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Ecological niches and vector-borne pathogens transmission

Nicolas Moiroux

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Niches écologiques et transmission de pathogènes par des insectes vecteurs

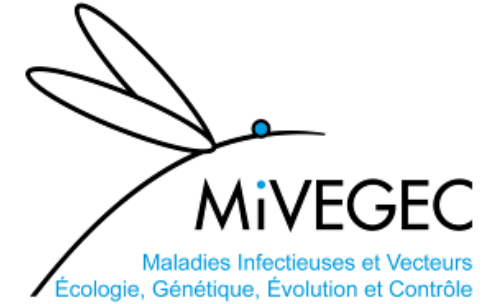
Nicolas Moiroux, CR IRD, UMR MIVEGEC

Master Dynamique des interactions Parasite-Hôte Environnement

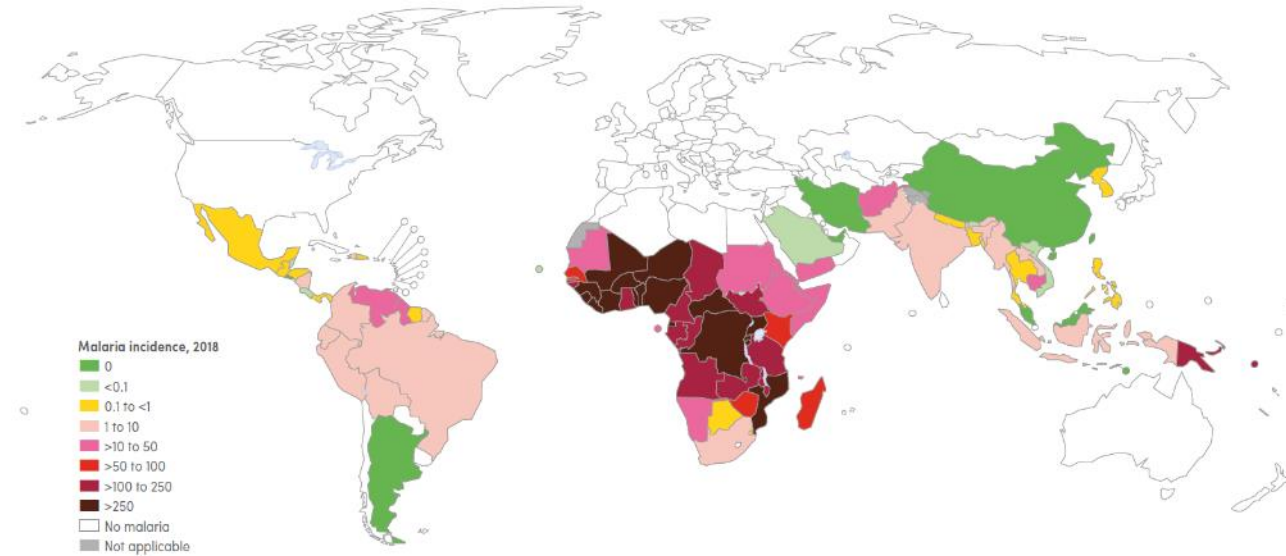
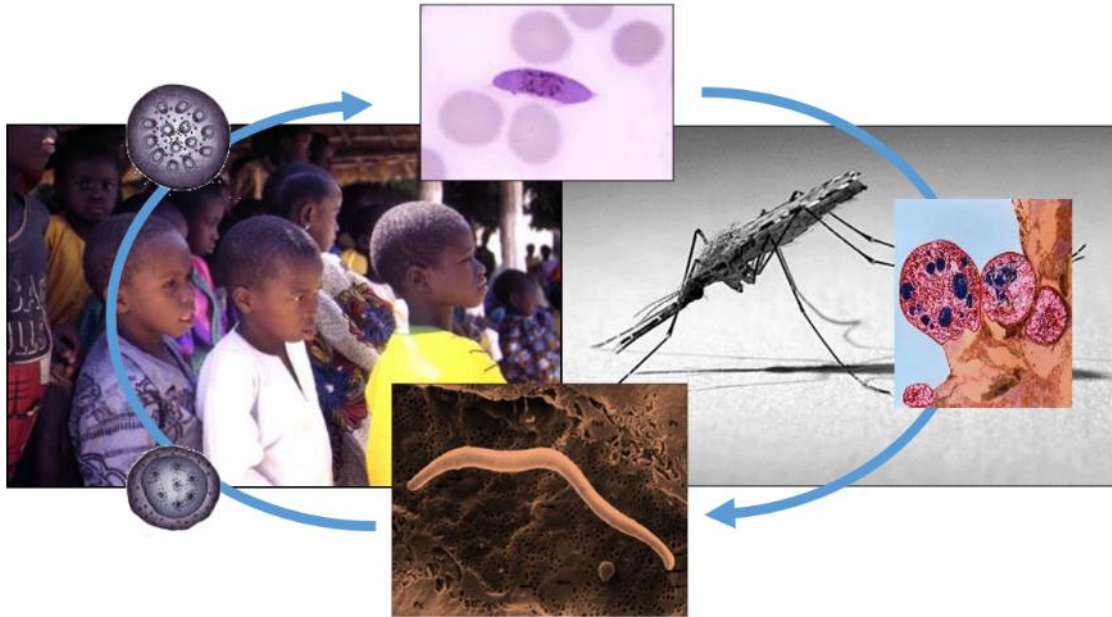
21 Septembre 2020

nicolas.moiroux@ird.fr

www.mivegec.fr



Principales maladies à transmission vectorielle



- | | |
|-------------------------|-------------------|
| Typhus | Poux |
| Rickettsioses | Puces, Tiques |
| Peste | Puces |
| Onchocercose | Simulies |
| Loase | Chrysops |
| Maladie du sommeil | Glossines |
| Maladie de Chagas | Triatomes |
| Leishmanioses | Phlébotomes |
| Filariose de Bancroft | Moustiques |
| Paludisme | Moustiques |
| Dengue | Moustiques |
| Chikungunya | Moustiques |
| Zika | Moustiques |
| Fièvre Vallée du Rift | Moustiques |
| West Nile | Moustiques |
| Encéphalites à tiques | Tiques (Ixodes) |
| Fièvres hémor. à tiques | Tiques (Hyalomma) |

Paludisme:

½ humanité à risque
 200-300 millions de cas/an
 400.000 morts/an

Dengue/DHF

½ humanité à risque
 100 millions de cas/an
 ??? morts/an

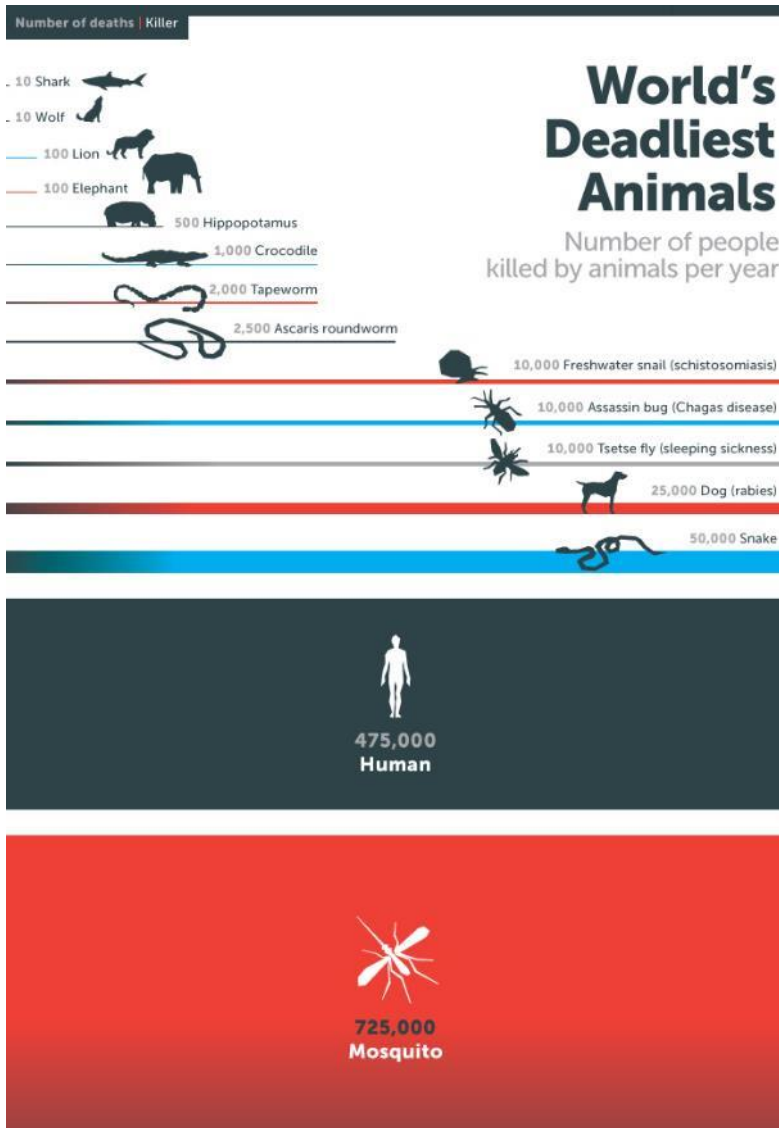
Les moustiques

Position systématique

Règne: Animal
 Embranchement: Arthropodes
 Classe: Insectes
 Ordre: Diptères
 Famille: Culicidae = **Moustiques**

+ de 3500 espèces de moustiques
 ≈ 35 genres

3 genres impliqués dans la transmission de pathogènes

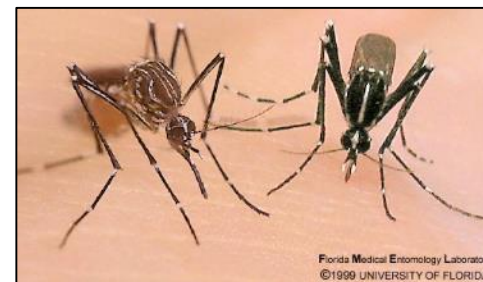


Culex



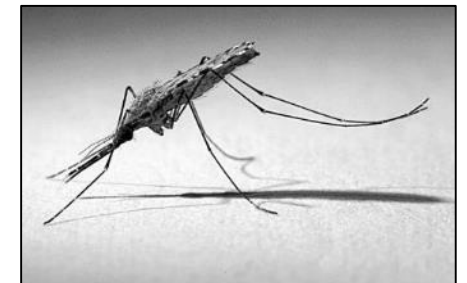
Filaires, arbovirus

Aedes



Arbovirus

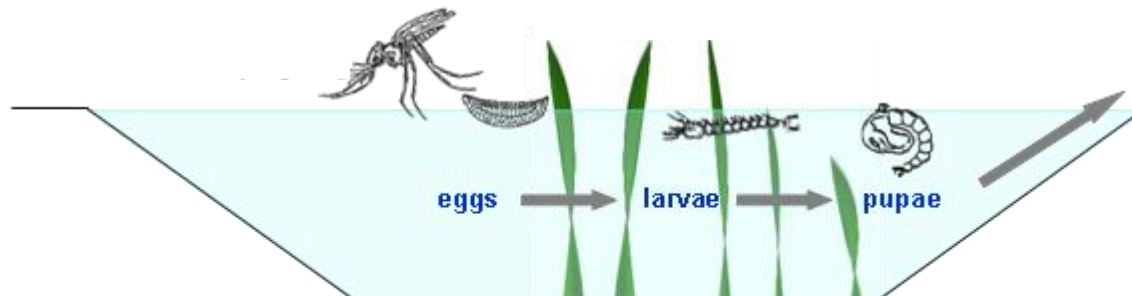
Anopheles
 (~60 sp vectrice)



Plasmodium, filaires

SOURCES: WHO; crocodile-attack info; Kasturiratne et al. (doi.org/10.1371/journal.pmed.0050218); FAO (webcitation.org/6Ogp585V0); Linnell et al. (webcitation.org/6ORL7DBUO); Packer et al. (doi.org/10.1038/22436927a); Alessandro De Maddalena. All calculations have wide error margins.

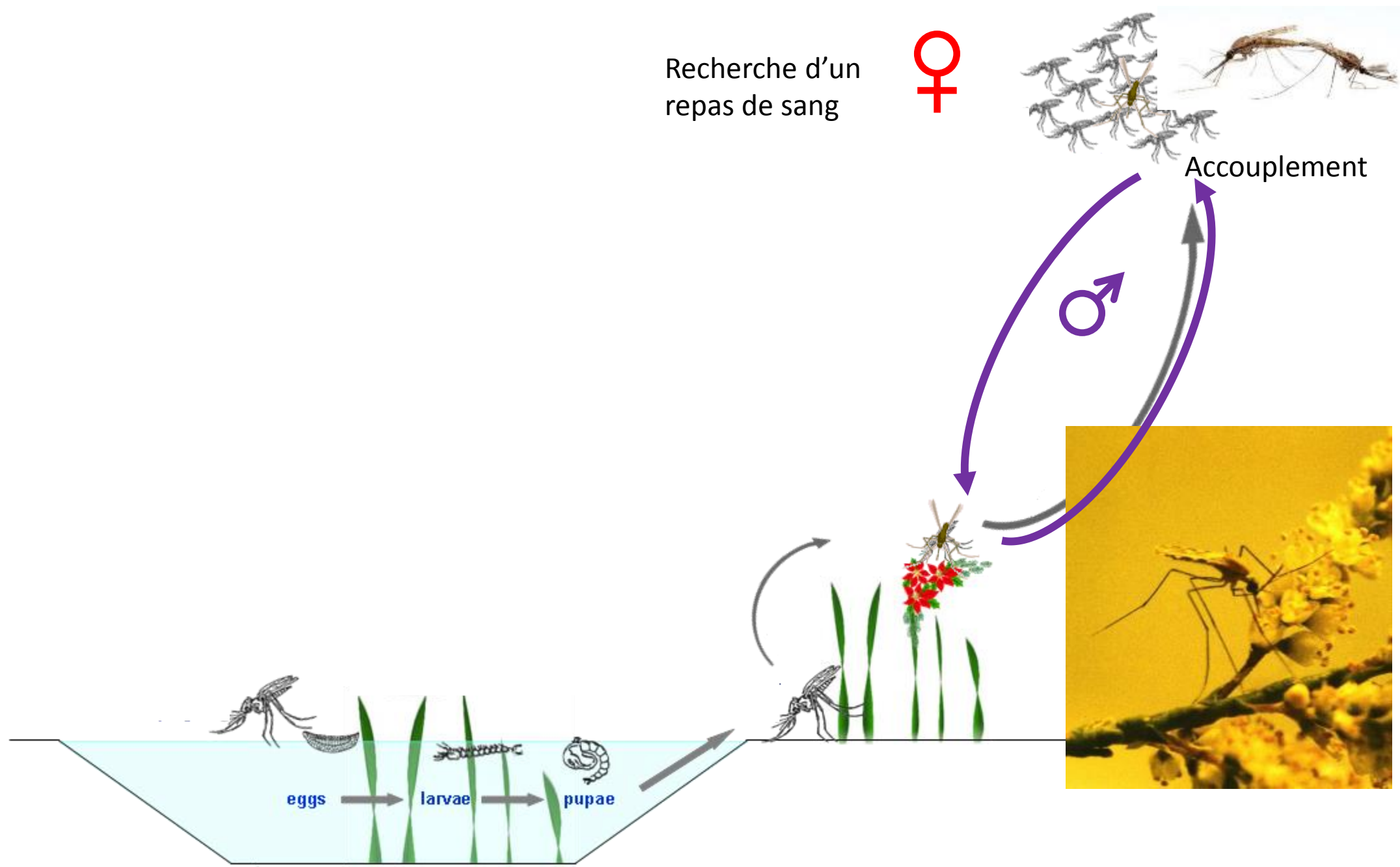
Cycle de vie du moustique, un insecte aquatique :



Recherche d'un repas de sang



Accouplement



Cycle Gonotrophique

Repos – digestion –
maturation des œufs

Recherche d'un
repas de sang

Accouplement

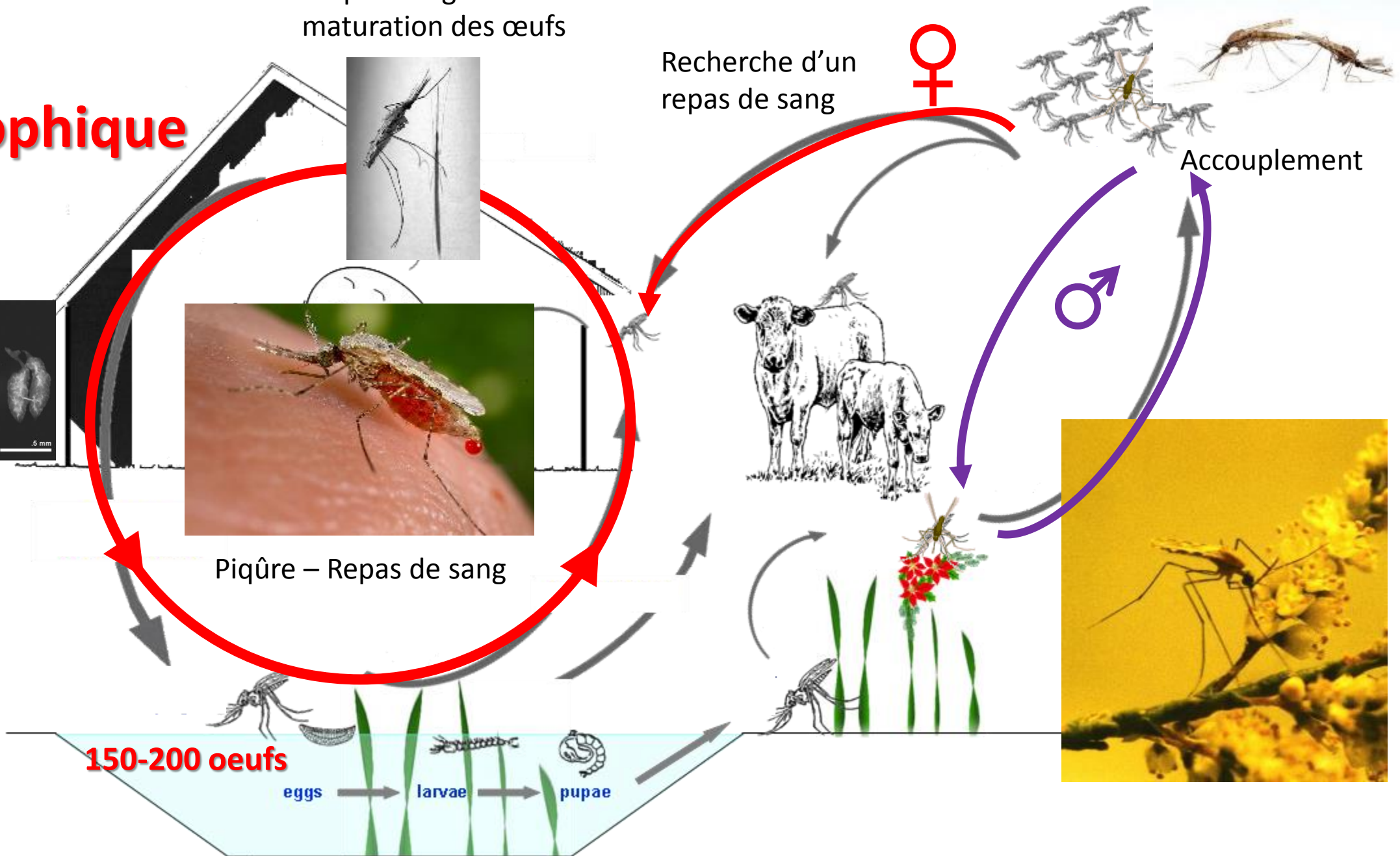
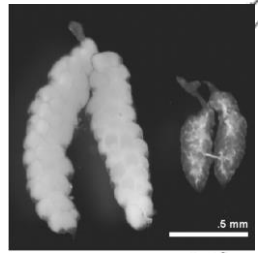
Piqûre – Repas de sang

150-200 œufs

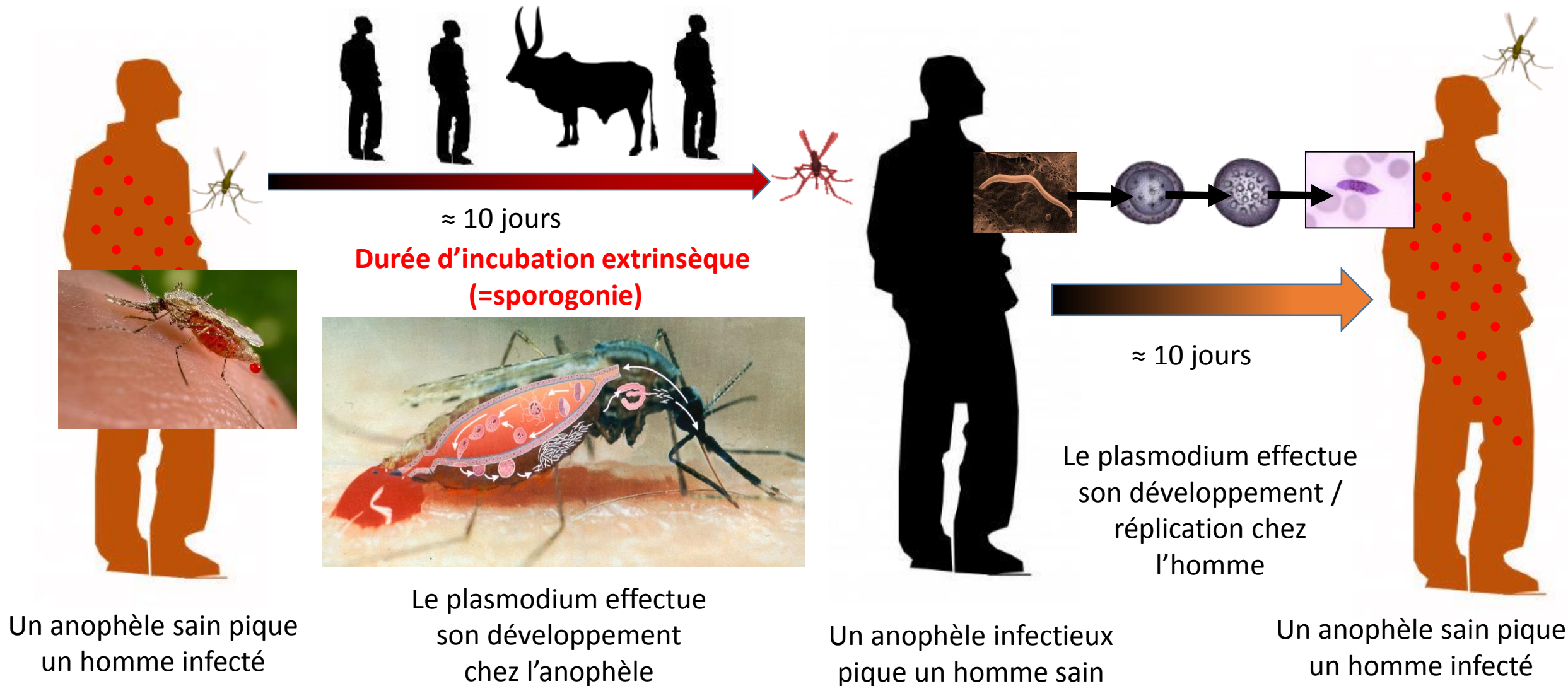
eggs

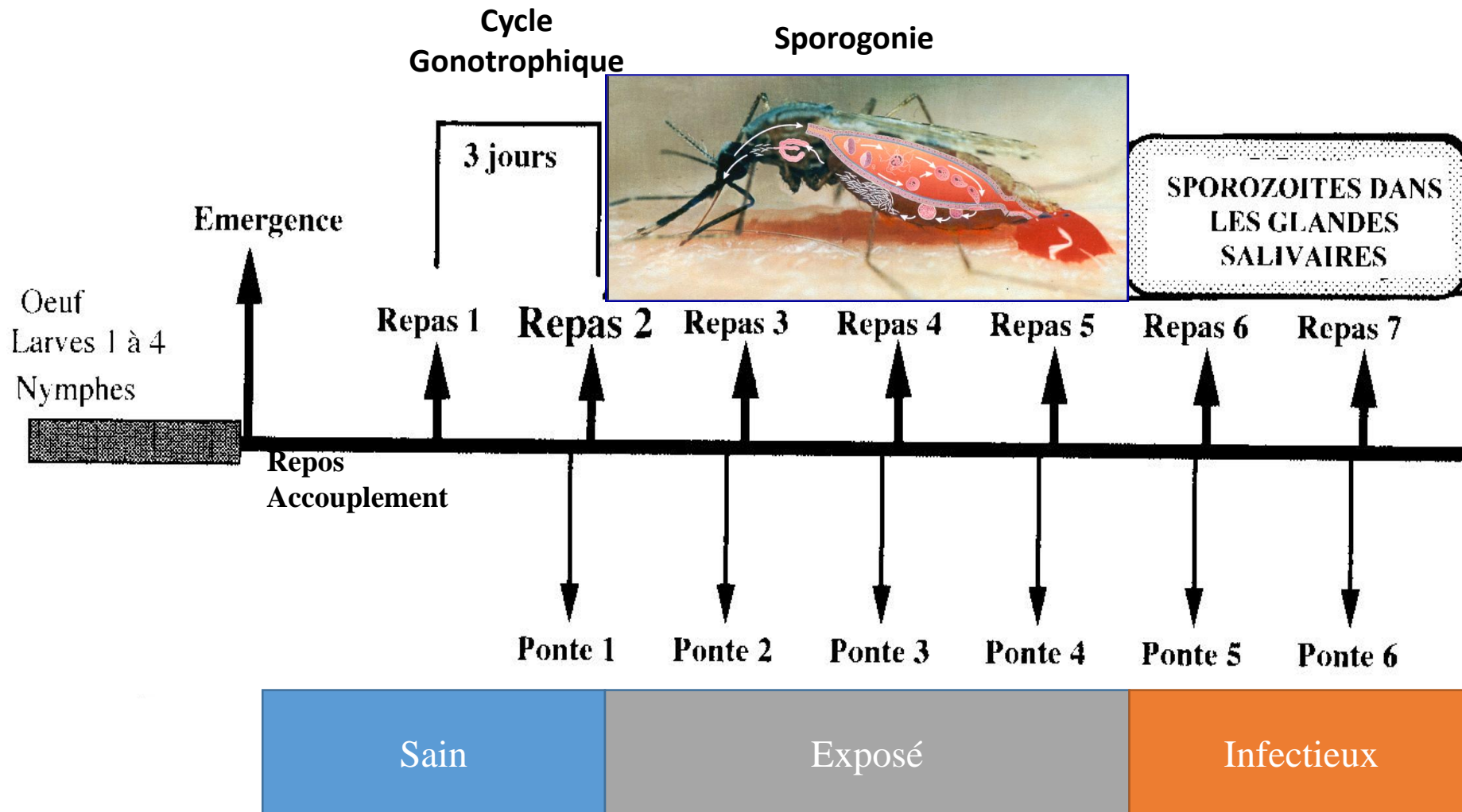
larvae

pupae



La transmission du paludisme

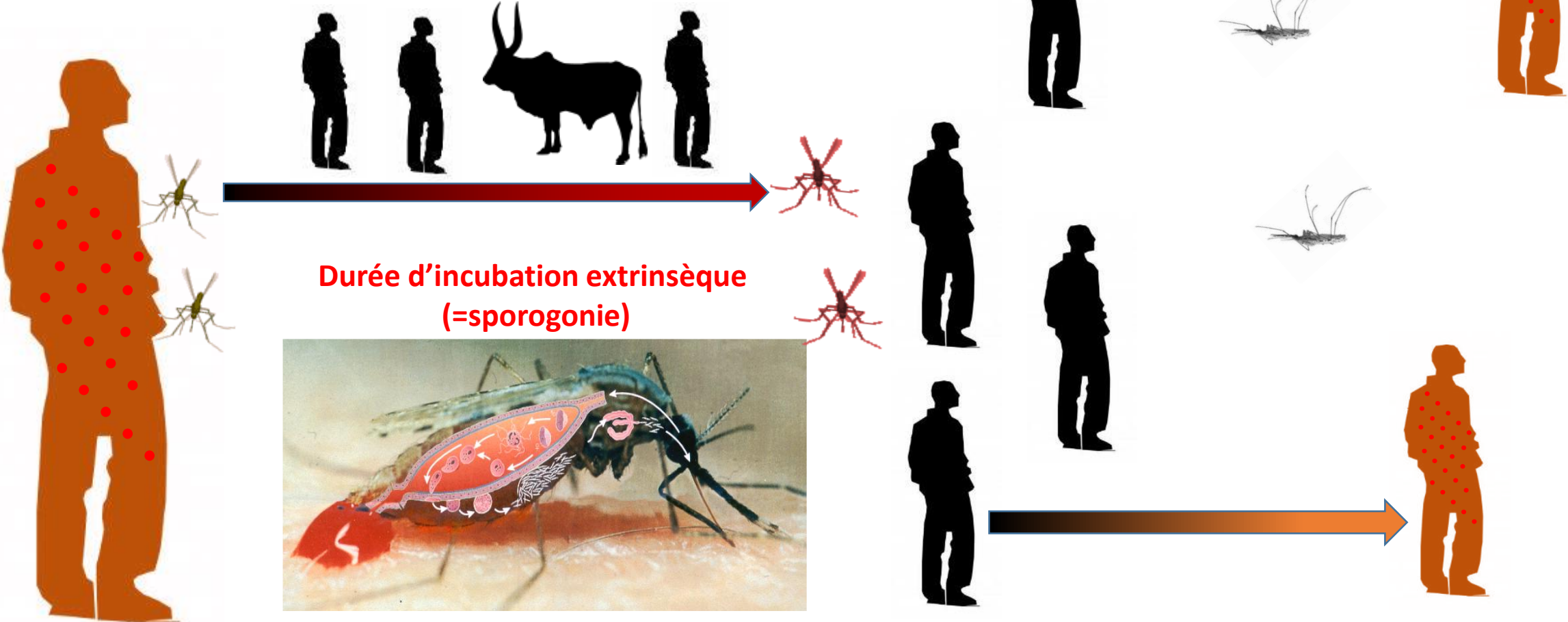




Pour qu'il y ait transmission, la femelle doit survivre assez longtemps pour:

- permettre l'intégralité du développement extrinsèque du *Plasmodium*,
- pouvoir piquer ensuite pour transmettre.

