

Evaluating the Biggenden Banded Snail (*Figuladra bayensis*) as a climate archive for SE Queensland, Australia, using stable isotopes and ^{14}C dating

The Holocene

1–14

© The Author(s) 2026



Article reuse guidelines:

sagepub.com/journals-permissions

DOI: 10.1177/09596836261477272

journals.sagepub.com/home/hol



Nicholas R. Patton^{1,2,3} , James Shulmeister^{1,2} , Melanie J. Leng^{4,5},
Matthew Jones⁶ , Quan Hua^{1,7} and Jennifer R. Kielhofer⁸

Abstract

Land snails can be utilized to infer paleoclimate variability due to the preservation and incorporation of stable isotopes in their aragonite shells ($\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$). A *Figuladra bayensis* (Biggenden Banded Snail) shell was collected shortly after death from Coalstoun Lakes National Park (CLNP), Queensland, Australia to investigate if this species is suitable for paleoclimate investigations. A total of 200 samples were collected for $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ analyses and additional eight radiocarbon (^{14}C) dating samples were collected along the shell's growth axis from the apex to the aperture (234 mm) from one typical modern (recently dead) specimen. Results indicate that the Biggenden Banded Snail lived approximately 4.5 years with “step-like” shell growth rates between 23.7 and 144.3 mm yr⁻¹. Our ^{14}C ages permit the record to be tied to observed extreme rain events (i.e. ex-tropical cyclones) without inferring time-based growth intervals or isotopic fluctuations alone. The $\delta^{18}\text{O}_{\text{shell}}$ values depict seasonal variability with a rapid decrease immediately after large precipitation events, followed by more gradual increases in $\delta^{18}\text{O}_{\text{shell}}$ as conditions dry. In contrast, the $\delta^{13}\text{C}_{\text{shell}}$ record reflects variability in the snail's C_3 diet with the seasons and as the specimen matures. The one exception to this pattern is the one large decrease during a phase of higher moisture and warmer temperature that may be related to snail reproduction. The development of an event-informed interpretive age-growth model constrained using multiple ^{14}C measurements along the growth axis represents an important innovation in snail isotope studies. This work establishes the first Biggenden Banded Snail isotope time-series while improving our understanding of the general relationships between land snail shell stable isotope records and climate.

Keywords

$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, radiocarbon, ^{14}C , Coalstoun Lakes National Park, land snails, sclerochronology, terrestrial gastropods, paleoclimate, seasonality, extreme events, cyclones

Received: 26 February 2026; accepted: 10 July 2026

Introduction

Land snails are prevalent throughout the world. They are associated with small, localized geographic areas and habitat that is particular to their species due to their limited vagility and sensitivity to environmental variables (Douris et al., 1998; Staniscic, 1998, 1999; Staniscic and Ponder, 2004; Wu et al., 2018). The oxygen and carbon stable isotope ratios preserved in the aragonite shell of land snails provide records of local environmental conditions and physiological changes of the organism (Balakrishnan and Yapp, 2004; Goodfriend, 1992; Nicolai and Ansart, 2017;

¹University of Queensland, Brisbane, QLD, Australia

²University of Canterbury, Christchurch, New Zealand

³Idaho State University, Pocatello, ID, USA

⁴British Geological Survey, Keyworth, Nottingham, UK

⁵University of Nottingham, Loughborough, UK

⁶University of Nottingham, Nottingham, UK

⁷Australian Nuclear Science and Technology Organisation, Kirrawee DC, NSW, Australia

⁸Desert Research Institute, Reno, NV, USA

Corresponding author:

Nicholas R. Patton, Department of Geosciences, Idaho State University, Pocatello, ID, USA.

Email: NicholasPatton@isu.edu

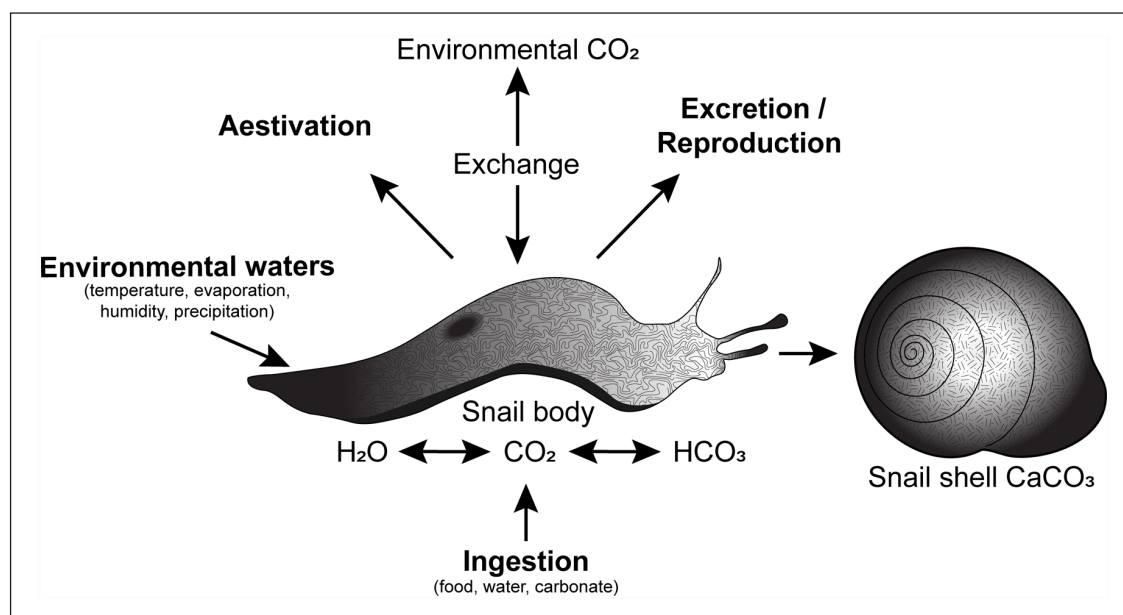


Figure 1. Generalized diagram depicting various environmental factors that influence both the oxygen ($\delta^{18}\text{O}_{\text{shell}}$) and carbon ($\delta^{13}\text{C}_{\text{shell}}$) isotopic composition of land snail shells. Shell carbonate, more specifically aragonite, is derived from dissolved bicarbonate in the snail's body fluids. Major controls on the isotopic composition of the bicarbonate, and consequently the shell, include: (1) environmental waters, which are influenced by climatic and environmental factors such as temperature, evaporation, humidity, and precipitation, (2) ingestion of dietary materials, which become metabolic CO_2 via respiration, and (3) atmospheric or environmental CO_2 , which can exchange across the snail's soft tissue. Life cycle processes of the snail, such as reproduction and estivation, may also affect the snail's isotopic composition. Figure modified from Leng et al. (1998).

Pigati et al., 2013). Shell oxygen isotope composition ($\delta^{18}\text{O}_{\text{shell}}$) is inferred to be primarily controlled by temperature, the oxygen isotopic composition of environmental waters such as precipitation ($\delta^{18}\text{O}_{\text{precip}}$), and the evaporation of local water or snail body water (Figure 1) (Balakrishnan and Yapp, 2004; Dettman et al., 2024; Leng et al., 1998; Prendergast et al., 2015; Zaarur et al., 2011). As a result, studies utilize $\delta^{18}\text{O}_{\text{shell}}$ to reconstruct precipitation or rainfall isotopic composition, given that land snails are mainly active after rain events and largely consume rainwater (Nield et al., 2022; Ward and Slotow, 1992; Zong et al., 2023). Similarly, shell carbon isotopic composition ($\delta^{13}\text{C}_{\text{shell}}$) has been used to infer long-term shifts in precipitation and environmental change (e.g. Bao et al., 2023), but most commonly is a proxy for respiration and diet (i.e. C_3 vs C_4 vegetation), with diet contributing the predominant source of carbon within the shell (Figure 1; DeNiro and Epstein, 1978; Goodfriend and Ellis, 2002; Hill et al., 2017; Li et al., 2025; Stott, 2002; Zaarur et al., 2011).

Isotope variability in snail shells has been extensively analyzed using whole shells to represent average $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ (e.g. Balakrishnan et al., 2005; Goodfriend and Ellis, 2002; Magaritz and Heller, 1983; Rech et al., 2021; Yanes et al., 2014). The advantage of bulk shell analysis is its low cost, reproducibility, and application in longitudinal or spatial studies (e.g. Prendergast et al., 2017; Yanes et al., 2019). Although bulk shell samples provide average information on local climatic and ecological conditions and dominant food sources, temporal information is lost (Dettman et al., 2024). To access this information, multiple samples representing a time series from individual shells may be used (e.g. Dettman et al., 2024; Dong et al., 2022; Wang et al., 2020; Zong et al., 2023).

Depending on the sampling frequency, this technique can produce high-resolution, intra-shell records of climatic and environmental change over a single snail's lifetime (Zong et al., 2025). Moreover, multiple specimens of varying ages can be analyzed and combined into a composite record that can yield snapshots of climate variability through time, which may include evidence of climate stability, inter-annual to seasonal variability, frequency of extreme events, habitat conductivity, and resource availability (Dettman et al., 2024; Zhang et al., 2025).

Here we investigate a modern Biggenden Banded Snail within the humid subtropical Coalstoun Lakes National Park (CLNP), southeastern Queensland, Australia. Our aim is to determine if $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ can be used as a proxy for paleoclimate reconstruction for this species. We collected stable isotope samples along the whorl of the shell and set a chronological framework coupling multiple radiocarbon (^{14}C) dates along the shell's growth axis with observed synoptic events within the CLNP to produce an event-informed age model. Results provide insight on the biological life cycle of the Biggenden Banded Snail, for which little is known, and show the potential for this taxon to be used as a paleoenvironmental proxy.

