Remote Sensing/GIS techniques for risk assessment of *Borrelia burgdorferi* infection.

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Abstract
The associations between the presence of infection of *Ixodes ricinus* with *Borrelia burgdorferi* and environmental variables can be quantified using remote sensing data processed in a Geographic Information System (GIS).
The research was focused on vegetation and geomorphologic considerations, since animals do not influence significantly the presence of ticks in the Karst.
A Landsat 5 Thematic Mapper image (31/07/97) was used to extract the moisture index (TM4/TM1), the surface temperature and vegetation maps and to identify the most favourable habitats for *Ixodes ricinus.*
Using cartographic data on urban areas and footpaths, it was possible to identify potential transmission risk areas.

Introduction
The objective of this study is the elaboration of infection risk and transmission risk maps of Lyme borreliosis (LB), in the Karst of Trieste.
Landscape epidemiology involves the identification of geographical areas where disease is transmitted. The Russian epidemiologist Pavlovsky (1966) expressed the theory of landscape epidemiology, that by knowing the vegetation and geological conditions necessary for the maintenance of specific pathogens in nature, one can use the landscape to identify the spatial and temporal distribution of disease risk. Remote sensing and GIS can be combined to study the structure and composition of a landscape.
Lyme disease is a syndrome, the diffusion of which is closely connected to environmental and ecological variables, associated with the territory. Lyme disease is a multi-system disorder, found throughout the world, that presents an endemic character in Friuli Venezia Giulia. It is not fatal, but can involve complications that are severely disabling if not treated or if treated too late (Cinco, 1998).
The causative agent of Lyme disease is *Borrelia burgdoferi*, a gram-negative bacterium, that belongs to the family *Spirochetaceae*, order *Spirochetales*, the diffusion of which regards invertebrate vectors and vertebrate hosts (reservoir and occasional).
A vector is an animal that transmits infectious agents from one host to another, usually a biting or piercing arthropod like the tick, mosquito or fly (Talaro, 1993). In Europe the main vector of LB is *Ixodes ricinus*, a hard tick that belongs to the class of *Aracnida*, order *Acarina. Ixodes ricinus* needs elevated humidity (more than 80%) to maintain its water balance, and mild temperatures. It has a three-stage life cycle (larva, nymph and adult) and feeds only once during each stage.
A reservoir host is a vertebrate animal species that harbours a particular pathogen and acts as a long-term source of infection for other vertebrates or vectors. Important reservoir hosts are

rodents like mice and voles, several insectivores, lagomorphs such as hares; and some birds such as pheasants and blackbirds.
An occasional host is a vertebrate, that cannot transmit infection, but could become ill, for example humans, cats, dogs, roe deer, horses, sheep and cows (EUCALB).
The infection is usually acquired from a reservoir host by larvae or nymphs and transmitted horizontally by nymphs or adults, during the blood feeding.
EUCALB (European Union Concerted Action of Lyme Borreliosis) parameters, that determinate the risk of contracting LB in a geographic area, are:

- vegetation type
- anthropization degree and possible contact tick-human
- micro-climate
- reservoir and occasional host presence
- tick presence and concentration
- tick infection rate

Knowing those parameters it is possible to monitor the diffusion of LB.
In 1997 the risk of Borreliosis was evaluated in a small recreational area located on the Karst plateau of Trieste, representative of the whole Karst. *Ixodes ricinus* ticks, collected in different ecotypes monthly throughout a year, were tested for the presence of *Borrelia burgdoferi*. The highest presence of ticks (60%) and infected ticks (38%) were found in doline (Bernardis, 1998; Cinco et al., 1999).
Concerning the faunistic analysis, particular importance was given to small rodents (main reservoir hosts) and to the presence of roe deer, *Capreolus capreolus* (main reproduction hosts), which are very common ungulate in the Karst territory (Petrucco, 1997).
Since the distribution of small rodents did not vary significantly from one ecotype to another and roe deer live in the whole Karst, the research focused on vegetation, climatic and geomorphologic considerations.

Study area

The study area included almost all of the province of Trieste. Around the city of Trieste there is the Karst, a plateau with an average altitude of 250 metres above sea level, broken up by a series of hills reaching a maximum of 670 metres. It is characterised by the typical morphology of limestone terrain, including a wide range of surface morphotypes such as doline (depressions in the landscape with high humidity and deciduous woodland), clints, grykes, uvulas and ancient inactive river tracks. The flora and vegetation are very rich and heterogeneous.

