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Infectious Diseases of Poverty

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The landscape epidemiology of echinococcoses

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Abstract

Echinococcoses are parasitic diseases of major public health importance globally. Human infection results in chronic disease with poor prognosis and serious medical, social and economic consequences for vulnerable populations. According to recent estimates, the geographical distribution of *Echinococcus* spp. infections is expanding and becoming an emerging and re-emerging problem in several regions of the world. Echinococcosis endemicity is geographically heterogeneous and over time it may be affected by global environmental change. Therefore, landscape epidemiology offers a unique opportunity to quantify and predict the ecological risk of infection at multiple spatial and temporal scales. Here, we review the most relevant environmental sources of spatial variation in human echinococcosis risk, and describe the potential applications of landscape epidemiological studies to characterise the current patterns of parasite transmission across natural and human-altered landscapes. We advocate future work promoting the use of this approach as a support tool for decision-making that facilitates the design, implementation and monitoring of spatially targeted interventions to reduce the burden of human echinococcoses in disease-endemic areas.

Keywords: Landscape epidemiology, Helminth infection, Human echinococcosis, *Echinococcus* spp, Environmental change, Geographic information systems, Remote sensing, Geostatistics

Multilingual abstracts

Please see Additional file 1 for translations of the abstract into the six official working languages of the United Nations.

Introduction

Landscape epidemiology is the study of the spatial variation in disease risk, in strong connexion with landscape characteristics and relevant environmental factors that influence the dynamics and distribution of host, vector and pathogen populations. The fundamental concepts of landscape epidemiology were formalised and introduced by the Russian parasitologist, Pavlovsky, in 1966 [1]. According to Pavlovsky, landscape epidemiology is based on three observations: first, diseases tend to be limited geographically; second, the spatial variation in the distribution of a disease is determined by variations of physical and/or biological conditions that support a pathogen, its vectors and reservoirs; and third, the contemporaneous and future risk of a disease can be predicted if those conditions are mapped [2]. This conceptual framework has been developed and extended progressively to integrate concepts and approaches from multidisciplinary studies, including landscape ecology, for a better understanding of the complex composition of the landscape and its relationship with the transmission processes and geographical distribution of a disease [3–5]. The current principles of landscape epidemiology have been recently summarised in a set of propositions outlined by Lambin and colleagues (Table 1) [6].

Most modern landscape epidemiological studies use Earth observation (EO) to obtain remotely sensed (RS) and in situ data about the environment [5]. Geographic information systems (GIS) are used to capture, store, analyse and display geo-referenced data that may be exported to various analytical and statistical platforms [5]. The integrated use of these technologies and the application of spatiotemporal statistics allow investigators

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Table 1 The 10 principles of landscape epidemiology proposed by Lambin and colleagues

Principle	Description
1	Landscape attributes may influence the level of transmission of an infection
2	Spatial variations in disease risk depend not only on the presence and area of critical habitats but also on their spatial configuration
3	Disease risk depends on the connectivity of habitats for vectors and hosts
4	The landscape is a proxy for specific associations of reservoir hosts and vectors linked with the emergence of multi-host disease
5	To understand ecological factors influencing spatial variations of disease risk, one needs to take into account the pathways of pathogen transmission between vectors, hosts, and the physical environment
6	The emergence and distribution of infection through time and space is controlled by different factors acting at multiple scales
7	Landscape and meteorological factors control not just the emergence but also the spatial concentration and spatial diffusion of infection risk
8	Spatial variation in disease risk depends not only on land cover but also on land use, via the probability of contact between, on one hand, human hosts and, on the other hand, infectious vectors, animal hosts or their infected habitats
9	The relationship between land use and the probability of contact between vectors and animal hosts and human hosts is influenced by land ownership
10	Human behaviour is a crucial controlling factor of vector-human contacts, and of infection.

to explore in detail the landscape patterns that influence the transmission dynamics of an infectious disease at different spatiotemporal scales. EO, GIS and the use of innovative analytical methods also provide the opportunity to visualise and predict the geographical variations in disease risk in response to shifting environmental patterns [7, 8]. In this way, landscape epidemiology may offer a feasible and acceptable framework to reduce disease burdens by allowing a more precise estimation of populations at high risk and the identification of priority areas where allocation of disease control resources is most required [9].

To date, landscape epidemiology has been mainly applied to examine associations between the environment and the transmission dynamics of mosquito-borne diseases such as malaria, dengue, leishmaniasis, filariasis and trypanosomiasis [10–13]. However, with the advent of global environmental change, there has been an increasing interest in conducting studies centred on the understanding of the landscape epidemiological aspects of non-mosquito-borne helminth infections, such as schistosomiasis [14–16]. This approach has been successful in providing valuable information to enhance the implementation of strategies for surveillance, control and elimination of helminth infections in various settings [17–19].

