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THE AZOREAN ENDEMIC SNAILS ARE DISAPPEARING!
WHO IS TO BLAME?

António M. de Frias Martins[1,2], Diamantino V. Henriques[2,3] & Robert A.D. Cameron[4]

[1] *CIBIO-Açores, Department of Biology, University of the Azores, 9501-801 Ponta Delgada, São Miguel, Azores, Portugal*
E-mail: a.friasmartins@gmail.com

[2] *Sociedade Afonso Chaves, Observatório Afonso Chaves, 9500-321 Ponta Delgada, São Miguel,* Açores, Portugal

[3] *Instituto Português do Mar e da Atmosfera, 9500-321 Ponta Delgada, São Miguel,* Açores, Portugal
E-mail: diamantino.henriques@ipma.pt

[4] *Department of Zoology, Natural History Museum, London, SW7 5BD, U.K.*
E-mail: radc@blueyonder.co.uk

ABSTRACT

About 50 years of land snail collections are stored in the Reference Collection of the Department of Biology of the University of the Azores (DBUAç-MT); this timeframe is herein used to investigate changes in abundance, and eventually to search for possible causes of variation. The methodology employed during the various collecting missions (selective search for endemics and handpicking the specimens) does not allow for formal statistical treatment of the relative abundances through time within the malacofauna. Yet, by biasing the search effort towards endemic species, such a collecting approach has shown more convincingly a tendency for decline among these species, accentuated in the last 20 years.

Focus on the endemics, rather than the overall malacofauna, is justified by their supposed lower resilience to habitat change due to narrow niche adaptation, as compared with the non-endemic, mostly introduced malacofauna, often with broad habitat tolerances with respect both to climate and anthropogenic disturbance. The details of this study reveal an alarming trend toward extinction of these endemics. Analysis of meteorological parameters (air temperature, precipitation, relative humidity) has provided evidence for climatic change, and inspection of land use through the years has shown extensive habitat fragmentation, increase in secondary forest and spread of invasive species. It is suggested that climate change and habitat destruction, coupled with introduced plant and animal invaders, are responsible for such demise.

To counteract this extinction trend, the project LIFE SNAILS NAT/PT001377 was set in motion in Santa Maria, aiming at the habitat restoration on the protected area of Pico Alto, once the hottest endemic spot of the island. It is still too soon to expect results.

SUMÁRIO

Cerca de 50 anos de recolhas de moluscos terrestres estão depositadas na Colecção de Referência do Departamento de Biologia da Universidade dos Açores (DBUAç-MT); esse enquadramento temporal é usado aqui para investigar alterações na abundância, e eventualmente procurar possíveis causas de variação. A metodologia utilizada durante as várias missões de recolha (procura selectiva de endémicos e recolha manual dos exemplares) não permite tratamento estatístico formal das abundâncias relativas na malacofauna ao longo do tempo. No entanto, ao enviesar o esforço de procura para os endémicos, tal abordagem de recolha evidenciou de modo mais convincente uma tendência para o declínio nos endémicos, de modo acentuado durante os últimos 20 anos.

O foco nos endémicos, em vez de sobre a malacofauna em geral, justifica-se pela suposta menor resiliência daqueles à alteração do habitat devido a estreita adaptação ao nicho, quando comparada com a malacofauna não endémica, maioritariamente introduzida, tendencialmente generalista e propensa a adaptação. Tal facto foi abordado em pormenor, revelando uma alarmante tendência para a extinção destes endémicos. Análise de parâmetros meteorológicos (temperatura do ar, precipitação, humidade relativa) proporcionou evidência para influência da alteração climática, e inspecção do uso da terra ao longo dos anos mostrou extensa fragmentação do habitat, aumento da floresta secundária e propagação de espécies invasoras. Sugere-se que as alterações climáticas e a destruição do habitat, juntamente com a introdução de plantas e animais invasores, são responsáveis por tal desaparecimento.

No intuito de contrariar esta tendência para a extinção, iniciou-se em Santa Maria o projecto LIFE SNAILS NAT/PT001377, com a intenção de restaurar o habitat na área protegida do Pico Alto, outrora o mais significativo lugar para endemismos na ilha. Ainda é muito cedo para que se esperem resultados.

INTRODUCTION

Climate change is a commonly accepted reality of major concern in intergovernmental forums (*e.g.* IPCC, 2023, IUCN-CCC, 2023; WMO-GADCU, 2023). However, that climate change is directly responsible for species extinction is an issue of much debate. Assertions of climate change driven extinctions have been scrutinized and most have been dismissed as such due to unclear direct cause/effect relationship of the factors involved (Cahill *et al.*, 2013; Altaba, 2022; but see Parmesan & Yohe, 2003). Models have been developed to ascertain the impact of climate change directly on species, *e.g.* through physiology (Whittaker, 1999; Nicolai & Ansart 2017; Halsh *et al.,* 2020; Köhler *et al*., 2021), indirectly through habitat alteration (Harris *et al*., 2006; Dong *et al*., 2020), or altogether as a ‘bioclimatic envelope’ (Pearson & Dawson, 2003), the complexity of which brings forward the tight intricacy of the multitude of stress inducing factors caused by climate change due to global warming (Chatterjee, 2013).

