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Water temperature and microenvironmental factors predict the presence and detection of the snail host of *Fasciola hepatica* in Andean Patagonia

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ABSTRACT

The transmission of *Fasciola hepatica* occurs only where there are -or recently were- aquatic or amphibious snails of the Lymnaeidae family, the intermediate host of this parasite. Direct detection of these snails is time-consuming and imprecise, hindering accurate and detailed mapping of transmission risk. To identify which microenvironmental factors could be used as proxies for the occurrence of the lymnaeid snail *Galba viator*, a major intermediate host in South America, a total of 183 1-m^2 quadrants across diverse water bodies in an endemic area in Andean Patagonia were manually timed-searched for snails and microenvironmental variables were registered. Data was analyzed using a Bayesian hierarchical occupancy model that assessed the effects of the microenvironmental variables on the presence of snails while considering imperfect snail detection. The model estimated that *G. viator* predominantly inhabits shallow aquatic environments, in the presence of grasses, where snails of the genus *Biomphalaria* are also detected, and with scarce tree canopy cover. Physical factors affecting occupancy presumably act as proxies for the average water temperature, while the temperature at the time of sampling was found to affect snail detectability. The identified variables are easy, fast, and inexpensive to measure, and can complement management decisions and risk maps based on coarser remote-sensing data, particularly relevant in a context of growing resistance to anthelminthic drugs.

1. Introduction

The parasite *Fasciola hepatica* (Trematoda, Digenea) causes fasciolosis, a zoonotic disease that affects herbivorous and omnivorous mammals such as livestock, wild mammals, and humans acting as definitive hosts (Hurtrez-Boussès et al., 2001; Mas-Coma et al., 2005). The disease causes global economic losses due to the deficiencies in livestock production (Charlier et al., 2014; May et al., 2020; Mehmood et al., 2017; Mezo et al., 2011). It also represents a serious public health problem in certain areas of South America, where it can reach >50% prevalence in humans (Mas-Coma et al., 2014, 2009; World Health Organization, 2013). Furthermore, infection in wildlife mammals can have implications for their health and eventually their conservation, as well as the health of their ecosystems, posing a challenge in protected natural areas (Chang Reissig et al., 2018; Cuervo et al., 2015; Gayo et al., 2011; Issia et al., 2009; Mezo et al., 2013; Shimalov and Shimalov, 2000). Transmission occurs only where there are -or recently were- snails of the Lymnaeidae family, intermediate hosts in the life cycle of *F. hepatica*. These aquatic or amphibious snails develop asexual stages of the parasite, which then emerge and become encysted metacercariae in the vegetation that livestock, wildlife, and humans may ingest, acquiring the infection (Dalton, 2021). Thus, strategies based on environmental control or livestock management can benefit from spatially detailed information on snail occurrence (Min et al., 2022; Standley et al., 2013).

Several models, based on remote sensing data, have been developed that allow the study of different helminth-borne diseases (Bennema et al., 2011; Sun et al., 2020; Walz et al., 2015). This conveniently allows to assess wide regions identifying risk areas without the hassle of field work. However, the fine-grained heterogeneity related to the presence

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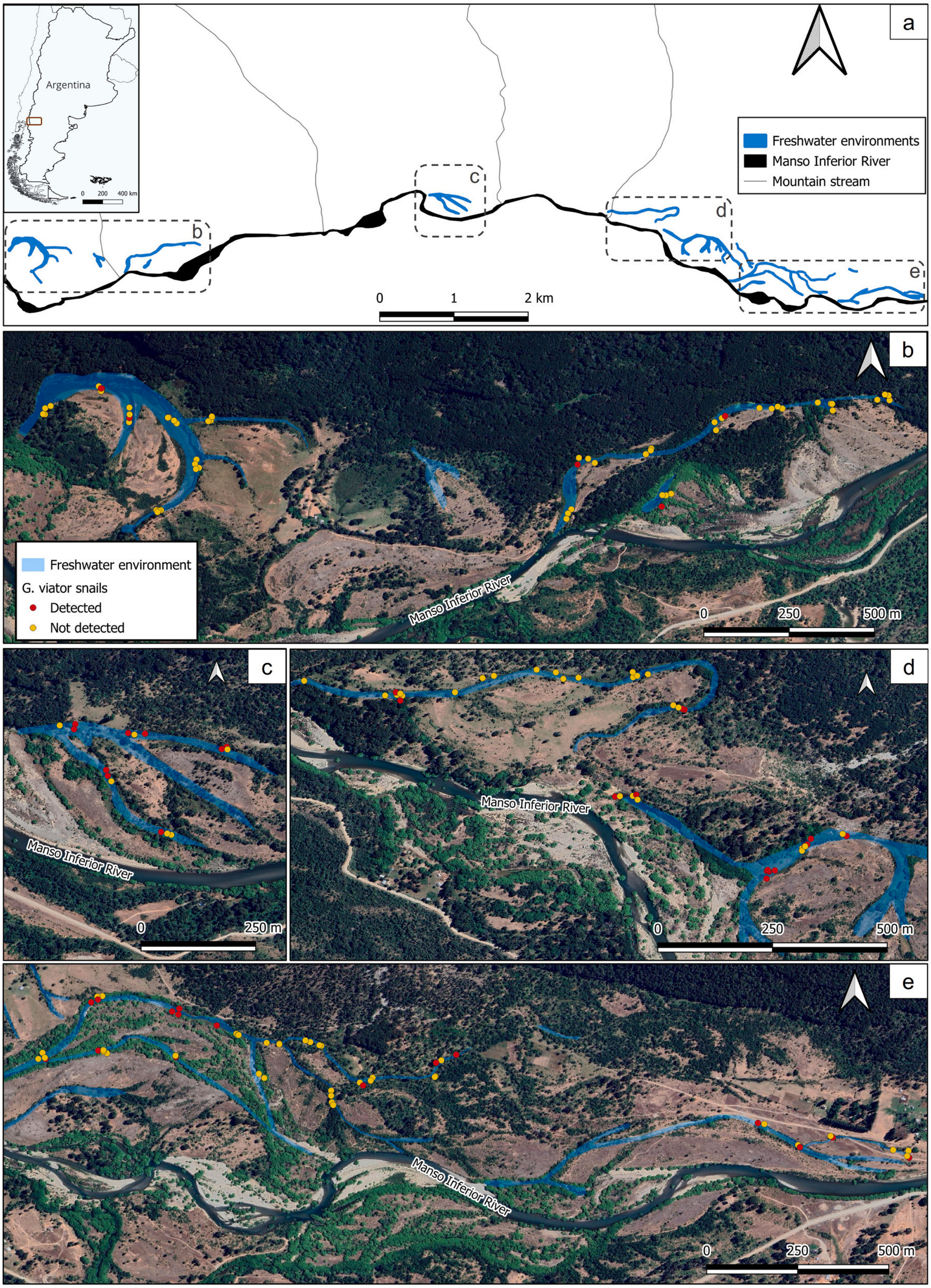