Echinococcoses are zoonotic parasitic diseases caused by larval stages of taeniid cestodes of the genus *Echinococcus*. Currently, there are nine recognised species within the genus and six of these species cause infection in humans, *E. granulosus*, *E. multilocularis*, *E. canadensis*, *E. ortleppi*, *E. vogeli* and *E. oligarthrus* [20, 21]. Among them, *E. granulosus*, the main aetiological agent of cystic echinococcosis (CE), and *E. multilocularis*, the causative agent of alveolar echinococcosis (AE), are the species of major public health importance globally [22]. Both have a wide geographic distribution and cause severe disease in humans that can be fatal if left untreated [23–25]. The other two less common forms of human infection are polycystic echinococcosis and unicystic echinococcosis caused by *Echinococcus* species restricted to Central and South America [25].

There are approximately 200,000 new cases of human CE or AE cases diagnosed every year and a total of 2–3 million people infected worldwide [26, 27]. According to the *Office International des Epizooties* databases and published case reports, the estimated human burden of CE measured in terms of Disability-Adjusted Life Years (DALYs) lost is 285,407. When underreporting in accounted for, the global burden of this form of infection exceeds 1 million DALYS, which results in an annual estimated cost of $760 million [26]. Global estimates of AE suggest that there are approximately 18,235 people infected every year and a total of 0.3–0.5 million AE cases diagnosed worldwide. Most of the disease burden of AE is focused on Western China and results in the loss of 666,434 DALYs per annum [28]. Although these reports may be underestimates due to challenges with the early detection of the diseases and lack of mandatory reporting in most countries, it is apparent that the burden of echinococcoses has increased in recent years and human infection is becoming an emerging or re-emerging problem in several regions in the world [29–36]. Consequently, landscape epidemiological approaches have been incorporated progressively into echinococcosis research to identify the environmental mechanisms underlying the variation in disease risk and the most plausible drivers of parasite dispersion [37–43].

This review aims to describe the potential applications of landscape epidemiological studies to establish, quantify and predict the geographical distribution of human echinococcoses and as a decision-making tool to enhance the implementation of spatially targeted interventions against the disease. First, the review describes important epidemiological features of the parasite and discusses some of the most relevant biophysical environmental factors that may affect the distribution of echinococcosis risk at different spatial scales. Next, the review describes how landscape epidemiology may use geospatial resources and techniques to improve the understanding of the transmission dynamics of *Echinococcus* spp., and facilitate the strategic allocation of resources for interventions to the appropriate geographic locations. Finally, challenges and gaps in the current evidence are identified and research priorities to support the surveillance and control of human echinococcoses are proposed.

Search strategy

A search was conducted of literature including all relevant articles that were published until September 2015, identified from Medline, Google Scholar, PubMED and Web of Knowledge. The key terms used in the search strategy included one word and/or phrase from each of the following three categories: first, terms related to the disease, including zoonoses, parasitic disease, helminth infections, human hydatidosis, hydatid cyst, cystic echinococcosis and alveolar echinococcosis; second, terms related to risk factors for parasite transmission, including environmental influences, climate change, anthropogenic environmental factors, and landscape; and third, terms related to the analytical approach, including landscape epidemiology, risk mapping, geographic information systems, remote sensing, Bayesian analysis, geostatistics and geospatial techniques and/or methods. Additionally, secondary searches were conducted in reference lists of peer-reviewed studies. The language of the literature was restricted to English.

Environmental determinants of the multi-spatial variation in human echinococcosis risk

Echinococcus spp. have complex domestic and sylvatic life cycles that involve a wide range of intermediate and definitive hosts. Therefore, echinococcosis transmission can take place in different landscape types in which a variety of physical and biological factors combine to determine the transmission intensity of the parasite [25]. Although these factors remain poorly understood, it is apparent that the environment plays an important role in the life cycle of *Echinococcus* spp. Climate and landscape structure influence particularly human behaviour, animal population dynamics, spatial and temporal overlap of intermediate and definitive hosts and the survival of the parasite eggs [41, 44–47]. Humans, who become infected by ingesting the parasite eggs directly through contact with definitive hosts or indirectly from a contaminated environment, are regarded as accidental intermediate hosts who do not usually contribute to the developmental cycle of the parasite. However, reports from hyperendemic areas in north-western Kenya indicate that humans may act as intermediate hosts in the life cycle of the parasite under unique circumstances. The close human-dog relationship and the absence of burial customs among the Turkana people in this region, seem to have made possible the transmission of *E. granulosus* from tribesmen to dogs or wild carnivores which are able to access and scavenge potentially infected human remains [48]. Comprehensive reviews of the parasite life cycle, environmental factors influencing parasite transmission, clinical manifestations, diagnosis and management of the disease are available [22, 25, 44, 49].

There is an important spatial dimension in the relationship between the risk of echinococcosis infection and environmental factors that influence both the distribution of the hosts and the rate of development of the parasite [45, 50]. Despite the extent of epidemiological variations within the genus *Echinococcus*, a general framework may be used to describe factors driving the transmission of the parasite at the continental, sub-continental and local spatial scales. At the continental level, echinococcosis risk may be related to the philogeography (biogeography) of animal communities and to variations in climatic conditions that control the presence/absence of host species within a particular landscape type [41]. At the sub-continental level, the spatiotemporal patterns of echinococcosis risk depend upon animal population dynamics, predator–prey interactions and parasite free living stage survival. Thus, at this spatial scale, the infection is likely to be associated with landscape characteristics, such as composition (variety and abundance of patch types in the landscape), and configuration (spatial arrangement and complexity of patches present in the landscape) that together with climatic factors determine the seasonal and interannual variation in population density of the hosts, parasite free stage survival, and subsequently the geographical distribution of *Echinococcus* spp. [50].