Biggenden Banded Snail (Figuladra bayensis)

The Biggenden Banded Snail is part of the largest and most successful terrestrial gastropod family in Australia, the Camaenidae, and is found in a wide range of habitats (e.g. rainforests, open-woodlands, and savannahs; e.g. Hugall et al., 2002; Köhler, 2011; Parkyn and Newell, 2013; Stanisic et al., 2010, 2018). The *Figuladra* genus is distributed across mid- and southeastern Queensland. Two

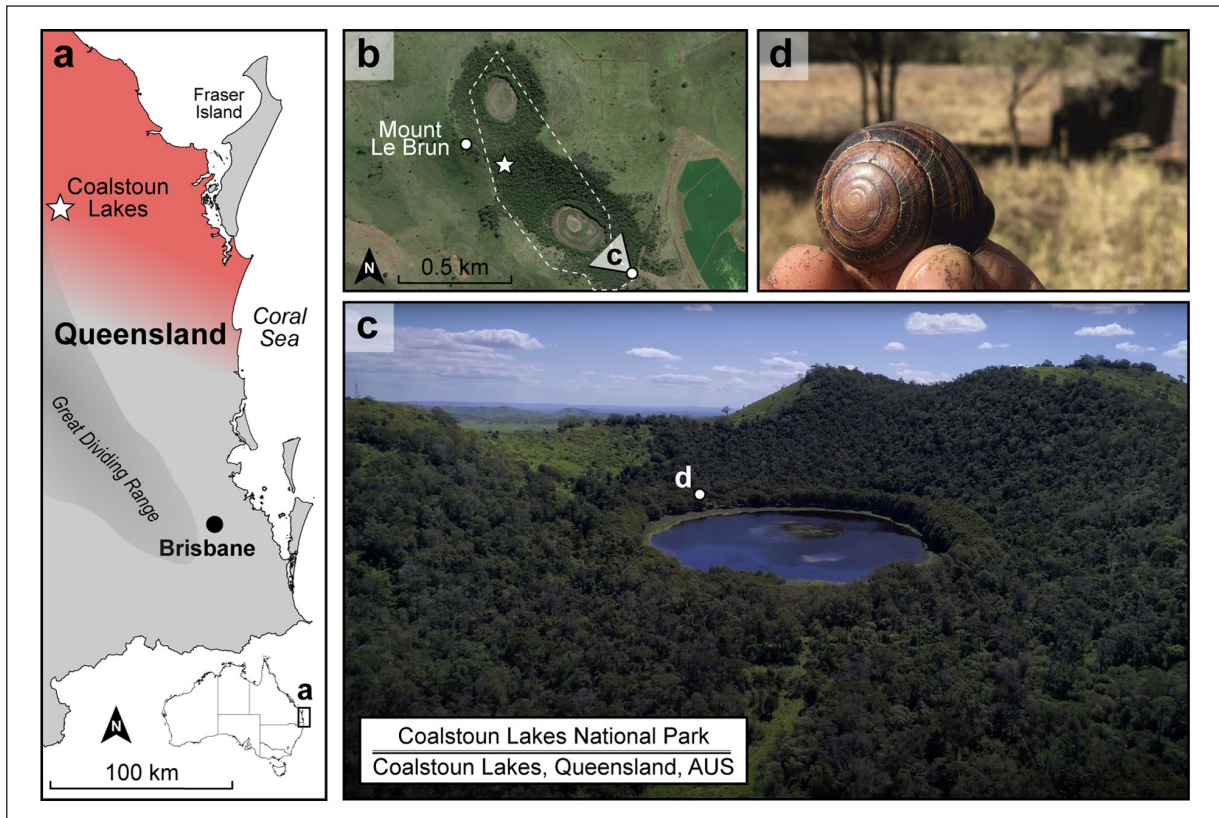


Figure 2. Site location of Coalstoun Lakes National Park (CLNP) in southeastern Queensland, Australia. (a) Country and regional views of the field area with the approximate distribution of the Biggenden Banded Snail populations (red area) as delineated by Stanisic et al. (2010). (b) Aerial view of the two volcanic calderas highlighting the location of the snail shell sampled in this study (star), summit of Mount Le Brun (dot), and the CLNP extent (dashed line). (c) Drone imagery of the lower crater of the lower crater on 4 February 2017 after ex-tropical cyclone Debbie filled both lakes. (d) Close-up image of the Biggenden Banded Snail shell utilized in this research. (Photo credit: panel (c) – John Hale).

species are found further inland amongst the upland, dry seasonal tropical forest and subtropical dry forest habitats, one of which is the Biggenden Banded Snail (SEQ upland–Clade 1A taxa; Hugall and Stanisic, 2011; Stanisic et al., 2022). Little is known of the Biggenden Banded Snail life cycle. Stanisic et al. (2010, 2024) provide ecological depiction, species distribution, and family description (phylogenetics and comparative morphoanatomy); however, no information is reported on lifespan. Similar to other snails, they have an aragonite shell that is formed at the aperture and grows along the growth axis in a clockwise manner (dextral). This continues until the snail has reached full maturity, after which its shell lip begins to thicken and shell growth essentially ceases. We anticipate the snails are active during the warm, wet summer months, and estivate in the cool, drier winter. Food is likely to be semi-decayed C_3 vegetation found within the CLNP's vine thickets.

Materials and methods

Study site: Coalstoun Lakes National Park (CLNP)

Located 230 km north of the city of Brisbane, Queensland, the CLNP (25.5966°S, 151.9099°E) is situated subjacent to Mount Le Brun (Figure 2). The proximal but separate twin lakes were created by one of the most recent volcanic eruptions in southeastern Queensland approximately 600,000 years

ago (Department of the Environment, Tourism, Science and Innovation, 2026). The climate is humid subtropical (Cfa, Köppen climate classification) with humid, hot summers (October–March) and drier, mild winters (April–September; Peel et al., 2007). The closest and most continuous meteorological station (Gayndah Airport ~30 km west) indicates mean monthly minimum and maximum temperatures that range from 7.3°C to 33.6°C (mean 28.8°C) and average annual rainfall of approximately 630 mm. Roughly 75% of the precipitation falls in the summer months, largely due to ex-tropical cyclones (BOM, 2026). Mean monthly $\delta^{18}O_{precip}$ compositions are estimated to range from −6.0 to −1.9‰ (VSMOW) with the lowest and highest values observed in late summer and late winter, respectively (Supplemental Figure 1; Falster et al., 2026). Precipitation is the only source of water for the perched lakes system due to its position >150 m above the surrounding terrain. After prolonged periods without substantial rainfall (typically in late winter), lake levels begin to lower as water infiltrates into the subsurface, subsequently draining the lakes and forming a dry, grass-covered lake bed (e.g. Figure 2b and c – wet to dry).

The volcanic cone is composed of vesiculated basalt (Baramba Basalt; Johnson et al., 1989). The upper and lower crater basins sit at an elevation of 400 and 349 m, respectively, and are enclosed by short, steep scree (talus) covered slopes. The weathered bedrock forms shallow, rocky and well drained Ferrosols, which are characterized by medium clay content and are neutral to slightly acidic.

These soils are found at all locations within the interior walls of the caldera rim. When the lakes periodically dry, the clay-rich basin floor forms large vertical cracks (McCarroll and Brough, 2000). The lakes experience drying roughly every 5 years (Mahar, 1993) with the most recent prolific dry spell during the “Millennium Drought” from 2001 to 2009. Despite variability in lake levels, vegetation has remained consistent since the establishment of the park in 1929 (Queensland Parks & Wildlife Service (QPWS), 2023), highlighting the area as a potential vegetation and biologic refugium.

The exterior and crest of the caldera cones are dominated by drier softwood scrub and brigalow woodlands, whereas the more mesic interior slopes have a diverse assortment of dry rainforest taxa including three-leaved bosistoa (*Bosistoa transversa*), crow ash (*Flindersia australis*) and leopard ash trees (*Flindersia collina*) while black tea-tree (*Melaleuca bracteata*) occurs near the edges of the lakes. When the lakes dry, an assortment of sedge-land plants such as Bunchy flat-sedge (*Cyperus polystachyos*), Bachelors buttons (*Cotula australis*), Sword Sedge (*Gahnia aspera*), Rhodes grass (*Chloris gayana*), Bermuda grass (*Cynodon dactylon* var. *dactylon*), among others, are rapidly established.

Climate and environmental data

As noted, the climate for the CLNP generally trends between wet, warm summers and dry, mild winters; however, precipitation events are temporally and spatially sporadic. There are few active and continuous meteorological stations within 50 km of our study and none within the CLNP. Data obtained from one, or any, of these stations are likely to represent site specific conditions or events that may not be experienced within our field area. Therefore, we opt to utilize a direct and indirect approximation of climate and environmental conditions over the snail’s life using the Scientific Information for Land Owners (SILO) weather dataset and the Wetland Insights Tool (WIT), respectively.

SILO is an open-sourced 0.05° daily gridded meteorological database which provides estimated synthetic data interpolated from ground-based weather stations across Australia (Frost et al., 2018; Jeffrey et al., 2001). Areas surrounding the CLNP have complex terrain that causes large heterogeneity and uncertainties in meteorological gridded datasets at local scales (Fu et al., 2022). As a result, we utilize the SILO dataset to represent general, regional climate trends in daily total rainfall, evaporation, and temperature.

In the absence of reliable local climate data, we use the WIT as a proxy for environmental conditions. WIT is an open-source dataset providing land surface coverage time-series data (biweekly) at 30 m resolution (Department of Environment Science and Innovation Queensland (DESIQ), 2019). The tool designates land cover using Landsat satellite imagery for a defined area of interest into five classifications from wettest to driest: open water, wet vegetation, green vegetation, dry vegetation, and bare

ground (Dunn et al., 2019). This tool has been utilized to evaluate seasonal and interannual variability for wetland ecosystems (Dunn et al., 2023); however, for this study we use it to observe changes in the snail’s ecosystem as a whole (e.g. rain and cyclone events, condition of the lakes, and droughts) that may not be captured in the SILO dataset. The only source of water entering the caldera is rainfall. Therefore, we can appropriately assume and validate those changes in the designated land cover to a wetter classification (e.g. dry vegetation to open water, or bare earth to green vegetation) indicating the presence of rain.