An alternative factor with higher impact on survival of endemic species are the invasive species (Clavero & Garcia-Berthou, 2005; Doherty *et al*., 2016), whichever way they arrive: naturally as an expansion of their range, or anthropically introduced either accidentally or intentionally. Careful inspection of some cases formerly attributed to direct climate change have been explained through invasive competition (Altaba, 2022).

Projections of the number of species to disappear due to climate change alone is 9.5% of the currently known taxa in the next 100 years, but if all factors negatively influencing the species are considered, that percentage rises to 21% (Javeline *et al*., 2015). Other comprehensive analyses have projected that, by 2050, 15–37% of species will be ‘committed to extinction’ (Thomas *et al*., 2004); such percentages, when undescribed taxa are included, will amount to many hundreds of thousands of species lost from nature.

The vulnerability of islands and of their endemic species to extinction has been attributed to many factors; small ranges and narrow niche adaptations play a part (Darwin, 1859; Leclerck *et al*., 2020), as do the drastic changes imposed by humans and the introduction of predators (Cameron & Cook, 1996; Cowie, 2022). Climate change increases these pressures, and modelling of island faunas suggests that many species are at risk (*e.g*. Gouveia, 2015). The negative effects of climate change are also being felt in the Azores Islands with worrisome concern.

In this study, we report, for the first time, evidence of such a problem for the endemic terrestrial molluscs typical of Santa Maria Island, through the number of specimens collected in various missions over about 50 years; these specimens are deposited at the Reference collection of the Department of Biology of the University of the Azores (DBUAç-MT). The findings herein presented had a pivotal role in the preparation of the project LIFE SNAILS NAT/PT001377.

SANTA MARIA AND ITS MALACOFAUNA

Brief history

Santa Maria, the oldest island of the Azores, is 97 km^2 and 580 m at its highest point. Having emerged around 6 My ago, the island then subsided, finally to re-emerge about 3.5 My ago (Ramalho *et al*., 2017). It is the richest in island endemic snails (Figure 1). Extensive collecting on the island dates back to the 1850's when the French naturalists Arthur Morelet and Henri Drouët conducted the first major expedition on the Azorean terrestrial molluscs; 32 endemic species were recorded, 8 of which were found only on Santa Maria (Morelet, 1860); Backhuys (1975), in a revision of the Azorean terrestrial and freshwater malacofauna, recorded 35 endemic species, 10 of which were living only on Santa Maria.

The establishment of the University of the Azores, in 1976, prompted a new wave of collecting and description of terrestrial molluscs, raising the number of endemics to 53, of which 19 are restricted to Santa Maria. The Department of Biology of the University had taken upon itself to organize yearly expeditions, of two to three weeks duration, covering all islands, during which extensive and intensive collecting took place; additionally, various scientific projects (STRDB/C/CEN/508/92; PRAXIS XXI: 2/2.1/BIA/169/94; PTDC/BIA-BDE/73467/ 2006) contributed with collected material, to which the author's (AMFM) previous personal collection was added. The resulting Reference Collection (DBUAç-MT) covers 382 sta-

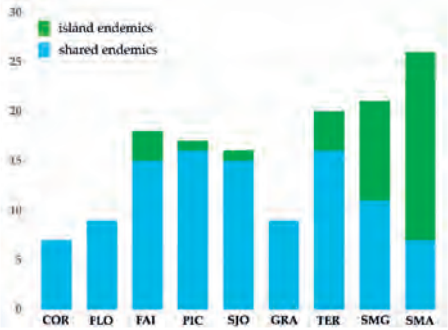

FIGURE 1. Distribution of shared and island endemic species throughout the 9 islands of the archipelago. **COR**, Corvo; **FAI**, Faial; **FLO**, Flores; **GRA**, Graciosa; **PIC**, Pico; **SJO**, São Jorge; **SMA**; Santa Maria; **SMG**, São Miguel; **TER**, Terceira.

tions, of which 60 are in Santa Maria. Only about 10% of the collection has been catalogued, but priority was given to the endemic terrestrial molluscs of Santa Maria due to the imperative for description of new species. This information served as the basis for the present study, through examination of the change in abundance of the collected specimens during that time span.

Collecting methodology and analysis

Collecting was essentially by handpicking and did not follow any pre-set methodology for statistical analysis. There was a bias toward the endemic species and most of all toward those that could not be immediately identified. In more recent years, additional searching effort was dedicated to the increasingly rarer species.

TABLE 1. Temporal distribution of the specimens of Santa Maria Island endemics collected during five decades. Numbers represent the total number of specimens collected during the decade, divided by the number of missions conducted during that decade (in parentheses). Black cells represent species of which no specimens were collected in over 20 years, and therefore are presumed to be extinct; gray cells represent species of which specimens were very rarely collected during the last 20 years, and therefore are feared to become extinct.

