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An interactive map to assess the potential spread of *Lymnaea truncatula* and the free-living stages of *Fasciola hepatica* in Switzerland

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Abstract

The intermediate host of *Fasciola hepatica* is *Lymnaea truncatula* in Switzerland. The snail and the free-living stages of the parasite require a moderate climate and moisture for survival, reproduction, and transmission. In Switzerland, these conditions are present in many regions, resulting in a mean prevalence of bovine fasciolosis from 8.4 to 21.4%. An interactive map was created in order to demonstrate the relative risk of transmission by modelling the environmental conditions that promote the survival and reproduction of the larval stages of the parasite and the parasite's intermediate host. The map is based on temperature and rainfall data, soil conditions including ground water and forest cover in Switzerland. Extensive information on the free-living stages of *F. hepatica* and the intermediate host *L. truncatula* and how the development of these are affected by these environmental factors was used to create the interactive risk map.

Keywords: *Fasciola hepatica*; Risk modelling; Interactive map; Multimedia cartography; Switzerland

1. Introduction

Fasciolosis, caused by *Fasciola hepatica*, is a serious parasitic disease in Switzerland. Transmission depends on susceptible definitive hosts (e.g. sheep and cattle) and appropriate habitats for development of both the parasite larvae and the intermediate host *Lymnaea truncatula*. This snail requires a moderate climate and moisture for survival and reproduction (Thomas, 1883). In Switzerland, these conditions are present in many regions, resulting in a mean prevalence from 8.4 to 21.4% in cattle (Eckert et al., 1975; Ducommun and Pfister, 1991; Schweizer et al., 2003; Rapsch, 2005; Rapsch et al., 2006).

As a result of the widespread distribution of bovine fasciolosis, significant economic losses occur. This is due to confiscated livers, reduced milk yield, reduced fertility and reduced meat production. Median financial

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loss due to bovine fasciolosis in Switzerland is approximately €52 million (95% CI €22–92 million) per annum, which represents a median loss of €299 per infected animal (Schweizer et al., 2005). Suitable control strategies, such as pasture management strategies (Boray, 1971, 1972), could help to avoid some of these losses. Geographical information systems such as risk maps could help identify areas where disease monitoring should be established. Since *F. hepatica* transmission is linked to its intermediate host *L. truncatula*, information on suitable environmental conditions can help locate possible areas with enhanced infection risk by means of cartography.

The aim of this study was to create a map based on multimedia cartography illustrating regions with good environmental conditions for the development of *L. truncatula* and the free-living stages of *F. hepatica* as basis for the implementation of control strategies.

2. Material and methods

2.1. Risk model

The occurrence of *L. truncatula* and the transmission of *F. hepatica* mainly depend on temperature, moisture, soil conditions, and solar irradiation (Thomas, 1883; Kendall and McCullough, 1951; Ollerenshaw, 1959; Ross, 1970a; Armour, 1975; Christensen et al., 1976, 1978; Petzold, 1989). Therefore, a risk model was developed based on temperature, rainfall, soil condition and forest cover as these data were readily available. The model's output is an environmental relative risk measurement for the development of *L. truncatula* and the free-living stages of *F. hepatica* in Switzerland.

2.1.1. Environmental risk factor temperature

Development in the *F. hepatica* eggs starts at 10 °C and above (Thomas, 1883; Ollerenshaw, 1959). At low temperature risk is low, because development takes up to 6 months. There is an increased risk between 12 and 16 °C, but development still takes 2–3 months (Thomas, 1883). As the development takes only 2–3 weeks at temperatures of 23–26 °C, risk in this temperature range is high (Thomas, 1883; Christensen et al., 1978). The highest risk for the development of eggs is defined at 30 °C, where development only takes 8–10 days. Above this temperature, there is a rapid decrease of risk, as eggs die at temperatures above 30 °C (Andrews, 1999).

The temperature-dependent survival time and host-finding capacity of the miracidia has been described by Christensen et al. (1976) in detail. Due to the short life span of miracidia, this stage can be omitted, as temperature ranges favourable for eggs and snails will also be beneficial for the miracidia.

