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Rift Valley fever dynamics in Senegal: a project for pro-active adaptation and improvement of livestock raising management

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Abstract. The multi-disciplinary French project "Adaptation à la Fièvre de la Vallée du Rift" (AdaptFVR) has concluded a 10-year constructive interaction between many scientists/partners involved with the Rift Valley fever (RVF) dynamics in Senegal. The three targeted objectives reached were (i) to produce - in near real-time - validated risk maps for parked livestock exposed to RVF mosquitoes/vectors bites; (ii) to assess the impacts on RVF vectors from climate variability at different time-scales including climate change; and (iii) to isolate processes improving local livestock management and animal health. Based on these results, concrete, pro-active adaptive actions were taken on site, which led to the establishment of a RVF early warning system (RVFews). Bulletins were released in a timely fashion during the project, tested and validated in close collaboration with the local populations, i.e. the primary users. Among the strategic, adaptive methods developed, conducted and evaluated in terms of cost/benefit analyses are the larvicide campaigns and the coupled bio-mathematical (hydrological and entomological) model technologies, which are being transferred to the staff of the "Centre de Suivi Ecologique" (CSE) in Dakar during 2013. Based on the results from the AdaptFVR project, other projects with similar conceptual and modelling approaches are currently being implemented, e.g. for urban and rural malaria and dengue in the French Antilles.

Keywords: Rift Valley fever, dynamic ponds modelling, early warning systems, Senegal.

Introduction

The "Gestion et Impacts du Changement Climatique" (GICC, 2001) and the Intergovernmental Panel on Climate Change (IPCC) (http://www.ipcc.ch/) define climate adaptation in the following terms: "Natural and/anthropogenic systems reactions when submitted to climate events (real or predicted) in order to minimize the negative impacts and enhance potential advantages". With that definition in view, the "Centre National d'Etudes Spatiales" (CNES) in France, developed a conceptual and deterministic approach named tele-epidemiology, in which high-resolution, satellite remote sensing dealing with physical mechanisms linking climate, environment and public health issues, has been developed (Marechal et al., 2008).

Among many infectious diseases, Rift Valley fever (RVF) has become one of the most important emerging and/or re-emerging arboviroses. For example, RVF is on the top of the list of epidemics of importance according to the Senegalese "Système National de Surveillance des Épidémies (SNSE)". In particular, it is a key public health issue in the Ferlo region of Senegal (Fig. 1), where socioeconomical impacts are similar to those in Kenya (Pherez, 2007; Rich and Wanyoike, 2010).

Against this background, the "Adaptation à la Fièvre de la Vallée du Rift" (AdaptFVR) project, which involves several disciplines (ecology, climatology, hydrology, entomology, virology, among others) and therefore engages many scientific partners, has been carried out since 2009 under the sponsorship of the GICC French programme.

Due to the movement and expansion of Senegalese population, public health issues and changes in envi-

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Fig. 1. Map of Senegal including its geographical situation on the African continent. The site of the study area around the village of Barkedji in the Ferlo region (bounded by the dotted line) is within the black rectangle. Map adapted from Encarta 2007 (©), 1993-2006 Microsoft Corporation (all rights reserved).

ronmental conditions, many activities have been delegated to local organisations. The main Senegalese agents involved with the AdaptFVR project are: the "Institut Pasteur de Dakar" (IPD), the "Centre de Suivi Ecologique" (CSE) in Dakar, the "Direction des Services Vétérinaires" (DSV) in Dakar and various regional services including the Barkedji Veterinarian Section, the Rural Community and the "Unité Pastorale" (UP) of Barkedji. These organisations together made possible adaptive responses based on risk maps established from remote sensing, which have been distributed to all partners and stakeholders, as described in this paper.

The impacts of RVF depend strongly on (i) the rate of reproduction and diffusion of the mosquito vectors such as the *Aedes vexans* and *Culex poicilipes* species; (ii) the environmental and ecological conditions linked to heterogeneous rainfall and environmental variability, both contributing to virus emergence and diffusion; and (iii) the contacts between aggressive infected vectors and hosts, which represent the risk factors (i.e. hazards and vulnerability).

The activities carried out during the 2010 rainy season addressed three objectives:

(i) production and validation of RVF dynamic risk maps for herdsmen with the aim of protecting parked livestock potentially exposed to the RVF vectors at night;
(ii) assessment of the impact on vector aggressiveness of climate variability (from seasonal to low-frequency time-scales), including temperature and rainfall tendencies as well as issues related to anthropogenic climate change; and
(iii) development of pro-active adaptive actions to improving livestock management and animal health issues.