Island endemic species	**Distribution of collected specimens per decade**				
	1970 (4)	1980 (3)	1990 (7)	2000 (2)	2010 (3)
Leiostyla tesselata (Morelet, 1860)		**1**	**1**		■
Leiostyla pomboi Martins, 2023	**1**		**1**		**11**
Leiostyla elegans Martins, 2023	**2**	**7**	**12**		■
Napaeus hartungi (Morelet & Drouët, 1857)	**12**	**1**	**22**	**9**	**20**
Napaeus tremulans (Mousson, 1858)	**8**	**3**	**30**	**5**	**11**
Napaeus sp			**21**	**6**	**6**
Oxychilus agostinhoi Martins, 1981	**16**	**2**	**9**		**1**
Oxychilus brincki Riedel, 1964	**2**	**39**	**68**	**63**	**21**
Oxychilus lineolatus Martins & Ripken, 1991	**1**	**1**	**11**	**17**	**14**
Oxychilus spectabilis (Milne-Edwards, 1885)	**21**	**10**	**11**	**9**	**15**
Oxychilus viridescens Martins, Brito & Backeljau, 2013	**3**	**2**	**16**	**29**	**5**
Oxychilus andrei Martins 2017		**1**	**13**		**7**
Oxychilus melanoides Martins 2017	**15**	**30**	**19**	**1**	**13**
Oxychilus micromphalus Martins 2017	**1**	**2**	**4**		**1**
Azorivitrina angulosa (Morelet, 1860)	**2**	**1**	**1**		■
Azorivitrina brevispira (Morelet, 1860)	**4**	**1**	**1**		**4**
Azorivitrina pelagica (Morelet, 1860)	**9**	**5**	**2**		**1**
Moreletina obruta (Morelet, 1860)	**4**		**14**	**19**	**9**
Leptaxis minor Backhuys, 1975	**12**	**7**	**5**	**3**	**7**
Leptaxis sanctaemariae (Morelet & Drouët, 1857)	**23**	**20**	**35**	**16**	**19**
"? *Moreletina* n.sp. a	**18**	**32**	**14**		**10**
"? *Moreletina* n.sp. b	**11**	**14**	**34**	**4**	**4**
"? *Moreletina* n.sp. c	**9**		**10**		■

The collecting effort was not homogeneously spread along these 50 years. To establish some common ground for comparison, the time frame was divided into decades and the pooled number of specimens collected per decade was divided by the number of missions in that decade (Table 1).

Inspection of Table 1 shows a trend for diminishing abundance following the 1990 decade. Four species are presumed lost, for no specimens having been found for over 20 years (Figure 2A-D), and at least three other species have become so rare that they are feared to become extinct (Figure 2E-G). Of the still undescribed species, ?*Moreletina* sp. c, a new genus and a new species in the process of description, has already vanished from recent collecting and is presumed to have become extinct (Figure 2D).

FIGURE 2. Species at risk in Santa Maria (see Table 1). **A-D**, presumed extinct: **A**, *Leiostyla tesselata*; **B**, *Leiostyla elegans*; **C**, *Azorivitrina angulosa*; **D**, ?*Moreletina sp.* c. **E-G**, feared to become extinct: **E**, *Oxychilus micromphalus*; **F**, *Azorivitrina pelagica*; **G**, *Oxychilus agostinhoi*.

The most affected species are mountain dwellers; those which live at low altitudes, some near the shoreline (*Leiostyla pomboi*, *Moreletina obruta*, *Napaeus sp*.), are less affected, as are those species that can be found from the shoreline to the highest elevation (Pico Alto) (*Napaeus hartungi*, *Napaeus tremulans*).

In 2008, a special mission was set up with Robert A.D. Cameron and the late Beata Pokryszko, in which a numerical approach was used for the collecting methodology. The results were later published (Cameron *et al*., 2012*)* and the list of collected specimens is in the "Supplementary material" of that publication. The information therein contained was not integrated in the present study due to the different methodology then followed, namely the use of a sieving instrument and time constraint at each station. However, a trend very similar to the one found in this study can be observed in Cameron's data, that is, the rarefaction of the same species as found in the present study. In particular, only a single specimen of *O. agostinhoi* was found, and only in the richest site on Pico Alto, perhaps the least damaged of any. *Leiostyla* species were also hard to find, and were absent in 2011.

SEARCHING FOR EXPLANATIONS

Many factors can be summoned to explain this concerning trend toward the dwindling of populations or disappearance of species. We will focus on three groups: climate change; habitat fragmentation/destruction; introduction of invaders/predators.

Climate change

The more readily perceived, easily measured factor of climate change is temperature rise. Yet, other concurrent meteorological factors, namely precipitation and relative humidity, do influence the environment and the habitat molluscs are adapted to. These three factors will be dealt with now.

Owing to the presence of an airport on Santa Maria since 1944, a series of meteorological data are available. Monthly climatological series were retrieved from average daily values of air temperature, relative humidity, precipitation and global radiation observed at Santa Maria airport weather station and available in the Portuguese meteorological archives of the Portuguese Institute for Sea and Atmosphere - IPMA (*Instituto Português do Mar e da Atmosfera*).

Weather observations consist of direct readings using manual (1971 - 2002) and automated (2003 - 2022) instruments. However, these series have large missing values periods or gaps that can introduce bias and inconsistencies on trends, leading to less accurate results. Therefore, to fill the existing gaps and assure the consistency of the time series, monthly values from the ERA5 reanalyses (Hersbach *et al*., 2020) from Copernicus Climate Data Store (Hersbach *et al.,* 2023) were also used. Gridded data were interpolated to the coordinates of the weather station (36.975412°N, 25.172600°W). ERA5 monthly averaged data on single levels has a spatial resolution of 0.25°x 0.25° for all the globe and since 1940 to the present.