Materials and methods

Atmospheric correction

First of all, the Landsat 5 Thematic Mapper image (31/7/1997), used in this study, was corrected to minimise the effects of the atmosphere on the measured radiance.
The process of atmospheric correction is one of the most difficult tasks facing the remote sensing community.
Two essential processes affect the propagation of electromagnetic radiation through the atmosphere: absorption and scattering. Moreover, particular importance is given to that radiation, which does not reach the object, but is received directly by the sensor. This component, called path radiance, does not give any information about the terrain, so it

constitutes an interference to delete or, at least, to reduce (Mather, 1969).
The atmospheric correction was carried out by the application of a radiation propagation model, the SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) software (Ricchiazzi, 1998).
SBDART is a free software for DOS, based on Lowtran 7 model (Kneizyz et al., 1988), in which the atmosphere is divided into 33 layers. This program provides a choice of various options, replacing only default values for those parameters necessary for the desired calculation. An example of the input parameters for band TM1 is:

ISAT	=	0 (filter function types)
WLINF	=	0.45 (lower wavelength limit, in μm)
WLSUP	=	0.52 (upper wavelength limit, in μm)
SZA	=	35.7162 (solar zenith angle)
IDAY	=	212 (the day number of the satellite passage)
TIME	=	9.383 (hour, in decimal, of the satellite passage)
ALAT	=	46.030 (latitude of point on earth's surface)
ALON	=	13.680 (longitude of point on earth's surface)
ISALB	=	6 (surface albedo feature)
IDATM	=	2 (atmospheric profile = mid-latitude summer)
IAER	=	1 (boundary layer aerosol = rural)
RHAER	=	0.6112 (relative humidity)
V	=	20.00 (visibility in km)
PBAR	=	1013.7 (surface pressure in mbar)
ZOUT	=	0, 100 (specify BOT and TOP altitude point -km- for IOUT output
IOUT	=	21 (standard output selector = radiance output a ZOUT (2) km, that is 100 km. If IOUT=20, the program calculates the radiance a ZOUT (1) km, that is 0 km)

The output is the radiance at 100 and 0 kilometres. The difference between radiance at 100 km and at 0 km is the path radiance, that was then converted into DN (Digital Number) using the formula (Lillesand and Kiefer, 1994):
where: gain and offset are two in-flight parameters of satellite calibration (ESA).

$$DN = \frac{PathRadiance - Offset}{Gain}$$

Satellite data analysis
The GIS software used was GRASS (Geographical Research Analysis Support System) developed by the US Corporation of Engineers. This is a free GIS which can be obtained by downloading the source codes from Internet. By the analysis of satellite data, it was possible to produce several maps. The first was the land cover map, obtained by the application of Goodall's index (Altobelli et al., 1995; Altobelli et al., in press), a classification method. Nine classes were identified:
1. Pine-wood
2. Thicket
3. Bushy area
4. Wood
5. Mosaic vegetation
6. Urban area

7. Karstic grassland
8. Grass
9. Bare soil

The moisture index (Dupigny and Lewis, 1999) used in this study is given by the ratio of band 4 to band 1 (TM4/TM1). The combination of these bands best captured the difference between urban areas, water bodies and full-leaf versus leafless conditions.
NDVI index was calculated by the formula (Rouse et al., 1974):
In band 4 (NIR) and band 3 (red) the contrast of soil and vegetation is maximum and they contain the 90% of vegetal cover information.

$$NDVI = \frac{DNtm4 - DNtm3}{DNtm4 + DNtm3}$$

The surface temperature map derived from band 6 (TIR), using Markham and Barker (1986) formulas:
$L_{tm6} = 0;0056322 * DN_{tm6} + 0,1238$
where: L_{tm6} = thermal radiance (mW/cm² sr µm)

$$T\ \text{sup} = \frac{K_2}{\ln\left(\frac{K_1}{L_{tm6}} + 1\right)}$$

where K_2= 1260.56 and K_1 = 60,766. K_1 and K_2 are the Landsat 5 thermal band calibration constants.
The cumulative frequency of pixel value was divided into quartiles (Castino, 1991) to obtain four classes of humidity and of temperature.
A doline map was produced by digitalisation of the 552 doline represented on IGM map (1:50000, Trieste, 1982). 90% of doline are covered by woodland and the 80% have humidity from mid-high to high.
A footpath map was obtained by digitalisation of the toponomastic and topographic map of the C.A.I. footpaths (S. Ciriello, 1997).
The urban area map and the viability map were extracted from the C.T.R. (1:25000).

