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The abundance of an invasive freshwater snail *Tarebia granifera* (Lamarck, 1822) in the Nseleni River, South Africa

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The invasive freshwater snail *Tarebia granifera* (Lamarck, 1822) was first reported in South Africa in 1999 and it has become widespread across the country, with some evidence to suggest that it reduces benthic macroinvertebrate biodiversity. The current study aimed to identify the primary abiotic drivers behind abundance patterns of *T. granifera*, by comparing the current abundance of the snail in three different regions, and at three depths, of the highly modified Nseleni River in KwaZulu-Natal, South Africa. *Tarebia granifera* was well established throughout the Nseleni River system, with an overall preference for shallow waters and seasonal temporal patterns of abundance. Although it is uncertain what the ecological impacts of the snail in this system are, its high abundances suggest that it should be controlled where possible and prevented from invading other systems in the region.

Keywords: distribution, invasion, Mollusca, physicochemical drivers, Quilted Melania

Introduction

Tarebia granifera (Lamarck, 1822) (Gastropoda: Thiaridae) is a freshwater prosobranch gastropod commonly referred to as the 'Quilted Melania'. Although originally from South-East Asia, it has become an invasive snail on at least three continents, including North and South America and Africa (Appleton et al. 2009). *Tarebia granifera* was first reported in South Africa in 1999, established in a concrete lined reservoir in Mandeni, northern KwaZulu-Natal (Appleton and Nadasan 2002). Presumably introduced via the aquarium trade (Madsen and Frandsen 1989; Appleton et al. 2009), it has since become widespread in the eastern half of South Africa, particularly in the provinces of KwaZulu-Natal and Mpumalanga (Appleton et al. 2009). Kruger National Park, South Africa's flagship national park, has also seen recent invasions with spread of *T. granifera* increasing substantially between 2001 and 2006 (Wolmarans and de Kock 2006). Although predominantly a freshwater snail, *T. granifera* has also established populations in several South African estuaries (Appleton et al. 2009; Miranda et al. 2011b), showing tolerance for wide ranges of both, salinity and temperature (Miranda et al. 2011b). According to the unified framework proposed by Blackburn et al. (2011), *T. granifera* can be classified as fully invasive in South Africa (category E), 'with individuals dispersing, surviving and reproducing at multiple sites across a greater or lesser spectrum of habitats and extent of occurrence', because it has spread over approximately five degrees of latitude (25 °S–30 °S) since its discovery in 1999 (Appleton et al. 2009).

The spread of *T. granifera* in South Africa has been rapid and both passive (e.g. dispersal through aquatic weeds attached to boats or trailers, or via water transfers) and active (e.g. via attachment to feathers or droppings of waterfowl) pathways have been proposed for its swift dispersal (e.g. Gittenberger et al. 2006; Appleton et al. 2009; van Leeuwen et al. 2012; Reynolds et al. 2015). Its broad physiological tolerances and reproductive strategies, including parthenogenesis and ovoviviparity, have resulted in population explosions of the *T. granifera* in South African ecosystems (Miranda et al. 2011b). Reported population densities of >1 000 individuals/m² makes this invader the dominant component of local invertebrate macrofauna in many localities (Miranda et al. 2011b).

Tarebia granifera is a microphagous feeder and despite minimal evidence for direct food resource competition with indigenous benthic macroinvertebrates (Miranda and Perissinotto 2012; Hill et al. 2015), high densities may indirectly limit energy transfers within a food web (Moslemi et al. 2012; Hill et al. 2015), and in the case of nutrient limitation, may also result in reduced growth rates for coexisting macroinvertebrates (Connor et al. 2008; Riley et al. 2008; Riley and Dybdahl 2015). In addition, there is some evidence to suggest that the establishment of *T. granifera* populations may be followed by the extirpation of indigenous snails (Chaniotis et al. 1980; Prentice 1983; Samadi et al. 1997; Pointier et al. 1998; López-López et al. 2009). Comparatively, the effects of *T. granifera* invasions on aquatic ecosystem biodiversity have been

difficult to quantify, but in recent years, several studies have suggested that the establishment of *T. granifera* populations often (however, not always; see Miranda et al. 2010) result in decreased benthic macroinvertebrate biodiversity e.g. Quintana et al. 2000; Pointier 2001 (as cited in Facon and David 2006); Perissinotto et al. 2014.