To date, most studies conducted at sub-continental spatial scale have focused on describing the role of landscape composition in determining the risk of infection with *E. multilocularis* in wildlife [41–43, 51–55]. In eastern France, high population densities of *Microtus arvalis* and *Arvicola terrestris*, vole species that are key intermediate hosts for *E. multilocularis*, were identified in areas where ploughed fields were converted into permanent grassland as a result of the local specialisation in milk production in the 1960s and 1970s [41, 56]. In addition, significant positive relationships between percentage of area covered by grassland and *E. multilocularis* infection in humans and foxes have also been reported in the same region [39, 41, 57]. Studies conducted in Zhang County, Gansu Province, China, indicated that the transmission of *E. multilocularis* may be related to the transient augmentation of grassland/shrubland following a period of deforestation. In this hyperendemic area for AE, land cover change favoured the creation of optimal peri-domestic habitats for AE intermediate host species, and the development of a peri-domestic cycles involving dogs [41, 58]. In AE-endemic areas from the north-western part of Sichuan Province on the Tibetan Plateau, private partial fencing has been common among Tibetan pastoral communities since the 1980s. This practice allows the creation of private grazing areas to support livestock during the winter period and early spring. Although fenced pasture has reduced grazing pressure in private areas, it has also exacerbated overgrazing in common lands and has improved suitability of habitats for various rodent species that are vulnerable to the parasite. As a result, the risk of AE has also increased in the region [54, 59, 60]. By contrast, in northern Japan, grey-sided voles form large populations in dense bamboo undergrowth of forest. Since this land cover is natural vegetation, AE prevalence in this part of the country appears to be not related to anthropogenic landscape changes [61, 62].

Despite compelling evidence supports the association of the environment with the spatial variation of *E. multilocularis* infection in sylvatic systems [41, 43, 51–55, 63], little is known about the host-environment interactions that take place at sub-continental levels to regulate the transmission of *E. granulosus* in domestic settings, where dogs are identified as typical definitive hosts, and sheep and other ungulates, as intermediate hosts [25]. Livestock like any other animal system can be influenced by climate and landscape resources that shape animal feeding behaviour, growing rates, reproductive efficiency and immunological mechanisms that protect against pathological and non-pathological stressors [64]. Heat stress, particularly, declines feeding intake, conception rates and the immune response to infectious diseases in sheep and cattle [64, 65]. Therefore, climate change and landscape transformation, together with high level of environmental contamination with parasite eggs have the potential to affect parasite transmission intensity not only in wildlife but also in urban settings, and consequently increase the risk of human CE. Reports from abattoir meat inspections suggested seasonal variations in the prevalence of *E. granulosus* infection in Iran and Saudi Arabia [66, 67]. Additionally, high altitudes and annual rainfall were associated with high infection rates of CE in livestock from hyperendemic regions for this infection in north-central Chile and Ethiopia [68, 69]. The observations from these countries were explained by factors such as sources of slaughtered animals, different animal age-structures among seasons, changes in agricultural management practices and environmental factors. The geographical location of livestock farms and the animal spatial structure also appeared to have an important effect on the prevalence of CE in the Campania region of southern Italy. Using geo-referenced data, a survey conducted in this region suggested that the significantly higher prevalence of CE on cattle farms compared to water buffalo farms was associated with their closer distance to potentially infected sheep [70].

At local or community spatial scales, microclimate is one of the most significant factors underlying the variation in the risk of echinococcosis infection [46, 47]. Temperature and moisture/humidity, particularly, are major determinants of the survival and longevity of the parasite eggs in the external environment [46, 47]. Although the optimal temperature range for egg survival has been estimated to be between 0 and 10 °C, the tolerance of the eggs to external environmental conditions varies between parasite species and strains [46, 47]. For *E. multilocularis* eggs, temperatures of 4 and of −18 °C were found to be well tolerated, with survival times of 478 and 240 days, respectively [46]. In addition, a recent study showed that *E. multilocularis* eggs are more resistant to heat if suspended in water compared to eggs exposed to heat on a filter paper at 70 % relative humidity. Eggs suspended in water can remain infectious for up to 120 min if expose to temperatures of 65 °C [71]. In vivo studies also revealed that the eggs of *E. granulosus* remain viable and infective after 41 months of exposure to an inferior arid climate, which is characterised by large thermal amplitude (from −3 to 37 °C), with warm summers, cold winters and low precipitation (under 300 mm/year) [47].