Biggenden Banded Snail collection

In early September 2018, we observed an abundance of land snail shells amongst the dense vine thicket, softwood scrubs, and protected shelter of boulders and logs within the CLNP crater’s understory. The specimens ranged in size from 10 to 55 mm in diameter and were composed of two species. Species were identified via photographs by J. Stanisic at the Queensland Museum (personal communication, 2019), who found the dominant specimen to be the Biggenden Banded Snail (*Figuladra bayensis*) with the less common Maryborough Dark Snail (*Sphaerospira sidneyi*). The largest, intact and apparently most recently deceased snail shell was selected for this study (Figure 2d). The death of the snail was inferred to be recent due to the presence of dried, decomposed soft-tissue and abundant, intact periostracum preserved in and on the shell, respectively. The aim was to ensure we analyzed the best-preserved shell with the longest, most continuous record for this work.

Stable isotope ($\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$) preparation and analyses

The shell was first cleaned with a brush in 10% hydrogen peroxide (H_2O_2) to remove organic matter, placed in an ultrasonic bath of deionized water (3x), and then oven dried at 50°C for 24 h. The specimen was evaluated under a Scanning Electron Microscope (SEM) to support that the shell was well preserved and retained an aragonitic composition with no evidence of recrystallization. The specimen was sent to the British Geological Survey (BGS) and carbonate samples were collected using a 0.8 mm Dremel drill bit, sampled from the apex to aperture along the growth axis using a uniform sample interval of ~1.1 mm. The top layer of shell (the periosteum) was carefully removed prior to analysis. Approximately 100 µg of powdered aragonite per sample was extracted into glass exetainers, purged with H_2 , and placed on a hot plate with phosphoric acid. The CO_2 gas released in the exetainer headspace was analyzed on an Isoprime dual inlet mass spectrometer coupled to a Multiprep device. Carbon (^{13}C) and oxygen (^{18}O) isotopes are reported in standard delta notation (e.g. $\delta^{18}\text{O}$), relative to the Vienna Pee Dee Belemnite (VPDB) standard. Analytical precision was calculated utilizing an internal laboratory standard (KCM) calibrated against an international NBS standard. Both the

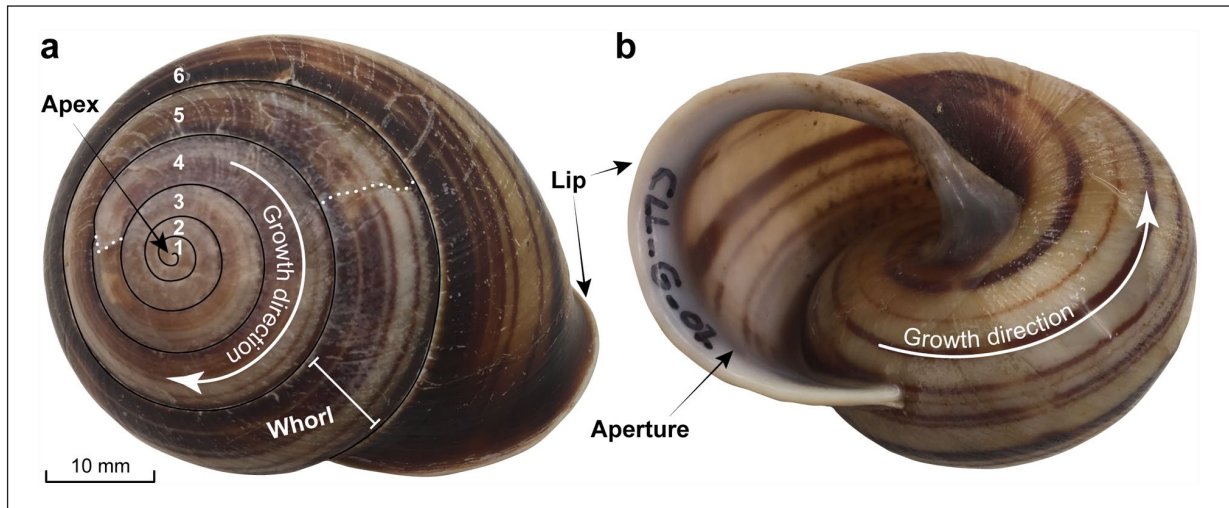


Figure 3. Photographs of the modern Biggenden Banded Snail (*Figuladra bayensis*) shell collected for this project for $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ stable isotope analyses and ^{14}C dating from two different perspectives: (a) side and (b) below views, respectively. Images highlight shell characteristics (patterns, colors), terminology locations, number of whorls, and depicts discontinuities/fractures on the shell (dotted white lines) that are discussed in this manuscript.

^{18}O and ^{13}C reproducibility for KCM was $<0.1\%$. The mineral-gas fractionation factor used for aragonite was 1.00854 (Kim et al., 2007).

^{14}C dating and growth rates

Five sample locations were selected for ^{14}C dating spaced evenly through the whorl of the snail shell using a 2 mm Dremel bit. For the Biggenden Banded Snail to be a suitable candidate for ^{14}C dating there must be minimal to no reservoir effects within the shell (i.e. through the consumption of “old” carbon such as other shells or limestone that would result in anomalously older ages). As a result, we collected additional three samples on the youngest material (aperture of the shell) assumed to be mid-August, 2018. This date was inferred by the presence of desiccated, soft tissue in the snail shell which decomposes rapidly, days to weeks, after death (Pearce, 2008). The aragonite shell samples (ca. 10 mg) were hydrolyzed to CO_2 using 85% phosphoric acid and converted to graphite using the H_2/Fe method (Hua et al., 2001) and loaded into an aluminum cathode for ^{14}C analysis using the VEGA AMS Facility at the Australian Nuclear Science and Technology Organisation (ANSTO; Wilcken et al., 2015). All measured ^{14}C values and associated uncertainties at 0.20–0.22% precision (1σ) are reported in fraction of modern carbon (F^{14}C) and calendar years. To place our stable isotope values in time, we create two age-growth models utilizing linear interpolation. The first model is generated by estimating sample age only with ^{14}C dates, whereas the second model includes timing of known ex-tropical cyclones and rain events that resulted in lake filling and vegetation greening (Supplemental Table 1). Existing work demonstrates that such events result in a distinct decrease in $\delta^{18}\text{O}_{\text{precip}}$ values (Hollins et al., 2018) that are preserved in snail $\delta^{18}\text{O}_{\text{shell}}$ records (Wang et al., 2024a, 2024b). Therefore, including the timing of observed large synoptic events as anchor points within our age-growth model provides increased confidence

and a more temporally continuous dataset. This refinement is not used in this study as an independent validation, but rather it improves our understanding of snail growth patterns and lifecycle within a chronological framework.

Results

Specimen's collection and morphometric measures

The shell is classified as *very large* with a 51.5 mm diameter, 37.5 mm height, 0.73 height to diameter ratio, and a 6.25 whorl count (Figure 3). The total length of the snail shell along the sampling line (growth axis from the apex to aperture) is 234 mm with two apparent and minor shell discontinuities (i.e. fractures or defects) at 55 and 139 mm. The specimen has a reflected, slightly thickened lip, and the shell is smooth with extremely fine microsculptures, consistent with measurements and observations from other mature Biggenden Banded Snails (Stanisic et al., 2022, 2024).

$\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ isotopes

The isotope time series are relatively smooth and continuous with no significant shifts in values associated with visual shell defects (Figure 4). The $\delta^{18}\text{O}_{\text{shell}}$ mean, standard deviation, median, and range values are -2.22% , $+1.57\%$, -1.77% , and $+7.22\%$, respectively. These results are consistent with expected mean $\delta^{18}\text{O}_{\text{shell}}$ values from land snails of similar latitude, average annual $\delta^{18}\text{O}_{\text{precip}}$, and mean annual temperatures (Yanes et al., 2019). The $\delta^{18}\text{O}_{\text{shell}}$ value for the time of the snail's death (i.e. at aperture) is -2.35% . There is an apparent cyclic pattern with two broad troughs and three peaks spaced such that two wavelengths of similar length are observed (0–130 mm and 130–234 mm). They have amplitudes greater than 6%. Within these larger features are smaller, more narrow

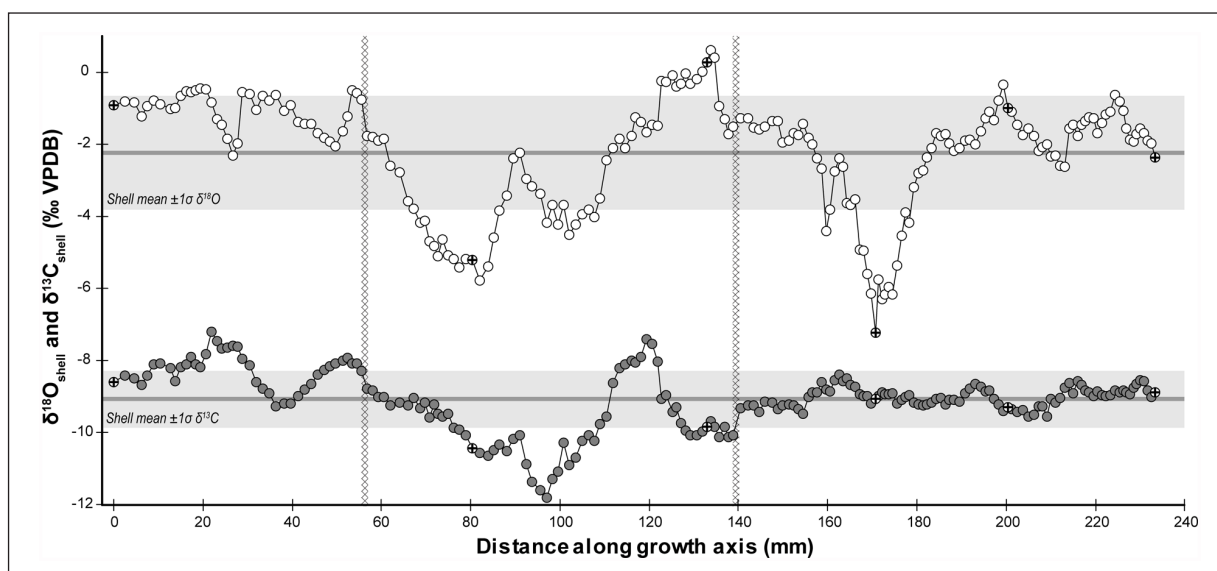


Figure 4. The $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ stable isotopes (white and gray dots, respectively) analyzed from the apex to the aperture (0–234 mm). The mean values for $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ within the shell are -2.22‰ and -9.05‰ , respectively, indicated by a solid, gray horizontal line with the lighter horizontal bar representing their standard deviation. Vertical hashed columns correspond to discontinuities/fractures observed on the surface of the shell, whereas dots with crosses denote locations of ^{14}C age estimates. All isotopic data was provided by the National Environmental Isotope Facility (NEIF) at the British Geological Society (BGS).

troughs and peaks ranging in length (20–65 mm) with amplitudes of approximately 2‰.