Capacité vectorielle



Nombre de piqûres infectantes reçues dans une pop. humaine à partir des piqûres reçue en 1 jour par une seule personne infectée.

$$CV = 4$$

$$R0 = 2$$

Capacité vectorielle

Mesure de la capacité d'une population de vecteurs à assurer la transmission d'un pathogène.

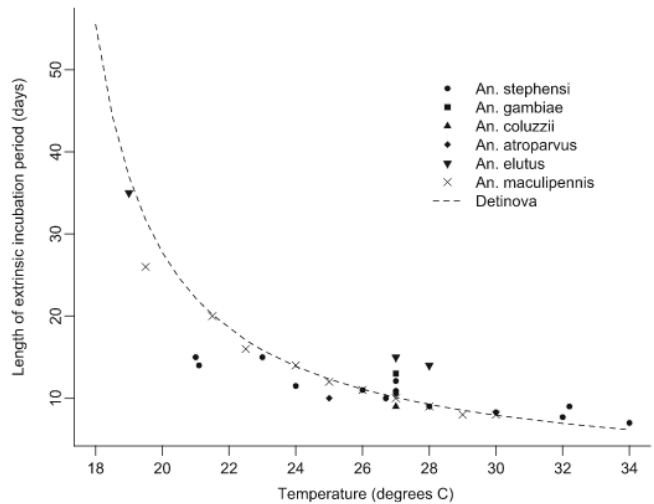
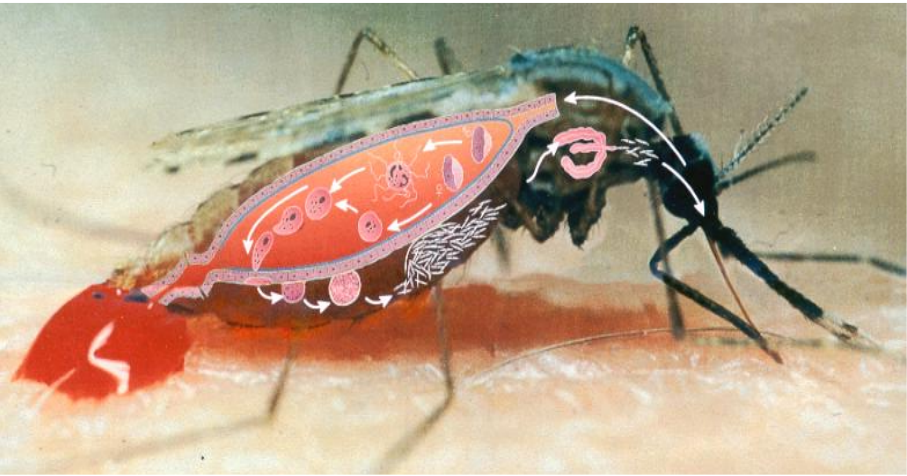
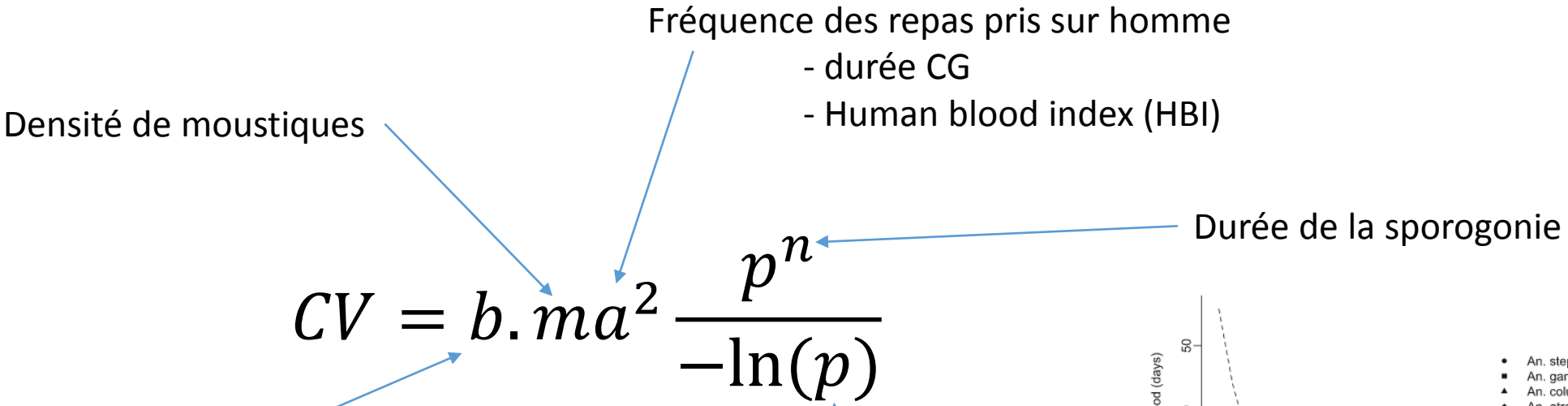
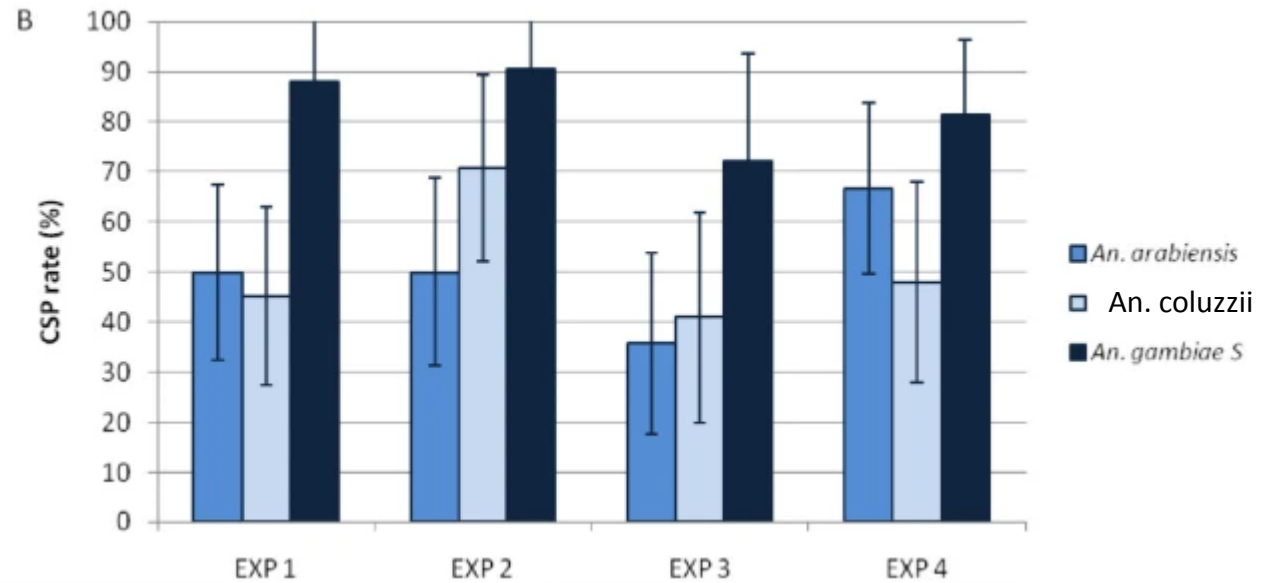


Fig. 1 Empirical estimates of EIP for *P. falciparum* across a range of studies. The dotted black line represents the standard degree-day model of Detinova [1] parameterized using the data for *An. maculipennis* [5].

Compétence vectorielle

Capacité d'un arthropode à acquérir un pathogène, permettre sa multiplication (son développement) et le transmettre.



14 days post-feeding at 27°C

Ndiath *et al* 2011

Le système vectorielle

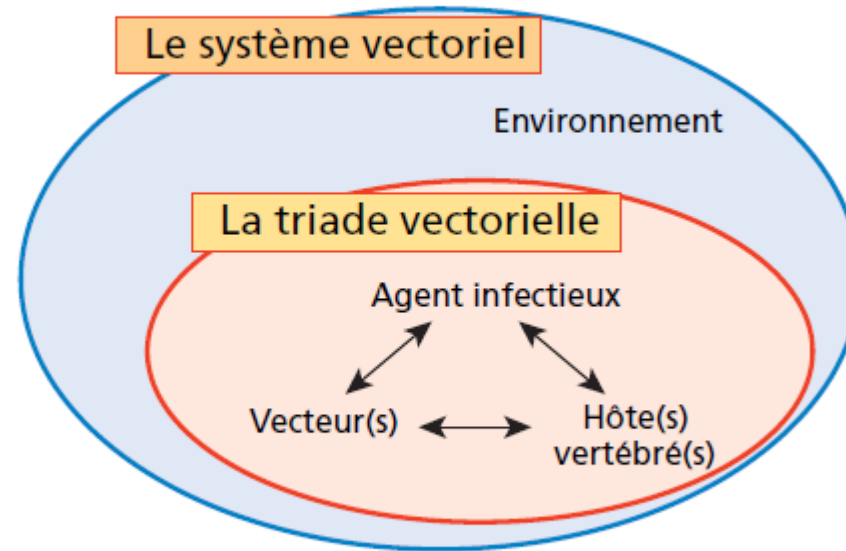
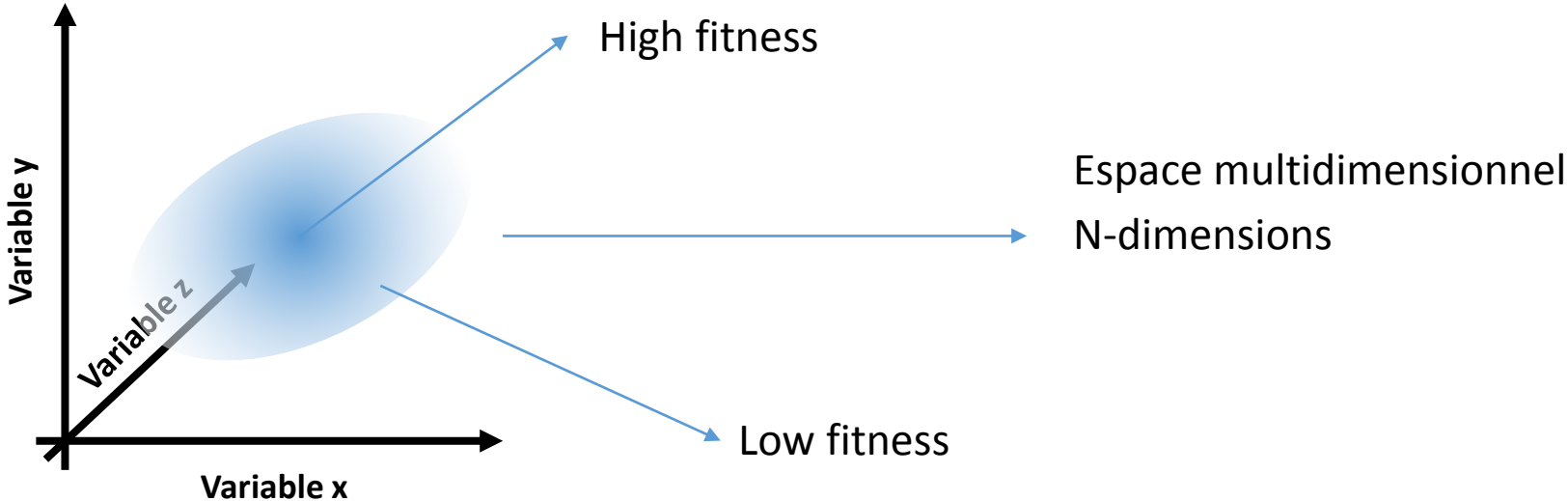
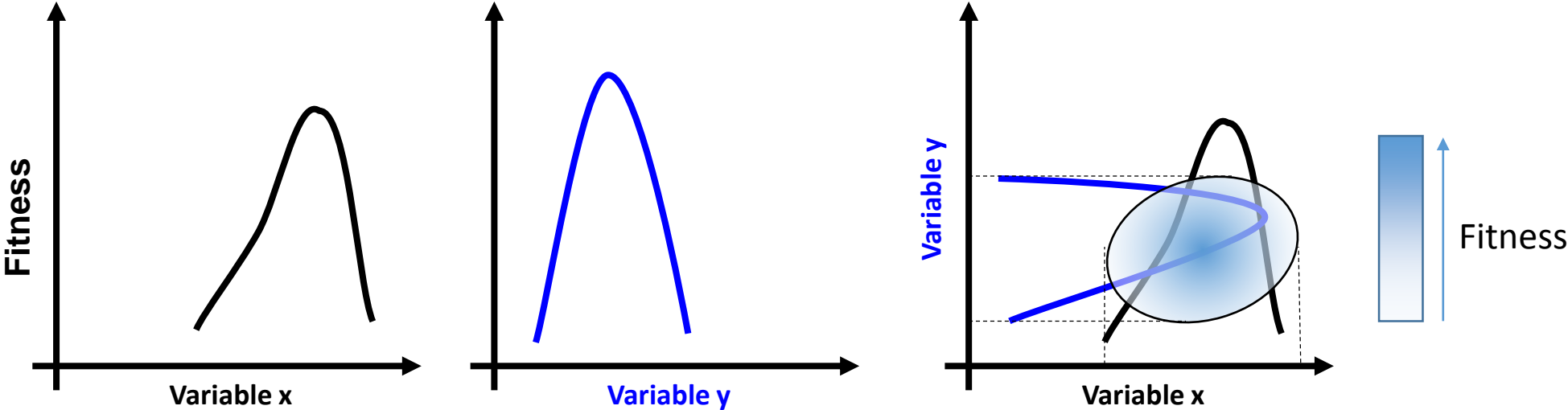
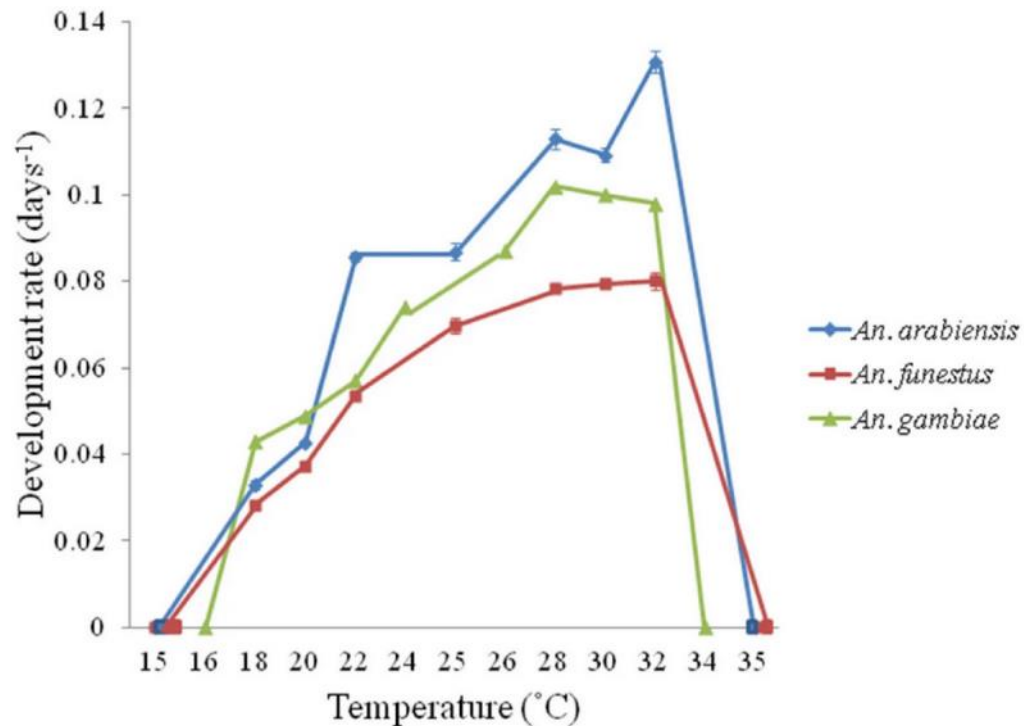


Figure 2.6 – Le concept de système vectoriel englobe la triade vectorielle et l'environnement.

Concept de Niche écologique

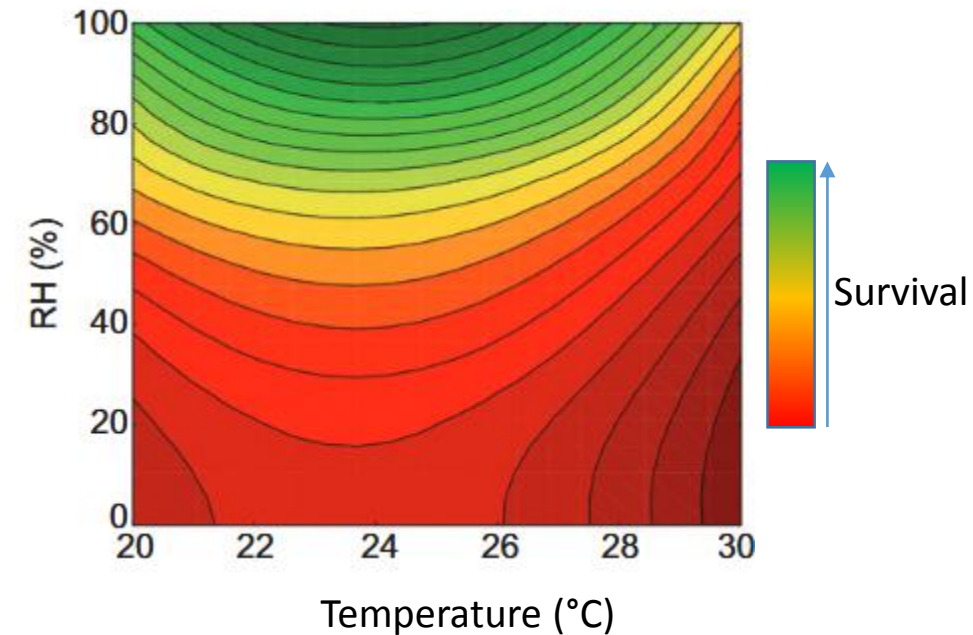


Concept de Niche écologique



Mean development rate and constant temperature. Mean development rate (days⁻¹) per constant temperature (ranging from 15°C to 35°C) for *Anopheles arabiensis* (blue ●), *An. funestus* (red ■) and *An. gambiae* (green ▲) (data for *An. gambiae* obtained from [7]). Lines linking data points are not

Lyons *et al. Parasites & Vectors* 2013, **6**:104



Lyons *et al.* 2014, *J. of Exp. Biol.*

Niche écologique (évolution du concept)

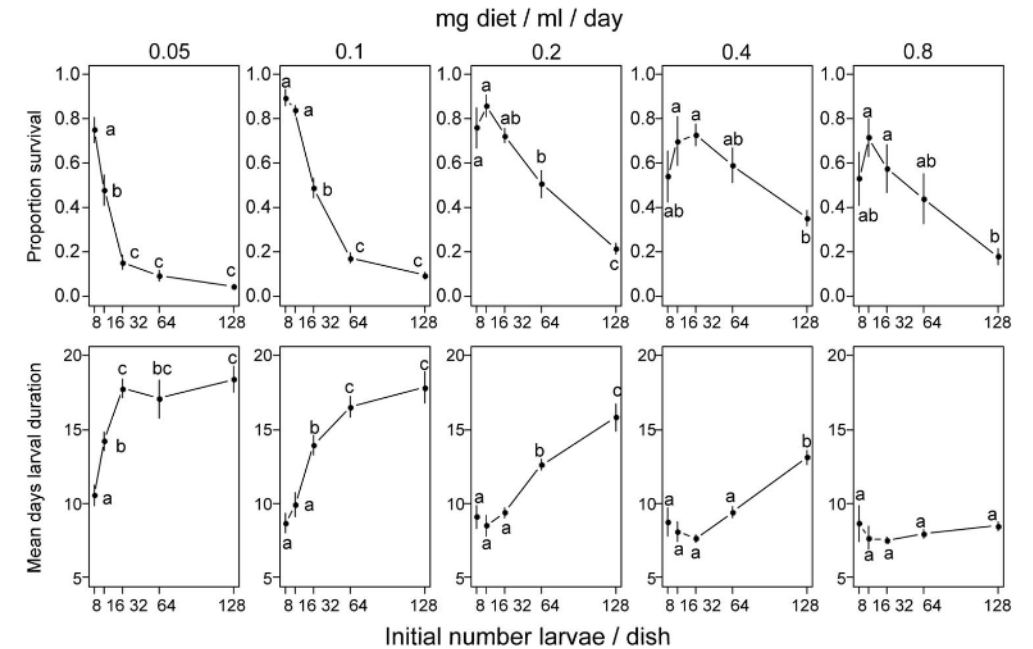
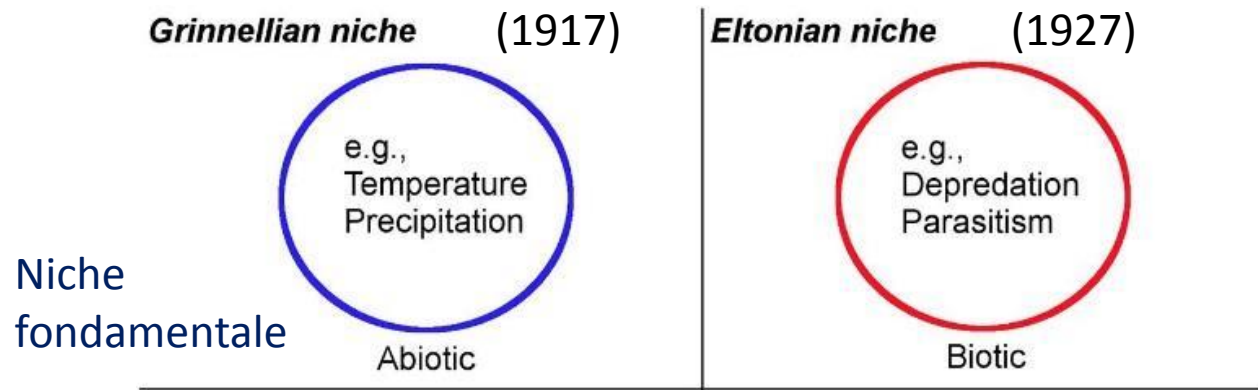


Fig. 1. Effect on diet amount (mg/ml/d) and larval density on survival rates and larval duration. In the upper panels, survival rates at various diet amounts (mg/ml/d) and larval numbers are shown (\pm SEM). Lower panels show the mean larval duration in days (\pm SEM). Points sharing letters are not significantly different.

