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Commercially assisted migration
– Invasive species and their future
in a globalized world: A perspective

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Abstract

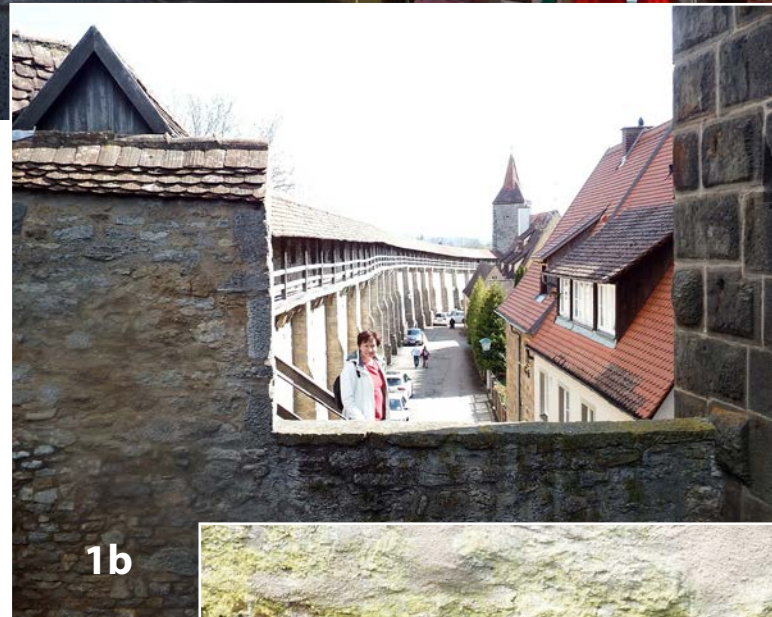
The negative role and the forces for the distribution of invasive species in general is shortly addressed which will then be focused towards the situation of invasive turtles in Europe, Southeast Asia, Australia and Latin America. Discussing the generally accepted point of view that their introduction to the wild should be terminated and already established exotic turtles have to be eliminated. But here I provide an overview of the many species which have already adapted to foreign environments and developed self-sustaining populations in all the above-mentioned continents and several islands. Despite that situation the trade of invasive turtles continues more or less globally and climate change may not only contribute to their survival at more northern latitudes on all continents but will also speed up reproduction at more northern latitudes or higher elevations. Invasive turtle species are already in many countries so widely distributed in natural environments that their eradication is only possible in small isolated locations, but will no longer be an option without doing more harm than good to co-occurring endemic species. Furthermore, in war zones and during the worldwide increase of flooding due to the still advancing extreme weather conditions, will make it more or less

impossible for turtle rescue institutions, zoos and private keepers to prevent the uncontrolled escape of invasive species. In view of that scenario, I argue that we should change our view toward a more scientific one, trying to learn from that species by investigating their genetic and physiological adaptation to their new and foreign environments. Here we have the unique chance to study evolution, not only via the molecular analysis of their history like on the Galapagos Islands, but in real time and live. From that we can probably also learn a lot for saving endangered species and help them to escape climate change related extinction by assisted migration which in my view offers a practical way to make use of our self-inflicted commercially assisted establishment of globally distributed “invasive” metapopulations, which may help these species to find environments which may compensate for the climate change related loss of their native ones. For turtles, humans are part of their environment and therefore human mediated changes may also have the potential to help to continue their 260 million yearlong fossil record. Maybe our own following generations call those which made it, the “modern survivors”.



1a

Fig 1a-d: The pilgrimage route that leads through Rotenburg ob d. Tauber (a) has made the town a UNESCO World Heritage Site and the 3.5 km long town wall (b) is maintained by worldwide sponsorship, with countless plaques referring to the many national and especially international sponsors. Among them are many US citizens. If you enter the city via the bridge to Rödertor, you will not only encounter tourists from a wide variety of nations in summer. If you look either to the left or right of the bridge down to the water, you will also see a number of carapax carriers, native, year-round Americans of the genus *Trachemys* and *Pseudemys*, which hibernate there quite well. These photos were taken on April 21, 2023.



