

The use of remote sensing for the ecological description of multi-host disease systems: a case study on West Nile virus in southern France

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Summary

A large number of diseases that affect humans and animals are influenced by environmental factors. For multi-host infectious diseases, various species might be involved in the transmission process and the circulation of the pathogenic agent might result from the occurrence of certain specific association(s) between host and vector species. The need to characterise multi-species assemblage requires the development of new methods to derive integrated environmental risk factors. We have given remote sensing an ecological application to study the potential distribution of West Nile virus (WNV) in the Rhone River delta in southern France. West Nile fever is a vector-borne disease transmitted in natural cycles between birds and mosquitoes. Satellite images were used to create an ecological map on land cover. Appropriate typology was employed for the description of both hosts and vectors distributions. A database including the

probability of occurrence of bird and mosquito species in each landscape unit is linked to this ecological map. Spatial and temporal information on host and vector distribution is then integrated using geographic information systems. This integrative tool is designed to test some hypotheses on the epidemiological process of WNV and to identify environmental configurations and environmental changes likely to favour the emergence of WNV.

Keywords

Ecology, Epidemiology, France, Geographic information system, Multi-host disease, Remote sensing, West Nile virus.

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L'uso del telerilevamento per la descrizione ecologica di un sistema multi-ospite di patologia: un caso studio sul West Nile virus nel sud della Francia

Riassunto

Molte malattie che colpiscono uomini ed animali sono condizionate da fattori ambientali. Nel caso delle malattie infettive cosiddette "multi-ospite", le specie coinvolte nel processo di trasmissione possono essere diverse, la presenza dell'agente patogeno, infatti, può essere il risultato della presenza di specifiche associazioni tra diverse specie di ospiti e di vettori. La necessità di classificare le possibili associazioni tra le varie specie richiede lo sviluppo di nuovi metodi da cui desumere fattori integrati di rischio ambientale. E' stata data al telerilevamento un'impostazione ecologica per studiare la distribuzione potenziale del virus della West Nile (WNV) nel delta del Rodano, sud della Francia. la West Nile disease è una malattia trasmessa da vettori in un ciclo naturale tra uccelli e zanzare. Le immagini satellitari sono state utilizzate per creare una mappa ecologica sulla copertura del suolo. Una specifica tipologia è stata utilizzata per la rappresentazione della distribuzione sia delle specie portatrici sia ospiti. In ciascuna unità ecologica un database sulla probabilità di presenza sul territorio di specie di uccelli e zanzare è stato associato alla mappa. Le informazioni inerenti alle variazioni della distribuzione, nello spazio e nel tempo, di specie ospite e vettore, sono poi monitorate attraverso l'integrazione con un sistema informativo geografico. Questo strumento integrativo viene disegnato per verificare alcune ipotesi sul ciclo epidemiologico del WNV e per individuare eventuali configurazioni e cambiamenti ambientali atti a favorire l'insorgenza del WNV.

Parole chiave

Ecologia, Epidemiologia, Francia, Malattie multi-ospite, Sistema informativo geografico, Telerilevamento, West Nile virus.

Introduction

Remote sensing is generally defined as 'the acquisition of information about an object without being in physical contact with it' (21). In particular it refers to the observation of the Earth using sensors placed on satellites or aeroplanes. For 40 years, the capabilities of the environmental satellite systems have increased in terms of spatial, spectral and temporal resolutions and the potential of the use of remotely sensed data in epidemiological studies has been described (4, 11, 27, 29).

Indeed, because it provides spatial-referenced information on the environment, remote sensing could be of particular relevance for the study of diseases related to environmental conditions (14), such as vector-borne or zoonotic diseases (31, 42). Various attempts to apply remote sensing to epidemiology are reported in the literature, mostly concerning human diseases, such as malaria (3, 36) and helminth infections (7, 45) or zoonotic diseases, such as Rift valley fever (33, 37) and Lyme disease (17, 20). In the veterinary domain, remotely sensed data were used for the study of animal trypanosomes (6), African horse sickness and bluetongue viruses (2, 38, 41). The integration of remotely sensed data into epidemiological studies has been facilitated by the recent development of geographic information systems (GIS) which are computer systems used for storage, integration, analysis and mapping of geographic data (25).