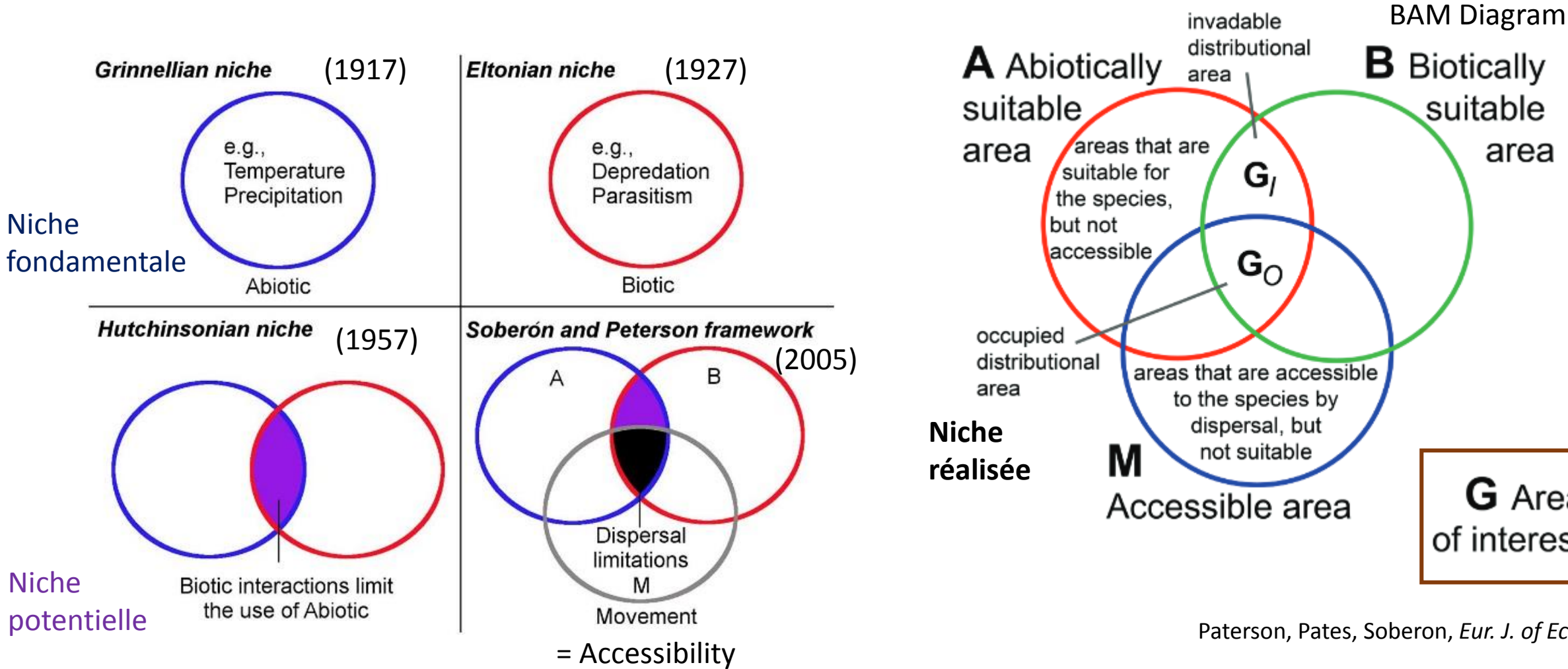
Gillies *et al.* 2011

Escobar & Craft, *Front. Microbiol.* 2016



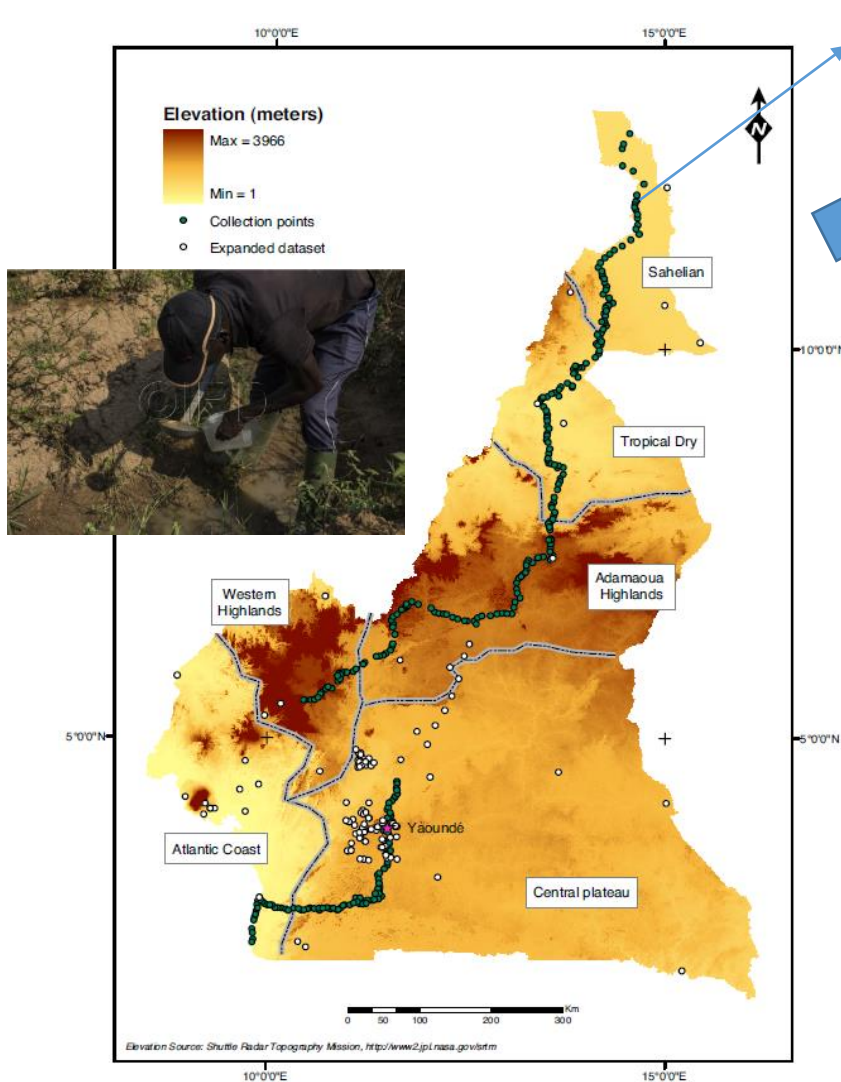
Caractérisée au laboratoire

Niche écologique (évolution du concept)

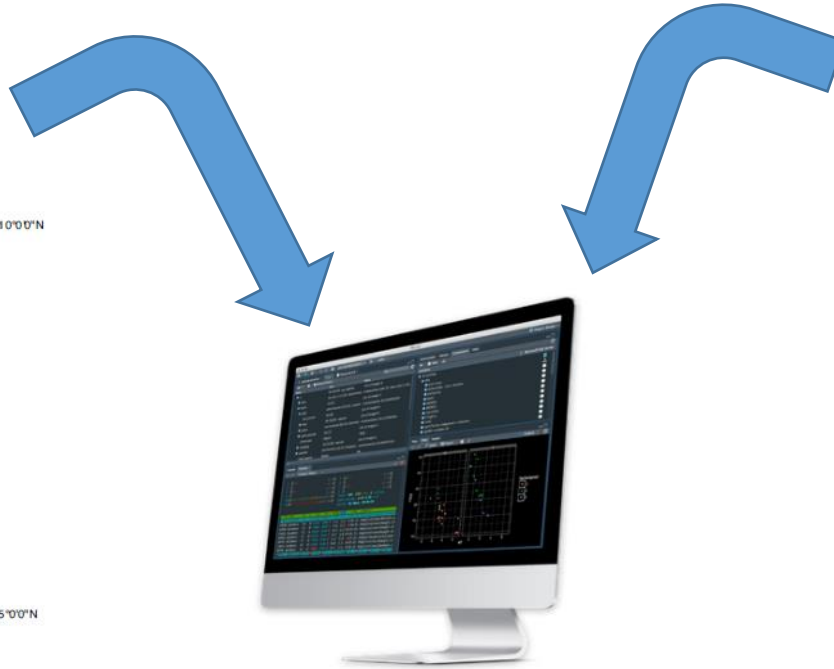


Paterson, Pates, Soberon, *Eur. J. of Eco.* 2015

Ecological niche modelling / mapping (ENM)



Présence data
 Abondance



Maxent, GLM,
 ENFA, Random Forest...

GIS: Geographic Information System

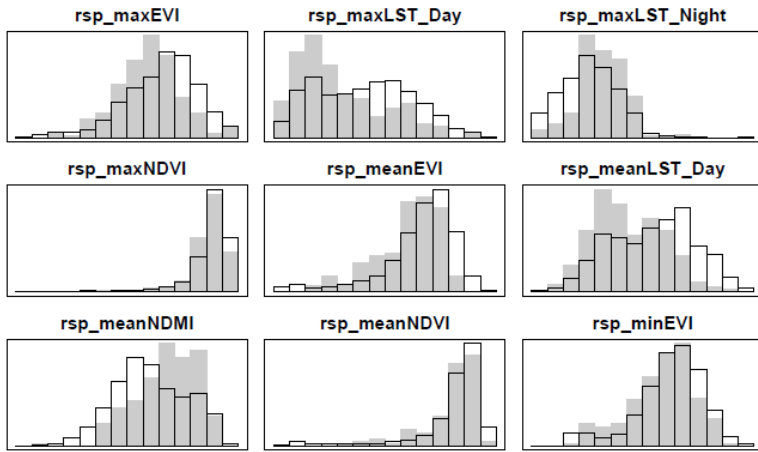


Eco-geographical variables:

- **Topographic** (altitude, aspect, slope, dist. to hydrographic network)
- **Climatic** (rainfall, T°, ET, RH, H_sun, windspeed)
- **Land cover/Land use** (rainforest, deciduous, FSmosaics, savanna, cropland)
- **Anthropogenic** (dist. to villages, roads)

Figure 1
 Map of Cameroon with sampled localities. Topographic map of Cameroon showing elevation (from buff = low-altitude to dark brown = high-altitude). Dotted lines delimit biogeographic domains as defined in the *Methods* from [47]. Dark dots indi-

Maxent, GLM,
ENFA, Random Forest...



Maps of suitable habitats

= projection spatiale de la niche

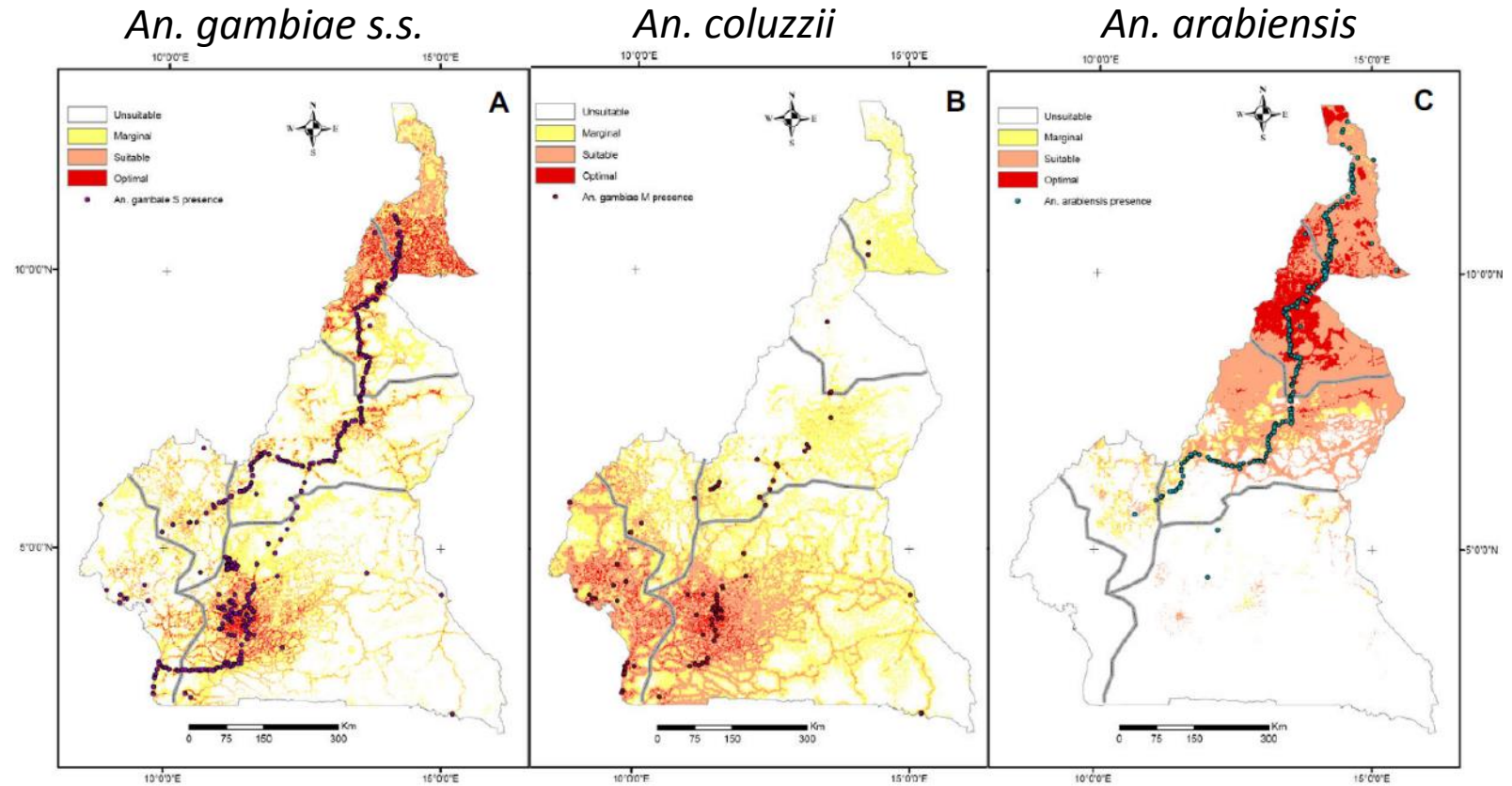
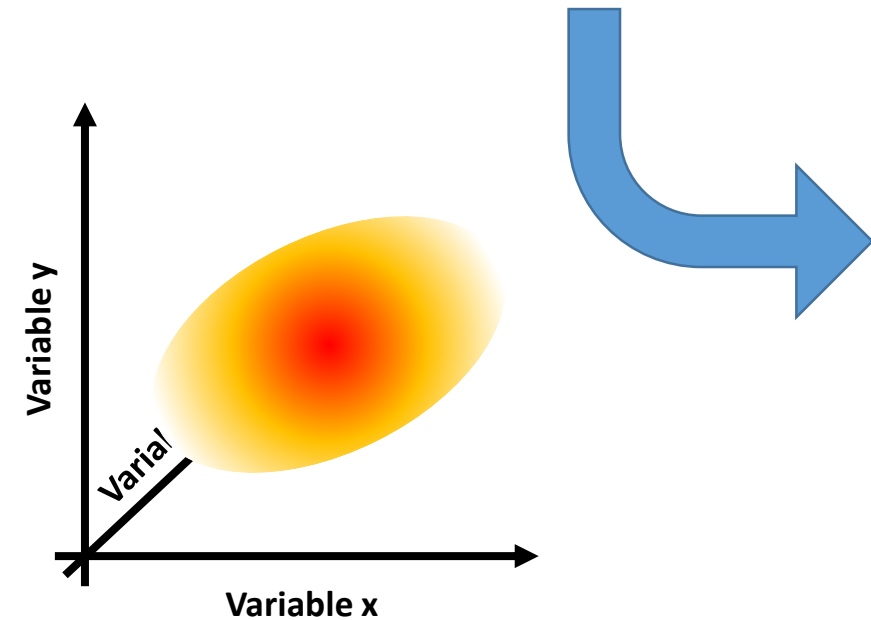
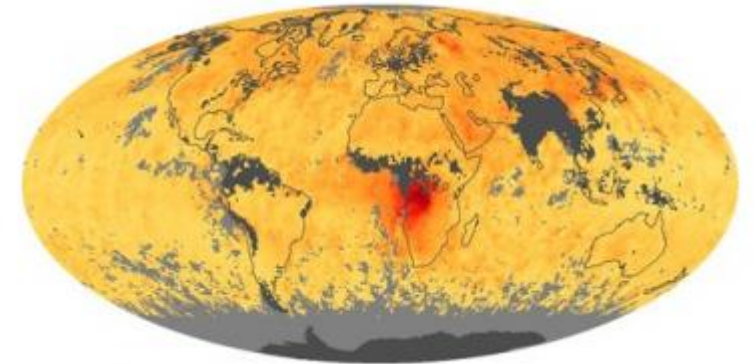
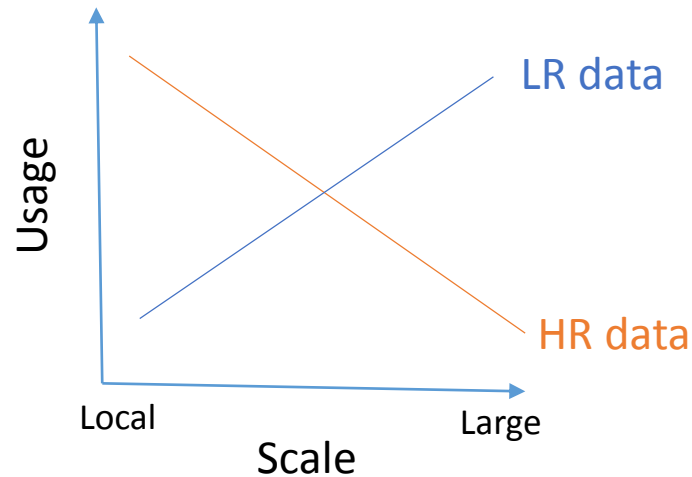


Figure 3 Habitat suitability maps of *An. gambiae* complex mosquitoes in Cameroon. Habitat suitability (HS) maps showing

Simard et al, BMC Ecol. 2009

Niches écologiques et échelle spatiale

La caractérisation de la niche va dépendre des données utilisées (disponibilité / résolution spatiale et temporelle)

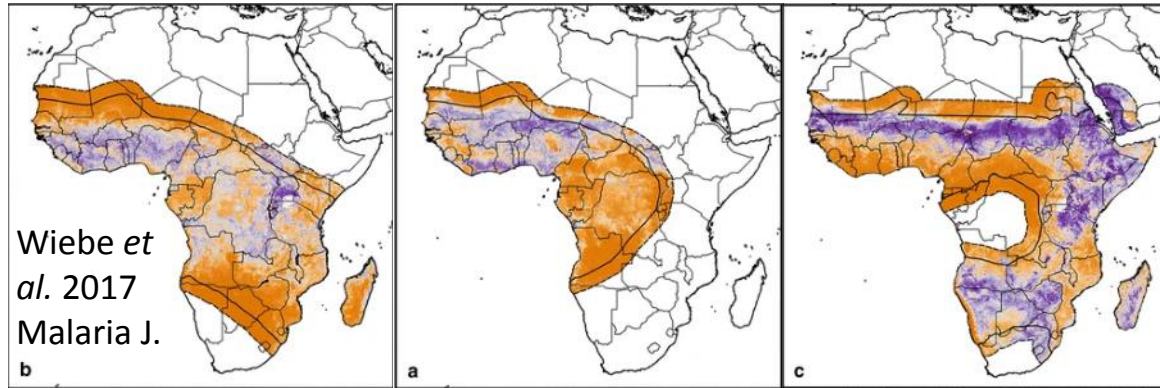


-> impact sur la précision de la carte des habitats favorables

Ex: Paysage / utilisation du sol
Données mesurées sur le terrain
Résolution < 10m

Ex: Données atmosphériques
Résolution > 10km

Niches écologiques et échelle spatiale



Wiebe *et al.* 2017
Malaria J.

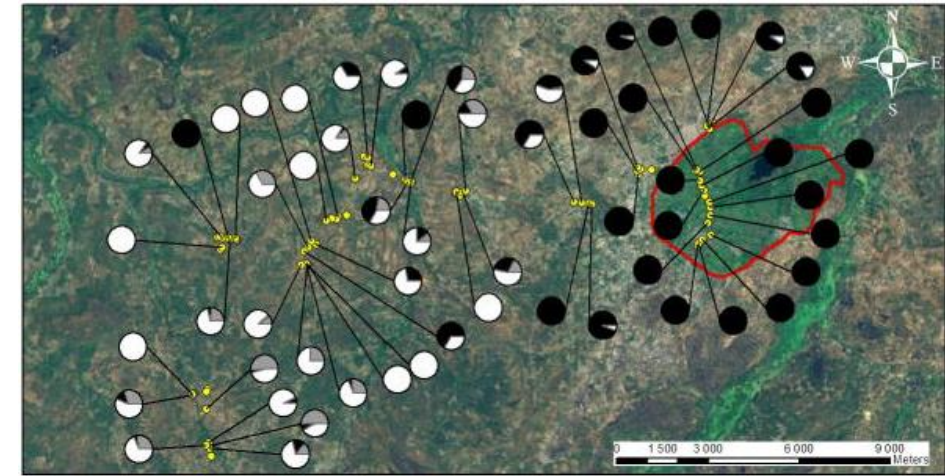
Continental
Climat

An. gambiae s.s.

An. coluzzii

An. arabiensis

Gimonneau *et al.*, 2011



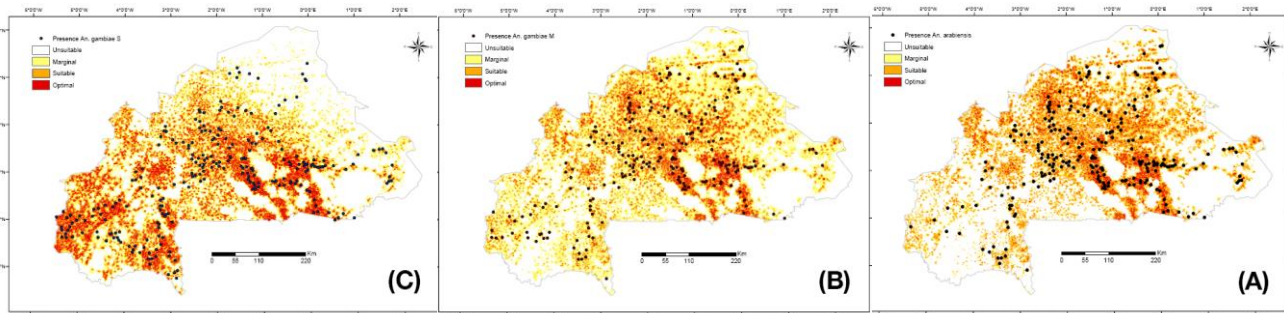
Country

Climat
Relief
Hydrographie



Local

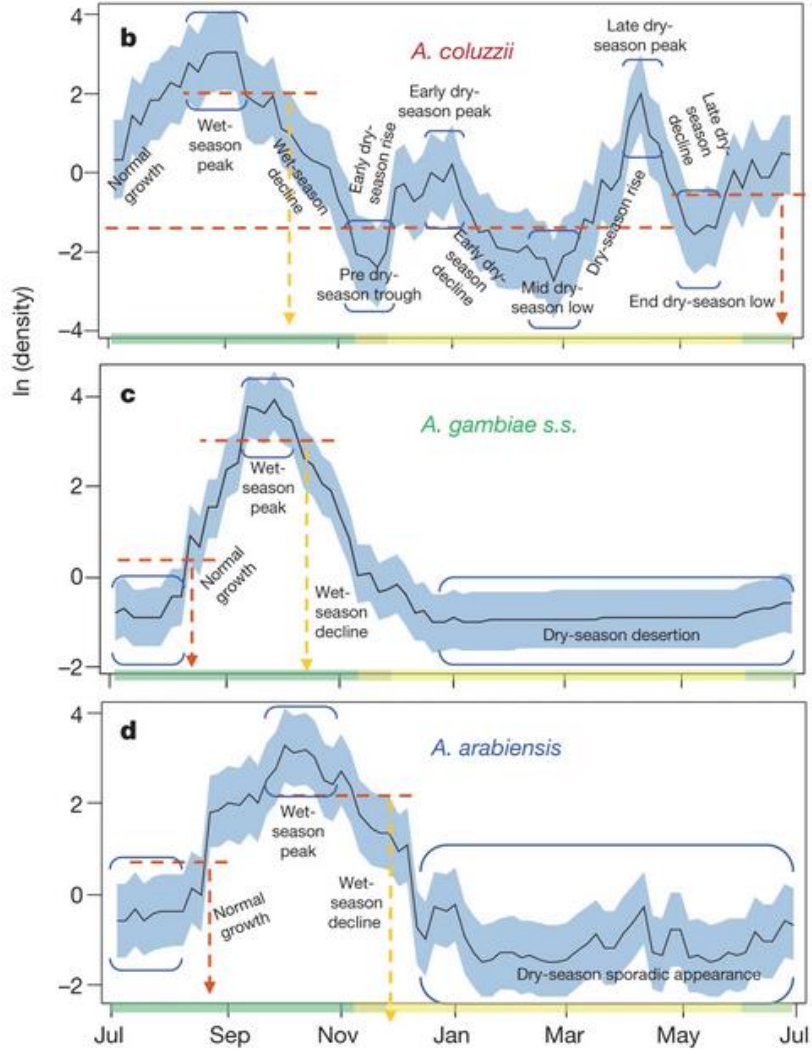
Relief
Hydrographie
Paysage
Pratiques agricoles



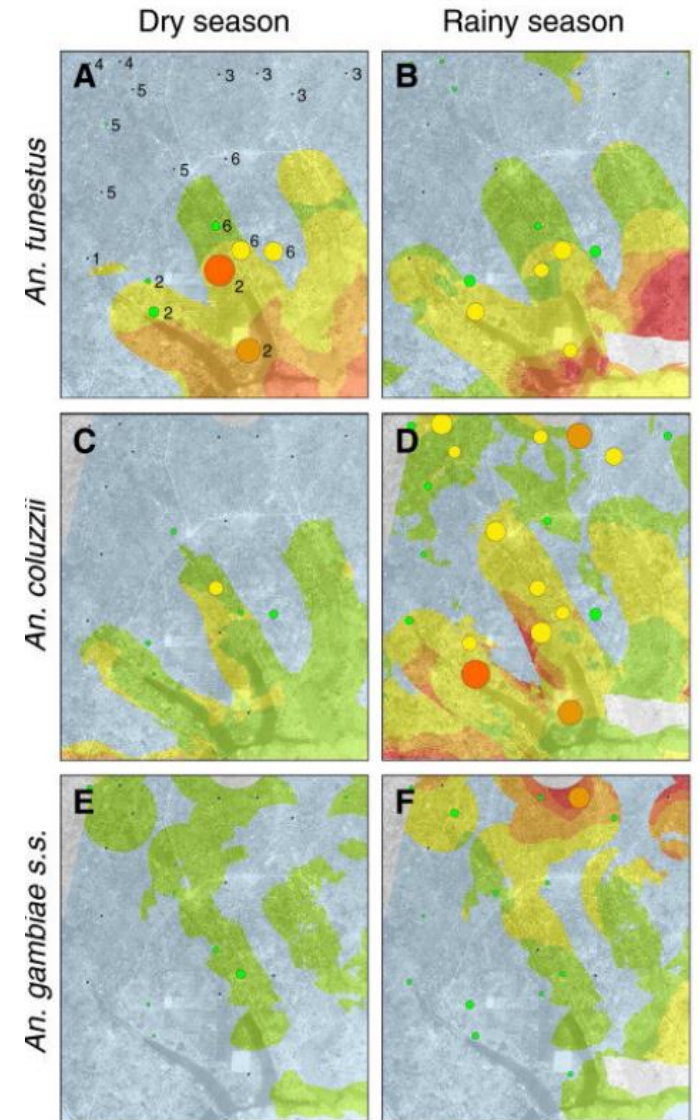
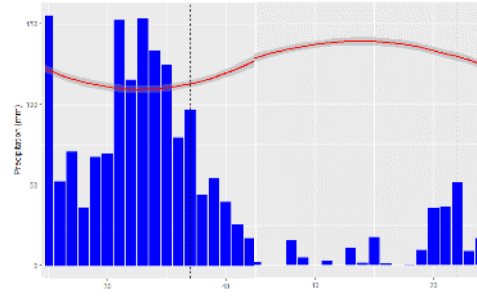
Costantini *et al.*, BMC Ecol. 2009

Une caractérisation de niche à une échelle spatiale n'est pas extrapolable à une autre échelle
L'échelle d'étude dépend de la problématique

Dynamiques spatio-temporelles



Dao et al. Nature 2014



Moiroux et al, Parasites & Vectors 2014

La période d'échantillonnage peut faire varier la représentation de la niche
La niche réalisée varie en fonction de la saison

Echelle temporelle

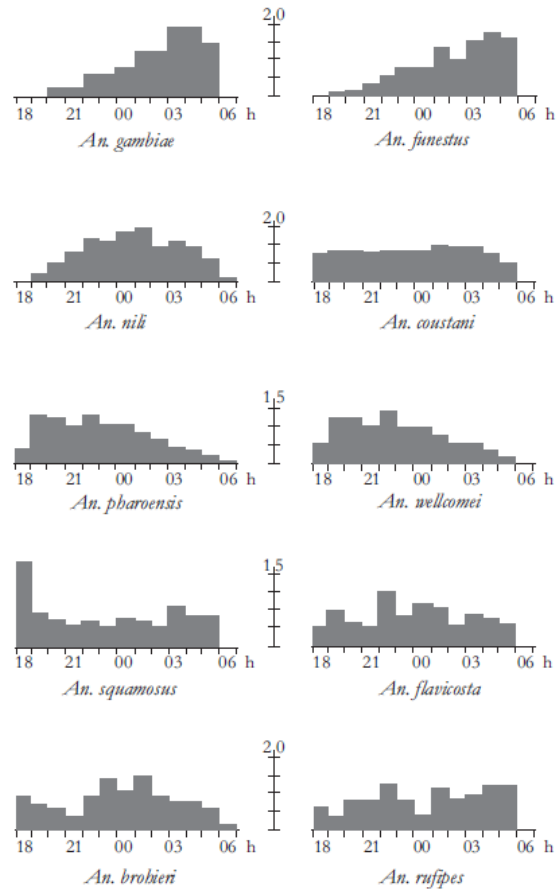


Figure 30
Principaux cycles d'agressivité des *Anopheles*
d'Afrique sud-saharienne,
d'après HAMON, 1963

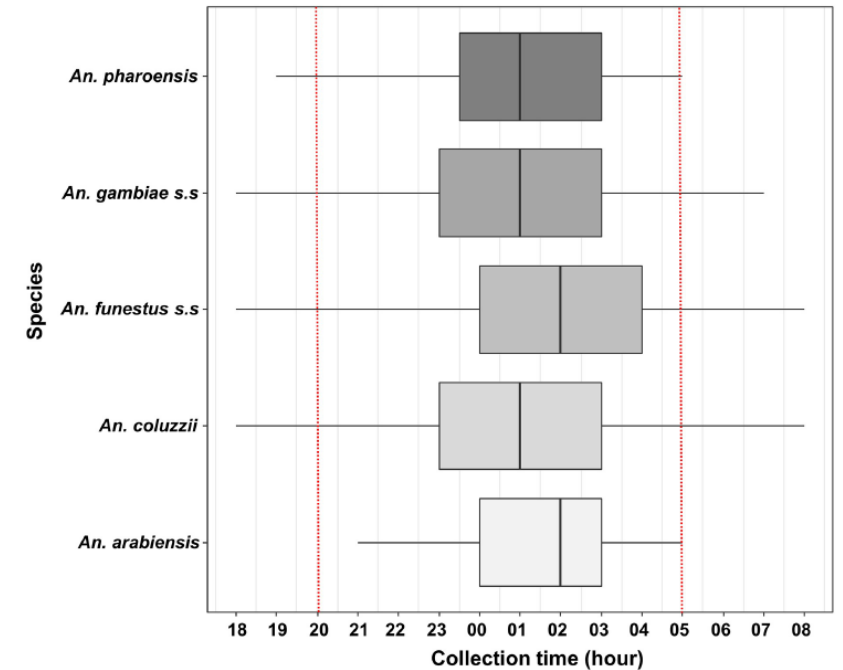


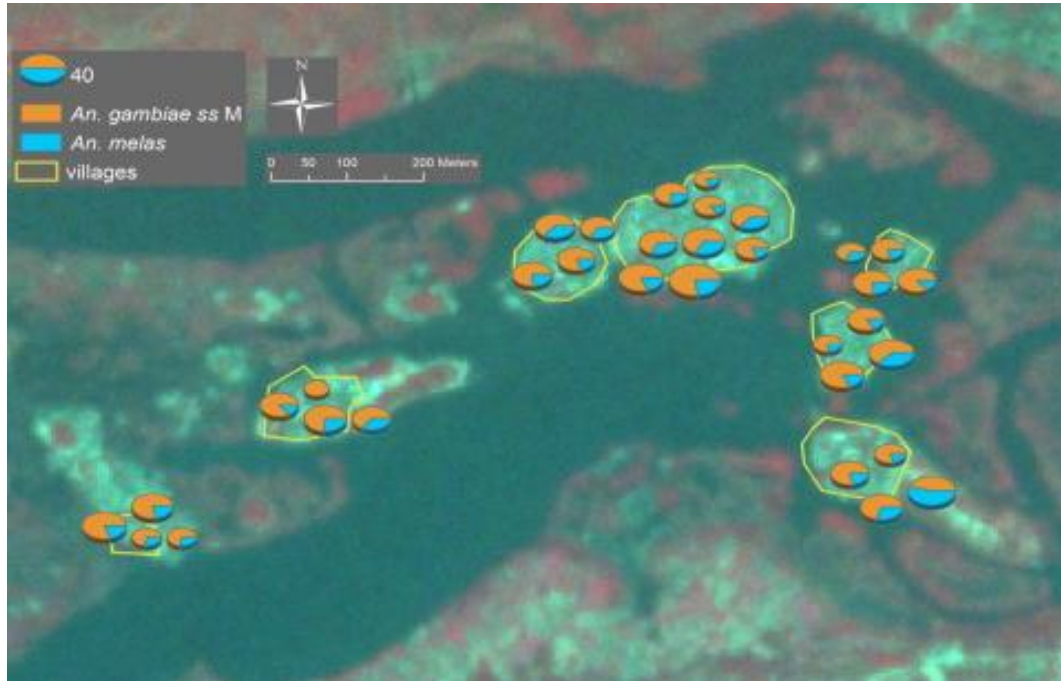
Fig 3. Median catching time of *Anopheles*. Boxes indicate 1st-3rd quartile and median hours of biting activity. Whiskers indicate 2.5-97.5 percentiles. Red dashed line indicated time at which 50% of the population are asleep (20h) and woke up (05h).

