Spatial prediction of the risk of exposure to *Echinococcus* spp. among schoolchildren and dogs in Ningxia Hui Autonomous Region, People's Republic of China

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Abstract

The geographical distribution of *Echinococcus* spp. infections in Ningxia Hui Autonomous Region (NHAR) has been reported to be expanding in response to environmental change. The aim of the present study was to predict and compare the spatial distribution of human seropositivity for *Echinococcus granulosus* and *Echinococcus multilocularis* and infections with these parasites in dogs in four counties in the south of NHAR to identify communities where targeted prevention and control efforts are required. Predicted seroprevalence of *E. granulosus* in schoolchildren and *E. granulosus* infections in dogs concurred spatially, whereas predicted seroprevalence of *E. multilocularis* in schoolchildren and *E. multilocularis* infections in dogs differed spatially. Enhanced vegetation index was significantly associated with *E. multilocularis* seropositivity among schoolchildren, and infections with *E. granulosus* and *E. multilocularis* in dogs. A positive association was also found between dog infection with *E. granulosus* and cultivated land, and a negative association between human seropositivity for *E. granulosus* and bare-land/artificial surfaces. The findings of this study support the importance of land cover and climatic variables in determining habitat suitability for *Echinococcus* spp. infections, and suggest that definitive hosts other than dogs (*e.g.* foxes) are important in defining the geographical risk of human seropositivity for *E. multilocularis* in NHAR.

Introduction

Cystic echinococcosis (CE), caused predominantly by infection with *Echinococcus granulosus*, and alveolar echinococcosis (AE), due to infection with *E. multilocularis*, have long incubation periods (5-15 years) that delay diagnosis and treatment (Ammann and Eckert, 1996), and require long-term monitoring and medical care for most patients (Brunetti *et al.*, 2011; Kern *et al.*, 2017). It is estimated that 188,000 people are infected with *E. granulosus* globally every year which represents a human health burden of 184,000 disability-adjusted life years (DALYs) lost (Torgerson *et al.*, 2015). An estimate of 18,235 cases of AE occur annually resulting in a loss of approximately 666,433 DALYs (Torgerson *et al.*, 2010). From these figures, 91% of the total number of cases and 95% of the disease burden of AE are estimated to be in the People's Republic of China (PR China) (Torgerson *et al.*, 2010).

The transmission of *E. granulosus* and *E. multilocularis* in domestic and sylvatic life cycles, respectively, is maintained by a wide range of intermediate and definitive hosts (Romig *et al.*,

2017). The transmission of *E. granulosus* involves domestic dogs and other canids as typical definitive hosts, and sheep and other ungulates as intermediate hosts (Eckert and Deplazes 2004). *E. multilocularis* is transmitted within predator-prey cycles that involve different species of foxes as main definitive hosts and small mammals as intermediate hosts (Eckert and Deplazes, 2004; Kapel *et al.,* 2006). Domestic dogs are susceptible to infection with both parasites, and are currently regarded as significant hosts for *E. granulosus* and *E. multilocularis* (Moss *et al.,* 2013; Rausch, 1995). In Gansu Province and the eastern Tibetan plateau, PR China, particularly, domestic dogs have been identified as the main transmission source of both parasites to the local human population (Craig *et al.,* 2000; Wang *et al.,* 2010). Comprehensive reviews of the life cycles of *E. granulosus* and *E. multilocularis*, clinical manifestations of human echinococcoses, diagnosis, treatment, prevention and control are available (Craig *et al.,* 2017; Kern *et al.,* 2017; Romig *et al.,* 2017).

CE and AE are characterised by great variation in their geographical distributions, with important differences at regional and local spatial scales (Cringoli *et al.,* 2007; Eckert, 2001; Giraudoux *et al.,* 2006; Giraudoux *et al.,* 2013a; Mastin *et al.,* 2011). CE has a widespread global distribution with the highest disease burden in poor pastoralist communities, whilst AE occurs within defined areas of temperate and subarctic regions of the northern hemisphere (Deplazes *et al.,* 2017). Various socio-demographic, economic and environmental factors that act at different spatial scales have been found to be associated with the distributions of CE and AE risk (Atkinson *et al.,* 2013; Cadavid Restrepo *et al.,* 2015; Danson *et al.,* 2003; Giraudoux *et al.,* 2007). These factors determine the population dynamics and behaviour of the hosts, predator-prey interactions and the survival and development of the parasites.

Land cover change factors have been found to be linked to the distribution and dynamics of *E. multilocularis* intermediate hosts (Raoul *et al.,* 2008; Silva *et al.,* 2005). Deforestation (Giraudoux *et al.,* 1998; Giraudoux *et al.,* 2003), afforestation (Raoul *et al.,* 2008), and specific farming and fencing practices (Raoul *et al.,* 2006; Wang *et al.,* 2004) have been shown to modify the distribution of various species of small mammals. Overgrazing and low grass height were also linked positively to the presence and abundance of intermediate hosts for *E. multilocularis* in highly endemic areas on the Tibetan Plateau (Raoul *et al.,* 2006; Wang *et al.,* 2010), while enhanced vegetation index (EVI) had a negative association with the presence of *Ochotona curzoniae* (plateau pika) and *Ochotona cansus* (Gansu pika), key intermediate hosts for the parasite in Serxu County, Sichuan Province (Marston *et al.,* 2016). To date, surprisingly few studies have been conducted to investigate the host-environment interactions that regulate the domestic life cycle of *E. granulosus* (Eckert and Deplazes, 2004).

Spatial epidemiological approaches that integrate the use of geographical information systems (GIS), remote sensing and model-based geostatistics serve as valuable analytical tools to quantify and predict the spatial heterogeneities in the risk of echinococcoses across different spatial scales (Cadavid Restrepo *et al.,* 2015). Because control interventions against CE and AE require a long period of implementation in order to be successful, the outcome of spatial epidemiological approaches may help define national and regional policies to reduce the burden of these diseases, and also to prioritise areas where interventions are required (Cadavid Restrepo *et al.,* 2015; Craig *et al.,* 2017).

Nine valid species are currently recognised within the genus *Echinococcus*: *E. granulosus*, *E. multilocularis*, *E. ortleppi*, *E. canadensis*, *E. oligarthrus*, *E. vogeli*, *E. shiquicus*, *E. felidis*, *E. equinus*. *E. granulosus* and *E. multilocularis* are the species found in Ningxia Hui Autonomous Region (NHAR) (McManus *et al.,* 1994; Yang *et al.,* 2005). A spatial prediction study of *E. multilocularis* in Xiji county, south of NHAR found that *E. multilocularis* transmission was determined by landscape factors, such as presence of lowland pasture (Pleydell *et al.,* 2008). It was also suggested that the infection did not occur primarily through arvicolines species which are key intermediate hosts for this parasite in other areas (Pleydell *et al.,* 2008). In this study, we extend the previous work that was undertaken in Xiji County to encompass three additional neighbouring counties, Haiyuan, Guyuan and Tongxin, located in the south of NHAR. Using Bayesian model-based geostatistics, we aimed to create spatial predictions of the risk of human seropositivity for *E. granulosus* and *E. multilocularis*, and the risk of dog infections with these parasites. In the present study, the term human exposure was meant to signify that children harboured possibly the metacestode stage of *E. granulosus* and/or *E. multilocularis*, whether or not, they had clinical, serological or ultrasound evidence of active cysts (based on the description of a possible echinococcosis case suggested elsewhere (Brunetti *et al.,* 2010). These maps can guide decision-makers to spatially target echinococcosis control interventions.

Materials and Methods

Study area

The surveys were conducted in four contiguous counties of NHAR, Xiji, Haiyuan, Guyuan and Tongxin Counties, which are located in the south of the Autonomous Region between latitudes 35°33'–36°98' N, and between longitudes 105°64'–106°24 E. The four counties together cover an area of approximately 21,557 km². Based on the estimates of the national census in 2015, the total populations were, 344,045 in Xiji, 396,938 in Haiyuan, 1,211,789 Guyuan and 325,441 in Tongxin, of whom 58.0%, 70.8%, 46.1% and 86.1% were of the Hui Islamic ethnic minority, respectively, while almost all others were Han Chinese (National Bureau of Statistics of China 2015) (Figure 1).