The $\delta^{13}\text{C}_{\text{shell}}$ mean, standard deviation, median, and range values are -9.05‰ , 0.79‰ , -8.99‰ , and 4.60‰ , respectively. The $\delta^{13}\text{C}_{\text{shell}}$ value for the time of the snail's death (i.e. at aperture) is -8.88‰ . The $\delta^{13}\text{C}_{\text{shell}}$ and $\delta^{18}\text{O}_{\text{shell}}$ records depict similar in-phase cyclic patterns with the $\delta^{13}\text{C}_{\text{shell}}$ data being more consistent along the transect, especially in the latter portion of the record. We observe regular amplitude shifts of nearly 2‰ with one distinct 4‰ shift $\delta^{13}\text{C}_{\text{shell}}$ that corresponds with the first major decline in $\delta^{18}\text{O}_{\text{shell}}$. The only clear discrepancy between the two isotopic records occurs at $\sim 170\text{ mm}$ where the second major decline in $\delta^{18}\text{O}_{\text{shell}}$ does not have a concordant shift in $\delta^{13}\text{C}_{\text{shell}}$.

^{14}C dating

Eight ^{14}C samples were collected and analyzed (Table 1). The three samples collected at the snail's aperture show consistent measured $F^{14}\text{C}$, with all values agreeing within 1σ uncertainties, which is equal to a weighted mean value of 1.0604 ± 0.0015 . This $F^{14}\text{C}$ value was used for the estimation of the radiocarbon reservoir age (R) for the shell by comparing with contemporaneous atmospheric $F^{14}\text{C}$ value (1.0204 ± 0.0006) from bomb radiocarbon data for the Southern Hemisphere (SH) Zone 1–2 for the assumed time of death of the shell of 19 August 2018 or 2018.63 (Hua et al., 2022). We were able to account for this offset or R value of -366 ± 14 ^{14}C years in the remaining samples by utilizing the associated atmosphere to shell $F^{14}\text{C}$ ratio (0.9623 ± 0.0015) that indicates the food consumed by the snail and incorporated into the shell has a mean age of approximately 10 calendar years (Table 1). Reservoir effect corrected $F^{14}\text{C}$ values (for detailed calculation, see Supplemental Section 1) were employed for chronological

construction using the “Sequence” function in OxCal program v.4.4 (Bronk Ramsey, 2008), with an assumption that the outer samples are younger than the inner samples, and the SH Zone 1–2 bomb ^{14}C data at 0.1-year resolution. General outlier analysis (prior probability = 0.05) was also used in the modeling. The modeled calendar ages of the shell are shown in Table 1.

Age-growth models and duration

The ability to date and constrain our specimen's lifespan provides confidence that our isotope record can be placed in an environmental and climatic context. The lifespan of our specimen was approximately 4.5 years, which is consistent with the estimated age of an adult snail of this size (Figure 5; Johnson and Black, 1991). Utilizing ^{14}C dates alone (^{14}C constrained age-growth model), shell growth rates along the growth axis display a sigmoidal trend (white dots with crosses connected by dashed line in Figure 5). Growth rate mean ($\pm$ standard deviation), median, and range are equal to 105 ± 73 , 74, and 239 mm yr^{-1} , respectively. The two fastest periods of growth occur within the first and last years of the snail's life, whereas the slowest growth is recorded between 2015 and 2017.

The second, and our preferred age-growth model (event-informed interpretive model: gray dots connected by solid black line in Figure 5) incorporates the timing of observed weather events within the CLNP (Supplemental Table 1 and Supplemental Figure 2), and depicts a step-like growth pattern that is bounded by the ^{14}C date uncertainties. The rates for this model are more consistent. The fastest rates occur immediately after cyclone events, whereas the slowest rates occur from mid-2015 to early 2017. Growth rate mean ($\pm$ standard deviation), median,

Table 1. ¹⁴C results and modeled shell chronology.

Figure ID	Distance along shell (mm)	Lab ID ^a	F ¹⁴ C		Estimated Atmospheric ¹⁴ C			Atmosphere: Shell Ratio		Reservoir age (R) ^b		R-Corrected Shell – ¹⁴ C		Modeled cal. Ages (AD)		
			Mean	1 σ	Year	F ¹⁴ C	1 σ	Ratio	1 σ	Year	F ¹⁴ C	1 σ	68% CI Range	95% CI Range	Median	
1	234	OZY715	1.0594	0.0023												
2	234	OZY716	1.0620	0.0022												
3	234	OZY717	1.0596	0.0026												
		Average	1.0604	0.0015	2018.63	1.0204	0.0006	0.9623	0.0015	–366	14	1.0162	0.0027	2018.4	2018.7	2018.63
4	203	OZY718	1.0560	0.0023												
5	173	OZY719	1.0593	0.0021												
6	135	OZY720	1.0645	0.0021												
7	80	OZY721	1.0783	0.0021												
8	0	OZY722	1.0739	0.0022												

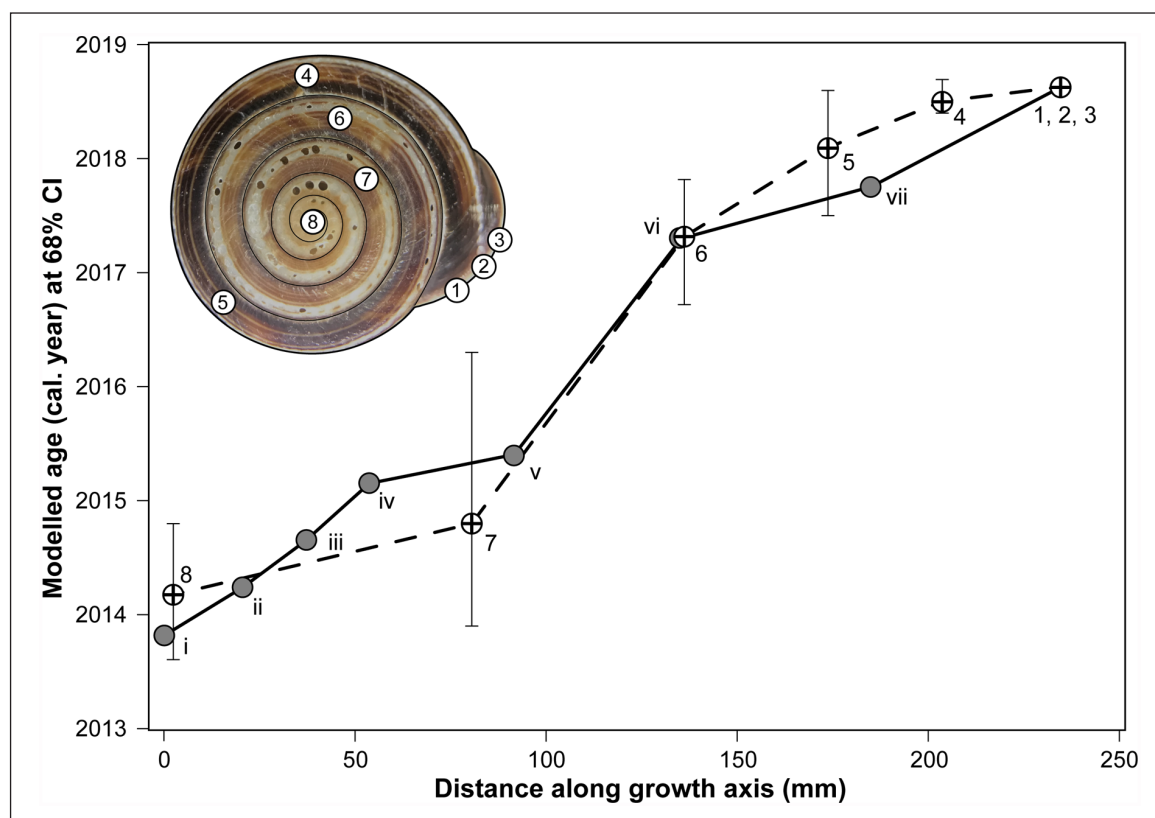


Figure 5. Age-growth models. Dots with crosses and numbers indicate modeled median ages with bars denoting 68% CI range shown in Table 1. Samples 1–3 were collected from the shell aperture and the remaining samples were spaced along the growth axis to the apex. The top-left insert shows corresponding ^{14}C locations. The dashed line connecting the white dots with crosses represents the ^{14}C constrained age-growth model. Gray dots and roman numerals denote observed synoptic events within the CLNP (Supplemental Table 1) with the solid black line depicting our preferred event-informed interpretive age-growth model in this study.

and range are equal to 70 ± 40 , 55, and 144 mm yr^{-1} , respectively. The growth rates and the step-like, or episodic, pattern are consistent with determinate growth found in other similar snail species (Supplemental Figure 3; Béguinot, 2022; Johnson and Black, 1991).