The Nseleni River in KwaZulu-Natal, South Africa, is a highly invaded freshwater ecosystem (Appleton et al. 2009; Jones et al. 2013; Hill et al. 2015), which falls within the protected Nseleni Nature Reserve and within which *T. granifera* has been established for more than a decade. Densities in the Nseleni River of $20\,764 \pm 13\,828$ individuals/m² in 2006 (Appleton et al. 2009) are an order of magnitude higher than found elsewhere in South Africa. Differences in density are attributed to a preference for slow moving water, with soft mud devoid of rooted vegetation, in comparison with sandy mud and sparsely vegetated shores, exposed to wave action (Appleton et al. 2009). Understanding patterns in *T. granifera* abundance and its potential impacts on benthic biodiversity may inform biodiversity conservation and management plans. The aims of the current study were to quantify the current relative abundance of *T. granifera* in three different regions of the Nseleni River to identify the primary abiotic drivers of abundance patterns.

Material and methods

Records of relative abundance of *T. granifera* were taken on three separate sections of the Nseleni River; the Nseleni River (Figure 1; sites 1–3), the Mposa River tributary (Figure 1; sites 4–6) and the river after the confluence of the Mposa and Nseleni rivers, just above the inflow into Lake Nsezi (Figure 1; sites 7–9). Jones et al. (2013) provides detailed river section descriptions. For each of the three sites in each river section, three depths were sampled; shallow (~0.5–2.4 m), (~2.5–3.4 m) and deep (~3.5–4.0 m). Relative abundance of benthic macroinvertebrates was quantified using colonization rates of artificial substrates, as described by Thirion (2000), Midgley et al. (2006) and Coetzee et al. (2014). Briefly, artificial substrates were constructed using mesh bags (20 cm wide × 50 cm long) of coarse shade cloth (12 mm mesh netting to allow for recruitment of macroinvertebrates) and filled with 2.0 kg of small pebbles (4.0–8.0 cm diameter). Bags were closed using cable ties and attached to a 2.4 mm nylon string running from the riverbank (shallow) to the centre of the river (deep). Substrates were then deployed for six weeks, one substrate for each site × depth combination, to allow complete colonization by invertebrates (see Thirion 2000; Midgley et al. 2006; Coetzee et al. 2014). Upon sample collection, each substrate bag was carefully removed from the water and placed separately into a large, individually labelled, plastic bag. Upon removal, each substrate was immediately replaced by a new artificial substrate bag at each site. This was repeated every six weeks for ten sampling events from March 2011 to March 2012.

After collection, the contents of each bag were emptied into a separate sorting tray and both contents (pebbles) and bag were washed with clean water to separate out

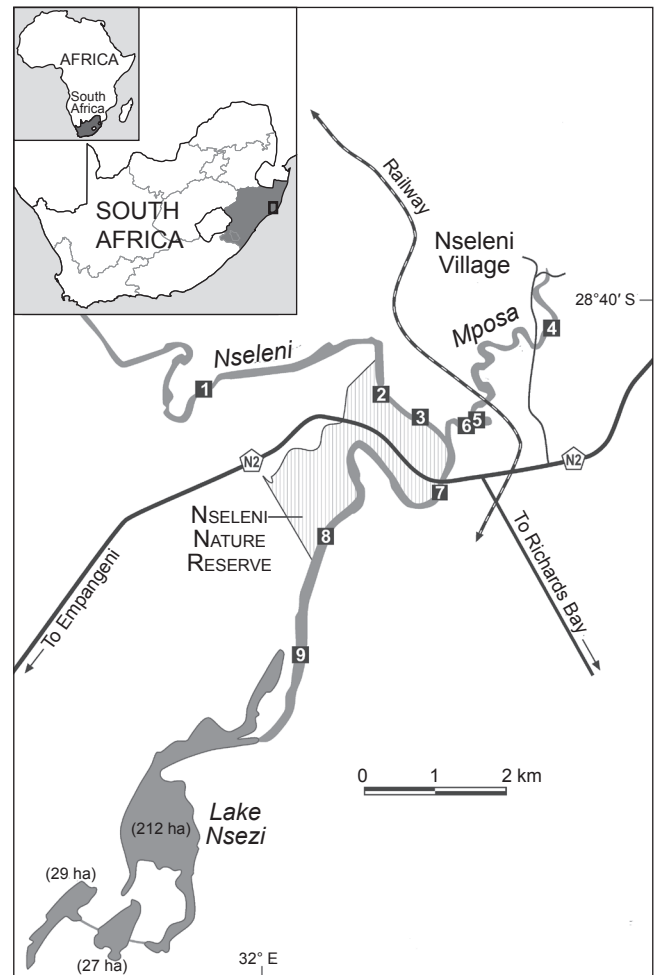


Figure 1: Map of the Nseleni River system in KwaZulu-Natal, South Africa, reproduced from Hill et al. 2015

macroinvertebrates. Each pebble was individually cleaned with fresh water and a small paintbrush before removal from the sorting tray. The contents of the sorting tray were then poured through a sheet of mosquito gauze (1.0 mm mesh size) and all macroinvertebrates were removed with forceps and placed into 20% formalin for later identification and enumeration.