The counties lie in a temperate continental monsoon climate zone that is characterized by four distinct seasons. The annual average temperature is 5.37 °C and the average annual precipitation is 418.2 mm. Approximately 60% of the precipitation is in the form of rainstorms that take place during the rainy season, from June to September. Elevation ranges from 1500 to 2800 meters above sea level. The geography of this part of NHAR include mountainous areas around Mt. Liupan, and the Loess hills. Vegetation varies from forest mainly in the southeast to slope farmland that accounts for most of the cultivated land, and to desert in the northeast and northwest.

Data on seroprevalence of *E. granulosus* and *E. multilocularis*

Data on the seroprevalence of *E. granulosus* and *E. multilocularis* were obtained from a cross-sectional school-based survey conducted across the four counties in 2012-2013. Children aged 6-18 years were selected to ensure that the collected data were representative of recent exposure risk (as adults might have been

exposed over a long duration in the past). A geostatistical design (grid plus close pairs) was used to select the schools for the survey (Diggle and Ribeiro 2007). A 15×15 km grid was created and overlaid on the entire study area using ArcGIS software version 10.3.1 (ESRI 2015). The primary set of schools selected for the survey consisted of those schools located in closest proximity to the grid nodes. A second set of schools was also selected comprising schools located in near proximity to those selected at the nodes of the grid (the close pairs). The origin of the grid, the distance and direction of the close pairs from the primary set, and the primary subset for which close pairs were selected, were generated using a random number generator. This approach was used because it has been identified as the most efficient survey design for estimating spatial variability in environmental variables (Diggle and Ribeiro, 2007).

All children who agreed to participate in the survey were first assembled and asked to provide demographic and exposure information using standardised questionnaires that were administered by the school teachers. Then, a blood sample from the ear lobe was collected from participants for specific antibody testing by enzyme linked immunosorbent assay (ELISA) using *E. granulosus* cyst fluid antigen B and *E. multilocularis* crude protoscolex extract (Craig *et al.,* 1992; Yang *et al.,* 2008). EgB and EmP ELISA sensitivity is >85% for CE and >90% for AE, respectively (Bartholomot *et al.,* 2002; Craig *et al.,* 1992; Craig *et al.,* 2000). Specificity is from 70% to 100% for CE (Carmena *et al.,* 2006) and 87% for AE (Bartholomot *et al.,* 2002). Finally, abdominal ultrasound was used to screen schoolchildren and detect and classify early CE and/or AE cysts. The classification scheme of CE and AE proposed by the World Health Organization was used to categorise

the hepatic lesions (Kern *et al.,* 2006; WHO Informal Working Group 2003; WHO Informal Working Group on Echinococcosis 2001). Although ultrasound is the method of choice to confirm human echinococcoses, it has low sensitivity to detect small cysts (McManus *et al.,* 2012). Therefore, due to the young age of participants and the slow rate of growth of the cysts, the results of the ultrasound are not reported here. Schoolchildren, who were screen-positive for one of the infections or both, were referred to the local medical centre for free treatment.

Data on dog infection

Faecal samples were collected from dogs presenting to the veterinary centre nearest to the selected schools, including rural and urban locations, between 2012 and 2013. The faecal samples were initially stored separately for at least 7 days at −80 °C to inactivate the parasite eggs, and then transferred to a −20 °C freezer. The processing and copro-analysis were conducted at the Zoonoses Laboratory of the Ministry of Agriculture in the Lanzhou Veterinary Research Institute, Gansu Province, PR China. A Multiplex polymerase chain reaction (PCR) assay was used for simultaneous detection of *E. granulosus* and *E. multilocularis* DNA (Liu *et al.,* 2015). The geographic coordinates of each school and veterinary centre were collected using a hand-held global positioning system. Maps of the surveyed locations is available (Figure 2).

Environmental and remotely sensed data

Land cover maps at a 30-meter spatial resolution for the years 2005, 2010 and 2015 were obtained from a previous study that assessed and quantified land cover change in NHAR between 1991 and 2015 (Cadavid Restrepo *et al.,* 2017). The maps were created using time series images retrieved from the Landsat Surface Reflectance Climate Data Record available in Earth Explorer (The United States Geological Survey, USGS). Seven land cover categories were initially identified: water bodies, artificial surfaces, bare or sparsely vegetated areas, herbaceous vegetation, cultivated land, scrubland and forest (Table 1). However, due to significant spectral confusion between artificial surfaces and bare or sparsely vegetated areas, these land cover classes were merged and represented as a single category in the maps and further analyses. Details of the process of land cover classification and accuracy assessment are provided elsewhere (Cadavid Restrepo *et al.,* 2017).

Landsat 30-meter enhanced vegetation index (EVI) data were extracted from the Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) On Demand Interface. Data were downloaded from a month during the growing season in NHAR (June-November) for the years 2008 and 2012. However, when there were no data available for the specified time period, the closest-in-time EVI estimates were retrieved for the analyses.

Elevation estimates were obtained in a GeoTIFF format at the spatial resolution of 1 arc-second (approximately 30 m) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2 (The National Aeronautics and Space Administration (NASA) and Ministry of Economy Trade and Industry (METI)). The ASTER GDEM was downloaded from the Earth Explorerwebsite.

Average monthly values of temperature and precipitation for the period January 1, 2008 to December 31, 2013 were provided by the Chinese Academy of Sciences in a raster format at the spa-
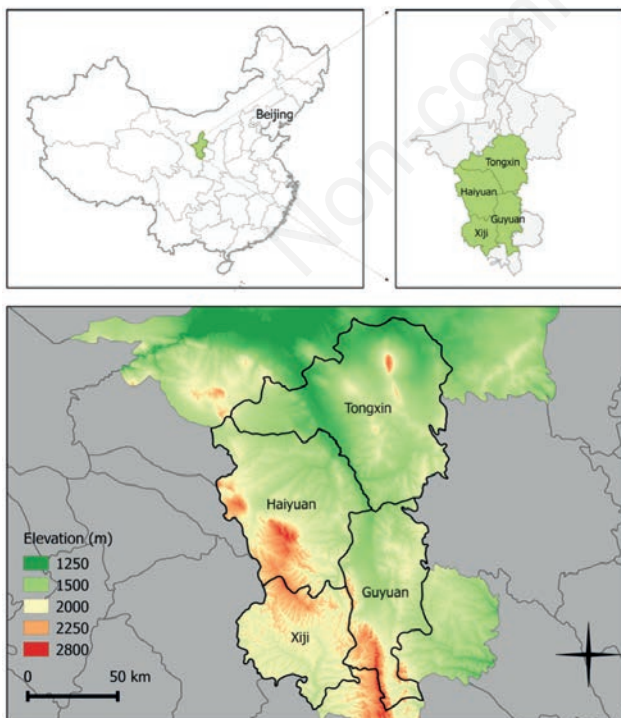

Figure 1. Map and elevation of Xiji, Haiyuan, Guyuan and Tongxin counties and location of NHAR within China.

tial resolution of 1 km. The monthly climate values had first been collected from 16 local weather stations and then interpolated using the Inverse Distance Weighting (IDW) method.

A boundary map of the four counties was downloaded from the DIVA-GIS website (DIVA GIS). The geo-referenced data sets that included the locations of the surveyed schools and veterinary centres were imported into ArcGIS and projected to the Universal Transverse Mercator (UTM) coordinate system zone 48N. ArcGIS was used to delineate 1 km and 5 km radii buffer zones around the centres of the survey site locations and all covariates were summary estimates extracted from these buffer zones. The buffer sizes were selected in order to examine areas of environmental conditions that provide suitable habitat for the parasite hosts. Land cover variables were summarized as percentages of each land cover type within the buffer zones for the years 2005, 2010 and 2015. The extracted estimates were then used to calculate change rates for the periods 2005-2010, and 2010-2015. In this way, it was possible to estimate the spatial extent of all land cover classes by buffer area for the years 2008 and 2012. For climate, elevation and EVI variables, a moving 5-year average (MA) of the values of the independent variables was generated for the period 2008-2012 to examine the host/environment interplay over an extended period of time rather than at a single point. For each surveyed location, the data extracted included: annual, summer (June, July and August) and winter (December, January and February) weighted average temperature and precipitation, and spatial mean values of EVI and elevation within the buffer zone.