At the local level, human behavioural changes, driven in large part by population growth and economic and technological development, have been associated with the creation of novel interactions between humans, domestic animals and wildlife [72]. This new human-environment interplay also appears to be altering human exposure to *Echinococcus* spp. by facilitating the establishment and introduction of competent intermediate and definitive hosts in the life cycle of the parasite [73, 74]. Foxes, the primary definitive host of *E. multilocularis*, take advantage of the most accessible and abundant resources of water and food. Therefore, the reported movement of foxes towards urban areas, where the transformed landscapes provide optimal conditions for surges of small mammal species, have explained the observed higher circulation of the parasite within local urban landscapes [73]. In addition, the role of dogs in semi-domestic life cycles of *E. multilocularis* appears to be the result of human-related activities in certain communities where dog ownership and close association between humans and dogs were identified as significant predictors of human AE risk. [75–77]. Similarly, reports have revealed that urban coyotes are currently playing a key role in the maintenance of the life-cycle of *E. multilocularis* within North American urban settings [78].

Genetic factors and immunological interactions between the parasite and hosts are also associated with echinococcosis risk at local and community levels. These factors affect the development of the adult parasite in the intestine of definitive hosts and determine the time course of the production and viability of the eggs [79]. Genetic and immunological factors also govern differences in the reproductive potential of the hosts and influence the susceptibility/resistance of humans and animals to the infection [80]. Patients with impaired immune response appear to have increased susceptibility to *E. granulosus* and *E. multilocularis* infections, and are more prone to develop severe disease [81–83]. Similarly, an increase risk of infection with *E. multilocularis* has been observed in experimental immunosuppressed animals [80]. Figures 1 and 2 show a conceptual diagram of the environmental factors influencing the transmission dynamics of *E. granulosus and E. multilocularis*, respectively, at different spatial scales.

The use of landscape epidemiological approaches to understand the transmission dynamics of *Echinococcus* spp.

The inherently multi-scale nature of the life cycle of *Echinococcus* spp. has represented a challenge to comprehensively understand the mechanisms that govern parasite transmission and the subsequent variation in disease risk [79, 84]. However, over the past decade, advances in EO, that have led to the increased availability of high-quality environmental data, and developments in GIS and methods for spatial analysis have improved the ability of investigators to explore and predict the spatio-temporal dynamics of echinococcosis infections.

Much progress has been made in the use of geospatial technologies to map the prevalence of infection with *Echinococcus* spp. and identify space-time clusters of human disease in various settings [58, 70, 85–88]. With global environmental change, there has been a growing interest in determining the role of climatic factors and the process of landscape transformation in the recent observed patterns of parasite transmission. Thus, deforestation, grazing practices, climate variability and direct or indirect control of intermediate and definitive hosts