Regional climatic and local environmental conditions compared to isotopic records

From 2013 through 2019, the regional SILO dataset depicts seasonal cyclic patterns associated with temperature, evaporation, and to a lesser extent precipitation. These trends are expected in the CLNP's humid subtropical climate zone. The largest contribution of water to the region occurs during ex-tropical cyclones that pass through the area once every 2 years (i.e. Tropical Cyclone Oswald, Severe Tropical Cyclone Marcia, and Tropical Cyclone Debbie; Figure 6b and c and Supplemental Table 1).

The WIT data depicts marked changes in vegetation cover. The most dramatic signal is the rapid increase in percent open water and wet vegetation aligning with ex-tropical cyclone events. These events are followed by a gradual increase in green and subsequent dry vegetation (Figure 6d). Unlike the regional SILO data, the WIT record depicts only minor seasonal trends. When the lakes are full (2013–2016) shifts from humid, hot summers to drier,

mild winters are not apparent; however, once the lakes dry the fluctuations between green and dry vegetation appear to follow this expected trend (2016–2019).

The regional climatic trends described above appear to be preserved in our isotopic records. The two largest shifts in $\delta^{18}\text{O}_{\text{shell}}$ values ($\sim 6\text{‰}$) are tied to Severe Tropical Cyclone Marcia and Tropical Cyclone Debbie. We see minor amplitude shifts ($< 2\text{‰}$) corresponding to seasonality throughout the record; however, this seasonal signal is less obvious during periods immediately following the cyclones. The minor shifts in $\delta^{13}\text{C}_{\text{shell}}$ ($< 2\text{‰}$) appear to fluctuate with the change in seasons, particularly within the first half of the record. The larger shift in $\delta^{13}\text{C}_{\text{shell}}$ values ($\sim 4\text{‰}$) occurs near the same timing as Severe Tropical Cyclone Marcia, but no shift is observed during Tropical Cyclone Debbie.

Discussion

Both age-growth models depict similar patterns between the timing of isotopic excursions and changes in local conditions. In the following sections, we present our record only in the context of the event-informed age-growth model. We recognize that anchoring our isotopic record with known synoptic events limits the ability to independently test environmental and climatic mechanisms for our

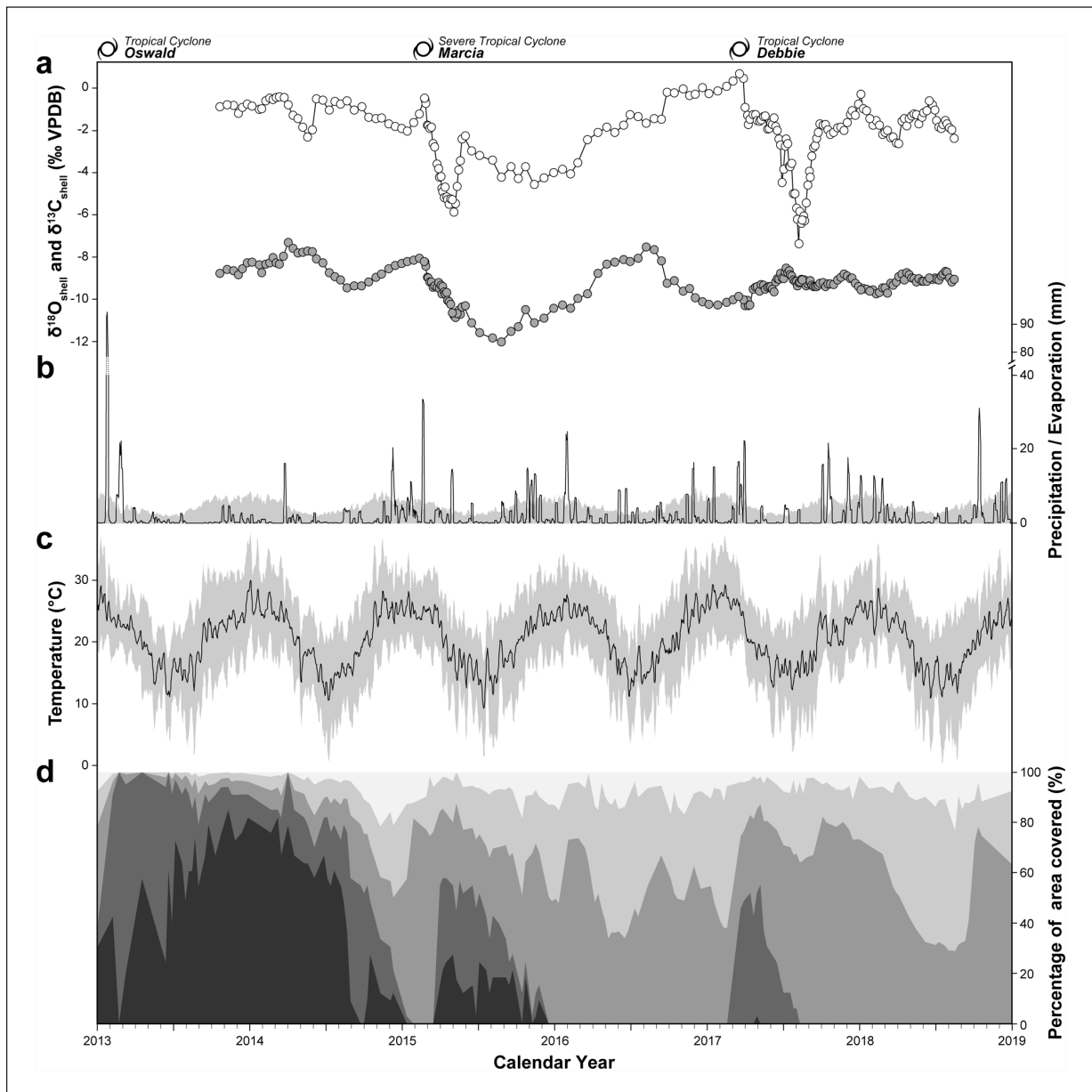


Figure 6. Snail shell stable isotope values compared to extracted regional climate data from SILO gridded dataset and environmental conditions using the Wetland Insights Tool (WIT). (a) $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{13}\text{C}_{\text{shell}}$ stable isotopes (white and gray dots, respectively) placed in calendar years utilizing the event-informed interpretive age-growth model (Figure 5). (b) Total daily precipitation (solid black line), evaporation (gray area) and major ex-tropical cyclones that passed nearby (symbol). (c) Mean (solid black line) with maximum and minimum (gray area) daily temperature, and (d) Local environmental conditions for the Coalstoun Lakes National Park (CLNP) based on changes in percent area cover for open water, wet vegetation, green vegetation, dry vegetation, and bare ground (from darkest to lightest, respectively). All isotopic data was provided by the National Environmental Isotope Facility (NEIF) at the British Geological Society (BGS).

dataset. Nevertheless, this more robust chronological framework reduces the range of plausible drivers of observed isotopic patterns.

Biggenden Banded Snail as a paleoenvironmental proxy

In the humid subtropical climate zones, there should be isotope variability in precipitation related to shifts from hot, wet summers to drier, cooler winters. Temporal estimates of $\delta^{18}\text{O}_{\text{precip}}$ values generated from machine learning models indicate that the CLNP's $\delta^{18}\text{O}_{\text{precip}}$ can swing

more than 7‰ from summer to winter (Supplemental Figure 1; Falster et al., 2026). This is largely a result of temperature-controlled dissolution in air masses as they cool and precipitate, traveling across and over higher latitudes and elevation (Bowen et al., 2005; Bowen and Wilkinson, 2002; Falster et al., 2026; Hollins et al., 2018).

Variation in land snail $\delta^{18}\text{O}_{\text{shell}}$ records has been inferred to capture these seasonal fluctuations (Dettman et al., 2024; Wang et al., 2020; Yanes et al., 2019). Dettman et al. (2024) propose possible mechanisms for either small- or large-scale temporal variability in $\delta^{18}\text{O}_{\text{shell}}$ values during snail growth. Small amplitude shifts ($\leq 5\text{‰}$) record either local

environments that are consistently humid or consistently dry, whereas large amplitude shifts ($>5\%$) record local environments with pronounced wet-dry seasonal fluctuation. Knowing that our snail lived for 4.5 years in a region with strong seasonal variability, we would expect at minimum four large-amplitude oscillations in $\delta^{18}\text{O}_{\text{shell}}$ values; however, we do not observe this pattern. As discussed by Fu et al. (2022), gridded datasets created from limited, spatially continuous control points can have substantial uncertainties in complex terrain at finer spatial and temporal scales. The CLNP's local conditions do not match the regional climatic signals. The steep caldera walls promote the capture and persistence of water by shielding incoming solar radiation and wind. Higher local humidity acts to buffer the study area from regional climate variability (e.g. heat waves and cold snaps). Even when open water is absent and dry vegetation is the highest, the topography provides the CLNP with some protection from the elements (2016–2019; Figure 6d). The presence and persistence of mesic vine thicket forest, the two ephemeral lakes, and the Biggenden Banded Snail in the CLNP support these assertions, as these conditions stand in stark contrast to the surrounding dryland areas (Figure 2).

Therefore, the most plausible mechanism for significant shifts in $\delta^{18}\text{O}_{\text{shell}}$ record within the CLNP is the delivery of isotopically-depleted water from ex-tropical cyclones. Ex-tropical cyclones have a distinctly lower mean $\delta^{18}\text{O}_{\text{precip}}$ signal compared to seasonal precipitation (Hollins et al., 2018), and these large events can be recorded in land snail shells (e.g. Wang et al., 2024b; Zhang et al., 2025). Alternative explanations for these large shifts in $\delta^{18}\text{O}_{\text{shell}}$ include either significant alteration of vegetation communities (e.g. long-term droughts), or the snail's ingestion of old shell fragments. These scenarios for the CLNP are unlikely, based on historical and field observations, radiocarbon ages, and low variability in $\delta^{13}\text{C}_{\text{shell}}$. Ruling out these alternatives, the small-amplitude shifts of roughly 2% in our snail's $\delta^{18}\text{O}_{\text{shell}}$ record are likely driven by broad seasonal signals, whereas large-amplitude shifts of $>5\%$ are consistent with extreme precipitation events within the event-informed age model, such as ex-tropical cyclones (Figure 6a).