Variable selection

Using R software version 3.2.2. (R Core Team 2015), non-spatial univariate binomial logistic regression models were developed to examine the association between the environmental variables with *E. granulosus* and *E. multilocularis* infections in humans and dogs. Spearman correlation analyses were conducted to assess collinearity among all independent variables. If the correlation coefficient between a pair of covariates was >0.9, the covariate with the highest value of Akaike Information Criterion (AIC) in the univariate regression models was excluded. Various non-spatial binomial multivariate logistic regression models were also created to compare differences in model fit. Multivariate logistic regression models were also developed for human and dog infections and for each species. The models with the lowest AIC were selected for subsequent geostatistical analyses. Nonlinear associations between the environmental covariates and the infections were modelled using quadratic terms.

Model-based geostatistics

Separate multivariable geostatistical logistic regression models were created in a Bayesian framework for human serological status and dog infections with each parasite species using the OpenBUGS software 3.2.3 rev 1012 (Members of OpenBUGS Project Management Group 2014). First, Bayesian geostatistical models were developed with the explanatory variables as fixed-effects but without considering the spatial dependence structure of the data. Then, Bayesian geostatistical models for each infection were created including the explanatory variables and a spatially structured random effect.

The fit of the models was compared using the deviance information criterion (DIC), where low DIC values indicate a better fit. Statistical significance of the covariates in the models was deemed to be achieved if the 95% credible intervals (95% CrI) of the estimated odds ratios (OR) excluded 1.

For all infections, the best-fit model was the one that included the spatial random effect. Assuming a Bernoulli-distributed dependent variable, Y_{ij}, corresponding to the serological/infection status (0=seronegative/noninfected, 1=seropositive/infected) of an individual i in location j, the model structures for schoolchildren (formula 1) and dogs, (formula 2), were as follows:

$$Y_{ij} \sim Bern(p_{ij})$$

$$\text{logit}\,(p_{ij}) = \alpha + \gamma \times \text{age}_i + \sum_{z=1}^{z} \beta_z \times \lambda_{zj} + s_j \qquad \text{Eq 1.}$$

Table 1. Land cover classification scheme and definitions.

Code	Land cover	Description	Content
1	Water bodies	All areas of water	Streams and canals, lakes, reservoirs, bays and estuaries
2	Artificial surfaces	Land modified by human activities	Residential areas, industrial and commercial complexes, transport infrastructure, communications and utilities, mixed urban or built-up land and other built-up land
3	Bare or sparsely vegetated areas	Areas with little or no green vegetation present	Dry salt flats, sandy areas, bared exposed rock and mixed barren land
4	Herbaceous vegetation	Areas characterized by natural or semi-natural vegetation	Grasses and forbs
5	Cultivated land	Areas where the natural vegetation has been emoved/modified and replaced by other types of vegetative cover that have been planted for specific purposes such as food, feed and gardening	Cropland and pasture, orchards, groves, vineyards, nurseries and ornamental horticultural, other cultivated land
6	Scrubland	Natural or semi-natural woody vegetation with aerial stems <6 m tall	Evergreen and deciduous species of true shrubs and trees or shrubs that are small or stunted
7	Forest	Areas characterized by tree cover or semi-natural woody vegetation greater than <6 m tall	Deciduous forest, evergreen forest and mixed forest

$$Y_{ij} \sim Bern(p_{ij})$$

$$\mathrm{ogit}\,(p_{ij}) = \alpha + \sum_{z=1}^{z} \beta_z \times \lambda_{zj} + s_j \qquad \text{Eq 2.}$$

where α is the intercept, γ is the coefficient for age, β is a matrix of z coefficients, λ is a matrix of z environmental variables, and s_j a geostatistical random effect. The correlation structure of the geostatistical random effect was assumed to be an exponential function of the distance between points:

$$f\,(d_{kl};\,\phi) = \exp[-\phi d_{kl}] \qquad \text{Eq. 3}$$

where d_{kl} are the distances between pairs of points k and l, and ϕ is the rate of decline of spatial correlation per unit of distance. A normal distribution was used for the priors for the intercept and the coefficients (mean = 0 and precision, the inverse of variance, = 1 $\times$ 10^{-3}), whereas a uniform distribution was specified for ϕ (with upper and lower bounds s= 0.01 and 100; the lower bound set to ensure spatial correlation at the maximum separating distance between survey locations was <0.5). A non-informative gamma distribution was used to specify the priors for the precision (shape and scale parameters = 0.001, 0.001).

A burn-in of 1000 iterations was run first and discarded. Sets of 20,000 iterations were then run and examined for convergence. Convergence was assessed by visual inspection of history and density plots and by examining autocorrelation of the model parameters. Because autocorrelation was observed for most variables, thinning was applied by storing every 10th iteration. In each model, convergence was achieved for all variables at approximately 80,000 iterations. The last 10,000 values from the posterior distributions of each model parameter were recorded. The rate of decay of spatial correlation between locations (ϕ) with distance and the variance of the spatial structured random effect (σ^2) were also stored. To define the prediction locations, a regular 5 km $\times$ 5 km grid was overlaid over the entire study territory. The risk of human seropositivity and dog infection at the prediction locations was estimated using the *spatial.unipred* function in OpenBUGS. The function applies the model equation at each non-sampled location using the covariates values extracted for them and the separating distance between those locations and the surveyed locations.

Maps that represent the posterior distributions of predicted seroprevalence of these parasite species in humans and predicted prevalence of both infections in dogs were created in ArcGIS for the four counties.

Results

Sample description

The final data set of the surveyed schools consisted of 106 locations and a total of 7547 schoolchildren who were screened for *Echinococcus* spp. seropositivity. Haiyuan (64.5%) and Xiji (54.0%) were the two counties with the highest observed overall seroprevalence of both infections, followed by Guyuan (43.3%) and then by Tongxin (24.6%). The seroprevalence of *E. granulosus* among schoolchildren by county was higher (45.6%) in Xiji, while a higher seroprevalence of *E. multilocularis* was observed in Haiyuan (21.1%) (Table 2). The mean age of participants who were seropositive for *E. granulosus* was 11.4 years (median: 11, standard deviation (SD): 2.6), and the mean age for those who were seropositive for *E. multilocularis* was 11.3 years (median: 13, SD: 2.5).

The final data set of the survey conducted in the veterinary centres included 111 locations and a total of 3,324 dogs. The county with the highest overall prevalence of dogs infected with each of the parasite species, *E. granulosus* and *E. multilocularis*, was Xiji County (16.5% and 14.2%, respectively). The prevalence rates of dog infection with *E. granulosus* in the other three counties were 12.0%, 11.8% and 9.5% in Tongxin, Haiyuan and Guyuan, respectively. The prevalence of dog infection with *E. multilocularis* were notably lower in Haiyuan (3.4%), Tongxin (1.6%) and Guyuan (1.5%) compared with Xiji (Table 2).

Figure 2 shows the observed spatial distributions of the prevalence of the infections in humans and dogs by parasite species and locations. From the maps, it is difficult to identify a clear geographical pattern. However, the maps confirm that seropositivity for *E. granulosus* was more widespread than the seropositivity for *E. multilocularis* in the study areas.

