Bioscience Evidence 2025, Vol.15, No.3, 103-114
http://bioscipublisher.com/index.php/be

Feature Review Open Access

Adaptive Radiation and Convergent Evolution in African Terrestrial Snails Phylogenomic and Morphological Evidence

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Bioscience Evidence, 2025, Vol.15, No.3 doi: 10.5376/be.2025.15.0011
Received: 20 Mar., 2025
Accepted: 26 Apr., 2025
Published: 07 May, 2025

Preferred citation for this article:
Wang H.M., and Liu Z., 2025, Adaptive Radiation and Convergent Evolution in African Terrestrial Snails Phylogenomic and Morphological Evidence, Bioscience Evidence, 15(2): 103-114 (doi: 10.5376/be.2025.15.0011)

Abstract The African land snail is a good example of how environmental diversity and evolutionary processes affect biodiversity. In this review, we summarize recent research on the phylogenetic genome and morphology, primarily to explore how different snail lineages undergo adaptive radiation and convergent evolution. We analyzed genomic data and shell morphology data together to understand how the complex terrain, climate change, and various habitats in Africa drive rapid evolutionary differentiation of these snails in mountainous forests, savannas, isolated hills, and other environments. These places have different ecological conditions, which have given snails many opportunities for evolution. We also specifically mentioned some examples of morphological convergence. In these examples, although snail lineages are different, they will evolve very similar shell types and ecological characteristics when facing similar environmental pressures. That is to say, they have made similar adaptive responses in their respective environments. Among them, we also specifically analyzed the evolutionary process of the Tropidophora group. This example demonstrates how the diversity of phylogenetic genomic data and shell shape changes interact with each other, especially in different ecological environments where the changes are most pronounced. These studies indicate that in order to truly understand the evolutionary history of these snails, we must combine molecular (genetic) and morphological (morphological) methods. We also hope that this review can provide a framework and methodology for future research. At the same time, we would like to emphasize that when protecting the rapidly disappearing snail habitats in Africa, we cannot only focus on ecology, but also consider their unique evolutionary history behind them.

Keywords Adaptive radiation; Convergent evolution; Phylogenomics; Terrestrial snails; Morphological evolution

1 Introduction

Adaptive radiation refers to the rapid evolution of an ancestral species into many new species over a relatively short geological period of time. These new species are adapted to different living environments. This usually happens when there are new environments or new opportunities, and the number of species and ecological functions become more diverse. Convergent evolution is another evolutionary phenomenon. It means that although some animals have different ancestors, they eventually evolve similar-looking forms or functions when facing similar environmental pressures. This shows that natural selection will push them in similar directions (McGirr and Martin, 2018; Hausdorf and Neiber, 2022).

Land snails are a good example for studying these two evolutionary processes. First, they have a wide variety of appearances, lifestyles, and body structures. In addition, some species are not easy to move around and are often separated by geographical environments, so it is easy to form independent evolutionary branches in different places (Hausdorf and Neiber, 2022; Raphalo et al., 2023).

In addition, in the process of land snails changing from living in water to living on land, many changes have occurred in their genes, and many new functions have also been generated. For example, their whole genome has been repeated (WGD), and this change has helped them adapt to land, such as being able to breathe air, hibernate in dry conditions, and having stronger immunity (Liu et al., 2020a; 2020b). In addition, the shape of their shells and the structure of their closure organs have appeared similarly many times in different evolutionary routes, which is a typical case of convergent evolution (Hausdorf and Neiber, 2022).

African terrestrial snails live in a variety of different places, from humid tropical rainforests to arid grasslands. African giant snails (such as Achatina immaculata and Achatina fulica) are very adaptable to the environment. And some special evolutionary history can also be seen in their genes, such as the time of their genome duplication and the Cretaceous-Tertiary (K-T) extinction event. Perhaps it is these changes that allow them to survive and spread in harsh environments (Liu et al., 2020a; 2020b). In South Africa, some local snail groups also have obvious geographical and genetic differences, which is largely related to ancient climate change and ecological isolation (Raphalo et al., 2023).

Through this review, we have compiled the research results on African land snails in recent years, and from these research results, we can see how they have diversified in the process of evolution. The article combines multiple evidences such as phylogeny, genome and appearance to analyze the adaptive strategies and evolutionary mechanisms of African land snails, and explore its significance to evolutionary biology from these findings. Through the comparison of different species and regions, we hope to enable readers to have a better understanding of the unique value of African land snails and find some universal evolutionary laws from them.