Snails can survive and reproduce at a temperature range from 10 to 25 °C (Kendall and McCullough, 1951; Armour, 1975). The maximal risk that the snail contributes to the overall infection risk can be defined between 22 and 25 °C since such temperatures provide optimal growth conditions for the snail (Williamson and Wilson, 1978; Petzold, 1989). Starting from a relative risk of 30% at 10 °C, the relative risk increases and achieves a percentage of 85% of the maximum at a temperature of 18 °C. Above temperatures of 25 °C, the risk declines rapidly and can be considered as approximately 0.

As neither eggs nor snails develop at temperatures below 10 °C, the overall infection risk can be set to 0 below 10 °C.

On the base of a study by Kendall and McCullough (1951), migration risk was assumed to be constant between 10 and 25 °C. At 10 °C relative risk increases abruptly from 0 to 100% and decreases abruptly at 25 °C to 0%. Since this is a uniform distribution, this step of the parasite cycle can be disregarded, as relative risk would only change at one constant.

The temperature-dependent risk curve of metacercaria is much more complex. At a temperature of 2–5 °C 10% of the metacercaria survive for a year. From 12 to 14 °C metacercaria survive up to 6 months, hence the relative risk that the metacercaria contribute to the whole temperature-based infection risk reaches its maximum at 13 °C. Survival time decreases with increasing temperatures. At 20 °C, the risk contribution equals approximately 60% of the maximum with an estimated survival time of 8 weeks. The risk contribution declines down to 35% at 25 °C, taking into account that the survival time of the metacercaria is less than 6 weeks. The temperature-based risk contribution of metacercaria can be neglected for higher temperatures (Andrews, 1999).

2.1.2. Environmental risk factor rainfall

It is known that snails need moisture and rainfall for survival and reproduction (Frömming, 1956).

Several forecast models are based on monthly rainfall data to predict relative monthly or seasonal infection risk (Ollerenshaw and Rowlands, 1959; Ollerenshaw and Smith, 1969; Ross, 1970b; Malone et al., 1987). But none of them is based on monthly means over several years to predict potential risk regions. Hence, the following approach was made: rainfall has a positive effect upon all free-living stages of the parasite and the intermediate host. Thus, risk frequency increases with increasing rainfall, with a maximal risk at approximately 90 mm per month. However, large amounts of rainfall can wash away parasite larvae and snails and separate them from each other, thus inhibit transmission. Therefore, amounts of more than 210 mm are considered to decrease the risk frequency rapidly.

2.1.3. Environmental risk factor soil condition

L. truncatula prefers small water courses (pools, small streams, drainage ditches, e.g.; Frömming, 1956). It is assumed, that these small water bodies are more likely to occur with suitable soil condition and ground water, as clay soils are more water retentive than sandy soils (Ollerenshaw and Smith, 1969).

F. hepatica infection in *L. truncatula* is modelled as a function of soil conditions including ground water by an ordinal variable in four categories. Category 4 indicates a humid, rank soil with ideal conditions for transmission and hence the maximum soil condition risk is attributed to this category. Category 3 represents soil with much vegetation and bears an estimated relative contribution of 75% compared to the maximum soil condition risk since transmission risk in such areas is still high. Category 2 stands for dry soil with few vegetation which will delay or even reduce the transmission. The relative risk compared to the maximum soil condition risk is set to 25%. Category 1 represents stony regions without or with negligible vegetation where no transmission of *F. hepatica* will take place and hence for this category, the soil condition risk is set to 0.

2.1.4. Environmental risk factor forest

Low level solar radiation has a negative effect on the occurrence of *L. truncatula*, as there is an insufficient growth of algae to feed snails (Petzold, 1989). For this reason it is assumed, that there is no risk for fasciolosis in forest. Hence the risk as function of the factor forest can be considered as a binary variable, taking value 0 when forest is present and hence no potential transmission is assumed, else 1 (100%).