Elaboration of the infection risk and the potential risk maps

The r.infer GRASS program was used to find areas with the most elevated risk of infection.
It is an inferential engine, which applies expert system type rules to a set of user maps and generates a new map. Expert systems are simply sets of logical rules that mirror the analysis process of an expert in some fields. The program utilises the following steps:

- find cells on a GRASS map layer that meet certain criteria by logical operators (IFMAP, ANDIFMAP, ANDIFNOTMAP);
- assign cells that meet those criteria to a hypothesis (THEN);
- assign a value in the newly created map called "infer" to those cells that meet the selection criteria.

Finally by the r.buffer and r.infer GRASS programs the potential risk map was produced. The potential risk map considered the possibility of contact human-tick, identifying areas near urban centres and near footpaths in habitats favourable to *I. Ricinus*.

Results

The results of atmospheric correction are reassumed in the table 1:

The higher value of path radiance to subtract on a band is found in band 1, because absorption

and scattering are wavelength dependent processes (Richards, 1986).
The ANOVA test (SPSS, 1999) demonstrated that there were significant differences between the classes of cover map, considering humidity, temperature and NDVI of 100 pixels, random extracted, for each class.
The most humid classes were represented by wood and doline that have also the lowest temperature and highest NDVI.
The resulting infection risk map (Fig. 1) by the r.infer grass program identifies the favourite habitats of *I. ricinus*. The input maps were humidity (Fig. 2), surface temperature (Fig. 3), land cover (Fig. 4) and doline maps.
The criteria used for the identification of risk areas were high humidity, mild temperature and woodland. Doline, that have those characteristics, were also considered.
The potential risk map (Fig. 5.) obtained considers the possibility of contact human-tick. The input maps were the infection risk map, and two buffer (100 metres) maps: one for the urban areas and one for the footpaths.

Summary and conclusion

In conclusion, the map of transmission represents a model to be followed to prevent the risk of diffusion of tick-borne disease, such as Lyme borreliosis, TBE, Ehrlichiosis and Babesiosis.
However, displacing sampling stations in the whole karstic plateau and considering the disease incidence should test this model.

Fig. 1. The infection risk map. Favourite habitats of *I. ricinus* are in red, doline with high risk of infection in blue, streets and urban areas in black.