1b



1d

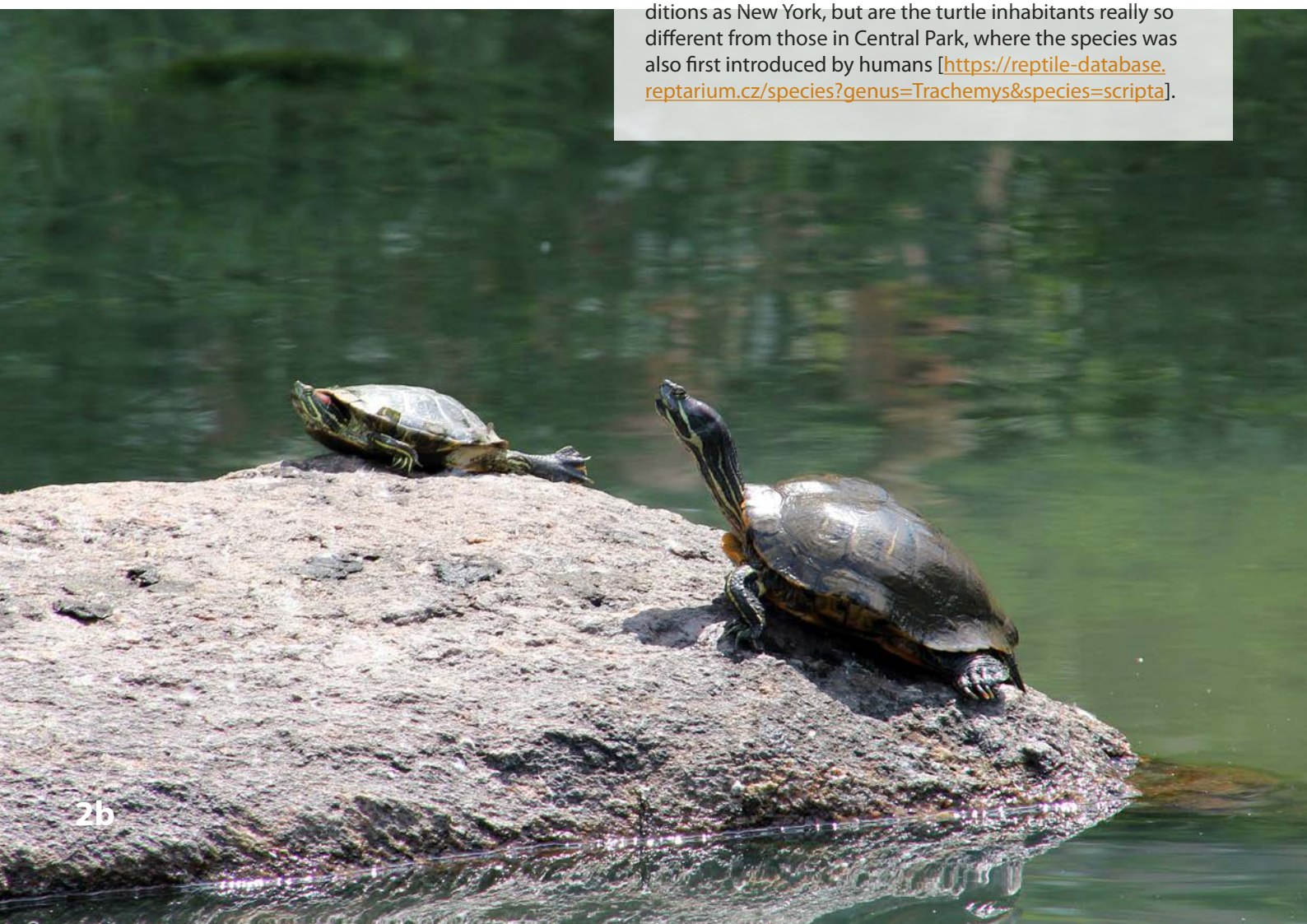


1c



2a

Fig 2a-c: German cities certainly do not offer the same conditions as New York, but are the turtle inhabitants really so different from those in Central Park, where the species was also first introduced by humans [<https://reptile-database.reptarium.cz/species?genus=Trachemys&species=scripta>].



2b

Invasive species from all tribes according to taxonomic rank have always spread worldwide. However, their spread has accelerated dramatically due to human influence. We do not even see or know most of them, which is why it would be an unsuccessful attempt to address them at this point, as we would certainly need artificial intelligence and quantum computers to record and analyze their effects. However, this is not a new phenomenon, as migratory creatures such as migratory birds, marine mammals and sea turtles have always transported parasites or plants, animals and bacteria that sit on them or live in their bodies as symbionts or parasites which contributed to their spread. The phenomenon has only accelerated dramatically through the passive and active involvement of humans, at least since the establishment of commercial shipping. We are all aware of the disadvantages caused by the spread of invasive species, not least of which are a number of zoonoses and infectious diseases as well as a number of ornamental and crop plants and livestock, some of which affect us directly in

both a negative and positive (nutritional) sense (see review article: THOMPSON et al. 2021; DIAGNE et al. 2020; EARLY et al. 2015)

