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Article

Relative condition factor and predictive model for the presence of the invasive snail *Achatina* (*Lissachatina*) *fulica* in Sergipe, Northeast Brazil

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Abstract: *Achatina fulica* is among the world's 100 most impactive invasive species, and is now found in almost all Brazilian states, including Sergipe. This exotic snail is known to have negative impacts, not only on the environment, due primarily to the rapid growth of its populations, but also on public health, given that it is an intermediate host of nematodes that cause zoonotic diseases. However, relatively little is known of the development of this snail, including its relative condition factor. We investigated the occurrence of *A. fulica* in 24 municipalities distributed in the eight subregions of the state of Sergipe in the dry and rainy season. Furthermore, we present here a predictive model for the occurrence of *A. fulica* based on the variation in climate and soil chemistry. This snail was more frequent on soils with a pH of 6.5–7.5. A negative correlation was found between the growth of *A. fulica* and the soil pH, then, the more acidic the soil, the more allometric the growth of *A. fulica*. The relative condition factor indicated differences in the development pattern of *A. fulica* among the eight subregions. The influence of rain in increasing the frequency of *A. fulica* showed a significant correlation. As well, higher temperatures influenced the resting behavior of *A. fulica*. The mathematical model used to identify the potential presence of *A. fulica* presented a high degree of agreement. This is the first ecological study of *A. fulica* to verify the association between the body mass-length relationship and the relative condition factor, and the results indicate that the development of this exotic land snail in Sergipe is influenced by climatic factors and principally, the soil pH. The predictive mathematical model provides valuable insights into the biotic and abiotic factors associated with the presence of *A. fulica*, and the influence of climatic variables and the chemical parameters of the soil on the occurrence of this species. These findings provide important guidelines for the development of measures for the control of *A. fulica* populations, which will contribute to both public and environment health.
Keywords: *Achatina fulica*; Invasive exotic snail; Relative Condition Factor; Environmental factors.

Fator de condição relativo e modelo preditivo para a presença do caracol invasor *Achatina* (*Lissachatina*) *fulica* em Sergipe, Nordeste do Brasil

Resumo: *Achatina fulica* está entre as 100 das piores espécies invasoras em todo o mundo, e no Brasil está presente em quase todos os estados, incluindo Sergipe. Este caracol exótico é conhecido por ter impactos negativos, não só no meio ambiente, devido principalmente ao rápido crescimento de suas populações, mas também na saúde pública, uma vez que é um hospedeiro intermediário de nematodeos causadores de doenças zoonóticas. No entanto, pouco se sabe a respeito do desenvolvimento dessa espécie, incluindo o fator de condição relativo. Investigamos a ocorrência de *A. fulica* em 24 municípios distribuídos nos oito territórios do estado de Sergipe no período seco e chuvoso. Além disso, apresentamos aqui um modelo preditivo para a ocorrência de *A. fulica* baseado na variação do clima e da química do solo. Esse caracol é mais frequente no solo com pH de 6,5 à 7,5, sendo esse padrão ideal para o crescimento isométrico. O crescimento alométrico de *A. fulica* apresentou correlação negativa com o pH do solo, quanto mais ácido for o solo, maior será o crescimento de *A. fulica*. O fator de condição de *A. fulica*, apresentou diferença no desenvolvimento nos oito Territórios. A influência da chuva na frequência de *A. fulica* apresentou correlação significativa. Além disso, temperaturas mais elevadas influenciaram no comportamento de repouso de *A. fulica*. O modelo matemático para identificar a possível presença de *A. fulica* apresentou uma concordância forte.

Este é o primeiro estudo ecológico de *A. fulica* a verificar a associação entre a relação massa-comprimento e o fator de condição relativo, sendo possível evidenciar que essa espécie exótica em Sergipe sofre alterações no desenvolvimento, por fatores climáticos e principalmente pelo pH do solo. O modelo matemático preditivo fornece informações valiosas sobre os fatores bióticos e abióticos associados à presença de *A. fulica* e a influência de variáveis climáticas e dos parâmetros químicos do solo na ocorrência desta espécie. Esses achados fornecem importantes diretrizes para o desenvolvimento de medidas de controle de populações de *A. fulica*, que poderão contribuir para a saúde pública e ambiental.
Palavras-chave: *Achatina fulica; Caracol exótico invasor; Fator de condição Relativo; Fatores ambientais.*

Introduction

The Giant African land snail *Achatina* (*Lissachatina) fulica* Bowdich, 1822 is native to East Africa, although human interference, combined with the efficient dispersal capacity of the species, has led to its distribution throughout much of the tropical and subtropical regions of the world, including Africa, the Americas, eastern and southern Asia, and Oceania (Thiengo et al. 2007, Silva & Omena 2014). It is considered an invasive species, which is generally found in dense populations and compete for food and space with native snail species (Raut & Barker 2002). This snail also acts as an intermediate host of parasitic nematodes that represent a threat to public health and veterinary medicine. Examples are the nematodes *Angiostrongylus cantonensis* (Chen 1935), an etiological agent of eosinophilic meningitis (EM) in humans (Zanol et al. 2010), and *Aelurostrongylus abstrusus* (Railliet 1898), which causes pneumonia in both domestic and wild felines (Thiengo et al. 2008).

In recent years, several studies have investigated the dispersal, invasion, distribution, and abundance of *A. fulica* in different countries around the world (e.g., Tomiyama 1992, 1993, 1994, Cowie 1998, Zanol et al. 2010, Fontanilla et al. 2014, Sarman et al. 2015, Gbadeyan et al. 2020, Oliveira et al. 2020; Silva et al. 2020). Large-scale eradication programs have been established in many regions, which include the manual collection and destruction of the snails and their eggs (Smith et al. 2013) and the use of traps to capture *A. fulica* (Roda et al. 2018). However, data on the influence of climatic variables and soil chemistry on the development and behavior are still scarce, and little is known of the relative condition factor (KR) of this species (Bolger 1989). The relative condition factor expresses the relationship between body mass and length, which provides important insights into the behavioral features of a species and the influence of biotic and abiotic factors in its development (Le Cren 1951). Albuquerque et al. (2009) concluded that the understanding of the factors that influence the body length and mass of this mollusk, and its condition factor, would provide a valuable tool for the management and control of *A. fulica* populations. The relationship between the body mass and length of a species provides valuable insights into the influence of environmental conditions on the organism and its development stages (Ghisi et al. 2012). The KR parameter also indicates the wellbeing of the individual in its environment and provides the potential for systematic comparison between two or more populations occurring under different conditions (Araujo et al. 2011).

According to Fischer & Colley (2005), abiotic factors, such as the chemical composition of the soil, may also influence the development of *A. fulica* and the establishment of its populations. Raut & Barker (2002) found that this species can exploit different types of soil for the extraction of nutrients, and as a refuge, with the type of soil having both quantitative and qualitative effects on the growth rate of this snail, its size shell, mass and coloration. *Achatina fulica* uses the soil for behaviors such as resting, burrowing and estivation (Fischer 2009), which should be considered for the development of measures for the control and eradication of the species (Roda et al. 2018). Climatic variables should also be considered, given that the frequencies of the different types of its defensive behavior are related directly to relative humidity and rainfall (Miranda et al. 2015, Pilate et al. 2017, Silva et al. 2020).

In 2015, the State Committee for the Control of the African Snail reported the presence of *A. fulica* in 19 municipalities in Sergipe/Brazil (IBAMA 2021). However, few data are available on its development and behavior in northeastern Brazil, much of which is relatively arid, with a long dry season and high temperatures. Given this, understanding the effects of biotic and abiotic factors on the development of *A. fulica* will be essential for the development of predictive models, which can be applied to the evaluation of potential dispersal patterns and demographic parameters (Johnson & Omland 2004). Fischer et al. (2010) consider the ability of *A. fulica* to adapt to different types of habitats to be a major concern and emphasize the need to understand its ecological characteristics in order to develop the most effective strategies for the control of this invasive species. The research into the behavior of this snail will also be important for the development of more effective control strategies, as well as providing parameters for the evaluation of the risks posed by this invasive species for the native land snails of a given area (Pilate et al. 2017).

The present study investigates of the occurrence of *A. fulica* in subregions of the Brazilian state of Sergipe. We try to answer the following questions (i) does it occur in all eight subregions of Sergipe? (ii) is the body mass-length relationship of *A. fulica*, including the relative condition factor, correlated with climatic variables and soil chemistry? (iii) does the development of *A. fulica* vary between the rainy and dry seasons? and (iv) can climatic variables or soil chemistry be used to compile a predictive model of the occurrence of *A. fulica* in Sergipe?