Physico-chemical data were collected quarterly during the sampling period (Mar 2011, Jul 2011, Oct 2011 and Feb 2012); pH, water temperature (°C), salinity, total dissolved solids (TDS; ppm) and conductivity (µS) were collected using a Hanna H1 9828 multiparameter probe; dissolved oxygen (DO; mg l⁻¹) was collected using a Sper Scientific DO Pen (850045) and NO₃⁻ and PO₄³⁻ were analysed at Integral Laboratories (Pty) Ltd, Empangeni, South Africa. Abundance of *T. granifera* was modelled for these four sampling occasions with corresponding physico-chemical data.

Generalized Linear Models (GLMs) were used to investigate the drivers of abundance of *T. granifera*. Models were created using factors for river section (Nseleni, Mposa, Confluence), depth (shallow, middle, deep) and physico-chemical variables (pH, DO, water temperature, salinity and conductivity). Longitudinal

effects or repeated measures during the four sampling dates with physico-chemical factors, and by including all sampling dates, were considered using a mixed-model approach. Site and/or river were included as a random intercept effect and/or river section as a random slope effect. Physico-chemical factors were first tested for collinearity and where highly correlated factors existed, the factor with the best range of values in relation to the response, or the factor with greater biological importance, was chosen. Including highly correlated factors within models inflates standard errors of coefficients causing issue with model fit and interpretation. GLMs were diagnosed for fit using diagnostic plots (e.g. Q-Q and residual plots). Interactions between model terms, e.g. depth and physico-chemical properties, were not considered, because they are nonsensical. Models were selected based on analysis of dispersion (where a value close to 1 validated model fit) and by the Akaike Information Criterion (AIC). Nested models were tested against each other using likelihood ratio tests (Zeileis and Hothorn 2002) and non-nested models using the Vuong tests (Vuong 1989).

Initially models using the Poisson distribution were created, because count data follow a Poisson distribution. However, because counts contained many zeros, they suffered from overdispersion (dispersion statistic >1.00), which is more zeros than expected for a Poisson/negative binomial distribution i.e. the variance was greater than the mean. Ultimately, zero-inflated negative binomial (ZINB)

models showed favourable dispersions indicating a better model fit (Zurr et al. 2013). ZINB models have two parts, the 'zero' part that models the presence of 'true' zeros using a binomial model with logit link and a 'count' part that models the response, in this case, abundance (counts) of *T. granifera* using a log link. Model coefficient differences with a probability value of $p < 0.01$ were considered significant, because p -values are estimates only (Zurr et al. 2013) and comparisons among model coefficients should be done conservatively (Colquhoun 2014). Similarly, models were considered statistically different using the same criterion. Group comparisons (e.g. shallow vs deep) and comparisons of model estimates to observed means were done using SE. Comparisons with overlapping SE are considered not statistically significant. All modelling analyses were completed in R version 3.2.2 (R Core Team 2015).

Results

Snail abundance was greatest at shallow depths, with shallow > middle > deep for all river sections (Figure 2, Table 1). Overall, abundance of *T. granifera* was highest in the confluence section and lowest in the Mposa River section; with an overall range in abundance of 0–694 individuals (Figure 2, Table 1). *Tarebia granifera* was found at >60% of all site-depth combinations over the 12-month period on all rivers, except for middle and deep depths on the Mposa River section. Here, *T. granifera* individuals were rare, recorded on five shallow and three