Materials and methods

To attain the objectives above, three necessary steps were identified. The first consisted of multi-disciplinary measuring campaigns involving intense observation followed by immunodiagnostic studies. To this end, key parameters (physical, chemical, biological, among others) contributing to RVF virus transmission were isolated and highlighted. The study area is shown in Fig. 1.

The measuring campaign took place during the rainy season (June to September) of 2010 within a 15 x 15 km zone around the Barkedji village in the Ferlo region, Senegal. Three main measuring campaigns, carried out between June and December 2010, incorporated those from the following disciplines and lead experts among the AdaptFVR partners:

(i) entomology: IPD identified the presence of RVF vectors in >80 areas where livestock herds (essentially bovine and ovine) were parked at night in the vicinity of ponds. The distances between the parking areas and ponds were also recorded. Six samplings were obtained during the rainy season (Fig. 2). Vectors were collected using CO_2 light traps from the Centres for Disease Control and Prevention (CDC) in the USA (http://www.afpmb.org/sites/default/files/pubs/standardlists/equipment/pdfs/3740-01-106-0091_Hock_Manual.pdf);

(ii) virology: the blood originating from the female biting mosquitoes was analysed using an enzyme-linked immunosorbent assay (ELISA). The Senegalese "Direction des Services Vétérinaires" (DSV) followed and monitored sentinel animals, while the immunological blood tests (http://www.differencebetween.net/science/health/difference-between-igm-and-igg/) were carried out by the IPD;