Methods

1. Study area

Sergipe is located in northeastern Brazil, and covers an area of 21,925.42 km², with an estimated population of 2,298,696 inhabitants (94.36 individuals/km²) in 2019 (IBGE 2020). The study area comprised 24 municipalities distributed in the eight subregions of the Brazilian state of Sergipe – Greater Aracaju, East Sergipe, the Lower São Francisco River, South Sergipe, the Eastern Plateau, Western Plateau, Central Highlands, and South Central Sergipe (IBGE 2011; see Fig. 1, Appendix S1). The climate in the state of Sergipe is divided into three distinct regions according to temperature and rainfall. Humid tropical region, with high temperature and high humidity along the coast (East); Sub-humid tropical region or drier intermediate region (Agreste), and inland semi-arid region (Semi-arid). The humid tropical region is characterized by high precipitation (average of 1,355 mm/year) and high relative humidity (annual average of 80%). In the Agreste, rainfall is slightly below that observed in the Tropical Humid region, with values around 1,000 mm/year, with a similar monthly distribution. The semiarid region in the interior of the state of Sergipe is considerably drier than the coastal region. The average rainfall is less than 700 mm/year, with values below 30 mm in the summer months (SEMARH, 2010). The 100-year means up to 2012 (Santos & Souza 2018) indicate that the months from April through August are the rainiest of the year in this region, although March and September are also considered to be part of the rainy season, albeit with slightly lower mean precipitation. The dry season proper extends between October and February, although over the past 12 years, the mean precipitation recorded in Aracaju in February was 59±41mm, while that in September was 63±29 mm (INIMET 2021).

2. Sampling

The *A. fulica* specimens were collected in February (the end of dry season) and September (end of the rainy season), in 2019 and 2020. The sampling points (plots) were established based on the records of the occurrence of *A. fulica* in Sergipe presented by the state's municipal authorities in the 2015 meeting of the State Committee for the Control of the African Snail during which, 19 municipalities reported the infestation of the urban zone by *A. fulica* (IBAMA 2021). The specimens were collected using the plot method, adapted from Pereira et al. (2015). A 20 m x 10 m plot was established in each of the 24 study municipalities. The plots were demarcated with wooden stakes, which were driven into each corner, with all the *A. fulica* individuals found within the perimeter during a 10-minute search being collected by the researcher.

3. Environnemental analyses

During each survey, the characteristics of the environment were noted on a field chart, including data on the weather (sunny, cloudy, rainy), the presence of household garbage., rubble, domestic animals or sewage, the characteristics of vegetation, the upkeep of the area, the characteristics of the soil (humid or dry), the behavior of *A. fulica* (active, resting), and the presence of *A. fulica* eggs (Appendix S2). The meteorological data, that is, the mean monthly temperature, relative humidity, and precipitation were obtained from the automatic and traditional meteorological stations maintained by the Brazilian National Meteorological Institute (INMET) in the different subregions of the state of Sergipe (INMET 2021). The meteorological data presented here refer to the following months: February and September of 2019 and 2020, when the snails were collected in Sergipe.

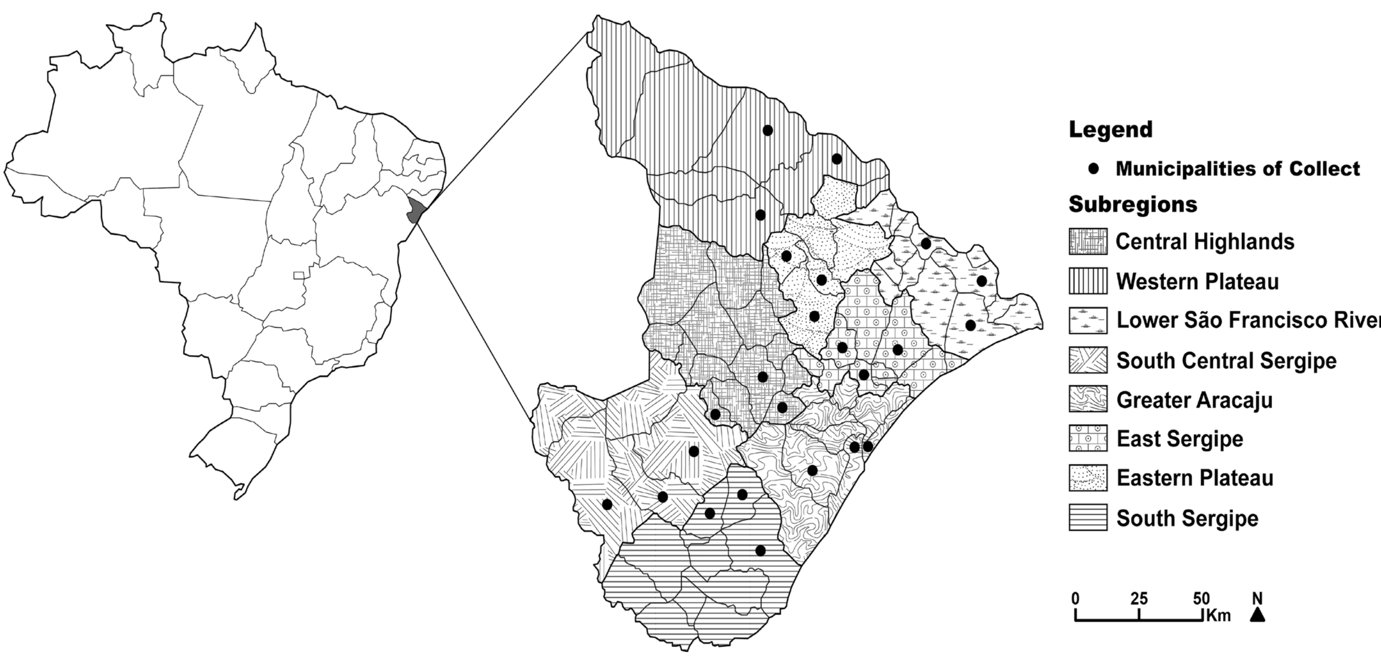

Figure 1. Map of the political divisions of the Brazilian state of Sergipe, showing the municipalities in which the *Achatina fulica* populations were surveyed in 2019 and 2020. The black dots represent the municipalities surveyed in the present study.

Soil samples were collected from each of the 24 plots after the collection of the *A. fulica* specimens. The samples were obtained at a depth of up to 5 cm using a stainless-steel spatula at the four corners of the plot, and from one "variable" point within the plot, to provide a total sample of 500 g. The variable point was selected based on the presence of the *A. fulica* specimens observed within the plot, either buried or in the aggregation phase, when these snails gather together at a single point (Fischer et al. 2012; Almeida et al. 2016). When no *A. fulica* were observed in the plot, the fifth sample was obtained from the center of the plot (Appendix S3). Once collected, the samples were mixed, homogenized and stored in 500-ml pots. The soil samples were analyzed using the method described by Camargo et al. (2009), which consists of the measurement of the pH in water, Calcium (Ca) and organic matter (OM).

4. Biometry, allometric growth (b), and the relative condition factor

Achatina fulica specimens were taken to the laboratory, where the total length (Lt) of the shell of each individual was measured using a digital Vernier calliper (0.01 mm precision) and the total mass (Wt) was determined using a digital balance (0.0001 g precision). These data were used to calculate the mean morphometric parameters of the specimens, and to determine the body mass-length relationship and the relative condition factor. The body mass-length relationship is based on the equation $Wt = _{a.} Lt^{b,}$ where Wt = total mass, Lt = total length, and *a* and *b* are the growth parameters (Le Cren 1951, Bolger & Connoly 1989). The value of the allometric coefficient (*b*) was used to determine whether growth was isometric ($b = 3$), that is, with a symmetrical relationship between the variation in mass and length, positively allometric ($b > 3$), when mass increases more quickly than length, or negatively allometric ($b < 3$), when length increases more quickly than mass (Araujo et al. 2011). The relative condition factor (KR) was then calculated by the equation KR = *M.obs*/*M.exp*, where *M.obs* = the observed body mass (the weight of the specimen), and *M.exp* = the expected mass, as determined by the slope of the body mass-length relationship. When KR =1, body mass is considered ideal, when KR >1, the individual is above its expected mass, and when KR <1, it is below its expected mass (Le Cren 1951). The *A. fulica* size (shell length) classes were adapted from Fischer & Colley (2005) and Almeida (2013): infants (< 1.00 cm), juveniles (1.01– 4.00 cm), young adults (4.01–7.00 cm) and adults (> 7.00 cm).

5. Data analysis

The variation in the relative condition factor (KR) of the *A. fulica* specimens among the eight subregions of the state of Sergipe was analysed using Pearson's nonparametric Chi-square. For the analysis of the numerical variables, the normality of the data was evaluated using the Lilliefors test, associated with the Kolmogorov-Smirnov test, to classify the distribution of each variable as either parametric (homogeneous distribution) or nonparametric (heterogeneous distribution), assigned to four conditions: 1) all the numerical variables that did not group with any independent variable (the condition factor [KR], variation in condition factor, the allometric growth of *A. fulica*, relative humidity and the variation in humidity, the temperature and the variation in temperature, rainfall and the variation in rainfall, the soil pH, calcium, and organic matter); for the conditions (2,3,4) numerical variables were treated as dependent and categorical variables as independent; 2) the association between rainfall and the presence of *A. fulica*, 3) the association between the soil pH and the presence of *A. fulica*), and 4) The relative condition factor, which was analysed per subregion. In the case of condition 1, as all the variables were classified as parametric, the analyses were based on Pearson's parametric correlation coefficient (*r*). The variables in conditions 2 and 3 were classified as nonparametric, so in this case, the analyses were based on the nonparametric Mann-Whitney *U* test. Condition 4 was evaluated using the Kruskal-Wallis nonparametric analysis of variance.