2 African Terrestrial Snails: Diversity and Ecological Context

2.1 Overview of snail families and genera endemic or native to Africa

There are many types of land snails in Africa, belonging to different families and genera. For example, in the Mfamosing limestone mountains in Nigeria, 23 species of snails from 7 families were found. Among them, Streptaxidae (a carnivorous snail) has the most species, while Urocyclidae has the largest number of individuals. In contrast, Eucolinidae and Aillyidae are relatively rare (Eguakhide et al., 2023). In the Yankari Nature Reserve, the dominant species has changed to Achatinidae (Abhulimen et al., 2023). There is also a type of snail called "terrestrial prosobranchs" that is not found in many African species, with only 4 families and 9 genera found. Among them, 5 genera are endemic to Africa and mostly live on the edge of Africa or on islands. Islands like Madagascar have more snail species and more varied body shapes. African giant snails (such as Achatina immaculata and Achatina fulica) are widespread and invasive, having spread to many parts of the world (Liu et al., 2020a; Vijayan et al., 2022).

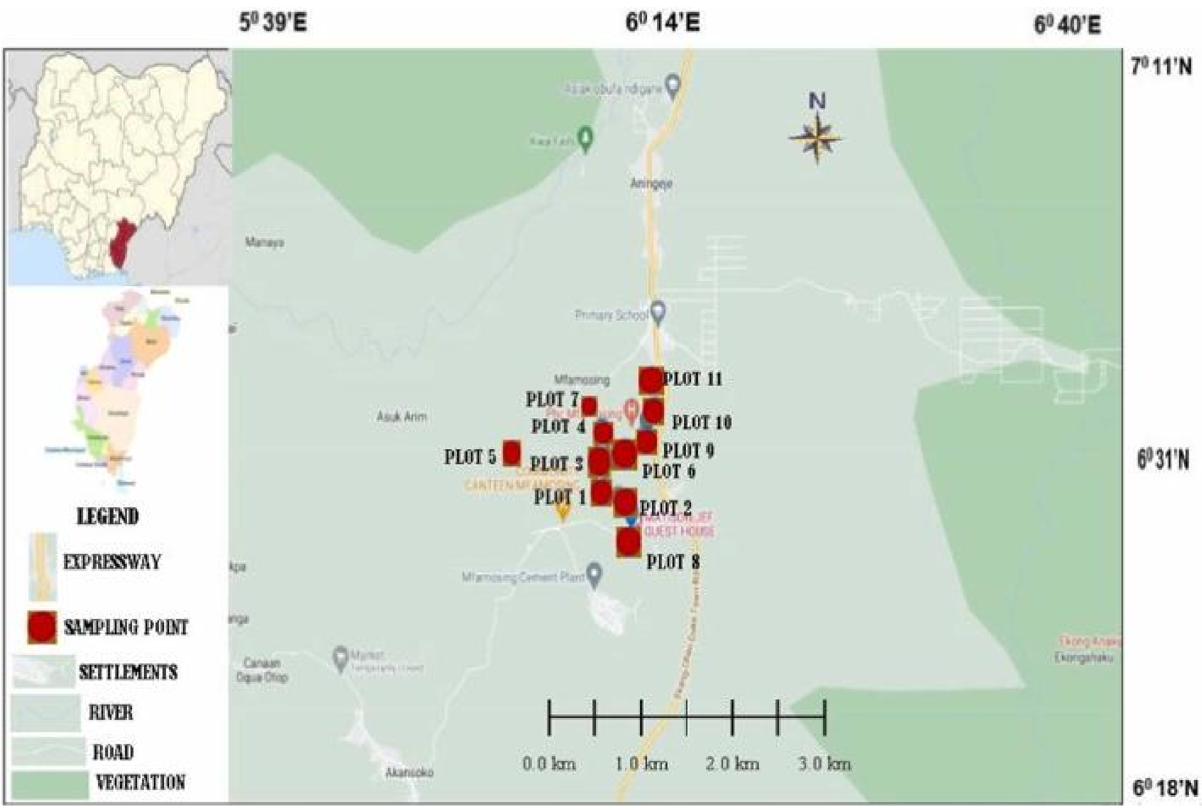

Figure 1 Map showing the study area- Mfamosing, Calabar, Cross River State, Nigeria

2.2 Key ecological niches inhabited by different lineages (forest, savanna, montane, arid zones)

African land snails have adapted to many different environments. In forests, snails are most diverse. For example, in Nyungwe National Park in Rwanda, 102 species of snails have been recorded, living between 1718 and 2573 meters above sea level. These snails prefer special microhabitats such as bare rock (Boxnick et al., 2015). In South Africa, there is a snail called Gittenedouardia, which mainly lives in small patches of forest, such as the Afrotemperate and Indian Ocean coastal zones. They are particularly adapted to this forest environment (Raphalo et al., 2020). In savannas and arid areas, snails are less common. In the Yankari Nature Reserve, snail species and numbers are not many (Abhulimen et al., 2023). Some limestone hills also have snails, which are generally unique and can only be found locally (Eguakhide et al., 2023). As for deserts and semi-deserts, there are almost no snails, only some land snails with shells in the Horn of Africa (Bruggen, 1981).