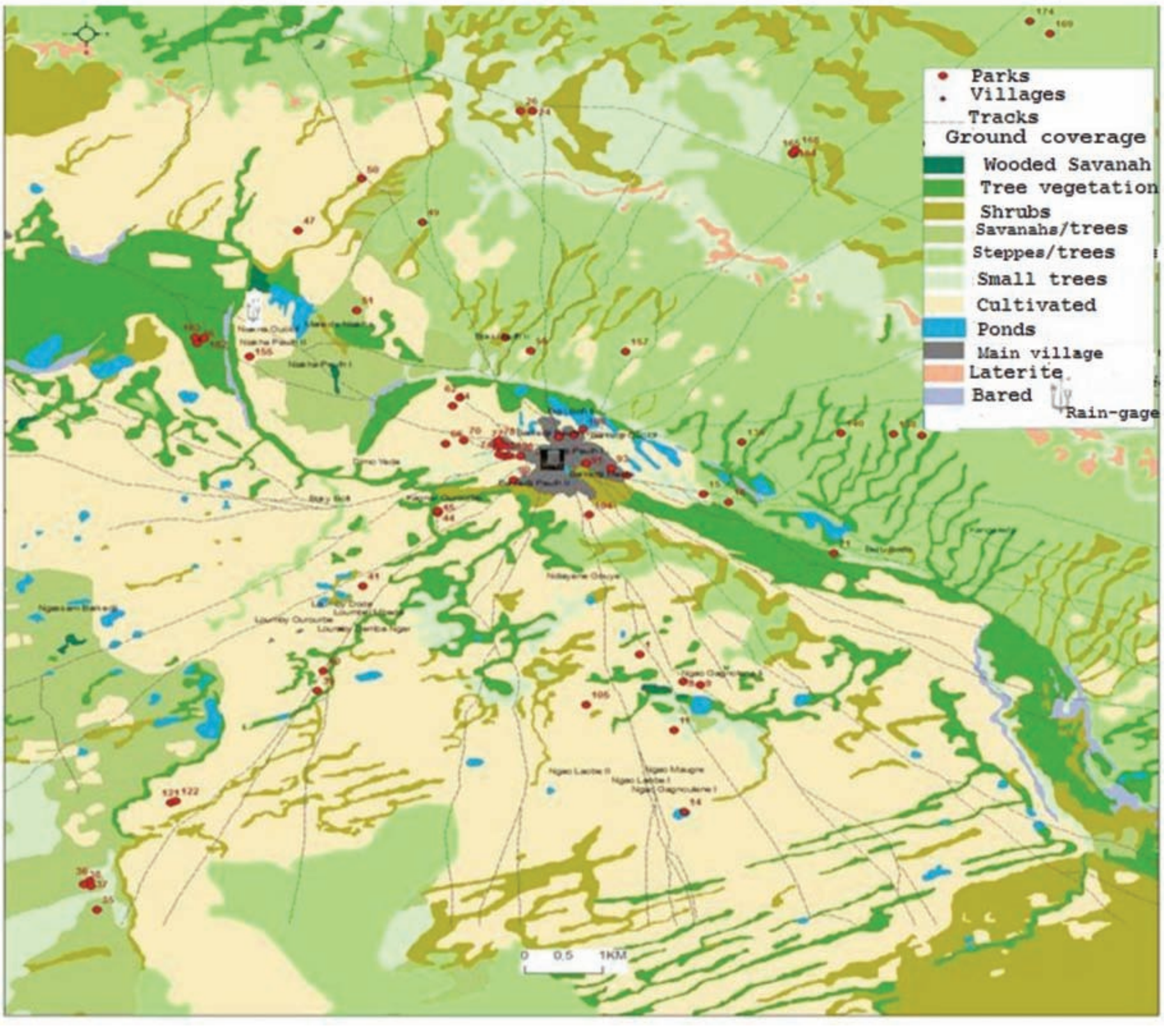

Fig. 2. Ponds, park locations and ground coverage within the 45 x 45 km rectangle where livestock was investigated by the Institute Pasteur Dakar (IPD) during the 2010 rainy season. The dark green areas indicate the "fossil river" where the largest ponds are found).

(iii) environmental variables: CSE collected all relevant hydrological, meteorological and agro-pastoral data. Rainfall data were obtained from raingages located near the Barkedji and Niakha villages;

(iv) pastoralism: both CSE and DSV distributed questionnaires to herdsmen along the various itineraries and paths followed during the transhumance period (Fig. 3);

(v) remote sensing: six images from the "Satellite Pour l'Observation de la Terre" (SPOT)-5 of 2, 5 and 10 m pixel resolution, were processed and analysed between June and December 2010 (approximately one image per month from the "Incentive for the Scientific use of Images from the SPOT system (ISIS) programme" (http://www.isis-cnes.fr) by the "Centre National d'Etudes Spatiales" or CNES; and

(vi) climate: in addition to seasonal climate prediction from the climatology centre of Météo-France team, the simulated data for West Africa for the 21st century was obtained through the World Climate Research Programme's (WCRP) Coordinated Regional Climate Downscaling Experiment (CORDEX) (http://www.cordex2013.wcrp-climate.org) - Africa and provided by the Centre National de Recherches Météorologiques (CNRM) from Météo-France in Toulouse (courtesy Dr. Samuel Somot). CORDEX is an internationally coordinated programme to produce an improved generation of regional climate change projections world-wide. Analyses and results are to be used as input to the IPCC fifth assessment report (to appear in 2014). CORDEX is also tasked to meet the growing demand for high-resolution downscaled climate projections, impacts and mitigation/adaptation programmes for the 21st century.

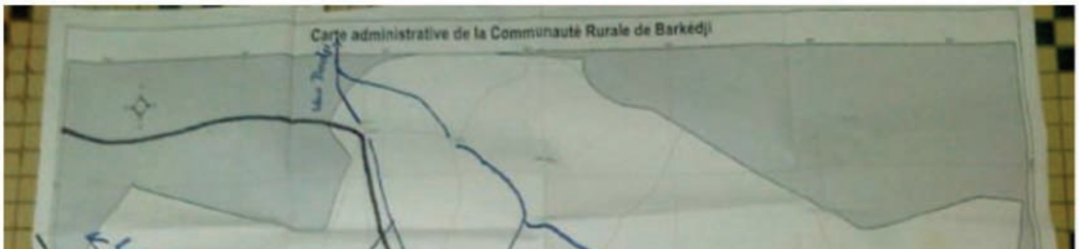

Fig. 3. Map showing paths of livestock movements near Barkedji during 2010. Blue arrows are the trajectories used by the Serer herdsmen. The Serer people constitute the third largest ethnic group making up to 14.7% of the Senegalese population. The blue and black lines are trajectories used by pastors from the Sahara-Sahel region or Peuls (Courtesy of Thomas Manga).

The second step was the creation of a predictive, bio-hydrological model. The conceptual approach of tele-epidemiology at CNES (Marechal et al., 2008; Tourre et al., 2009; Vignolles et al., 2010) was developed for the RVF in the Ferlo area during a 10-year constructive multidisciplinary approach that began in 2003. Dynamic, hazards maps were produced following rainfall events and emergence of the two main vectors *A. vexans* and *C. poicilipes* (Vignolles et al., 2009). Three factors were taken into account: rainfall, mosquito flying range, and mosquito aggressiveness. Rainfall events were to be the primary input, since the distribution and intensity of these events determine pond dynamics with regard to the presence of larvae sites and eggs hatching. The resulting maps were the zone potentially occupied by mosquitoes (ZPOMs) (Tourre et al., 2009; Vignolles et al., 2009), a product of hazards and vulnerability of livestock parked at night (Tourre et al., 2008; Ndione et al., 2009).