Considering that there are differences between reanalyses and observed values, a bias adjustment and a statistical downscaling was done to minimise these biases. The approach adopted consists of the Quantile Mapping (QM) method. In general, QM methods consist of optimising a transformation function of a distribution:

$$x^o = f(x^m)$$

where x^o is the observed variable, x^m is the modelled variable and $f()$ is the transformation function (Enayati *et al*. 2021). The Empirical Quantile Mapping bias-adjustment is a bias correction method that works by fitting the cumulative distribution function (CDF) of the model to that of the observations (Seo & Ahn, 2023; Gudmundsson *et al*., 2012):

$$x^o = F_o^{-1}\,[F_m\,(x^m)]$$

where F_m is the CDF of x^m and F_0^{-1} is the inverse form of the CDF of x^0, which is technically referred to as the quantile function.

A Python module of *xclim* package (Bourgault *et al*., 2023) was used for the bias adjustment and a statistical downscaling computations, *xclim.sdba.adjustment.EmpiricalQuantileMapping* (Déqué, 2007). In this case, we used the period 2003-2015 as a reference for the observational and model data and the number of quantiles was set at 15.

Figure 3 shows the twelve-month moving averages of the monthly air temperature averages at 2 metres resulting from the application of the above method.

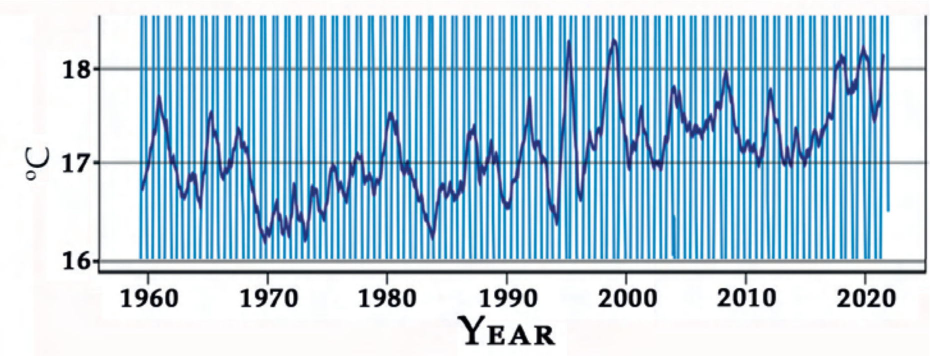

FIGURE 3. Twelve months moving averages of 2-meter air temperature monthly means observed at Santa Maria airport. Data was bias adjusted and statistically downscaled using ERA5 reanalyses.

TABLE 2. Computed linear trends for 2-meter air temperature at Santa Maria airport.

2m air temperature		
Period	**Trend (K/decade)**	**p-value**
1961-2020	0,16 ± 0,01	0,00
1961-1990	0,00 ± 0,02	0,88
1991-2020	0,14 ± 0,02	0,00

It can be seen that until the second half of the 1990s the average annual temperature was never higher than 18°C and that afterwards it was rarely lower than 17°C.

The linear trends calculated for the overall 60-year period 1961-2020 and for two separate periods of 30 years, 1961-1990 and 1991-2020 are shown in Table 2. It can be seen that overall (1961-2020) and in the later period (1990-2020), there are statistically significant trends at a significance level of 95 %, with the exception of the 1961-1990 period, which shows no trend. This result shows a stationary period during the first 30 years (until the 1990s), followed by a warming period of the same duration. To summarise, these results show that the warming over the last 60 years is mainly due to the last 30 years of the series.

Figure 4 shows the seasonal variation in monthly air temperature at 2 metres for the periods 1961-1990 and 1991-2020. It can be seen that, on average, the last 30-year period was warmer in all months and that the average annual deviation is 0.54 K, the highest being in October (0.67 K) and the lowest in May (0.41 K).

Figure 5 shows the average monthly precipitation rate for the periods 1961-1990 and 1991-2020. An increase can be seen in the months of May to October and December, and a decrease in the months of January to March and November. In general, the increase occurs mainly in late spring, summer and early autumn. The month of November shows a substantial decrease, altering the symmetry of the monthly distribution of precipitation throughout the year, which in the most recent period shows two relative maxima, one in December (main) and the other in December (secondary).

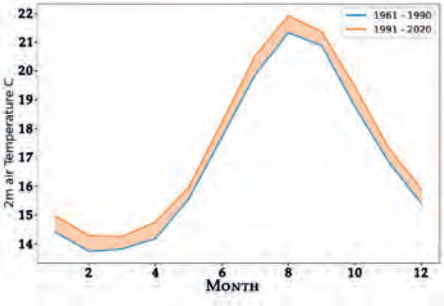

FIGURE 4. Two-meter air temperature monthly means observed at Santa Maria airport for 1961-1990 and 1991-2020 long term periods. Data was bias adjusted and statistically downscaled using ERA5 reanalyses.