Models of *E. granulosus* and *E. multilocularis* seropositivity in schoolchildren

The DICs of the models of seropositivity for *E. granulosus*

Table 2. Seroprevalence of human seropositivity for *E. granulosus* and *E. multilocularis* and dog infections by county.

| | *E. granulosus* | | *E. multilocularis* | | |
	Positive	Negative	Positive	Negative	Total
Humans					
Xiji	765 (45.6%)	912 (54.4%)	141 (8.4%)	1,536 (91.6%)	1,677 (100%)
Guyuan	601 (36.4%)	1,051 (63.6%)	114 (6.9%)	1,538 (93.1%)	1,652 (100%)
Haiyuan	842 (43.4%)	1,099 (56.6%)	409 (21.1%)	1,532 (78.9%)	1,941 (100%)
Tongxin	523 (22.9%)	1,754 (77.1%)	39 (1.7%)	2,238 (98.3%)	2,277 (100%)
Dogs					
Xiji	124 (16.5%)	626 (83.5%)	106 (14.1%)	644 (85.9%)	750 (100%)
Guyuan	63 (9.5%)	597 (90.5%)	10 (1.5%)	650 (98.5%)	660 (100%)
Haiyuan	91 (11.8%)	680 (88.2%)	26 (3.4%)	745 (96.6%)	771 (100%)
Tongxin	137 (12.0%)	1,006 (88%)	18 (1.6%)	1,125 (98.4%)	1,143 (100%)

Cross-sectional surveys conducted in schools and veterinary centres in 2012-2013.

with and without accounting for spatial correlation were 8,699 and 8,903, respectively. In the spatial model, bare-land/artificial surface land cover class, was the only variable that had a statistically significant association with seropositivity. The estimated decrease in seropositivity was 0.9% (95% CrI: 0.04%-1.8%) for an increase of 1% in the extent of bare-land/artificial surfaces (Table 3). The *E. multilocularis* model with the spatial component had a DIC of 3,575, while the model without the spatial component had a DIC of 3,667. In the spatial model, EVI had a significant positive association with seropositivity for *E. multilocularis*. There was an estimated increase of 0.2% (95% CrI: 0.1%-0.3%) in seropositivity for *E. multilocularis* for 1-unit increase in EVI within the 5-km buffer area at a 5-year lag. Additionally, the quadratic terms for winter and summer temperature in the 5-km buffers were statistically significant in the 5 years prior to the survey, indicating a significant nonlinear association (Table 4).

The variance of the spatially structured random effect was 0.6 (0.4 to 1.0) in the model of seropositivity for *E. granulosus* and 1.2 (0.7 to 1.9) in the model of seropositivity for *E. multilocularis*. These estimates imply that, after accounting for the effect of the statistically significant variables, the residual spatial variation was higher for human seropositivity for *E. multilocularis*. Phi (ϕ), that

is the rate of decay of spatial correlation (with bigger ϕ indicating smaller clusters), was 20.9 in the *E. granulosus* model and 45.2 in the *E. multilocularis* model. This means that, after accounting for the effect of covariates, the radii of the clusters were larger for human seropositivity for *E. multilocularis* than for human seropositivity for *E. granulosus*.

The models of dog infection with *E. granulosus* with the spatial component had a lower DIC, 2.121, compared with the one without the spatial component, 2250. There was an increase of 2.0% (95% CrI: 0.8-3.3%) in the prevalence of dog infection with *E. granulosus* for a 1% increase in the coverage of cultivated land, and 0.05% (95% CrI: 0.001-0.1%) for an increase of 1 unit of EVI (Table 5). The spatial model for E. *multilocularis* infection in dogs also had a lower DIC (805.2) compared with the non-spatial model (963.2) (Table 6). The prevalence of *E. multilocularis* infection was found to increase by 0.1% (95% CrI: 0.04-1.2%) with a 1-unit increase in EVI.

In the model of dog infection with *E. granulosus*, the variance of the spatially structured random effect was 0.6 (0.3 to 1.0) and in the model of dog infection with *E. multilocularis* this parameter was 1.6 (0.4 to 5.7), meaning residual spatial variation was higher for the model of infection with *E. multilocularis*. The values of the

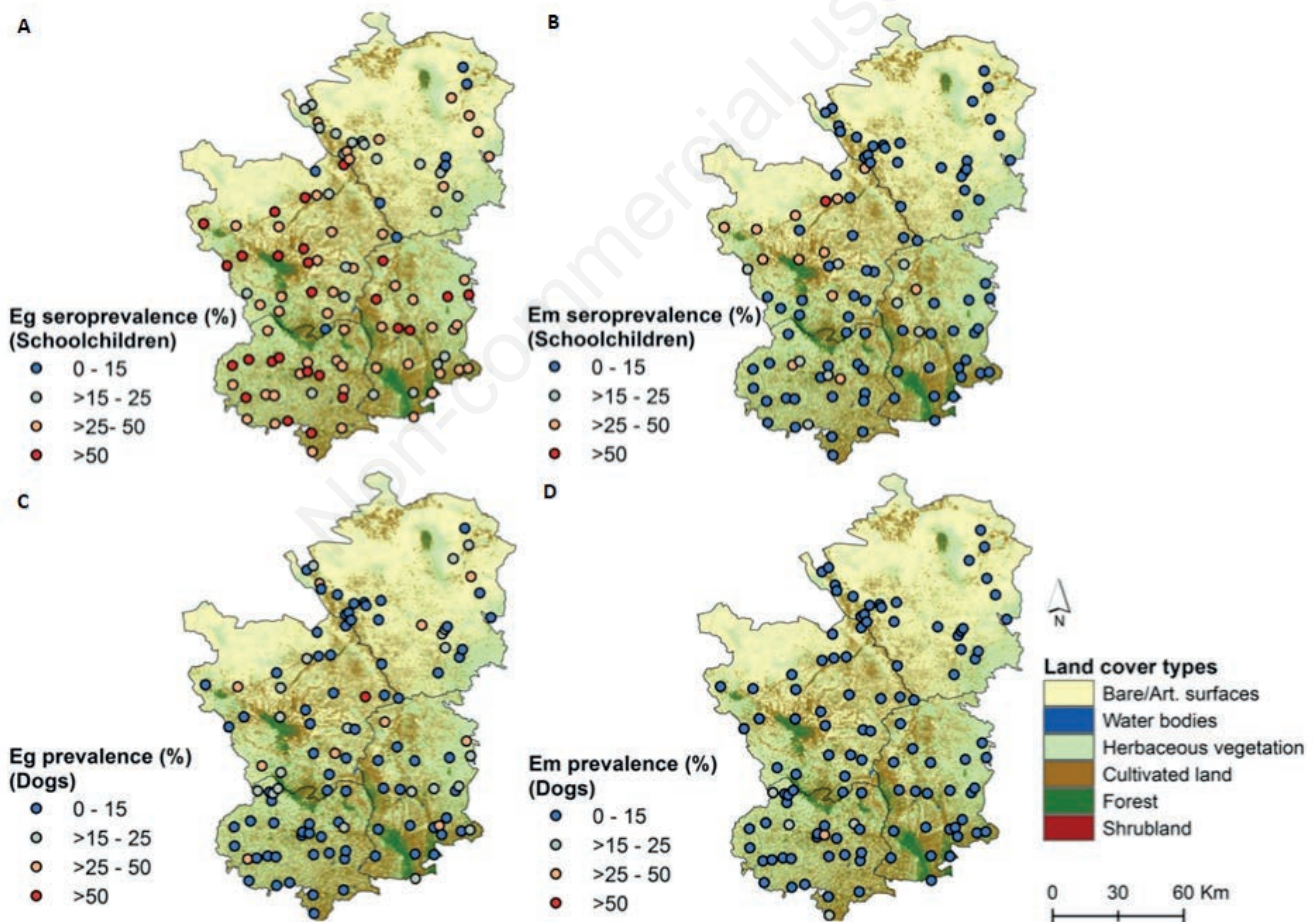**Figure 2. Distribution of surveys of *E. granulosus* and *E. multilocularis* exposure in schoolchildren and dogs and observed seroprevalence in 2012-2013 with locations of the different land cover types indicated in Xiji, Haiyuan, Guyuan and Tongxin counties, Ningxia Hui Autonomous Region, China. A) *E. granulosus*; B) *E. multilocularis*; C) infection with *E. granulosus* in dogs; D) infection with *E. multilocularis* in dogs.**

decay parameter for spatial correlation (ϕ) in the models of dog infection with *E. granulosus* and *E. multilocularis* were 69.4 and 41.2, respectively, indicating that the radii of the clusters were larger for dog infection with *E. granulosus* than infection with *E. multilocularis*.