In order to release risk maps (consisting of the combination of hazards and vulnerability) in quasi-real time, automatic hazard maps were since produced through a model using a process chain of causality in the interactive data language (IDL) code (https://www.cfa.harvard.edu/~scranmer/Ay201a/Data/idl_basics.pdf) based on ITTVIS software (http://www.itres.com/products/supporting/hyperspectral_image_analysis_software/), which is supported by Windows XP and Windows 7 by ENVI 4.7 and IDL 7.1 (http://www.ittvis.com/) providing at least one gigabyte random access memory and graphic facilities with at least 800 x 600 pixels. Three main functions were used to establish the final product:

(i) analysis of rainfall products from the tropical rainfall measuring mission (TRMM);
(ii) analysis of pond dynamics (filling-up and flushing-out) based on data obtained from the normalised difference pond index (NDPI) according to Lacaux et al. (2007); and
(iii) analysis of vector density as a function of integrated total water areas from clustered ponds.

In this model, a pond has the shape of a Gaussian trough with cylindrical symmetry. Any water input from a rainfall event changes the water surface area using a differential hydrological approach (Guilloteau et al., 2013). It was found that a pond can disappear quickly (through evaporation and percolation) when its exposed surface is less than 60 m^2. Finally the aggressiveness of *Aedes* was found equal to zero if ponds dry up within 4 days after a rainfall event as this rapidly stops the species' aquatic cycle.

The third step consisted of the evaluation of the products developed. This represents the integration of diagnostic studies with information obtained from remote sensing and *in-situ* data within the Ferlo area. Through the project, a bio-hydrological model was thus developed (where measured and predicted amounts of rainfall were the primary inputs). It was immediately recognised that effective management produces the required quantification of predicted risks at small spatio-temporal scales, For example, the model does not take into account anymore a unique rainfall value for the 2,000 km^2 area as before, but a geo-referenced rainfall field with isohyets contours within the area. The spatial heterogeneity of rainfall is thus considered. Moreover, *Culex* aggressiveness is now considered if a cumulated rainfall threshold is attained for a 28-day period, through the use of a moving window (Guilloteau et al., 2013). This final step led to the implementation of early warning systems (EWS) for RVF (or RVFews) to better adapt and mitigate to the risk for infection. Eight weekly bulletins with dynamic ZPOMs and proper interpretation were distributed to all stakeholders during the 2010 rainy season, from 7 July to 1 October 2010.

Results

Objective 1: production and validation of RVF dynamic risk maps for herdsmen to be used for protection of parked livestock potentially exposed to the RVF vectors at night

The first step geared at understanding the mechanisms involved in the different disciplines favouring the emergence and proliferation of vectors produced the following data:

(i) entomology: IPD collected 12,714 female mosquitoes. Of the 82% found to be responsible for RVF virus transmission, 58% were *A. vexans* and 13% *C. poicilipes*. The mean vector density was found to be a function of the distances from the ponds (the flying range). After the first rainfall event in July, *A. vexans* were produced massively. While their density decreased during August, a second peak occurred in September and the numbers then decreased until the end of the rainy season. The *C. poicilipes* density increased steadily from July onward to reach peaks in September and October (Fig. 5);
(ii) virology: DSV collected 1,129 serum samples (127 bovine ones and 1,002 from small ruminants). Immunoglobulins of the IgG and IgM classes allowed us to detect viral infections, to

Fig. 4. Most of the clayey bottom of the Niakha pond is still very dry when starting to slowly fill up after the first rainfall event of 24.6 mm (12/07/2010 at 17h45).