Biggenden Banded Snail life cycle and ecology

Little is known about the Biggenden Banded Snail's life cycle. Based on our record, we hypothesize that our specimen was hatched at the start of the Southern Hemisphere summer, during a period when both lakes were full, and lived roughly 4.5 years. Meeting expectations for a large land snail, the fastest growth period in both age-growth models occurred at the beginning of the snail's life and after larger rain events (Schmera et al., 2015). The flaring of shell near the aperture and a thickened lip and the number of whorls indicate the snail was a mature adult at the time of death (Stanisic et al., 2010). The absence of large fractures and scratches at the aperture suggest the cause of death was not due to predation from larger animals (e.g. birds). The estimated time of death (mid-August, 2018) falls at the end of winter, when conditions were drier (over

a month since the last rainfall) and temperature dropped to -1.7°C for the region, which was the coldest recorded temperature since the meteorological stations were established in 2003 (BOM, 2026). We posit that the snail died as a consequence of cold temperatures combined with lower humidity and lower water availability, supporting other work that has identified the important role of temperature in snail ecology (e.g. Zong et al., 2023). Moreover, the abundant number of deceased snail shells ranging in size found in the study area at the time of our specimen's collection supports this assertion.

Our analysis shows a mean $\delta^{13}\text{C}_{\text{shell}}$ of -9% , suggesting the Biggenden Banded Snail targeted decomposed C_3 plant litter. Studies have observed a roughly $14\text{--}16.8\%$ decrease in $\delta^{13}\text{C}_{\text{shell}}$ fractionation in snails from the ingestion of C_3 plants (Balakrishnan et al., 2005; Metref et al., 2003; Stott, 2002; Zhang et al., 2014; Zhu et al., 2015). Taking into consideration this plant to shell fractionation, our specimen would be ingesting $\delta^{13}\text{C}$ material ranging from -23 to -25.8% , which aligns with semi-decayed C_3 vegetation and measured surface soil (-24.84%) within the CLNP. This interpretation is supported by the mean age of consumed material for our specimen was ca. 10 cal. yr. old, which also reinforces that our specimen likely did not incorporate shell fragments or pedogenic carbonate into its diet. Moreover, the steep crater walls and confinement of forest within the crater at CLNP prevents the snail from foraging on a wide range of food and water sources, and most of the forest taxa are C_3 plants (Figure 2).

The cyclicity in $\delta^{13}\text{C}_{\text{shell}}$ appears to fluctuate on a seasonal basis, with the first half of the record showing more distinct cyclicity with higher amplitude shifts in $\delta^{13}\text{C}_{\text{shell}}$ compared to the second half. We hypothesize two potential mechanisms for the shift in amplitude variability: (1) variations in feeding habits due to shifts in local environmental conditions and (2) changes in snail physiological processes. From 2013 to 2016, when $\delta^{13}\text{C}_{\text{shell}}$ shifts are $\sim 2\%$, large quantities of rainfall delivered to the CLNP promoted increased primary productivity, resulting in a wider range of available higher-quality, fresh C_3 biomass and fungus for consumption. This pattern is in contrast to the subsequent drier years when $\delta^{13}\text{C}_{\text{shell}}$ has reduced variability ($\pm 0.5\%$). During this time, our specimen would have been limited to older, lower-quality, homogenous litter with more consistent $\delta^{13}\text{C}$ values (Astor et al., 2015). The change in variability could also be a physiological process in which juveniles depict a greater $\delta^{13}\text{C}_{\text{shell}}$ sensitivity to dietary and environmental conditions compared to later life stages when body mass is larger (Zong et al., 2025). Either mechanism alone or together could explain these observations.

The one exception to this mechanism is the approximately 4% shift observed immediately following Severe Tropical Cyclone Marcia. We posit that this pronounced drop in $\delta^{13}\text{C}_{\text{shell}}$ is related to the onset of reproductive activities when climate was ideal (i.e. wet and warm; Goodfriend et al., 1989; Leng et al., 1998). The lack of a similar isotopic response during Tropical Cyclone Debbie when environmental conditions were both drier and colder supports this assertion.

Conclusion

In this study, we determine the Biggenden Banded Snail is a suitable target for paleoenvironmental studies in south-eastern Queensland, Australia. We have shown that multiple radiocarbon ages allow the construction of isotope time series from such shells. While these age-growth models are effective, relatively large uncertainties make it difficult to assess mechanisms for isotopic change where meteorological data is limited and/or coarse. The incorporation of observed synoptic events produces a more temporally-constrained age-growth model that permits us to assess the nuances of the isotope record. Moreover, this event-informed age-growth model allows us to place our record in the context of the biological life cycle of the Biggenden Banded Snail, of which little is known, and the CLNP's environmental conditions. Contrary to the expectations from the regional humid subtropical climate, the largest shifts in the $\delta^{18}\text{O}_{\text{shell}}$ record appear more consistent with ex-tropical cyclone-related rainfall than with simple seasonality (Nicolai and Ansart, 2017). This pattern is due to the CLNP's microtopography that buffers the effects of regional climate and modulates expected isotope variability. Synoptic signals are expressed when rainfall events are large enough to overwhelm the system, or if the precipitation occurs when the system is more water-limited. In contrast, the $\delta^{13}\text{C}_{\text{shell}}$ record only depicts minor cyclic patterns associated with the snail's diet of semi-decayed C_3 plant litter that is indirectly affected by seasonality, and one larger shift likely related to reproduction under optimal climatic conditions. This study highlights the need to consider not only regional climate but also local conditions and the potential mechanisms that drive them.

To date, Eastern Australia has approximately 800 known species of land snail (Stanisic et al., 2010) that span a substantial climatic and ecologic gradient susceptible to aridification, as seen by the fragmentation and isolation of vegetation communities in the region over the Quaternary (e.g. refugia such as the CLNP). The *Figuladra* genus (Biggenden Banded Snail, one species in this genus) occupies this area within southeastern to mid-eastern Queensland. Although this species, as well as its greater genus, has not been explicitly reported in archeological or geological studies, it is reasonable to assume its presence within sediment deposits due to its abundance and preservation potential. The logical next step is to identify such archives and conduct a study using several specimens within a stratigraphic sequence to generate a multi-shell composite record of paleoclimatic conditions and/or paleo synoptic events (e.g. Wang et al., 2024a). Our work highlights the use of a single intra-shell case study, but species within the same genus and region should have comparable isotopic responses to environmental factors (Yanes and Fernández-Lopez-de-Pablo, 2017), thereby generating a novel indicator of past environments, in a region with comparatively sparse terrestrial paleoenvironmental records.

Acknowledgments

We acknowledge the Traditional Owners of the country where this research was conducted, the Wakka Wakka and Wakka Wakka Jinda peoples, and recognize their continuing connection

to land, waters, and culture. We pay our respects to their Elders past, present, and emerging. Field work and sample collection was under permit numbers WITK18591517 and PTU19001583. Financial support for the project was provided by Australian Nuclear Science and Technology Organisation (ANSTO) Research Portal Grant AP12135, the British Geological Survey (BGS/NERC) University Funding Initiative (BUFI) and the National Environmental Isotope Facility (NEIF). The authors would like to thank the staff at ANSTO and the BGS isotope facility for training and assistance. Lastly, thank you John Hale Media for granting permission to use their drone footage of Coalstoun Lakes National Park.

ORCID iDs

Nicholas R. Patton  <https://orcid.org/0000-0002-4137-0636>

James Shulmeister  <https://orcid.org/0000-0001-5863-9462>

Matthew Jones  <https://orcid.org/0000-0001-8116-5568>

Quan Hua  <https://orcid.org/0000-0003-0179-8539>

Jennifer R. Kielhofer  <https://orcid.org/0000-0001-9389-3570>

Author contributions

Nicholas R. Patton: Conceptualization; Data curation; Formal analysis; Investigation; Validation; Visualization; Writing – original draft; Writing – review & editing.

James Shulmeister: Funding acquisition; Investigation; Project administration; Supervision; Writing – original draft; Writing – review & editing.

Melanie J. Leng: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Supervision; Writing – review & editing.

Matthew Jones: Conceptualization; Resources; Supervision; Writing – review & editing.

Quan Hua: Funding acquisition; Methodology; Resources; Supervision; Writing – review & editing.

Jennifer R. Kielhofer: Conceptualization; Investigation; Writing – original draft; Writing – review & editing.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Funding for this study was provided by the ANSTO Research Portal Grant (AP12135), the British Geological Survey (BGS/NERC) University Funding Initiative (BUFI), and the National Environmental Isotope Facility (NEIF). Field work and sample collection was under permit numbers WITK18591517 and PTU19001583.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability statement

All meteorological and climate data necessary to generate the results for this study are available through the SILO (<http://www.longpaddock.qld.gov.au/silo>), and the BOM (<http://www.bom.gov.au/climate/data/> and <https://www.bom.gov.au/cyclone/>) websites. The Coalstoun Lakes National Park WIT dataset can be accessed through the Queensland Wetland Info (<https://wetland-info.detsi.qld.gov.au/wetlands/facts-maps/national-park-coalstoun-lakes/>). All precipitation isotope datasets were obtained from the Australian precipitation isotope calculator (<https://>

wateriso-aus.shinyapps.io/apic/) and any additional information can be found in the Supplemental Information.

Supplemental material

Supplemental material for this article is available online.