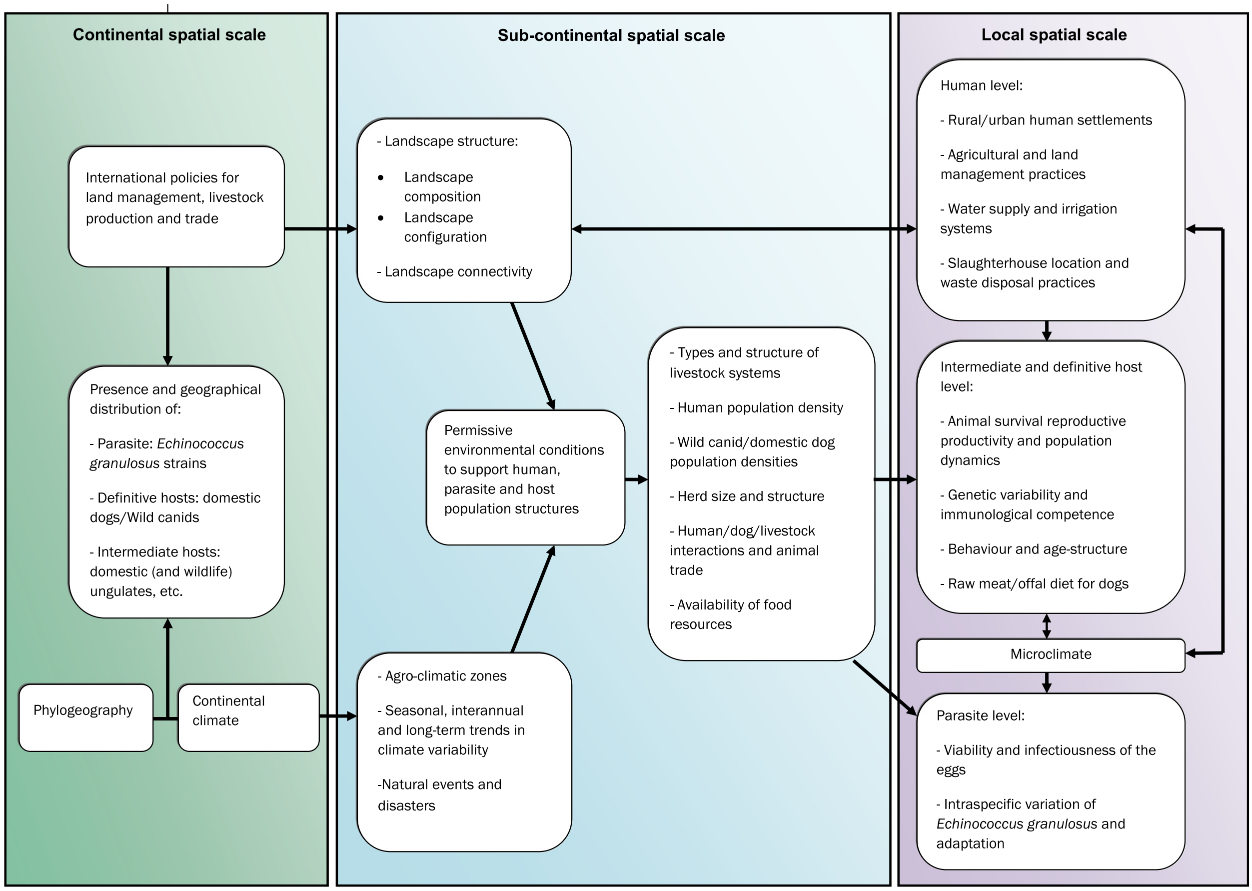

Fig. 1 Conceptual diagram of the environmental factors influencing the transmission dynamics of *Echinococcus granulosus* at different spatial scales

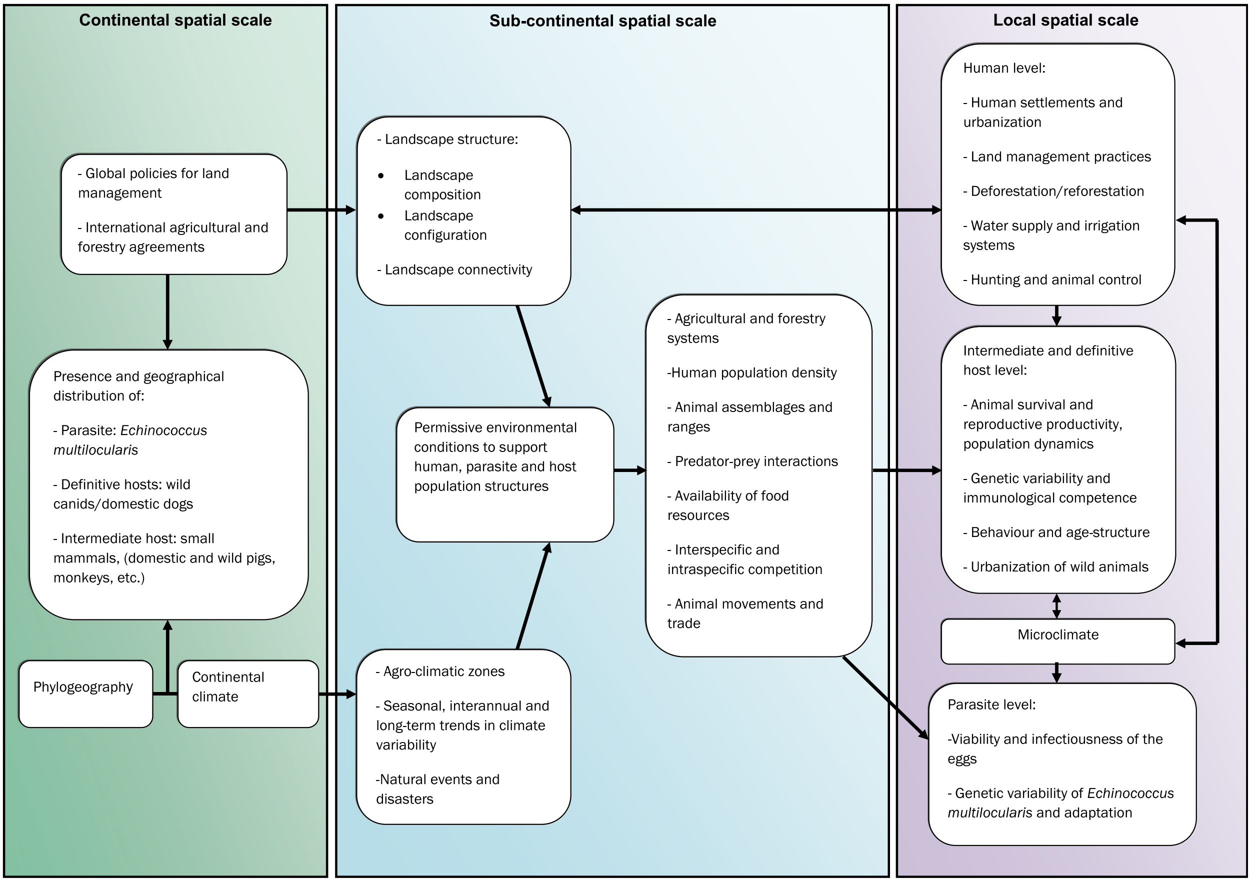

Fig. 2 Conceptual diagram of the environmental factors influencing the transmission dynamics of *Echinococcus multilocularis* at different spatial scales

are currently being studied as potential environmental factors that have favoured the persistence and geographical expansion of the parasite [41, 43, 61, 75].