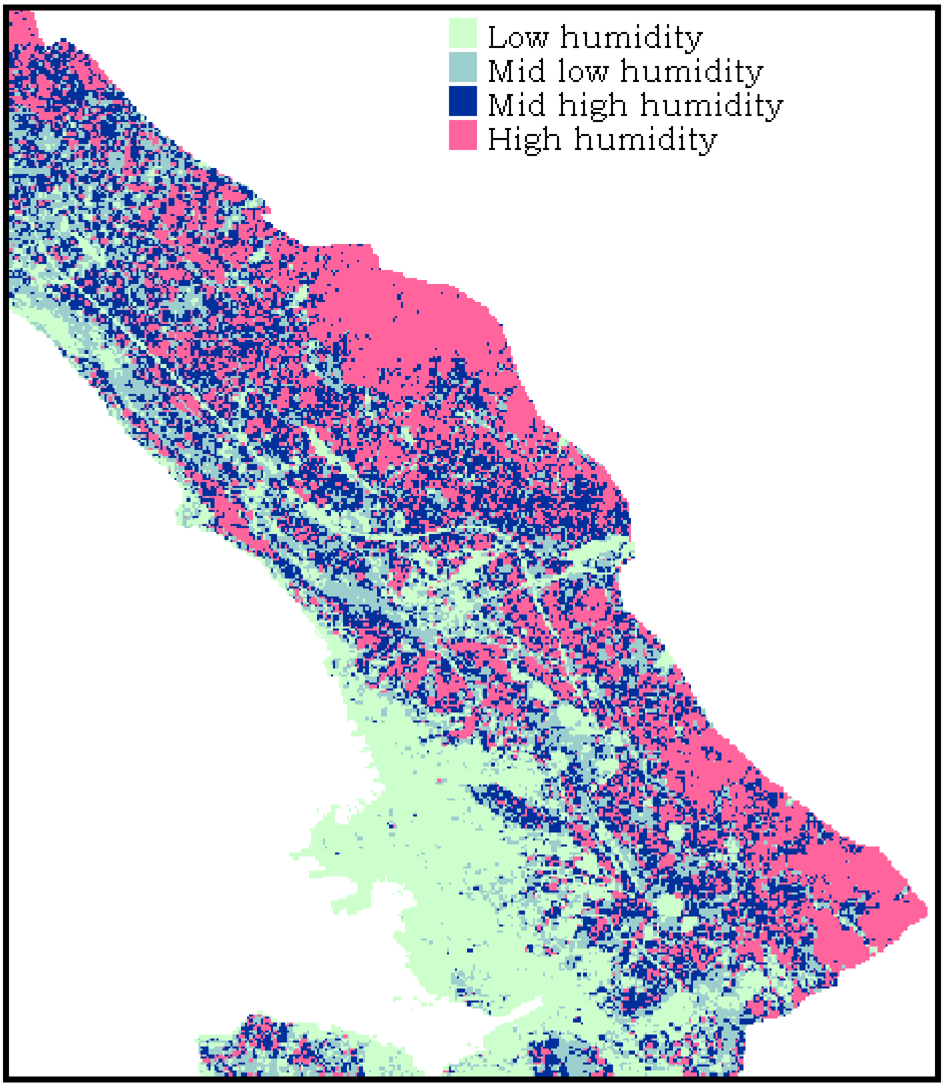

Fig. 2. The humidity map given by the ratio of band 4 to band 1 (TM4/TM1) of Landsat TM.