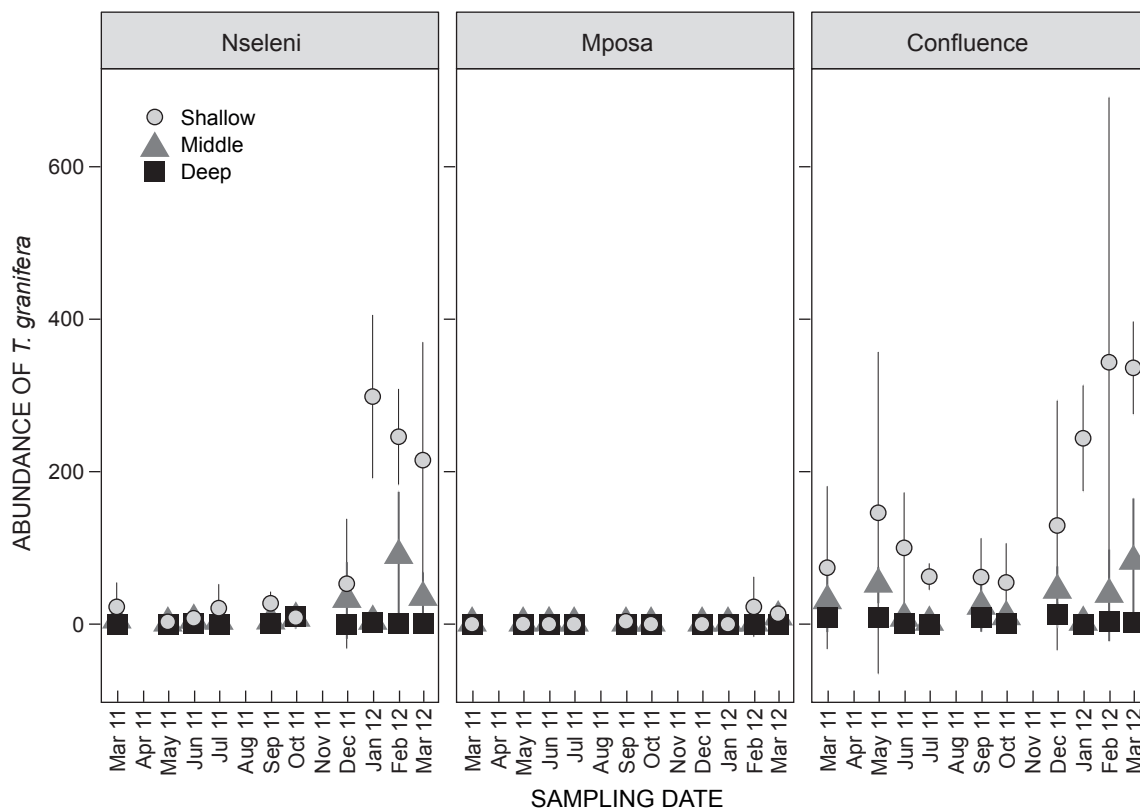


Figure 2: Mean abundance of *Tarebia granifera* (number of individuals \pm SD) over the 13 month sampling period, at three depths (shallow, middle and deep) on three sections of the Nseleni River System (Nseleni, Mposa and the Confluence).

middle depths, but never at deep depth. In addition, the majority of individuals were counted in February and March 2012, when it appears that the population generally increased (Figure 1).

Salinity, TDS and conductivity were all highly correlated (correlation coefficients all ≥ 0.98). Conductivity provided the best range of values and the most relevant physico-chemical measure and was chosen to represent this suite of physico-chemical properties. Temperature and pH were also highly negatively correlated (-0.805 , $p < 0.001$); however, because both were considered biologically important, initial (full) models were created with each. The full model that included temperature was better than the one with pH ($p < 0.001$), therefore, temperature was used in subsequent models. In addition, in any model that included pH, pH was never a significant factor.

Longitudinal mixed models with all sampling dates were restricted to factors of river, depth and site. The best model included river and site as random intercepts. The random effect of site (SD of intercept = 0.67) was about three times less variable than river sections (SD of intercept = 1.99). The model containing both random factors significantly improved the model over one with just river (site $p = 0.048$) or just site (river $p = 0.005$). In addition, a significant increase in abundance was observed during the year of sampling ($p < 0.001$; Figure 2). Variability in river section was primarily caused by rare Mposa counts (Figure 2). Increases in abundance are sporadically noted yet might be seasonal (Figure 2). Over the 12-month sampling period,

T. granifera was observed on other occasions and at all depths (Figure 2), but these values were not available for physico-chemical modelling, because of missing variables.

Tarebia granifera abundance declined with water depth. This trend was best described with a model that included river, depth, conductivity and temperature in the count part of the model; zeros were best described with river, depth and temperature. This model had a dispersion of 1.04 indicating that the variance was only slightly greater than the mean. Of the 12 samples per depth for the four dates included in the model, Mposa had only one *T. granifera* count greater than zero at one depth (shallow) resulting in a standard deviation greater than the mean (Figure 3; note the elongated lower error bar in Mposa that crosses 'zero' on the log scale). Model predicted

Table 1: Mean abundance (number of individuals \pm SD; range) of the invasive snail *Tarebia granifera* pooled over sampling events and sites (3 sites \times 10 months; $n = 30$) at shallow (~ 0.5 – 2.4 m), middle (~ 2.5 – 3.4 m) and deep (~ 3.5 – 4.0 m) depths.