As a significant correlation was observed (condition 1), the soil pH was the variable used to describe the linear equation, based on a simple linear regression, which evaluated the degree of influence and the linear relationship between the soil pH and the allometric growth of the species. A binary logistic regression (Mendes & Veja 2011) was then used to obtain a predictive model of *A. fulica* based on the environmental factors (temperature, relative humidity, rainfall, and soil pH). These variables have been chosen because they showed an influence or correlation value with the categorical variable presence of the species, through principal component analysis (PCA). From then on, the waste disposal model was included in the model, as well as the outlier values, thus avoiding compromising the explanatory power of the model. The result of the equation will steam from the replacement of the letters by their respective values, the result of the equation being 0 and close to 0 corresponding to the absence of *A. fulica*, while values close to 01 or 01 refer to the presence of this snail (being always considered the result module). Regarding the categorical variable (period) it considers the value of 01 for dry and 02 for rainy. The Kappa index was then applied to the results of this equation to compare the model (binary logistic regression) with the empirical results survey.

Results

1. Characteristics and distribution of Achatina fulica in Sergipe

The occurrence of *A. fulica* was confirmed in 18 of these plots, from which 735 snail specimens were collected. The *A. fulica* population was dominated by juvenile (n = 423; 57.5%) and young adult snails (n = 282; 38.3%) in all the study periods (Fig. 2). The majority (n = 649; 88.2%) of the snails were at rest, while 67 (9.3%) were estivating and 19 (2.5%) were active.

During the dry season of 2019, 124 specimens were collected from nine plots (Table 1). These specimens had a mean length of 5.36±1.11 cm (range: 2.8–9.0 cm). In the rainy season of 2019, 258 specimens were collected from 18 study plots. The mean length of the specimens collected during this period was 3.44±1.41 cm (range: 1.5–7.7 cm). A total of 90 specimens were collected during the dry season of 2020, from 12 plots. These specimens had a mean length of 4.02±1.17 cm (range: 0.9–6.7 cm). In the rainy season of 2020, 263 specimens were collected from 17 plots. These specimens had a mean length of 3.07±1.46 cm (range: 0.6–8.4 cm).

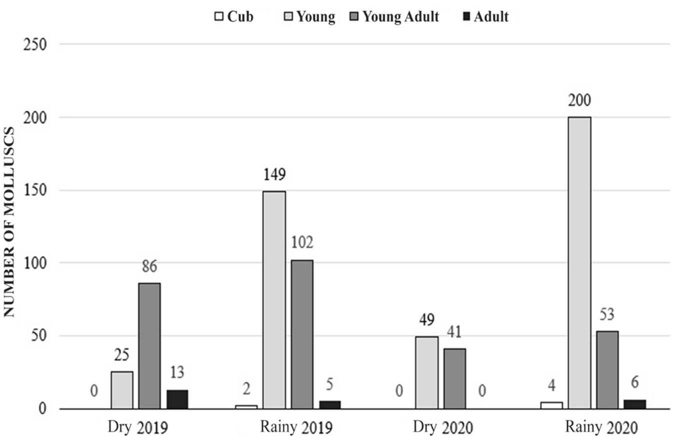

Figure 2. Distribution of the size classes of the *Achatina fulica* specimens collected in the dry and rainy seasons in 26 municipalities of the Brazilian state of Sergipe, in 2019 and 2020.

2. *Relationship between frequency of Achatina fulica and climatic characteristics*

During the dry season of 2019 (Fig. 3, 4), the largest numbers of *A. fulica* specimens were collected in the East Sergipe (n = 48 snails, 38.7% of the total number of specimens collected in the period) and Greater Aracaju subregions (n = 37, 29.8%). In the rainy season of this year, the largest samples were collected in the South Central (n = 73, 28.2%), East Sergipe (n = 58, 22.4%) and South Sergipe subregions (n = 45, 17.4%). In both seasons, there was a significant correlation (p = 0.01) between rainfall and the number of *A. fulica* specimens collected. In the dry season of 2020 (Fig. 3, 4), *A. fulica* was most frequent in the plots in the Greater Aracaju (n = 28, 31.1%), South Central (n = 21, 23.3%) and South Sergipe subregions (n = 20, 22.2%). In the rainy season of this year, *A. fulica* was most frequent in the South Central (n = 72, 27.3%) and South Sergipe subregions (n = 70, 26.6%).

Table 1. Variation in the body mass (g) and total length (cm) of the *Achatina fulica* specimens collected in the dry (February) and rainy (September) seasons of 2019 and 2020, in the eight subregions of the Brazilian state of Sergipe.

Season	Number of *A. fulica* specimens	Body length (cm)				Body mass (g)			
		Min.	Max.	Mean	SD	Min.	Max.	Mean	SD
Dry 2019	124	2.8	9.0	5.36	±1.11	2.5	68.3	15.87	±9.85
Rainy 2019	258	1.5	7.7	3.44	±1.41	0.5	54.4	6.86	±8.97
Dry 2020	90	0.9	6.7	4.02	±1.17	0.01	39.5	12.52	±9.11
Rainy 2020	263	0.6	8.4	3.07	±1.46	0.3	86.1	9.47	±13.33

Min = Minimum, Max = Maximum; SD = Standard Deviation.

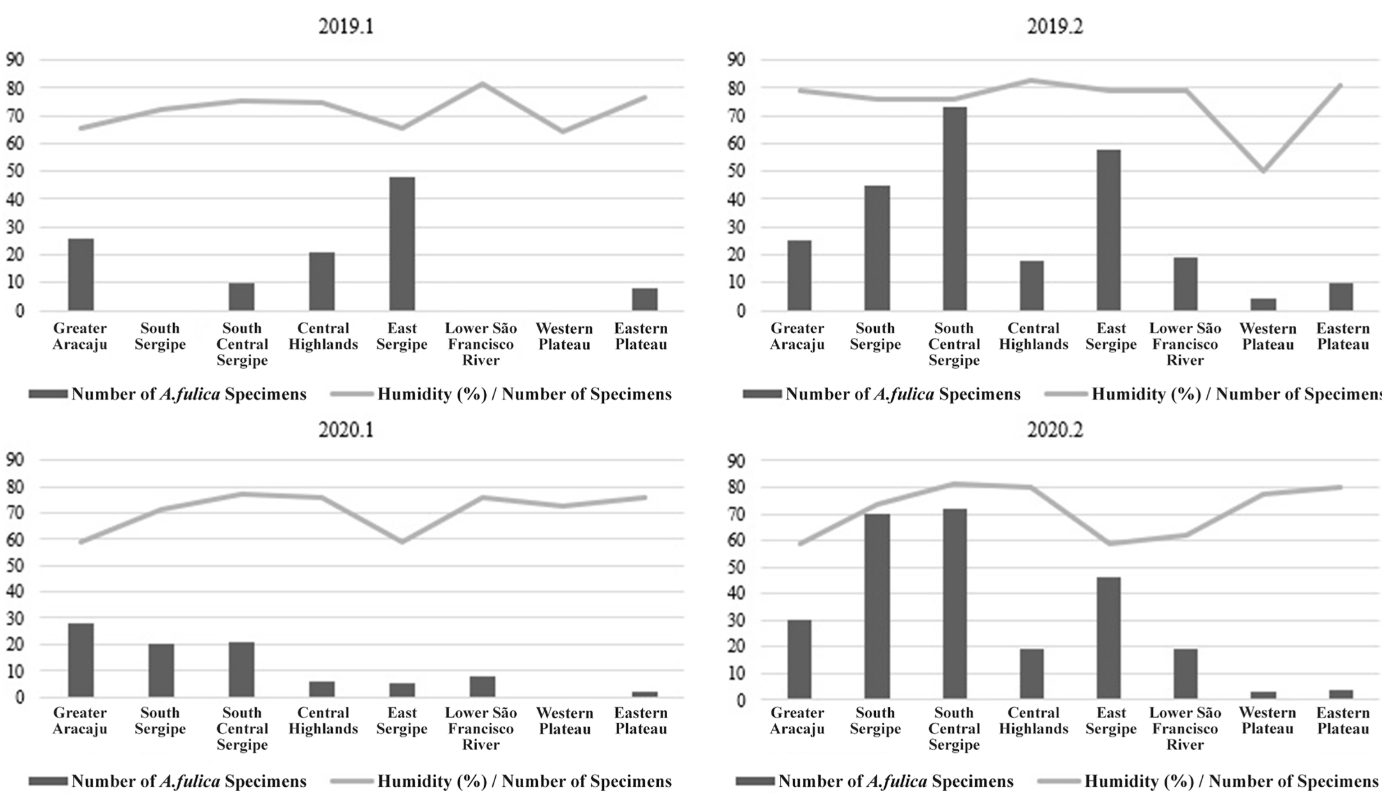

Figure 3. Number of *Achatina fulica* specimens and the relative humidity (%) recorded in the different subregions of the Brazilian state of Sergipe in the dry and rainy seasons of 2019 and 2020.