Spatial predictions of human seroprevalence of *E. granulosus* and *E. multilocularis*

The predictive risk maps of seroprevalence rates of *E. granulosus* and *E. multilocularis* in Xiji, Haiyuan, Guyuan and Tongxin Counties in 2012-2013 were created (Figure 3A and B). The highest seroprevalence of *E. granulosus*, >60%, was predicted for west-central Xiji and Haiyuan. However, *E. granulosus* seroprevalence rates between 40% and 60% were predicted in large areas throughout these two counties and in the central part of Guyuan. For most of the northern part of the study area, which corresponds to Tongxin county, low seroprevalence rates were predicted (<40%). The highest seroprevalence of *E. multilocularis*, >20%, was found in a large area of the central part of Haiyuan county. In northern Xiji and north-western Guyuan seroprevalence rates were between 8% and 16%, while low seroprevalence rates of E. *multilocularis*, 0-6%, were predicted for most of Tongxin and the southern part of Xiji County. Maps of the SDs of the posterior distributions of predicted seroprevalence rates of *E. granulosus* and *E. multilocularis* were also created (Figure 3C and D). The spatial distribution of high prediction uncertainty concurs with that of the areas with high seroprevalence rates of *E. granulosus* and *E. multilocularis*.

Table 3. Regression coefficients, odd ratios and 95% CrI from Bayesian spatial model for seroprevalence of *E. granulosus* in schoolchildren in Xiji, Haiyuan, Tongxin and Guyuan counties in 2012-2013.

Model	Coefficient, posterior mean (95% CrI*)	Odds ratios, posterior mean (95% CrI)
Intercept	−0.68 (−1.07 to −0.31)	–
Age	-4.2×10^{-3} (−0.03 to 0.02)	0.99 (0.97 to 1.02)
Summer precipitation same year (5 km)	-1.83×10^{-3} (-7.98×10^{-3} to 4.20×10^{-3})	0.99 (0.99 to 1.01)
Winter temperature 5 years prior (1 km)	−0.07 (−1.32 to 1.23)	0.93 (0.26 to 3.43)
Winter temperature 5 years prior (1 km) squared	0.22 (−0.17 to 0.59)	1.24 (0.84 to 1.80)
Winter temperature same year (5 km)	−0.71 (−2.00 to 0.68)	0.49 (0.13 to 1.99)
Winter temperature same year (5 km) squared	−0.07 (−0.27 to 0.13)	0.92 (0.76 to 1.14)
Bare-land/Art. surfaces same year (1 km)	−0.01 0.99	(−0.01 to -4.02×10^{-4}) (0.98 to 0.99)
Cultivated land 5 years prior (1 km)	-0.01 (−0.01 to 3.63×10^{-3})	0.99 (0.98 to 1.00)
Forest 5 years prior (1 km)	−0.01 (−0.04 to 0.02)	0.99 (0.95 to 1.02)
Herbaceous vegetation same year (1 km)	3.24×10^{-4} (−0.01 to 0.01)	0.99 (0.98 to 1.01)
Scrubland same year (1 km)	−7.36 (−16.43 to 1.73)	6.32×10^{-4} (7.26×10^{-8} to 5.68)
Heterogeneity structured	0.58 (0.36 to 0.99)	-
φ (Decay of spatial correlation)	20.89 (5.86 to 71.23)	-
Deviance information criterion	8,669	-

* 95% CrI, 95% credible interval.

Table 4. Regression coefficients, odd ratios and 95% CrI from Bayesian spatial model for seroprevalence of *E. multilocularis* in schoolchildren in Xiji, Haiyuan, Tongxin and Guyuan counties in 2012-2013.

Model	Coefficient, posterior mean (95% CrI*)	Odds ratios, posterior mean (95% CrI)
Intercept	−2.69 (−3.58 to −1.88)	-
Age	0.03 (−0.01 to 0.07)	1.03 (0.99 to 1.07)
Summer precipitation 5 years prior (5 km)	0.01 (−0.01 to 0.02)	1.01 (0.99 to 1.02)
Summer temperature 5 years prior (5 km)	−3.32 (−6.38 to −0.28)	0.03 (0.01 to 0.75)
Summer temperature 5 years prior (5 km) squared	−1.96 (−3.07 to −0.81)	0.14 (0.04 to 0.44)
Winter temperature 5 years prior (5 km)	−2.09 (−5.20 to 1.23)	0.12 (0.01 to 3.44)
Winter temperature 5 years prior (5 km) squared	0.97 (0.26 to 1.68)	2.64 (1.30 to 5.38)
Bare-land/Art. surfaces 5 years prior (5 km)	0.01 (−0.02 to 0.03)	1.00 (0.98 to 1.03)
Bare-land/Art. surfaces same year (5 km)	−0.01 (−0.03 to 0.02)	0.99 (0.96 to 1.02)
Cultivated land 5 years prior (5 km)	0.01 (−0.02 to 0.02)	1.00 (0.98 to 1.02)
Forest 5 years prior (5 km)	−0.01 (−0.05 to 0.04)	0.99 (0.94 to 1.04)
Scrubland 5 years prior (5 km)	−3.70 (−8.05 to 0.47)	0.02 (3.00×10^{-4} to 1.60)
Scrubland 5 same year (5 km)	−4.28 (−10.81 to 2.16)	0.01 (0.02×10^{-5} to 8.72)
Water bodies 5 years prior (5 km)	0.89 (−0.40 to 2.25)	2.44 0.66 to 9.52)
EVI** 5 years prior (1 km)	-3.39×10^{-4} (-1.01×10^{-3} to 4.00×10^{-4})	0.99 (0.99 to 1.00)
EVI 5 years prior (5 km)	1.80×10-3 (5.00×10^{-4} to 3.00×10^{-3})	1.00 (1.00 to 1.01)
Heterogeneity structured	1.18 (0.71 to 1.91)	-
φ (Decay of spatial correlation survey 1)	45.17 (11.74 to 95.22)	-
Deviance information criterion	3,575	-

* 95% CrI, 95% credible interval; **enhanced vegetation index.

Spatial predictions of prevalence of dog infection with *E. granulosus* and *E. multilocularis*

The highest predicted prevalence of dog infection with *E. granulosus* (>20%) was apparent in northern and eastern Haiyuan (Figure 4A). Almost all counties were predicted to be affected by this form of the infection except for Tongxin, where most of the territorial area had a predicted risk of 0-6%. A large high-risk area of dog infection with *E. multilocularis*, >0.20%, was found in a region covering most of the south of the study area, which corresponds to the eastern part of Xiji and the south of Guyuan. More circumscribed areas of high risk of this infection in dogs were observed in the central part of Haiyuan. There was a large area of low risk, 0-6%, in northeast Haiyuan and almost the entire territory of Tongxin (Figure 4B). The maps of predicted SDs also showed high prediction uncertainty in areas with high mean predicted risk (Figure 4C and D).

Discussion

This study presents detailed information on the predicted geographical distribution of the risk of seropositivity for *E. granulosus* and *E. multilocularis* among schoolchildren aged 6-18 years, and

Table 5. Regression coefficients, odd ratios and 95% CrI from Bayesian spatial model for dog infection with *E. granulosus* in Xiji, Haiyuan, Tongxin and Guyuan counties in 2012–2013.

Model	Coefficient, posterior mean (95% CrI*)	Odds ratios, posterior mean (95% CrI)
Intercept	−2.38 (−2.61 to −2.18)	-
Winter precipitation 5 years prior (5 km)	−0.04 (−0.11 to 0.01)	0.95 (0.89 to 1.01)
Winter temperature 5 years prior (1 km)	0.91 (−4.40 × 10⁻³ to 1.86)	2.51 (0.99 to 6.47)
Bare-land/Art. surfaces 5 years prior (5 km)	0.01 (−4.40 × 10⁻⁴ to 0.02)	1.01 (0.99 to 1.02)
Cultivated land 5 years prior (1 km)	0.02 (0.01 to 0.03)	1.02 (1.01 to 1.03)
Herbaceous vegetation 5 years prior (5 km)	0.01 (−3.10 × 10⁻⁴ to 0.02)	1.01 (0.99 to 1.02)
Scrubland 5 years prior (5 km)	−1.42 (−3.68 to 0.87)	0.24 (0.02 to 2.41)
Water bodies same year (5 km)	−0.16 (−0.57 to 0.23)	0.84 (0.56 to 1.25)
EVI** 5 years prior (1 km)	−5.51 × 10⁻⁴ (−1.20 × 10⁻³ to 1.00 × 10⁻⁴)	0.99 (0.99 to 1.00)
EVI 5 years prior (5 km)	5.77 × 10⁻⁴ (1.74 × 10-5 to 1.15 × 10⁻³)	1.00 (1.00 to 1.01)
Heterogeneity structured	0.59 (0.29 to 1.00)	-
φ (Decay of spatial correlation)	69.37 (25.85 to 98.64)	-
Deviance information criterion	2,121	-

* 95% CrI, 95% credible interval; **enhanced vegetation index.