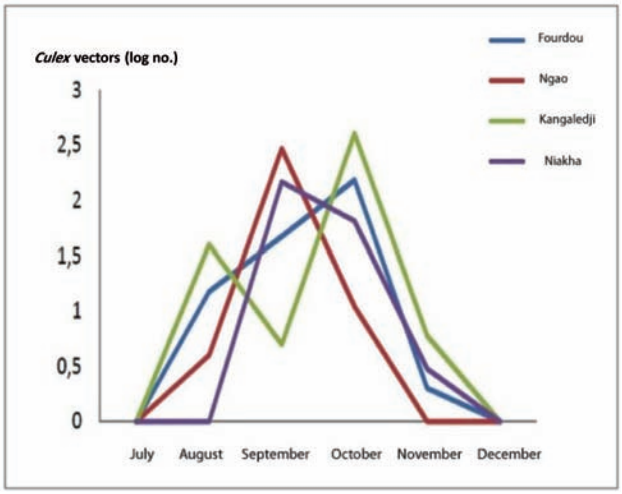

Fig. 5. Dynamic of *Culex poicilipes* density in the vicinity of four ponds within the study area during the 2010 rainy season. The highest densities are in September for Ngao (red) and in October for Kangaledji (light green).

know previous history on the virus circulation, and to indicate the more recent contact with the virus. Interestingly, there was no ancient circulation of the RVF virus found for any samples collected during the 2010 rainy season;

(iii) environmental variables: rainfall was near normal during the season but had a late start (end of June). Maximum rainfall amounts (convective types) occurred in August. The total amount of rainfall was 400 mm in Niakha and 450 mm in Barkedji. Limnimetric measurements showed that the ponds started to fill-up quite late (Fig. 4);

(iv) pastoralism: according to Thomas Manga, Head of the Barkedji veterinary services, the movement and displacement of cattle (Fig. 3) started early in 2010, with a slight increase of the number of small bovine and ruminants fluxes. The camel flux coming from Mauritania has been in constant increase for several years;

(v) remote sensing: the SPOT imagery showed location and extension of 1,350 ponds (all numbered) and the relative location of the 181 livestock parks were positioned with high accuracy (Fig. 2);

(vi) climate: since significant correlation was found between the tropical Atlantic sea-surface temperature variability and *Aedes* density in the Ferlo for the 1960-2010 period (AdaptFVR Report, 2012), a mid-term adaptive strategy became feasible (i.e. bed-nets distribution, vaccination, larviciding). Actual modulations of the interannual climate signal by the quasi-decadal and Atlantic multi-decadal fluctuations during the short-lived project were more difficult to apprehend. Adaptive strategy from anthropic climate change and for the 21st century using analyses and results from CORDEX-Africa seems minimal. While the temperature could increase by 1 °C over the next 50 years, very little changes of rainfall amount are predicted over the Ferlo. An overall seasonal decrease of 10 mm for rainfall amounts by 2050 in the vicinity of Barkedji will not only have little effect on ponds dynamics, but is also within the uncertainties of the numerical models.

The ZPOM maps were produced in a timely fashion (weekly) for the full rainy season around Barkedji (Vignolles et al., 2010) during the AdaptFVR project. In brief, ZPOMs were derived from clustered ponds identified from space along with their dynamics (filling-up and flushing-out) after a so-called heterogeneous “productive rainfall” event (more than 10 mm), in terms of vectors presence and aggressiveness (i.e. risks), using the much improved bio-hydrological model (Guilloteau et al., 2013). Throughout the project a better understanding of mechanisms involved in vector production allowed the development of a specific bio-mathematical model for the emergence of the two vector species. By comparing the measured and modelled vector risks for the 181 parks in the Ferlo region between July 15 and October 30, 2010 it was found that:

(i) the density of *C. poicilipes* was less than that of *A. vexans* with a quasi zero risk (99%), for both measured and modelled classes (Fig. 6); and

(ii) about 97% of the *A. vexans* density obtained for the four classes (zero, weak, average and high) are in the no-risk and weak-risk classes, both for measured modelled data (Fig. 7).