Soma et al, Plos One, 2020

La période d'activité est un élément de caractérisation de la niche.

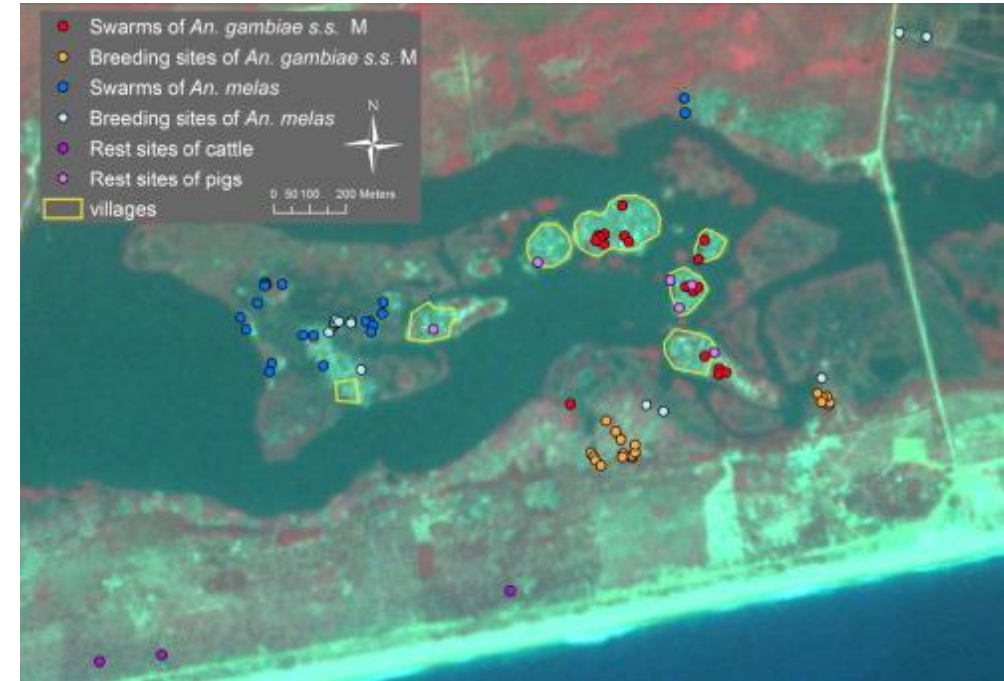
Niches et stades de développement

Assogba *et al.* 2014, *Acta Trop.*



Repos adultes

Sympathrie



Larves / Essaims adultes

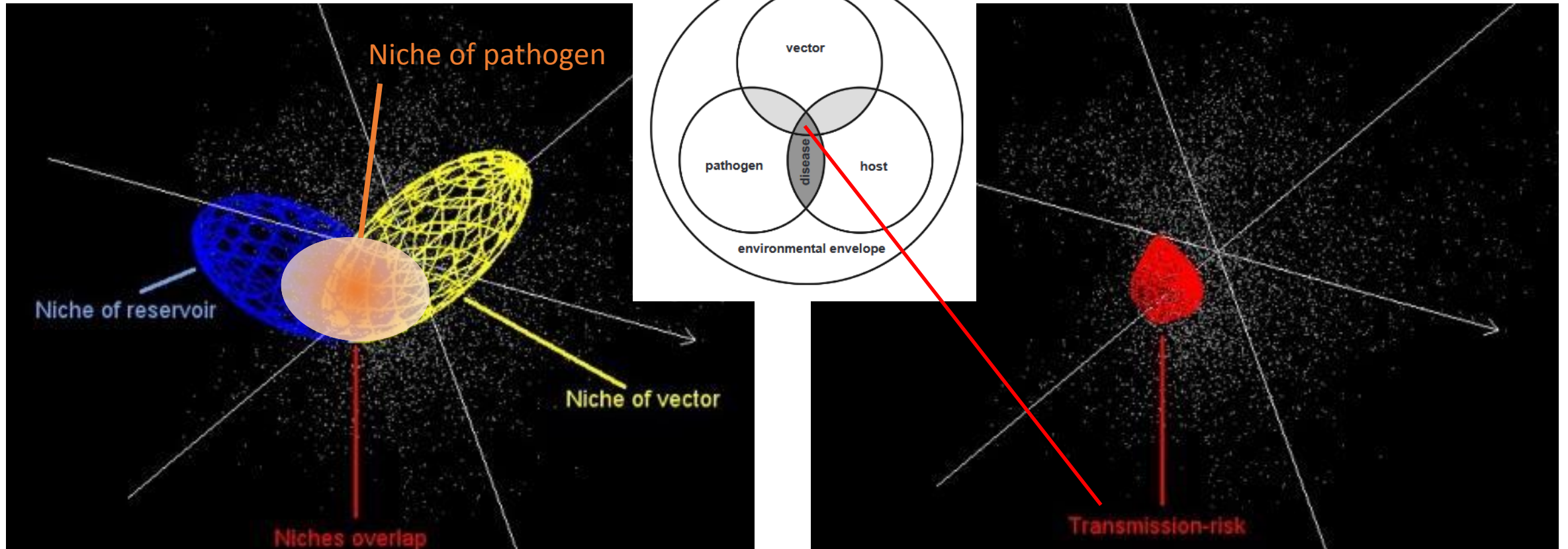
Ségrégation spatiale

spécialisation

La niche réalisée varie en fonction du stade de développement de l'organisme (et de son état physiologique)

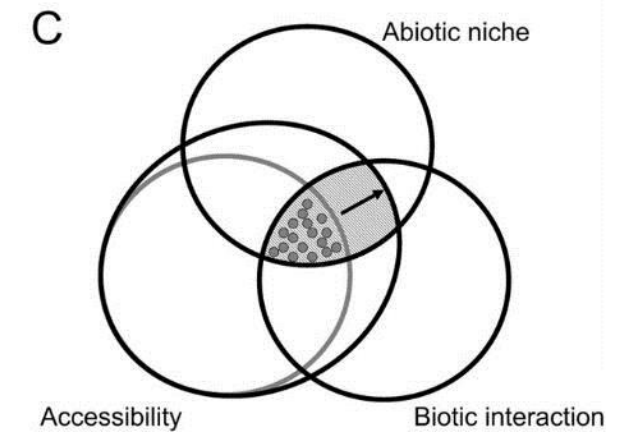
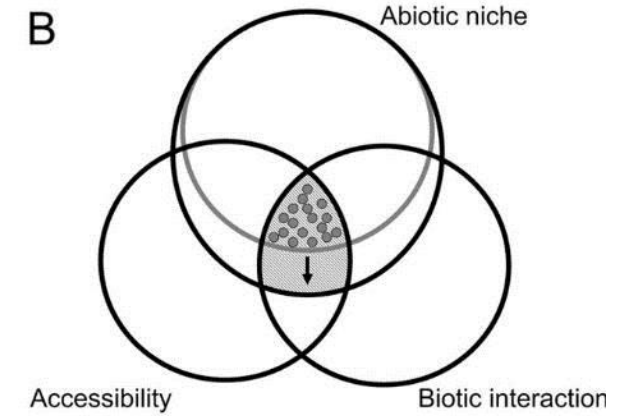
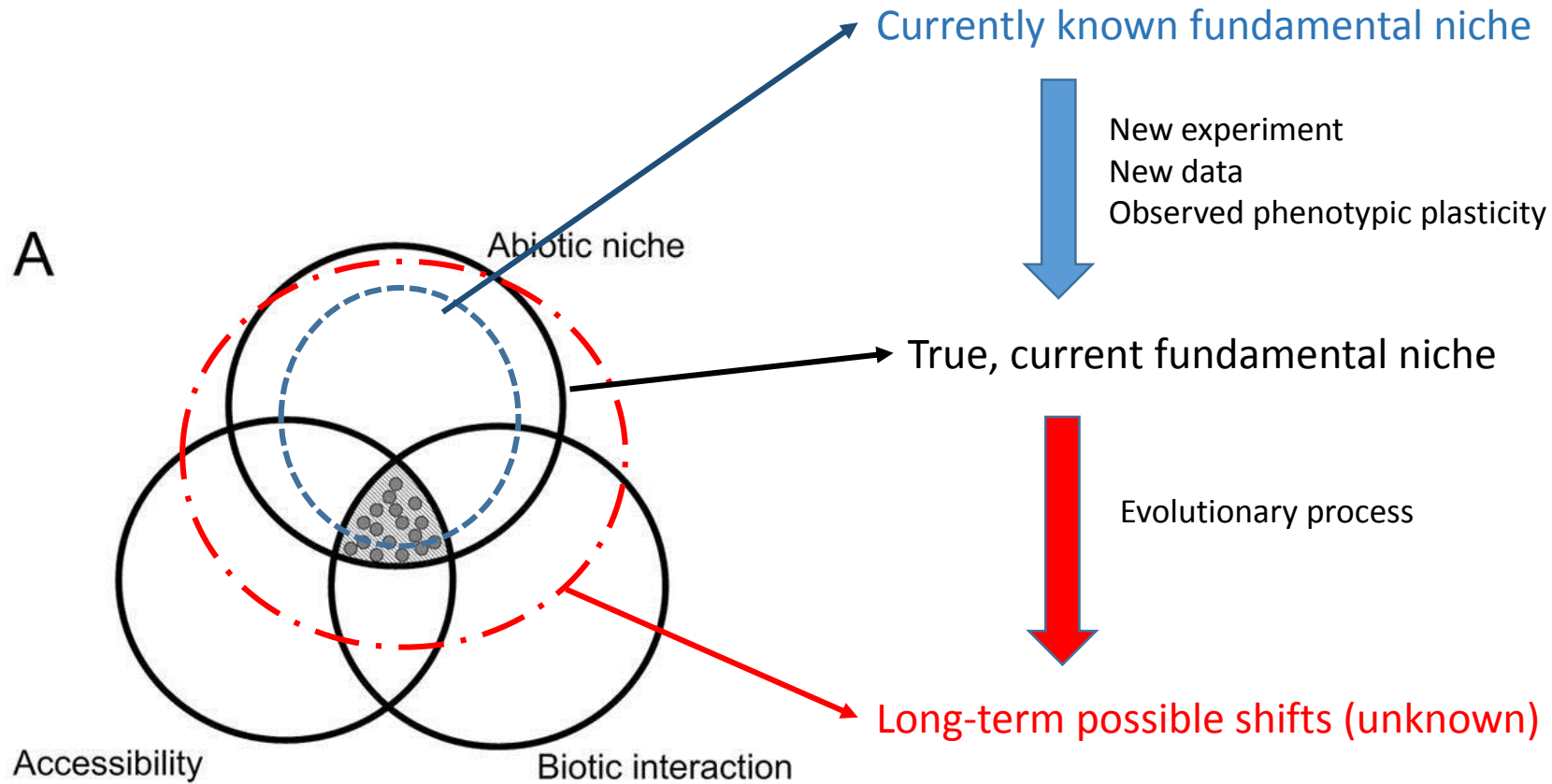
A l'intersection des niches : la transmission

Fodor 2011, *Annals of forest research*



Escobar & Craft, *Front. Microbiol.* 2016

Modifications de Niche

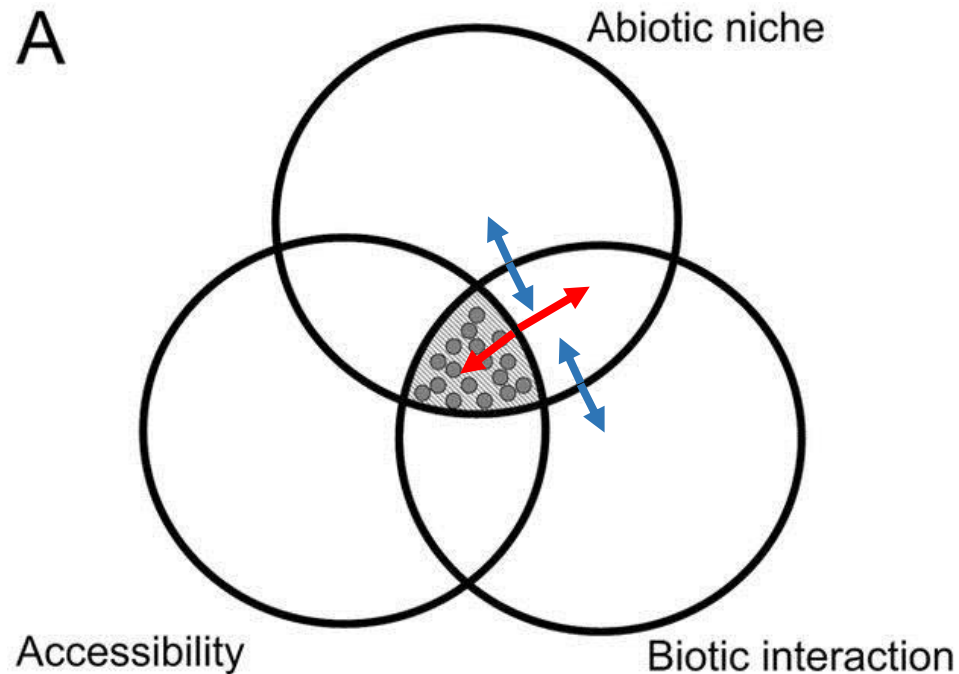


Rödger et al., Plos One, 2009

Changements anthropiques et impact sur la transmission

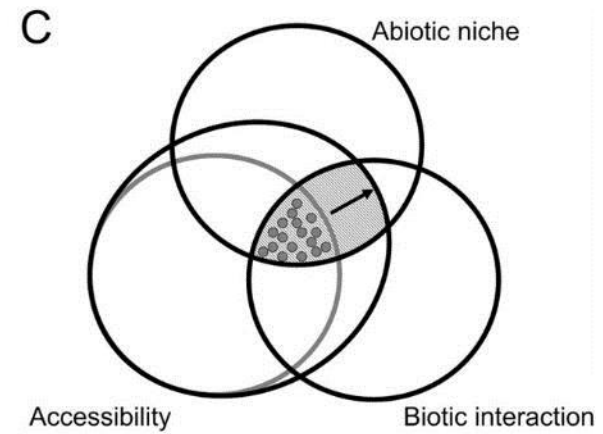
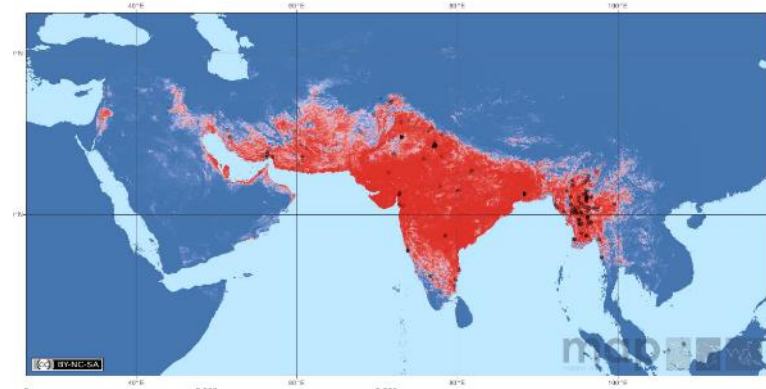


Principaux effets des changements anthropiques sur la niche des vecteurs:



- Création / destruction de milieux favorables
- Dispersion passive d'origine anthropique
- Modifications anthropique de niche réalisée
Accès a une ressource contraint / facilité
- Adaptation (sélection de traits phénotypiques qui induisent une modification de la niche fondamentale)

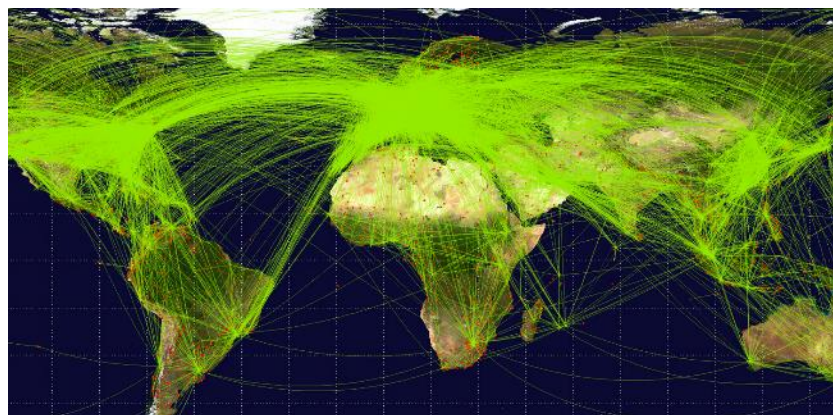
Dispersions passives



Mondialisation (échanges commerciaux)

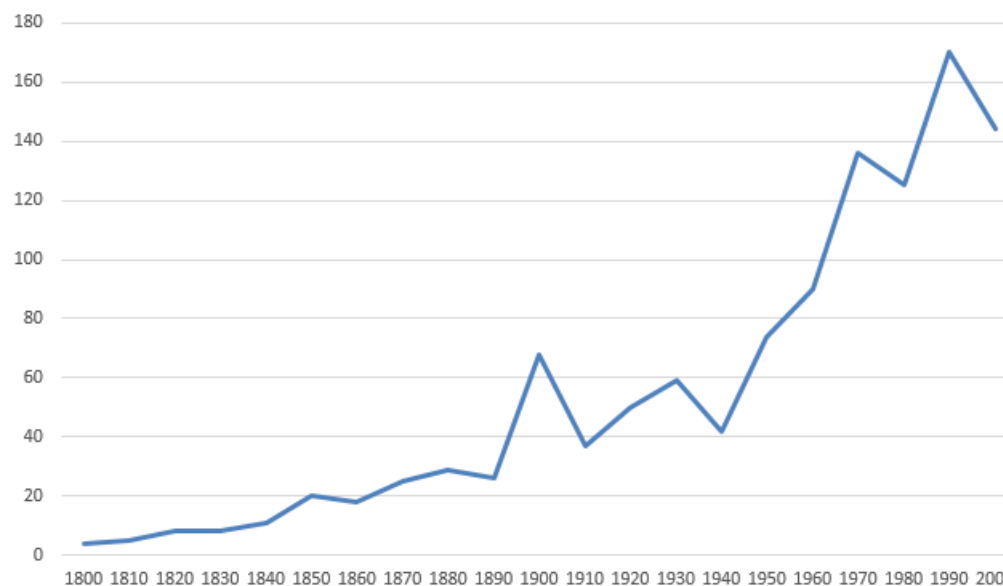


Shipmap.org



openflights.org

Nombre d'espèces d'insectes introduite en Europe par décennie



D'après Roques *et al*, 2016, *Biological Invasions*

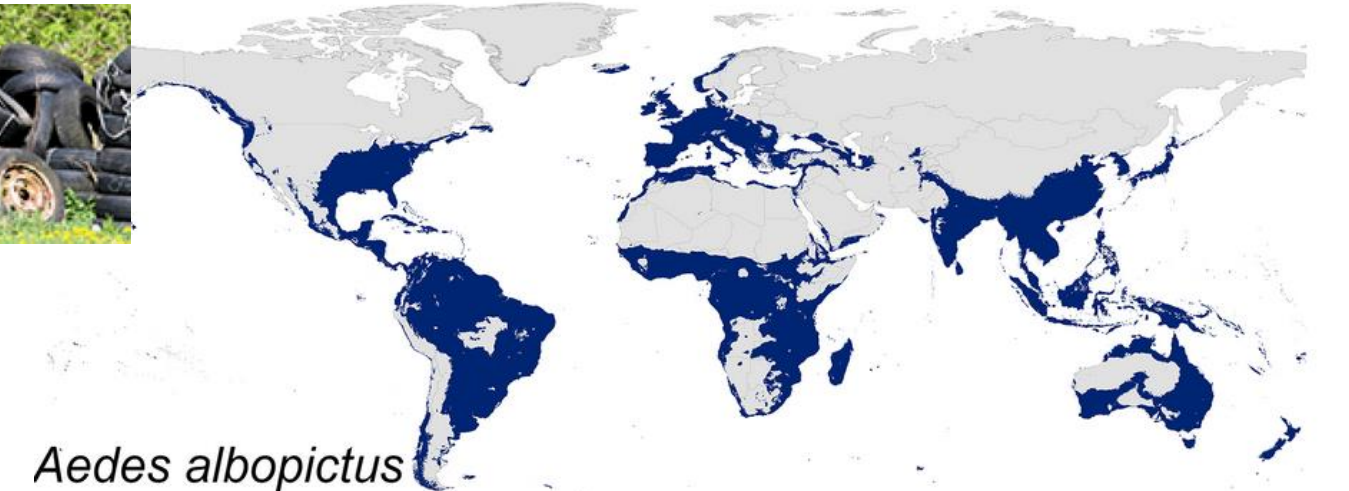
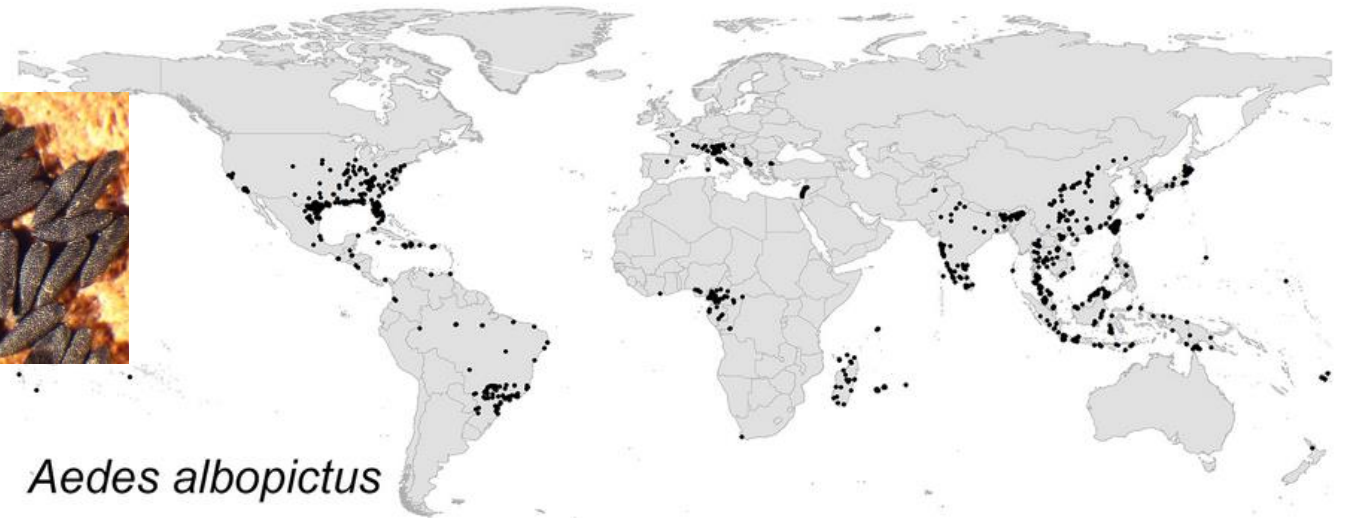
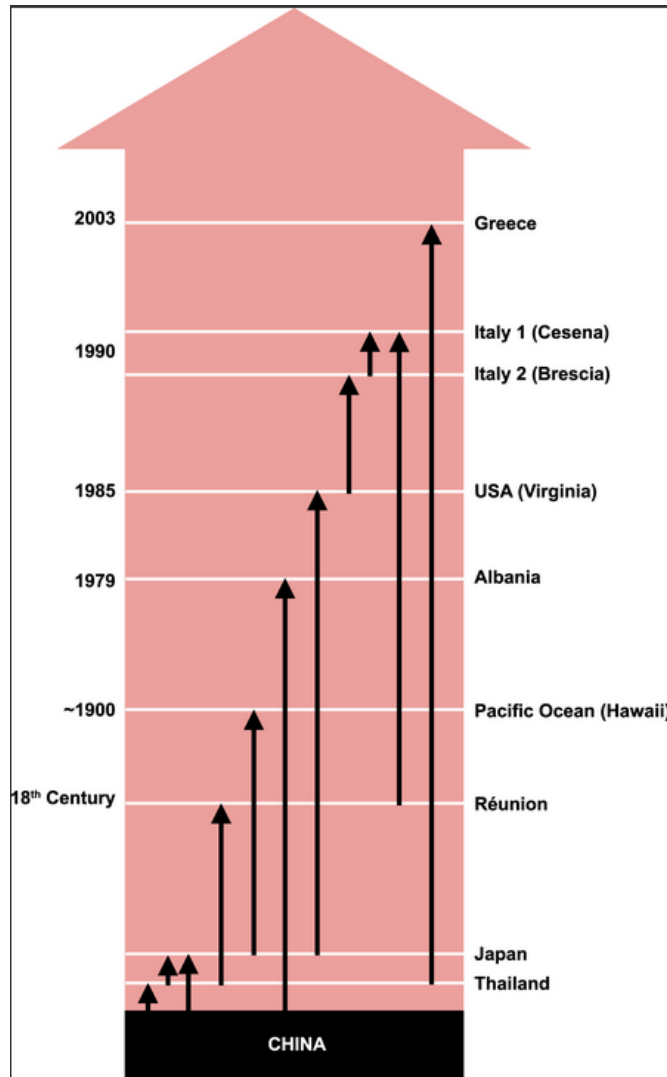
Aedes albopictus