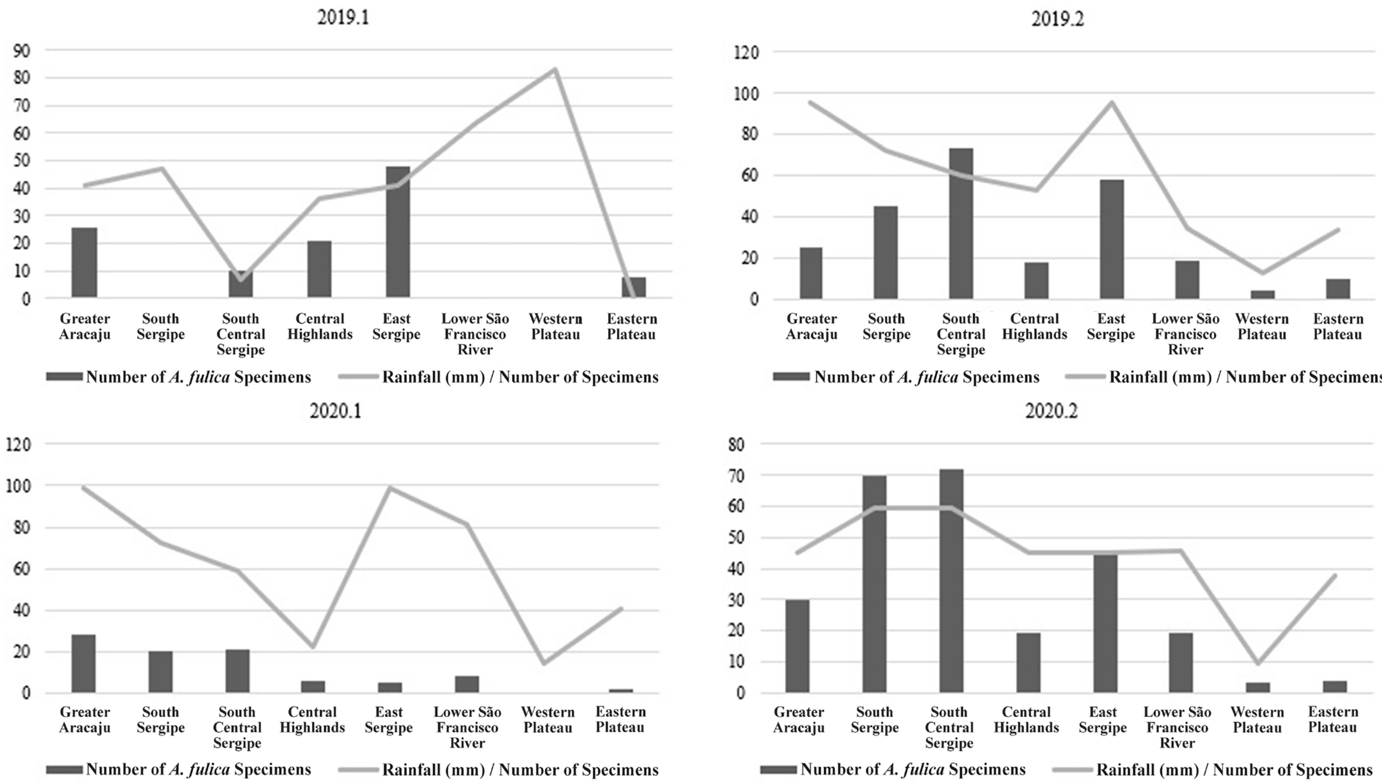

Figure 4. Number of *Achatina fulica* specimens collected (columns) and the rainfall (gray lines, in mm) recorded in the different subregions of the Brazilian state of Sergipe in the dry (2019.1 and 2020.1) and rainy (2019.2 and 2020.2) of the present study period.

During the dry season of 2019, relative humidity was highest in the Lower São Francisco subregion (81.6%), and lowest (64.0%) on the Western Plateau (Fig. 3). In the rainy season of this year, the highest relative humidity (82.7%) was recorded in the Central Highlands and the lowest (50.0%), once again, on the Western Plateau. In the dry season of 2020, the highest relative humidity (78.8%) was recorded in the Lower São Francisco subregion, while the lowest value (59.2%) was recorded in Greater Aracaju. During the rainy season, relative humidity peaked in South Central Sergipe (81.2%) and the Central Highlands (80.3%), and was lowest in Greater Aracaju (58.7%).

During the present study, a mean precipitation of 34.8±29 mm was recorded in the dry season month of February 2019 and 55.5±29 mm in September, whereas in 2020, the mean for February was 58.6±31 mm, and that for September was 43.3±15 mm. It is important to note, however, that the rainfall observed during the dry season occurred in isolated downpours, with an irregular distribution in February, in particular in 2020. In 2019, the different subregions, the highest monthly rainfall (83.2 mm) was recorded on the Western Plateau subregion, whereas in the rainy season, rainfall was highest (95.6 mm) in Greater Aracaju (Fig. 4). In 2020, the highest values in the dry season, which reached 98.8 mm, were recorded in Greater Aracaju and East Sergipe, whereas in the rainy season, the highest value (59.4 mm) was recorded in South Sergipe, with a similar level being registered in the South Central subregion.

In the dry season of 2019, all the 24 sample plots surveyed in the eight subregions of Sergipe had dry soil and the conditions were sunny, whereas in the rainy season, 13 of the plots had humid soil, and 18 were surveyed on cloudy days. In the dry season of 2020, by contrast, only nine of the plots had dry soil, and 15 were surveyed on cloudy days, while in the rainy season, 21 of the plots had dry soil, and all 24 were surveyed on sunny days. The plots with humid soil in the rainy season of 2019 were all located in the Greater Aracaju, South Sergipe, Central South Sergipe, East Sergipe and the Lower São Francisco subregions, which are all located within the humid coastal zone of the state. In 2020, plots with humid soil were all located in these same subregions, whereas in the rainy season, humid soil was observed only in the plots in Greater Aracaju, South Sergipe and East Sergipe.

The mean temperature recorded in Sergipe in the dry season (February) was 28.2±0.7°C, which is similar to the mean for the rainy season (September) of this year, that is, 26.0±1.3°C. In 2020, the mean temperature of the dry season was 27.9±0.7°C, while it was 24.4±2.7°C in the rainy season. A significant correlation ($p = 0.03$) was found between the resting behavior of *A. fulica* and the ambient temperature, that is, the higher the temperature, the more frequent resting behavior is in *A. fulica*.

3. *Characteristics of the soil in the different subregions of Sergipe*

The most acidic soil in the dry season of 2019 was recorded in the plot in the municipality of Japaratuba (pH = 5.73), which is located in the East Sergipe subregion (Table 2). The most alkaline soil was recorded in Nossa Senhora da Glória (pH = 8.93), on the Western Plateau. In the rainy season of this year, the most acidic soil (pH = 4.6) was recorded in the plot in Itabaiana, in the Central Highlands, while the most alkaline was Porto da Folha (pH = 8.11) on the Western Plateau.

The plots were more neutral in the dry season of 2020, with a mean pH of 7.0±0.4 (range: 6.1–7.8) being recorded in the 24 plots. In the rainy season of this year, the most acidic soil (pH = 4.95) was collected from the plot in Nossa Senhora das Dores (Eastern Plateau), while the most alkaline (pH = 8.14) was in Propriá, in the Lower São Francisco subregion.

The Calcium concentrations of the soil also varied considerably among plots (Table 2). In the dry season of 2019, the lowest value (0.92 $cmol_c/dm^3$) was recorded in Cumbe, on the Eastern Plateau, while the highest concentrations were observed in Porta da Folha, on the Western Plateau (12.3 $cmol_c/dm^3$) and Barra dos Coqueiros, in the Greater Aracaju subregion (11.4 $cmol_c/dm^3$). In the rainy season of this year, the highest Ca concentration (11.3 $cmol_c/dm^3$) was also recorded in Porto da Folha. Even higher concentrations were recorded in 2020, reaching 17.1 $cmol_c/dm^3$ in Barra dos Coqueiros in the dry season, and 21.2 $cmol_c/dm^3$ in this same plot in the rainy season.

The quantity of organic matter also varied considerably among plots. In the dry season of 2019, the lowest concentration (OM = 4.8 g/dm^3) was recorded in Nossa Senhora das Dores (Eastern Plateau), while the highest value (54.7 g/dm^3) was observed in Riachão dos Dantas (South Central Sergipe).

Table 2. Variation among seasons in the characteristics of the soil (pH in water, calcium [$cmol_c/dm^3$] and organic matter, g/dm^3) recorded during the survey of *Achatina fulica* in the eight subregions of the Brazilian state of Sergipe, in 2019 and 2020.