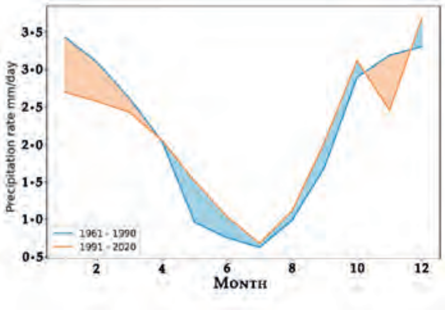

FIGURE 5. Average monthly precipitation rate for the periods 1961-1990 and 1991-2020. Data was bias adjusted and statistically downscaled using ERA5 reanalyses.

Table 3 shows that there are no statistically significant trends for rainfall in any of the periods analysed. This suggests that somehow precipitation deficits and excesses throughout the year compensate for each other. This may also mean that, on the one hand, the increase in air temperature may be hindering condensation in the case of orographic precipitation but may be increasing convective precipitation.

TABLE 3. Computed linear trends for precipitation rate at Santa Maria airport.

Precipitation rate				
Period	**Trend (mm day^{-1}/decade)**			**p-value**
1961-2020	0.01	±	0.01	0.57
1961-1990	0.01	±	0.01	0.57
1991-2020	-0.03	±	0.02	0.08

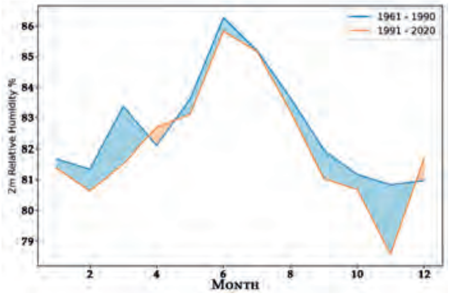

FIGURE 6. Two-meter relative humidity monthly means observed at Santa Maria airport for 1961-1990 and 1991-2020 long term periods. Data was bias adjusted and statistically downscaled using ERA5 reanalyses.

Figure 6 shows the average monthly relative humidity throughout the year for the two periods under study and shows a decrease in almost every month except April and December. The greatest decrease occurs in November, as well as in precipitation, suggesting that the decrease in precipitation in November may be related to less orographic precipitation or precipitation of non-convective origin.

Table 4 presents the computed linear trends for the relative humidity series and for the three long periods. The results show statistically significant trends at 95% significance level for the overall period 1961-2020 and for the first 30 years. The second period does not show a significant trend, however the trend for the overall period is negative, and therefore consistent with the differences found in the previous graphs, but small when compared to the trend of the first 30 years.

TABLE 4. Computed linear trends for relative humidity at Santa Maria airport.

2m relative humidity		
Period	**Trend (%/decade)**	**p-value**
1961-2020	-0.09 ± 0.02	0.00
1961-1990	0.28 ± 0.05	0.00
1991-2020	0.01 ± 0.07	0.87

As noted above, the disappearance of populations and species of these endemic snails is most probably due to the confluence of many factors. While the association of rising temperature and such declines and extinctions is strong, the increase in anthropic pressure might confound causes of change. Yet, the trend here noticed for the endemics of Santa Maria in a strongly human-influenced environment has been detected in pristine environments, free of direct human influence. The laurisilva forest of Caldeira de Santa Bárbara, Terceira Island (Figure 7), was visited by one of us (AMFM) in 1975, 1987, 1994 and 2010. Rich in abundance and variety of molluscan fauna during the first 3 visits, the one in 2010 was particularly disappointing for snails were very rare and many of the species formerly collected could not be found. One detail, however, could be observed in the vegetation, a forest of the juniper *Juniperus brevifolia*: once rich in epiphytic flora, the branches of the junipers were

FIGURE 7. Caldeira de Santa Bárbara, Terceira (2010).

noticeably barren. Such a situation can only be explained by the influence of climatic alteration, for the forest is completely sheltered from other type of human influence. It can be inferred, then, that what was influencing the epiphytic flora on the juniper branches could also be responsible for habitat alterations at the ground level, one which directly interferes with the snails' wellbeing (Martin & Sommer, 2004). The absence of lichens could be plausibly associated with lower humidity, or of long breaks in high humidity. The earlier of the two 30-year periods is more humid in 10 out of the 12 months of the year (Figure 6).

Habitat fragmentation/destruction

Gaspar Frutuoso [1522-1591], the first and foremost historian of the Azores, mentioned that, when the colonizers arrived in the Azores, the islands were covered with thick forests down to the shoreline (Frutuoso, IV: 244). However, clearing of the land must have been very quick for, in about a century's span, all sorts of tilth were flourishing with a bounty of crops. Morelet (1860: 35) sadly commented the disappearance of the magnificent yews from Flores Island, once property of the king of Portugal, and pointed the finger at the first colonizers, who "… far from grubbing up the land according to their needs, […] walked their axes everywhere, abandoned the ground to the futile pasture, and ended up exhausting a source of richness which their successors lament bitterly today". The "Industrial Revolution" of the XVIII and XIX centuries needed wood to keep its wheels in motion and, in the Azores as elsewhere, the industries searched for it in the forests, so much that by mid XX century, only about 7% of São Miguel island's area was forested. This situation elicited a prompt response from the Forestry Department of the Azorean Government, and by the end of the century the forest cover had risen to 21% (DRRF, 1988). Which species were replacing the original ones is an issue to be addressed later.