2.1.5. Environmental data

The mathematical model used in this paper requires real data of the environmental factors in order to evaluate the overall risk density distribution for each cell of 100 m $\times$ 100 m in Switzerland over the year (best resolution possible based on the available data). The mean monthly temperature and rainfall from 1994 to 2004 was obtained from MeteoSwiss (www.meteoschweiz.ch) and from the Atlas of Switzerland (www.atlasofswitzerland.ch), the soil conditions including ground water from the Atlas of Switzerland and the forest distribution in Switzerland also from the Atlas of Switzerland.

The temperature data from 24 representative Swiss meteorological stations were calculated for an altitude of zero meters using regression analysis and the digital elevation model of Switzerland DHM25 (swisstopo). A polynomial interpolation was used to calculate the monthly temperature across the entire area of Switzerland. Afterwards, the temperature was adjusted to altitude also with the digital elevation model of Switzerland DHM25 (swisstopo).

2.1.6. Combination of the environmental risk factors

To obtain an overall risk density distribution based on the environmental factors as described above, a risk density distribution for each of the risk factors separately is defined. The focused region (Switzerland) was divided into cells. For each cell, empirical data about the four environmental risk factors were available. Where more than one measurement is available for a factor, the average value is taken. Given such a (averaged) measurement x for a particular risk factor and given the corresponding risk density distribution $f(\cdot)$, the contributed risk density is simply defined as $f(x)$. Since the risk factors are considered to be independent, the overall risk for that cell can be calculated by multiplying the contributed risk densities. This procedure can be applied for each cell at any point in time to obtain finally an overall risk density distribution for the focused region over the whole year based on the environmental factors temperature, rainfall, soil condition and forest.

To obtain the risk density curve based on the risk factor temperature, the following stages are considered: the eggs, *L. truncatula* and the metacercaria. Since the number of cercariae migrating from an infected snail does not correlate with the number of miracidia infecting the snail (Pesigan et al., 1958), a random transmission dynamics between the two stages is assumed. As described, a discrete set of points is available for each stage (egg, snail and metacercaria) indicating the risk at different temperatures derived from the literature. This set is transformed into a continuous density distribution by a filtered polynomial density estimation (Heinzmann, in press). This density estimation approach provides an algebraic expression for the resulting continuous density curve which simplifies the multiplication of density curves. The risk density distributions of the individual stages can now be combined to the process specific risk density distribution. Multiplying the resulting distributions yields a risk density curve for the environmental factor temperature.

The discrete set of points describing the risk of infection in function of the factor rainfall is transformed into a continuous density distribution using the same filtered polynomial density estimation approach as described above. The resulting continuous risk density distribution for the factor rainfall indicates the risk of infection depending on the amount of rainfall over a certain time period.

Since the two environmental risk factors soil condition and forest are categorical variables, their underlying risk density distributions are discrete and straightforward to implement based on the individual information for soil condition and forest described.

L. truncatula has been found in regions as high as 2100 m in Switzerland (Eckert et al., 1975) and has been recorded at altitudes of 2600 m elsewhere in Europe (Brohmer et al., 1956). However, in alpine regions it takes the parasite 2 years to complete a life cycle (Eckert et al., 2005).

In addition to the temperature-dependent risk, it is also assumed that the risk exponentially decreases in function of height after approximately 1800 m, at 2000 m only 50% of the relative risk is present and at 2600 m the risk is reduced to 1% (negligible). The implementation of those assumptions in our model is done as follows: we fit an exponential function of the form $y = a\exp(bx)$, where x is the altitude and y is the proportional presence of the relative risk (e.g. 0.5 for 2000 m). For reasons of simplicity, we subdivide the height into intervals as [0,1800], (1800,2000], (2200,2600] and (2600+). Then for the centres of the intervals, we interpolate from the fitted exponential function the corresponding y value which yields the values 0.68 and 0.06 for the centres 1900 and 2300 m. Finally, the height-dependent threshold is implemented such that the computed risk for altitudes until 1800 m are multiplied by 1, for altitudes in (1800,2000] with 0.68, for altitudes in (2000,2600] with 0.06 and for altitudes larger than 2600, the computed risk is multiplied by 0 meaning that there is no potential risk at such heights.