Un modèle de dispersion anthropique



THE USED TIRE TRADE: A MECHANISM FOR THE WORLDWIDE DISPERSAL OF CONTAINER BREEDING MOSQUITOES

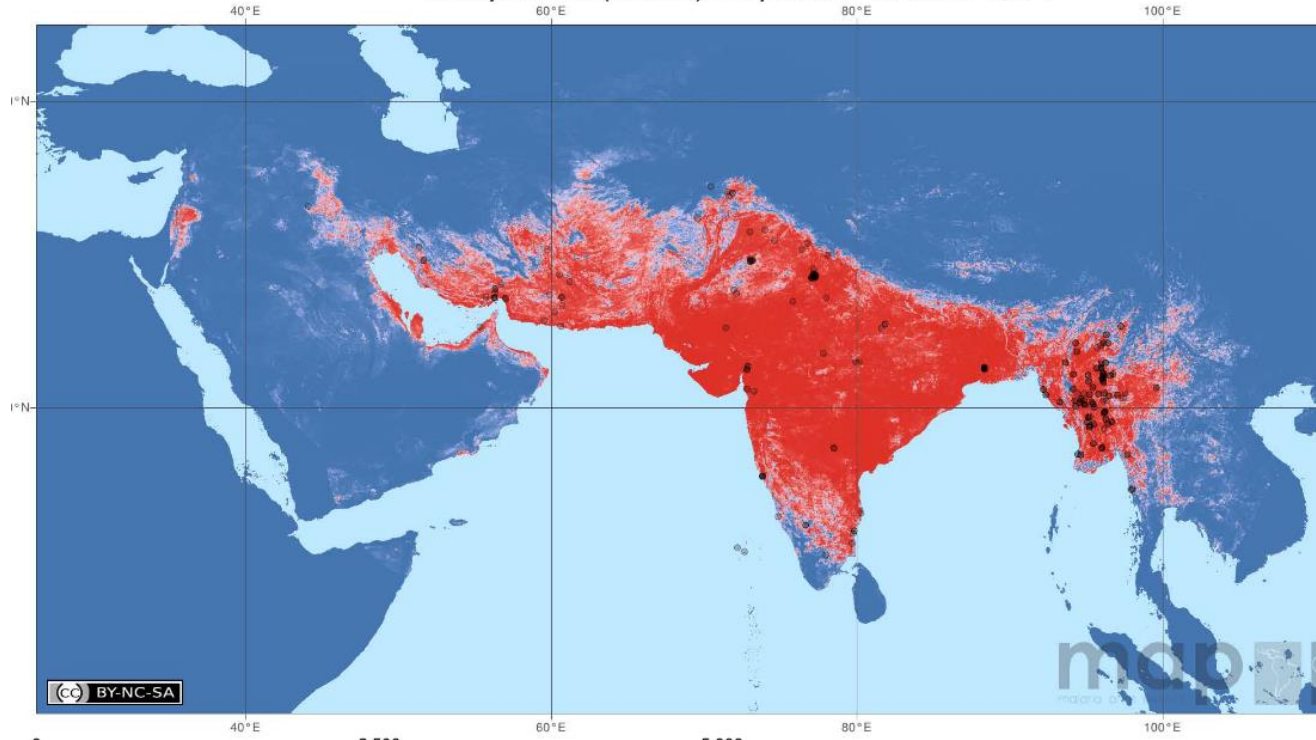
PAUL REITER¹ AND DANIEL SPRENGER²



Anopheles stephensi

Un vecteur urbain, une dispersion en cours

Anopheles (Cellia) stephensi Liston, 1901



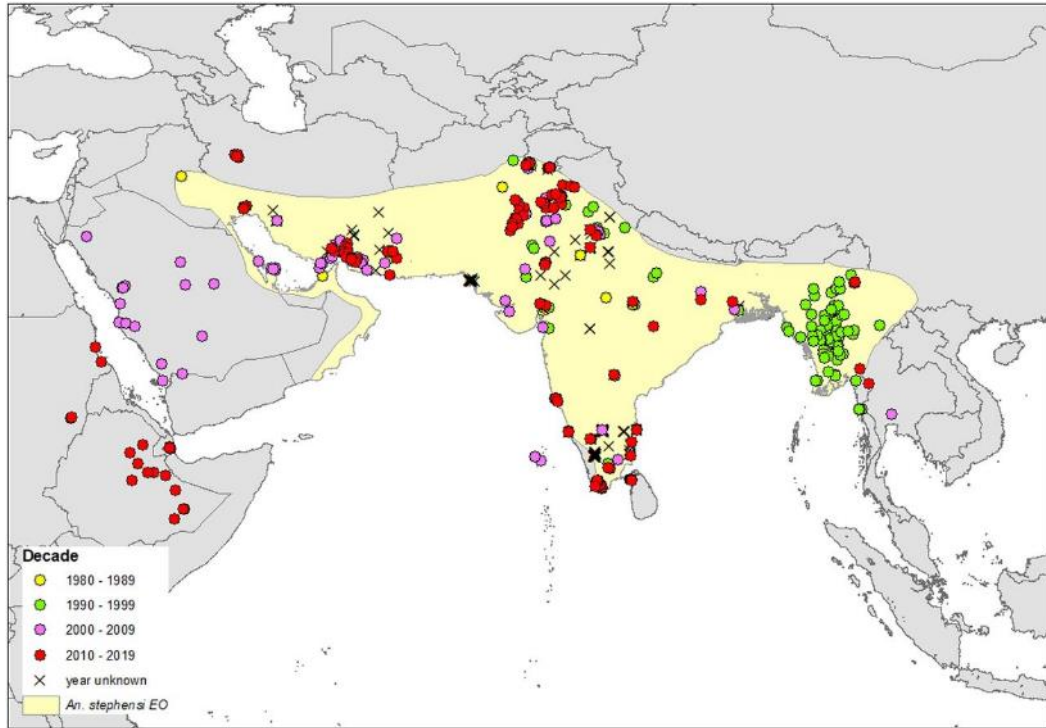
Sinka *et al*, *Parasites & Vectors* 2012



Examples of breeding sites where *An. stephensi* larvae and pupae were found: a water tank trucks; b construction water storage reservoirs; c discarded tires; d buckets; e steel drums; f water tanks; g temporary water storage reservoirs; h birkas

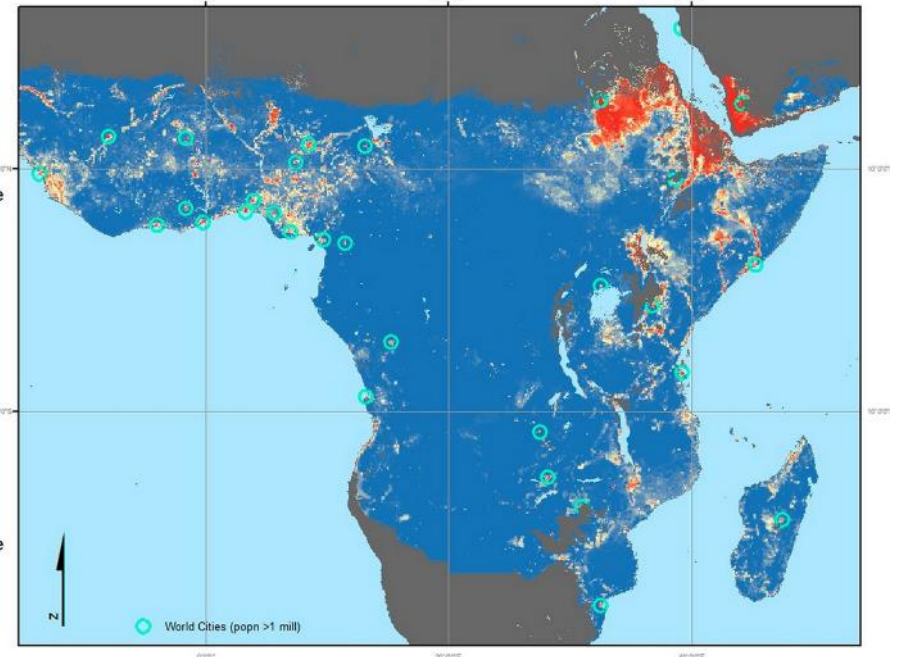
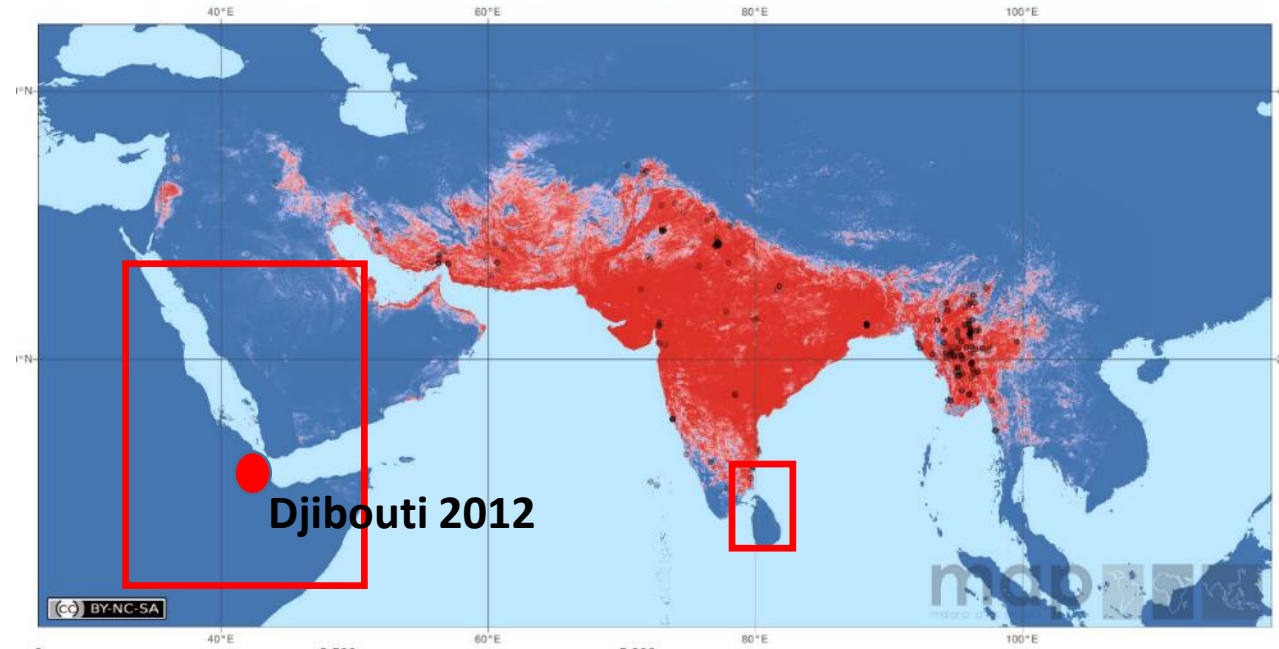
Anopheles stephensi

Un vecteur urbain, une dispersion en cours



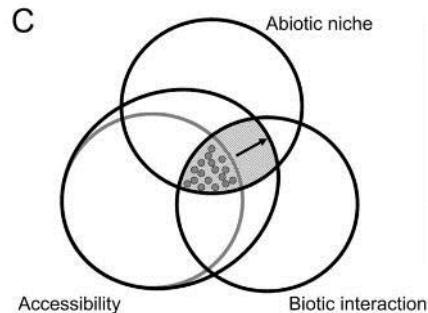
Sinka et al. PNAS, 2020

Mauvaise caractérisation initiale de la niche ? (écosystème urbains)
Adaptation ?



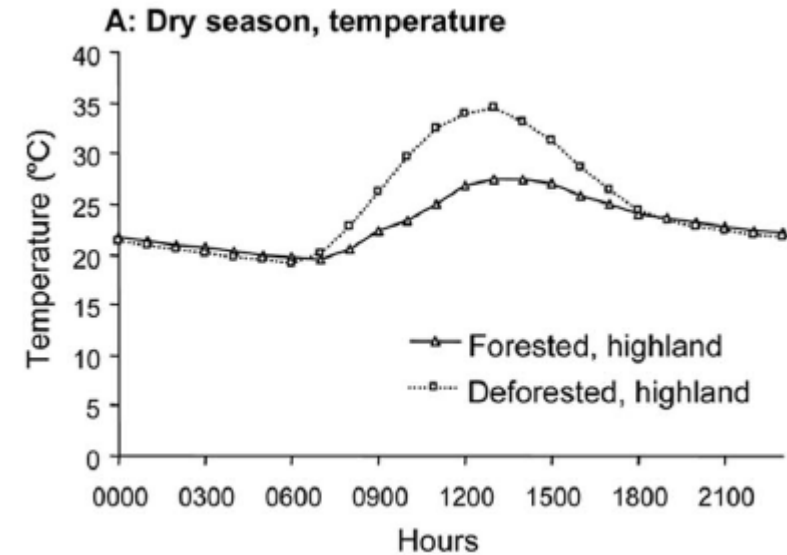
Création / destruction de milieux favorables aux vecteurs

Expansion Démographique
Urbanisation
Déforestation
Agriculture intensive
Changements Climatiques



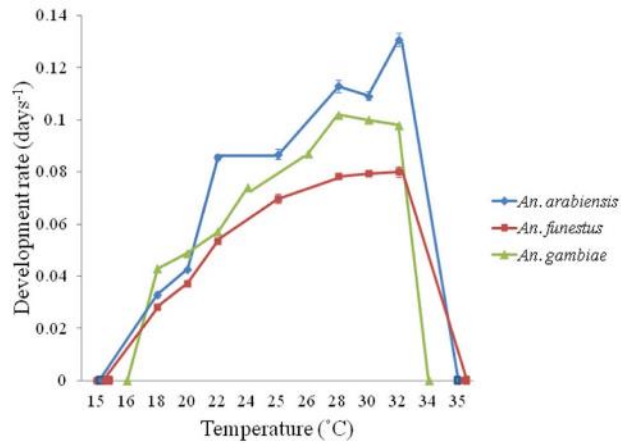
Extension des niches réalisée
Rencontres Hôtes-Vecteurs-Pathogènes
=> Emergences & Réémergences

La déforestation comme facteur de modification des conditions abiotiques



Augmentation de la température

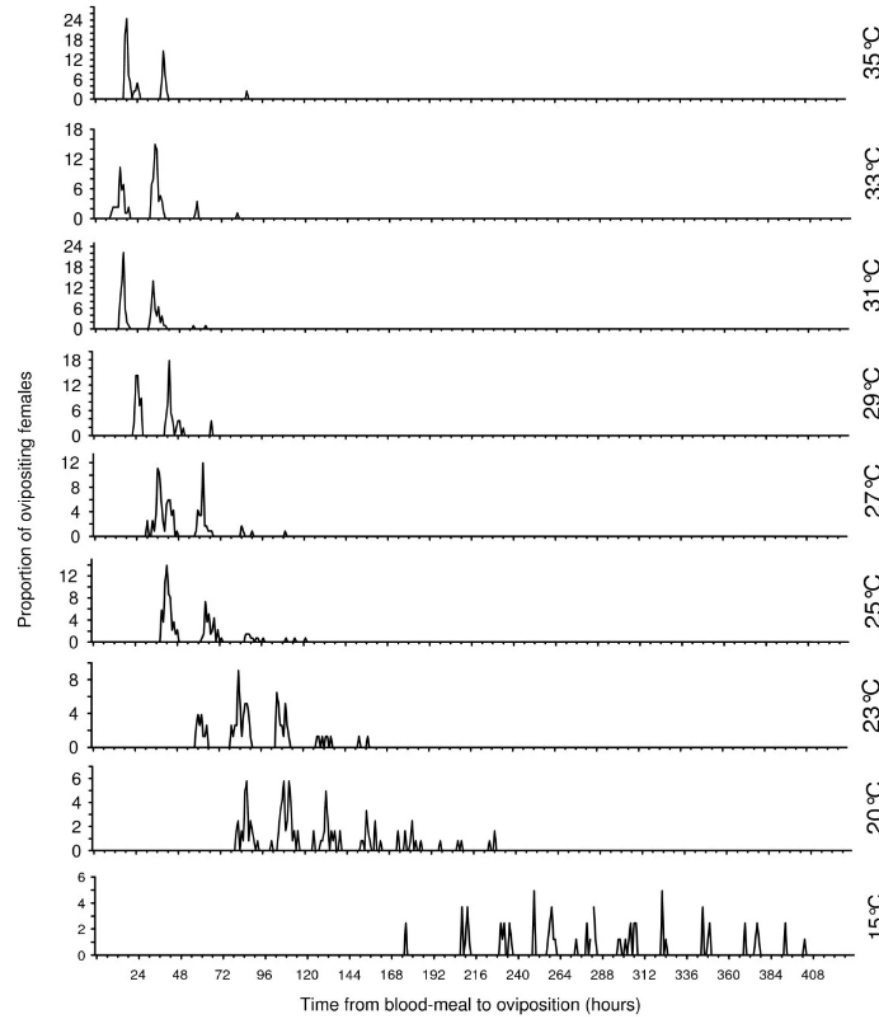
Quelques effet de la température Données expérimentales



Mean development rate and constant temperature. Mean development rate (days⁻¹) per constant temperature (ranging from 15°C to 35°C) for *Anopheles arabiensis* (blue ●), *An. funestus* (red ■) and *An. gambiae* (green ▲) (data for *An. gambiae* obtained from [2]). Lines linking data points are not

Lyons et al. Parasites & Vectors 2013, 6:104

Vitesse développement larvaire



Egg laying patterns for *An. pseudopunctipennis* at various constant temperatures. The number of ovipositing nights is pictured by the observed "pulses" which have a pseudo Gaussian mode.

Durée cycle gonotrophique



Durée sporogonie

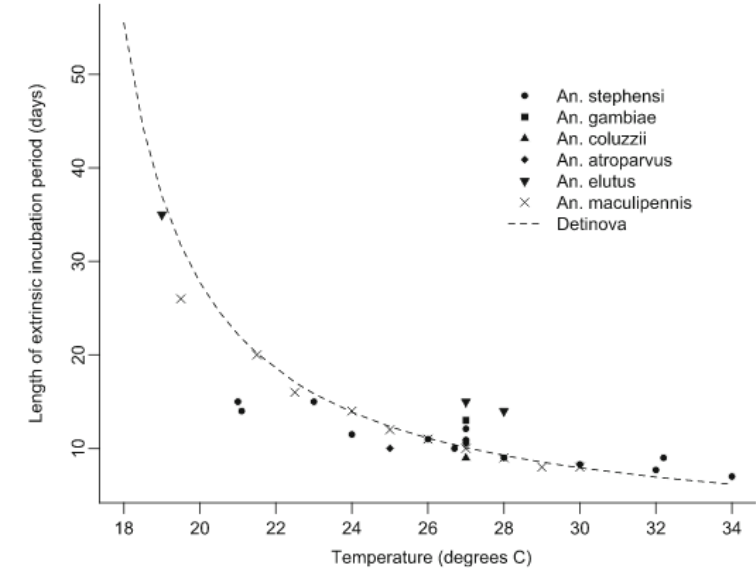
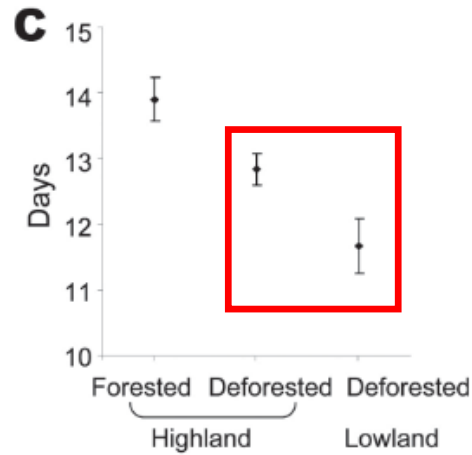


Fig. 1 Empirical estimates of EIP for *P. falciparum* across a range of studies. The dotted black line represents the standard degree-day model of Detinova [1] parameterized using the data for *An. maculipennis* [5].

Impact de la déforestation sur la transmission

Afrane *et al*, 2008, *EID*



Time to sporozoite detection vs. Land use

Table 1. Duration of the first and second gonotrophic cycles of *A. gambiae* mosquitoes in different land cover types in western Kenya highland and lowland sites

Area	Season	Land cover type	Mean indoor temp (°C)	Mean outdoor temp (°C)	First gonotrophic cycle			Second gonotrophic cycle	
					Proportion of mosquitoes that laid eggs (%)	Mean duration (d)	Mean fecundity	Proportion of mosquitoes laid eggs (%)	Mean duration (d)
Highland	Dry	Forested	23.0 ± 0.6	20.8 ± 1.3	42.7	4.6 ± 2.7	43.4 ± 19.3	7.3	3.0 ± 1.1
		Deforested	24.8 ± 0.8	21.6 ± 1.4	53.7	2.9 ± 1.7	62.1 ± 32.0	7.7	2.1 ± 0.3
Lowland	Rainy	Forested	21.0 ± 0.9	18.7 ± 1.1	54.3	10.1 ± 5.8	85.4 ± 44.9	22.7	6.6 ± 2.4
		Deforested	22.2 ± 0.8	19.2 ± 0.8	60.0	8.6 ± 4.9	74.2 ± 38.5	23.7	5.2 ± 2.6
Lowland	Rainy	Deforested	24.9 ± 0.4	22.2 ± 0.9	67.3	4.3 ± 2.1	73.7 ± 34.2	30.4	3.8 ± 1.7

Field collected F₁ female mosquitoes that had blood fed and mated were used. Standard deviation for mean indoor and mean outdoor temperatures, gonotrophic cycle duration, and fecundity is shown.

Table 2. Estimated vectorial capacity of *Anopheles gambiae* mosquitoes in forested and deforested areas, western Kenyan highland and lowland*

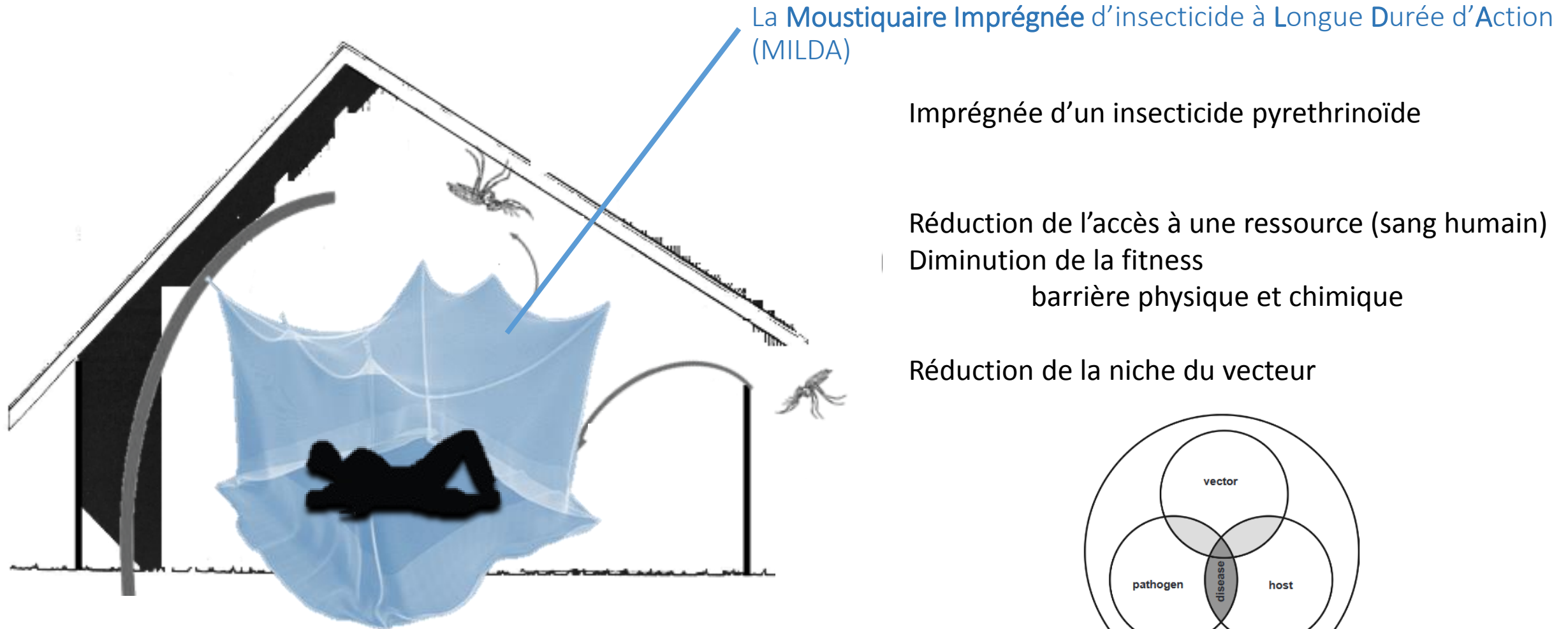
Site	Land use type	<i>m</i>	<i>a</i>	<i>N</i>	<i>P</i>	Vectorial capacity
Highland	Forested	3.05	0.198	13.9	0.927	0.54
Highland	Deforested	4.64	0.233	12.8	0.917	0.96
Lowland	Deforested	7.85	0.465	11.7	0.923	8.30

**m*, relative density of vectors in relation to humans; *a*, average no. children bitten by 1 mosquito in 1 day; *n*, duration of sporogony in days; *P*, proportion of vectors surviving per day. See text for details on data source and assumptions made for calculating each variable.