River section	<i>Tarebia granifera</i> abundance		
	Shallow	Middle	Deep
Nseleni	90 \pm 125 (0–391)	18 \pm 39 (0–169)	2 \pm 5 (0–23)
Mposa	4 \pm 13 (0–68)	1 \pm 3 (0–15)	0 \pm 0 (0–0)
Confluence	155 \pm 165 (0–694)	28 \pm 41 (0–173)	5 \pm 9 (0–31)

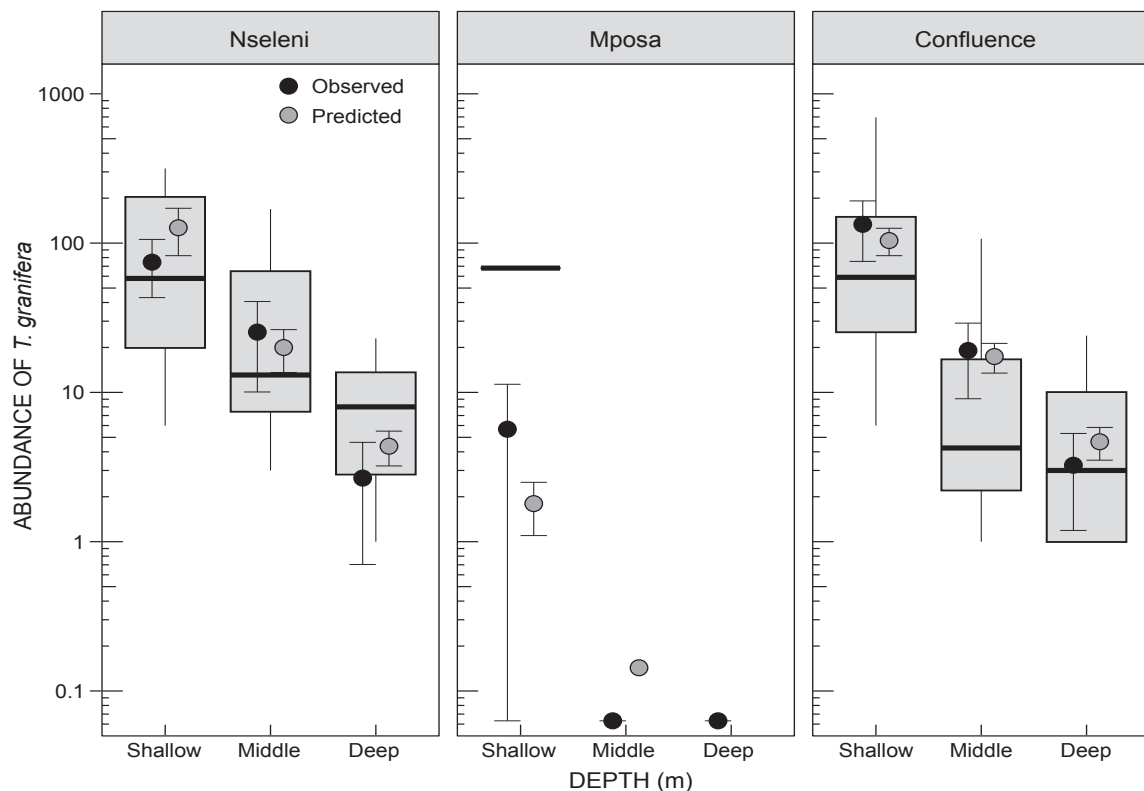


Figure 3: Observed vs model predicted abundances (counts) of *Tarebia granifera*, driven predominantly by conductivity and water temperature. Boxplots are of observed data overlaid with both observed means (black dots \pm SE) and predicted means (grey dots \pm SE).

values were in general agreement with observed mean and median counts, except for the Mposa River section (Figure 3). In the Mposa section, the predicted abundance for middle depth waters was greater than observed, but in shallow waters, the predicted abundance was lower than observed. The latter is a result of only one observation in the Mposa section in shallow waters within the four sampling dates used in modelling. Consequently, in the case of Mposa, predicted abundances are derived from estimates considering all river sections; that is, the overall model estimates regardless of river section. It was concluded sampling methods (e.g. adding habitat bags) and time between repeated site sampling (3 or 4 months) for the four-date model likely reduces autocorrelation effects. Low variability associated with sites in comparison to rivers and general agreement between observed and predicted values, increase confidence in model outcomes. The reduced variability in predicted values is a result of exclusion of a portion of zero values from the zero-inflated modelling method.

Discussion

The abundance data demonstrate that *T. granifera* is firmly established throughout the Nseleni River system, with an overall preference for shallow waters and an apparent seasonal pattern of abundance. Distributions of *T. granifera* were patchy, a common phenomenon with freshwater benthic macroinvertebrates (Covich et al. 1999), which was consistent with *T. granifera* distribution patterns in other South African localities (Appleton et al. 2009; Miranda et al. 2010, 2011b; Miranda and Perissinotto 2014b). The seasonal abundance pattern and sporadic pulses in abundance are likely explained in part by the continuous boom and bust population dynamics reported for *T. granifera* (Perissinotto et al. 2013) and its capacity for reproduction, embryo development and live births throughout the year (Kun-Jun 2004; Miranda et al. 2011b). Overall, *T. granifera* abundance was highest in the confluence section of the Nseleni River, but surprisingly, was much lower in the Mposa River section. Although not specifically investigated, this might be related to periodic inputs of sewage from a wastewater facility situated on the banks of the Mposa River (Jones 2001). It is possible that *T. granifera* are sensitive to high sewage loads and prefer to establish in areas less impacted by wastewater pollution.