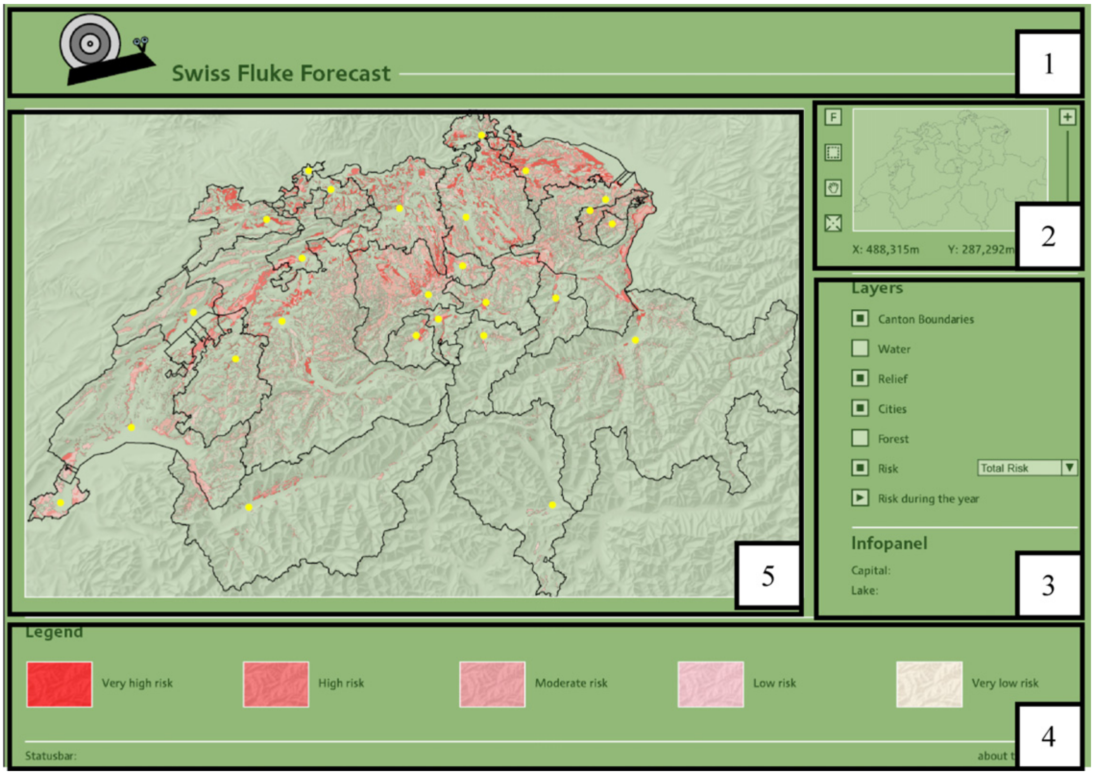

Fig. 1. The interactive map for the assessment of mean annual risk for survival, reproduction and transmission of *Fasciola hepatica* and *Lymnaea truncatula* in the environment in Switzerland and its functional areas: Title and logo (1), reference map and navigation tools (2), layers (3), legend (4), and main map (5).

2.2. Map design and visualization technique

The overall risk density for each cell is visualized by a colour scale ranging from red to white representing five risk classes (very high risk, high risk, moderate risk, low risk, very low risk).

In addition, the risk map includes some extra information such as borderlines of cantons, water bodies, relief, capitals of cantons and spatial distribution of the forest in Switzerland. A special feature is provided by the animation of the monthly risk over the course of the year.

The map is composed of following areas: title and logo, reference map and elements of interaction, layers, legends and the main map (Fig. 1). In the logo area the title can be seen. The reference map shows the cut out indicated in the main map. Beneath, the geographic coordinates show the exact position of the mouse pointer. It is possible to scroll on the whole map, to select a new map centre or to zoom into the map. The navigation tools are organised next to the reference map and are labelled with corresponding symbols. The elements of the map are grouped in layers which can be activated or deactivated. A month can be chosen from the selection list. Furthermore, an animation of the monthly risk over the course of the year can be displayed. As the animation runs, the name of the active month is shown. Names of cities and water bodies under the mouse pointer are shown in the info panel. Furthermore, this area shows the status of the map and project information. The legend illustrates the colour scale of the risk. The main map displays the chosen area with the activated elements (Fig. 2).