2.3 Influence of Africa's biogeographic history and climate heterogeneity on snail diversification

Africa has a vast landmass with great environmental variation across different latitudes and longitudes, which has had a profound impact on the evolution of terrestrial snails. Near the Nyungwe Forest, there is a region known as the "Pleistocene forest refugium." As the distance between African snails and this refugium changes, their species composition also varies. During past climatic shifts, this refugium served as a haven for many organisms, and as a result, it facilitated the diversification of African snails, leading to the emergence of more new species and greater interspecific differences (Boxnick et al., 2015). In South Africa, a genus of snails known as Gittenedouardia shows evidence of diversification that occurred during the Miocene to Pliocene period. During this time, Africa's overall climate became drier and forested areas shrank, causing populations to become geographically isolated and gradually evolve into distinct species. Some forest-dwelling snails, such as two species found in the Maputaland–Pondoland–Albany biodiversity hotspot, also underwent a series of lineage divergences and geographic isolations in response to climatic fluctuations during the Pleistocene (Raphalo et al., 2023). Moreover, an interesting finding in the genome of giant African snails is that they experienced a whole-genome duplication event around 70 million years ago—coinciding with the mass extinction at the end of the Cretaceous period. This duplication may have helped them survive in unstable environments and promoted their diversification (Liu et al., 2020a).

3 Application of phylogenetic genomics methods in the study of snail evolution

3.1 Introduction to phylogenetic genomics: methods and significance

The phylogenetic genomics method uses data from many genes, especially the information in the entire genome, to analyze the evolutionary relationship between species. Compared with the previous method of only looking at one or a few genes, this method is more comprehensive and more accurate. It is particularly suitable for organisms like snails, which have many species and a relatively complex evolutionary history. Whether it is studying the deep differences between species or analyzing some relatively recent differentiations, this method is very useful (Abdelkrim et al., 2018; Cunha et al., 2021; Price et al., 2021).

3.2 Commonly used genomic markers for snail phylogeny

When researchers conduct phylogenetic studies of snails, they use several common genomic markers. The first is mitochondrial genes, such as COI and 16S rRNA, which are very common. They are mainly used to determine the relationship between species or within populations, and are particularly suitable for studying geographical distribution and shallow differentiation (Puillandre et al., 2014; Price et al., 2021; Raphalo et al., 2023). The second is RAD-seq, which is a method that can get a lot of SNPs (single nucleotide polymorphisms) at once. It can be used to understand population structure, distinguish species, and find adaptive differences among species, especially for those "non-model" species that are not studied much (Price et al., 2021). There are also exon capture and ultraconserved elements (UCEs) methods, which mainly study deeper taxonomic relationships (such as evolutionary differentiation between different genera or families) by capturing a large amount of genetic information. There is also something called nuclear genome data, like rDNA and some protein-coding genes. This type of data is often used in combination with mitochondria to improve the accuracy of the analyzed evolutionary tree (Puillandre et al., 2014; Zareie-Vaux et al., 2018; Price et al., 2021).

3.3 Progress in the phylogenetic genomics of African snails

In recent years, some studies have specifically analyzed terrestrial snails in Africa and nearby areas, and mitochondrial genes (such as COI and 16S rRNA) and RAD-seq are commonly used. These methods have helped scientists discover many differences between species and also seen the effects of geographical isolation and adaptive changes. For example, when studying some endemic snail species in South Africa, COI and 16S analysis found that they had obvious differentiation under the influence of ancient climate change (Raphalo et al., 2023). In Hawaii, scientists also used RAD-seq and mitochondrial genomes to study tree snails, and found many deep lineage differentiations, and even discovered hidden species that were not recognized before. This is also very helpful for conservation work (Price et al., 2021). Some studies have combined the shell morphology of snails with genetic data and found that the morphological differences at the genus level can match the genetic lineage (Zareie-Vaux et al., 2018).