Here in this journal, which focuses more on reptiles and turtles in particular, I would like to limit myself to the latter, as there is already enough to discuss that could possibly be transferred to other species. The invasiveness of the yellow or red eared slider turtle *Trachemys scripta* (one single species see VAMBERGER et al. 2020) has been reported for years, as one of the species that was probably the first to become widespread worldwide (e.g. ARIANOUTSOU et al. 2023; KALAENTZIS et al. 2023; BAEK et al. 2023; GONG et al. 2023; MARICIC et al. 2023; NISHIBORI et al. 2023; ROHAN et al., 2023; ESPINOLA et al. 2022; ZHANG et al. 2020; STANDFUSS et al. 2016; TZANKOV et al. 2015; GARCIA-DIAZ et al. 2015) and the latter even applies to North America (DROST et al. 2021, PARHAM et al. 2020). Recently, however, more and more invasive turtle species have been listed, at least for southern Europe and Southeast Asia as well as South America, and

their distribution is also expanding northwards into the higher latitudes. These include the Florida red-bellied turtle *Pseudemys nelsoni*, the Florida green turtle *Pseudemys concinna*, the Chinese striped turtle *Mauremys sinensis*, the Chinese softshell turtle *Pelodiscus sinensis* and the snapping turtle *Chelydra serpentina* (CHEON et al. 2023; KALAENTZIS et al. 2023; GRAMENTZ, 2023; MU & LI, 2023; KOO et al. 2022; DI BLASIO et al. 2021; KOO et al. 2020). However, I suspect that *Trachemys venusta* (see also MAGALHAES et al. 2023) and *Mauremys reevesii* will also be among the species that could and will spread invasively there (BU et al. 2023; XU et al. 2015). Probably facilitated by climate change, it is also increasingly being observed that these turtle species are not only spread by humans, but that they also reproduce independently. Hatchlings successfully hatched in the wild are increasingly being reported (BAEK et al. 2023; CHEON et al. 2023; DI BLASIO et al. 2023, NISHIBORI et al. 2023; KOO et al. 2022; KORNILEV et al., 2020; PETOKA et al., 2018; DONG et al. 2016; MARCHETTI & ENGSTROM 2015).



3a1



3a2



3b2

3b1





Fig. 3a-e: In the meantime, German and American universities not only increasingly share a common international language of teaching and publication, but also a converging campus landscape. The university pond in front of the Oeconomicum of the University of Düsseldorf (3a-a2) harbors the same turtle species as the University Lake of the University of North Carolina, Chapel Hill (3c-e) while basking together with *Plestiodon fasciatus* (3d). At both locations, these species (*T. scripta*/*T. s. elegans*) are among the invasive released species. As you can see, mating can also be observed in Düsseldorf (3b1-3b2).





4a



4b

Fig. 4a-c: As the river Erft always has slightly warmer water all year round due to the waste water from the power plants cooling towers, quite large specimens of *T. scripta* or *Pseudemys concinna* (a) can often be observed here, seen here not far from its mouth into the Rhine at Eppinghoven Monastery. Similar turtle communities can be observed in the parks of Mönchengladbach (b). Yes, and if you are wondering why this is so and would like to enjoy turtles in a warm, covered environment, you only need to browse the large pet shops where you can take them home for around 29,99-59,99 euros.



4c

We must blame ourselves for this problem, because we have spread these species worldwide through trade and in most cases still do (KIKILLUS et al. 2012; GARCIA-DIAZ et al. 2015; WILLOUGHBY & CHRISTIE 2018; MACEDA-VEIGA et al. 2019; MAGALHAES et al. 2023; GONG et al. 2023; KALENTZIS et al. 2023; Fig. 1-10). Responsible keepers, sanctuaries and zoos are making efforts to minimize these problems. The increasing number of extreme weather events worldwide as a result of climate change (e.g. SHAN et al., 2023), such as floods like those we have witnessed in recent years in the Ahr Valley (Germany), Pakistan, Australia, Croatia and southern Austria, as well as in Italy, Spain, Greece and currently in Vietnam and for the second time in 2023 in Italy, ensure that it will be impossible even for such institutions to prevent such exotic species from escaping into the wild. This will also apply to war zones, as we witnessed when the Kachowka dam was blown up (e.g. NEKRASOVA et al., 2022). Especially where such disasters occur, most of the manpower and financial resources inevitably have to go into reconstruction and feral exotic turtles are likely to be one of the least of the problems for the affected regions for decades to come. In this respect, one could certainly agree with the stakeholders concerned, as exotic or invasive turtle species have far fewer negative effects than exotic pathogens such as the bird flu virus (Galapagos)

or American crayfish species that introduced crayfish plague to Europe. The argument that exotic turtles threaten native turtle species also only seems to apply where the biotopes for native species have already been so impaired by humans (AUGE et al 2023; ESPINDOLA et al. 2022; ROMERO et al. 2014) that they have contributed to their decline anyway (water level increase, reservoirs, colonization, etc. Fig. 9). Even for some parasite infections, *Trachemys* appear to be more affected than native species (HIDALGO-VILA et al., 2020) and some of the so-called invasive species are already more threatened in their original habitats than in the invasive metapopulations in foreign countries (see e. g. e.g. *Palea steindachneri* and *Pelodiscus sinensis* (LI et al., 2022; IUCN, 2021; GONG et al. 2018; DONG et al. 2016; MARCHETTI & ENGSTROM 2015) or even *T. scripta* (BROWN et al. 2012; CEBALLOS & FITZGERALD 2004).