Restriction d'accès à une ressource: la moustiquaire imprégnée



La lutte anti-vectorielle



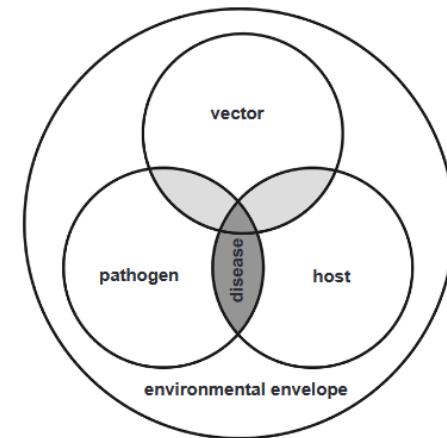
Imprégnée d'un insecticide pyrethrinoïde

Réduction de l'accès à une ressource (sang humain)

Diminution de la fitness

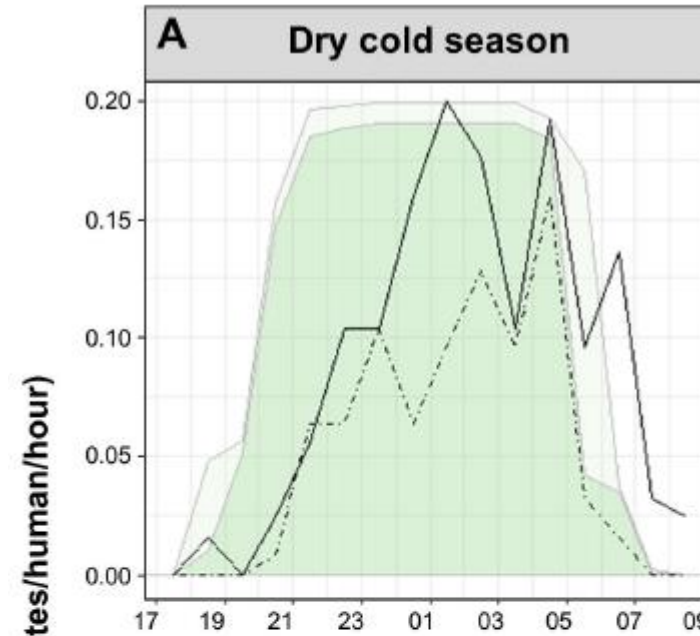
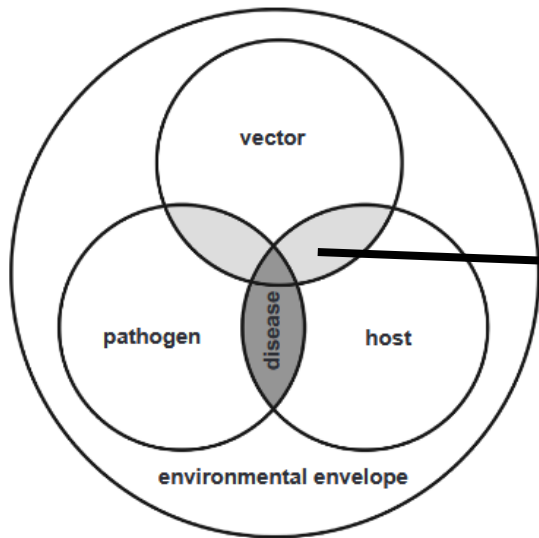
barrière physique et chimique

Réduction de la niche du vecteur

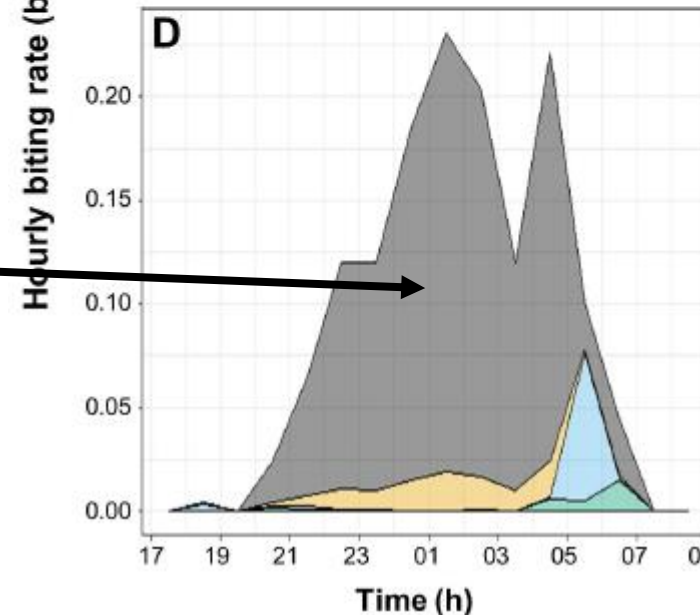
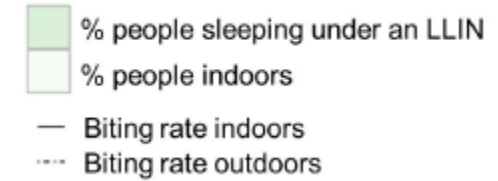


MILDA et réduction de la niche (réalisée) des vecteurs

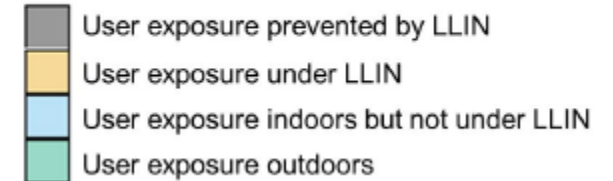
- Pas/peu visible au niveau spatial (= pas d'observation de réduction de l'aire de distribution des vecteurs)
- Observable au niveau temporel (interactions comportementales)



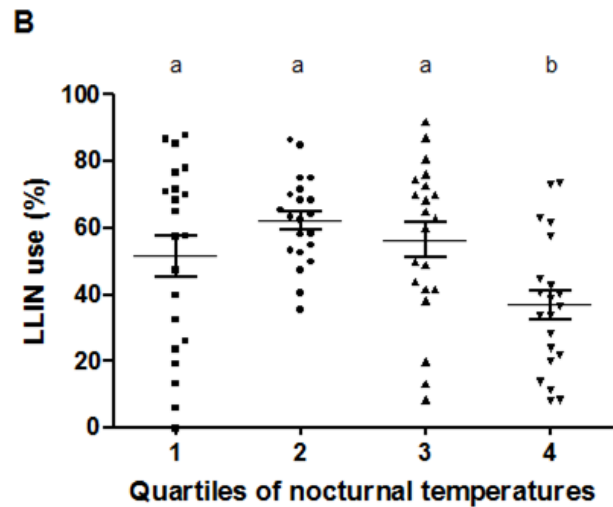
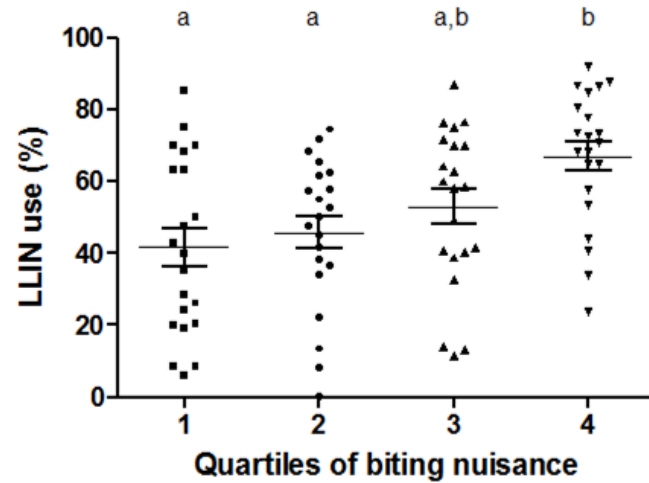
People and *Anopheles* spp behavior



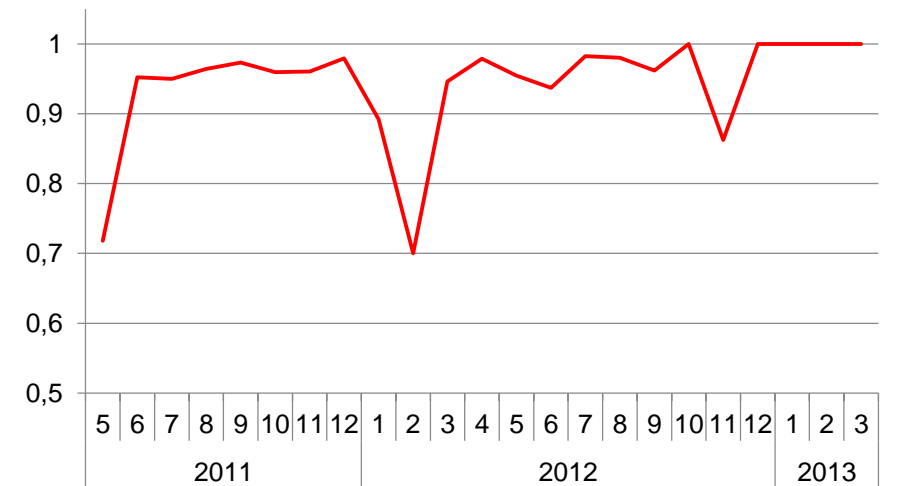
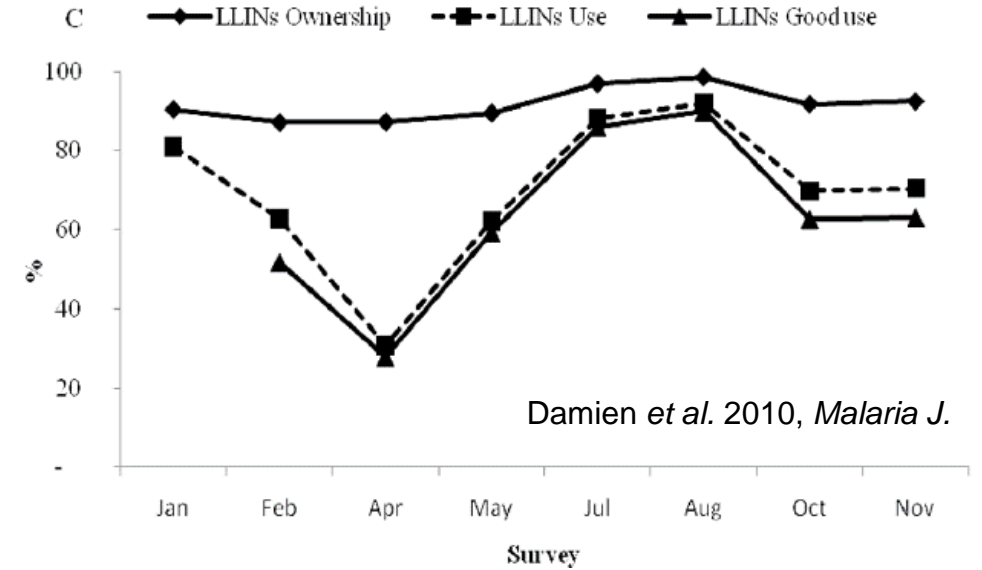
User exposure = Risque de transmission



Dynamique saisonnière

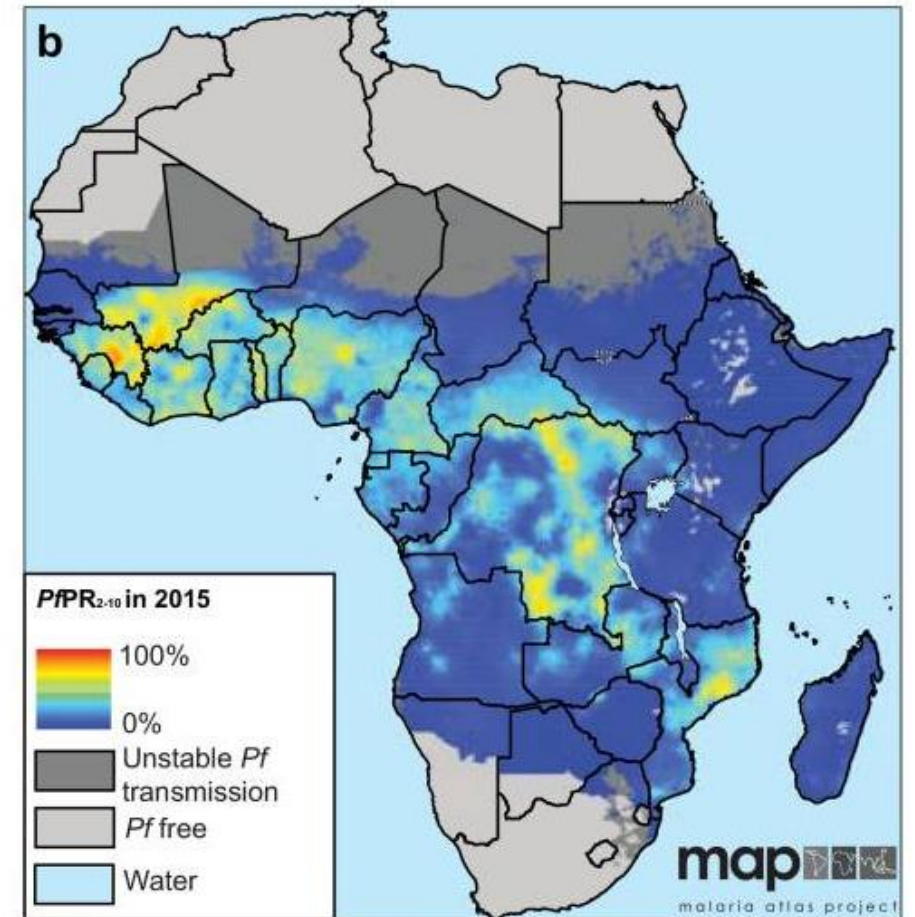
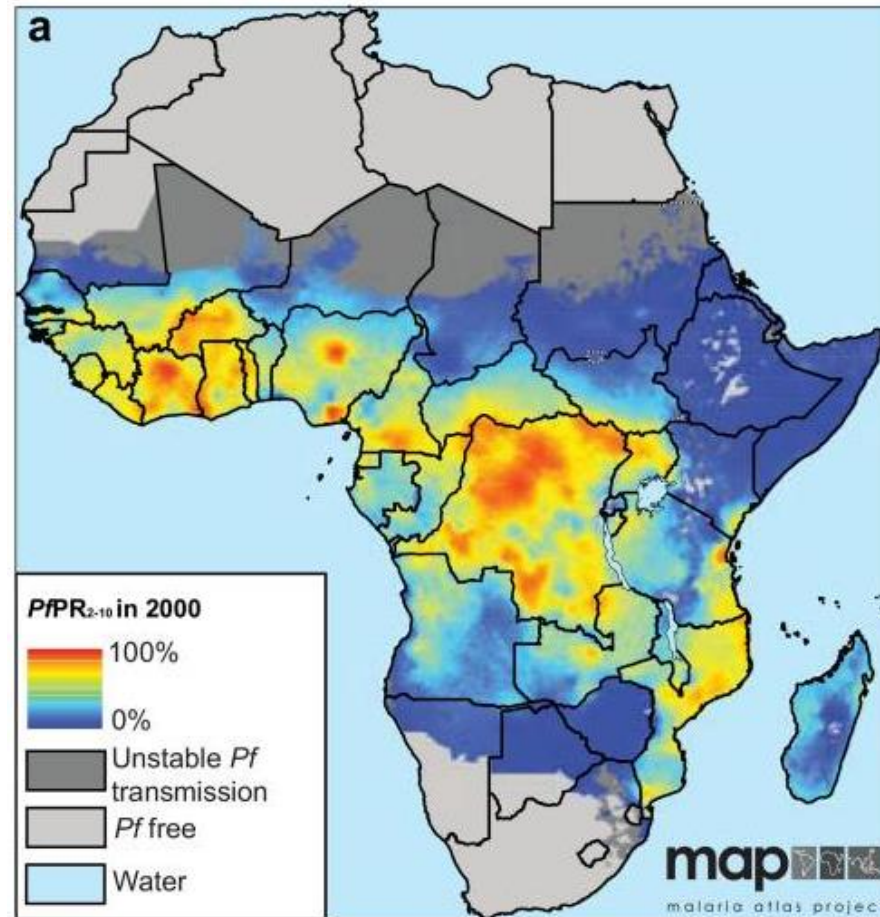


Moiroux et al. 2012, PlosOne.



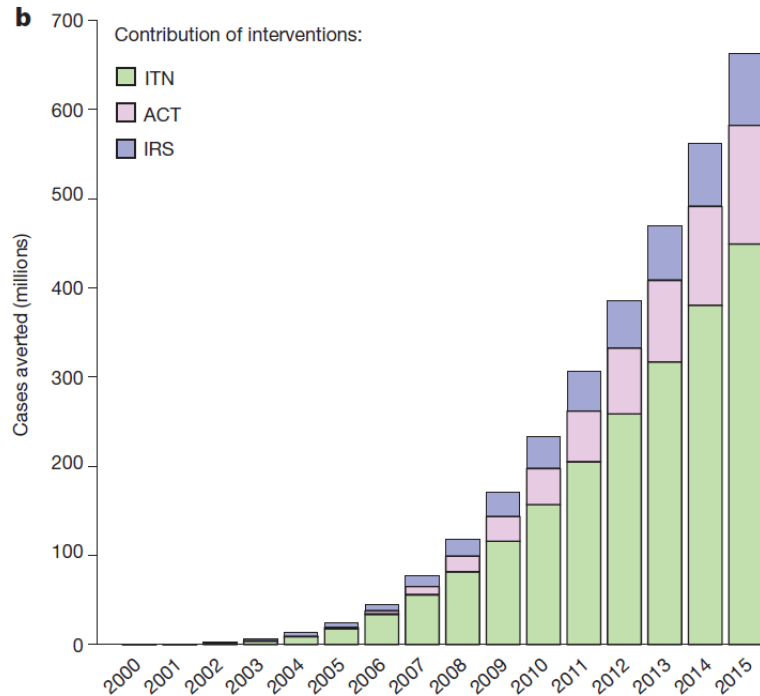
Donnée non publiée, ANR TOLIMMUNPAL.

MILDA et réduction de la niche (réalisée) de *P. falciparum*



Bhatt *et al*, *Nature*, 2015

MILDA et maladie



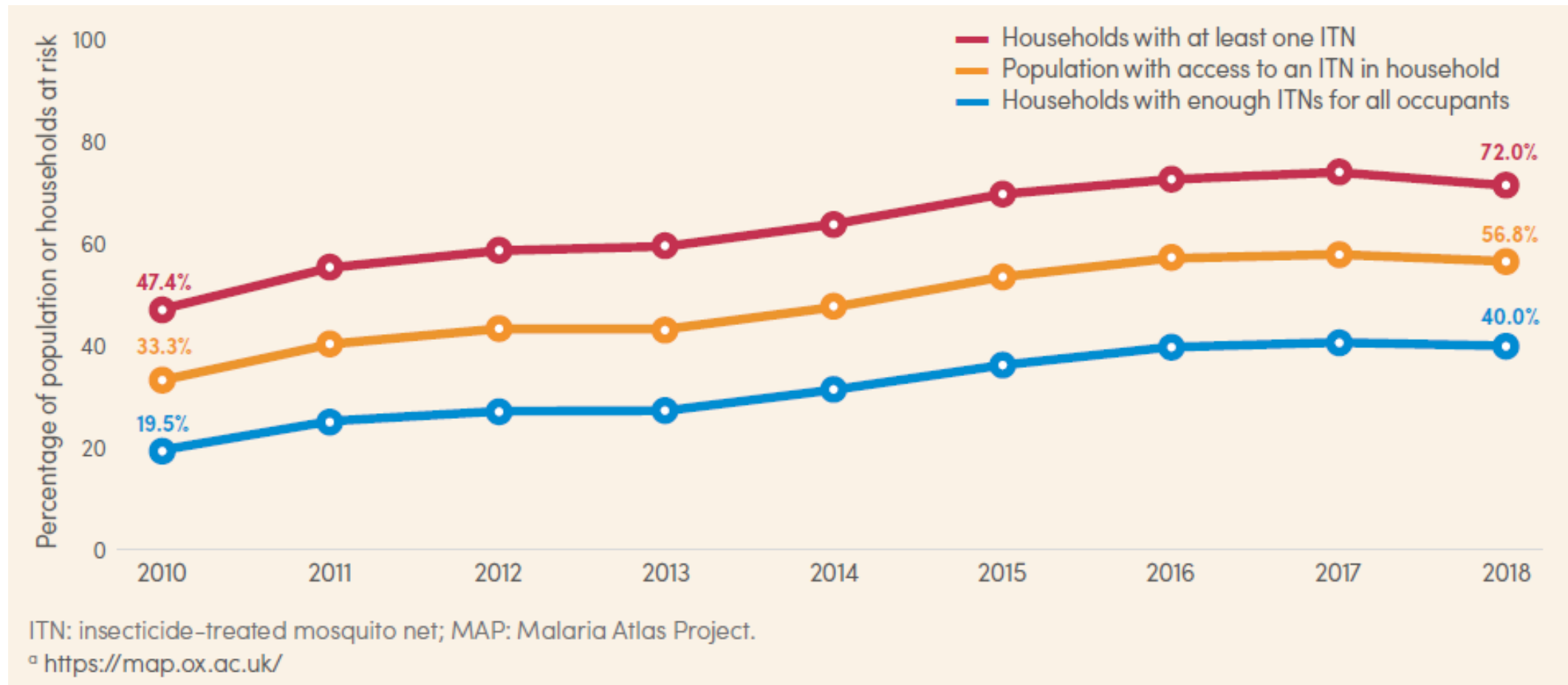
Bhatt et al 2015

450 millions de cas de palu évités
entre 2000 et 2015 soit \approx 1 million
de décès



Augmentation de la valeur sélective des utilisateurs ?

La MILDA fait parti de l'environnement et induit des adaptations



Résistances physiologiques aux insecticides

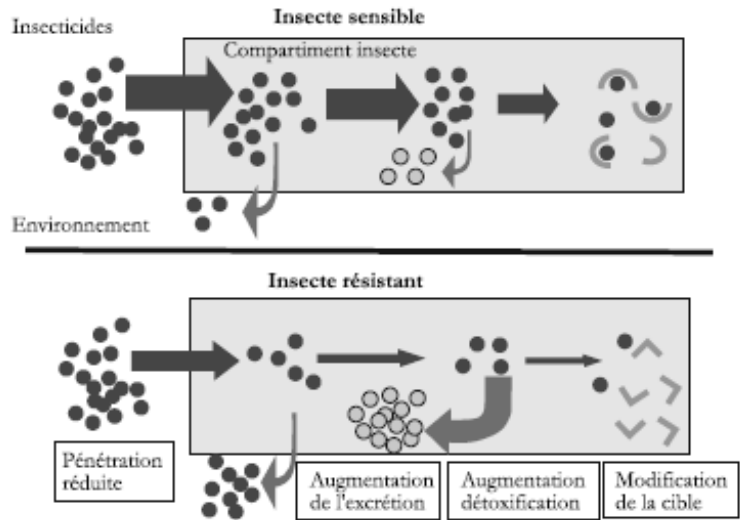
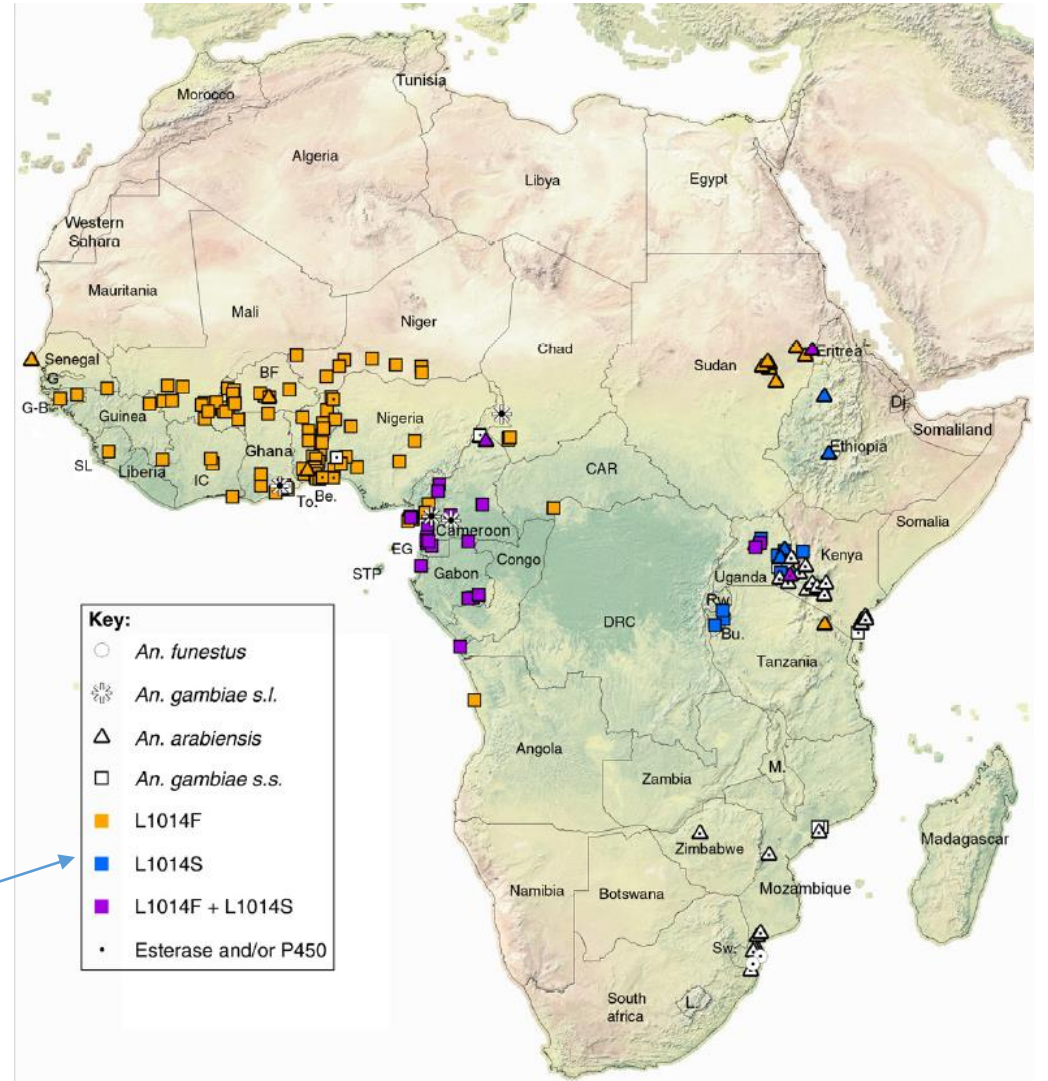
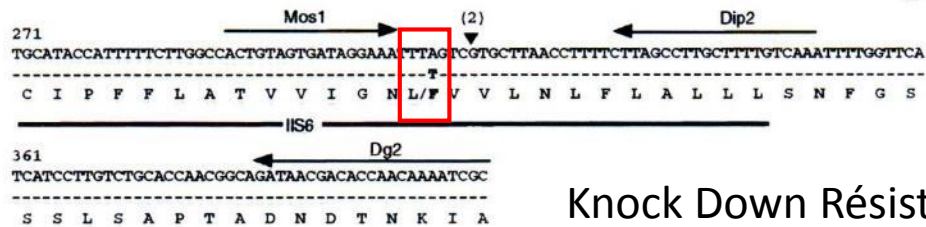


Figure 89
Représentation schématique des mécanismes impliqués dans la résistance physiologique aux insecticides, d'après POIRIÉ & PASTEUR, 1991



Ranson et al. 2011, Trends in Parasitology



Knock Down Résistance (*Kdr*)

(2)
5' GTAAGTAATGCAAATTAACATGGACCAAGATCGTTTTTACATGACATTGTTTGCAG

Figure 1. Sequence analysis of the IIS4-IIS6 region of the voltage-sensitive sodium channel in susceptible Bobo (Bo) and Kisumu (Kis) strains and in *kdr* Kou Valley (KV) and Toia (Toi) strains of *A. gambiae*. Identical positions are indicated by a dash (-). In the predicted amino acid sequence below, the single change (leucine/phenylalanine) is highlighted. The positions of the two introns present in this region are indicated by a ▼. The sequence of the second intron which was necessary for designing the '*kdr* specific' primer used in the diagnostic test is presented below. This sequence is identical in the four strains. The sequence has been deposited in the GenBank database (accession number Y13592).