Landscape epidemiology uses a wide variety of data and statistical techniques [5]. Accurate data, both in space and time, are required to develop statistical models that describe the complex associations between the environment and the transmission of the parasite [89]. Data collected at a specific geographic location can be geo-referenced using spatial coordinates, such as those obtained from global positioning systems (GPS). By contrast, data collected from a defined spatial region, such as clinical surveillance data for an administrative area, are geo-referenced by specifying the administrative boundaries, with some associated limitations for subsequent spatial analysis [89]. Because reporting of echinococcosis infections is not mandatory in most countries, epidemiological data are usually fragmented and scarce. In most endemic areas, human cases are primarily identified through clinical case reports, hospital records or mass screening surveys that usually combine questionnaires based-interviews, abdominal ultrasound and specific serology tests [90–93]. These initiatives have resulted in a valuable source of geospatial data for the estimation of echinococcosis risk at local and regional spatial scales, and at certain points in time in several endemic regions. However, these represent inefficient measures that are difficult to sustain in the long term [43]. The European Echinococcosis Registry (EurEchinoReg) Project was the first attempt to establish a continent-wide database for echinococcosis, with the aim being to estimate the impact of AE in western and central Europe. However, the routine collection of data by individual countries has been heterogeneous in terms of completeness and reliability across regions [94]. Since the beginning of the project, Austria, France, Germany and Switzerland are among the few countries that have maintained population-based human AE data registries that can be used to analyse patterns of this form of disease at various spatial scales [94–96].

In addition to data on human echinococcosis cases, data on environmental factors and survey data to determine the presence of echinococcosis host species and their infection status may also be combined in landscape epidemiological studies [45]. Although infection in definitive and intermediate hosts are key indicators of the presence of the parasite in the environment, the identification of infected animals does not directly reflect transmission pressures of *Echinococcus* spp. to human populations. Nevertheless, it can be assumed that environmental processes that support variation in host population densities are also likely to influence the risk of human infection [31, 41]. Sources of EO for environmental data include satellite remote sensing and spatially distributed in situ sensors, such as meteorological stations [97]. EO and its derived products provide extensive coverage of vast areas of the earth at periodic intervals. In the case of in situ data, interpolation methods can be applied to obtain data for those locations where there are no meteorological observations locally available [98, 99]. Currently, a wide range of high-quality environmental datasets are freely available and can be used to identify continental, sub-continental or local environmental variability [97]. The International Union for Conservation of Nature has also created databases for mapping the distribution of animal species, including most definitive and intermediate hosts of *Echinococcus* spp. [100]. The environmental variables most commonly used in echinococcosis research include altitude, temperature, precipitation, land cover, land use, vegetation indices and geographical distribution of the hosts [44, 75].

The characterisation and prediction of echinococcosis risk using landscape epidemiology can be achieved by using geospatial resources and spatial analysis methods that allow visualisation, exploration and modelling of multi-source geo-referenced data. Among them, GIS mapping and cluster detection techniques are useful tools that have been widely applied in echinococcosis research to prioritise areas for further studies and plan preventive and control interventions [70, 95, 101–103]. In general, these methods have indicated that echinococcosis infections have a focal spatial distribution, with defined areas at high risk for parasite transmission between definitive and intermediate hosts, in which the prevalence or incidence of human disease may be higher than in surrounding areas. Examples include studies undertaken in France, Japan and China, countries heavily affected by AE. In these countries, the evidence has suggested that the number of human cases of AE is a nested hierarchy of spatial aggregates in the eastern part of France. Aggregative distribution has also been shown in the northern island of Hokkaido, Japan, and in provinces located in the central and western part of China, where the Qinghai-Tibetan plateau has been identified as the geographic area with the highest rates of human AE recorded globally [41, 104, 105]. Similarly, epidemiological studies in north-western China revealed much higher prevalence of CE among local communities from the Tibet Autonomous Region, Xinjiang Uygur Autonomous Region, Ningxia Hui Autonomous Region (NHAR), and Sichuan and Qinghai Provinces [106]. Demographic, socio-economic and human behavioural factors are also variables that have been commonly explored as potential factors interacting with the environment to determine the heterogeneous spatial distribution of echinococcoses in several endemic regions. The Buddhist doctrine among pastoral communities that allows old livestock to die naturally, coupled with the practice of unrestricted disposal of animal viscera and the presence of free ranging dogs have been identified as factors influencing the high prevalence of human CE in Tibetan communities in China [106]. Significant difference in prevalence rates of human infection has also been observed between males and females. Women are more likely to be exposed to *E. granulosus* and *E. multilocularis* as a result of their daily family activities such as feeding dogs, herding livestock and collecting yak dung for fuel [85, 107, 108]. Additional risk factors found to be related to high risk of exposure to both parasite species include dog ownership, poor hygienic practices, low income and limited education. In contrast, the use of tap water has been identified as a factor that can protect against the disease [85, 93, 101, 107–109].