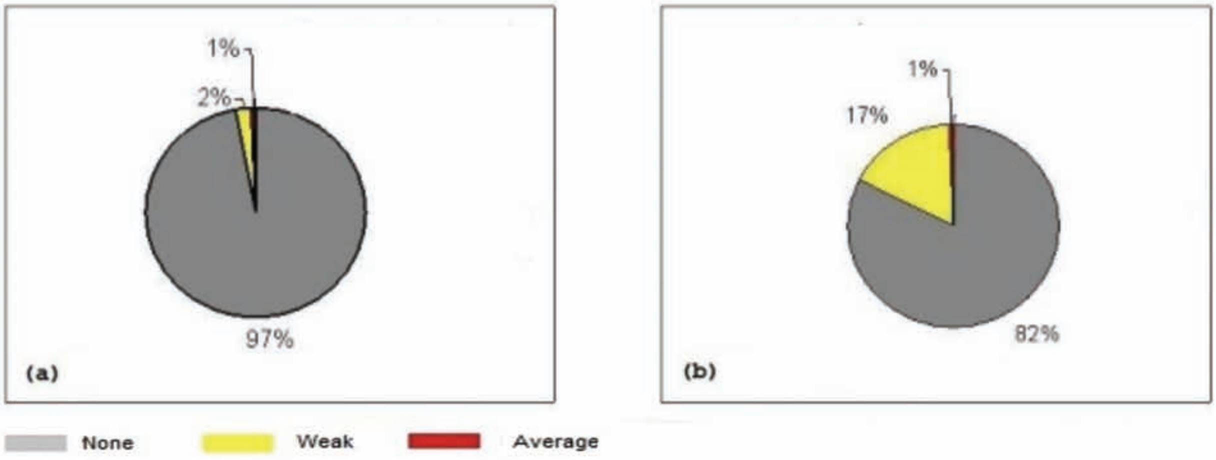

Fig. 6. Comparing *in-situ* measures and model's output for *Culex poicilipes* presence around the Niakha pond. *In-situ* measures from parks (a) and output obtained from the modeled ZPOM (b). Risk varies from no risk (grey) to average risk (red) over weak risk (yellow).

Objective 2: assessment of the impacts of climate variability (from seasonal to low-frequency time-scales and vector-risk aggressiveness

Rainfall dynamics in the Sahel is tightly linked to climatic squall-lines activity (Aspliden et al., 1976; Desbois et al., 1988) modulated by at least four different, natural time-scales: seasonal, inter-annual, quasi-decadal (8-12 years) and multi-decadal (20-60 years), i.e. what is called the low-frequencies climate signals, and also possibly by the anthropogenic climate change associated with the increase in global concentrations of greenhouse gases. The main important points found during this project on impacts from climate variability and change, were:

(i) that the seasonal probabilistic forecasts (i.e. quintile type) are limited to spatio-temporal scales. Although downscaling techniques are being developed, the statistical information made available (e.g. from Eurosip Products; http://www.ecmwf.int/products/catalogue/VIII.html, should allow health information services (HIS) to initiate and anticipate strategies early in the season;

(ii) that the inter-annual and low-frequencies predictions are essentially based on statistical correlations between the Atlantic sea-surface temperature (SST) and the density of *A. vexans* mosquitoes. Significant correlations with positive lags have been found for the 1960-2010 period (hindcasting period) and adaptive methods can be applied for the medium-term period, i.e. positive/negative SST anomalies for a 10-15 year period are associated with increase/decrease of *A. vexans* density at the beginning of the rainy

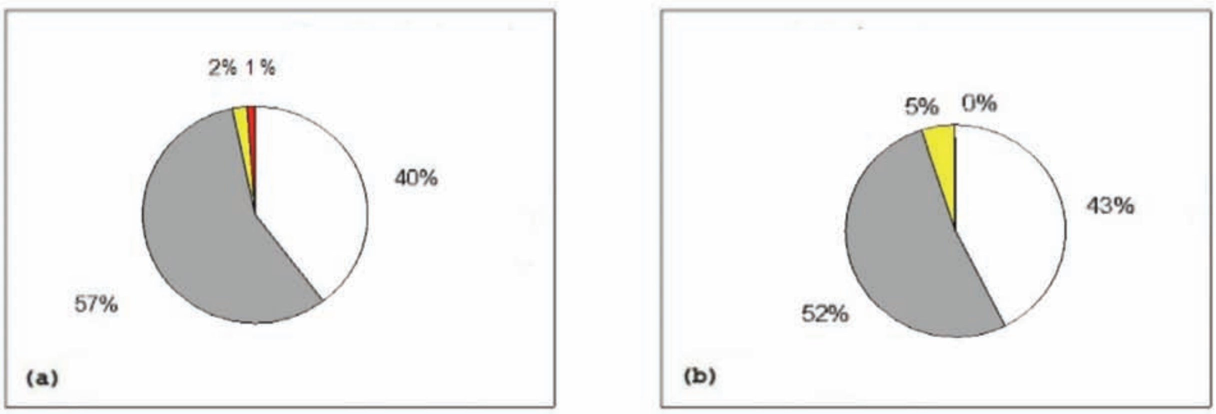

Fig. 7. Comparing *in-situ* measures and model's output for *Aedes vexans* presence around the Niakha pond. *In-situ* measures from parks (a) and output obtained from the modeled ZPOM; (b) risk varies from no risk (white) to strong risk (red) over average risk (grey).