However, the vast majority of scientific publications repeatedly call for the elimination of these exotic, invasive turtles. This is difficult and has so far only been successful in small, demarcated localities (e.g. DROST et al. 2021). In many regions, this has been attempted by trapping or, much more frequently, by shooting. Collecting such species has also been propagated, but this is the first step towards further disturbance of native species, as the invasive turtle species usually share hab-

itats with them and many of the natural marshes and deltas are difficult to access even for the use of traps (e.g. Fig. 8-9). Biological control measures such as the use of large numbers of sterile males are usually not practical for eliminating exotic, invasive turtles, as these are long-lived species and the females can store sperm for several years. It remains to be seen whether even some of the invasive species hybridize either with each other or even with one or the other native turtle species, as has long been known from *Mauremys sinensis* & *Mauremys reevesii*, *M. reevesii* & *M. japonica* and *M. reevesii* & *M. mutica* as well as *Trachemys* species (LEE et al. 2019; FUJI et al. 2014; SUZUKI et al. 2014; PARHAM et al. 2020). All of these elimination measures could only be successfully implemented on a small scale and would also require accompanying protection and conservation measures for the native species that would be additionally threatened as a result. In summary the latter seems almost impossible and will be not suitable for reducing the global spread that has already occurred. Especially as, despite this knowledge, we are still hardly able to effectively regulate the trade in these species (see Fig. 3-7) and, despite the best intentions of the keepers, they are unable to prevent them from escaping into the wild in the long term due to the extreme weather events mentioned above.

Are there signs of a reorientation?

In the USA, however, there are also some signs that a rethink seems to be taking place in this regard, with even the “old masters” of turtle research beginning to initiate corresponding discussions (DUPUIS-DESORMEAUX et al. 2022). This is because turtles have an important function in certain habitats (to avoid the word ecosystem). It is therefore being discussed that invasive species could be introduced as a substitute in habitats that have been altered by humans to such an extent that the native species that once lived there could no longer survive, in order to prevent or even partially reverse further habitat changes. This is actually a similar idea to that discussed and already practiced for the restoration of native endemic flora on a number of islands (BUSH et al. 2022; GRIFFITHS et al. 2010). This could also pay off in terms of human well-being, as turtles are among the most sympathetic animals and can certainly make a contribution to wetland restoration (Fig. 1-2; see also FISHER et al., 2023).

A look towards an “uncertain” future

Against this background and the very likely hopeless situation of suppressing these globally widespread species, I think it would also be appropriate here in Europe to think about how we should deal with them in the future.

To be clear from the beginning, I am not advocating the continued or even targeted reintroduction of invasive turtle species and certainly not advocating that we should carry out such interventions in places where, for example, native pond turtles have just been reintroduced. However, we should also think pragmatically about whether we still have the chance

to rid ourselves of invasive species everywhere, especially in southern Europe, south-east Asia and South America. If you look at the arguments about the new CITES regulations for Germany, there is already speculation even in this country about the consequences. Because people may just release the currently upgraded species into the wild, as keeping them under the new regulations since they seem too problematic for some people, especially as these species were widespread in trade until recently and in some cases still are (Fig. 3-4).

Even for the exotic and invasive species already living in the wild today, it has been shown in many places that they survive European and even northern European winters quite well (NEKRASOVA et al., 2022; GRAMENTZ, 2023). I myself know of several park ponds, rivers and lakes where the same specimens can be seen year after year over long periods in spring and summer and can also be documented photographically. Even from northern Hessen – my home region – I remember a mining lake from my childhood where you could see a red-eared slider sunbathing year after year. The lake was located near the 600 m altitude mark in a region that was often referred to as “Hessian Siberia” because the winters were quite long and snowy.

It has therefore been shown, both in the garden and in the open field, that many of the invasive exotic species can survive here in the northern latitudes and even more so in southern Europe, where they also seem to reproduce (Fig. 1-10).