In most of these studies, remote sensing data are used as additional information to provide a better understanding of disease transmission processes involving one main vector (or host) species. Environmental parameters, such as land cover, land and sea surface temperature, rainfall indices, etc., are derived from the images and a statistical analysis is performed to test the link between these parameters and entomological or epidemiological field data. The interpretation of statistical analysis results as risk factors relies on the knowledge of the life history of the vector or host under consideration. This approach allows researchers to improve the understanding of

the disease and identify risk areas or risk periods.

Nevertheless, results of such an approach might be difficult to interpret for infectious diseases involving a large number of vector or host species. Such is the case for the West Nile virus (WNV) for which few studies have explored the link between disease and environment (18, 26, 32, 44, 47). West Nile fever is a mosquito-borne disease for which many birds serve as the primary reservoir hosts (8). Several mosquito species have been identified as potential vectors (28). Horses and humans are sensitive but are dead-end hosts. For such multi-host systems, instead of the presence/absence of a unique species, the assemblage between reservoir hosts and vectors species seems to be determinant for the risk of the disease (23, 30).

The purpose of the present study is to evaluate the efficiency of the use of remotely sensed data and GIS to characterise the spatial and temporal variability of configurations between WNV reservoirs and vectors. We used multi-spectral images from the satellite Landsat to map the ecological units associated to the different mosquitoes and bird species potentially involved in the transmission cycle. A GIS was dedicated to the integration of all the information on the probability of occurrence of bird and mosquito species in each ecological unit and to the calculation of abundance and richness indices.

The study was conducted in southern France, where recent WNV circulation has been highlighted since 2000 (35, 46). In this area, WNV causes sporadic equine outbreaks, separated by periods of apparent disease absence (36). The final geodatabase is designed to contribute to the identification of environmental configurations likely to favour the emergence of WNV in southern France. This paper presents the method used and some preliminary results.

Material and methods

Study area

The study area (5 024 km²) is located in southern France, between 43.33-43.91°N and 3.68-4.99°E (Fig 1). It encompasses two landscape types, namely: wet areas on the coast, including marshes and rice fields, and dry areas constituted mainly by agricultural zones, Mediterranean scrubland and forest.

Landscape map generation

We used a Landsat Enhanced Thematic Mapper (ETM+) image (21 July 2001) to identify and map the landscape units within the study area (Fig. 1). Landsat imagery was chosen because the characteristics of this sensor (Table I) enable coverage of the entire study area (100 × 60 km) in one scene with a moderate spatial resolution that is adequate to describe the principal habitats of WNV hosts and vectors species. A second ETM+ image (25 October 2001) was processed to map the flooded areas after the main rainfall period that occurs at the end of summer and in autumn. Both scenes were cloud-free and had no apparent haze.

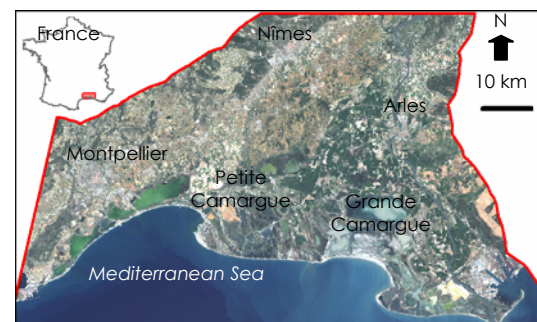


Figure 1
Location of study area
Background: Landsat ETM+ image, 25 October 2001, Eurimage®

The ETM+ sensor onboard Landsat-7 satellite is a multi-spectral sensor that measures the intensity of radiation reflected and emitted by objects on the Earth in several spectral bands. This spectral information enables differentiation between objects that have different spectral responses and thus to map different land cover types (13).