3.4 Advantages of genome-scale data in differentiation analysis

There are many advantages to using the data of the entire genome to study evolution. First, it can simultaneously clarify the relationship between species at the deep level (such as different genera and families) and the shallow level (such as variants within the same species). Compared with using only one or two genes, this method can better solve some problems that have always troubled researchers, such as the mismatch between gene trees and species trees, or the occurrence of "long branch attraction" (Abdelkrim et al., 2018; Cunha et al., 2021; Price et al., 2021). In addition, genomic data can also help us discover hidden species, find out whether there is hybridization and gene flow, and track how which traits have evolved. These have laid a good foundation for us to study the adaptive radiation and convergent evolution of African terrestrial snails (Zareie-Vaux et al., 2018; Price et al., 2021; Raphalo et al., 2023).

4 Patterns of adaptive radiation

4.1 Examples of rapid diversification in isolated or newly emerged niches

In isolated or newly emerged new environments, such as islands, isolated mountains and lakes, African terrestrial snails can quickly diversify. One example is the giant African snail (genus Achatina). Their genome once underwent a duplication (WGD), which made them more adaptable to the environment. This genomic change occurred at the same time as the emergence of new ecological environments after the mass extinction between the Cretaceous and the Tertiary. This may be the reason why they were able to spread rapidly and form many new species later (Liu et al., 2020a). Another example is freshwater snails living in lakes, such as Lake Tanganyika in East Africa. These snails also rapidly diversified in new environments and are classic examples of adaptive radiation (Glaubrecht and Rintelen, 2008).

4.2 Traits associated with ecological diversity

In the process of adapting to different environments, African terrestrial snails have changed many physical characteristics and lifestyles. For example, their shells vary in size and shape, some are dark in color, and some are thicker, which can help them cope with heat and drought (Schweizer et al., 2019). They can also enter a dormant state (such as aestivation) to avoid heat and drought. At this time, their bodies will regulate metabolism, such as increasing antioxidant capacity and activating some "protective" proteins (Schweizer et al., 2019; Liu et al., 2020a). Some physical characteristics have also changed, such as different species of snails independently developing similar genital lengths, or repeatedly disappearing ridges at the base of the shell. This suggests that they will respond in similar ways when faced with similar environmental pressures (Hausdorf and Neiber, 2022).

4.3 Evidence of lineage-specific radiation in different geographical regions

Different evolutionary routes have emerged for terrestrial snails in different parts of Africa. For example, in the Maputaland-Pondoland-Albany biodiversity zone in South Africa, there are two forest snails (Gittenedouardia spadicea and Maizania wahlbergi) that are geographically separated and genetically very different. Studies have shown that they evolved independently during the Pleistocene climate change (Raphalo et al., 2023). For snails such as the tribe Clausiliini, phylogenetic analysis shows that the shell structure and reproductive organs of different lineages have also evolved very similarly, indicating that they have undergone adaptive radiation in different regions (Hausdorf and Neiber, 2022). In addition, genomic studies have found that many lineages have experienced expansion of gene families and the generation of some new genes in the process of adapting to terrestrial life. This change did not happen once, but recurred in different snail groups, helping them to occupy more diverse ecological environments (Liu et al., 2020a; Chen et al., 2022; Aristide and Fernández, 2023) (Figure 2).