Fig. 1. Maps of the study area in the valley of the Manso Inferior River, Andean Patagonia. (a) General map displaying the freshwater bodies used for sampling design in relation to the Manso Inferior River and other rivers and mountain streams. Dashed line boxes indicate the sites shown in expanded view in the subsequent panels. (b-e) Detailed views of the map displaying the location of the quadrants surveyed in the freshwater environments, indicating the detection (red) or not (yellow) of the lymnaeid snail *G. viator*.

of freshwater snail intermediate host is missed as it is not possible to establish which specific waterbodies are risky within risk areas (Fuentes, 2006). The most direct method, i.e., snail search, is inevitably manual, very time-consuming, and only provides information about the site inspected at the time of inspection. Microenvironmental variables can be the link between both scales and approaches, as they capture what the snails actually experience from the environment and can be easily measured. It has been demonstrated that the development and establishment of snails, as well as the free-living stages of the parasite, depend on humidity and temperature conditions (Aziz and Raut, 1996; Claxton et al., 1999; Gérard, 2001). Also, the spatial distribution of snails in the environment might be influenced by additional ecological factors which may vary at different scales, thereby defining areas of higher risk of transmission within a given locality (Min et al., 2022; Roessler et al., 2022; Yigezu et al., 2018). Lastly, water temperature is a key factor as it strongly conditions snail development and, on a shorter time scale, could have an important effect on the detection of lymnaeid snails (Bargues et al., 2021).

Galba viator -also referred to as *Galba viatrix* or *Lymnaea viatrix* or *Lymnaea viator* (Correa et al., 2010; Thompson, 2011)- is one of the main intermediate hosts of *F. hepatica* in South America, being a key species associated with endemic areas of human populations (Bargues et al., 2007; Vázquez et al., 2023). In Argentina, it extends south, being the only confirmed intermediate host in Patagonia (Kleiman et al., 2007, 2004; Olaechea, 2007; Rubel et al., 2005; Soler et al., 2023) despite other lymnaeid species also being present further south in Chubut and Santa Cruz provinces (Carvalho et al., 2004; Duffy et al., 2009). In the Patagonian Andean valleys, where resistance of the parasite to anthelmintics in livestock has been reported (Larroza et al., 2023; Olaechea et al., 2011), the population dynamics of this amphibious snail has been shown to be influenced by the pronounced annual temperature seasonality, rather than by humidity (Kleiman et al., 2007). There are still no ecological studies on *G. viator* that evidence how microenvironmental factors -biotic and abiotic- of waterbodies relate to the occurrence of the snail. Thus, the aim of the current study is to quantify the effects of microenvironmental factors on the occupancy of freshwater sites by *G. viator* and identify which of those factors could be used as proxies for snail occurrence.

2. Materials and methods

2.1. Study area

The study was conducted in the valley of the Manso Inferior River (41°35S, 71°35'W), a mountainous area in the southwest of Rio Negro Province in Argentine Patagonia (Fig. 1a). The mean temperature is 15.2 °C in January, 3.8 °C in July and mean annual temperature is 9.3 °C. Most precipitation occurs between April and September with an annual average of 1255 mm (Fick and Hijmans, 2017).

The explored area is in the north riverside of the Manso Inferior River, southern limit of the Nahuel Huapi National Park. The vegetation of the valley is heterogeneous, creating a patchwork environment as a result of human resource exploitation (Madariaga, 2019, 2018). The local rural inhabitants rear livestock, mostly cattle and sheep, and grow vegetables and fruits, primarily for self-consumption and, to a lesser extent, local trade (Madariaga, 2019). Both the National Parks Administration and locals have reported *F. hepatica* infections in livestock. The combination of extensive animal farming and lack of resources make it difficult to regularly apply antiparasitic drugs to livestock and to alternate grazing areas. Furthermore, numerous wild species that could serve as reservoir hosts cohabit with these domestic species, including the European brown hare (*Lepus europaeus*), wild boar (*Sus scrofa*), red deer (*Cervus elaphus*), and nutria (*Myocastor coypus*).

There are numerous freshwater bodies that are potentially suitable for the lymnaeid snails to develop such as streams, permanent ponds, and temporary ponds. These freshwater environments are influenced by seasonal changes in temperature and rainfall and their flow can decrease -or they can dry up completely- in summer due to high temperatures and low rainfall. Conversely, they can become saturated and interconnected when precipitation and thaw are plentiful.

2.2. Sample design

The survey was conducted between January 7th and 14th, 2022, usually a time of high lymnaeid abundance, making it more likely to find the snails (Kleiman et al., 2007). Previously, we integrated information from satellite maps, on-foot surveys of the study area, and previous descriptions of suitable habitats for lymnaeids (Boray, 1969; Kleiman et al., 2007, 2004; Standley et al., 2013) to create a map of freshwater environments for exploration (Fig. 1a). Using this map, we established sampling points every ~200 m.

2.3. Data collection

During fieldwork, we delineated 3–4 quadrants of 1-m^2 at each sampling site. Each quadrant was explored for 15 min by a single person manually or with the aid of a metal mesh strainer with a 1-mm wide pore to find lymnaeid snails (Prepelitchi, 2009; Rabinovich, 1980). For each quadrant, the detection and number of lymnaeid snails, quadrant coordinates, and 14 variables associated with biotic and abiotic factors were recorded (Table 1). The temperature and pH of the quadrant water were assessed using a portable pH meter (Adwa AD 12 Pocket Tester Waterproof Multiparametric iP67 pH/T°). The depth of the water column was determined with a metal measuring tape, measuring vertically from the bottom to the water surface. To assess the speed of water, we measured the time it took for a small floating object (a leaf) to move 1 m ahead on the water surface. The presence and coverage of vegetation were assessed visually, classifying the existing vegetation into three main groups: i) aquatic plants, emergent or submerged aquatic macrophytes strictly related to the presence of freshwater; ii) grasses, herbaceous plants related to terrestrial ecosystems but found within the quadrants of explored freshwater bodies; and iii) algae, generally filamentous, observed forming thread-like layers in the water (Schneider et al., 2018). Canopy coverage was determined with the assistance of the CanopyCapture mobile application (Lusk, 2022), utilizing the same device for taking the photographs and analyzing them. Turbidity was assessed visually and categorized into two groups: "clear" if water evidenced no suspended sediments or particles, otherwise, "turbid." Similarly, soil type was classified as either "mud" (i.e., substrate with no

Table 1
Biotic and abiotic factors recorded at each sampling site and evaluated in the model. Numerical and categorical variables, measurement unit, median, the 80% interquantile range (Q10-90%) of the observed numerical variables and number of quadrants (n) in which categorical variables are detected.