Table 6. Regression coefficients, odd ratios and 95% CrI from Bayesian spatial model for dog infection with *E. multilocularis* in Xiji, Haiyuan, Tongxin and Guyuan counties in 2012-2013.

Model	Coefficient, posterior mean (95% CrI*)	Odds ratios, posterior mean (95% CrI)
IIntercept	−4.09 (−4.99 to −2.41)	-
Annual temperature 5 years prior (1 km)	−1.57 (−17.50 to 9.6)	0.20 (2.50×10^{-8} to 1.50×10^4)
Annual temperature same year (1 km)	−4.53 (−19.58 to 10.08)	0.01 (3.10×10^{-9} to 2.24×10^4)
Summer temperature 5 years prior (5 km)	0.92 (−9.78 to 14.50)	2.52 ($5.61 \times 1^{0-5}$ to 1.99×10^6)
Summer temperature same year (5 km)	2.82 (−8.75 to 13.49)	16.89 (1.57×10^{-4} to 7.26×10^5)
Winter temperature 5 years prior (1 km)	3.62 (−12.59 to 21.39)	37.65 (3.38×10^{-6} to 1.95×10^9)
Winter temperature 5 years prior (1 km) squared	0.85 (−0.66 to 2.14)	2.34 (0.51 to 8.56)
Winter temperature same year (1 km)	28.74 (−4.27 to 56.02)	3.02×10^{12} (0.01 to 2.13×10^{24})
Winter temperature same year (1 km) squared	4.42 (−3.54 to 13.70)	83.49 (0.02 to 8.95×10^5)
Winter temperature 5 years prior (5 km)	−0.28 (−18.58 to 19.62)	0.75 ($8.44 \times 10-9$ to 3.33×10^8)
Winter temperature same year (5 km)	−28.97 (−56.69 to 0.06)	$2.61 \times 10-13$ ($2.37 \times 10-25$ to 1.06)
Winter temperature same year (5 km) squared	−6.12 (−16.11 to 2.11)	2.22×10^{-3} ($1.00 \times 10-7$ to 8.26)
Bare-land/Art surfaces 5 years prior (5 km)	0.01 (−0.01 to 0.03)	1.01 (0.98 to 1.03)
Cultivated land 5 years prior (5 km)	$−6.01 \times 10^{-3}$ (−0.03 to 0.02)	0.99 (0.95 to 1.02)
Forest same year (5 km)	$−7.61 \times 10^{-3}$ (−0.04 to 0.02)	0.99 (0.95 to 1.02)
Herbaceous vegetation 5 years prior (5 km)	$−8.82 \times 10^{-3}$ (−0.01 to 0.03)	1.01 (0.98 to 1.03)
Scrubland 5 years prior (5 km)	−4.60 (−9.88 to 0.17)	0.01 (5.10×10^{-5} to 1.19)
Scrubland same year (5 km)	−8.73 (−26.85 to 3.63)	1.61×10^{-4} (2.17×10^{-12} to 37.79)
Water bodies 5 years prior (5 km)	−0.39 (−2.06 to 1.08)	0.67 (0.12 to 2.95)
Elevation (1 km)	1.90×10^{-3} ($−8.37 \times 10^{-4}$ 4.80×10^{-3})	1.00 (0.99 to 1.00)
EVI** 5 years prior (1 km)	6.84×10^{-4} (1.90×10^{-3} to 5.00×10^{-4})	0.99 (0.99 to 1.00)
EVI 5 years prior (5 km)	1.00×10^{-3} (4.90×10^{-5} to 1.97×10^{-3})	1.00 (1.00 to 1.00)
Heterogeneity structured	1.62 (0.36 to 5.74)	-
φ (Decay of spatial correlation)	41.23 (1.14 to 96.61)	-
Deviance information criterion	805.2	-

* 95% CrI, 95% credible interval; **enhanced vegetation index.

infection with these parasites in dogs, in an important endemic area of PR China. To our knowledge, these are the first species-specific risk maps created for the region that concurrently reveal the spatial variation in echinococcosis risk for humans and dogs at a local spatial scale. Important climatic and land cover factors associated with the observed geographical heterogeneity in the risk of seropositivity were also identified. The findings are of current relevance in NHAR due to the ongoing process of landscape restoration in the Autonomous Region (Cadavid Restrepo *et al.,* 2017; Li *et al.,* 2013). Since 2002, the Grain for Green Project (GGP), a large national initiative to recover the degraded landscape, has been implemented in NHAR (Liu *et al.,* 2008; Wang *et al.,* 2007; Zhang *et al.,* 2008). With the aim of reducing cropland on steep slopes, the GGP promotes three different types of land conversions: cropland to grassland, cropland to forest, and wasteland to forest (The University of Nottingham, 2010; Zhou *et al.,* 2012). The project also advocates for desertification control and prohibition of enclo-

sures for grazing practices (Wang *et al.,* 2007). Studies conducted in other echinococcosis-endemic regions, where landscape transformation processes have taken place, indicate that some types of land cover change may have had an impact on the transmission patterns of *E. multilocularis* and, consequently, the risk of infection has increased for animals and humans (Craig *et al.,* 2000; Giraudoux *et al.,* 1998; Giraudoux *et al.,* 2003).

This study demonstrated similarities in the spatial distribution of the predicted seroprevalence of *E. granulosus* among schoolchildren and infection in domestic dogs in the four counties in 2012-2013. Human seropositivity for *E. granulosus* was predicted for most of the study area, and dog infections with *E. granulosus* was predicted for almost all of Xiji County and in large areas of Haiyuan, Guyuan and Tongxin Counties. The North-Eastern and central parts of Tongxin were shown to have the lowest predicted prevalence of this parasite in humans and dogs. This geographical area of Tongxin is covered primarily by dry steppe vegetation and
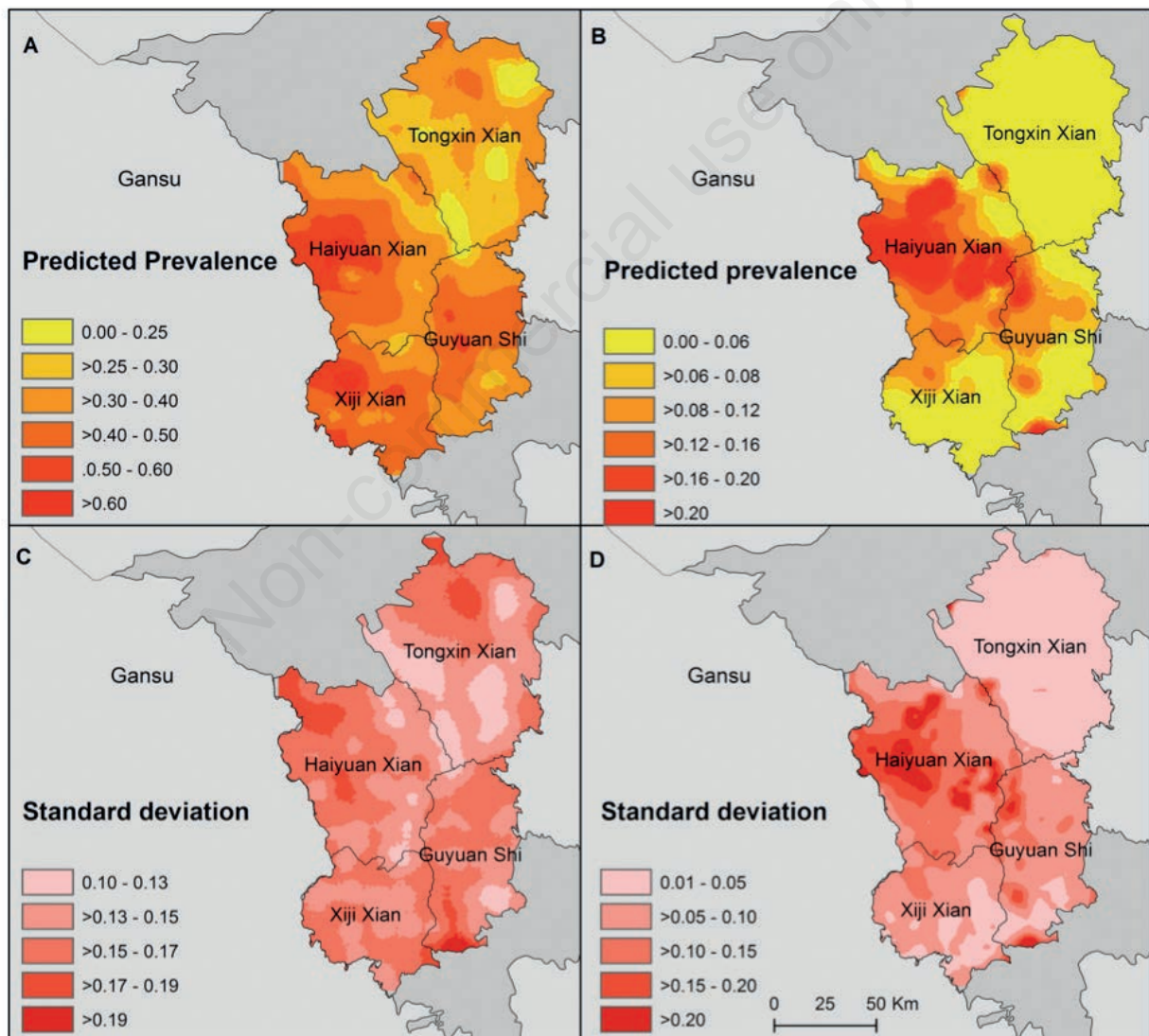