season (AdaptFVR Report, 2012). The use of climate indices such as the quasi-decadal oscillations (QDOs) and Atlantic multi-decadal oscillations (AMOs), respectively, seems more difficult to utilise since the two signals modulate each other and a changing phase of the AMO require at least 6 months of observations to be definite. For example, during 2010-2012 the values for negative phases of the AMO were very small and a definite return to a positive phasing of AMO could not be anticipated; and

(iii) that the preliminary results from the CORDEX programme indicate that only a minimal climate change seems to have taken place during the 21st century in Senegal (http://www.wcrp-climate.org/wgcm/WGCM16/Jones_CORDEX_WGCM16.pdf), in particular from Cordex-Africa (http://start.org/cordex-africa/about/) and the representative concentration pathway -4.5 (RCP, 4.5), which is a scenario that stabilizes radiative forcing at 4.5 Watts/m^2 in the year 2100 without ever exceeding that value.

With respect to rainfall amounts over the Ferlo, very little change is expected (<10 mm for the next 50 years). In addition no significant temperature tendencies are noted. Changes in pond dynamics are thus within the model uncertainties, and little change is expected. Consequently, the seasonal forecasts must be improved, particularly on smaller spatio-temporal scales, goals of the new the observing system research and predictability experiment (THORPEX) interactive grand global ensemble (TIGGE) project (http://tigge.ecmwf.int/). TIGGE is a key component of a WCRP 10-year international research and development programme to accelerate improvements in the accuracy of 1-day to 2-week high-impact weather forecasts for the benefit of society, the economy and the environment. Prediction of pond dynamics for public health issues should thus be improved accordingly. It should be noted that for the next 50 years, the major factor could in fact be the increase of agriculture needs at the expense of raising livestock.

Objective 3: development of pro-active adaptation to improve livestock management and animal health issues

Several approaches were identified: individual adaptation, private and public adaptation, and reactive adaptation. At the present time the anthropogenic climate change signal is not sufficiently well defined and quantified in the Sahel. Nevertheless, vertical and transverse actions were chosen to adapt in advance, well before the actual effects of climate change are seen (pro-active adaptation). The main action needs based on a multi-disciplinary and integrated approach are as follows:

(i) production and distribution of the Adapt FVR Bulletin, predicting the presence of *A. vexans* and *C. poicipiles*. Bulletins were distributed to veterinary services in a timely fashion and near real-time in 2010;

(ii) use of timely Bulletins to guide targeted actions. The three main actions (including special radio shows in local language for local herdsmen) needed should aim at:

  (i) displacement of herds and livestock from zones under potential risk every 15 days. Special signs in local language (Fulani) will be installed to identify zones where cattle can be parked more safely (at least 500 m from the nearest "productive" ponds in terms of vectors);

  (ii) organising tactical larvicide deployment. This will be based upon the ZPOM maps. For example during 2010 (Figs. 8 and 9) out of the 1,354 ponds around Barkedji (45 x 45 km) only 457 ponds are potentially sources for *C. poicipiles* production (vegetation cover more than 50% of the surface). This is a total area of 373 ha. On average, the area to be treated is 68.2 ha corresponding to 115 ponds. From this type of information the amount of larvicide to be used can be better evaluated and distributed so that money and

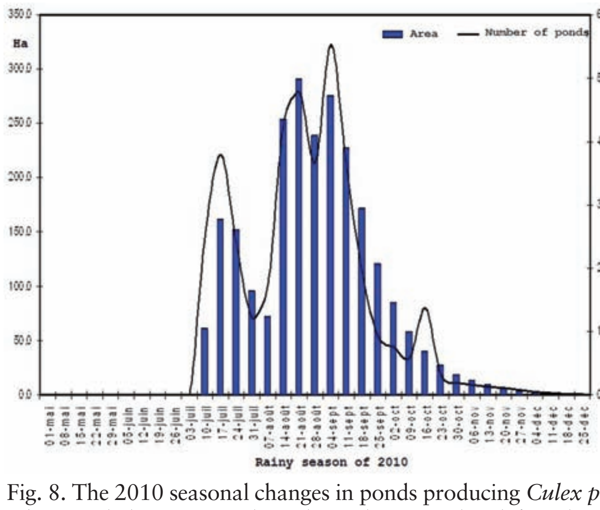

Fig. 8. The 2010 seasonal changes in ponds producing *Culex poicilipes* and the associated total pond area in ha (left ordinate) based on the ZPOM concept. The right ordinate denotes number of ponds.