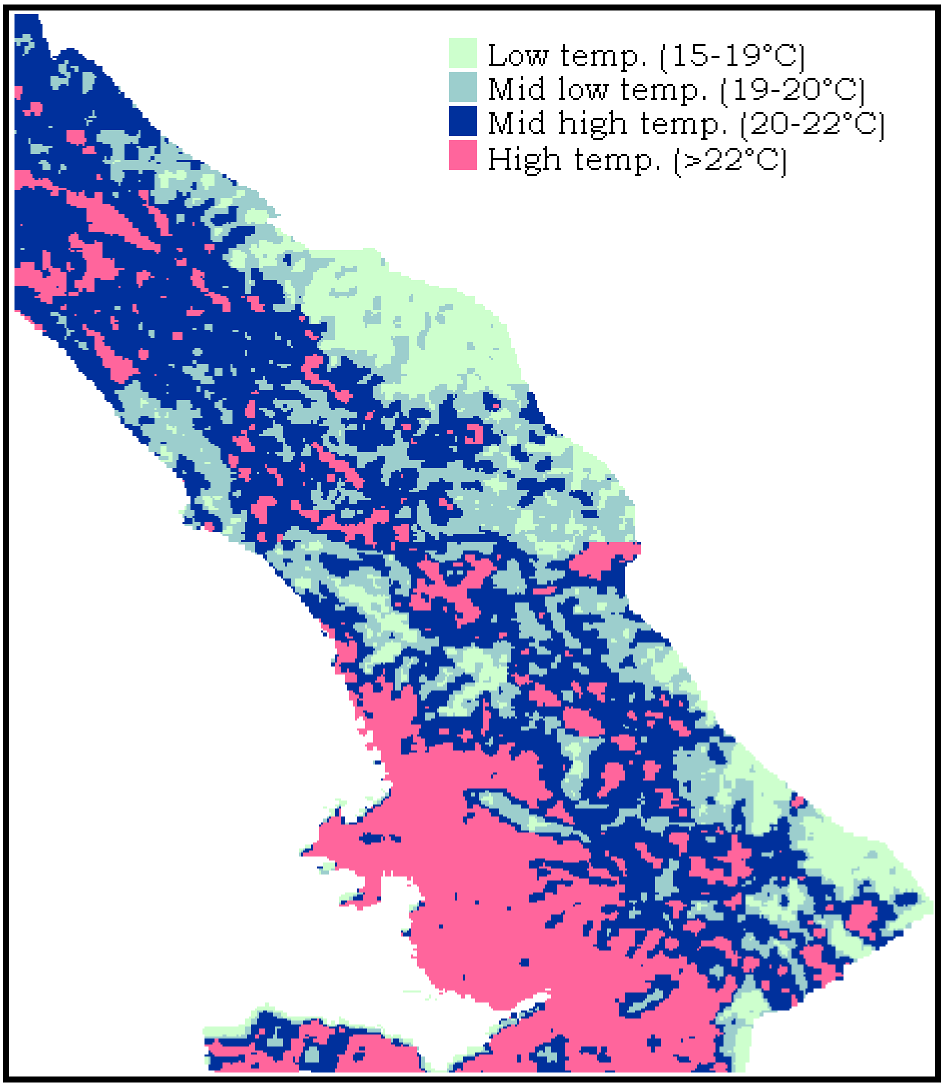

Fig. 3. The surface temperature map derived from band 6 (TIR) of Landsat TM.

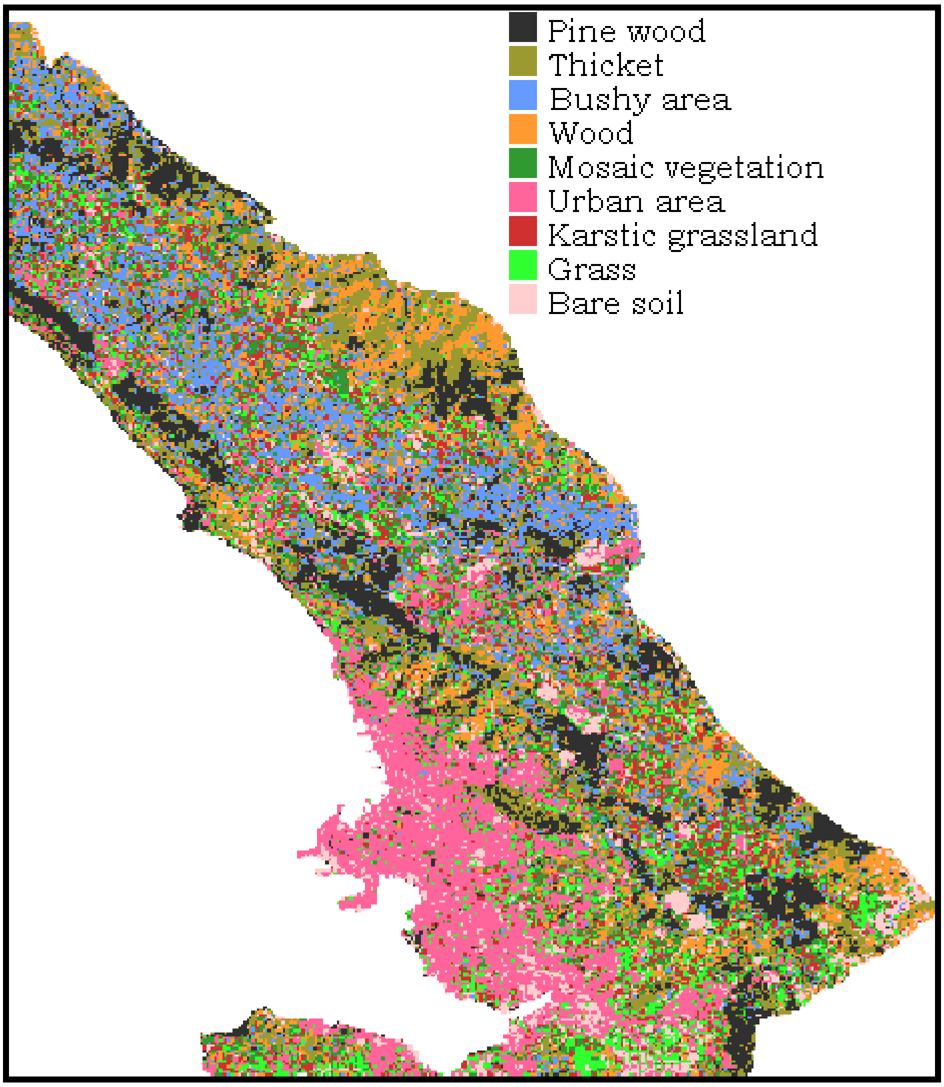

Fig. 4. The land cover map obtained by the application of Goodall's index from the Landsat TM satellite.

