).

Table 8 Life cycle parameters and cumulative fecundity of *Acusta tourannensis* maintained under optimal laboratory conditions (25°C; 80% relative humidity).

Observation indicators	Metrics		
	Min	Max	Average (Av ± SD)
Life cycle duration (days)	107	130	117.3 ± 11.6
Incubation period (days)	11	15	13.2 ± 1.4
Hatching rate (%)	89	100	98.1 ± 3.34
Total number of eggs (eggs/adult)	448	647	564.6 ± 96.1

Note: Standard Deviation (SD) ; Average (Av); Min - Minimum, Max - Maximum

DISCUSSION

The findings of this study provide the first comprehensive evaluation of terrestrial gastropod assemblages infesting orange (*Citrus sinensis* (L.)) orchards across both northern and southern Vietnam. A total of 16 species representing nine families were documented, identifying *Acusta tourannensis* (Souleyet, 1842) as the predominant malacological pest within these agroecosystems. The observed patterns of species richness and regional dominance align with previous studies on molluscan communities in tropical fruit production systems, where ambient microclimate, canopy architecture, and orchard management practices strongly shape community structure and species distribution [10, 17].

The consistent prevalence and high occurrence frequency of *A. tourannensis* across both surveyed geographic regions reinforce its status as an adaptable and destructive agricultural pest. Its polyphagous feeding strategy and ability to consume multiple plant components, including young foliage, tender shoots, and developing fruit rinds, present a severe threat to tree health, overall yield, and commercial fruit quality. Furthermore, the nocturnal foraging behavior, cryptic microhabitat selection, and overlapping generations characteristic of this species complicate early field detection and reduce the efficacy of conventional management interventions.

Controlled laboratory investigations provided key insights into the ecological plasticity and thermal tolerance limits of *A. tourannensis*. Elevating ambient temperatures to 30°C significantly accelerated juvenile growth rates and total body mass

accumulation, a pattern consistent with the metabolic theory of ecology. Under contemporary climate projections, rising mean global temperatures could accelerate generation times, increase seasonal population densities, and expand the potential geographic range of this species across tropical and subtropical citrus-growing zones [39, 40].

However, although warmer conditions shortened embryonic development duration, elevated temperatures did not correspond to higher reproductive success. Embryonic viability peaked at 25°C, exhibited a moderate reduction at 30°C, and resulted in complete developmental failure at 35°C. These observations demonstrate a clear physiological thermal limit beyond which embryonic survival is severely compromised, likely due to heat-shock protein denaturation or cellular metabolic distress [41, 42]. These thermal constraints indicate that despite rapid juvenile growth during warmer months, *A. tourannensis* populations remain vulnerable to extreme heat events. Establishing these physiological boundary offers a scientific foundation for refining population forecasting models and optimizing the timing of control interventions [43, 44].

Dietary experiments demonstrated that nutritional quality strongly influences both the development trajectories and adult fecundity. Snails provided with a protein-enriched supplement alongside *Citrus* foliage exhibited a 4.4fold increase in final body mass and an approximate eightfold increase in total egg production compared to individuals restricted to foliage alone. These results concur with previous malacological research showing that protein and calcium availability are limiting factors for shell biomineralisation, soft-tissue growth, and reproductive output in terrestrial gastropods [45, 46]. Within citrus agroecosystems, organic inputs such as fallen decaying fruit or cover-crop residues may act as supplemental nutritional reservoirs, inadvertently promoting rapid population growth.

From a pest management perspective, this study emphasizes the necessity of targeted interventions against *A. tourannensis* during critical phenological windows. Integrated Pest Management strategies combining cultural controls, such as leaf litter management, weed clearance, and orchard sanitation, with judicious selective chemical applications or potential biological control agents are far more sustainable than complete reliance on broad-spectrum molluscicides. Given that *A. tourannensis* completes its life cycle in approximately 117 days under optimal conditions, control measures should be strategically timed to disrupt reproductive cohorts prior to peak oviposition periods.