Effet de la mutation *Kdr* sur la mortalité des *Anopheles* exposés aux insecticides

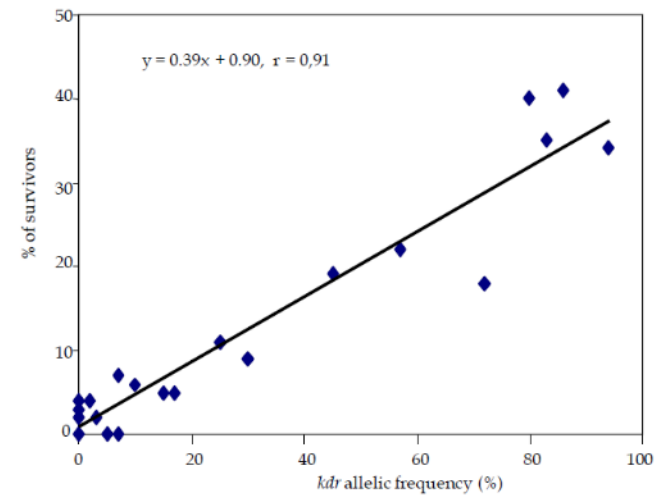
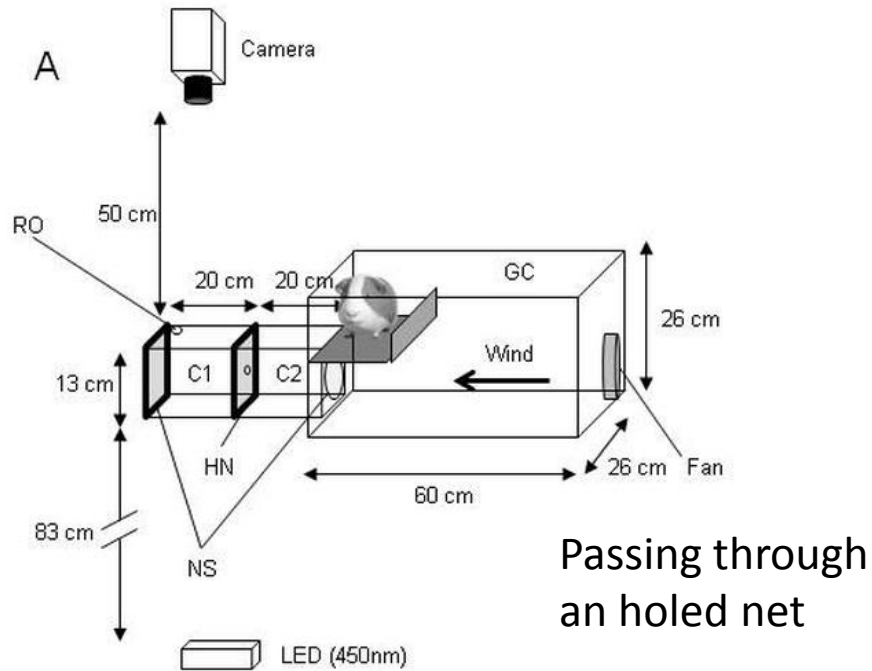
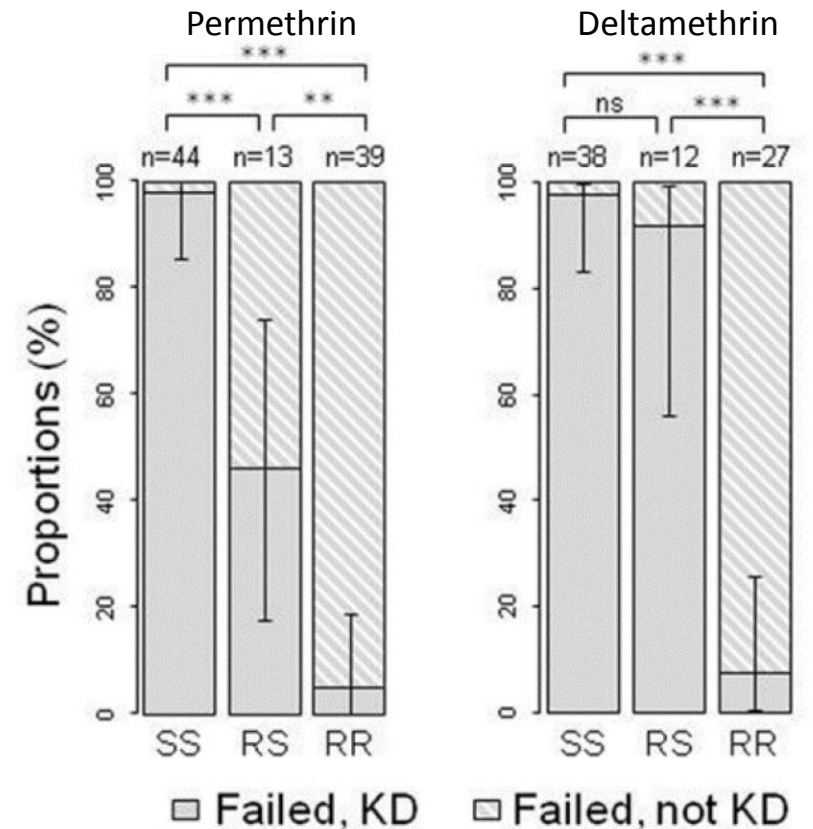


Fig. 7. Correlation between *kdr* frequency and mortality rates of *An. gambiae s.l.* tested with permethrin 0.75%.



Diop *et al.* 2015



Pressions de sélections et Dynamiques de la fréquence de la mutation *Kdr*

Trends in Insecticide Resistance in Natural Populations of Malaria Vectors in Burkina Faso, West Africa: 10 Years' Surveys

487

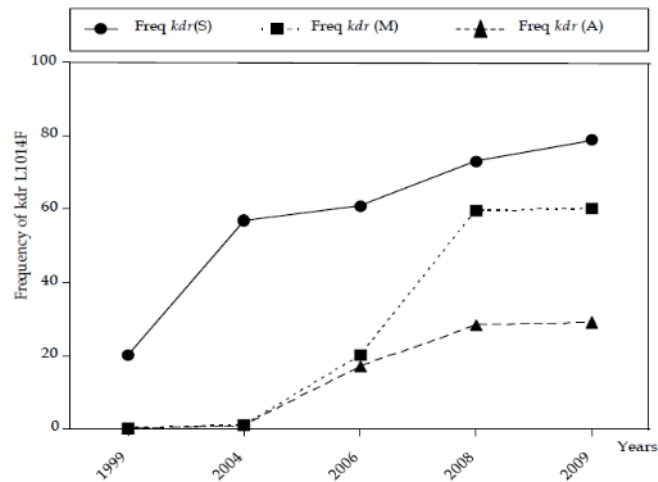
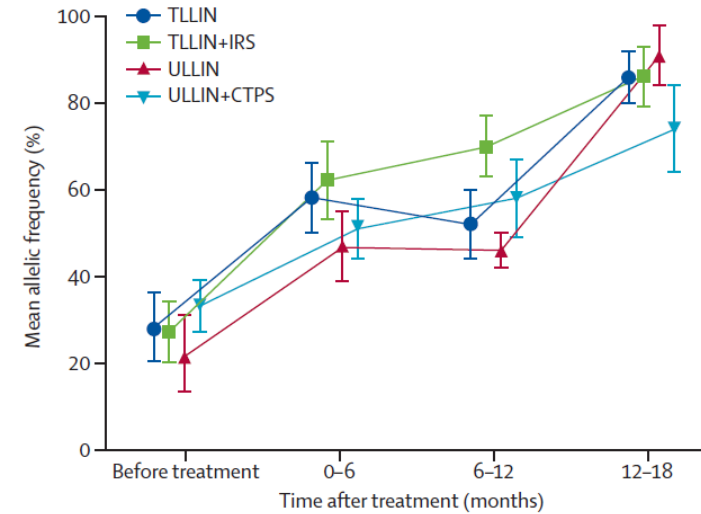
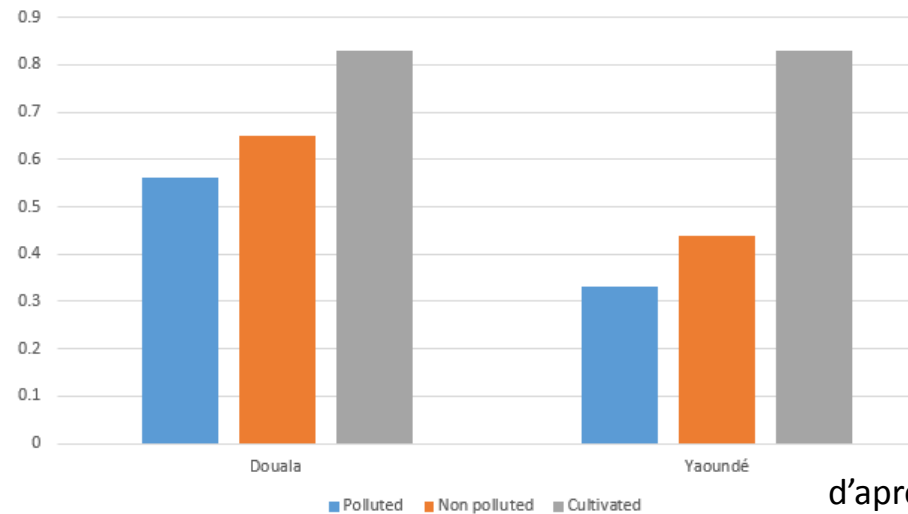


Fig. 6. Evolution of allelic frequencies (in percentages) of L1014F *kdr* in natural populations of *An. gambiae s.l.* from 1999 to 2009 in Burkina Faso[S: *An. gambiae* S form; M: *An. gambiae* M form, A: *An. arabiensis*].



Corbel et al. 2012, Lancet Inf. Dis.

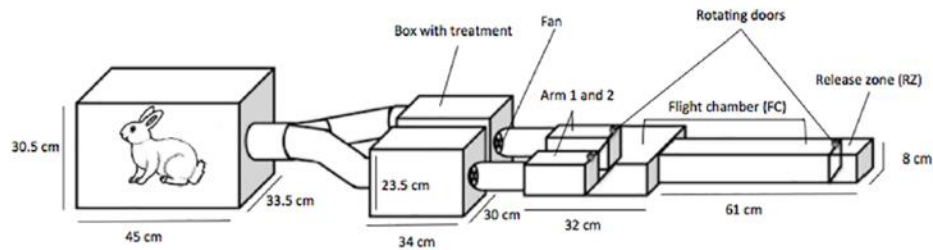


d'après Antonio-Nkondjio et al., 2011, Malaria J.

Interaction *Kdr* et comportement

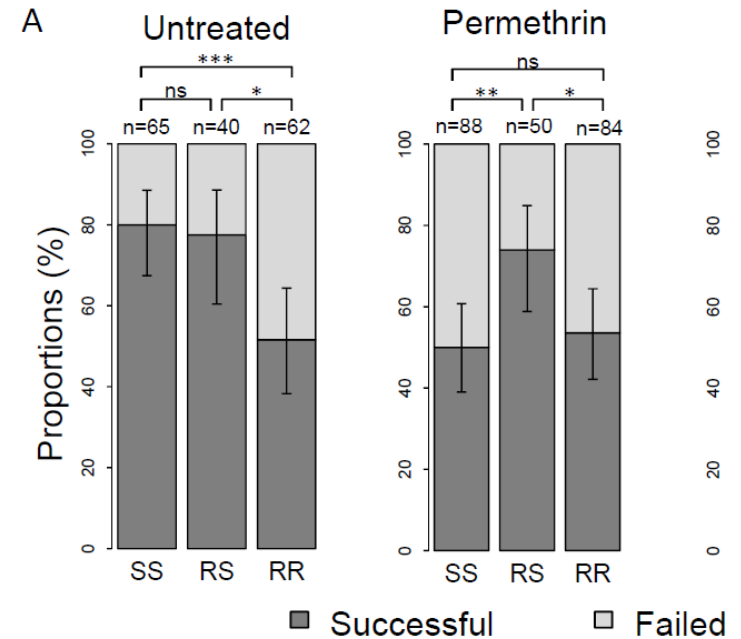
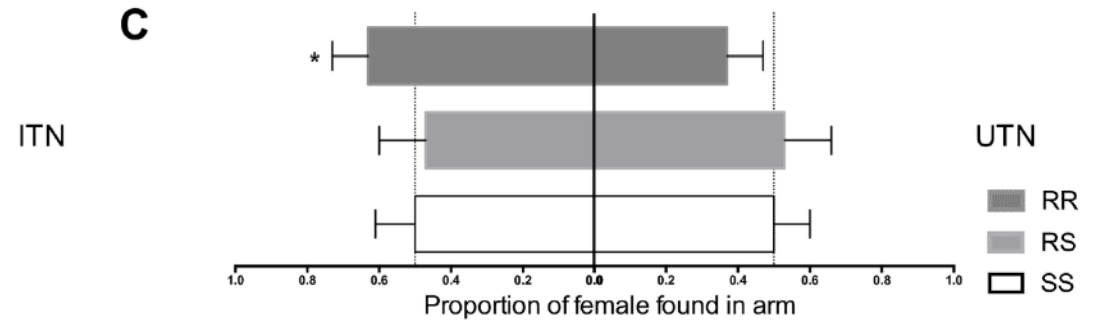
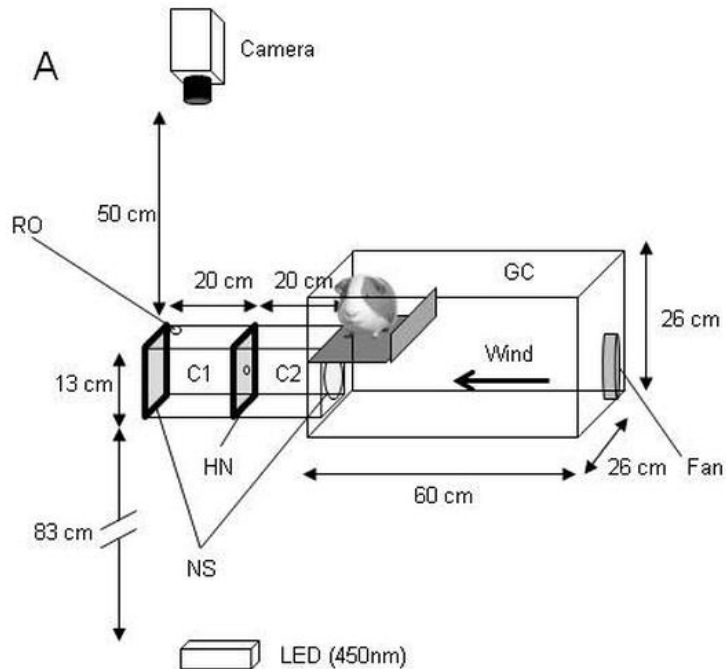
Host location

Porciani *et al.* 2017



Passing through an holed net

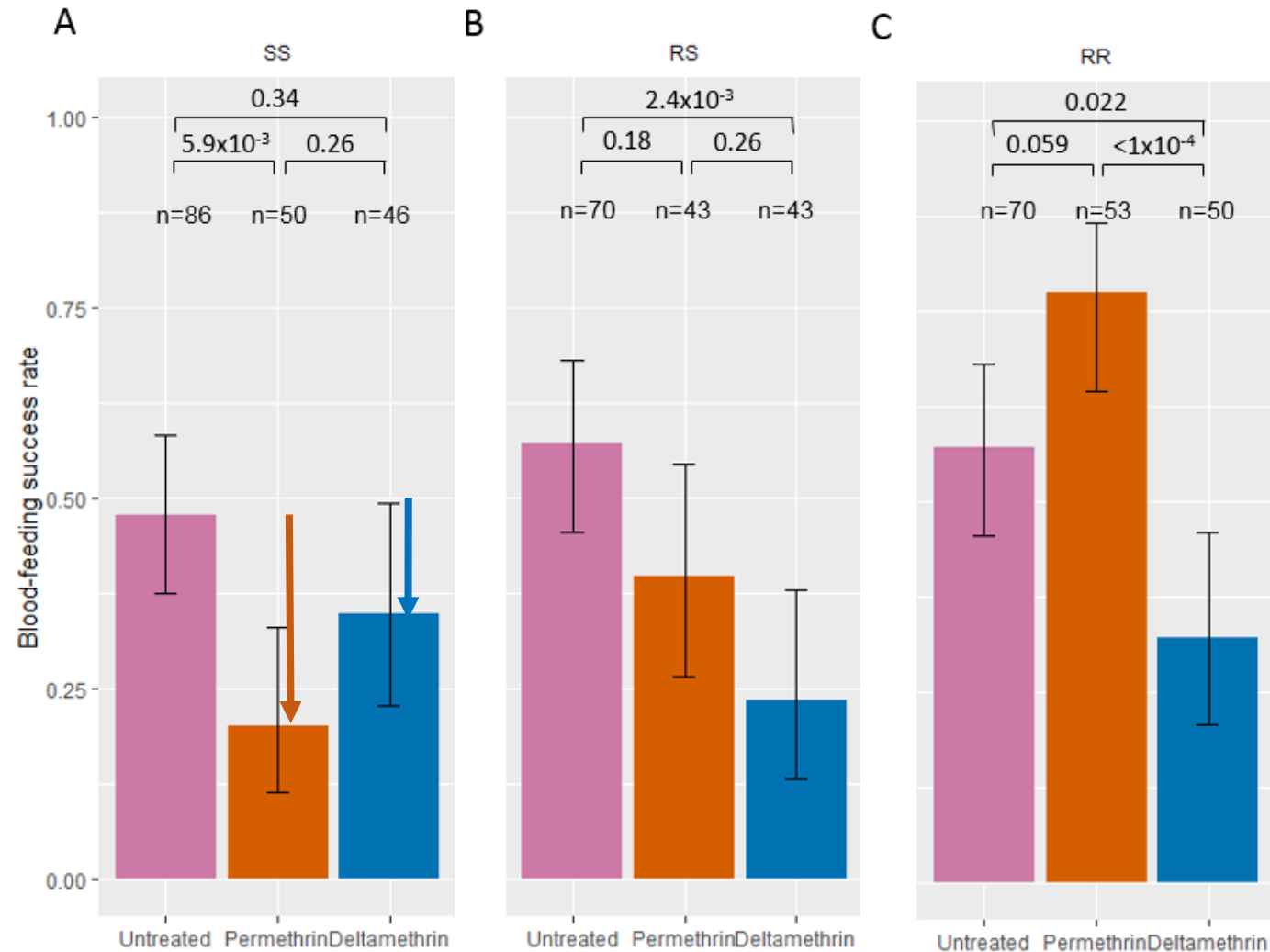
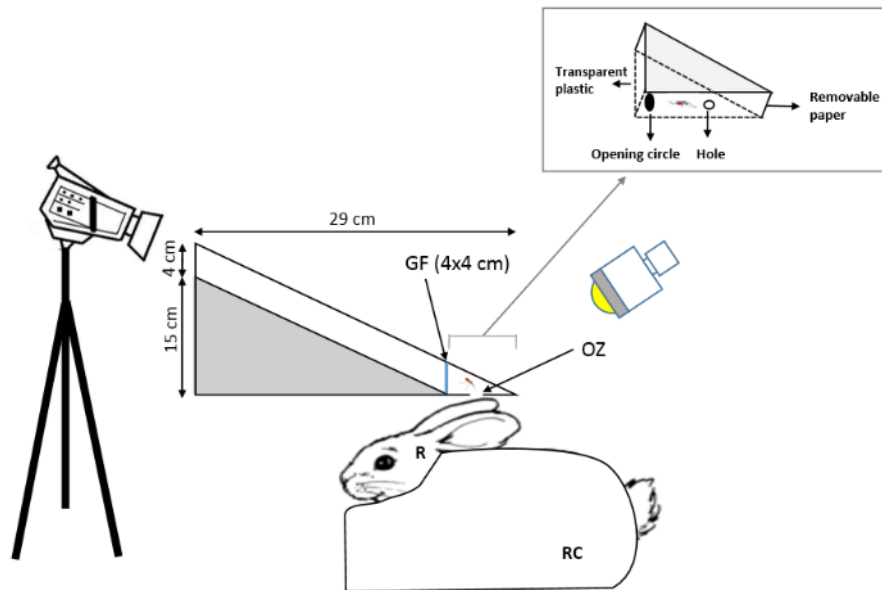
Diop *et al.* 2015



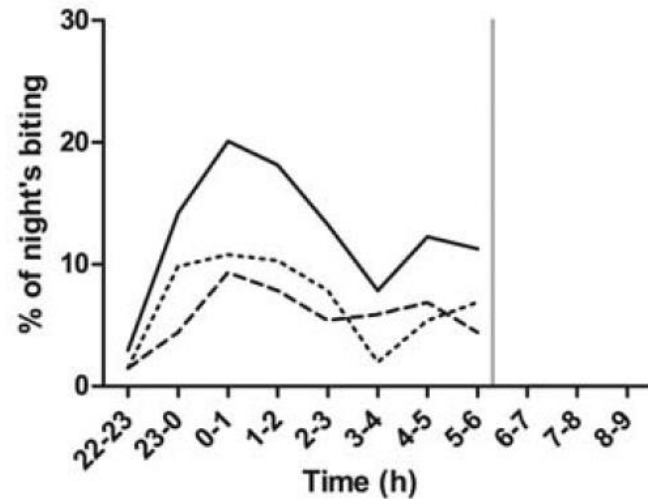
Interaction *Kdr* et comportement

Blood-meal success after a sub-lethal exposure to an LLIN

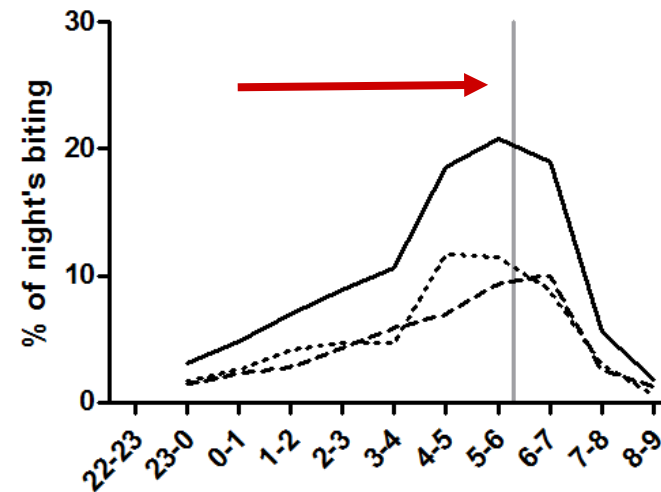
Diop *et al.* 2020



Résistances comportementales



3 ans
d'utilisation de
MILDA



An. funestus
Sensible aux insecticides
Décalage du pic
d'agressivité +
activité diurne

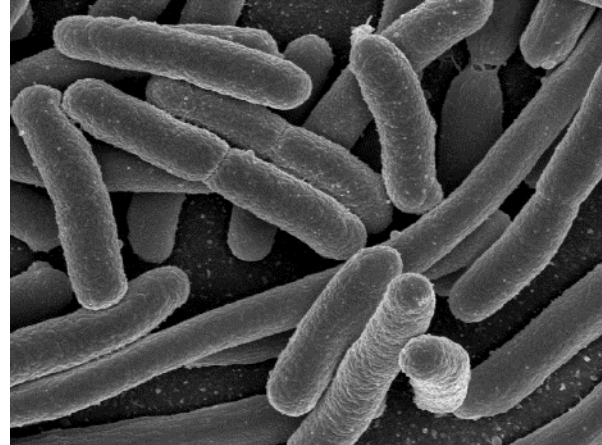
Moiroux et al, JID 2012

Elargissement de la niche fondamentale (processus sélectif) ou
plasticité phénotypique (meilleure connaissance de la niche) ?

Restauration partielle du risque de transmission

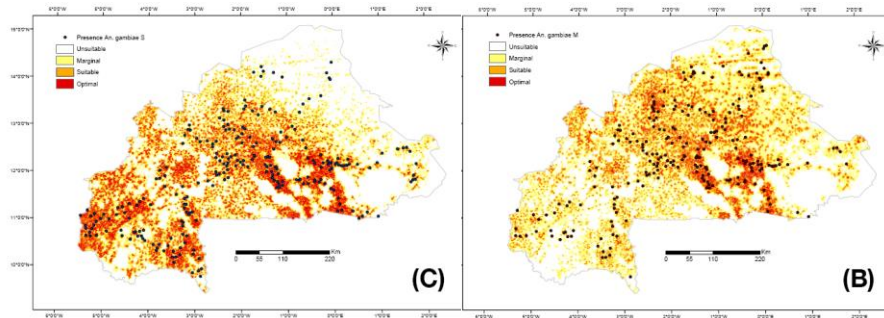
Autres interactions biotiques ayant un effet sur la transmission

Comment les interactions biotiques du vecteur peuvent influencer la niche du pathogènes.

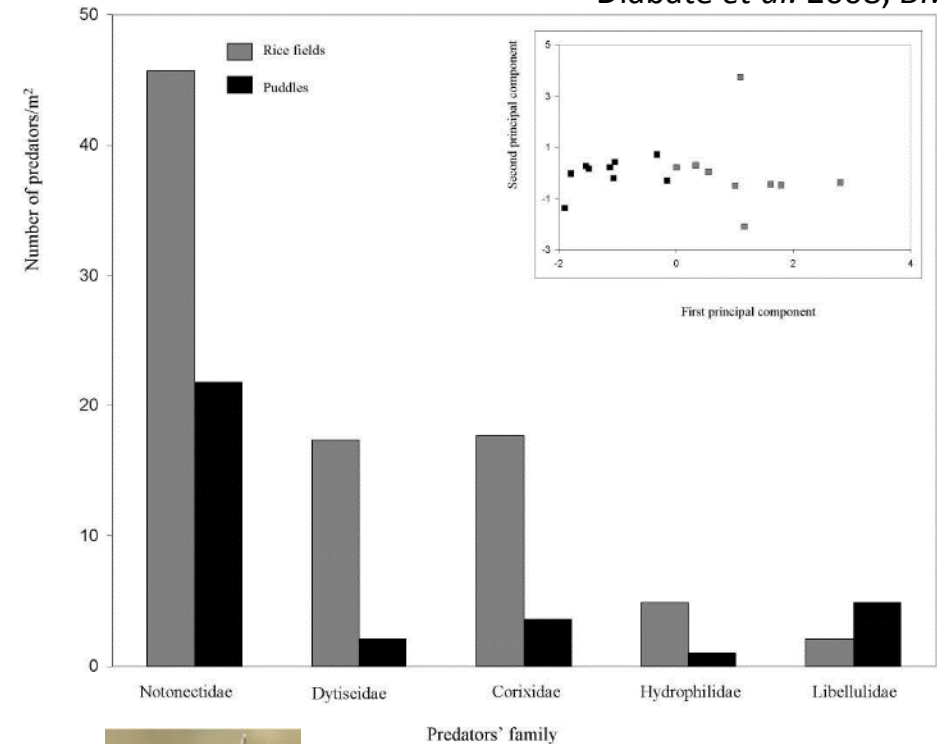


Prédation des vecteurs et transmission

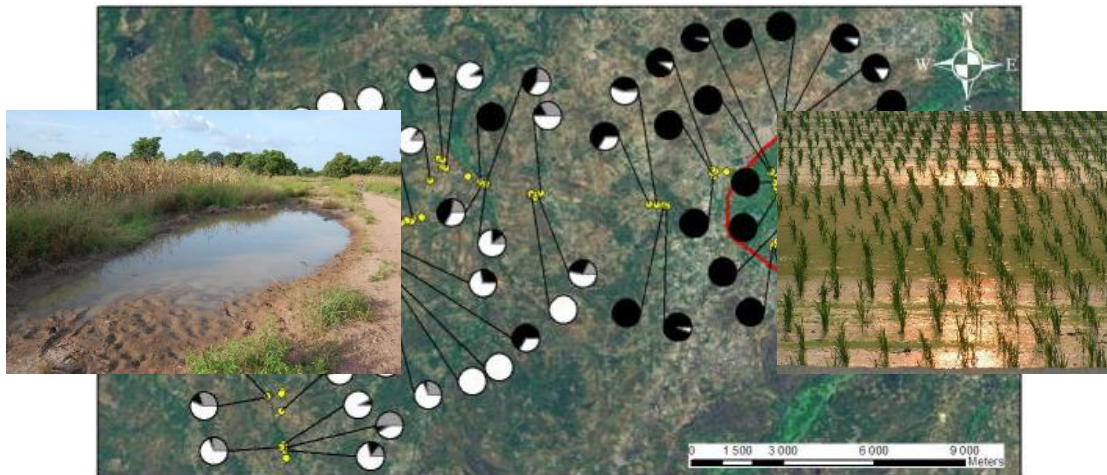
Costantini *et al*, BMC Ecol. 2009



Diabaté *et al*. 2008, BMC Evol. Biol.