Table I
Characteristics of the remotely sensed images used for the landscape map generation

Date	Satellite	Sensor	Scene size (km)	Pixel size (m)	Spectral bands
21/07/2001	Landsat-7	ETM+	170 x 183	30	6 bands (3 visible, 1 near infrared, 2 mid infrared)
25/10/2001					

The ecological units, relevant for characterising the distribution of both mosquito and bird species, were defined based on bibliography and expert knowledge. To map these ecological units, a supervised object-oriented classification was performed using Definiens-imaging eCognition™ software (Munich, Germany).

The July 2001 image was first segmented into homogeneous polygons (objects).

Subsequently, sites of known land cover were identified within the image to produce a set of training sites representative of the ecological units identified as relevant for the description of WNV host and vector distribution. Sites identified in the field using a GPS (global positioning system) receiver as well as sites identified in existing vegetation maps (22, 39) were used. The criterion to select ground control points (GCP) was the homogeneity of the parcel covering more than 4 Landsat pixels (3 600 m²). The land-cover classification system (LCCS) was used as the standard to define the classes (16).

In a subsequent step, a supervised classification algorithm was applied to compare each object in the image to the training set and to allocate it to the land-cover class to which it is the most similar. In a pre-processing step, a mask was applied to classify wet and dry areas. Class separability tests were performed to identify the best features (among spectral or textural features) to include as entry in the classification process. Finally, the classification was applied to the mean radiance values of the six spectral bands using a nearest neighbour classifier: after the representative set of sample objects has been declared for each class, each image object is assigned to the class of the nearest sample object in the feature (spectral) space (15).

Some post-classification operations (merging, splitting) were required to produce the final

map with the typology chosen for entomological and ornithological purposes. In particular, we used the second image from the autumn to map the water bodies so as to distinguish the areas flooded by late summer and autumn rainfalls from those that had never been flooded.

Finally, the accuracy of the classification was assessed using a new set of training data (ground control points that were not used for the classification).

Characterisation of the bird-host community

A list of 202 wild bird species that inhabit the study area, excluding rare and vagrant species, was compiled. To describe the seasonal variability of the activity, diversity and abundance of bird species, a time cut-out in four seasons (winter, spring, summer and autumn) was chosen. The relative abundance of each species in each ecological unit was evaluated from bibliographic and ornithologist empirical knowledge. Abundance was defined as the probability of occurrence of a bird species in a defined patch of a uniform ecological unit, per defined season. The probability of occurrence was allocated in six classes (Table II). Since some bird species use distinct ecological units for feeding, roosting or breeding, probability of occurrence was also evaluated for these three distinct types of activity.

Characterisation of the mosquito-vector community

The same method was used to characterise the variability of vector population within the study area in space and time. In a first approximation, we used the same temporal cut-off as the one chosen for the bird community. The most abundant ornithophilic species in the Camargue area, *Culex modestus*, Ficalbi 1889, and *Culex pipiens*, Linnaeus 1758,

Table II

Definition of classes of probability of occurrence of wild bird species, considering the probability of observation of a bird species in a defined patch of a uniform ecological unit only (excluding surrounding and bordering ecological units) during a routine ornithological visit

Class	Probability of occurrence	Definition
0	Absent	Never or accidentally observed at a site
1	Uncommon	Observed every year, but with only few observations per year
2	Frequent	Observed frequently at a site, but not at every visit
3	Common	1 to 10 individual observed at a site during a visit
4	Abundant	10 to 100 individual observed at a site during a visit
5	Very abundant	>100 individual observed at a site during a visit

were taken into consideration. *Cx modestus* that breeds in reed marshes and rice fields has been considered as the main WNV vector in wetlands of southern France since the 1960s, when entomological studies were conducted after outbreaks were recorded in horses (34). Nevertheless, recent WNV transmission in dry areas, where *Cx modestus* is rare, suggests the involvement of others vectors (9, 19). In these zones, *Cx pipiens* was identified as the most abundant bird-feeder by a recent entomological study performed in the Camargue area (1). This species was involved in WNV transmission in many others countries, through the Old (40) and the New World (5). The relative abundance of these two species in each ecological unit was evaluated from a bibliographic review and bird-baited trap collections (1; G. L'Ambert, unpublished data). Abundance was defined as the number of mosquitoes collected in a bird-baited trap per collection night. A description of these traps is given by Balenghien *et al.* and Cipriai *et al.* (1, 10). Abundance is evaluated according to five classes (Table III). Two types of activity were distinguished, namely: breeding and host-seeking. This information was integrated in the database.