Group	Variable (Unit)	Median (Q 10–90%)	n
Physical	Water teperature (°C)	19.1 (13.5–26.5)	-
	Water pH	8.14 (7.46–9.06)	-
	Water depth (cm)	7.0 (1.6–17.0)	-
	Speed of water (m/s)	0.00 (0.00–0.13)	-
	Vegetation cover (%)	40 (10−90)	-
	Canopy cover (%)	0 (0−75)	-
	Turbidity (Clear = 0 / Turbid = 1)	-	169/14
	Soil type (Mud = 0 / No mud = 1)	-	169/14
Vegetation type	Aquatic plants (Absence = 0 / Presence = 1)	-	70/113
	Grasses (Absence = 0 / Presence = 1)	-	67/116
	Algae (Absence = 0 / Presence = 1)	-	153/30
Other mollusks	*Biomphalaria* (Absence = 0 / Presence = 1)	-	150/33
	Other gastropods (Absence = 0 / Presence = 1)	-	94/89
	Pisidium (Absence = 0 / Presence = 1)	-	119/64

visually distinguishable particles) or “no mud,” with medium- to coarse-grain particles, such as sandy or rocky soil. Additionally, during searches for lymnaeid snails, other mollusks were collected. The collected snails and other mollusks were placed in labeled plastic containers filled with water from the environment and transported to the laboratory. In the case of lymnaeid snails, molecular identification has been previously conducted using specimens from the same sites, revealing that the only species present in these locations was *Galba viator* (Soler et al., 2023). For the present study, identification of *Galba viator* and other mollusks (at the genus level) was carried out based on morphologic characteristics of the shell shape (Collado et al., 2020, 2014; Gutiérrez Gregoric et al., 2014; Ituarte, 2007; Paraense, 1976). Identification was performed using a stereoscopic magnifying glass (40X).

2.4. Data analysis

To assess the effects of environmental factors in the presence of lymnaeid snails in microsites of freshwater environments, we developed an occupancy model. This is a hierarchical linear model which consists of two linked parts: the biological process and the observational process. The latter aims to account for false absences in the data, i.e., the possibility of snails occupying the site but not being detected. For this, the detection/non-detection of the snail at the *i*-th microsite (y_i) was described as following a Bernoulli distribution with probability of detection p_i. In our model, this probability was a function of water temperature measured at the microsite at the moment of sampling (T_i). In previous studies snail encounters have been linked to increased solar exposure, which may be related to warmer water temperature enhancing snail activity and detection (Bargues et al., 2021). Based on existing literature and our experience in our study area, we considered that the other microenvironmental variables we registered were unlikely to impact the observational process, but could affect the biological process. The lymnaeid snail presence/absence in microsites (z_i) was also described with a Bernoulli distribution with a probability ψ_i, that was a function of the *k*-th biotic or abiotic factor (X_{ik}) as described in Table 1.

Observational process:

$$y_i | z_i \sim \text{Bernoulli}(p_i z_i)$$

$$\text{logit}(p_i) = a + bT_i$$

Biological process:

$$z_i \sim \text{Bernoulli}(\psi_i)$$

$$\text{logit}(\psi_i) = \alpha + \sum_k \beta_k X_{ik}$$

We fitted the model to the survey data using a Bayesian approach. Continuous covariates were centered and standardized to ease their analysis and comparison. For the intercepts of both equations we used as non-informative priors a logistic transformation of a beta distribution with shape parameters 1,1. For the other parameters we chose regularizing priors using a normal distribution of zero mean and unit standard deviation. We obtained samples from the posterior distributions using MCMC techniques implemented in JAGS (Plummer, 2017) and interfaced with R (R Core Team, 2022) via the jagsUI package (Kellner, 2021). We run three MCMC chains for 10000 iterations each, with a burn-in of 5000 iterations.

3. Results

The lymnaeid snail species *Galba viator* was detected in all explored water bodies throughout the study area. However, during the fieldwork, some of the mapped freshwater environments were dry and were excluded from the survey. Out of the 183 sampled quadrants, 49 (36.6%) were positive for the detection of *G. viator* (Fig. 1b-e). A total of 481 individuals of *G. viator* were collected. In general, no more than 39 individuals were counted in each quadrant, being 1–2 the most common number collected, with the exception of one single quadrant where 142 snails were found (Supplementary Table). Three gastropod genera -*Biomphalaria*, *Chilina*, and *Heleobia*- as well as one bivalve -*Pisidium*- were also detected in the quadrants in addition to *G. viator*.

Table 2
Summary of the hierarchical occupancy model for *G. viator*. Intercept (a) and slope (b) of the logistic regression for the probability of detection; intercept (α) and slopes (β) of the logistic regression for the probability of occupancy of *G. viator*; mean estimate (mean); lower (Q 2.5%) and upper (Q 97.5%) limit of the 95% credible interval of the posterior distribution of the parameters; proportion of samples with the same sign as the mean (f); potential scale reduction factor (R-hat) and number of effective samples (n.eff) from the posteriors.

Parameter	mean	Q 2.5%	Q 97.5%	f	R-hat	n.eff
a	0.57	-0.33	1.78	0.86	1.00	2111
$b_{\text{water temperature}}$	1.13	0.33	2.1	1	1.00	2240
α	-0.19	-1.61	1.45	0.59	1.00	1129
$\beta_{\text{water depth}}$	-1.64	-2.75	-0.66	1	1.00	1621
β_{grass}	0.74	-0.52	1.98	0.88	1.00	1518
$\beta_{\text{aquatic plants}}$	-1.47	-2.64	-0.34	0.99	1.00	2383
β_{algae}	-0.05	-1.43	1.47	0.55	1.00	7134
$\beta_{\text{biomphalaria}}$	1.18	-0.15	2.59	0.96	1.00	516
$\beta_{\text{other gastropods}}$	-1.18	-2.44	0.04	0.97	1.00	4686
β_{pisidium}	-0.1	-1.25	1.17	0.58	1.00	7500
$\beta_{\text{canopy cover}}$	-0.8	-1.53	-0.1	0.99	1.00	1145
$\beta_{\text{water pH}}$	0.7	0.04	1.43	0.98	1.00	4073
$\beta_{\text{turbidity}}$	0.4	-1.11	1.93	0.69	1.00	4453
$\beta_{\text{soil type}}$	0.26	-1.42	1.97	0.62	1.00	2384
$\beta_{\text{speed of water}}$	-0.17	-1.02	0.71	0.67	1.00	4176
$\beta_{\text{plant cover}}$	-0.05	-0.78	0.62	0.54	1.00	396

Water temperature in the quadrants ranged from 10.2 to 36.0 °C, although *G. viator* was only found with water temperature >15 °C. The water column depth of the explored sites reached up to 50 cm. *G. viator* was frequently detected in environments with almost no water depth, having only a superficial film of water. The maximum depth at which *G. viator* was detected was 16 cm. Vegetation (of any type) was present in 95% of the quadrants. Even though the presence of one type of vegetation did not preclude the presence of others, most records were of a single type. Grasses (63.4%) and aquatic plants (61.7%) were the most frequent, with only 16.4% quadrants containing algae. Furthermore, out of the 49 quadrants where *G. viator* were detected, 85.7%, showed grasses, 28.6% aquatic plants, and only 16.3% algae. Vegetation cover was highly variable (0–100%), and *G. viator* was found in sites ranging from unvegetated to fully covered quadrants. Tree canopy cover varied across the entire range (0–100%), with sites with no cover being more common (54.1%). *Galba viator* was always found in quadrants with <81% canopy cover.