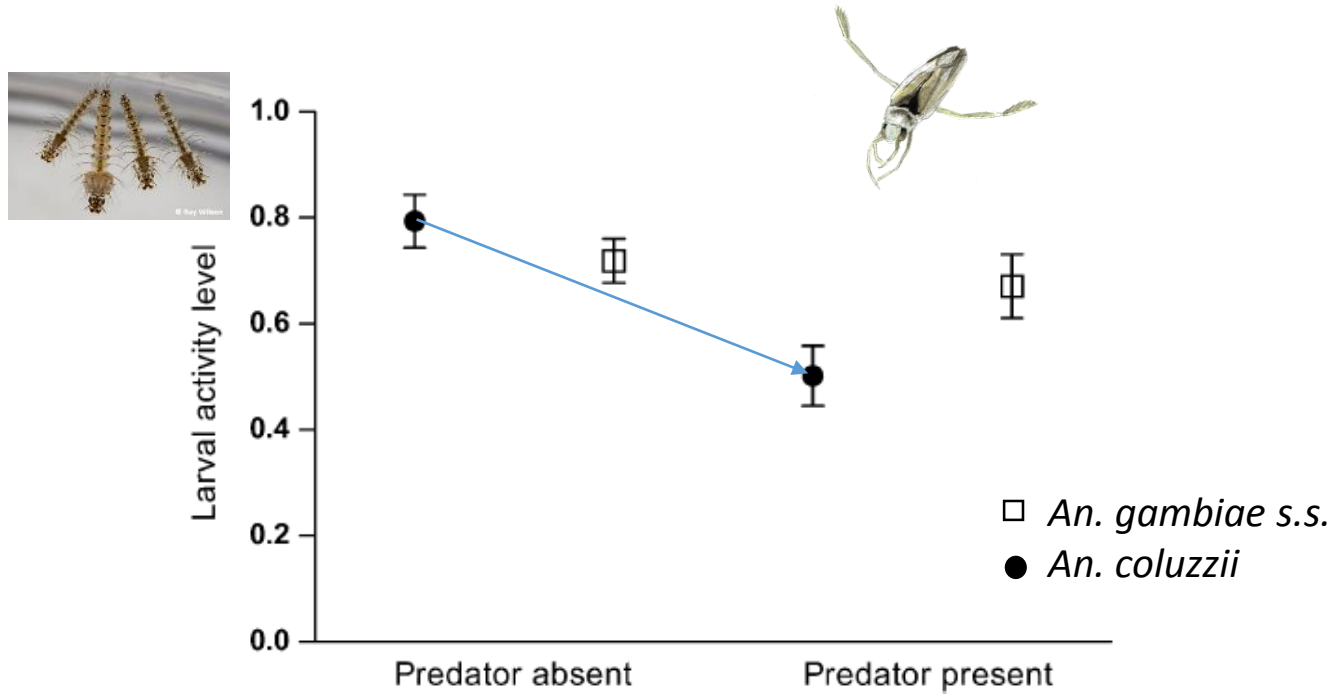
Gimonneau *et al*, 2011



- *An. gambiae s.s.*
- *An. coluzzii*

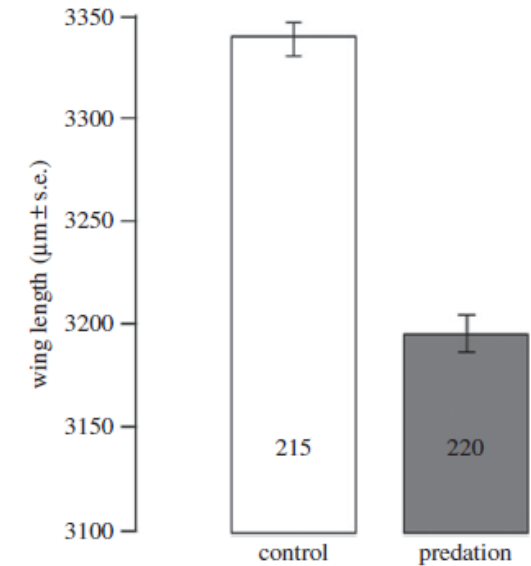
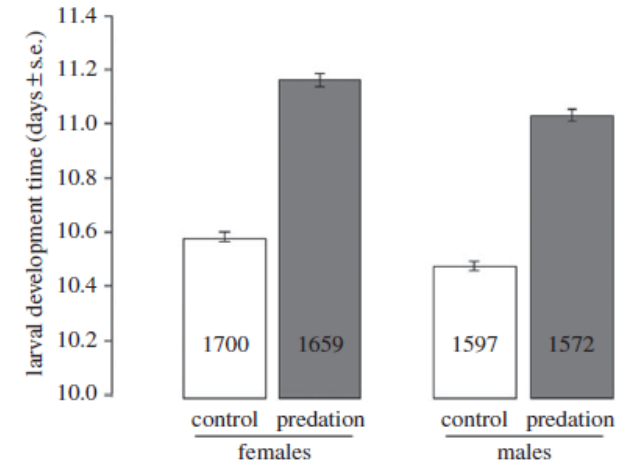


Prédation des vecteurs et transmission



Gimonneau *et al.*, 2010, 2012

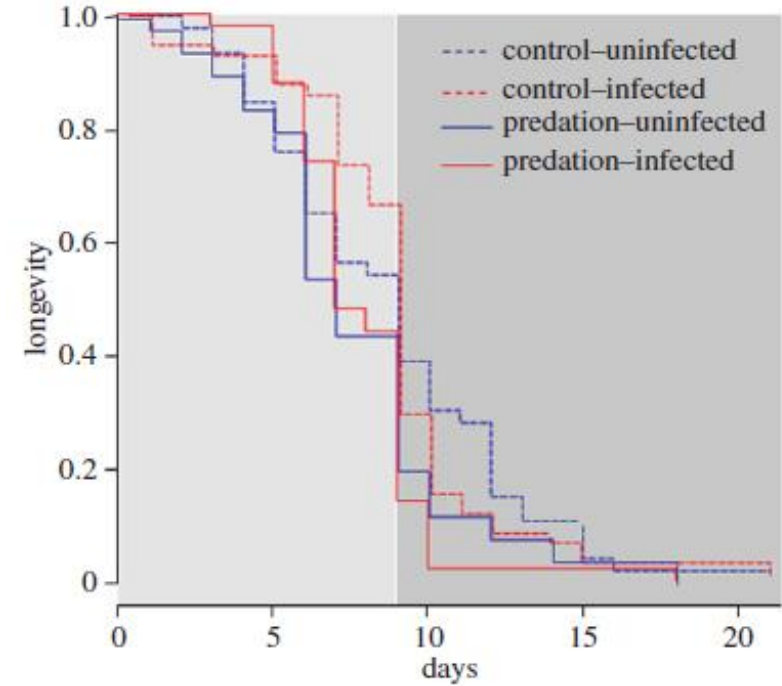
Roux *et al.*, 2015. *Proc. B*



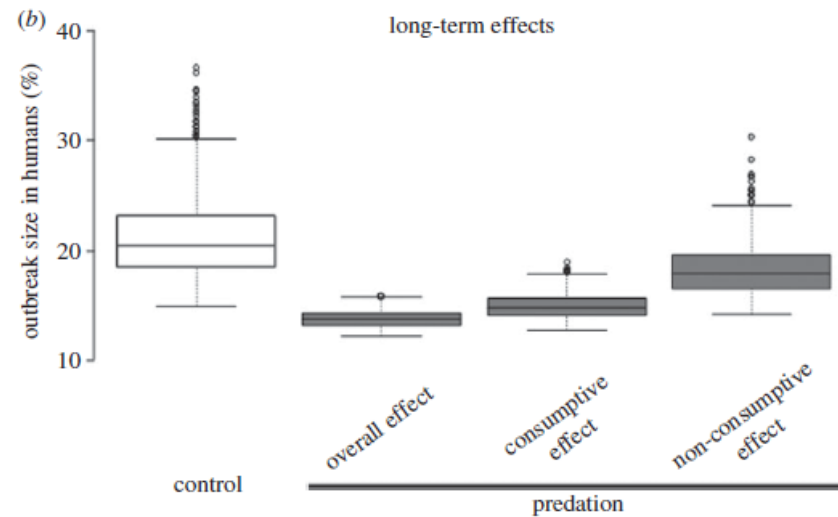
Prédation des vecteurs et transmission



Infections expérimentales

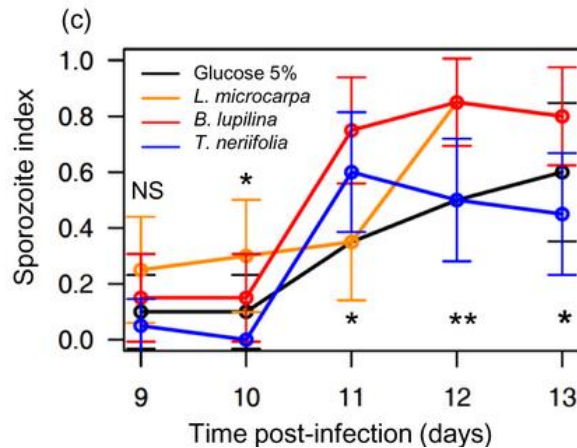
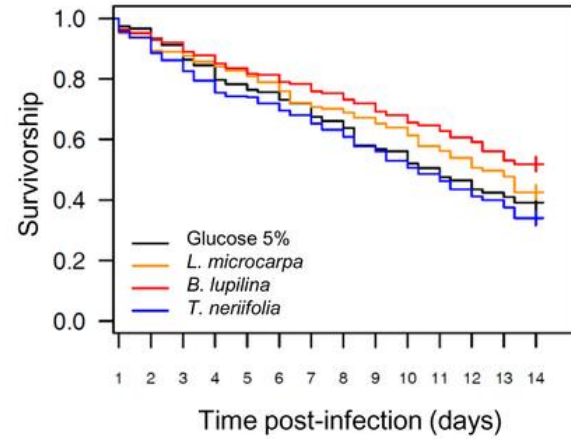
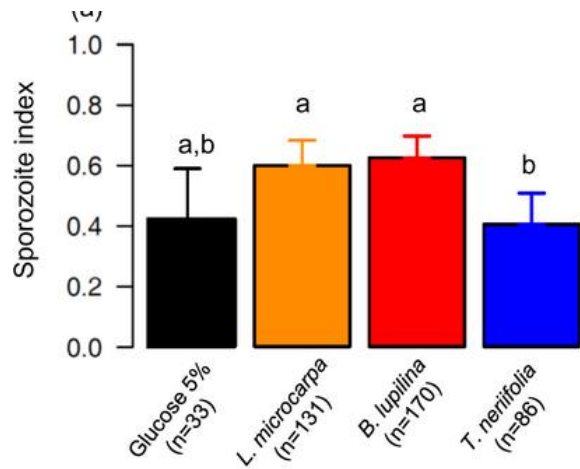


Roux *et al*, 2015. *Proc. B*



Diversité floristique et transmission

Hien et al., Plos Path. 2016



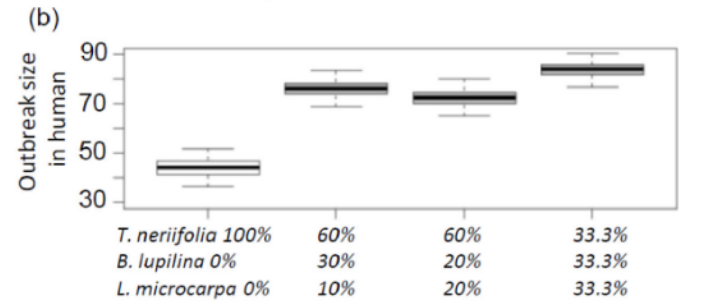
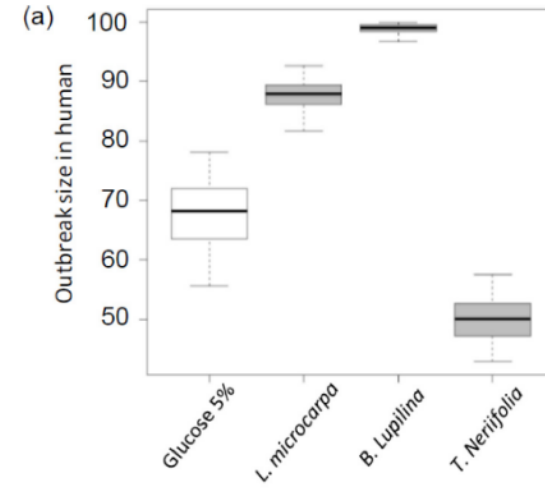
Lannea microcarpa



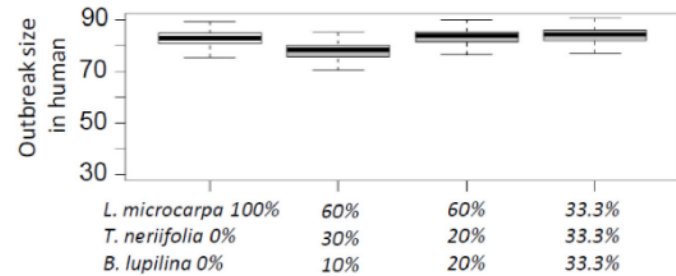
Barleria lupulina



Thevetia neriifolia



Four configurations of plant relative abundance in urban areas

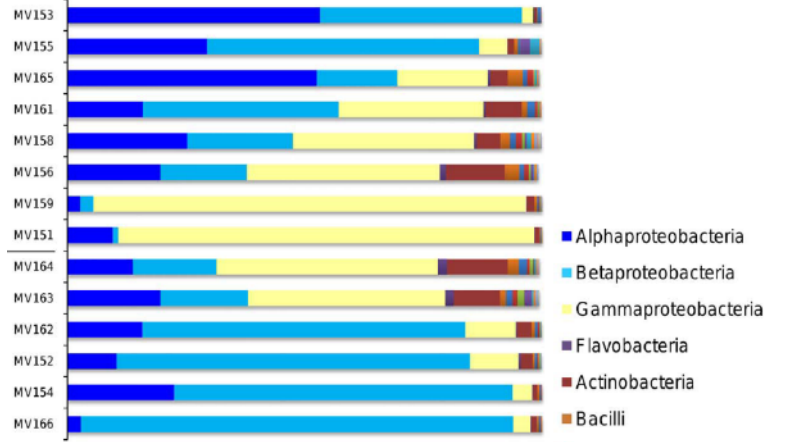


Four configurations of plant relative abundance in rural areas

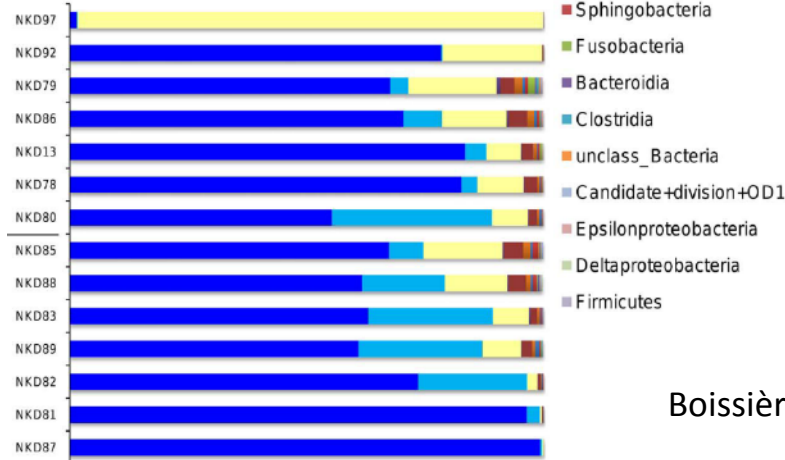
Fig 4. Theoretical difference in the distribution of outbreak sizes among plant sugars.

Microbiote des vecteurs et transmission

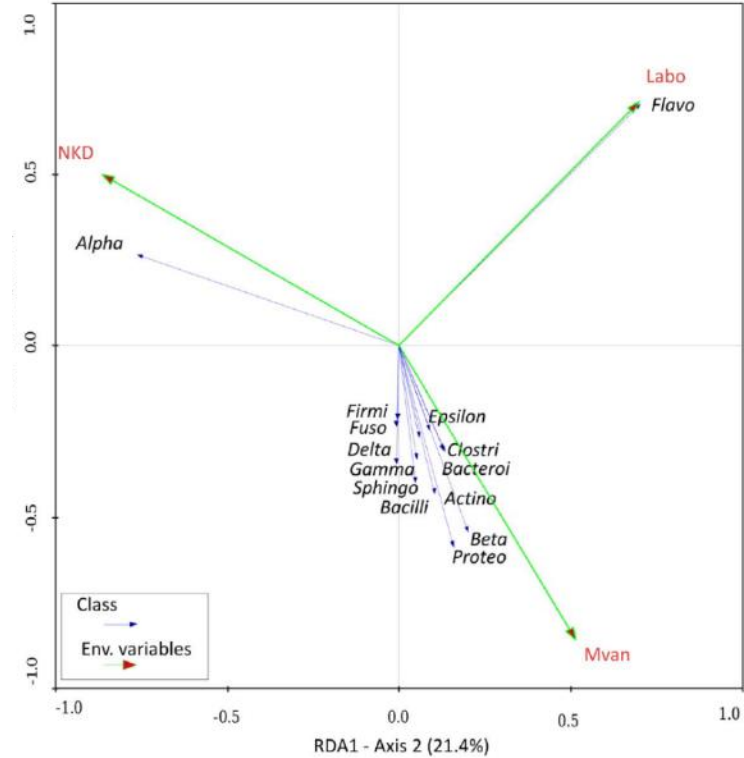
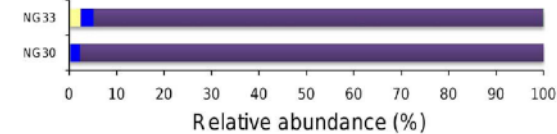
Mvan



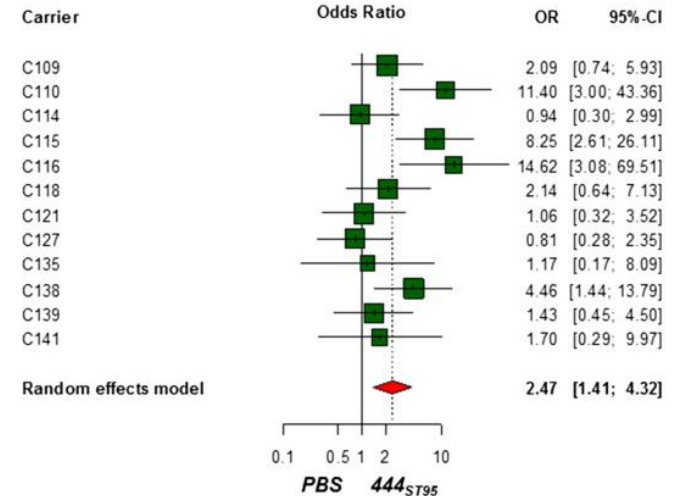
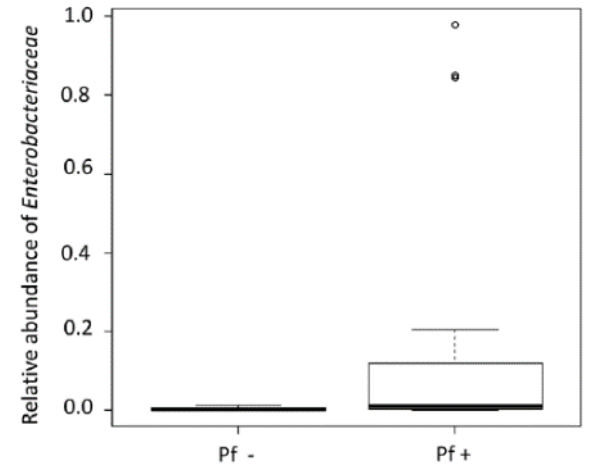
NKD



Labo



Boissière *et al.*, 2012, *Plos Path.*



Tchioffo *et al.*, 2016, *IGE*

Elevage (source de sang alternative) et transmission



Host preference

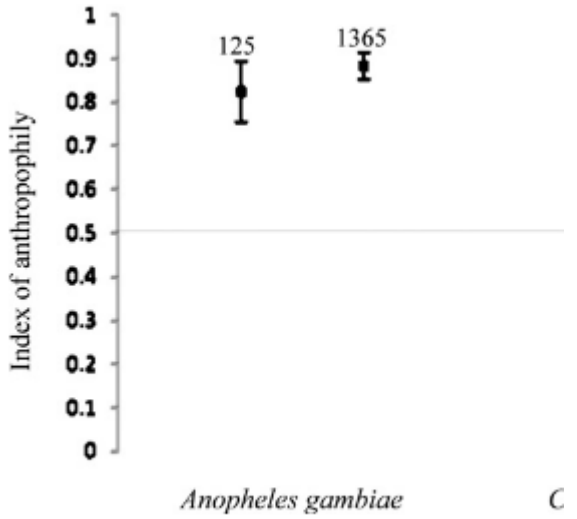
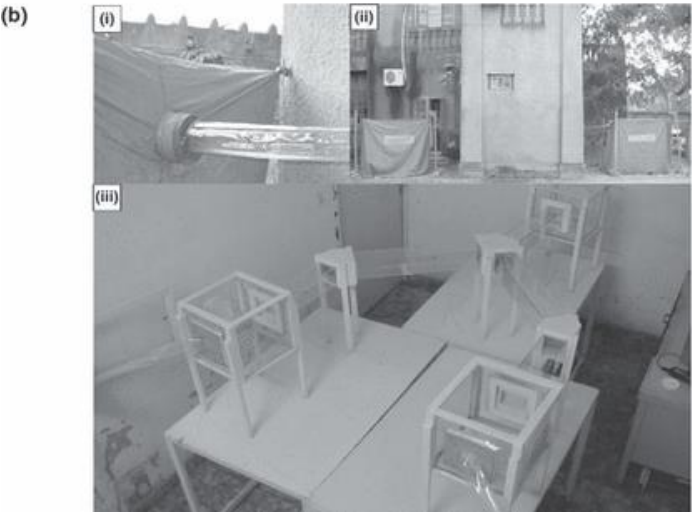
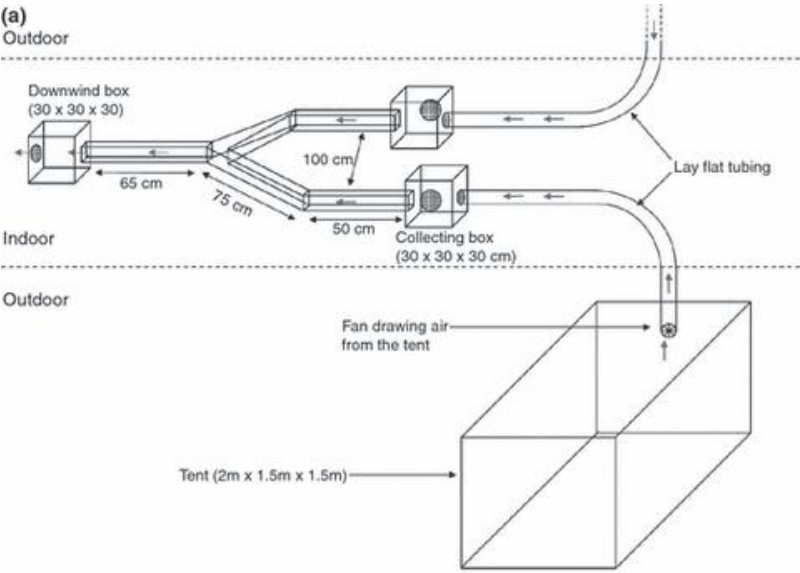
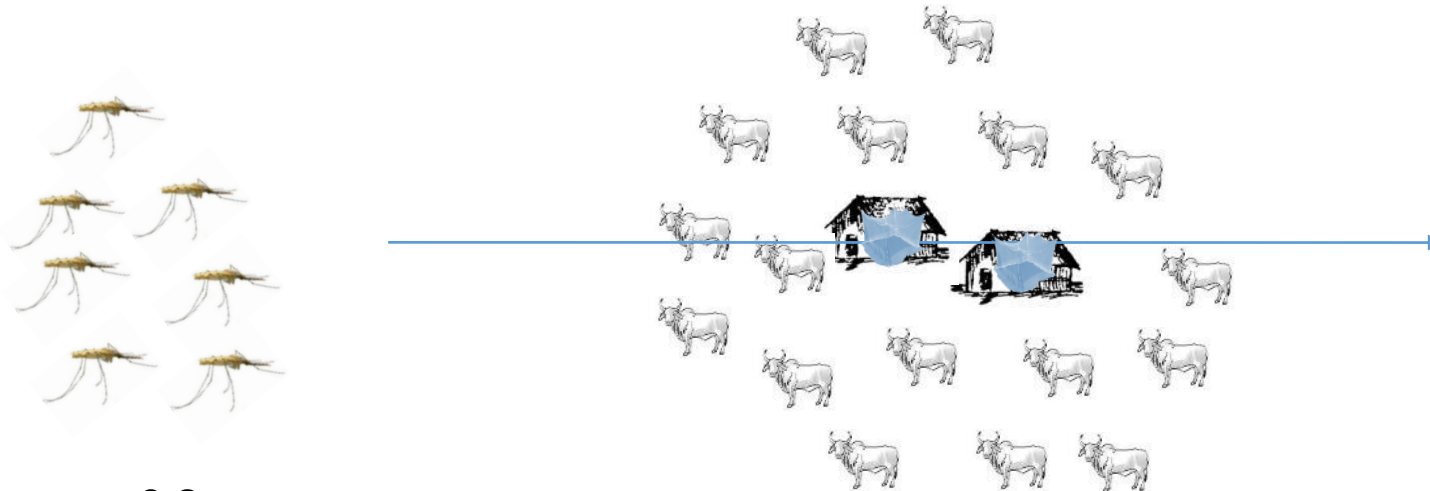


FIGURE 1. Choice test: human vs. calf odor.

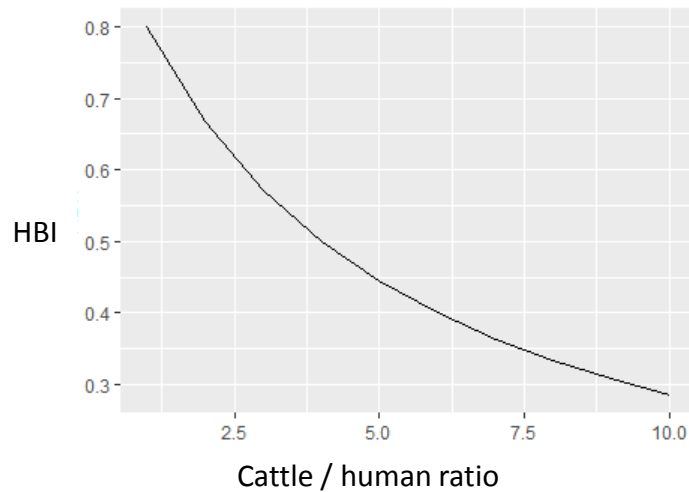
Anthropophily (experimental)

Elevage (source de sang alternative) et transmission



$p = 0.8$

Availability

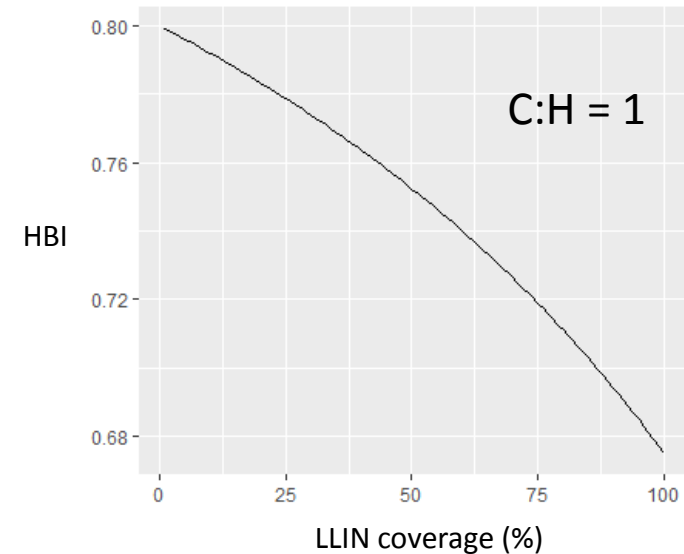


$$CV = b \cdot m a^2 \frac{p^n}{-\ln(p)}$$

Realised bloodmeal (field)

Blood meal origin of *Anopheles gambiae* s.l. (> 95

Sample	Human	Bovine	Equine	Ovine	Porcine
IRC-1	97 30%	160 50%	8 2%	3 1%	5 2%
IRC-2	30 32%	44 47%	—	—	—
OBT-H	11 22%	25 50%	6 12%	0 0%	1 2%
OBT-C	7 22%	14 44%	0 0%	0 0%	0 0%



Merci de votre attention