Subregion/Municipality	pH	Calcium	Organic Matter	pH	Calcium	Organic Matter	pH	Calcium	Organic Matter	pH	Calcium	Organic Matter
	Season											
	Dry 2019			Rainy 2019			Dry 2020			Rainy 2020		
Greater Aracaju												
Aracaju	7,98	4,69	17,1	7,59	6,26	18,8	7,3	7,62	25,5	7,79	4,86	9,52
Barra dos Coqueiros	5,59	3,13	17,5	7,71	5,72	28,7	6,17	17,1	7,88	6,3	21,2	11,9
São Cristóvão	6,93	11,4	29,4	7,62	6,26	16,8	7,6	5,22	15,2	7,1	6,82	25,4
South Sergipano												
Estância	7,89	3,72	11	6,7	7,19	34,1	6,7	4,23	12,7	7,37	6,87	17,6
Boquim	7,69	6,07	22,2	7,38	5,06	19,1	7,16	7,02	26,5	7,81	6,87	17,6
Salgado	7,22	6,69	26,8	7,88	4,5	12,9	6,76	2,42	11	6,46	3,11	13,3
South Central												
Lagarto	6,83	3,86	16,3	6,7	7,19	34,1	6,12	2	5,26	7,58	7,05	14,9
Tobias Barreto	8,11	10,1	31,8	7,88	4,5	12,9	7,48	6,95	7,23	7,22	6,29	11,2
Riachão dos Dantas	7,93	9,85	54,7	7,38	5,06	19,1	7,39	10,2	22,1	7,93	6,31	11,17
Central Higlands												
Itabaiana	8,17	7,32	12,9	4,65	1,34	9,21	6,76	1,53	10,5	7,75	7,06	16,3
Areia Branca	7,7	7,31	20,1	7,31	5,2	15,3	7,22	7,79	21,1	7,59	9,4	19,6
São Domingos	8,89	3,56	5,79	7,78	4,37	14,5	6,83	5,11	13,9	7,54	5,71	14,6
East												
Rosário do Catete	8,71	2,45	5,49	6,86	7,58	26,1	7,25	5,02	16,2	6,59	3,64	15,8
Siriri	7,69	8,39	28,5	7,07	6,1	21,1	6,96	6,7	28,8	7,91	5,73	9,1
Japaratuba	5,73	3,54	12,6	6,63	4,82	24,4	7,17	5,1	15,4	7,73	5,57	15,4
Easten Plateau												
N. S. das Dores	6,54	2,23	4,85	8,09	4,47	8,09	7,44	3,20	7,44	4,95	1,37	5,89
Cumbe	8,88	0,92	5,57	7,71	5,72	11,2	-	-	-	6,55	2,17	7,86
Feira Nova	7,38	6,92	7,77	7,71	5,72	11,2	6,16	5,00	17,6	7,56	8,23	18,8
Western Plateau												
N.S. da Glória	8,93	3,8	7,89	8,05	5,49	13,4	7,63	11,8	17,8	8,08	8,28	12,6
Porto da Folha	6,8	12,3	9,71	7,79	11,3	16,1	7,07	10,0	8,96	8,11	8,18	6,65
Gararu	7,88	9,87	30,7	7,75	6,89	30,1	7,82	7,05	11,6	7,83	6,24	20,8
Lower São Francisco												
Neópolis	7,88	8,84	23,2	7,83	6,43	28,1	7,29	5,20	13,7	7,61	7,72	13,7
Propriá	8,16	8,58	21,7	8,19	5,08	15,5	7,81	12,2	11,1	8,14	4,66	8,36
Pacatuba	7,74	3,06	6,88	6,78	4,83	17,4	6,24	4,32	10,7	7,33	2,96	6,79

-No data collected.

In the rainy season of this year, the highest values (up to 34.1 g/dm^3) were recorded in Estância (South Sergipe) and Lagarto (South Central Sergipe). In the dry season of 2020, the highest value was recorded in Siriri, East Sergipe (28.8 g/dm^3), while in the rainy season, the highest value (25.4 g/dm^3) was observed in Barra dos Coqueiros (Greater Aracaju).

4. Allometric growth (b) of Achatina fulica by season

The body mass-total length relationship of the *A. fulica* specimens did not vary significantly ($p > 0.05$) between 2019 and 2020. However, higher *b* values were recorded in both dry seasons. Negative allometric growth ($b = 2.78$) was recorded in the dry season of 2019, while in the same season of 2020, growth was isometric ($b = 3.04$), based on the equation $Wt = 0.1463\ Lt^{3.04}$ representing, theoretically, the most adequate growth pattern, in which the shell grows in direct proportion to the body mass of the individual (Fig. 5, 6; Appendix S4).

5. Allometric growth of Achatina fulica in relation to the chemical conditions of the soil

In 2019, a negative correlation was found between the growth of *A. fulica* and the soil pH ($r = -0.4388$, $p < 0.05$), with allometric growth being greater with decreasing pH. This allowed us to use the soil pH to develop a predictive linear model for the identification of allometric growth in *A. fulica* ($R^2 = 0.156$, $p < 0.05$). In Sergipe, then, the more acidic the soil, the more allometric the growth of *A. fulica* ($b > 3$). However, *A. fulica* was more common, in general, on soils with a pH of 6.5–7.5, which is the ideal condition for isometric growth ($b = 3$). As the soil pH increases, the value of *b* decreases ($b < 3$), inverting the pattern observed where soils are more acidic, i.e., pH < 7 (Appendix S5). The frequency of *A. fulica* decreased significantly ($p < 0.05$) on increasingly alkaline (pH > 7) soils (Fig. 7). In 2020, however, no significant correlation ($p > 0.05$) was found between growth patterns and soil pH.

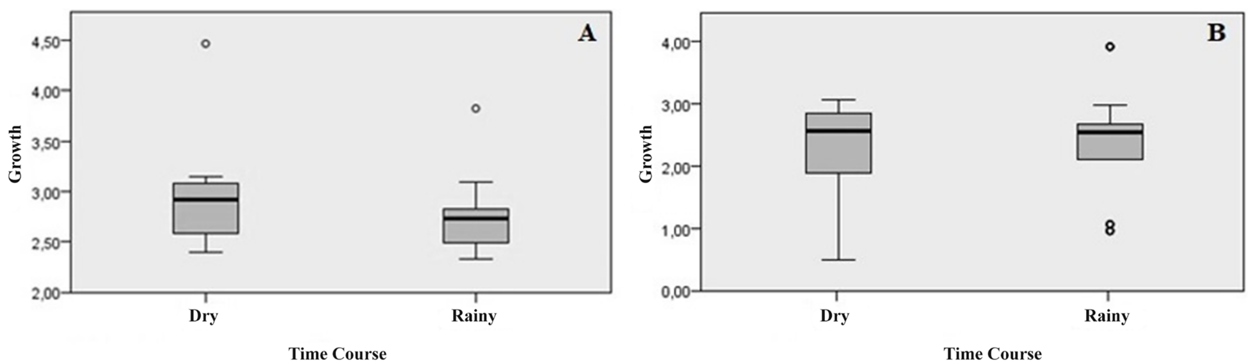

Figure 5. Allometric growth of *Achatina fulica* in the dry and rainy seasons of 2019(A) and 2020(B) in the eight subregions of the Brazilian state of Sergipe. * Kruskall-Wallis.

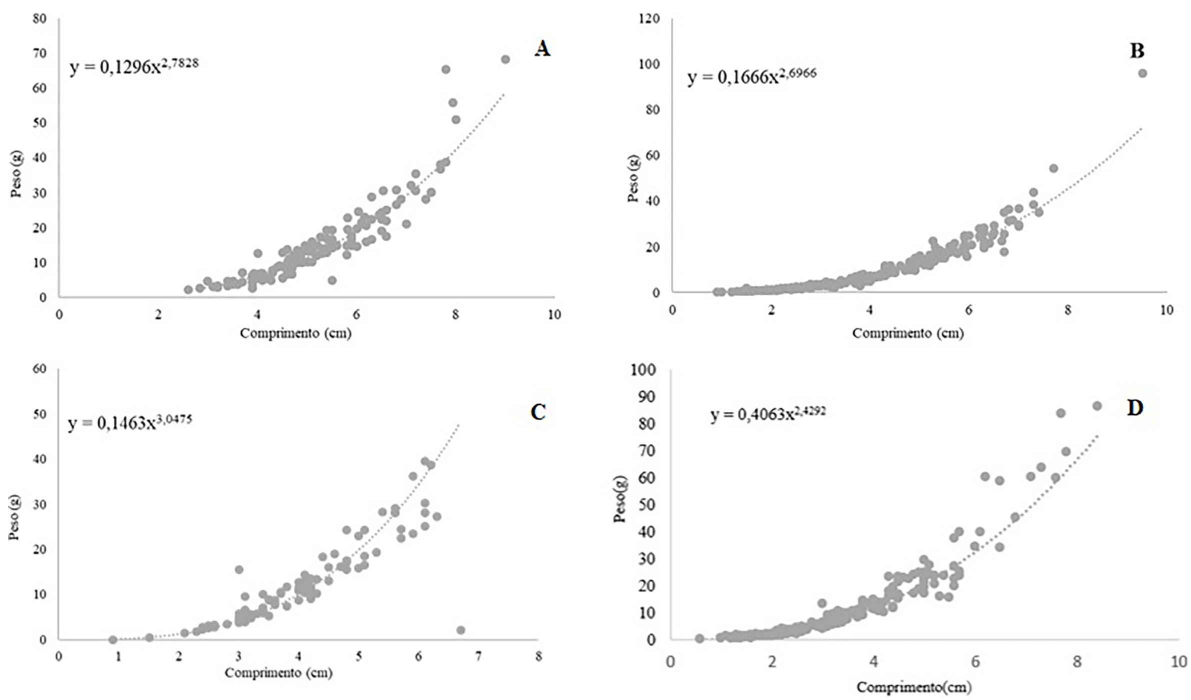

Figure 6. Seasonal variation in the allometric growth of *Achatina fulica* in the eight subregions of the Brazilian state of Sergipe, in 2019 and 2020. (A) 2019 dry period with negative allometric growth of *b*= 2.78. (B) 2019 rainy season with negative allometric growth of *b*= 2.69. (C) 2020 dry period with isometric allometric growth of *b*= 3.04. (D) Rainy season 2020 with negative allometric growth *b*=2.42.