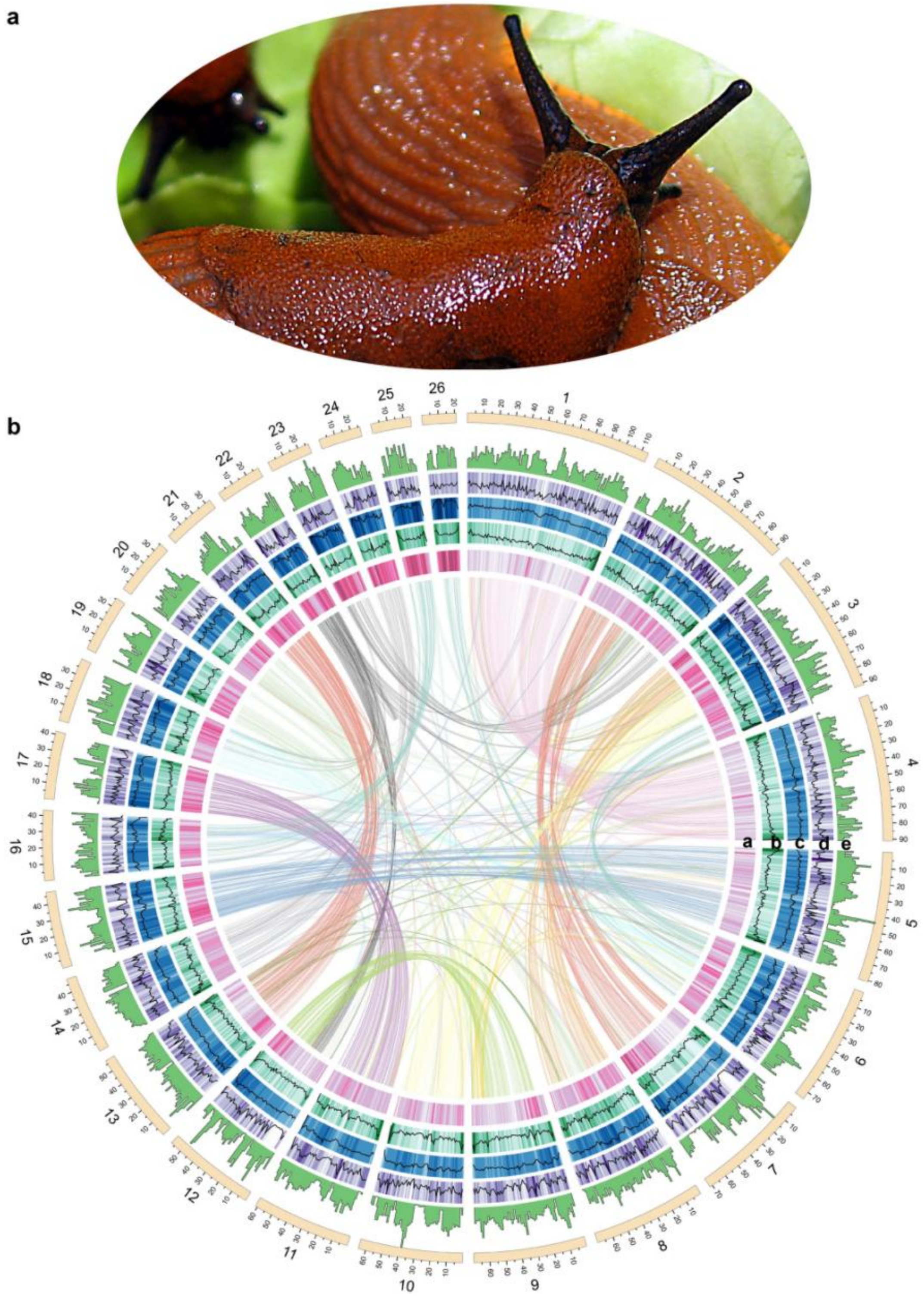

Figure 2 Genome features of Arion vulgaris. (a) Adult A. vulgaris. (b) General characteristics of the A. vulgaris genome. Tracks from inside to outside correspond to (a) GC content, (b) LTRs density, (c) TEs density, (d) genes density, and (e) heterozygosity in sliding windows of 1 Mb across each of the 26 pseudochromosomes. Inner lines connect syntenic genes due to ancestral whole-genome duplication events

5 Convergent evolution in morphological traits

5.1 Definition and examples of convergent evolution: shell shape, color and behavior

Convergent evolution refers to the evolution of different species of animals or plants into similar-looking shapes, colors or behaviors when faced with similar environments or survival pressures. Although they have different ancestors, they evolve in the same direction because they live in similar environments. African land snails are a good example. Some species are very different in genes, but their shell shapes and body appearances look very similar. For example, the Nata snails in southern Africa have obvious differences in DNA, but their shells look almost the same, indicating that their shapes are very stable, and they may also have evolved convergently due to similar environments (Moussalli and Herbert, 2016). There are also the Lautoconus snails in Senegal, which have similar changes in shell shape and radula structure more than once. Some species look similar in appearance and are difficult to distinguish. They may actually be different cryptic species, or their appearance may change with the environment. This is called "phenotypic plasticity" (Abalde et al., 2017).

5.2 Similar habitats and selection pressures lead to repeated evolution of traits

In different regions, African land snails often evolve similar appearances under similar climate or environmental pressures. This situation is also called "parallel evolution". For example, in Israel, there is a famous "Evolutionary Canyon" study. On the south slope of the canyon, the climate is dry and the sun is strong, so the shells of the snails there are generally smaller, which can help them dissipate heat. On the north slope, the climate is humid, and the shells are higher, which is conducive to retaining water. This shows that when faced with different environments, they will change the shape of the shell to adapt, which is actually a kind of convergent evolution (Raz et al., 2012). Similarly, in Senegal, Lautoconus snails also face pressures such as sea level changes and temperature changes. Although they are from different lineages, they have developed similar radulas. This structural change may be the result of a change in eating habits, and it also shows that environmental selection played a role behind it (Abalde et al., 2017).