Geographic information system integration

The databases including data on host and vector relative abundance were linked to a GIS using ArcGis™ (Environmental Systems Research Institute, Redlands, California). As information on probability of occurrence and activity were recorded according to an ecological unit, GIS software offers the possibility to map, for each season, the spatial distribution of each species. For the mosquito species, the type of activity (breeding/host-seeking) was taken into account by creating a buffer zone around the breeding sites; outside this area, if the occurrence probability index was non null, the value 1 (uncommon) was mapped. The size of the buffer (5 km) was chosen according to field knowledge.

Table III

Definition of classes of probability of occurrence of mosquito species, considering the number of host-seeking females in a bird-baited trap per collection night in a defined patch

Class	Probability of occurrence	Definition
0	Absent	Never or accidentally collected
1	Very low densities	Few individuals collected
2	Low densities	1 to 40 individuals collected
3	High densities	40 to 100 individuals collected
4	Very high densities	>100 individuals collected

Additional maps on species abundance, richness and contact rates were created by the computation for each ecological unit and each season of simple indices are presented in Table IV.

Results

The landscape map derived from the satellite imagery (Fig. 2) includes 27 classes from the five main ecotypes, as follows:

- maritime areas (sea, beaches and herbaceous dunes, dune forest, lagoons, salted bare soil, salt marsh vegetation, salt works)

Table IV
Definition, notation and values range of abundance, richness and contact indices

Index	Notation	Definition	Values range
Host richness	R_H	Number of bird species	[0-202]
Vector richness	R_V	Number of mosquitoes species	[0-2]
Contact richness	C_{HV}	$C_{HV} = R_V \cdot R_H$	[0-404]
Global host abundance	A_H	$A_H = \frac{\sum_{i=1}^{RH} c_i}{N_H}$, c_i being the class of occurrence probability and N_H the total number of host species considered in the study	[0-5]
Global vector abundance	A_V	$A_V = \frac{\sum_{i=1}^{RV} c_i}{N_V}$, c_i being the class of occurrence probability and N_V the total number of vector species considered in the study	[0-4]