The highest abundances and densities were consistently recorded from shallow (~0.50–2.40 m water depth) sites, supporting recent findings that *T. granifera* are numerically dominant in shallow habitats (<2.6 m depth) in South Africa (Miranda et al. 2011b; Miranda and Perissinotto 2014a; Perissinotto et al. 2014) and elsewhere (Abbott 1952; Lachner et al. 1970; Chaniotis et al. 1980). Models that best described the abundance of *T. granifera* in the Nseleni River system were driven by conductivity and water temperature. Comparatively, Miranda et al. (2011b) suggest that *T. granifera* populations are not strongly affected by any one physico-chemical factor, rather they demonstrate increased abundance in response to heightened environmental

stress (e.g. salinity and/or desiccation) (Miranda et al. 2011a). Aquatic shelled molluscs are often particularly sensitive to low pH values, which may impair Ca^{2+} uptake and deposition, resulting in shell erosion (Wilbur 1964; Økland 1983; Raddum et al. 1988; Ewald et al. 2009) and there is some evidence to suggest that *T. granifera* is sensitive to lower pH (Abbot 1952; Yong et al. 1987; Miranda et al. 2011b; Miranda and Perissinotto 2014b). However, pH values in the current study were highly negatively correlated with water temperature and were not a significant factor when replacing temperature in models. Models clearly showed that water temperature was a driving factor describing the abundance of *T. granifera*. The association between *T. granifera* abundance and conductivity may indicate that population numbers are linked to the availability of detritus, because conductivity can be positively related to increases in detrital inputs and its subsequent degradation (Carvalho et al. 2005). Appleton et al. (2009) described a similar scenario suggesting the variability in *T. granifera* population sizes is linked to habitat heterogeneity and food availability associated with allochthonous input (e.g. leaf litter). Routinely described as a generalist feeder, *T. granifera* can utilise large amounts of microphytobenthos in addition to detritus (Miranda et al. 2011; Miranda and Perissinotto 2012) and Hill et al. (2015) reported that in the Nseleni River, a large proportion of *T. granifera* diet comprises degrading leaf litter primarily from the invasive *Eichhornia crassipes* (Mart.) (Solms-Laubach) (1883) and *Azolla filiculoides* (Lamarck 1783), but also from the indigenous mangrove *Barringtonia racemosa* (L.) Spreng. (1826).

The Nseleni River is a heavily disturbed ecosystem, with flow modifications, sewage inputs and recent establishments of multiple invasive species (Jones et al. 2013; Hill et al. 2015). *Tarebia granifera*, with large tolerance ranges for salinity and temperature, high fecundity and a lack of natural predators, may represent a highly opportunistic and resilient species, which can flourish in highly disturbed environments.

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References

- Abbott RT. 1952. A study of an intermediate snail host (*Thiara granifera*) of the oriental lung fluke (paragonimus). *Proceedings of the United States National Museum* 102: 71–116.
- Appleton CC, Forbes AT, Demetriades NT. 2009. The occurrence, bionomics and potential impacts of the invasive freshwater snail