It was also in the 1970's that the Azorean Government promoted cattle-farming to be the major land production, with direct impact on the landscape (Figure 8); presently, about 50% of the Azorean land has been transformed into pasture, frequently at the cost of altitudinal native shrubland (Martins, 1993: figure 4). Important as it is for the archipelago's economy, a much stronger hand is needed to assist protective policies toward the preservation of the fragmented remnants of native shrubland.

Usually there is a time lag in the population's response to changes, intermediated by successive adaptation attempts. The critical effect, being felt much later when the population hits the survival threshold, is masked by the time of the last response, the cause being inappro-

FIGURE 8. Eastern Santa Maria, viewed from Pico Alto (1975).

priately attributed to the habitat conditions at that time. However, some alterations may elicit a sudden, catastrophic response, as was the case witnessed by one of us (AMFM). From 1984 to 2010, 11 exploratory missions were conducted on Pico do Fogo, São Miguel Island, a hill resulting from a 1652 volcanic eruption. The area, a private property covered mostly with secondary, non-endemic forest (Figure 9A) surrounded by pastureland, was nevertheless rich in molluscs. Thirty-six species were found on the forest, and 9 of the 21 endemics from São Miguel Island were reported from there (Table 5). Tacit complacency of the owners had allowed the frequent, innocuous research visits, as the place was secretly elected the natural laboratory for malacology classes. There, the island endemics *Napaeus pruninus* and *Napaeus vulgaris* were particularly abundant and variable, and they exemplified a clear case of the forms identified by Morelet (1860: 186-187) as the "adulterine" result of species crossing, selected by Martins (2011) as a paradigmatic case of specific boundary transgression resulting in mosaic evolution. In 2011 the site was again visited and, sadly, the precious habitat had but disappeared: the rightful owners, understandably unaware of the malacological importance of what was going on in their property, had legitimately decided to lumber their timber (Figure 9B). Revisiting what once was a malacological haven, only slugs under pieces of cardboard and dead shells of the omnipresent palaearctic *Oxychilus draparnaudi* were found, but no sign whatsoever of any endemic shell. The molluscan community of that hill could not cope with the drastic habitat change caused by radical lumbering.

TABLE 5. Presence of species before and after forest clearcutting on Pico do Fogo, São Miguel. **2010**, pooled observations of 11 collecting trips (1984-2010); **2011**, year of clearcutting; **2023**, observations of a 2023 collecting trip.

	Species	**2010**	**2011**	**2023**
ENDEMIC	*Lauria fasciolata*	▨	■	
	Leiostyla fuscidula	▨	■	
	Moreletina horripila	▨	■	
	Napaeus pruninus	▨	■	▨
	Napaeus vulgaris	▨	■	
	Oxychilus batalhanus	▨	■	
	Oxychilus miguelinus	▨	■	
	Oxychilus volutella	▨	■	
	Punctum azoricum	▨	■	▨
NON-ENDEMIC	*Arion distinctus*	▨	■	
	Balea heydeni	▨	■	
	Carychium ibazoricum	▨	■	
	Cochlicella barbara	▨	■	
	Cochiclopa lubrica	▨	■	▨
	Cochiclopa lubricella	▨	■	
	Columella microspora	▨	■	▨
	Cornu aspersum	▨	■	▨
	Deroceras cf invadens	▨	■	
	Deroceras reticulatum	▨	■	▨
	Discus rotundatus	▨	■	
	Euconulus fulvus	▨	■	▨
	Hydrocena gutta	▨	■	▨
	Lauria cylindracea	▨	■	
	Lauria fanalensis	▨	■	
	Lehmannia valentiana	▨	■	
	Leptaxis simia	▨	■	
	Limacus flavus	▨	■	
	Limax maximus	▨	■	
	Microxeromagna lowei	▨	■	
	Milax gagates	▨	■	
	Nesovitrea hammonis	▨	■	▨
	Oestophora barbula	▨	■	
	Oxychilus alliarius	▨	■	
	Oxychilus draparnaudi	▨	■	▨
	Testacella maugei	▨	■	▨
	Vitrea contracta	▨	■	

And so did slip away the opportunity to catch evolution red-handed at work in a living laboratory, relegating the nevertheless precious preserved material to the dull obscurity of a reference collection.

Twelve years later the site was revisited. The forest appeared to have recovered (Figure 9C), but the malacofauna continued devastated (Table 5). Handpicking revealed the presence of *Oxychilus draparnaud* and dead shells of *Napaeus pruninus;* the sieving method retrieved *Punctum azoricum*. The pattern appears to be very much like that reported in Martins (2018) for the recolonization following the 1957/1958 volcanic eruption of Capelinhos, Faial. One can extrapolate, then, that a complete recovery of the malacofauna following clear-cutting will, optimistically, take at least several decades and that most endemics will appear last.

Introduction of invaders/predators

Wherever humans go, they carry with them their survival kits, the plants and animals they are familiar with in their places of origin, usually overcharged with an array of unnoticed, mostly unwanted stowaways. A few will not adapt and will vanish, but some will flourish strongly and take over the new place. They are the invaders.