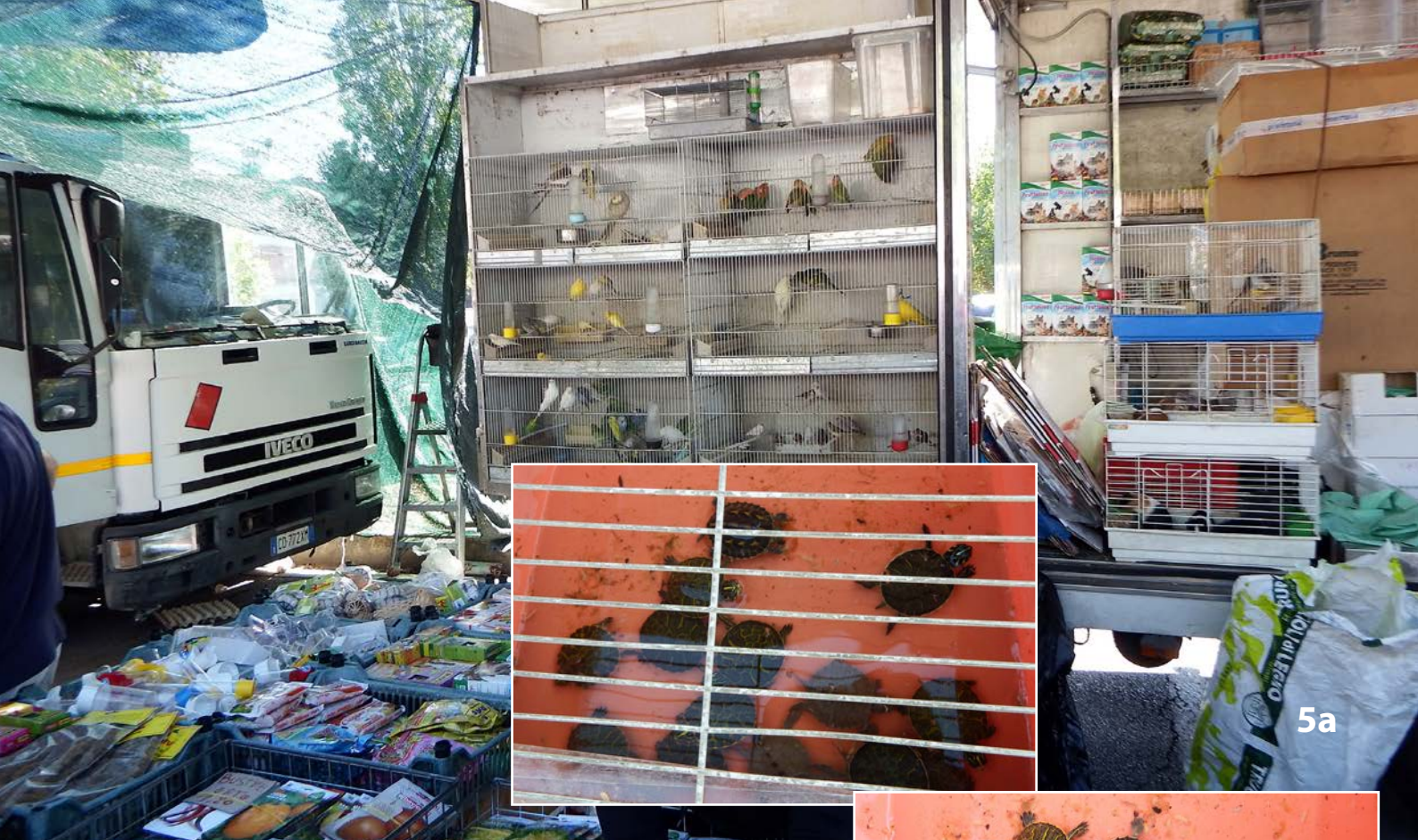
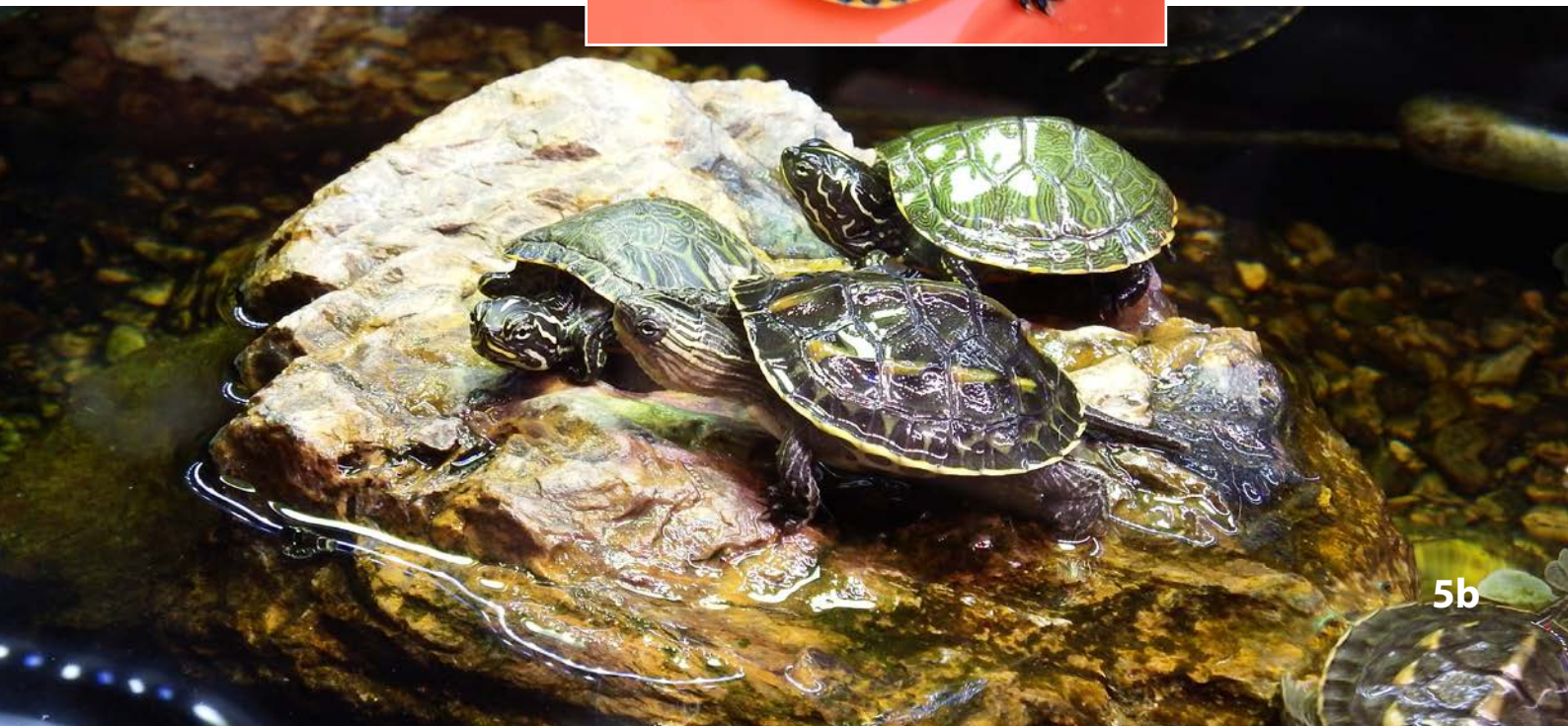