As a result of the apparently expanding geographical distribution of *Echinococcus* spp. [29–35], particular emphasis has recently been placed on the implementation of landscape epidemiological approaches that use spatial statistical techniques to identify environmental conditions that may be affecting the habitat suitability for sustaining the sylvatic life cycle of the parasite [42, 43, 53, 75, 110]. Spatial statistics are statistical methods that can be applied to explore geographically referenced data and investigate associations between the observed number of human cases and the most plausible factors that underlie the transmission dynamics of the parasite. On the basis of the information provided by this approach, traditional or spatially explicit statistical models can also be constructed to predict the spatial distribution of disease based on environmental variables. Of note, the statistical methods applied in epidemiology that fail to account for spatial autocorrelation in the variables used to model and predict disease risk, may possibly lead to erroneous statistical inference [111]. Thus, spatially explicit models that incorporate information on spatial autocorrelation, obtained using Bayesian methods are increasingly incorporated in landscape epidemiological research. Bayesian methods are sufficiently flexible to allow the development of complex hierarchical spatio-temporal models that quantify uncertainty in the analysis of disease risk by assuming that parameter values, including spatial predictions, vary as random quantities [112]. Predictive risk maps of echinococcoses that account for uncertainty estimates can be essential to inform decision-makers about the uncertainty and implications of the interventions against these infections [14, 113]. A Bayesian statistical framework was used in Xiji County, NHAR, China, for risk mapping and transmission modelling of human AE [43]. The study indicated that the landscape characteristics favouring *E. multilocularis* transmission in Xiji County differed from the previous observations in Zhang County located in the neighbouring Gansu Province. While grassland around villages did not correlate with the prevalence of human AE, abundance of degraded lowland pastures was associated with higher prevalence of the disease in Xiji County. From the results, it was possible to infer that *E. multilocularis* can sustain transmission through a diversity of host communities in China [43]. A similar Bayesian approach was carried out in Tibetan plateau communities, which led to confirm and predict human disease hotspots over a 200,000 km^2 region and showed that human AE risk was better predicted from landscape features [75].

Applications to surveillance, prevention and control programmes

Landscape epidemiology has been applied progressively in echinococcosis research, particularly AE research, in order to identify the environmental determinants of echinococcosis risk. However, there is still limited guidance on the practical implementation of this approach to improve echinococcosis surveillance and maximise the impact of prevention and control efforts.

Most of the evidence in the use of landscape epidemiology to support the effective implementation of interventions against infectious diseases has been obtained from studies of mosquito-borne diseases [10, 11, 13], and non-mosquito-borne helminth infections, particularly schistosomiasis and soil-transmitted helminthiases [17–19]. At the global scale, atlases have been developed that may potentially guide international priority setting for investments in disease control and elimination [114–116].

In the context of echinococcosis surveillance and control, mass screening surveys of echinococcoses have provided valuable data to help reduce the medical, social and economic burden of the infection by ensuring early detection and prompt treatment of human cases. However, this measure may be inefficient and resource intensive if implemented in areas of low prevalence of the disease. Echinococcoses affect particularly remote pastoral communities with low socioeconomic development that may have limited access to health care [108, 117]. Therefore, landscape epidemiological studies have the potential to assist local and national initiatives against echinococcoses such as the one launched by the Chinese government to reduce the impact of these infections in 217 endemic counties in western China [23, 118]. Such studies generate both quantitative evidence and visual representation of the geographical distribution of these diseases and allow a more precise estimation of populations at high risk. Updated maps of echinococcoses and accurate information about individuals and households at high risk may allow decision makers to optimally target resources and interventions for prevention and control.

In China, particularly, the current measures adopted against echinococcoses include community-based epidemiological surveys, patient treatment and monitoring, health education campaigns, and regular antihelmintic treatment for dog deworming [23, 118]. Under the strategic and operational context of these interventions and other potential strategies that may help reduce the burden of these infections in endemic regions, landscape epidemiological approaches represent a cost-effective measure not only to prioritise geographical areas at high risk, but also to identify the type of parasite control activity that is most required in specific locations. Deworming of wild foxes using baits with antihelmintic treatment is being established in some countries as a preventive technique against environmental contamination with *E. multilocularis* eggs [119–121]. In order to improve the cost-benefit performance of these efforts, spatial models were developed in Hokkaido, Japan, and in eastern France to identify the environmental factors that determine the most suitable micro-habitats for delivering the baits. The outcomes of these studies suggested that baiting programmes should be adapted to the local environmental characteristics of domestic and urban settings [119, 122].

Many of the relationships that have been explored in the studies outlined above have provided compelling evidence about the environmental conditions that together with socio-economic and demographic factors support the transmission of *Echinococcus spp.* in endemic regions. However, they fall short of allowing resource managers and policy makers to understand and anticipate the real impact of the infections, and the economic and medical implications of their decisions. Thus, approaches that incorporate the use of geospatial resources and spatial analysis to identify environmental drivers of echinococcoses can be applied as decision-making tools for the design of effective surveillance and response systems. In this way, landscape epidemiological studies may help monitor and predict parasite transmission based on changing environmental factors, and in response to the implementation of interventions for disease control. Most importantly, these approaches have the potential to guide echinococcosis control programmes in those regions with limited availability of surveillance data on echinococcoses [123].