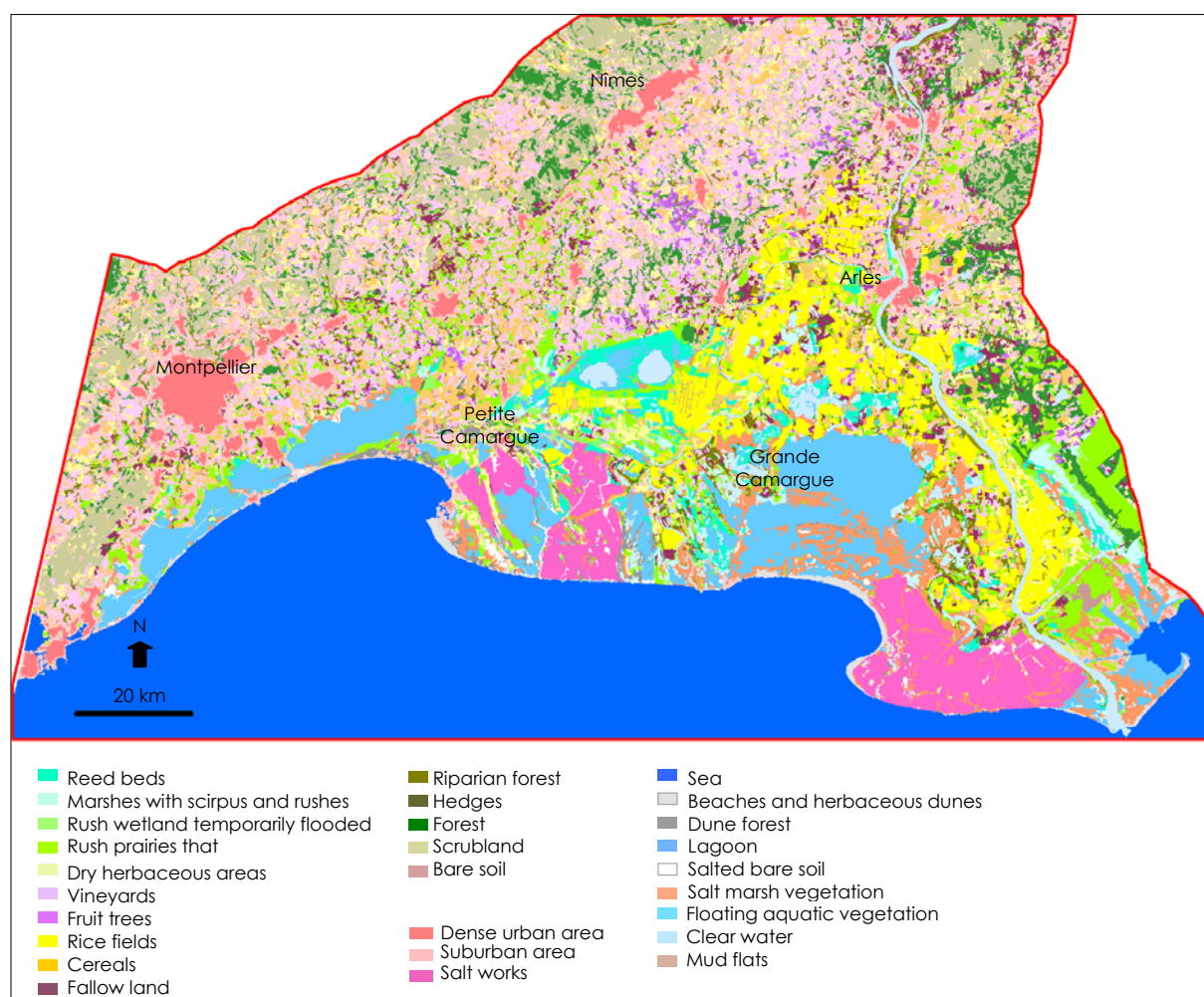


Figure 2
Classification of the Landsat image into ecological units relevant for West Nile virus studies

- natural coastal areas (clear water, floating aquatic vegetation, mud flat, reed beds, marshes with scirpus and rushes, rush wetland temporarily flooded, rush prairies never flooded)
- natural continental areas (forest, scrubland, riparian forests)
- agricultural areas (dry herbaceous areas, vineyard, fruit trees, rice fields, cereals, fallow land, bare soil, hedges)
- urban areas (dense urban area, suburban and rural areas).

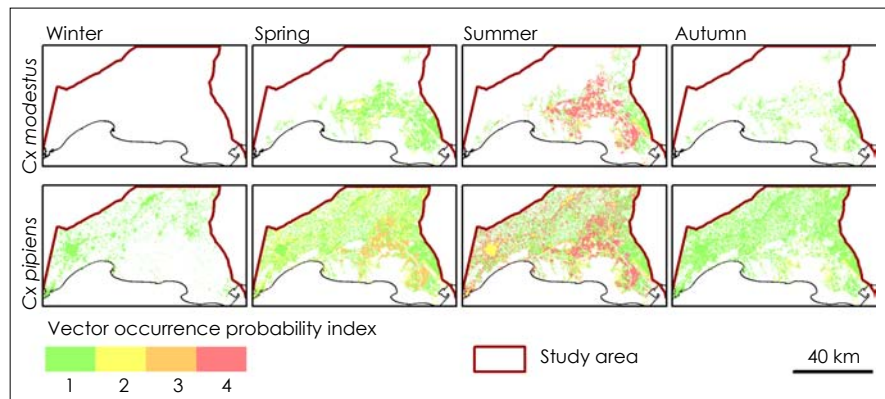


Figure 3
Spatial and temporal distribution of two *Culex* species in southern France