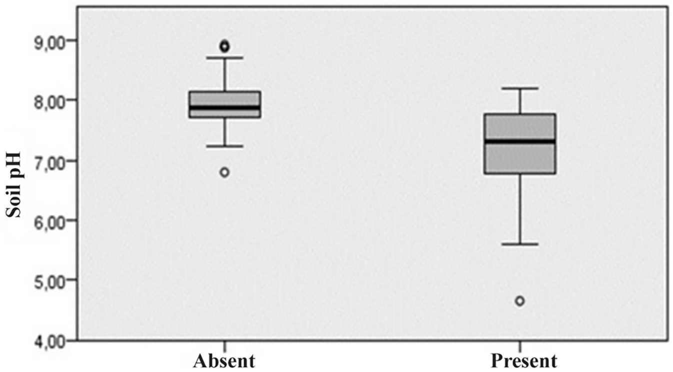

Figure 7. Presence of *Achatina fulica* in relation to the soil pH in the eight subregions of the Brazilian state of Sergipe, 2019.

6. *Relative condition factor of Achatina fulica in the different subregions of Sergipe*

In 2019, the relative condition factor varied significantly ($p = 0.02$) among the eight subregions of Sergipe. This parameter represents the theoretically ideal condition of an individual when its value is 1. In 2019 (Appendix S6), the highest proportion of *A. fulica* specimens with less than ideal body mass (KR <1) was recorded in the Greater Aracaju subregion (n = 29 snails, 41.4% of the total), while the ideal factor (KR = 1) was recorded most on the Western Plateau (n = 3, 75%) and specimens were mostly above the expected body mass (KR >1) in South Sergipe (n = 19, 48.7%).

Significant variation ($p = 0.01$) in the KR of *A. fulica* among subregions was also recorded in 2020 (Fig. 8). The largest proportion of individuals with lower than expected body mass (KR < 1) was recorded in the East Sergipe subregion (n = 41, 80.0%) and on the Western Plateau (n = 4, 57.1%). The highest proportion of snails with ideal body mass (KR = 1) was collected in the Lower São Francisco subregion (n = 7, 25.9%), followed by South Central Sergipe (n = 24, 25.8%). The largest proportion of snails above the expected mass (KR > 1) was recorded in South Sergipe (n = 39, 43.3%), followed by South Central Sergipe (n = 30, 32.3%).

Individual extremes in the relative condition factor were observed in different municipalities in the two seasons of 2019 (Table 3). In the dry season of 2019, the extreme values were recorded in the municipality of Japaratuba, in East Sergipe, where the lowest (KR = 0.34) and highest (KR = 1.99) values were recorded in the same plot. The latter value represents a body mass almost double that expected theoretically. In the rainy season of 2019, the lowest KR value (0.49) was recorded in the plot in Estância, in South Central Sergipe, that is, a body mass less than half that expected, while the highest value in this period was recorded in the same subregion, in Lagarto (KR = 3.16).

In the dry season of 2020, the lowest (KR = 0.17) and highest (KR = 2.36) values were both recorded in the same plot, in São Cristóvão, in the Greater Aracaju subregion. In the rainy season, the lowest KR value was recorded in Boquim (KR = 0.50), in South Sergipe, and the highest, in Riachão dos Dantas (KR = 1.94) in South Central Sergipe.

7. *Seasonal variation in the relative condition factor*

The relative condition factor of *A. fulica* in Sergipe did not vary significantly ($p > 0.05$) between the dry and rainy seasons in 2019. In 2020, by contrast, the condition factor was significantly higher ($p = 0.02$) in the dry season. In the rainy season of 2020, 223 snails were collected, of which, 139 (52.9%) had a body mass lower than expected (KR < 1). In the dry season, 90 *A. fulica* specimens were collected, of which, 20 (22.2%) had an ideal body mass (KR = 1) and 37 (41.1%) were above the expected mass (KR > 1). In both seasons, the larger the number of *A. fulica* specimens collected, the larger the KR values ($p = 0.01$), and in general, the higher the relative condition factor, the larger the proportion of snails observed at rest ($p = 0.001$).

8. *Relative condition factor of Achatina fulica, climatic variables and soil conditions*

The analysis of the relationship between the growth parameters and environmental variables (Table 4) indicated that soil pH was the only factor to have a significant influence on the growth of *A. fulica* ($p < 0.05$), and only in 2019. None of the other variables, including the soil pH in 2020, had any significant effect ($p > 0.05$) on the *A. fulica* growth parameters.

9. *Binary logistic regression associating climatic variables and soil chemistry*

The mathematical model created by the addition of variables such as "season (dry ou rainy), humidity, rainfall and soil pH" presented a significant relationship ($R^2 = 0.858$, $p < 0.001$) with the occurrence of *A. fulica* in the municipalities surveyed in the present study. The equation produced for the prediction of the occurrence of *A. fulica* in a given municipality is shown in Fig. 9. The reliability of this model was confirmed by the Kappa index ($k = 0.849$; $p < 0.001$), and the model provided a correct result for 94.1% of the sample tested (Appendix S7).

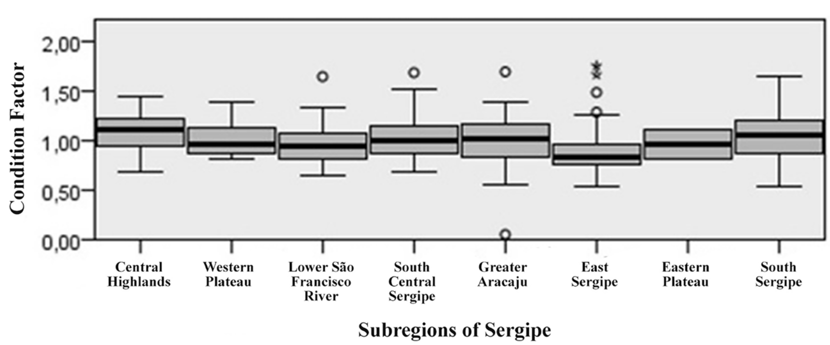

Figure 8. Relative condition factor of the *Achatina fulica* specimens collected in the eight subregions of the Brazilian state of Sergipe in 2020. * p = 0.001(Kruskal-Wallis).

Table 3. Variation in the relative condition factor (KR) of the *Achatina fulica* specimens collected in the different municipalities of the Brazilian state of Sergipe in 2019 and 2020.

Territories/municipalities	Min	Max	Mean±sd	Min	Max	Mean±sd	Min	Max	Mean±sd	Min	Max	Mean±sd
	2019.1			2019.2			2020.1			2020.2		
Greater Aracaju												
Aracaju	0,78	1,18	1,00±0,13	0,84	1,10	1,00±0,09	0,82	1,14	1,00±0,11	0,80	1,33	1,01±0,14
São Cristóvão	0,75	1,47	1,01±0,17	0,75	1,21	1,00±0,13	0,17	2,36	1,12±0,47	0,81	1,33	1,01±0,17
Barra dos Coqueiros	0,94	1,08	1,00±0,05	0,81	1,25	1,01±0,16	1,39†	1,39†	1,39†	0,66	1,32	1,01±0,16
South Sergipe												
Estância	-	-	-	0,49	1,24	1,01±0,13	0,81	1,51	1,00±0,15	0,52	1,77	0,99±0,27
Boquim	-	-	-	0,96	1,03	1,00±0,02	0,83	1,12	0,97±0,20	0,50	1,66	0,97±0,39
Salgado	-	-	-	1,13†	1,13†	1,13†	-	-	-	1,11†	1,11†	1,11†
South Central												
Lagarto	0,71	1,36	1,01±0,19	0,63	3,16	1,02±0,33	0,82	1,17	1,00±0,11	0,73	1,26	1,01±0,12
Tobias Barreto	-	-	-	-	-	-	-	-	-	-	-	-
Riachão dos Dantas	-	-	-	0,91	1,18	1,00±0,08	0,88†	0,88†	0,88†	0,75	1,94	1,02±0,22
Central Higlands												
Itabaiana	0,94†	0,94†	0,94†	0,75	1,20	1,00±0,14	-	-	-	0,85	1,16	1,01±0,12
Areia Branca	0,83	1,13	1,00±0,06	0,92	1,11	1,00±0,60	0,80	1,16	1,01±0,15	0,88	1,21	1,00±0,09
São Domingos	-	-	-	-	-	-	-	-	-	-	-	-
East												
Rosário do Catete	-	-	-	0,84	1,23	1,00±0,09	1,00	1,00	0,99±0,00	0,74	1,67	1,03±0,27
Siriri	0,47	1,64	1,07±0,40	0,91	1,07	1,00±0,69	-	-	-	0,70	1,44	1,03±0,26
Japaratuba	0,34	1,99	1,02±0,24	0,50	1,47	0,95±0,16	0,97	1,04	1,00±0,33	0,71	1,21	1,01±0,17
Easten Plateau												
N. S. das Dores	0,80	1,38	1,01±0,19	0,89	1,17	1,00±0,80	0,82	1,17	1,40±0,11	0,90	1,16	1,00±0,11
Cumbe	-	-	-	-	-	-	-	-	-	-	-	-
Feira Nova	-	-	-	-	-	-	-	-	-	-	-	-
Western Plateau												
N.S. da Glória	-	-	-	0,95	1,05	1,00±0,04	-	-	-	1,00	1,00	1,00±0,00
Porto da Folha	-	-	-	-	-	-	-	-	-	-	-	-
Gararu	-	-	-	-	-	-	-	-	-	-	-	-
Lower São Francisco												
Neópolis	-	-	-	0,84	1,12	1,00±0,10	-	-	-	0,81	1,65	1,02±0,23
Propriá	-	-	-	0,83	1,12	1,00±0,13	0,81	1,27	1,00±0,11	0,85	1,14	1,01±0,13
Pacatuba	-	-	-	0,90	1,10	1,00±0,08	-	-	-	-	-	-

† Only one *A. fulica* specimen collected in this season. – No *A. fulica* specimens collected in the plot in this season. Min = Minimum, Max = Maximum, SD = Standard Deviation.