References

- Astor T, Lenoir L and Berg MP (2015) Measuring feeding traits of a range of litter-consuming terrestrial snails: Leaf litter consumption, faeces production and scaling with body size. *Oecologia* 178(3): 833–845. <https://doi.org/10.1007/s00442-015-3257-y>
- Balakrishnan M and Yapp CJ (2004) Flux balance models for the oxygen and carbon isotope compositions of land snail shells. *Geochimica et Cosmochimica Acta* 68(9): 2007–2024. <https://doi.org/10.1016/j.gca.2003.10.027>
- Balakrishnan M, Yapp CJ, Meltzer DJ, et al. (2005) Paleoenvironment of the Folsom archaeological site, New Mexico, USA, approximately 10,500 14C yr BP as inferred from the stable isotope composition of fossil land snail shells. *Quaternary Research* 63(1): 31–44. <https://doi.org/10.1016/j.yqres.2004.09.010>
- Bao R, Sheng X, Meng X, et al. (2023) 100 k.y. Pacing of the East Asian summer monsoon over the past five glacial cycles inferred from land snails. *Geology* 51(2): 179–183. <https://doi.org/10.1130/g50243.1>
- Béguinot J (2022) Damping the impact of intraspecific variability of whorl growth-rate on the range of intraspecific variation of adult shell-size in gastropods with determinate growth: Evidence of a finely-tuned regulating process. *Annual Research & Review in Biology* 37(2): 1–12. <https://doi.org/10.9734/arrb/2022/v37i230482>
- BOM (2026) *Climate Data Online* [online]. Australian Government, Bureau of Meteorology.
- Bowen GJ, Wassenaar LI and Hobson KA (2005) Global application of stable hydrogen and oxygen isotopes to wildlife forensics. *Oecologia* 143: 337–348. <https://doi.org/10.1007/s00442-004-1813-y>
- Bowen GJ and Wilkinson B (2002) Spatial distribution of $\delta^{18}\text{O}$ in meteoric precipitation. *Geology* 30: 315–318. [https://doi.org/10.1130/0091-7613\(2002\)0302.0.co;2](https://doi.org/10.1130/0091-7613(2002)0302.0.co;2)
- Bronk Ramsey CB (2008) Deposition models for chronological records. *Quaternary Science Reviews* 27: 42–60. <https://doi.org/10.1016/j.quascirev.2007.01.019>
- DeNiro MJ and Epstein S (1978) Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta* 42(5): 495–506. [https://doi.org/10.1016/0016-7037\(78\)90199-0](https://doi.org/10.1016/0016-7037(78)90199-0)
- Department of Environment, Science and Innovation, Queensland (DESIQ) (2019) WetlandMaps–Interactive Maps and Wetlands Data in Queensland, WetlandInfo website. Available at: <https://wetlandinfo.des.qld.gov.au/wetlands/facts-maps/get-mapping-help/wetland-maps/> (accessed 5 January 2025).
- Dettman DL, Sawada Y and Pickford M (2024) High resolution stable isotope ratios in modern African land snails: Testing inferred environmental conditions. *Quaternary Science Reviews* 344: 108943. <https://doi.org/10.1016/j.quascirev.2024.108943>
- Dong J, Yan H, Zong X, et al. (2022) Ultra-high resolution $\delta^{18}\text{O}$ of land snail shell: A potential tool to reconstruct frequency and intensity of paleoprecipitation events. *Geochimica et Cosmochimica Acta* 327: 21–33. <https://doi.org/10.1016/j.gca.2022.04.015>
- Douris V, Cameron RAD, Rodakis GC, et al. (1998) Mitochondrial phylogeography of the land snail *Albinaria* in Crete: long-term geological and short-term vicariance effects. *Evolution* 52(1): 116–125. <https://doi.org/10.1111/j.1558-5646.1998.tb05144.x>
- Dunn B, Ai E, Alger MJ, et al. (2023) Wetlands insight tool: Characterising the surface water and vegetation cover dynamics of individual wetlands using multidecadal land-sat satellite data. *Wetlands* 43: 37. <https://doi.org/10.1007/s13157-023-01682-7>
- Dunn B, Lymburner L, Newey V, et al. (2019) Developing a tool for wetland characterization using fractional cover, Tasseled Cap Wetness and Water Observations from Space. In: *IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium*, July, pp.6095–6097. <https://doi.org/10.1109/IGARSS.2019.8897806>
- Falster G, Abramowitz G, Hobeichi S, et al. (2026) High resolution monthly precipitation isotope estimates across Australia from machine learning. *Hydrology and Earth System Sciences* 30: 289–315. <https://doi.org/10.5194/hess-30-289-2026>
- Frost AJ, Ramchurn A and Smith A (2018) The Australian Landscape Water Balance model (AWRA-L v6). Technical Description of the Australian Water Resources Assessment Landscape model version 6. Bureau of Meteorology Technical Report. Available at: https://water-outlook.staging.service.bom.gov.au/assets/notes/publications/AWRALv6_Model_Description_Report.pdf
- Fu G, Barron O, Charles SP, et al. (2022) Uncertainty of gridded precipitation at local and continent scales: A direct comparison of rainfall from SILO and AWAP in Australia. *Asia-Pacific Journal of Atmospheric Sciences* 58(4): 471–488. <https://doi.org/10.1007/s13143-022-00267-4>
- Department of the Environment, Tourism, Science and Innovation (2026) *Coalstoun Lakes National Park*. Queensland Government. Available at: <https://parks.qld.gov.au/parks/coalstoun-lakes> (accessed 14 August 2026).
- Goodfriend GA (1992) The use of land snail shells in paleoenvironmental reconstruction. *Quaternary Science Reviews* 11(6): 665–685. [https://doi.org/10.1016/0277-3791\(92\)90076-k](https://doi.org/10.1016/0277-3791(92)90076-k)
- Goodfriend GA and Ellis GL (2002) Stable carbon and oxygen isotopic variations in modern *Rabdotus* land snail shells in the southern Great Plains, USA, and their relation to environment. *Geochimica et Cosmochimica Acta* 66(11): 1987–2002. [https://doi.org/10.1016/s0016-7037\(02\)00824-4](https://doi.org/10.1016/s0016-7037(02)00824-4)
- Goodfriend GA, Magaritz M and Gat JR (1989) Stable isotope composition of land snail body water and its relation to environmental waters and shell carbonate. *Geochimica et Cosmochimica Acta* 53(12): 3215–3221. [https://doi.org/10.1016/0016-7037\(89\)90102-6](https://doi.org/10.1016/0016-7037(89)90102-6)
- Hill EA, Reimer PJ, Hunt CO, et al. (2017) Radiocarbon ecology of the land snail *Helix melanocephala* in northeastern Libya. *Radiocarbon* 59(5): 1521–1542. <https://doi.org/10.1017/rdc.2017.49>
- Hollins SE, Hughes CE, Crawford J, et al. (2018) Rainfall isotope variations over the Australian continent - Implications for hydrology and isoscape applications. *Science of the Total Environment* 645: 630–645. <https://doi.org/10.1016/j.scitotenv.2018.07.082>
- Hua Q, Jacobsen GE, Zoppi U, et al. (2001) Progress in radiocarbon target preparation at the Antares AMS Centre. *Radiocarbon* 43: 275–282. <https://doi.org/10.1017/s003382220003811x>
- Hua Q, Turnbull JC, Santos GM, et al. (2022) Atmospheric radiocarbon for the period 1950–2019. *Radiocarbon* 64(4): 723–745. <https://doi.org/10.1017/rdc.2021.95>
- Hugall A, Moritz C, Moussalli A, et al. (2002) Reconciling paleodistribution models and comparative phylogeography in the