Plants are the commonest terrestrial introductions, and they are carried in for a multitude of reasons. Above we referred the reforestation of the archipelago. Although the first introductions

FIGURE 9 Pico do Fogo, São Miguel. **A**, 2010; **B**, 2011; **C**, 2023.

date to mid XIX century, only a century later a programmed governmental reforestation project took place (Martins, 1993). The selected species came from Australia (several species of *Accacia*) and from Japan. The effects of the floral composition of the habitat on the malacofauna living therein are intuitively grasped and have been studied (Martin & Sommer, 2004; Jordan & Black, 2012); however, studies of the effects of the new type of forest being introduced in the Azores on the fauna inhabiting their undergrowth are wanting. *Cryptomeria japonica* (Figure 10A), a fast-growing, softwood tree, suited for quick reforestation, received and continues receiving the strongest governmental support; this new monoculture amounts now to about 60% of forest cover. However, when tree density is high, undergrowth in *Cryptomeria* forests is practically absent, the only species therein surviving being an extremely aggressive invader, the Himalayan ginger *Hedychium gardneranum* (Figure 10B). We have observed that, in such conditions, molluscs are preferentially found at the margins or at the clearings of the forest, the malacofauna in the interior being comparatively scarcer or even absent; on the other hand, it was found that molluscs can adapt well to invaders (Pearson *et al*., 2022) and to moderate densities of the undergrowing *Hedychium gardneranum* (Van Riel *et al*., 2000). With judicious distribution of the trees at planting, considering not only maximum production but integrating continuous light availability throughout growth, and a mosaic approach for harvesting, a satisfactory compromise could probably be reached.

A problem of different sort exists with the Australian *Pittosporum undulatum*; introduced also around mid XIX century to fence orchards and orange groves, it soon aggressively conquered the low to mid altitudes to become the most prominent component of the forest landscape. Figure 11 provides a visual example of the change in habitat coverage in fifty years, with *Cryptomeria* and *Pittosporum* forests taking over endemic vegetation. Like *Cryptomeria*, *Pittosporum* has essential oils and resins, and like with *Cryptomeria* although not so

FIGURE 10. Introduced flora. **A**, *Cryptomeria japonica;* **B**, *Hedychium gardneranum*.

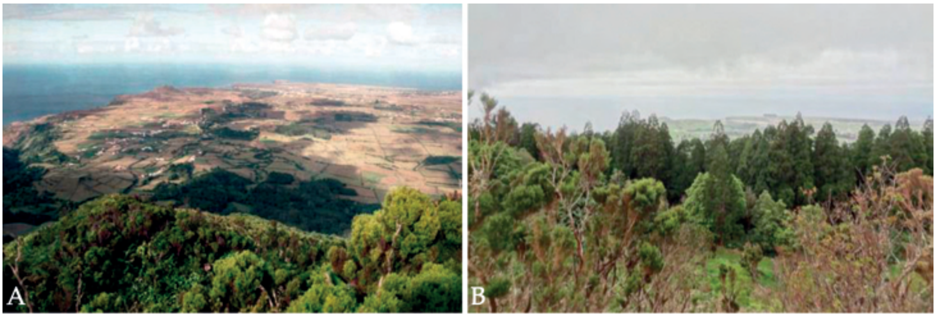

FIGURE 11. A view from Pico Alto, Santa Maria. **A**, 1975; **B**, 2019.

radical, the undergrowth in *Pittosporum* stands is scarce and mostly *Hedychium*; the effect of the biochemical components of these species on the biological control of their shaded area is wanting appropriate ecological research, and the effects on the malacofauna still need to be studied.

Panasco station (see SMA05 in Martins, 2023), a once rich spot for endemics in Santa Maria, is a stand of *Pittosporum undulatum* of about 50x100 m (Figure 12). When first visited in 1990, the ground was barren but very humid, with shallow, muddy puddles. Endemic species were abundantly collected then, but less so two years later (Table 6). However, when visited in 1995, the habitat conditions were drastically different: the ground was dry, the soil flaky and only sparse specimens of *Oxychilus lineolatus* were observed. Thirteen years later, only *Oxychilus lineolatus* and *Craspedopoma hespericum* were reported from the site. Inspection of the meteorological data (Figures 3 and 5) shows temperature and precipitation anomalies for the 1990s decade, and one is tempted to establish a correlation between the observed extirpation of species and the recorded meteorological conditions. The absence of ground coverage may have greatly contributed to the situation, for it made the habitat much exposed to adverse weather conditions, namely severely diminishing its capacity for retaining humidity. Apart from human activity directly, exceptional drying out is the most probable cause of local extinction, most of all in small species that rarely have to encounter long periods of drying inactivity.

The introduction of predators usually has more rapid and drastic effects on the endemic biota, and many were introduced with the intent to control biolog-

TABLE 6. Presence of endemic species at Panasco station, showing the drastic reduction after the second half of the 1990s. *collected 1988.

Species	Date		
	1990	1992	2008
?Moreletina sp c	72	2	
?Moreletina sp b	13	2	
Oxychilus spectabilis	30		
Napaeus tremulans	1	2	
Napaeus hartungi		2	
Leptaxis sanctaemariae	6		
Craspedopoma hespericum			2
Oxychilus lineolatus	3*		13

FIGURE 12. The *Pittosporum undulatum* woods at Panasco, Santa Maria (2023).

ically other unfortunate introductions (Gerlach *et al*., 2020). As often happens, nature does not always comply with textbooks, and predators have tastes of their own, as shown by the classic example of the predatory snail *Euglandina rosea*, introduced in Hawai'i to control the introduced African giant snail, *Achatina fulica*, but which ended up devouring to extinction a great percentage of the small, endemic Hawai'ian achatinellid species.