The pH of the water ranged 6.9–10.5. *Galba viator* was found over the entire range, although 95% of detections occurred within the pH range of 7.1–9.7. Most *G. viator* detections were in muddy soil, which was common (92.3%) in the explored sites. Few sites (7.7%) were found that did not contain mud and were made up of another type of substrate, such as gravel or sand. Turbid water was found in only 8% of the quadrants, but 142 snails were discovered in one of these quadrants. The variability in water speed was low (0–0.25 m/s), and, despite snails were detected at various speeds, they were mostly (66.7%) found in quadrants with water speed <0.013 m/s (Table 1).

For the fitted hierarchical occupancy model, chains converged to a stable distribution (R-hat < 1.1) and effective posterior sample sizes were adequate for all parameters (Table 2). The model enabled to assess the effects of different covariates on the presence of *G. viator* at different sites while considering the influence of water temperature on detection. We found a positive relationship between water temperature measured at the site and the detection of *G. viator*, meaning that at higher temperatures, there were more chances to find snails if they were present. Even the lowest measurement of 10.2 °C showed credible interval that did not include the null probability of finding snails if present, while at

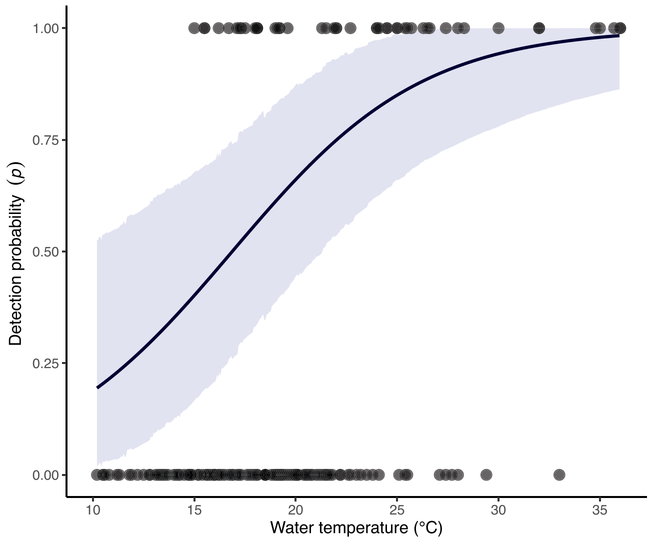

Fig. 2. Estimated detection probability of *G. viator* as a function of water temperature at the time of sampling. The shaded area represents the 95% credible interval of the estimated detection probability, while the solid line represents the mean. The points indicate the observed detection/non-detection of snails in each sampled quadrant.

$>\sim$25 °C the probability of finding them was maximum (Fig. 2).

According to the model, the probability of occupancy by *G. viator* was affected by the presence of other mollusks. The presence of *Biomphalaria* snails in the quadrant was associated with a higher mean occupancy probability of 0.68, whereas a lower mean occupancy probability of 0.23 for lymnaeid snails was linked to the presence of *Chilina* and/or *Heleobia* snails (grouped for model adjustment in the category "other gastropods"). The *Pisidium* bivalves did not appear to have an effect on the occupancy of *G. viator* (Fig. 3a). Snail occupancy was also affected by the type of vegetation present in the quadrant. The mean probability of occupancy decreased from 0.46 in sites with no vegetation to 0.19 in the presence of aquatic plants, whereas the presence of grasses increased the mean probability to 0.62. The presence of algae did not seem to have an important effect on the occupancy by snails (Fig. 3b). Although specific vegetation types in the sites had an impact on the presence of *G. viator*, the percentage of the quadrant coverage had no influence on the occupancy.

The depth of the water column showed a strong negative relationship with the probability of occupancy. When the water column was represented by a very thin film (almost null depth), this probability was highest, whereas it decreased to (almost) null values at depths > 30 cm (Fig. 4a). The tree canopy cover showed a negative relationship with snail occupancy (Fig. 4b). The presence of *G. viator* in the sites seemed not to be strongly influenced by the pH of the water; however, the model showed that, on average, the probability of occupancy increased with water pH (Fig. 4c). Water speed and turbidity, soil type and the remainder of factors analyzed did not evidence an effect on *G. viator* occupancy.

4. Discussion

Our results show that, after adjusting for the effects of water temperature on imperfect detection by means of a hierarchical occupancy model fitted to our field data, a set of microenvironmental characteristics can be associated with the presence of *G. viator* snails. We found that snails predominantly inhabit shallow aquatic environments, with little canopy shade, in the presence of grasses, and where planorbid snails of the *Biomphalaria* genus are also detected. In contrast, deep aquatic sites with aquatic plants, the presence of other gastropods from the *Chilina* and *Heleobia* genera, and a dense tree canopy cover resulted in a lower probability of *G. viator* presence. Understanding these ecological aspects of *G. viator* provides an insight into some of the determinants of the snail distribution, essential to improve field interventions to control *F. hepatica* transmission.

Several of the variables we found associated with the presence of *G. viator* are related to water temperature, a key determinant of snail development and detection (Bargues et al., 2021; Malone et al., 1984). Water depth conditions how similar is water temperature to air temperature. Deeper aquatic sites buffer more effectively variations in air temperature. Thus, in summer, with warmer air temperature, deeper sites are often colder than shallower environments and seldom reach favorable water temperatures for snail development (Boray, 1964; Soler et al., 2024). The canopy cover we measured can prevent water from warming up by solar incidence, keeping water temperature colder impairing development of *G. viator* (Yigezu et al., 2018). While the flow of water in most of our studied sites may lessen the effects of exposure to sunlight (inversely related to canopy shade), the shade could have a negative impact on food resources of *G. viator*, thereby limiting site