Table 4. Correlations between environmental factors (soil and climatic parameters) and the growth and relative condition factor (KR) of the *Achatina fulica* specimens collected in the present study in the Brazilian state of Sergipe, in 2019 and 2020.

CORRELATION/YEAR		Variable								
		pH	Calcium	Organic matter	Humidity (%)	Humidity (variation)	Temperature ºC	Temperature (variation)	Rainfall (mm)	Rainfall (variation)
Growth (b) 2019	r	-0.438	-0.252	-0.186	0.065	-0.203	0.207	0.222	-0.272	-0.280
	p	*0.029	0.224	0.348	0.759	0.330	0.320	0.287	0.188	0.174
Condition factor (KR) 2019	r	0.072	0.209	0.224	-0.082	0.164	0.237	0.210	-0.109	-0.146
	p	0.733	0.316	0.283	0.695	0.433	0.197	0.314	0.603	0.486
Variation in the KR 2019	r	-0.322	0.104	0.265	0.077	1.105	0.230	0.104	-0.049	-0.053
	p	0.117	0.622	0.201	0.716	0.618	0.270	0.622	0.817	0.802
Growth (b) 2020	r	-0.040	0.104	0.072	-0.040	-0.043	0.055	-0.192	0.132	0.209
	p	0.764	0.430	0.586	0.775	0.759	0.690	0.391	0.350	0.134
Condition factor (KR) 2020	r	-0.017	0.061	0.158	-0.186	-0.193	-0.064	-0.167	0.086	0.003
	p	0.906	0.666	0.263	0.210	0.194	0.662	0.257	0.570	0.984
Variation in the KR 2020	r	0.105	0.020	0.013	0.037	0.062	-0.121	-0.119	0.006	-0.121
	p	0.429	0.080	0.925	0.789	0.659	0.381	0.391	0.969	0.387

r = Pearson's correlation coefficient. * significant correlation ($p < 0.05$).

$$Presence\ of\ "Achatinafulica = \frac{e^{(-117.502+[30.548]*a+[0.300]*b+[67.965]*c+[8.307]*d}}{1+e^{(-117.502+[30.548]*a+[0.300]*b+[67.965]*c+[8.307]*d}}$$

Figure 9. Equation of the mathematical model developed to predict the occurrence of *Achatina fulica* in the municipalities of different subregions of the Brazilian state of Sergipe, based on the climatic variables and soil pH recorded in 2019 and 2020. Where *a* = the season, *b* = relative humidity, *c* = rainfall, *d* = soil pH, and *e* = Euller's number.

Discussion

Of the 19 municipalities notified in Sergipe by the State Committee for the Control of African Snails, seven of these are not part of the studied sample (Arauá, Capela, Maruim, Santa Luzia do Itanhi, Umbaúba, Muribeca and Itaporanga d'Ajuda) (IBAMA, 2021). The 18 sites recorded here brings the total number of municipalities in Sergipe known to be infested with *A. fulica* to 25 (see also Carvalho et al. 2012, Ramos-de-Souza et al. 2018, Silva et al. 2020).

In the dry season, *A. fulica* was recorded in nine plots in 2019 and in 12 plots in 2020. These plots were located primarily in the humid coastal and central highland climatic zones (Aragão et al. 2013), which is probably the principal factor determining the presence of the snails in the plots in the dry season.

The vast majority of the *A. fulica* specimens collected during the present study were either juveniles (n = 423, 57.5%) or young adults (n = 282, 38.3%). The gregarious type of behavior pattern was the most commonly observed, and resting (n = 649, 88.2%) was likely a response to the climatic conditions that predominate during the dry season. Fischer et al. (2012) studied the gregarious behavior of *A. fulica* in the field and the laboratory, and found that this behavior is more frequent in urban areas, and more frequent in the infants and juveniles during the dry season. Cook (2001) concluded that one of the principal advantages of aggregation in these snails is the creation of a humid microclimate, which minimizes dehydration by restricting the surface area of the body exposed to evaporation. On Christmas Island, in the eastern Indian Ocean, O'Loughlin & Green (2017) observed that 96.9% of the *A. fulica* specimens were resting during the day, whereas at night, 51.6% were active and on the soil. As the surveys in the present study were conducted during the morning, the timing of the specimen collection may have determined the large number of resting *A. fulica* specimens found in the plots.

The significant association found between the number of *A. fulica* and rainfall would likely account for the larger numbers of snails collected during the rainy seasons. In the metropolitan region of Aracaju, in Sergipe, Silva et al. (2020) found that rainfall had a positive influence on the frequency of *A. fulica*, a pattern also observed in Nigeria by Onyshi et al. (2018), who observed that the conditions of high humidity and rainfall were associated with an increase in the population of *A. fulica*. Despite this, the largest *A. fulica* specimens were collected during the dry season in the present study, reaching a mean of length of 5.36±1.11 cm and mass of 15.87±9.85 g. This may be accounted for by the fact that, even at high temperatures and under low rainfall, *A. fulica*, in particular the larger individuals, use specific behavioral strategies to cope with the relative humidity (Pilate et al. 2017).

The plots surveyed in the present study all presented similar general characteristics, however, that is, vacant lots containing domestic refuse and rubble. The *A. fulica* specimens were encountered under dense tufts of herbaceous vegetation, dead leaves, in piles of litter, and near walls. Silva et al. (2020) found that *A. fulica* was five times more likely to be present in areas with domestic refuse than clean sites. It is important to note, in this case, that three of the study plots, in Aracaju, Barra dos Coqueiros and Nossa Senhora das Dores, did not contain litter at any time during the study period, but in this case, the *A. fulica* specimens were found in the most humid parts of the plot, including tufts of herbaceous vegetation, ornamental plants, tree trunks, shaded locations near walls, and under bricks. Like other land snails, *A. fulica* prefers humid environments and seeks them out actively.

In terms of body size, Civeyrel & Simberloff (1996) identified three phases in the establishment of *A. fulica* in new areas: (i) an initial, exponential phase, characterized by the presence of large, robust individuals, (ii) a second, establishment phase of variable duration, during which the population expands, and (iii) a declining phase, dominated by small individuals with fragile shells. In Sergipe, the survey data indicate that the *A. fulica* populations are currently in the second phase, which is dominated by the presence of juveniles and young adults. This was the scenario observed in the sample plots, and a similar situation has been observed in other urban and peri-urban areas in Sergipe, given the accentuated dispersal capacity of this snail.

The growth data indicate that the most favorable conditions for the growth of *A. fulica* in Sergipe were found in the dry season, in both 2019 (b = 2.78) and in 2020 (b = 3.04), when growth was isometric. This may be accounted for by the relatively high calcium concentrations and the large amounts of organic matter found in the plots in the dry seasons of both years. The soil pH in the rainy season of both 2019 and 2020 was also more acidic, which was associated with negative allometric growth. The negative trends in this growth parameter may be related to a lack of food, predation pressure or even the parasitic infections known to affect *A. fulica* (Almeida 2014). The pH is an indicator of the general chemical conditions of the soil (Silva et al. 2005), with more acidic conditions reflecting a lack of bases, including calcium. The physical and biological properties outlined above may also have had a direct effect on the body length, mass, shape, and shell color of the *A. fulica* specimens (Fischer et al. 2010).

Achatina fulica is tolerant of a wide range of abiotic factors, and is thus able to occupy a diversity of natural habitats and anthropogenic environments (Fisher & Colley 2005). In the present study, a negative correlation ($r = -0.4388$, $p < 0.05$) was found between the soil pH and the allometric growth of *A. fulica*, which supported the inclusion of the soil pH in the predictive linear model of the allometric growth of *A. fulica*. The more acidic the soil, the greater the allometric growth of *A. fulica in* Sergipe ($b > 3$).

This snail is most frequent on soils with a pH of 6.5–7.5, which is the ideal range for isometric growth ($b = 3$). There was also a significant decline ($p < 0.05$) in the number of snails on more alkaline soils.