Figure 3. Spatial distribution of predicted seroprevalence rates of *E. granulosus* and *E. multilocularis* in schoolchildren aged 6-18 years in Xiji, Haiyuan, Guyuan and Tongxin counties, Ningxia Hui Autonomous Region, China in 2012-2013. A) *E. granulosus;* B) *E. multilocularis*; C) and D) corresponding standard deviations.

desert grassland (Li *et al.,* 2008). These characteristics of the local environment may be providing unfavourable ecological conditions for the transmission of *E. granulosus*, most probably due to the effects on the parasite eggs. Soil moisture/humidity and temperature particularly have been identified as important determinants of the survival and longevity of the *Echinococcus* spp. eggs in the external environment (Thevenet *et al.,* 2005; Veit *et al.,* 1995). Notably, the highest predicted prevalence of human seropositivity, unlike the highest predicted prevalence of dog infection, was found in areas from Xiji and Haiyuan Counties that share borders with the south of Gansu Province. In Gansu, human seropositivity and animal infections are also highly prevalent, with current estimates indicating that the annual incidence of human CE is between 2 and 10 cases per 10^5 inhabitants (Deplazes *et al.,* 2017). Therefore, the high predicted prevalence of human seropositivity for *E. granulosus* in these areas may be partially explained by the pastoral nomadic culture practices and the movement of people and domestic dogs across the provincial borders (Miller 2006; Shen 2012) .

The geographical distribution of the predicted prevalence of *E. multilocularis* among the students did not concur with the distribution of the predicted prevalence of *E. multilocularis* infection in dogs. While high prevalence of human seropositivity for *E. multilocularis* was predicted for almost all Haiyuan County, high prevalence of dog infection with this species was predicted for the eastern Xiji and southern Guyuan Counties. Although this study involved a different population group, the finding in Xiji confirms the prediction of the distribution of human seropositivity for *E. multilocularis* conducted in the county in 2008, showing a similar geographical pattern (Pleydell *et al.,* 2008). However, the findings do not support the current hypothesis that domestic dogs serve as the primary host of *E. multilocularis* in south NHAR (Budke *et al.,* 2005a; Budke *et al.,* 2005b; Romig *et al.,* 2017). Dog ownership
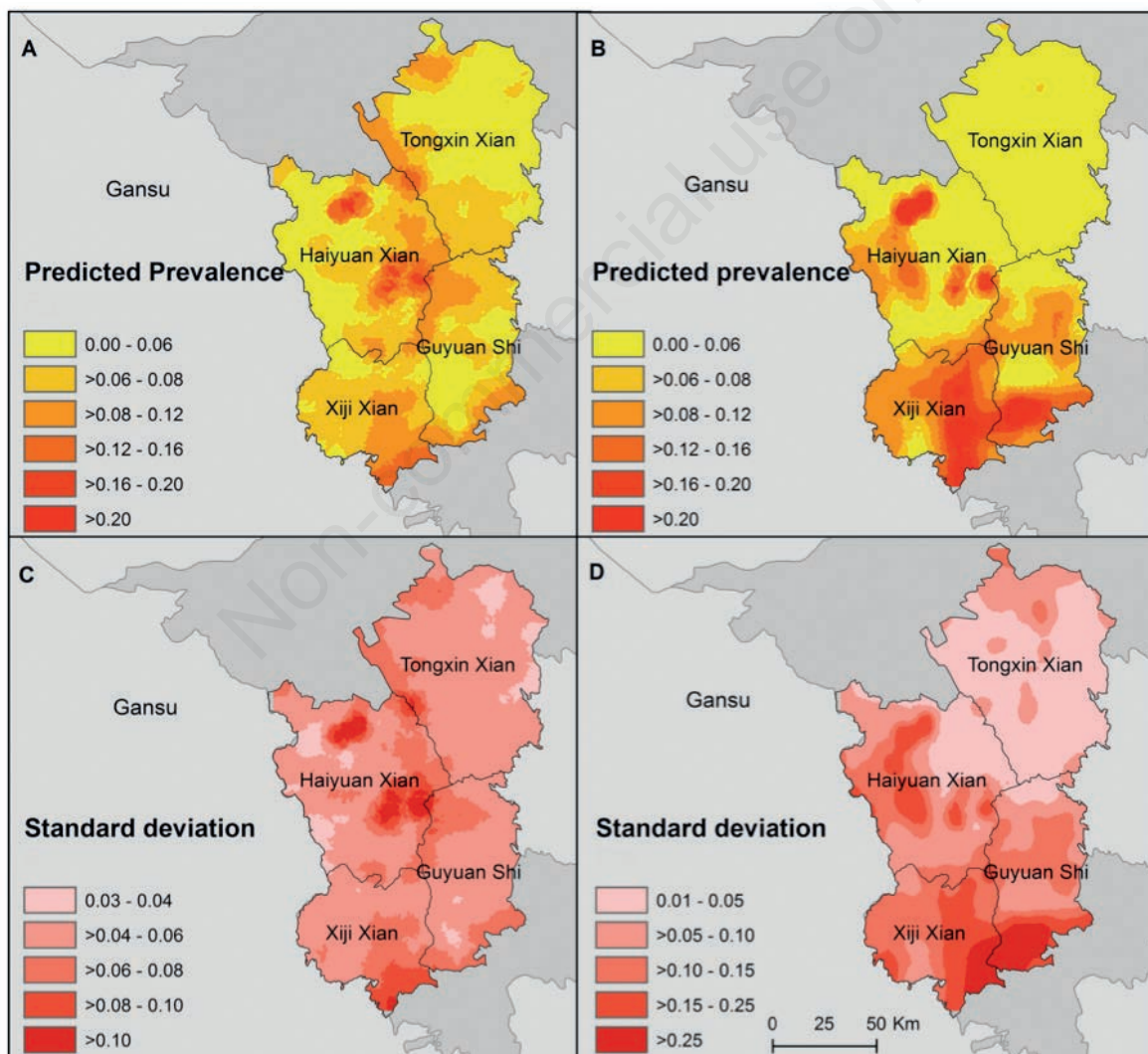