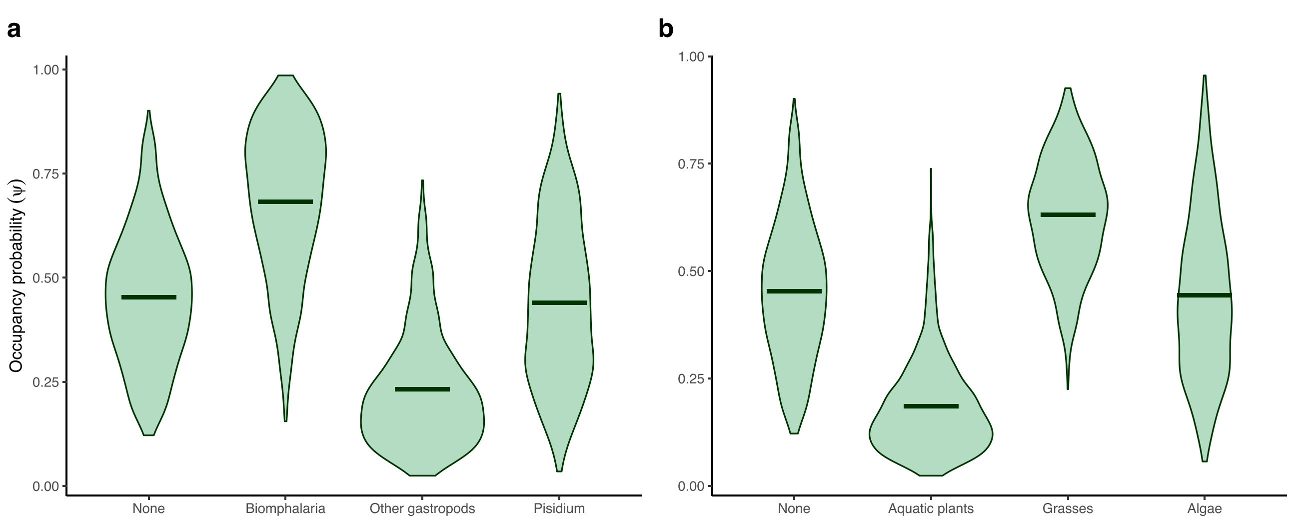

Fig. 3. Estimated quadrant occupancy probability for *G. viator* based on categorical covariates: (a) Other mollusks and (b) Vegetation type. The shaded area represents the distribution of the density of the samples from the posterior distribution of parameters; the solid horizontal line shows the mean estimate of the occupancy probability.

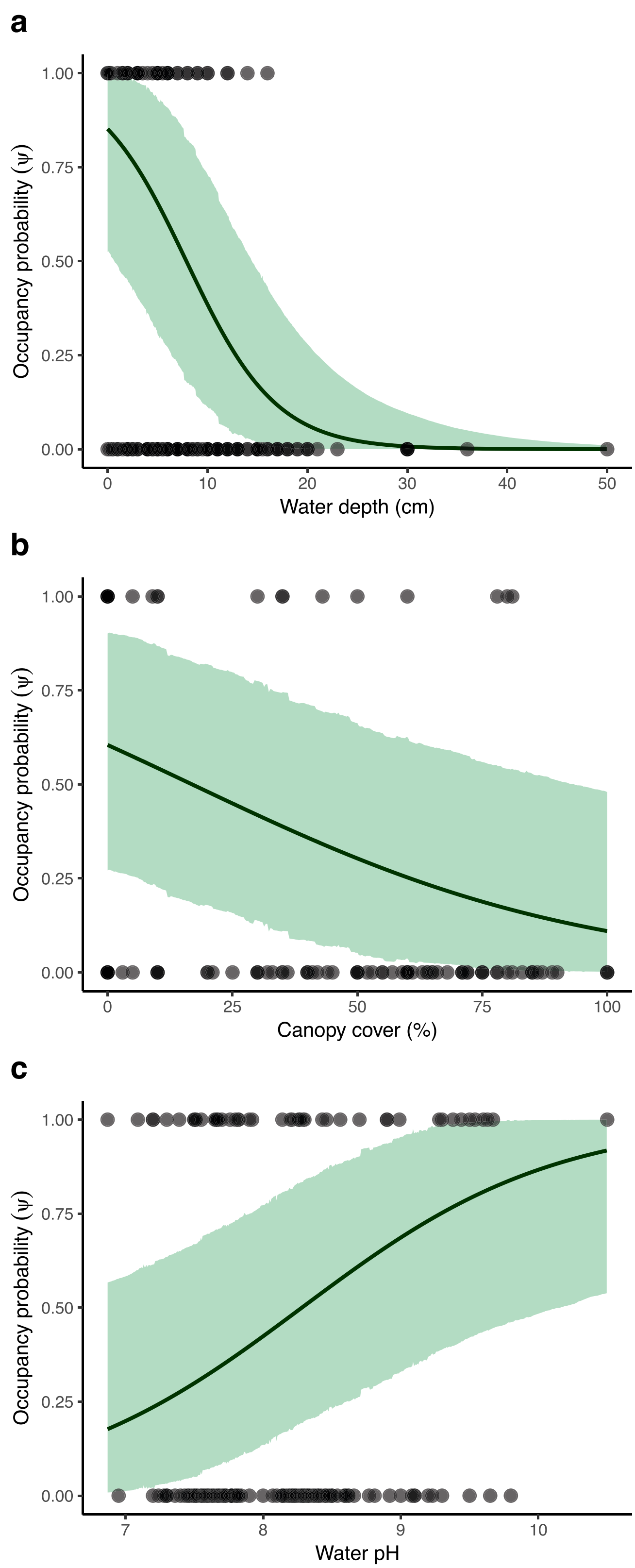

Fig. 4. Estimated occupancy probability of *G. viator* as a function of continuous covariates: (a) Water depth, (b) Canopy cover, and (c) Water pH. The shaded area represents the 95% credible interval of the estimated occupancy probability, while the mean is represented by the central line. Dots indicate the actual data of presence/absence of snails in each sampled quadrant.

occupancy (Roessler et al., 2022). Grassy vegetation in our study area is typically observed in the transition zones between the terrestrial environment and water bodies. These zones experience seasonal variations in water depth, and potentially may produce shallow shores during summer (Kleiman et al., 2007). This observation suggests that the type of vegetation would be an indicator of the depth and/or the dynamics of the water body in our region. Additionally, as shown in previous works, plants taxonomically related to grasses can act as powerful indicators of the presence of other lymnaeid snails due to their association with soil moisture and food resources (Rondelaud et al., 2011; Vignoles et al., 2022). Lastly, the warmer temperatures that enable lymnaeid snails to establish and grow by increasing their metabolic rate also favor the development of *Biomphalaria* planorbids, possibly resulting in competition for resources (Dillon, 2000; Prepelitchi et al., 2011; Yigezu et al., 2018).

In addition to analyzing the effects of the covariates on the presence of snails, our hierarchical occupancy model allowed us to separate and estimate the detectability of snails based on the water temperature at the time of sampling. The probability of detecting *G. viator* increased as the water temperature rose above the threshold conventionally accepted at 10 °C, below which development stops and hibernation is elicited (Aziz and Raut, 1996; Claxton et al., 1999; Malone et al., 1984; Nari et al., 1983). Water temperature appears to have effects at different time scales, impacting not only on development and population dynamics but also on daily activity (Bargues et al., 2021; Yigezu et al., 2018). In line with Soler et al., 2024, our results highlight the importance of taking into account the effect of water temperature on snail detection.