The understanding of the landscape epidemiological aspects of echinococcoses may also provide scientific evidence that can be used to support environmental policy-making and landscape planning processes in hyperendemic areas for these diseases. Thus landscape epidemiology may also prove useful to promote environmentally-based strategies that have minimal impact on the transmission dynamics of the different *Echinococcus* spp. This is particularly relevant in regions where climate variability and landscape transformation may be facilitating the transmission of the parasite.

Previous studies conducted in echinococcosis-endemic regions have provided valuable insight into the landscape processes underlying the transmission of *E. multilocularis* at various spatial scales. However, most of these analyses involved environmental data collected at a single point in time and did not capture major environmental changes over time [50]. Because human echinococcoses may be the result of cumulative events that occurred over many years prior to the detection of the disease, the use of multi-temporal Earth observation datasets to identify environmental change will be necessary in order to conduct a meaningful landscape epidemiological analysis of the forms of human echinococcosis infections. Therefore, we advocate future research that incorporates time-series analyses of environmental data for the identification of the long-term trends in climatic and landscape conditions that may be facilitating the persistence and spread of *Echinococcus* spp. across heterogeneous landscapes.

Despite the potential applications of landscape epidemiology in echinococcosis research, it is evident that work is still necessary to address the limited availability of human echinococcosis data. Thus, further advances are required to improve long-term and multi-scale monitoring of these infections. We believe that the design and implementation of systematic and standardised protocols for the diagnosis, collection and recording of human cases may help to better estimate and monitor the prevalence of these infections in endemic areas, and also to increase awareness among all actors involved in the control of these infections. In addition, we also recommend the development of national and sub-national data collection systems to record all confirmed cases of echinococcoses identified through mass screening surveys or clinical and laboratory reports. Systematic surveillance systems may be used as efficient, reliable and secure data sources for the implementation of clinical and landscape epidemiological studies. Because echinococcoses are complex diseases that involve animal and human hosts, as well as ecological and environmental factors, integrated multisectoral efforts are clearly required to monitor the interactions between the landscape and parasite, hosts and human diseases. The availability of data on annual infection rates in humans, definitive and intermediate hosts in hyperendemic areas combined with annual averages of climate data and land cover change may be particularly useful to improve cost-effectiveness of small-scale campaigns and reduce local risk. These data are essential to establish pre-intervention baseline, monitor the efficacy of interventions and inform the strategic planning of future control measures.

Factors that need to be considered for the routinely implementation of these approaches include the availability of resources for collecting, processing, and modelling geospatial data at various spatial scales, training of personnel on the use of these technologies and the proper interpretation of results, and the continuous availability of high quality environmental data. It should be emphasized that the allocation of resources for the implementation of these novel techniques should not come at the cost of preventive and control efforts against the infections. Co-endemicity and polyparasitism are common in several regions of the world [124]. Therefore, initiatives to combine control strategies against human echinococcoses with other zoonotic diseases could potentially help to optimise resources, ensure sustainability of interventions and improve awareness among local people [124]. Major integrated programmes to map the distribution and enhance control strategies against some neglected tropical diseases such as onchocerciasis, lymphatic filariasis, soil-transmitted helminthiases and schistosomiasis are currently being implemented successfully in various regions [125]. In the context of echinococcoses, integrated dog control/deworming and health promotion may be proposed as a cost-effective measure to reduce the impact of these infections in highly endemic areas.

Conclusion

This review demonstrates the potential of landscape epidemiology to explore the complex life cycle of *Echinococcus* spp. that involves time-dependent interactions of multiple definitive and intermediate hosts at different spatial scales. Landscape epidemiology has also proven helpful in characterising the geographical distribution of human AE risk and in determining the association between the geographical patterns of infection and environmental factors. Therefore, the implementation of this approach together with the recent advances in geospatial technologies and spatial analysis techniques provide a unique opportunity to explore the causes of persistence, emergence and re-emergence of some parasite species in several regions, and a better guidance for the design, implementation and monitoring of preventive and control interventions.

Additional file

Additional file 1: Multilingual abstracts in the six official working languages of the United Nations. (PDF 336 kb)

Abbreviations

EO: Earth observation; GIS: geographic information systems; RS: remote sensing; CE: cystic echinococcosis; AE: alveolar echinococcosis; DALYs: disability-adjusted life years; GPS: global positioning systems; EURECHINREG: the European Echinococcosis Registry; NHAR: Ningxia Hui Autonomous Region.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AMCR and ACAC conceived the idea for the review. AMCR prepared the first draft of the manuscript. ACAC, YRY, DPM, DJG, PG, RJSM, TSB, GMW and NASH provided critical comments and helped in drafting subsequent revisions. AMCR and ACAC finalized the manuscript. All authors read and approved the final manuscript.

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