3. Results

3.1. Risk model

The risk density distributions for the factor temperature for eggs of *F. hepatica*, for *L. truncatula* and for metacercaria as well as the overall temperature risk curve are displayed in Fig. 3.

The x-axis displays the temperature in °C and the y-axis shows the corresponding density curve which when integrated over the whole temperature spectrum equals one. Hence the whole risk based on the factor

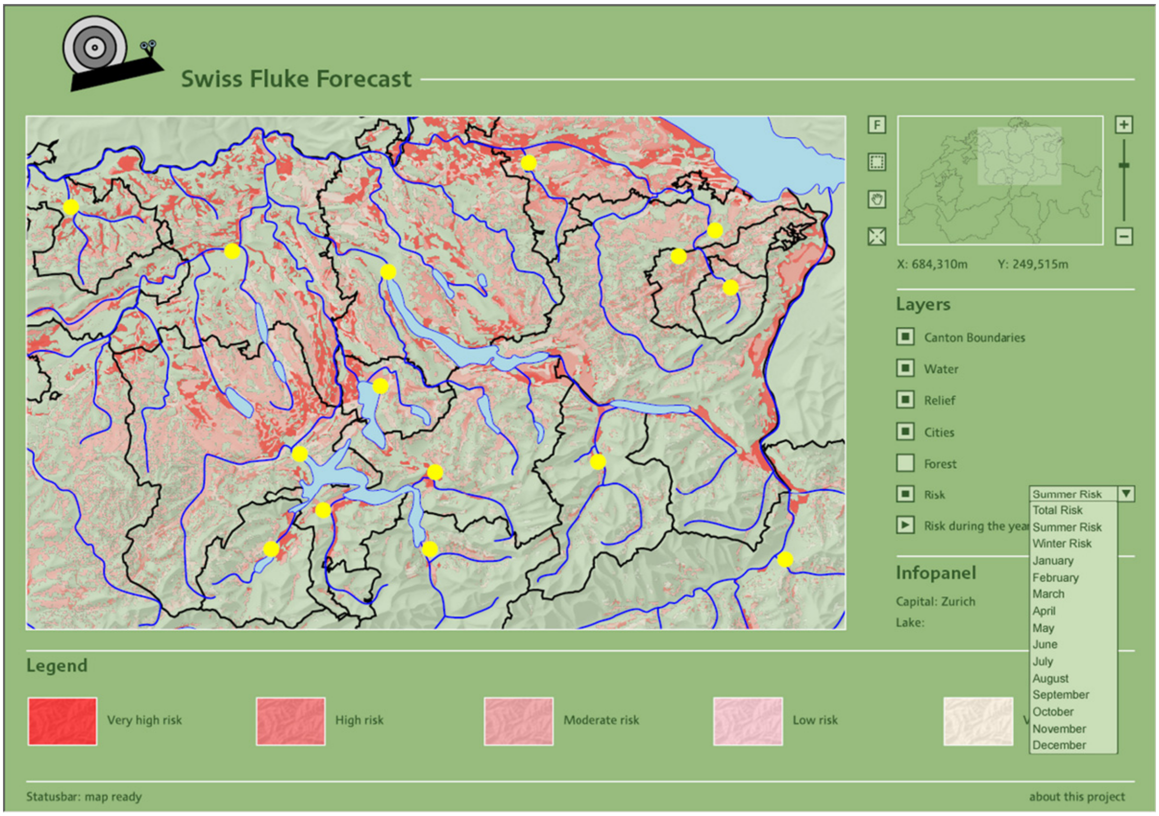

Fig. 2. A screenshot of the map showing a section at a larger scale and the opened selection list. The summer risk is displayed with several layers activated.