As any work based on observational field data, this one has several limitations. Some of the variables analyzed, mainly pH and water speed, have a relatively narrow range of recorded values, in addition to the fact that there were few observations in a large part of the observed range. This limits the precision with which functional relationships for those variables can be estimated as well as the chances of detecting some effects. Nevertheless, the assessed ranges of values reflect the usual real conditions, at least in our study area. The restricted geographical extension of the study could limit generalizing our results to very different environments (and to other lymnaeids), although we speculate that our results would still be informative for other areas and regions with *G. viator* particularly regarding the effects of physical factors (temperature, pH, water speed), since they affect basic aspects of the physiology of snails (Aziz and Raut, 1996; Bargues et al., 2021; Boray, 1964; Kleiman et al., 2007). These limitations do not undermine the understanding our results provide on the ecology of *G. viator*, in our region and probably beyond, nor the usefulness of our approach in dissecting the effects of imperfect detection from the biological processes.

The ecological understanding provided by our results, as well as from previous studies, shows that snail occurrence is very heterogenous at a scale of a few meters as a result of the high spatial heterogeneity of the microenvironmental variables (Bargues et al., 2021; Min et al., 2022; Prepelitchi et al., 2011; Yigezu et al., 2018). Data on this heterogeneity, completely ungraspable for remote sensing tools, can be decisive for accurate and effective interventions (Fuentes, 2006). Understanding and mapping this heterogeneity could provide essential information to deal with *F. hepatica* transmission.

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CRediT authorship contribution statement

Ana Clara Rodriguez Quinteros: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Marcela Larroza:** Writing – original draft, Methodology. **Paula Soler:** Writing – review & editing, Methodology. **Juan Manuel Gurevitz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis. **Juan Manuel Morales:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.vetpar.2024.110209.

References

Aziz, M.A., Raut, S.K., 1996. Thermal effect on the life-cycle parameters of the medically important freshwater snail species *Lymnaea (Radix) luteola* (Lamarck). Mem. Inst. Oswaldo Cruz 91, 119–128. https://doi.org/10.1590/S0074-02761996000100022.

Bargues, M.D., Angles, R., Coello, J., Artigas, P., Funatsu, I.R., Cuervo, P.F., Buchon, P., Mas-Coma, S., 2021. One Health initiative in the Bolivian Altiplano human fascioliasis hyperendemic area: lymnaeid biology, population dynamics, microecology and climatic factor influences. Rev. Bras. Parasitol. Vet. 30, e025620 https://doi.org/10.1590/S1984-29612021014.

Bargues, M.D., Artigas, P., Mera y Sierra, R.L., Pointier, J.P., Mas-Coma, S., 2007. Characterisation of *Lymnaea cubensis*, *L. viatrix* and *L. neotropica n. sp.*, the main vectors of *Fasciola hepatica* in Latin America, by analysis of their ribosomal and mitochondrial DNA. Ann. Trop. Med. Parasitol. 101, 621–641. https://doi.org/10.1179/136485907×229077.

Bennema, S.C., Ducheyne, E., Vercruysse, J., Claerebout, E., Hendrickx, G., Charlier, J., 2011. Relative importance of management, meteorological and environmental factors in the spatial distribution of *Fasciola hepatica* in dairy cattle in a temperate climate zone. Int. J. Parasitol. 41, 225–233. https://doi.org/10.1016/j.ijpara.2010.09.003.

Boray, J.C., 1969. Experimental Fascioliasis in Australia. in: Advances in Parasitology. Elsevier, pp. 95–210. https://doi.org/10.1016/S0065-308X(08)60435-2.

Boray, J.C., 1964. Studies on the ecology of *Lymnaea tomentosa*, the intermediate host of *Fasciola hepatica*. 1. History, geographical distribution, and environment. Aust. J. Zool. 12, 217–230. https://doi.org/10.1071/zo9640217.

Carvalho, O.S., Cardoso, P.C., Lira, P.M., Rumi, A., Roche, A., Berne, E., Müller, G., Caldeira, R.L., 2004. The use of the polymerase chain reaction and restriction fragment length polymorphism technique associated with the classical morphology for characterization of *Lymnaea columella*, *L. viatrix*, and *L. diaphana* (Mollusca: Lymnaeidae). Mem. Inst. Oswaldo Cruz 99, 503–507. https://doi.org/10.1590/S0074-02762004000500008.

Chang Reissig, E., Massone, A.R., Iovanitti, B., Gimeno, E.J., Uzal, F.A., 2018. A survey of parasite lesions in wild red deer (*Cervus elaphus*) from Argentina. J. Wildl. Dis. 54, 782–789. https://doi.org/10.7589/2017-06-136.

Charlier, J., Soenen, K., De Roeck, E., Hantson, W., Ducheyne, E., Van Coillie, F., De Wulf, R., Hendrickx, G., Vercruysse, J., 2014. Longitudinal study on the temporal and micro-spatial distribution of *Galba truncatula* in four farms in Belgium as a base for small-scale risk mapping of *Fasciola hepatica*. Parasites Vectors 7, 528. https://doi.org/10.1186/s13071-014-0528-0.

Claxton, J.R., Sutherst, J., Ortiz, P., Clarkson, M.J., 1999. The effect of cyclic temperatures on the growth of *Fasciola hepatica* and *Lymnaea viatrix*. Vet. J. 157, 166–171. https://doi.org/10.1053/tvjl.1998.0293.

Collado, G.A., Fuentealba, C.G., Cazzaniga, N.J., Valladares, M.A., 2020. Assessing biodiversity within the range of *Heleobia chimbaensis* (Caenogastropoda: Cochliopidae) on the Atacama Desert coast. Syst. Biodivers. 18, 708–719. https://doi.org/10.1080/14772000.2020.1783018.

Collado, G.A., Salinas, H.F., Méndez, M., 2014. Genetic, morphological, and life history traits variation in freshwater snails from extremely high environments of the Andean Altiplano. Zool. Stud. https://doi.org/10.1186/1810-522X-53-14.

Correa, A.C., Escobar, J.S., Durand, P., Renaud, F., David, P., Jarne, P., Pointier, J.-P., Hurtrez-Boussès, S., 2010. Bridging gaps in the molecular phylogeny of the Lymnaeidae (Gastropoda: Pulmonata), vectors of Fascioliasis. BMC Evol. Biol. 10, 381 https://doi.org/10.1186/1471-2148-10-381.

Cuervo, P.F., Cataldo, S.D., Fantozzi, M.C., Deis, E., Isenrath, G.D., Viberti, G., Artigas, P., Peixoto, R., Valero, M.A., Sierra, R.M. y, Mas-Coma, S., 2015. Liver fluke (*Fasciola hepatica*) naturally infecting introduced European brown hare (*Lepus europaeus*) in northern Patagonia: phenotype, prevalence and potential risk. Acta Parasitol. 60 https://doi.org/10.1515/ap-2015-0076.

Dalton, J.P., 2021. Fasciolosis, 2nd Edition. CABI.

Dillon, R.T., 2000. The ecology of freshwater molluscs. Cambridge University Press.

Duffy, T., Kleiman, F., Pietrokovsky, S., Issia, L., Schijman, A.G., Wisnivesky-Colli, C., 2009. Real-time PCR strategy for rapid discrimination among main lymnaeid species from Argentina. Acta Trop. 109, 1–4. https://doi.org/10.1016/j.actatropica.2008.08.003.