5.3 Evidence of geometric morphological measurement and comparative analysis

To study the convergent evolution of snails, researchers often use geometric morphometric methods to analyze detailed morphological differences among species. These methods allow the shapes of various snail shells to be quantified numerically, enabling comparisons across different species. In a study conducted in Israel's “Evolution Canyon,” researchers measured features such as shell height, the degree of shell coiling, and the number of whorls along the suture to examine snails living on opposing slopes. They found that despite the environmental differences, the direction of shell morphological change was similar among the snails, indicating that they were all adapting to their respective environments (Raz et al., 2012). In 2016, a study by Moussalli and Herbert on the genus Nata reached similar conclusions: despite significant genetic differences, shell morphology remained relatively consistent. This further supports the idea that African snails may have undergone morphological convergence. In 2017, Abalde and colleagues studied snails of the genus Lautoconus and also found convergent traits in shell shape and radular structures across different lineages, a pattern that was corroborated by phylogenetic analyses.

6 Fusion of morphological and genomic data

6.1 Challenges and benefits of combining morphological classification with phylogenetic data

Combining appearance characteristics (morphology) with genomic data is a useful approach for studying non-model species such as African land snails. This combination can help us better understand their evolutionary process and how they adapt to the environment. Many times, it is difficult to distinguish different species by appearance alone, but genomic data can reveal deeper differences behind them, such as lineage differentiation and evolutionary history (Moussalli et al., 2009; Guo et al., 2019; Liu et al., 2020a; 2020b; Raphalo et al., 2020).

However, this combination is not without difficulties. Appearance is affected by the environment, and animals from different lineages may evolve to look similar because of similar environments. This "look-alike" may mislead traditional classification methods. In addition, genome analysis is costly, has strict requirements on sample quality, and the analysis process is also complicated (Moussalli et al., 2009; Raphalo et al., 2020).

Nevertheless, combining the two methods is still very helpful. It can correct the errors that may be caused by only looking at the appearance, find hidden genetic diversity, and also give us a more comprehensive understanding of the relationship between species and how they evolve (Moussalli et al., 2009; Raphalo et al., 2020).

6.2 Examples of morphological convergence misleading traditional classification

Many different species of African land snails have very similar appearances, which often leads to errors in their classification. For example, in the past, snails of the genus Prestonella were classified into different categories based on their appearance. Later, after combining genetic and morphological data, it was found that they actually belonged to the Bulimulidae family. This discovery also gives us inspiration: there may be very ancient biological connections between Africa, South America, and Australia (Herbert and Mitchell, 2008). In 2009, Moussalli's team studied snails of the genus Natalina. Although overall, its appearance and genetic classification are consistent, at the species level, some individuals that look almost identical actually have very different genes.

6.3 Methods for solving cryptic species complexes

For those "cryptic species" that are almost the same in appearance but different in genes, scientists now use a variety of methods to identify them. Among them, the commonly used methods include: combining multiple genes for phylogenetic analysis, looking at the genetic structure between populations, and some methods specifically used to divide species, such as PTP and STACEY. These methods, combined with observations on appearance, can help us find populations that are independent in genes but difficult to distinguish in appearance (Moussalli et al., 2009; Raphalo et al., 2020). For example, when studying the genus Gittenedouardia, scientists used mitochondrial and nuclear gene data, plus two species identification methods, to discover many genetic lineages that had not been recognized before. This also shows that this genus may need to be reclassified (Raphalo et al., 2020). Studies on the Natalina genus also show that morphological and molecular data should be further combined to find out how many species there are and to find the diversity that has not yet been discovered (Raphalo et al., 2020).

7 Evolutionary drivers and constraints

7.1 Key drivers: habitat fragmentation, climate gradients, predator-prey dynamics, dispersal barriers

Behind the adaptive radiation and convergent evolution of African terrestrial snails are the regulation of various environmental and geographical factors. Initially, habitat fragmentation and geographical isolation will reduce the genetic exchange between different populations, which will gradually produce genetic differences between different populations and even slowly evolve into different species. In the South African biodiversity zone, there are two species of forest snails that are separated both geographically and genetically. The reason for this differentiation is that they have poor diffusion ability and can only live in a small area. After their living environment is divided into small pieces, they have differentiated (Raphalo et al., 2023).

Climate change, such as climate fluctuations from the Pliocene to the Pleistocene, will also promote the division of populations and the evolution of lineages (Greve et al., 2017; Raphalo et al., 2023). There are also predator-prey relationships (such as predator pressure and wave intensity) that will allow some individuals to gradually adapt locally. These selection pressures will, to a certain extent, make snails in different places grow similar shells or body structures. Although there is some genetic exchange between them, this is also a form of convergent evolution (Butlin et al., 2013).