- Tarebia granifera* (Lamarck, 1822) (Gastropoda: Thiaridae) in South Africa. *Zoologische Mededelingen* 83: 525–536.
- Appleton CC, Nadasan DS. 2002. First report of *Tarebia granifera* (Lamarck, 1816) (Gastropoda: Thiaridae) from Africa. *Journal of Molluscan Studies* 68: 399–402.
- Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JRU, Richardson DM. 2011. A proposed unified framework for biological invasions. *Trends in Ecology and Evolution* 26: 333–339.
- Britton JR, Davies GD, Harrod C. 2010. Trophic interactions and consequent impacts of the invasive fish *Pseudorasbora parva* in a native aquatic foodweb, a field investigation in the UK. *Biological Invasions* 12: 1533–1542.
- Carey MP, Wahl DH. 2010. Native fish diversity alters the effects of an invasive species on food webs. *Ecology* 91: 2965–2974.
- Carvalho P, Thomaz SM, Bini LM. 2005. Effects of temperature on decomposition of a potential nuisance species: the submerged aquatic macrophyte *Egeria najas* Planchom (Hydrocharitaceae). *Brazilian Journal of Biology* 65: 51–60.
- Chanotis BN, Butler JM, Ferguson F, Jobin WR. 1980. Bionomics of *Tarebia granifera* (Gastropoda: Thiaridae) in Puerto Rico, an Asian vector of *Paragonimiasis westermani*. *Caribbean Journal of Science* 16: 81–89.
- Coetzee JA, Jones RW, Hill MP. 2014. Water hyacinth, *Eichhornia crassipes* (Pontederiaceae), reduces benthic macroinvertebrate diversity in a protected subtropical lake in South Africa. *Biodiversity and Conservation* 23: 1319–1330.
- Colquhoun D. 2014. An investigation of the false discovery rate and the misinterpretation of *p*-values. *Royal Society Open Science* 1: 140216.
- Conner SLC, Pomory CM, Darby PC. 2008. Density effects of native and exotic snails on growth in juvenile apple snails *Pomacea paludosa* (Gastropoda: Ampullariidae): a laboratory experiment. *Journal of Molluscan Studies* 74: 355–362.
- Covich AP, Palmer MA, Crowl TA. 1999. The role of benthic invertebrate species in freshwater ecosystems. *Bioscience* 49: 119–127.
- Ewald ML, Feminella JW, Lenertz KK, Henry RP. 2009. Acute physiological responses of the freshwater snail *Elimia Flava* (Mollusca: Pleuroceridae) to environmental pH and calcium. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology* 150: 237–245.
- Facon B, David P. 2006. Metapopulation dynamics and biological invasions: a spatially explicit model applied to a freshwater snail. *American Naturalist* 168: 769–783.
- Gerber A, Gabriel MJM. 2002. Aquatic invertebrates of South African rivers - field guide (1st Edition). Institute Of Water Quality Studies, Department Of Water Affairs and Forestry Pretoria, 150 pp.
- Gittenberger E, Groenenberg DSJ, Kokshoorn B, Preece RC. 2006. Molecular trails from hitch-hiking snails. *Nature* 439: 409.
- Hill JM, Jones RW, Hill MP, Weyl OLF. 2015. Comparisons of isotopic niche widths of some invasive and indigenous fauna in a South African river. *Freshwater Biology* 60: 893–902.
- Jones RW. 2001. Integrated control of water hyacinth on the Nseleni/Mposa Rivers and Lake Nsezi, Kwazulu-Natal, South Africa. In: Julien MH, Hill MP, Center TD, Jianqing D (eds) Biological and Integrated Control of Water Hyacinth, *Eichhornia Crassipes*. Proceedings of the Second Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth. ACIAR Proceedings No. 102. ACIAR, Canberra. Pp 123–129.
- Jones RW, Weyl OLF, Swartz ER, Hill MP. 2013. Using a unified invasion framework to characterize Africa's first loricariid catfish invasion. *Biological Invasions* 15: 2139–2145.
- Kun-Jun C. 2004. A preliminary study on the reproductive ecology of the freshwater snail *Tarebia granifera* (Lamarck, 1822) (Prosobranchia: Thiaridae) in Jinlun River, South Eastern Taiwan. Msc Thesis, Nation Sun Yat-Sen University, Tawian.
- Lachner EA, Robins CR, Courtenay WR. 1970. Exotic fishes and other aquatic organisms introduced into North America. *Smithsonian Contributions to Zoology* 59: 1–29.
- López-López E, Sedeño-Díaz JE, Vega PT, Oliveros E. 2009. Invasive mollusks *Tarebia granifera* Lamarck, 1822 and *Corbicula fluminea* Müller, 1774 in the Tuxpam and Tecolutla Rivers, Mexico: spatial and seasonal distribution patterns. *Aquatic Invasions* 4: 435–450.
- Madsen H, Frandsen FR. 1989. The spread of freshwater snails including those of medical and veterinary importance. *Acta Tropica* 46: 139–146.
- Midgley JM, Hill MP, Villet MH. 2006. The effect of water hyacinth, *Eichhornia crassipes* (Martius) Solmslaubach (Pontederiaceae), on benthic biodiversity in two impoundments on the New Year's River, South Africa. *African Journal of Aquatic Sciences* 31: 25–30.
- Miranda NAF, Perissinotto R. 2012. Stable isotope evidence for dietary overlap between alien and native gastropods in coastal lakes of northern KwaZulu-Natal, South Africa. *Plos One* 7: e31897.
- Miranda NAF, Perissinotto R. 2014a. Benthic assemblages of wetlands invaded by *Tarebia granifera* (Lamarck, 1822) (Caenogastropoda: Thiaridae) in the Isimangaliso Wetland Park, South Africa. *Molluscan Research* 34: 40–48.
- Miranda NAF, Perissinotto R. 2014b. Effects of an alien invasive gastropod on native benthic assemblages in coastal lakes of the Isimangaliso Wetland Park, South Africa. *African Invertebrates* 55: 209–228.
- Miranda NAF, Perissinotto R, Appleton CC. 2010. Salinity and temperature tolerance of the invasive freshwater gastropod *Tarebia granifera*. *South African Journal of Science* 106: 55–61.
- Miranda NAF, Perissinotto R, Appleton CC. 2011a. Feeding dynamics of the invasive gastropod *Tarebia granifera* in coastal and estuarine lakes of northern KwaZulu-Natal, South Africa. *Estuarine Coastal and Shelf Science* 91: 442–449.
- Miranda NAF, Perissinotto R, Appleton CC. 2011b. Population structure of an invasive parthenogenetic gastropod in coastal lakes and estuaries of northern KwaZulu-Natal, South Africa. *Plos One* 6: e24337.
- Mooney HA, Cleland EE. 2001. The evolutionary impact of invasive species. *Proceedings of the National Academy of Sciences USA* 98: 5446–5451.
- Moslemi JM, Snider SB, Macneill K, Gilliam JF, Flecker AS. 2012. Impacts of an invasive snail (*Tarebia granifera*) on nutrient cycling in tropical streams: the role of riparian deforestation in Trinidad, West Indies. *Plos One* 7: e38806.
- Økland J. 1983. Factors regulating the distribution of freshwater snails (Gastropoda) in Norway. *Malacologia* 24: 277–288.
- Perissinotto R, Miranda NAF, Raw JL, Peer N. 2014. Biodiversity census of Lake St Lucia, Isimangaliso Wetland Park (South Africa): gastropod molluscs. *Zookeys* 440: 1–43.
- Pointier JP, Samadi S, Jarne P, Delay B. 1998. Introduction and spread of *Thiara granifera* (Lamarck, 1822) in Martinique, French West Indies. *Biodiversity and Conservation* 7: 1277–1290.
- Prentice MA. 1983. Displacement of *Biomphalaria glabrata* by the snail *Thiara granifera* in field habitats in Santa Lucia, West Indies. *Annals of Tropical Medicine and Parasitology* 77: 51–59.
- Raddum GG, Fjellheim A, Hesthagen T. 1988. Monitoring of acidification by the use of aquatic organisms. *Verhandlungen des Internationalen Verein Limnologie* 23: 2291–2297.
- Reynolds C, Miranda NAF, Cumming GS. 2015. The role of waterbirds in the dispersal of aquatic alien and invasive species. *Diversity and Distributions* 21: 744–754.
- Riley LA, Dybdahl MF. 2015. The roles of resource availability and competition in mediating growth rates of invasive and native freshwater snails. *Freshwater Biology* 60: 1308–1315.
- Riley LA, Dybdahl MF, Hall RO. 2008. Invasive species impact: asymmetric interactions between invasive and endemic