Fig. 5a-b: A Saturday market in Italy (30. 09. 2023) with animal and turtle trade (a & inset) on offer were *Mauremys sinensis*, *Pseudemys concinna* (a'), and *T. venusta* (a'') although outdoor reproduction in the wild has already been proven for Italy (DI BLASIO et al., 2021). Compared to the German pet trade (b), there is no difference except for the price, because in Italy all three species are available at the same price of 12 euros. It doesn't help that *Mauremys sinensis* populations have even been confirmed in Lithuania (NEKRASOVA et al., 2022). This is the "commercial establishment of globally distributed metapopulations" in action.



5a

5a'

5a''

5b



So what should we do?

This offers enormous opportunities for science and evolutionary biologists, which could probably also be realized within the framework of the so-called Citizen Science Initiative. This opportunity consists of accompanying the evolutionary process during such invasion and expansion events using molecular biology. The first attempts at this are just beginning to emerge, because if the findings of PARK et al. (2023a, b) are correct, then in contrast to the *Sternotherus carinatus*, the *Chrysemys picta bellii* that have established themselves in Korea can be distinguished according to their haplotype cluster from those in the United States as well as from those that occur as invaders in China. It would certainly be very informative to find out from which foreign local populations the invaders originated that can or have already established themselves here in southern and northern Europe as well as globally, and which

adaptive genetic changes occur or have already occurred within that exotic populations. Ultimately, it would be possible to follow “live” how such invasive metapopulations establish and adaptively develop and consequently begin to adapt to the new environmental conditions. It would therefore be possible to directly and actively study what happens in these turtle

species or hybrids and how evolutionary lines might develop in the long term or even new ones emerge. This is something that, for example on the Galapagos Islands and elsewhere, we would still like to find out in detail for a wide variety of species through, let’s say, retrospective molecular genetic analyses in order to better understand the processes of speciation and radiation that had occurred during the history of these islands (DALÉN et al. 2023; MEIER et al. 2023; KERSTEN et al. 2023; HEDRIK 2019; HENNESSY 2015; BIDMON, 2015; GARRICK et al. 2014) and which still may be speculative as currently proposed (TORRES et al., 2023). This would then be similar for example as the study by SOSA et al. (2023), investigating the mutual influence and further development of the two rat species, one of which was invasively introduced here and once brought the





plague pathogen *Yersinia pestis* to Europe. On the Galapagos Islands, for example, the colonization of the islands involved invasive expansion processes of tortoises or bird species (see ENBODY et al. 2023; MILLER et al. 2018; KEHLMAIER et al. 2017) and for tortoises it may have started with *Chelonoidis chilensis*. If we cannot prevent such invasive turtle species in the long term (see TORRES et al., 2023)– and it looks like we cannot do it in many places around the world – then we should actually try to derive the greatest possible scientific benefit from them! This knowledge could even help us to assess the consequences of climate change for reptiles, because we can no longer prevent the latter, as the data from the northernmost latitudes recently showed us again (KERSTEN et al. 2023). In addition, accompanying, more physiologically oriented studies could certainly also teach us something about the practice of targeted resettlement or assisted colonization already used today for species conservation

(PAGET et al. 2023; MORRIS 2023 and the cited literature there). In the long term, I think that we or our children and future generations will perhaps be glad that there are still turtles at all! Yes, our own human successor generations would very likely also show an interest in how these survival artists were able to extend their “fossil record” here in Europe beyond the past 260 million years (CORDERO 2023), not only with the support of climate change.