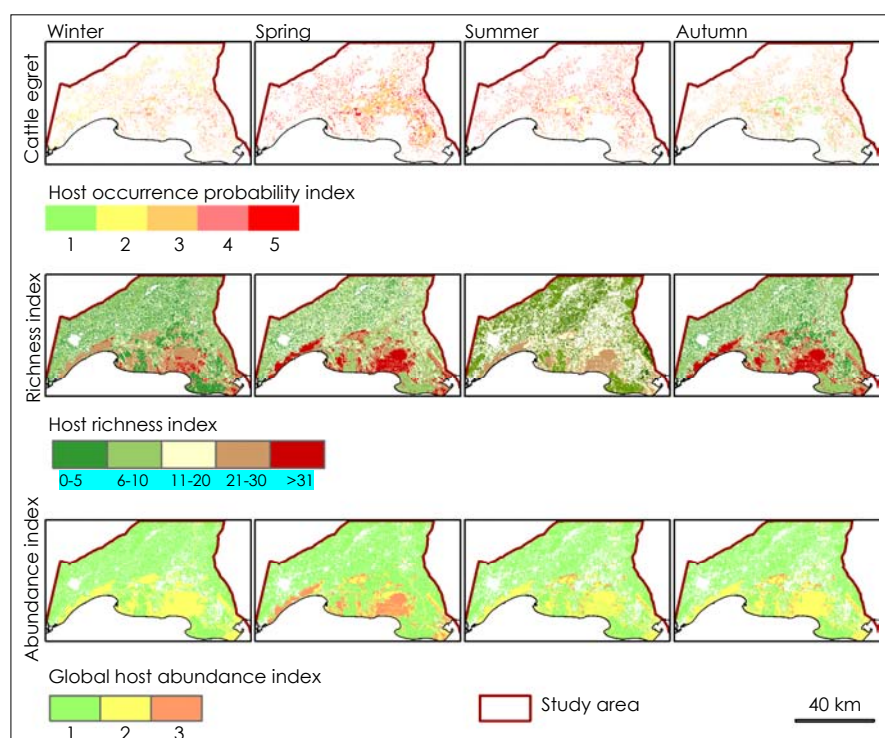


Figure 4
Abundance and richness indexes for the host species in southern France (temporary results)

The overall accuracy of the classification estimated with an error matrix was fair (68%). Initial results on vector probability occurrences highlight the spatial and temporal variability in the distribution of the WNV potential vectors (Fig. 3). While *Cx modestus* displays a concentrated spatial pattern in the wet areas, the distribution of *Cx pipiens* is more scattered over the entire study area, with high occurrence probabilities both in dry and wet areas. Spatio-temporal diffusion patterns of *Cx pipiens* focus on the urban and suburban

areas and spread to the dry and wet areas during spring and summer. In contrast, *Cx modestus* spread from the wet areas to drier ones. Other indices (global vector abundance, vector richness) synthesise the simultaneous presence of the two species in space and time. These results match the field observations (qualitative evaluation).

Results on the spatial and temporal dynamics of the birds have not been finalised yet: 60 bird species of the 202 listed were integrated in the database. Nevertheless, preliminary maps of

distribution shows the variability in host species abundance and richness indexes during the year (Fig. 4) due to local and regional migratory movements (spring and autumn) and breeding (spring). The geodatabase allows mapping the spatio-temporal distribution of a unique species of interest (example given for the cattle egret [*Bubulcus ibis*] in Fig. 4) as well as global indices characterising the species diversity of the birds.