7.2 The role of sexual selection and reproductive isolation

Sexual selection and reproductive isolation also played a big role in the species differentiation of African land snails. Some snails lay eggs, while others raise their young. Such different reproductive methods will cause the offspring of the hybridization of these two snails to be unable to survive. This phenomenon is called "postzygotic isolation", which can prevent hybridization between different species and help them maintain their respective boundaries (Stankowski et al., 2020).

Even if some populations live together, they will not mate with each other. This phenomenon shows that reproductive isolation was established when they were first separated geographically, so that they can live together later but maintain their respective species identities (Stankowski et al., 2020). In addition, some adaptive changes in snails, such as shell shape or the length of the copulatory organ, are also related to reproductive isolation. This difference can further strengthen the isolation between them and promote the emergence of more new species (Butlin et al., 2013; Hausdorf and Neiber, 2022).

7.3 Evolutionary constraints: developmental pathways and historical contingency

In addition to environmental drivers, the evolution of African land snails is also subject to some constraints, such as their developmental methods and historical contingencies. Sometimes, some changes in characteristics are not for adaptation to the environment, but because the developmental path limits their range of variation. In other words, they can only make choices in a limited "morphological space". This will make some originally unrelated species evolve into similar appearances in the end (Hausdorf and Neiber, 2022). Historical contingencies, such as large-scale genome duplications (WGD), will also affect subsequent evolution. On the one hand, such events provide more genes for selection, which is conducive to adapting to new environments, but at the same time, they may also make certain evolutionary directions fixed and difficult to change (Liu et al., 2020a). Furthermore, due to the incomplete fossil record and the many uncertainties in geological history, we still do not have a clear understanding of how snails evolved in their early days (Hausdorf and Neiber, 2022).

8 Case Study: Adaptive Radiation of the Tropidophora Group (Hypothetical Example)

8.1 Group Background and Regional Distribution

The genus Tropidophora is a representative group of African land snails. They are found in many different environments across the continent, such as forests, grasslands, and rocky areas. These snails have a wide range of appearances and are very adaptable. Because of these characteristics, they are well suited to studying adaptive radiation and convergent evolution in African land snails (Liu et al., 2020a; Hausdorf and Neiber, 2022; Raphalo et al., 2023).

8.2 Research Methods

This study used several different methods. We first collected samples of the genus Tropidophora in different environments, from multiple regions, to ensure that they were representative of their overall situation (Raphalo et al., 2023). Next, we used some genetic analysis methods, including mitochondrial genes and nuclear genes, such as COI and 16S rRNA, to reconstruct the evolutionary relationships between them and estimate when these lineages began to diverge (Hausdorf and Neiber, 2022; Raphalo et al., 2023).

In addition to genes, we also measured the size and shape of the shell and the structure of the closed capsule. Through these morphological data, we analyzed the similarities and differences in their appearance to see which ones are the result of convergent evolution and which ones are the result of independent evolution (Hausdorf and Neiber, 2022).

8.3 Main findings

The study found that the main differentiation of the Tropidophora genus occurred from the Neogene to the Pleistocene, during which time the climate in Africa fluctuated greatly and many new ecological environments appeared (Raphalo et al., 2023). During this period, different lineages experienced multiple ecological transitions, some moving from forest environments to grasslands or rocky areas, and some in the opposite direction. This shows that they are very adaptable to different microenvironments (Raphalo et al., 2023). In terms of appearance, there are many similar changes in the shell shape and closed capsule structure of different lineages. Although these lineages are not directly related, they have evolved similar appearances under similar environmental pressures. This is a typical phenomenon of convergent evolution (Hausdorf and Neiber, 2022).

8.4 Implications for the evolution of African molluscs

This example shows that African terrestrial snails can rapidly diverge from their lineages and evolve new morphological characteristics in the face of climate change and ecological diversity. Multiple independent ecological transitions and the emergence of similar appearances indicate that environmental conditions and ecological opportunities are important drivers of their evolution. The study also showed that combining genomic analysis with morphological measurements is an effective way to study their evolutionary history and adaptation mechanisms. This method can not only reveal hidden diversity, but also help us better understand the evolution of mollusks on the African continent (Liu et al., 2020a; Hausdorf and Neiber, 2022; Raphalo et al., 2023).

9 Conservation significance

9.1 Impact of habitat loss, invasive species and climate change on radiation hotspots

In some parts of Africa, such as Maputaland–Pondoland–Albany (MPA) and the East African Mountains, there are many species of African terrestrial snails. However, due to deforestation, land use change, road construction, house construction, etc., the habitats of these snails are being destroyed, resulting in fewer and fewer living environments and increasing survival pressure. These human activities have a particularly great impact on local snails, especially some snails that only live in this area (Osemeobo, 1992; Tattersfield et al., 1998; Perera et al., 2021). In addition to human activities, alien species also pose some survival threats to African snails, such as the African giant snail Achatina fulica, which not only competes with local African snails for food, but also preys on other snails and even spreads diseases. In the context of climate change, this invasive snail can also expand to more areas and occupy new ecological niches. Its spread will make it more difficult for native species to survive (Sarma et al., 2015; Miranda and Pecora, 2017; Wu et al., 2023; Panisi et al., 2024). Climate change may also make some areas more suitable for the survival of this alien snail, which will further threaten the diversity of native snails (Sarma et al., 2015; Wu et al., 2023).