Fig. 6a-d: A visit to Assisi (a). A small pond near the road in the olive groves (b). Restoration work was still underway here to repair damage to the access roads caused by the heavy rainfall in July 2023. As luck would have it, the armored invasive pond dwellers already known from so many places could also be observed here (c-d).





Fig. 7a-b: The species known here from the German pet trade (a) are also found in Bulgarian waters, e.g. *Graptemys pseudogeographica* in a well.



Basically, the work on climate change with increasingly rising temperatures and our own inadequacy to react appropriately as a global society (see PALAZZO CORNER et al, 2023) shows us that we are at least offering warmth-loving species opportunities to further expand their range in terms of climate and, with our help, to colonize new habitats that may even offer compensation for the aridification of their original habitats. After all, the dispersal that has taken place and is still taking place as a result of human activity offers the same opportunities worldwide for many of these species, which are still referred to today as invaders, as those that we are now beginning to practice for rare and endangered species under the term “assisted migration” (see MORRIS 2023 and the literature there). Even PEDRONO (2004) once referred to the formation of metapopulations for the Malagasy beaked turtle. Therefore, we should ask ourselves: Are invasiveness, introgression, sperm storage and adaptability in combination a way out of a future scenario so strikingly formulated by GLAUBRECHT (2019) “As the end of evolution”?

I am aware that this article will not be accepted uncritically by many readers. However, if you look at the few detailed distribution maps for the invasive *Trachemys scripta* alone (see e.g. YAKIN et al, 2024; MU & LI, 2023; GONG et al. 2023, KORNILEV et al. 2020; CERASOLI et al., 2019; TZANKOV et al. 2015), then we should realize that we will have a hard time turning back the wheel of “commercially assisted establishment of metapopulations”, which started to turn really



Fig. 8a-b: As an example, an overview (a) and close-up (b) of the protected delta of the Ropotama in south-eastern Bulgaria. It is easy to imagine how difficult it would be to attempt to eliminate invasive species without causing serious disruption to the entire ecosystem. See also KORNILEV et al., (2020).

fast more than half a century ago due to the popularity of turtles. To this day, it is not even certain whether we will be able to stop it (e.g. PRATT et al. 2023). Especially as the majority if not all these studies indicate that the establishment of these invasive populations has spread further in recent years. So once again, as is so often the case, it will be history that will show our future generations how

and where these invasive evolutionary lineages have developed in the world. However, as mentioned above, we could already make a scientifically sound contribution to this today. Just as turtles were part of *Homo sapiens'* nature from the beginning, we were also part of the turtles' environment (e.g. FERRONATO & GEORGES, 2023; SANTOS & FIORI; 2020; NABAIS & ZILHÃO, 2019; THOMPSON & HENSHILWOOD, 2014). So why shouldn't the changes created by humans also become a survival advantage for them? Those who perhaps manage to extend their fossil record in this way may be called the "modern survivors" by our own descendants.