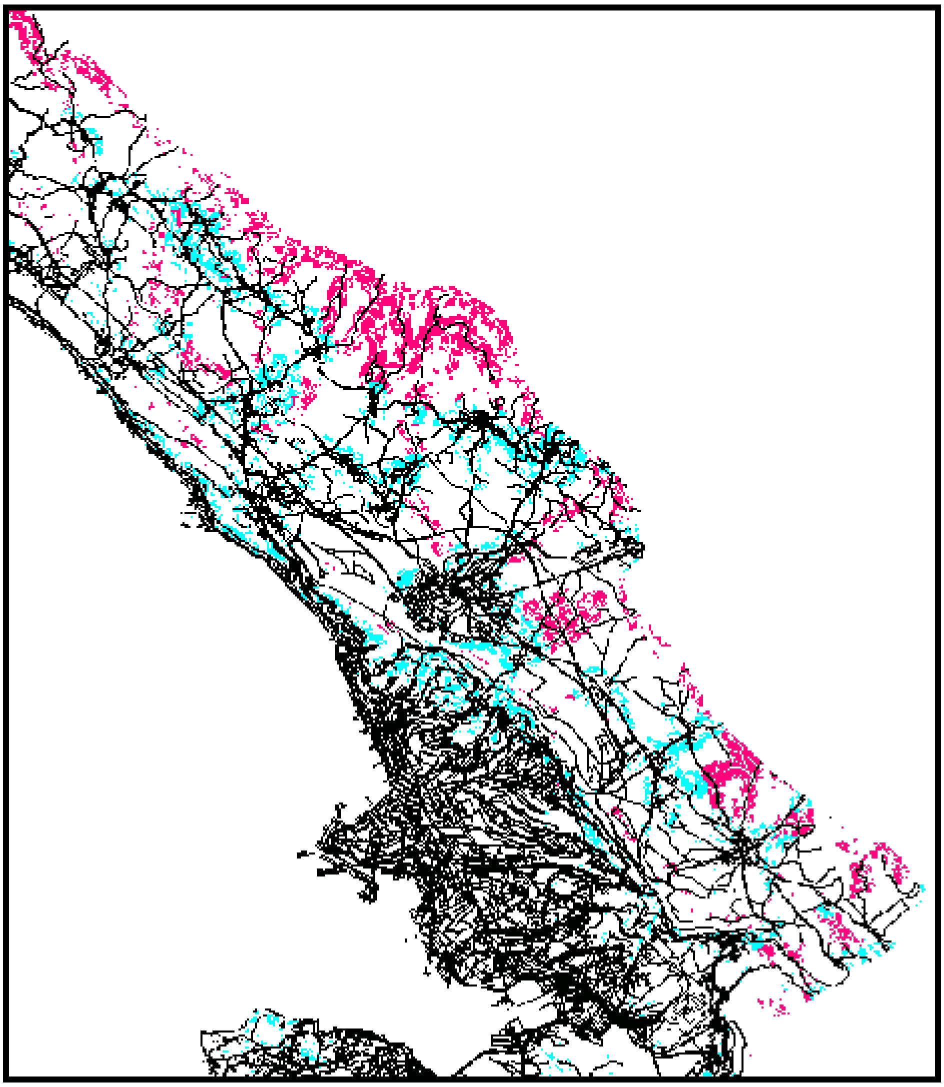

Fig. 5. The potential risk map. Risk areas near urban centres are in blue, risk areas near footpaths are in red, streets and urban areas are in black.

BAND	PATH RADIANCE	GAIN	OFFSET	EQUIVALENT DN
TM 1	2.437	0.7314	- 1.5	5.38
TM 2	1.433	1.3533	- 3.1	3.35
TM 3	0.463	0.9714	- 2.7	3.26
TM 4	- 0.70	1.0686	- 2.5	1.68

Tab. 1. Results of the atmospheric correction, carried out by the application of the SBDART software.

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