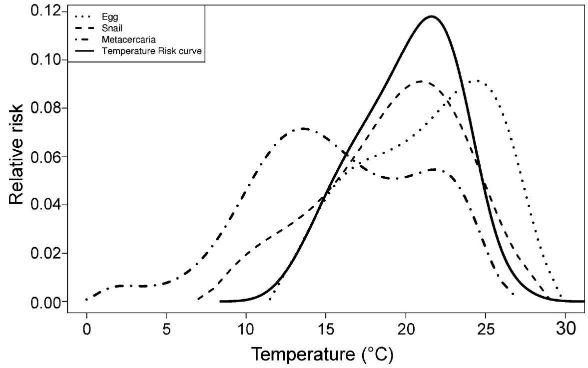

Fig. 3. Relative risk frequency for development and survival of eggs and metacercaria of *Fasciola hepatica* and *Lymnaea truncatula* as a function of temperature as well as the combined relative risk frequency as a function of temperature.

temperature is set to one and each density of a temperature range refers relatively to the whole temperature risk.

The risk density distribution for the environmental factor rainfall is displayed in Fig. 4.

3.2. Map

Visualizing the results of the risk model results in island maps without artificial control points. Some typical topographic elements such as lakes and the Alps can be identified (Fig. 5). The different risk regions are small spaced and seem to string together arbitrarily.

In August environmental conditions are especially suited for the development, reproduction, and transmission respectively, for *L. truncatula* and the free-living stages of *F. hepatica* (Fig. 5). Note that the risk values of the other months are graduated according to the risk in August.

Combining the risk maps with the other layers results in the definite map. Fig. 1 shows the annual risk for

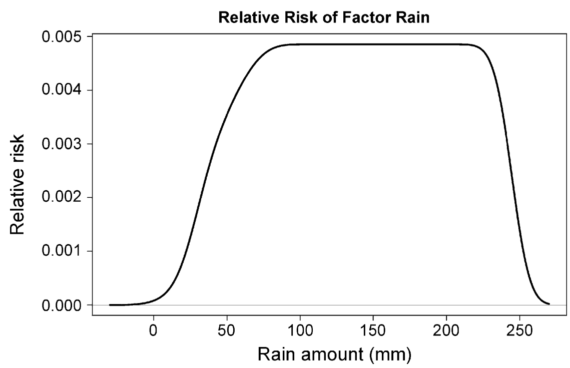

Fig. 4. Risk frequency of the parasite cycle as a function of rainfall.

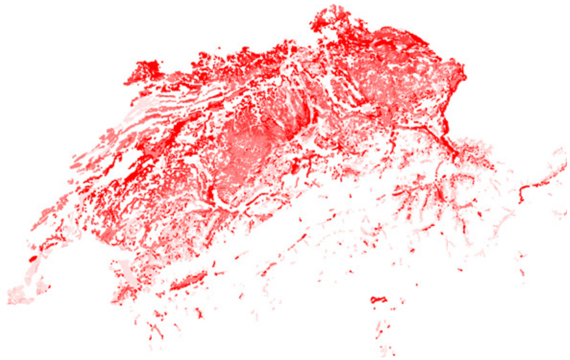

Fig. 5. Risk in August.

suitable environmental conditions for *L. truncatula* and the free-living stages of *F. hepatica* to develop in Switzerland. North of the Alps there is a far broader spread of regions with suitable environmental conditions. Regions in the north-east of Switzerland bear particular hazard of transmission of this parasite. When looking at mountainous regions, hazardous sites can be seen mainly in valleys, often adjacent to bodies of water.

The entire map can be inspected under http://www.carto.net/rapsch/riskmap/.

4. Discussion

Maps predicting fasciolosis risk have been created for several endemic areas. In Cambodia Tum et al. (2004) created a map based on inundation, proximity to rivers, land use, slope, elevation, and the density of cattle and buffaloes. Other studies in east Africa were based on moisture and temperature (Malone et al., 1998; Yilma and Malone, 1998).