- wet tropics rainforest land snail *Gnarosophia bellendenkerensis* (Brazier 1875). *Proceedings of the National Academy of Sciences* 99(9): 6112–6117. <https://doi.org/10.1073/pnas.092538699>
- Hugall AF and Stanislis J (2011) Beyond the prolegomenon: a molecular phylogeny of the Australian camaenid land snail radiation. *Zoological Journal of the Linnean Society* 161(3): 531–572. <https://doi.org/10.1111/j.1096-3642.2010.00644.x>
- Jeffrey SJ, Carter JO, Moodie KB, et al. (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* 16(4): 309–330. [https://doi.org/10.1016/s1364-8152\(01\)00008-1](https://doi.org/10.1016/s1364-8152(01)00008-1)
- Johnson MS and Black R (1991) Growth, survivorship, and population size in the land snail *Rhagada convicta* Cox, 1870 (Pulmonata: Camaenidae) from a semiarid environment in Western Australia. *Journal of Molluscan Studies* 57(3): 367–374. <https://doi.org/10.1093/mollus/57.3.367>
- Johnson W, Knutson J and Taylor SR (eds) (1989) *Intraplate volcanism in Eastern Australia and New Zealand*. Cambridge University Press.
- Kim ST, Mucci A and Taylor BE (2007) Phosphoric acid fractionation factors for calcite and aragonite between 25 and 75°C: revisited. *Chemical Geology* 246(3–4): 135–146. <https://doi.org/10.1016/j.chemgeo.2007.08.005>
- Köhler F (2011) The camaenid species of the Kimberley Islands, Western Australia (Stylommatophora: Helicoidea). *Malacologia* 54: 203–406. <https://doi.org/10.4002/040.054.0108>
- Leng MJ, Heaton THE, Lamb HF, et al. (1998) Carbon and oxygen isotope variations within the shell of an African land snail (*Limicolaria kambeul chudeaui* Germain): A high-resolution record of climate seasonality? *Holocene* 8(4): 407–412. <https://doi.org/10.1191/095968398669296159>
- Li C, Tan H, Wu M, et al. (2025) Carbon translocation within land snails affects the carbon isotopic fractionation. *Chemical Geology* 672: 122511. <https://doi.org/10.1016/j.chemgeo.2024.122511>
- Magaritz M and Heller J (1983) Annual cycle of $^{18}\text{O}/^{16}\text{O}$ and $^{13}\text{C}/^{12}\text{C}$ isotope ratios in landsnail shells. *Chemical Geology* 41: 243–255. [https://doi.org/10.1016/s0009-2541\(83\)80022-9](https://doi.org/10.1016/s0009-2541(83)80022-9)
- Mahar JM (ed.) (1993) *Understanding and Managing Soils in the Inland Burnett District*. Queensland Department of Primary Industries, Training Series QE93001.
- McCarroll SM and Brough DM (2000) *Agricultural Land Resource Assessment of Coalstoun Lakes, Queensland*. Department of Natural Resources, Land Resources Bulletin DNRQ00096.
- Metref S, Rousseau DD, Bentaleb I, et al. (2003) Study of the diet effect on $\delta^{13}\text{C}$ of shell carbonate of the land snail *Helix aspersa* in experimental conditions. *Earth and Planetary Science Letters* 211(3–4): 381–393. [https://doi.org/10.1016/s0012-821x\(03\)00224-3](https://doi.org/10.1016/s0012-821x(03)00224-3)
- Nicolai A and Ansart A (2017) Conservation at a slow pace: terrestrial gastropods facing fast-changing climate. *Conservation Physiology* 5(1): cox007. <https://doi.org/10.1093/conphys/cox007>
- Nield CB, Yanes Y, Pigati JS, et al. (2022) Oxygen isotopes of land snail shells in high latitude regions. *Quaternary Science Reviews* 279: 107382. <https://doi.org/10.1016/j.quascirev.2022.107382>
- Parkyn J and Newell DA (2013) Australian land snails: A review of ecological research and conservation approaches. *Molluscan Research* 33(2): 116–129. <https://doi.org/10.1080/013235818.2013.782793>
- Pearce TA (2008) When a snail dies in the forest, how long will the shell persist? Effect of dissolution and micro-bioerosion. *American Malacological Bulletin* 26(1/2): 111–117. <https://doi.org/10.4003/006.026.0211>
- Peel MC, Finlayson BL and McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* 11(5): 1633–1644. <https://doi.org/10.5194/hess-11-1633-2007>
- Pigati JS, McGeehin JP, Muhs DR, et al. (2013) Radiocarbon dating late Quaternary loess deposits using small terrestrial gastropod shells. *Quaternary Science Reviews* 76: 114–128. <https://doi.org/10.1016/j.quascirev.2013.05.013>
- Prendergast AL, Stevens RE, Barker G, et al. (2015) Oxygen isotope signatures from land snail (*Helix melanostoma*) shells and body fluid: Proxies for reconstructing Mediterranean and North African rainfall. *Chemical Geology* 409: 87–98. <https://doi.org/10.1016/j.chemgeo.2015.05.014>
- Prendergast AL, Stevens RE, Hill EA, et al. (2017) Carbon isotope signatures from land snail shells: Implications for palaeovegetation reconstruction in the eastern Mediterranean. *Quaternary International* 432: 48–57. <https://doi.org/10.1016/j.quaint.2014.12.053>
- Queensland Parks & Wildlife Service (QPWS) (2023) Department of Environment and Science Coalstoun Lakes National Park Management Plan 2000 - Extended 2023. Available at: <https://parks.qld.gov.au/management/plans-strategies/planning-documents>
- Rech JA, Pigati JS, Springer KB, et al. (2021) Oxygen isotopes in terrestrial gastropod shells track Quaternary climate change in the American Southwest. *Quaternary Research* 104: 43–53. <https://doi.org/10.1017/qua.2021.18>
- Schmera D, Baur A and Baur B (2015) Size-dependent shell growth and survival in natural populations of the rock-dwelling land snail *Chondrina clienta*. *Canadian Journal of Zoology* 93(5): 403–410. <https://doi.org/10.1139/cjz-2014-0307>
- Stanislis J (1998) *A Survey of the Land Snails of the Queensland Brigalow Lands: Their Distribution, Conservation Status and Close Association With Dry Vine Thickets*. Queensland Museum.
- Stanislis J (1999) Land snails and dry vine thickets in Queensland: using museum invertebrate collections in conservation. In: Ponder WF (ed.) *The Other 99%: The Conservation and Biodiversity of Invertebrates*. Royal Zoological Society of New South Wales, pp.257–263.
- Stanislis J and Ponder WF (2004) Forest snails in eastern Australia—one aspect of the other 99%. In: Lunney D (ed.) *Conservation of Australia's Forest Fauna*. Royal Zoological Society of New South Wales, pp.127–149. <https://doi.org/10.7882/FS.2004.011>
- Stanislis J, Shea M, Potter D, et al. (2010) *Australian Land Snails. Volume 1. A Field Guide to Eastern Australian Species*. Queensland Museum.
- Stanislis J, Shea M, Potter D, et al. (2018) *Australian Land Snails. Volume 2. A Field Guide to Southern, Central and Western Australian Species*. Bioculture Press.
- Stanislis L, Köhler F and McDougall C (2022) Two new genera of land snail from dry subtropical forests of eastern Australia: *Brigaladra* gen. nov. and *Euryladra* gen. nov. (Eupulmonata: Camaenidae). *Invertebrate Systematics* 36(6): 506–532. <https://doi.org/10.1071/is21075>
- Stanislis L, McDougall C and Oliver P (2024) Biogeography of vine thickets and open woodland in subtropical eastern Australia: A case study of three camaenid land snail

- genera. *Australian Journal of Zoology* 71(3): 1–15. <https://doi.org/10.1071/zo23032>
- Stott LD (2002) The influence of diet on the $\delta^{13}\text{C}$ of shell carbon in the pulmonate snail *Helix aspersa*. *Earth and Planetary Science Letters* 195(3–4): 249–259. [https://doi.org/10.1016/S0012-821X\(01\)00585-4](https://doi.org/10.1016/S0012-821X(01)00585-4)
- Wang G, Dong J, Han T, et al. (2024b) Quantitative reconstruction of a single super rainstorm using daily resolved $\delta^{18}\text{O}$ of land snail shells. *Science Bulletin* 69(14): 2281–2288. <https://doi.org/10.1016/j.scib.2024.04.037>
- Wang M, Wang X, Dettman DL, et al. (2024a) Stable carbon isotope composition of land snail shells in Westerlies Asia and monsoonal Asia: Paleoclimate implications. *Quaternary Science Reviews* 327: 108505. <https://doi.org/10.1016/j.quascirev.2024.108505>
- Wang X, Dettman DL, Wang M, et al. (2020) Seasonal wet-dry variability of the Asian monsoon since the middle Pleistocene. *Quaternary Science Reviews* 247: 106568. <https://doi.org/10.1016/j.quascirev.2020.106568>
- Ward D and Slotow R (1992) The effects of water availability on the life history of the desert snail, *Trochoidea seetzeni*: An experimental field manipulation. *Oecologia* 90(4): 572–580. <https://doi.org/10.1007/BF01875452>
- Wilcken KM, Hotchkis M, Levchenko V, et al. (2015) From carbon to actinides: a new universal 1MV accelerator mass spectrometer at ANSTO. *Nuclear Instruments & Methods in Physics Research Section B, Beam Interactions With Materials and Atoms* 361: 133–138. <https://doi.org/10.1016/j.nimb.2015.04.054>
- Wu N, Li F and Rousseau DD (2018) Terrestrial mollusk records from Chinese loess sequences and changes in the East Asian monsoonal environment. *Journal of Asian Earth Sciences* 155: 35–48. <https://doi.org/10.1016/j.jseaes.2017.11.003>
- Yanes Y, Al-Qattan NM, Rech JA, et al. (2019) Overview of the oxygen isotope systematics of land snails from North America. *Quaternary Research* 91(1): 329–344. <https://doi.org/10.1017/qua.2018.79>
- Yanes Y and Fernández-Lopez-de-Pablo J (2017) Calibration of the stable isotope composition and body size of the arid-dwelling land snail *Sphincterochila candidissima*, a climatic archive abundant in Mediterranean archaeological deposits. *Holocene* 27(6): 890–899. <https://doi.org/10.1177/0959683616675943>
- Yanes Y, Izeta AD, Cattáneo R, et al. (2014) Holocene (~4.5–1.7 cal. kyr BP) paleoenvironmental conditions in central Argentina inferred from entire-shell and intra-shell stable isotope composition of terrestrial gastropods. *Holocene* 24(10): 1193–1205. <https://doi.org/10.1177/0959683614540959>
- Zaarur S, Olack G and Affek HP (2011) Paleo-environmental implication of clumped isotopes in land snail shells. *Geochimica et Cosmochimica Acta* 75(22): 6859–6869. <https://doi.org/10.1016/j.gca.2011.08.044>
- Zhang N, Yamada K, Suzuki N, et al. (2014) Factors controlling shell carbon isotopic composition of land snail *Acusta despecta sieboldiana* estimated from laboratory culturing experiment. *Biogeosciences* 11(19): 5335–5348. <https://doi.org/10.5194/bg-11-5335-2014>
- Zhang Q, Dong J, Wang G, et al. (2025) Synoptic-scale precipitation events recorded by high-resolution intra-shell $\delta^{18}\text{O}$ of land snail in the Asian monsoon marginal zone. *Quaternary Science Reviews* 369: 109582. <https://doi.org/10.1016/j.quascirev.2025.109582>
- Zhu LL, Bao R and Sheng XF (2015) Experimental study on the effect of environmental factors on the carbon stable isotope composition of the snail *Achatina fulica* shell carbonate. *Geological Journal of China Universities* 21(2): 357. <https://doi.org/10.16108/j.issn1006-7493>
- Zong X, Dong J, Song Y, et al. (2023) Precipitation $\delta^{18}\text{O}$ paced the seasonal $\delta^{18}\text{O}$ variations of terrestrial snail body water and shells in the East Asian monsoon region. *Quaternary Science Reviews* 317: 108290. <https://doi.org/10.1016/j.quascirev.2023.108290>
- Zong X, Dong J, Yan H et al. (2025) Intra-shell stable isotopes in land snail as proxies of seasonal climate variability: Ontogenetic evidence from cultured and field specimens. *Geoscience Frontiers* 16: 102164. <https://doi.org/10.1016/j.gsf.2025.102164>