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int. J. Climatol. 37, 4302–4315. https://doi.org/10.1002/joc.5086.

Fuentes, M.V., 2006. Remote sensing and climate data as a key for understanding fasciolosis transmission in the Andes: review and update of an ongoing interdisciplinary project. Geospat. Health 1, 59–70. https://doi.org/10.4081/gh.2006.281.

Gayo, V., Cuervo, P., Rosadilla, D., Birriel, S., Dell'Oca, L., Trelles, A., Cuore, U., Sierra, R.M., 2011. Natural Fasciola hepatica Infection in Nutria (*Myocastor coypus*) in Uruguay (y). J. Zoo. Wildl. Med. 42, 354–356. https://doi.org/10.1638/2010-0226.1.

Gérard, C., 2001. Consequences of a drought on freshwater gastropod and trematode communities. Hydrobiologia 459, 9–18. https://doi.org/10.1023/A:1012567102396.

Gutiérrez Gregoric, D.E., Ciocco, N.F., Rumi, A., 2014. Two new species of Chilina Gray from Cuyo Malacological Province, Argentina (Gastropoda: Hygrophila: Chilinidae). Mollusca Res 34, 84–97. https://doi.org/10.1080/13235818.2013.866184.

Hurtrez-Boussès, S., Meunier, C., Durand, P., Renaud, F., 2001. Dynamics of host–parasite interactions: the example of population biology of the liver fluke (Fasciola hepatica). Microbes Infect. 3, 841–849. https://doi.org/10.1016/S1286-4579(01)01442-3.

Issia, L., Pietrokovsky, S., Sousa-Figueiredo, J., Stothard, J.R., Wisnivesky-Colli, C., 2009. *Fasciola hepatica* infections in livestock flock, guanacos and coypus in two wildlife reserves in Argentina. Vet. Parasitol. 165, 341–344. https://doi.org/10.1016/j.vetpar.2009.07.011.

Ituarte, C., 2007. Las especies de Pisidium Pfeiffer de Argentina, Bolivia, Chile, Perú y Uruguay (Bivalvia-Sphaeriidae) (n.s.). Rev. Mus. Argent. Cienc. Nat. 9, 169–203. https://doi.org/10.22179/REVMACN.9.307.

Kellner, K., 2021. jagsUI: A Wrapper "rjags" Streamline "JAGS" Anal.

Kleiman, F., Pietrokovsky, S., Paraense, W.L., Wisnivesky-Colli, C., 2004. Southernmost finding of *Lymnaea viatrix* Orbigny, 1835 (Pulmonata: Lymnaeidae), intermediate host of *Fasciola hepatica* (Linnaeus, 1758) (Trematoda: Digenea), in urban and rural areas of Patagonia, Argentina. Mem. Inst. Oswaldo Cruz 99, 23–24. https://doi.org/10.1590/S0074-02762004000100004.

Kleiman, F., Pietrokovsky, S., Prepelitchi, L., Carbajo, A.E., Wisnivesky-Colli, C., 2007. Dynamics of *Fasciola hepatica* transmission in the Andean Patagonian valleys, Argentina. Vet. Parasitol. 145, 274–286. https://doi.org/10.1016/j.vetpar.2006.12.020.

Larroza, M., Aguilar, M., Soler, P., Mora, J., Roa, M., Cabrera, R., Martinez Stanziola, J. P., Ceballos, L., Alvarez, L.I., 2023. Triclabendazole resistance in *Fasciola hepatica*: First report in sheep from the Santa Cruz province, Argentinian Patagonia. Vet. Parasitol. Reg. Stud. Rep. 45, 100927 https://doi.org/10.1016/j.vprsr.2023.100927.

Lusk, C.H., 2022. A field test of forest canopy structure measurements with the CanopyCapture smartphone application. PeerJ 10, e13450. https://doi.org/10.7717/peerj.13450.

Madariaga, M.C., 2019. El Valle del Río Manso Inferior y su funcionamiento como sistema (info:ar-repo/semantics/informe técnico. Ediciones INTA.

Madariaga, M.C., 2018. Diagnóstico del valle del Río Manso Inferior (info:ar-repo/semantics/informe técnico). Ediciones INTA.

Malone, J.B., Loyacano, A.F., Hugh-Jones, M.E., Corkum, K.C., 1984. A three-year study on seasonal transmission and control of *Fasciola hepatica* of cattle in Louisiana. Prev. Vet. Med. 3, 131–141. https://doi.org/10.1016/0167-5877(84)90003-5.

Mas-Coma, S., Bargues, M.D., Valero, M.A., 2014. Diagnosis of human fascioliasis by stool and blood techniques: update for the present global scenario. Parasitol 141, 1918–1946. https://doi.org/10.1017/S0031182014000869.

Mas-Coma, S., Bargues, M.D., Valero, M.A., 2005. Fascioliasis and other plant-borne trematode zoonoses. Int. J. Parasitol., Parasit. Zoonoses - Emerg. Issues 35, 1255–1278. https://doi.org/10.1016/j.ijpara.2005.07.010.

Mas-Coma, S., Valero, M.A., Bargues, M.D., 2009. Climate change effects on trematodiases, with emphasis on zoonotic fascioliasis and schistosomiasis. Vet. Parasitol. 163, 264–280. https://doi.org/10.1016/j.vetpar.2009.03.024.

May, K., Bohlsen, E., König, S., Strube, C., 2020. *Fasciola hepatica* seroprevalence in Northern German dairy herds and associations with milk production parameters and milk ketone bodies. Vet. Parasitol. 277, 109016 https://doi.org/10.1016/j.vetpar.2019.109016.

Mehmood, K., Zhang, H., Sabir, A.J., Abbas, R.Z., Ijaz, M., Durrani, A.Z., Saleem, M.H., Ur Rehman, M., Iqbal, M.K., Wang, Y., Ahmad, H.I., Abbas, T., Hussain, R., Ghori, M. T., Ali, S., Khan, A.U., Li, J., 2017. A review on epidemiology, global prevalence and economical losses of fasciolosis in ruminants. Microb. Pathog. 109, 253–262. https://doi.org/10.1016/j.micpath.2017.06.006.

Mezo, M., González-Warleta, M., Castro-Hermida, J.A., Manga-González, M.Y., Peixoto, R., Mas-Coma, S., Valero, M.A., 2013. The wild boar (*Sus scrofa* Linnaeus, 1758) as secondary reservoir of *Fasciola hepatica* in Galicia (NW Spain). Vet. Parasitol. 198, 274–283. https://doi.org/10.1016/j.vetpar.2013.09.009.

Mezo, M., González-Warleta, M., Castro-Hermida, J.A., Muiño, L., Ubeira, F.M., 2011. Association between anti-*F. hepatica* antibody levels in milk and production losses in dairy cows. Vet. Parasitol. 180, 237–242. https://doi.org/10.1016/j.vetpar.2011.03.009.