Finally, the regional variation in gastropod community structure, characterized by higher species richness in southern Vietnam, highlights the importance of localized agroecological monitoring. Management frameworks must be tailored to specific production environments. Furthermore, the presence of rare, non-pest species, such as *Quantula weinkauffiana* (Crosse & P. Fischer, 1863), serves as a useful biological indicator of orchard ecosystem stability and biodiversity [37, 47].

In conclusion, this investigation establishes baseline ecological and biological parameters for *A. tourannensis* as a primary pest of citrus crops in Vietnam. Future research should focus on validating these laboratory parameters under field conditions, evaluating candidate biological control agents, and developing sustainable, low-impact molluscicidal alternatives to protect citrus production while preserving beneficial non-target fauna.

CONCLUSIONS

This study provides the first systematic documentation of terrestrial gastropod diversity and the fundamental biological traits of the major pest *Acusta tourannensis* (Souleyet, 1842) within Vietnamese orange (*Citrus sinensis*) orchards. Field surveys across the key production provinces, including Tien Giang, Hau Giang, and Hung Yen, revealed a malacofauna of 16 species, with *A. tourannensis* consistently identified as the predominant economic threat to citrus cultivation across both northern and southern regions.

Experimental findings demonstrate that ambient temperature and dietary composition act the primary environmental drivers governing the ontogeny and reproductive performance of *A. tourannensis*. Although elevated temperatures up to 30°C accelerate juvenile growth rates and shorten incubation periods, embryonic survival is strictly constrained by an upper critical thermal threshold, evidenced by complete developmental failure at 35°C. Furthermore, the substantial increase in adult fecundity recorded under protein-supplemented dietary regimes underscores the opportunistic reproductive potential of this species in nutrient-rich agricultural systems.

These biological parameters provide an essential foundation for predicting seasonal population dynamics and designing integrated pest management strategies tailored to Southeast Asian citrus agroecosystems. Incorporating these physiological thresholds into

longitudinal monitoring frameworks will enable producers to optimize the timing of control interventions. Future research should prioritize field-level validation of these laboratory observations and evaluate environmentally sustainable, low-impact management tactics to protect citrus yields across tropical regions.

Declarations

Ethics approval and consent to participate

Field surveys and specimen collections of the land snail were conducted in citrus orchards with permission from the orchard owners. As this study involved terrestrial gastropods (invertebrates), no specific ethical approval or institutional permit was required under national regulations or institutional guidelines in Vietnam.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no conflicts of interest.

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Author contributions

Ha T.K.T.: Conceptualization, investigation, data curation, formal analysis, writing original draft, manuscript revision.

Pham H.H.: Methodology, validation.

Ngo V.D.: Field investigation, specimen collection.

Trinh X.H.: Resources, project administration, manuscript editing, corresponding author.

Fan Dong: Supervision, funding acquisition, manuscript editing, corresponding author.

Ravindra Chandra Joshi: Supervision, manuscript editing.

Do D.S.: Species collection and identification.

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Figures



Figure 1

Representative shells and external morphology of terrestrial gastropods identified in Vietnamese orange orchards. A. *Allopeas gracile*. B. *Lissachatina fulica*. C. *Subulina octona*. D. *Deroceras laeve*. E. *Sarika resplendens*. F. *Acusta tourannensis*. G. *Amphidromus inversus*. H. *Bradybaena jourdyi*.



Figure 2

Representative shells and external morphology of terrestrial gastropods. **A.** *Bradybaena similaris*, **B.** *Quantula weinkauffiana*, **C.** *Meghimatium bilineatum*, **D.** *Succinea* sp., **E.** *Valiguna siamensis*, **F.** *Laevicaulis alte*, **G.** *Succinea tenella*, **H.** *Gulella bicolor*.



Figure 3

Developmental and reproductive stages of the land snail *Acusta tourannensis*. (A) Shell morphology displaying apertural, side, dorsal, and ventral views. (B) Adult individual. (C) Mating behaviour. (D) Oviposition process. (E) Egg. (F) Newly hatched juvenile.