9.2 The importance of identifying cryptic species and evolutionarily distinct lineages for conservation priorities

African land snails are highly endemic in many places, living only in specific areas and with great evolutionary divergence between species. In many cases, they look similar but are genetically completely different. These “cryptic species” and evolutionarily distinct lineages exist in many places (Tattersfield et al., 1998; Fontaine et al., 2007; Perera et al., 2021; Raphalo et al., 2023). However, many traditional conservation plans are mainly aimed at protecting large vertebrates, such as lions and elephants, and as a result, snails in many places are ignored. These places may have many species and are very unique, but they are not included in protected areas (Tattersfield et al., 1998; Fontaine et al., 2007). If we use genetic phylogeny and distribution data to identify these cryptic species, we can more scientifically find truly important conservation areas. This can help us prevent some species from disappearing quietly when no one pays attention (Fontaine et al., 2007; Perera et al., 2021; Raphalo et al., 2023).

9.3 Suggestions for incorporating evolutionary perspectives into conservation planning

In order to better protect African terrestrial snails, we must also consider their evolutionary background when planning conservation measures. First, priority should be given to protecting areas with many species and strong endemicity, such as limestone areas and mountain forests. These places are hotspots for the reproduction and evolution of many snails (Tattersfield et al., 1998; Fontaine et al., 2007; Perera et al., 2021). In addition to large protected areas, some smaller but species-rich areas should not be ignored. These small protected areas can serve as supplements to improve the overall protection effect (Fontaine et al., 2007).

In addition, encouraging people to engage in small-scale snail farming is also a good measure, so that there is no need to collect a large number of wild individuals, which will reduce a lot of pressure on natural populations (Osemeobo, 1992). Of course, we still need to continue to strengthen the study of snail ecology and genes, and establish a clear species distribution map and evolutionary relationship database, so that conservation decisions can be more scientific and well-founded (Osemeobo, 1992; Perera et al., 2021; Raphalo et al., 2023). When controlling invasive alien species, we must also consider the lives of local residents. Local governments, researchers and communities can work together to protect the ecological environment while taking care of human needs (Miranda and Pecora, 2017; Panisi et al., 2024).

10 Concluding Remarks

We still don't know enough about the phylogeny and adaptive radiation of African land snails, and many areas are still blank. First, some regions and lineages have not been sampled enough, especially in southeastern Europe, where there are very few fossil data from the Neogene strata. This makes it difficult for us to figure out how some groups first came about, and their early evolution process is also unclear. Second, although there are more fossils in Western and Central Europe, most of these fossils have not been systematically time-calibrated. This will affect our judgment of the time of radiation events and it is not easy to restore an accurate timeline. There are also many studies that only use a single method, such as only looking at genes or only looking at appearance, lacking a comprehensive analysis that combines genomes, ecology and morphology.

For African terrestrial snails, future research should increase the intensity of field sampling, focusing on areas and groups that have not yet been clearly studied. In research, a variety of methods and techniques can be combined, such as combining genomics, morphology and ecology, so that we can have a more comprehensive understanding of the evolution of African terrestrial snails. Genomic data can help us discover major evolutionary events such as whole genome duplication (WGD) to see how they affect the environmental adaptation of snails; through appearance and ecological data, we can figure out which features correspond to functional adaptation and ecological differentiation. At the same time, in order to better restore the context of evolutionary events, it is also important to systematically organize and time-calibrate the existing fossil evidence.

African terrestrial snails are a very typical example of adaptive radiation and convergent evolution. Genome studies have found that groups such as African giant snails have experienced WGD events, which has increased their genetic diversity, helping them to better cope with environmental changes and adapt to terrestrial life. Studies on appearance and function have also found that different lineages will evolve similar characteristics when facing similar environmental pressures. For example, their shell structure, closed capsule style, and even the length of their reproductive organs have undergone multiple parallel evolutions. This shows that although they are from different lineages, they will come up with similar "solutions" when faced with the same problem. These examples not only show how snails adapt to the environment, but also let us see that evolution is not a single process. Sometimes convergence and divergence occur at the same time, and the process is actually very complicated.

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