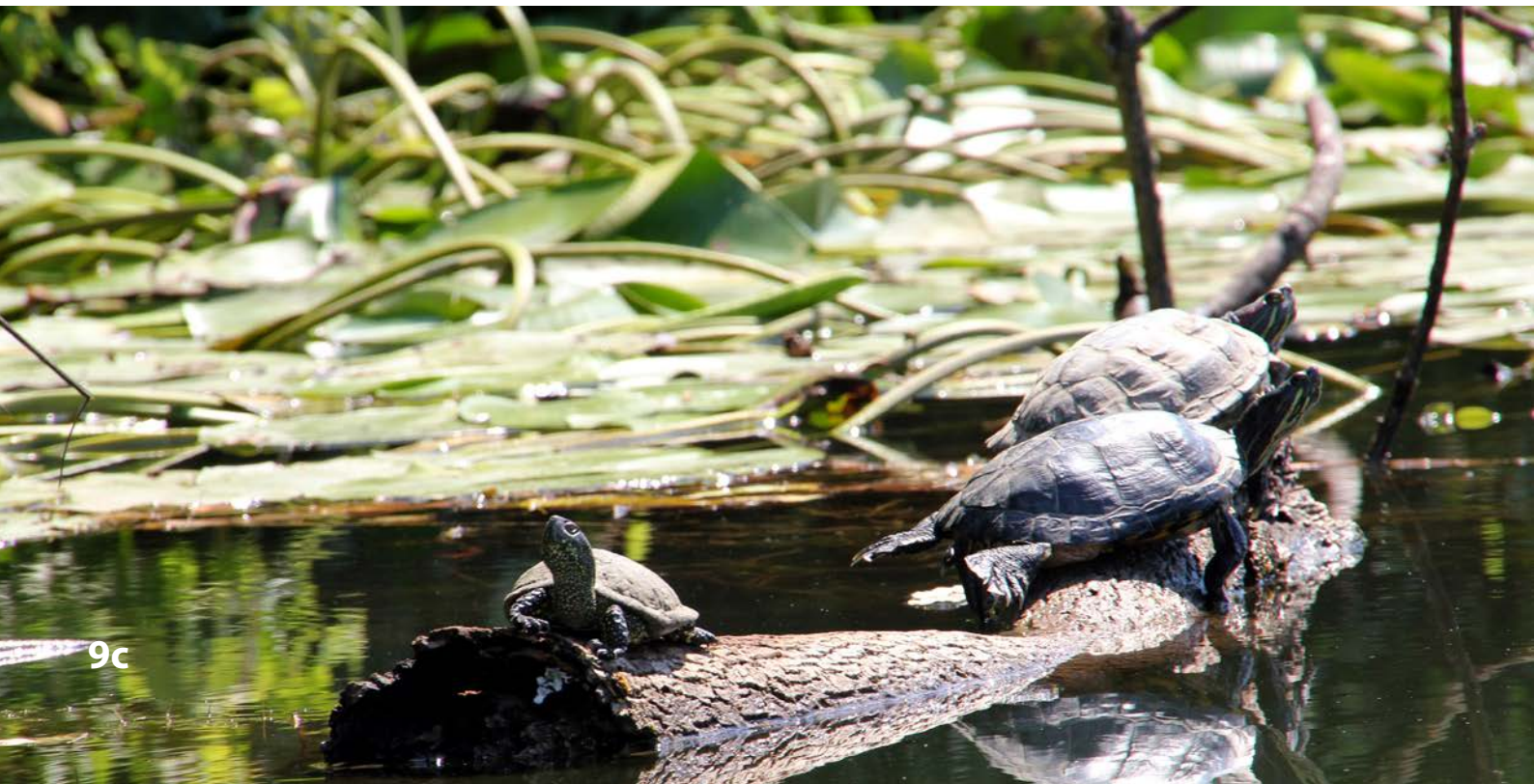
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Fig. 9a-c: From western Spain (near Barcelona) to the south-eastern edge of Europe, the observations are similar. A *Mauremys leprosa* tries to drive a *Trachemys s. elegans* away from its basking site or, as can often be observed, simply mounts it (a). *T. s. elegans* and *Mauremys caspica rivulata* sunbathing together (b) and *T. s. elegans* and *Emys orbicularis* (c) both could be observed from the kayak on the same day at the Veleka, Bulgaria. Here on the Veleka, *T. scripta* will certainly gain the upper hand at some point. Not because it is invasive, but because this river is beginning to be navigated by increasingly larger tourist boats which requires a rise in the water level and on the other hand the former numerous sunbathing opportunities have to be either removed from the navigation channel or flooded accordingly. Both are denied by the boat operators, but all that is needed is a few truckloads of beach sand every summer to narrow the estuary on the Black Sea coast.



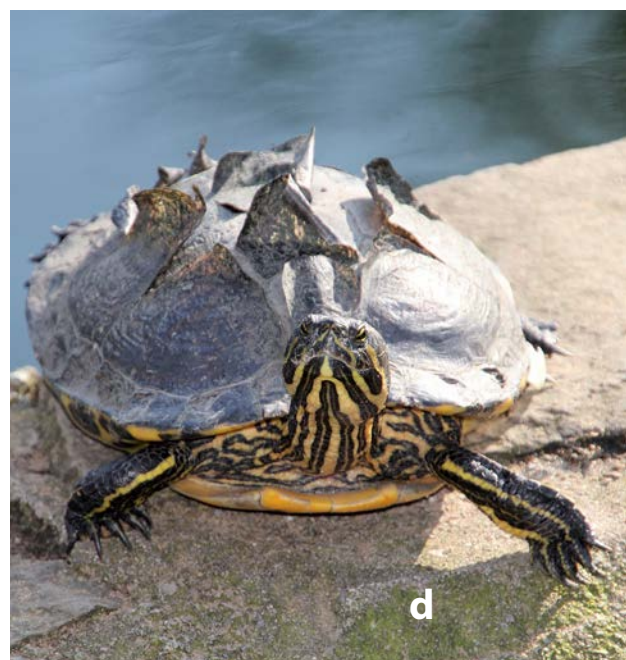
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Fig. 10 a-d: Spring awakening in a park pond in the Rhineland (Germany) and its carapace bearers consisting of adult *Graptemys pseudogeographica*, *T. s. elegans* and *T. s. scripta* (a). Some *G. pseudogeographica* (a') hibernate here year after year without any problems. The western painted turtle, *Chrysemys picta belli*, as this male shows, has no problems surviving the winter. Also *Pseudemys rubiventris* (c) and *T. scripta* show, they practise their "Spring-Scute-Shedding-Season" in the midday sun. The sequence of photos was taken on March 02. (a, b) and 08. 2024 (c, d) after a winter including cold periods, which had ensured that everything was covered with a supporting layer of ice during the 2nd and 3rd week of January.



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