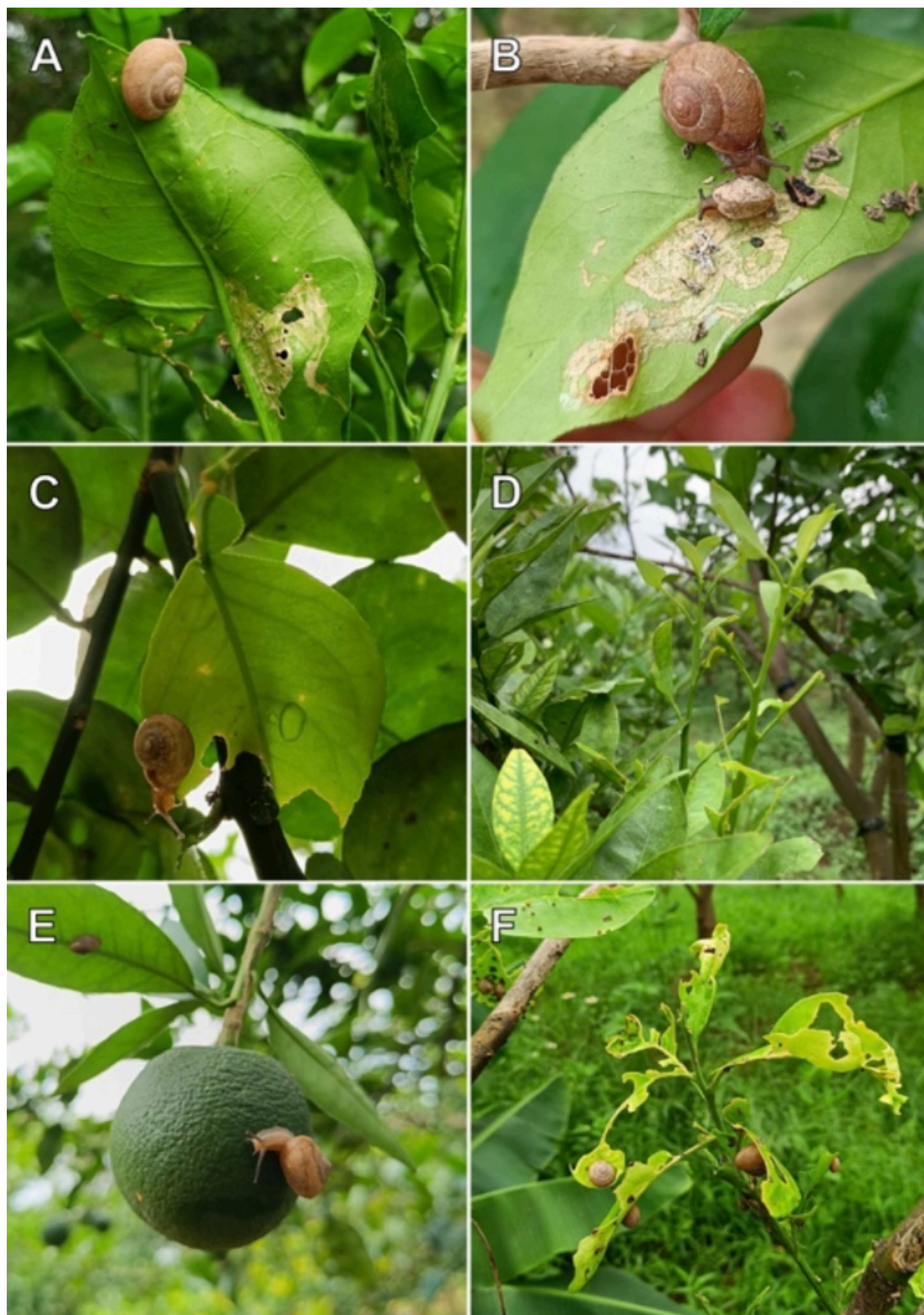


Figure 4

Damage symptoms caused by land snails and slugs on orange trees in Tien Giang, Hau Giang, and Hung Yen Provinces, Vietnam. (A, B, C) Symptoms of leaf damage; (E) Fruit damage; (D, F): young shoot damage