However, in none of these studies, temperature setting of the free-living parasite stages and of the intermediate host have been modelled this detailed as in the study at hand. But in Switzerland, the temperature dependence needs to be taken into account. Even though the data for the model derives from the literature, there remain uncertainties. Missing data was completed by the authors' own observations and from personal communications. Incomplete published data was augmented by interpolation to obtain intermediate data points for a considered range.

Nevertheless, this interactive map at hand is an aiding tool that illustrates the risk for free-living stages of *F. hepatica* and the intermediate host *L. truncatula* to occur subject to suitable environmental conditions.

The model is based on mean monthly temperatures without considering previous months, although the development of the cycle takes more than 1 month. This may result in an estimation bias of the true risk in some areas especially in high regions, where warm periods are short and the parasite cycle cannot be completed within a year. But since our model completely depends on environmental factors, the estimation of the risk in a cell at a certain time depends on the prevailing conditions in that cell at that time. The integration of a cumulative risk estimation over time would require to model the parasite cycle itself in a temporal and spatial framework, which is out of scope of the present paper.

The existence of permanent snail habitats depends on the geological formations and the topography of a land. These factors are constant and will determine whether or not snail habitats can occur in a given area (Ollerenshaw and Smith, 1969). Rainfall can influence the size of a permanent habitat or the migration distance of snails, but not the occurrence of the intermediate host itself. For this reason, and because the water content of a habitat is dependent on soil type (Wilson et al., 1982), it is assumed, that the occurrence of habitats is mainly detected by the data on soil condition and ground water. For this study, the soils were classified on the basis of water permeability and water logging.

The rainfall model is thought to be sufficient for this study to model monthly variations of the dimension of potential risk regions, as it was not the gain of this study to make an annual forecast for a specific year, but to model regions in Switzerland where *L. truncatula* and the free-living stages of *F. hepatica* potentially develop. Furthermore, rainfall is not assumed as a restricting factor in Belgium (Bossaert et al., 1999). This is assumed to be true also in Switzerland.

On the basis of the Swiss elevation altitude model DHM25 a 25 m $\times$ 25 m grid could be created with the temperature data. Limiting factors though are the data on rainfall and soil condition (Atlas of Switzerland) with an original scale of 1:200 000. Thus, on the basis of the available data the best resolution was realised. Due to the 100 m $\times$ 100 m grid, the presented map comes with a high resolution, and a user can seek potential habitats approaching farm level.

Today, multimedia cartography is used as a modern branch of classic cartography. With this technique, data can be visualized on a computer and provided online. The data can be modified and updated at any time and the target group has access whenever necessary.

When looking at the regional distribution of the risk in Switzerland, there is a remarkable split in two parts through the Alps. North of the Alps there is significantly higher risk of fasciolosis than south of the Alps. As the climate is warmer and dryer south of the Alps than north of them, environmental conditions are suboptimal for the free-living stages of *F. hepatica* and *L. truncatula* in the south of Switzerland. North of the Alps the climate is moderate which makes environmental conditions in some regions better for survival of parasite and intermediate host. Regions with high risk lie in the north-east of Switzerland. Also, in regions around lakes, the risk is found to be high. This is because lakeside ground water levels are relatively high and so the soil contains a lot of humidity (Bitterli et al., 2004) which provides ideal conditions for the free-living stages of the parasite and the intermediate host.

In the model, the best environmental conditions for the development of *L. truncatula* and the free-living stages of *F. hepatica* in Switzerland are in August. As a result of this, under adequate environmental conditions, high cercarial shedding would occur from late October to November. This finding is consistent with the highest infection risk in late summer and autumn in Europe (Ross et al., 1968; Ross, 1970a, 1977; Eckert et al., 2005).

No underlying transmission model of the complete parasite cycle is used to construct the map, thus cumulative effects were not considered. Nevertheless, the map gives a detailed review on regions in Switzerland potentially dangerous to hosts of *F. hepatica*. In a next step, the biology of the hosts, the reproduction, survival time and death rates of each parasite stage as well as of the intermediate host should be integrated in the model.

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