Discussion

We developed a method to integrate data on the spatio-temporal dynamics of vectors and hosts in the case of a multi-host disease system, WNV in southern France. As far as we know, this is the first attempt to map the ecological conditions likely to favour the emergence of WNV by the construction of a GIS database integrating information on both birds and vector communities on a local scale.

The use of satellite imagery enabled us to map the relevant ecological units to describe both mosquito and bird species distribution, instead of using existing vegetation maps with typologies that were not necessarily well adapted to the study of WNV. In particular, the use of two images on different dates was interesting to distinguish flooded areas, which are of significance for WNV vectors and host dynamics. Moreover, the large surface covered by the satellite images made it possible to map the entire study area in a homogeneous way. This highlights the flexibility offered by remote sensing sensors that provide a valuable source of environmental information for epidemiologists.

The capacity of GIS to integrate different databases and information of different kinds made it possible to translate a complex system into maps that are easy to interpret and exploit. Thus, indicators of biodiversity (species richness and global abundance) could be defined. The first maps obtained on the distribution of the vectors were in agreement with the results obtained during entomological field surveys.

While this approach offers great advantages, some limitations should be pointed out.

As the final result relies on the quality of image classification, a misclassified area can easily lead to a misinterpretation of the spatial distribution of vectors or hosts. Thus, assessing the classification's accuracy is important. Although accuracy assessment methods have several biases (43), the study of the error matrix (or confusion matrix) is required to identify the nature of the misclassifications (12). In our study, the overall accuracy was correct but had several misclassification errors due to spatial resolution (identification of small objects, such as hedges or riparian forest corridors), temporal differences between the reference data (2005-2006) and the classified images (2001), or some radiometric similarities (between rice fields and reed beds for example). Considering the high number of classes (27), which increases the risk of misclassifications, the classification accuracy (68%) was fair (24). On the other hand, as the areas misclassified were classified into classes of the same ecotype, the result corresponded with reality on the ground. Nonetheless, it is an aspect to be kept in mind.

Integrating the empirical knowledge on host and vector distribution into a GIS revealed that several additional factors should be taken into account to better reflect the bird and mosquito distribution and contact, such as mosquito control measures, hunting/protected areas and host preference of vectors. Moreover, the construction of the database raises questions about the temporal cut-off into four seasons; for the vector species, a finer cut-off would better transcribe the high variability of vector dynamics. Another focus point is the choice of vector species. Only ornithophilic mosquito species were considered in this study. Indeed, in this initial approach, we focused on the characterisation of the spatial and temporal variability of configurations between WNV reservoirs and vectors which is crucial to explain the WNV introduction, spread and amplification phases. Nevertheless, to assess the risk of emergence of WNV, i.e. transmission to humans and equids, the distribution of other mosquito species should also be described. Given the flexibility of the GIS tool, all of this additional information can readily be integrated to refine the initial maps.

Finally, bird and mosquito databases have to be validated through field observations. If the results are correct, the geodatabase is designed, in the long term, to help test some hypotheses on the epidemiological process by identifying specific ecological configurations 'at risk' and confront them with results of serological surveys or historical data. The use of the GIS will contribute to target the zones where field investigations or surveillance should be performed. For example, this tool could help investigate the role played by different migrant bird species in the introduction of the WNV or the role of the contact rates between host and vector species in WNV amplification and spread. In a subsequent step, this GIS database will be linked to WNV dynamics models (Multi-Agent Systems, mathematical modelling) to test emergence scenario and identify specific environmental changes likely to favour WN epidemics in the future.

Conclusion

The aim of this study was to develop a method to construct a common entomological and ornithological geodatabase for studying WNV in southern France. An ecological map and a mosquito-bird database were produced; preliminary results highlight the potential of remote sensing for the provision of relevant environmental information to describe a complex multi-host disease system and the efficiency of GIS technology to produce maps that illustrate the spatio-temporal dynamics of the different species. The method requires an

interdisciplinary approach; it is straightforward and could be applied to other areas infected by WNV to compare different epidemiological situations.

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