Raut & Barker (2002) found that the infant and juvenile *A. fulica* specimens tend to have more contact with the soil. In the present study, we can conclude that these individuals may have been affected more negatively by extremes (acidic or alkaline) of soil pH, given that they were usually encountered half-buried in the soil. In the municipality of Valença, in the Brazilian state of Rio of Janeiro, Durço et al. (2013) found a significant negative correlation between the age of the *A. fulica* specimens, and the time spent buried in the soil. Costa (2010) observed a similar pattern, with most of the juvenile snails being buried, while the young adults were observed at rest on the ground and in the bushes. This is consistent with the observations of Almeida et al. (2016), who found that only the infants and juveniles were completely buried in the soil. Fisher (2009) recorded the same scenario in the laboratory, under experimental conditions.

In Sergipe, we recorded the greatest frequency (n = 282, 38.3%) of young adult snails (4.01–7.0 cm) within the amplest range of soil pH (4.5–8.2). This is probably why growth was more allometric in more acidic soils, given that the young adults and adults (> 7.0 cm) are able to rest on other types of substrates. This behavior is probably a strategy that enables the snails to avoid adverse soil conditions, proliferate and develop optimally. In the Brazilian state of Paraná, Fischer & Colley (2005) found that *A. fulica* specimens of different sizes (shell length) rested in different sites, with the larger snails tending to be more frequent on plants and other organic substrates. Pilate et al. (2017) concluded that *A. fulica* adopts specific behavioral strategies to guarantee its survival, such as the retraction of the soft cephalopodal mass and the avoidance of unfavorable sites.

These snails may also present exploratory behavior to identify resources and other features of their environment, given that they have well-developed chemoreceptors, with neurosensory cells on the surface of the body related to environmental perception, feeding, reproductive communication and aggregation (Chase & Tolloczko 1985). In Japan, Tomiyama (1992) investigated the homing behavior of *A. fulica*, and found that the young adults disperse constantly, and over much larger distances than the other individuals, while the adults change resting sites only rarely. Tomiyama & Nakane (1993) found that the young adults produce only sperm, while the mature adults are capable of producing both spermatozoa and ova. This may determine the more ample ranging of the young adults, which disperse in search of reproductive partners, while the adults do not need to disperse to copulate, and may thus remain at rest for much longer periods.

A significant correlation was found between resting behavior and the relative condition factor of *A. fulica*, that is, the higher the relative condition factor, the more these snails remain at rest. Significant differences ($p < 0.05$) were also found in the condition factor of *A. fulica* among the eight subregions of Sergipe. The body mass-length relationship of a species provides important insights into the influence of environmental conditions on the developmental stages of the organism, through estimates of the relative condition factor (Araújo et al. 2011).

Theoretically, the relative condition factor (KR) represents the development as ideal when equal to 1, or otherwise, when the values of KR deviate significantly from 1 (Albuquerque et al. 2009). In 2019, for example, the *A. fulica* specimens presented reduced body mass (KR <1) in the Greater Aracaju subregion, but increased mass (KR >1) in South Sergipe. The scenario observed in Greater Aracaju may have been related to the fact that 21 of the specimens were in a condition of estivation, which may reflect the lack of food in the plot, resulting from the prolonged drought and high temperatures. Estivation is considered to be the most critical phase of the development of *A. fulica* (Raut & Barker 2002), which estivates during the driest parts of the year, when it may secrete an epiphragm, a calcified structure that seals off the shell opening to prevent dehydration (Almeida et al. 2016). During the dry season, then, the number of active snails in an area may decline significantly, while the snails become more active when conditions become more humid (Fischer 2009; Durço et al. 2013). In South Sergipe, the condition factor of *A. fulica* was higher than expected (KR >1), which may be related to the large quantities of refuse and decomposing organic matter in the plots in the municipalities of Estância and Boquim. The soil parameters in Estância were especially favorable during this dry season, with the second highest concentration of organic matter recorded in 2019 (34.1 g/dm^3), as well as a pH of 7.9 and of 7.9 $cmol_c/dm^3$ calcium, which may have contributed to the wellbeing and development of the snail during this period.

In 2020, snails with ideal body mass (KR = 1), were collected in the plots of the Lower São Francisco subregion, while *A. fulica* specimens above the ideal mass (KR >1) were collected in South and South Central Sergipe, with large numbers of snails in this condition. These findings may reflect the conditions in these areas, in particular the Lower São Francisco subregion, where the mean monthly temperature, relative humidity and rainfall were all relatively high during the period when the *A. fulica* specimens were collected. Similarly, the South Central and South Sergipe subregions had high temperatures (28–30°C) and relative humidity (77–81%), as well as frequent precipitation. In India, Sarma et al. (2015) modelled the niche of *A. fulica* and concluded that areas with a hot climate and frequent rainfall have a larger risk of invasion by this species. While this snail loses water through its tegument, it is also able to rehydrate itself through the contact between the tegument and the immediate environment (Cook 2001). Further studies of the development of *A. fulica* and its relationship with climatic and environmental variables will be essential for a better understanding of the factors that influence the development and wellbeing of *A. fulica* (Ghisi et al. 2012).

Predictive environmental models can be used to evaluate how a species will move in both time and space (Albuquerque et al. 2009), and the present study proposes a predictive model for the occurrence of *A. fulica*. The use of predictive environmental models can provide important, systematic insights into the factors that determine observed patterns of dispersal (Johnson & Omland 2004). In the present study, the binary logistic regression returned a significant correlation ($R^2 = 0.858$, $p < 0.01$), representing 85% of our sample from the Brazilian state of Sergipe.

This approach provides an important tool for the projection of future scenarios on the potential occurrence of *A. fulica* in relation to climatic variables and soil pH. Predictive models of this type can be applied to other areas, in particular in Brazil, where *A. fulica* is established over a wide area, and in other tropical and subtropical countries. The predictive model developed in the present study had a 94.1% hit rate for the samples collected in the eight subregions of Sergipe, with a high degree of reliability (Kappa index = 0.849).

Conclusions

This is the first ecological study of *A. fulica* to analyze systematically the body mass-length relationship and relative condition factor in the context of climatic variables and the chemical parameters of the soil, to determine the development pattern and welfare of this snail in the Brazilian state of Sergipe. The analyses also permitted the development of a mathematical model that can be used to determine the potential the presence or absence of *A. fulica* from other areas.

Populations of *A. fulica* were identified in 18 of the 24 municipalities surveyed in the eight subregions of the Brazilian state of Sergipe. These populations were dominated by juveniles and young adults. The patterns observed in the body mass-length relationship and relative condition factor in the different study populations indicate that the development of *A. fulica* is positive in the dry season. The data also indicate that the soil pH may have had the greatest negative effect on the infant and juvenile *A. fulica*, given that these specimens were typically covered in soil when collected. As they are less prone to seek refuge in the soil, the young adult and adult snails may have interacted much less with the substrate, as they were typically found resting on other types of surface.

It is important to note that the Kappa index showed that the variables tested by the predictive model were very reliable (k = 0.849), with a hit rate of 94.1%. The present study also elaborated a predictive mathematical model that should provide a useful analytical tool for the evaluation of other environmental scenarios, based on the biotic and abiotic factors associated with the Giant African land snail, climatic variables and the physicochemical parameters of the soil. These findings should provide fundamental guidelines for the development and improvement of measures for the control of *A. fulica* populations, contributing to improve both public health and environment health.

Supplementary Material

The following online material is available for this article:

Appendix S1 - Location of the 24 fixed plots established for the collection of *A. fulica* specimens in the eight subregions of the Brazilian state of Sergipe, in 2019 and 2020.

Appendix S2 - The field chart used in the present study and the characteristics of the study plots surveyed in the Brazilian state of Sergipe in 2019 and 2020.

Appendix S3 - Layout of the points for the collection of soil samples in the 20 m x 10 m plots surveyed for the presence of *A. fulica* populations in the Brazilian state of Sergipe.

Appendix S4 - Equations and the *a* and *b* parameters of the body mass-length relationships of the *A. fulica* specimens collected in the dry and rainy seasons in the eight subregions of the Brazilian state of Sergipe.

Appendix S5 - Allometric growth of *Achatina fulica* compared with the pH soil recorded in the eight subregions of the Brazilian state of Sergipe, 2019.

Appendix S6 - Relative condition factor of the *A. fulica* specimens collected in the eight subregions of the Brazilian state of Sergipe in 2019 and 2020.

Appendix S7 - Evaluation of the reliability of the mathematical model in comparison with the results of the surveys of the *Achatina fulica* populations conducted in the eight subregions of the Brazilian state of Sergipe in 2019 and 2020.

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Author Contributions

Guilherme Mota da Silva: Substantial contribution in the concept and design of the study; Contribution to data collection; Contribution to data analysis and interpretation; Contribution to manuscript preparation; Contribution to critical revision, adding intelectual content.

Silvana Carvalho Thiengo: Substantial contribution in the concept and design of the study; Contribution to critical revision, adding intelectual content.

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Verônica de Lourdes Sierpe Jeraldo: Substantial contribution in the concept and design of the study; Contribution to critical revision, adding intelectual content.

Conflicts of Interest

The authors declare that they have no conflict of interest related to the publication of this manuscript.

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