- freshwater snails. *Journal of the North American Benthological Society* 27: 509–520.
- Salafsky N, Margoluis R, Redford KH. 2001. Adaptive management: a tool for conservation practitioners. Biodiversity Support Program Publications, The World Wildlife Fund. Washington DC. 53 pp.
- Samadi S, Balzan C, Delay B, Pointier J-P. 1997. Local distribution and abundance of Thiarid snails in recently colonized rivers from the Caribbean area. *Malacological Review* 30: 45–52.
- Scholes RJ, Kruger JM. 2011. A framework for deriving and triggering thresholds for management intervention in uncertain, varying and time-lagged systems. *Koedoe* 53: v53i2.987.
- Thirion C. 2000. A new biomonitoring protocol to determine the ecological health of impoundments, using artificial substrates. *African Journal of Aquatic Science* 25: 123–133.
- van Leeuwen CHA, Van Der Velde G, Van Lith B, Klaassen M. 2012. Experimental quantification of long distance dispersal potential of aquatic snails in the gut of migratory birds. *Plos One* 7: e32292.
- Vuong QH. 1989. Likelihood ratio tests for model selection and non-nested hypotheses. *Econometrica* 57: 307–333.
- Wilbur KM. 1964. Shell formation and regeneration. In: Wilbur KM, Yonge CM (eds) *Physiology of Mollusca* V. 1 Academic Press, New York, 243–282.
- Wolmarans CT, de Kock KN. 2006. The current status of freshwater molluscs in the Kruger National Park. *Koedoe* 49: 9–44.
- Yong M, Sanchez R, Perera G, Ferrer R, Amador O. 1987. Seasonal studies of two populations of *Tarebia granifera*. *Walkerana, Transactions of the Poets Society* 2: 159–163.
- Zeileis A, Hothorn T. 2002. Diagnostic checking in regression relationships. *R News* 2: 7–10.
- Zurr AF, Hilbe JM, Leno EN. 2013. A beginner's guide to GLM and GLMM with R: a frequentist and Bayesian perspective for ecologists. Highland Statistics Ltd, Newburgh, UK.