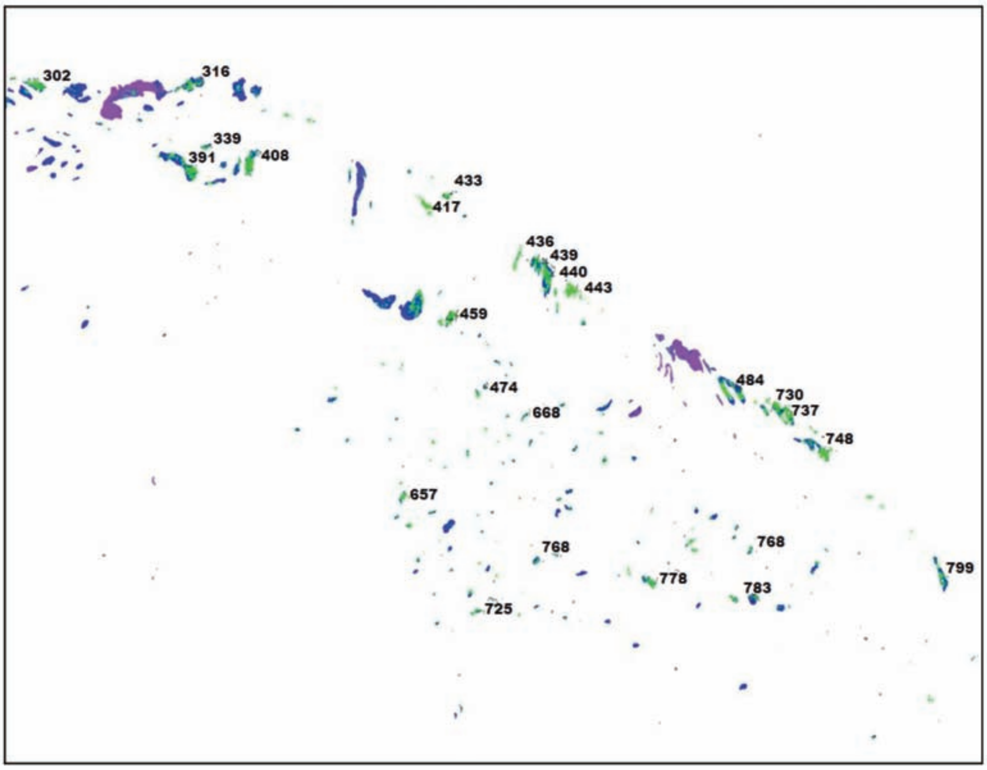

Fig. 9. Depending on the outcome of cost/benefit analysis, a limited number of ponds will be treated by larvicides around Barkedji. Turbid ponds in purple, free water surface is in blue and vegetation within ponds in green. Out of the total of 1,354 ponds considered, those with areas larger than 1 ha are denoted by sequential numbers. The number of them that will be treated is a function of resources.

resources can ultimately be saved (this particular work is still in progress); and

(iii) organising vaccination campaigns deemed necessary so that the DSV can deploy a vaccination strategy as a function of predicted risks.

Implementation of strategic adaptation through national, regional and local communications is basically needed to make sure that the smallest localities can use products such as ZPOM appropriately. Thus products must be not only distributed rapidly but understood by users/stakeholders. The DVS is to analyse the benefits of such actions by highlighting the benefits obtained by the local population and communities at large. Finally, it should be noted that the AdaptFVR Project and its preliminary results with strategic actions have been presented to the Senegalese government by the DSV (member of the national assembly).

Conclusion

The AdapttFVR project, supported by the French GICC programme of the "Ministère de l'Écologie, du Développement Durable et de l'Énergie" (MEDDE), was successful in accomplishing the main objectives addressed. Based upon the fruitful North-South multi-disciplinary collaboration that started 10 years ago, concrete measures such as pro-active adaptation can now be taken. Bulletins have been issued in a timely fashion, tested and validated by users/stakeholders. The DSV was able to deploy strategic adaptation, in close collaboration with local population. The first strategic measures are planned to be in place for the 2014 rainy season. The larvicide campaigns can be better evaluated in terms of cost/benefit analyses. Finally CNES will transfer all technologies to the CSE personnel by the end of 2013, including the coupled bio-mathematical model and its main output: predicting the emergence of RVF vectors as a function of heterogeneous rainfall amounts. Other studies using basically the same conceptual approach of the tele-epidemiology method described in this paper are being implemented for urban and rural malaria (PaluClim Project) and dengue in the French Antilles. Results of this are displayed in details within the http://RedGems.org website.

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