Min, F., Wang, J., Liu, X., Yuan, Y., Guo, Y., Zhu, K., Chai, Z., Zhang, Y., Li, S., 2022. Environmental factors affecting freshwater snail intermediate hosts in Shenzhen and adjacent region, South China. TropicalMed 7, 426. https://doi.org/10.3390/tropicalmed7120426.

Nari, A., Cardozo, H., Acosta, D., Solari, M.A., Petraccia, C., 1983. Efecto de la temperatura en el desarrollo de *Fasciola hepatica* en su huésped intermediario *Lymnaea viatrix* D'orbigny. Vet. (Montev.) 19 (1835), 36–39.

Olaechea, F., 2007. Fasciola hepatica. In: Suárez, V., Olaechea, F., Rossanigo, C., Romero, J. (Eds.), Enfermedades parasitarias de los ovinos y otros rumiantes menores en el cono sur de América, pp. 159–168.

Olaechea, F., Lovera, V., Larroza, M., Raffo, F., Cabrera, R., 2011. Resistance of *Fasciola hepatica* against triclabendazole in cattle in Patagonia (Argentina). Vet. Parasitol. 178, 364–366. https://doi.org/10.1016/j.vetpar.2010.12.047.

Paraense, W., 1976. *Lymnaea viatrix*: A study of topotypic specimens (Mollusca: Lymnaeidae). Rev. Bras. Biol. 36.

Plummer, M., 2017. JAGS Version 4.3. 0 user manual.

Prepelitchi, L., 2009. Ecoepidemiología de *Fasciola hepatica* (Trematoda, Digenea) en el norte de la provincia de Corrientes destacando aspectos ecológicos de *Lymnaea columella* (Pulmonata, Lymnaeidae) y su rol como hospedador intermediario. Facultad de Ciencias Exactas y Naturales. Universidad de Buenos Aires.

Prepelitchi, L., Pietrokovsky, S., Kleiman, F., Rubel, D., Issia, L., Moriena, R., Racioppi, O., Álvarez, J., Wisnivesky-Colli, C., 2011. Population structure and dynamics of *Lymnaea columella* (Say, 1817) (Gastropoda: Lymnaeidae) in wetlands of northeastern Argentina. Zool. Stud. 50, 164–176.

R Core Team, 2022. R: A Lang. Environ. Stat. Comput.

Rabinovich, J.E., 1980. Introducción a la ecología de poblaciones animales. CECSA.

Roessler, A.S., Oehm, A.W., Knubben-Schweizer, G., Groll, A., 2022. A machine learning approach for modelling the occurrence of *Galba truncatula* as the major intermediate host for *Fasciola hepatica* in Switzerland. Prev. Vet. Med. 200, 105569 https://doi.org/10.1016/j.prevetmed.2022.105569.

Rondelaud, D., Hourdin, P., Vignoles, P., Dreyfuss, G., Cabaret, J., 2011. The detection of snail host habitats in liver fluke infected farms by use of plant indicators. Vet. Parasitol. 181, 166–173. https://doi.org/10.1016/j.vetpar.2011.03.056.

Rubel, D., Prepelitchi, L., Kleiman, F., Carnevale, S., Wisnivesky-Colli, C., 2005. Estudio del foco en un caso de fasciolosis humana en Neuquén. Med. (Buenos Aires) 65, 207–212.

Schneider, B., Cunha, E.R., Marchese, M., Thomaz, S.M., 2018. Associations between macrophyte life forms and environmental and morphometric factors in a large sub-tropical floodplain. Front. Plant Sci. 9 https://doi.org/10.3389/fpls.2018.00195.

Shimalov, V.V., Shimalov, V.T., 2000. Findings of *Fasciola hepatica* Linnaeus, 1758 in wild animals in Belorussian Polesie. Parasitol. Res. 86 https://doi.org/10.1007/s004360050707.

Soler, P., Abdala, A.M., Larroza, M., 2023. Genetic characterization and regional distribution of lymnaeid snails in northern Patagonia, Argentina. Vet. Parasitol. Reg. Stud. Rep. 44, 100919 https://doi.org/10.1016/j.vprsr.2023.100919.

Soler, P., Gurevitz, J.M., Morales, J., Larroza, M., 2024. Modeling the Effects of Water Temperature on the Population Dynamics of *Galba viatrix* and Infection by *Fasciola hepatica*: A Two-Year Survey in Andean Patagonia, Argentina. Preprint available at SSRN: ⟨https://ssrn.com/abstract=4718436⟩ or https://doi.org/10.2139/ssrn.4718436.

Standley, C.J., Prepelitchi, L., Pietrokovsky, S.M., Issia, L., Stothard, J.R., Wisnivesky-Colli, C., 2013. Molecular characterization of cryptic and sympatric lymnaeid species from the *Galba/Fossaria* group in Mendoza Province, Northern Patagonia, Argentina. Parasites Vectors 6, 304. https://doi.org/10.1186/1756-3305-6-304.

Sun, P., Wronski, T., Apio, A., Edwards, L., 2020. A holistic model to assess risk factors of fasciolosis in Ankole cattle. Vet. Parasitol. Reg. Stud. Rep. 22, 100488 https://doi.org/10.1016/j.vprsr.2020.100488.

Thompson, F.G., 2011. An annotated checklist and bibliography of the land and freshwater snails of México and Central America. Fla. Mus. Nat. Hist. Bull. 50, 1–299. https://doi.org/10.58782/flmnh.bnej7351.

Vázquez, A.A., Alba, A., Alda, P., Vittecoq, M., Chapuis, E., Faugère, D., Pointier, J.-P., Hurtrez-Boussès, S., 2023. Lymnaeid Snails and the Transmission of Fasciolosis: Understanding the Differential Risks from Local to Global Scale. In: Vinarski, M.V., Vázquez, A.A. (Eds.), The Lymnaeidae: A Handbook on Their Natural History and Parasitological Significance. Springer International Publishing, Cham, pp. 359–394. https://doi.org/10.1007/978-3-031-30292-3_13.

Vignoles, P., Dreyfuss, G., Rondelaud, D., 2022. Decline in the number and size of populations of two Lymnaeidae living in central France over the last decade. Int. J. Lim. 58, 11. https://doi.org/10.1051/limn/2022011.

Walz, Y., Wegmann, M., Dech, S., Raso, G., Utzinger, J., 2015. Risk profiling of schistosomiasis using remote sensing: approaches, challenges and outlook. Parasites Vectors 8, 163. https://doi.org/10.1186/s13071-015-0732-6.

World Health Organization, 2013. Sustaining the drive to overcome the global impact of neglected tropical diseases: second WHO report on neglected diseases. World Health Organization.

Yigezu, G., Mandefro, B., Mengesha, Y., Yewhalaw, D., Beyene, A., Ahmednur, M., Abdie, Y., Kloos, H., Mereta, S.T., 2018. Habitat suitability modelling for predicting potential habitats of freshwater snail intermediate hosts in Omo-Gibe river basin, Southwest Ethiopia. Ecol. Inform. 45, 70–80. https://doi.org/10.1016/j.ecoinf.2018.04.002.