Figure 4. Spatial distribution of predicted prevalence rates of infection with *E. granulosus* and *E. multilocularis* in dogs in Xiji, Haiyuan, Guyuan and Tongxin counties, Ningxia Hui Autonomous Region, China in 2012-2013. A) *E. granulosus*; B) *E. multilocularis*; C) and D) corresponding standard deviations.

and high levels of interaction between domestic dogs and humans are risk factors identified commonly in AE endemic-regions in north-western PR China (Craig *et al.,* 2000; Craig, 2006; Schantz *et al.,* 2003; Tiaoying *et al.,* 2005), including NHAR (Yang *et al.,* 2006c). High prevalence rates of dog infections with *E. multilocularis* have also been reported in highly endemic areas for AE (Budke *et al.,* 2005a; Xiao *et al.,* 2006; Ziadinov *et al.,* 2010). Therefore, there is evidence that suggests dogs are an important reservoir of infections in humans (Romig *et al.,* 2017). However, the observed differences in the geographical distribution of the predicted prevalence of the infection in both hosts may suggest greater importance of other definitive host species in transmitting the parasite in the south of NHAR. The transmission of *E. multilocularis* through life cycles that involve both Tibetan sand foxes (*Vulpes ferrilata*) and domestic dogs has been reported in Sichuan Province (Vaniscotte *et al.,* 2011). Similar transmission patterns have been described in areas of the Altai, Tien Shan and Pamir mountains in the south of Kyrgyzstan and Kazakhstan (Ziadinov *et al.,* 2008; Ziadinov *et al.,* 2010). There, red foxes (*V. vulpes*) were identified as principal definitive hosts, while domestic dogs were identified secondary definitive hosts of *E. multilocularis* (Ziadinov *et al.,* 2008; Ziadinov *et al.,* 2010). Reports of infection with *E. multilocularis* in red foxes in NHAR are only available for the mid-1980's (Li W *et al.,* 1985). At that time, 15% of trapped red foxes were infected with *E. multilocularis* in Xiji and Guyuan Counties (Li W *et al.,* 1985). Although infection with *E. multilocularis* has also been described in wolves (*Canis lupus*) and corsac foxes (*V. corsac*) in other parts of PR China (Craig *et al.,* 2000), corsac and red foxes are presumed absent in areas of high risk of human AE in Xiji County (Giraudoux *et al.,* 2013a). Hence, there is still a need for a more holistic approach that can help identify other important predator-prey communities in the area and other potential key definitive host for this parasite species in the region.

The results indicate that differences in vegetation, as indicated by EVI values, played a key role in explaining the observed spatial variation in the seropositivity for *E. multilocularis* among children aged 6-18 years, and infections with *E. granulosus* and *E. multilocularis* in dogs in the four counties. In addition, a positive association was found between dog infection with *E. granulosus* and cultivated land and a negative association between human seropositivity for *E. granulosus* and bare-land/artificial surfaces. Associations between land cover and the spatial distribution of *E. multilocularis* seropositivity in humans and intermediate hosts are well documented in Eastern France, South Gansu, western Sichuan and Qinghai Provinces and in the South of NHAR (Giraudoux *et al.,* 2003; Giraudoux *et al.,* 2006; Giraudoux *et al.,* 2013b; Pleydell *et al.,* 2008; Wang *et al.,* 2004; Wang *et al.,* 2006). The previous study conducted in Xiji County indicated that the abundance of degraded lowland pasture was associated with a higher prevalence of AE in humans (Pleydell *et al.,* 2008). The presence of 16 species of small mammals communities was also revealed in a survey of small-mammal conducted in relation to different land cover types in the same area (Raoul *et al.,* 2008). That survey also showed that in areas that experienced afforestation, species diversity was lower than that in deforested areas (Raoul *et al.,* 2008). However, the richness of the species was not affected by land conversion processes (Raoul *et al.,* 2008). In abandoned grasslands and recently afforested set-aside fields, there was higher trapping success of potential intermediate hosts for *E. multilocularis* such as *Cricetulus longicaudatus* and *Ochotona daurica*, while in young plantations the species *Spermophilus alashanicus/dauricus* were

observed (Raoul *et al.,* 2008). Reports of the link between foxes and the landscape in France are available (Pleydell *et al.,* 2004). The evidence indicates that these associations are based on the influence of specific ecology characteristics on intermediate host population dynamics (Giraudoux *et al.,* 2013a).

With regard to climatic covariates, the observed non-linear relationship between human AE prevalence and the values of winter and summer temperatures at the 5 years prior to the survey are consistent and interpretable with animal population dynamics, predator-prey interactions and the biology of the parasites. Temperature has been identified as a contributing factor that affects the geographical range and composition of foxes and small mammal communities (Hersteinsson and Macdonald, 1992; Moritz *et al.,* 2008; Zhenghuan *et al.,* 2008). Experimental studies indicate that the *Echinococcus* spp. eggs develop at temperature-dependent rates in the external environment (Veit *et al.,* 1995). The optimal temperature range for their survival has been established to be between 0 °C and 10 °C (Veit *et al.,* 1995). However, differences have been found between species and strains (Thevenet *et al.,* 2005; Veit *et al.,* 1995). Temperatures of 4 °C and of – 18 °C particularly, are well tolerated by *E. multilocularis* eggs with survival times of 478 and 240 days, respectively (Veit *et al.,* 1995). Also, the evidence show that these eggs, if suspended in water, can remained infectious for a longer time than when exposed to heat (Federer *et al.,* 2015).

Current estimates of the burden of human echinococcoses in NHAR rely primarily on data collected from hospital records (Yang *et al.,* 2006b; Yang *et al.,* 2006c). These data include primarily symptomatic patients who seek medical care (Yang *et al.,* 2006a; Yang *et al.,* 2006b). Therefore, it is assumed that the extent and distribution of human CE and AE cases occurring in remote areas and asymptomatic infections may be underestimated in current epidemiological reports (Yang *et al.,* 2006b). In 2005, the National Control Programme against echinococcoses was developed by the National Health and Family Planning Commission (formerly the Ministry of Health) in PR China. The measures that are currently being implemented in endemic areas include: community-based epidemiological surveys for early detection, treatment and surveillance of the disease, education campaigns to increase awareness among local people and health officials, and regular anthelmintic treatment for deworming of dogs (World Health Organization and World Organisation for Animal Health, 2011; Yang *et al.,* 2006c). Prevalence data on these infections are essential for enhancing these control activities and monitoring their cost-effectiveness and sustainability over time. Therefore, the findings of this study indicate that there is scope for the predictive maps created here to inform and guide spatially targeted interventions in those areas where they are most necessary. An additional benefit of this type of approach is that the maps allow monitoring of the transmission patterns of *E. granulosus* and *E. multilocularis* based on local environmental factors. In this way, it is possible to provide detailed information on the potential health effects of anthropogenic environmental change factors, including those that are associated with the implementation of national policies to recover the degraded landscape.

An important limitation of the study was the use of specific antibody testing by enzyme linked immunosorbent assay using *E. granulosus* cyst fluid antigen B and *E. multilocularis* crude protoscolex extract to define seropositivity of schoolchildren to *E. granulosus* and/or *E. multilocularis*. These tests have poor diagnostic performance with limited specificity and cross-reactivity with

other helminth infections and gastrointestinal malignancies (Brunetti *et al.,* 2010; Torgerson *et al.,* 2009). However, serology, although not ideal, is the only diagnostic method available for small echinococcosis lesions that are probably asymptomatic. Therefore, follow-up examination is recommended to confirm the infections.

Conclusions

This work provides detailed information regarding the geographical distribution of echinococcoses in humans and dogs in NHAR. The different models developed in this study indicate that human seropositivity for *E. granulosus* and dog infection with *E. granulosus* are widespread across the southern part of the Autonomous Region. Discrepancies in the geographical distribution of human seropositivity for *E. multilocularis* and dog infection with *E. multilocularis* suggest that further research is required to better understand the transmission dynamics of this parasite species. The results presented help to identify priority areas for echinococcosis control and may be used to target interventions where they have the greatest impact on the transmission of the infections.

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