The Azorean malacofauna has its share of endemic molluscan predators, such that they were once used as biological controllers of fasciolosis (Cunha, 1993); among them the oxychilids are the most numerous and the semi-slugs *Azorivitrina* and *Plutonia* the most vicious. Vertebrates, like rats, mice, blackbirds, and invertebrates, like centipedes and carabid beetles take their toll on endemic molluscs. A relatively new threat to land molluscs are the carnivorous flatworms (Platyhelminthes) (Figure 13). *Rhynchodemus* and *Bipalium* have been previously recorded from the Azores (Raposeiro, 2010), but a new, greater threat comes from the South American *Obama nungara* (Carbayo *et al.*, 2016), a top-level predator here recorded for the first time from Pico Alto, Santa Maria (Figure 13C). The situation becomes of deeper concern due to the now observed drastic reduction in the molluscan populations, thus fearing an acceleration towards extinction of the vulnerable taxa.

WHO IS TO BLAME?

It has been shown that there is not a simple answer to this question, at least that there is not a single culprit. More

FIGURE 13. Terrestrial Platyhelminthes. **A**, *Rhynchodemus sylvaticus*; **B**, *Bipalium kewense*; **C**, *Obama nungara*.

obvious is the notion that they all are, potentiating each other's effects, accelerating the pace towards that critical threshold of no return, the antechamber of extinction. For some, climate change and habitat destruction are a deadly anthropogenic cocktail (Travis, 2003); for others, the bulk of the blame should rest on the introduced invasive species (Clavero & Garcia-Berthou, 2005; Doherty *et al*., 2016). The truth of the matter is that all those factors have always been at work and the species have delt with them successfully. The facultative predatory oxychilids have so flourished in the Azores to make the archipelago a world hotspot of diversity of the family (Figure 14; Martins, 2005; 2011), an indication of evolutionary balance; however, in this new scenario of ecological crisis predators and prey are becoming highly vulnerable.

Species turnover is a natural phenomenon. As an example, consider the history of the Santa Maria endemic *Leiostyla tesselata*: this species was abundant at Morelet and Drouët's time, who collected many specimens, 47 of which

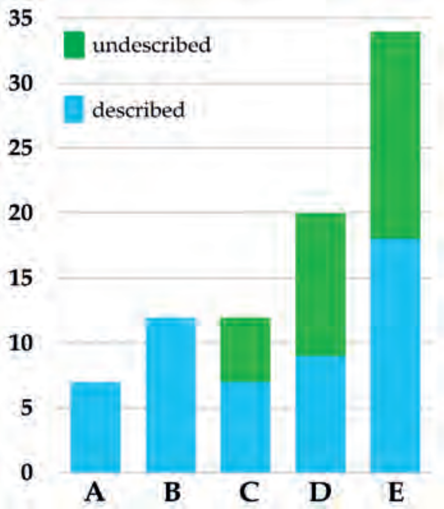

FIGURE 14. Number of endemic species in some families. **A**, Vitrinidae; **B**, Lauriidae; **C**, Enidae; **D**, Hygromiidae; **E**, Oxychilidae.

are at the Muséum d'Histoire naturelle de Dijon, France (Audibert *et al.*, 2013). Very few specimens were collected in the 1980's (Table 1) and records of this species (*e.g*. Backhuys, 1975) were misidentified for the newly described *Leiostyla elegans*, of which there are no records in Drouët's collection (Martins, 2023). The "extremely lucky" French naturalists, in the words of Wollaston (1878), would not have missed it in 1857. It appears, then, that the disappearance of the XIX century common *Leiostyla tesselata* gave way to the XX century moderately common *Leiostyla elegans* (Table 1). Unfortunately, both species are feared to be extinct. The present ecological crisis has accelerated the populational imbalance, depriving species of the necessary time for a proper evolutionary response.

WHAT CAN WE DO?

The situation is clearly of great concern. Climate change cannot be stopped in a year or a decade; in many places it probably has reached the threshold of irreversibility. However, mitigating efforts can be attempted to give survivors a chance. By intervening on our own direct actions that helped causing the imbalance, *viz*. habitat destruction or fragmentation, refuges can be provided for the hopeful survivors to cope with these hard times (Lucid *et al.*, 2021). This is the objective of the project LIFE SNAILS NAT/PT001377, at work on the Reserve Area of Pico Alto, Santa Maria. Its main intentions are: a) to reduce habitat fragmentation on historical areas of distribution of the endemic species, through the establishment of an integrated mosaic of ecological corridors that interconnect with waterlines and remaining spots of high-quality habitat; b) to increase habitat suitability, through (re)naturalization of forests by diversification of trees and shrubs, as well as of hedgerows and fences along the margins of pastureland; c) to improve habitat quality, through learning which environmental parameters control endemic rich areas, by controlling invasive plants, restricting cattle access and ensuring nature-based solutions favoring humidity and moisture in soil and ground cover; d) to repopulate the intervened areas, through leaf-litter transfer from nearby endemic rich(er) areas; e) to raise public awareness, for people are the privileged guardians of their own biodiversity and natural heritage.

We can only wish them luck, for the sake of our natural heritage.

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