INTRODUCTION

Among all the anophelines transmitting malaria to man, Anopheles gambiae s.l. Giles is by the most efficient vector in the world. According to the World Health Organization estimations (WHO, 2009), two billion people live in areas plagued by endemic malaria. This disease is responsible for three hundred to five hundred million clinical cases each year, more than 90% of which occurring on the African continent. An. gambiae larvae proliferate in clear water collections exposed to the sun, such as ponds, puddles and rice fields. Moreover the densities of anophelines larvae in rice paddies have been reported reaching peaks a few days after the pouring of nitrogenous fertilizer at the time of transplanting (Victor & Reuben, 2000; Mwangangi et al., 2006). For other mosquitoes like, the dengue vector Aedes aegypti, demonstration was made in laboratory that the presence of NPK fertilizer in water attracted the gravid females looking for a place to lay their eggs. Also, an NPK fertilizer combined to plant matter favored the development of larvae, hence the emergence of adult mosquitoes (Darriet & Corbel, 2008a; Darriet et al., 2010a).

Currently, An. gambiae has become resistant to common classes of insecticides throughout Africa.
(Chandre et al., 1999; N’guessan et al., 2003; Darriet, 2007; Ranson et al., 2011) thus representing a threat to the efficacy of vector control programs based on pyrethroids for indoor residual spraying or long-lasting nets. The widespread resistance of *An. gambiae* to pyrethroids partly results from the massive use of these insecticides in agriculture (Diabate et al., 2002; Yadouleton et al., 2011). Soils easily absorb the pyrethroids (Harris et al., 1981) which rain water drains into the rice fields and other water collections. The *An. gambiae* larvae that grow in such an environment are inevitably exposed to intense and long-lasting selection pressures that affect their susceptibility to insecticides.

Taking rice paddies as a model with their abundant *An. gambiae* mosquito populations, we attempt to find out how the biological cycles of resistant and susceptible strains of *An. gambiae* s.s. would be like when grew in an environment containing more or less plant matter and fertilizer, and how they are modified when larvae are exposed to an insecticide treatment, here deltamethrin. *An. gambiae* females from untreated environments were submitted to susceptibility tests using deltamethrin while those emerging from treated environments were weighed and analyzed to determine their soluble protein content.

### MATERIALS AND METHODS

#### MOSQUITO STRAINS

Two strains of *An. gambiae* s.s. were used in this study. A susceptible strain KIS (S form) originating from Kisumu in Kenya and a strain resistant to pyrethroids (VKPR: homozygous for knockdown resistance (*Kdr*) Leu-1014-Phe) originating from Kou Valley in Burkina-Faso have been maintained for 15 years under laboratory conditions (27 ± 2 °C and 80 % RH). The VKPR strain (M form) was already resistant to pyrethroid on the field and has been maintained subsequently under constant permethrin selection until homozygosis for *Kdr* (Darriet et al., 1997).

### NPK FERTILIZER, PLANT MATTER AND INSECTICIDE

The NPK fertilizer 5-7-5 (Algoflash®) contained 5 % of nitrogen (N) consisting in 3 % of nitric nitrogen (NO₃⁻) and 2 % of ammoniacal nitrogen (NH₄⁺), 7 % of phosphorus (P) in the form of phosphorous pentoxide (P₂O₅), 5 % of potassium (K) in the form of potassium oxide (K₂O). The plant matter (PM) composed of dry grasses (hay) is sold in pet shop for the feeding of rabbits and little rodents (Zolux®). The insecticide treatments were made by using 100 % technical grade of deltamethrin (Δ) (Hoechst and Schering, Berkhamsted, UK).

### COMBINATION OF PM-NPK FERTILIZER AND Δ

From two different concentrations of PM (2.5 and 5 g/l) and NPK (8-12-8 and 17-23-17 mg/l) and the dose of 2.5 g/ha of Δ, 12 environments (Fig. 1) were prepared in 0.06 m² plastic trays, each containing one liter of osmosed water. The two NPK doses chosen had already been studied on *Ae. aegypti* mosquito (Darriet & Corbel, 2008a; Darriet et al., 2010a). The 2.5 g/ha (= 0.25 mg/m²) deltamethrin dose is the one currently applied in rice fields to control rice gall midge *Orseolia oryzae* (Diptera: Cecidomyiidae) (Dakotto & Nacro, 1987). In our one liter plastic trays the deltamethrin concentration is equivalent to 0.015 mg/l. The artificial environments were all evaluated on a total of three replicates, except for PM1, PM2, PM1 + Δ et PM2 + Δ that were done on six replicates.

**Fig. 1.** - Quantities of plant matter (PM), NPK fertilizer and deltamethrin (Δ) included in the combination of the environments evaluated on *Anopheles gambiae* VKPR and KIS strains. *An. gambiae* females from untreated environments were submitted to susceptibility tests using deltamethrin while those emerging from treated environments were weighed and analyzed to determine their soluble protein content.
The reference data were obtained with mortality rates were compared using a \( \chi^2 \) test with Yates' correction. Throughout the duration of the experiment, the trays were maintained at temperature of 27 ± 2 °C in the laboratory. The treatments using deltamethrin were done 48 hr after larval introduction in tray. All 12 environments treated or not (Fig. 1) were evaluated depending solely on the constitutive elements of environments (plant matter and/or NPK fertilizer). The females from the treated breeding sites were exposed filter papers treated at the discriminating dosage of deltamethrin (0.05 % = 18.4 mg/m\(^2\)). The reference data were obtained with An. gambiae KIS strain raised in the insectarium. Filter papers were treated using acetone solution of insecticide and silicone oil as the carrier (WHO, 2006). Mortality was recorded 24 hr after exposure, corrected by the formula of Abbott if necessary (Abbott, 1925). The mortality rates were compared using a \( \chi^2 \) test with Yates' correction.

### RESULTS

#### POPULATION DYNAMICS OF ADULTS OF An. Gambiae VKPR STRAIN IN ACCORDANCE WITH THE ENVIRONMENT

The population dynamics of VKPR strain were very different depending on the composition of the environment.

- **PM1**: 2.5 g/l – NPK1: 8-12-8 mg/l – NPK2: 17-23-17 mg/l – \( \Delta \): 0.015 mg/l (Fig. 2)

Less than 4 % of the adults were collected in untreated environments. The dose of 2.5 g/l of plant matter was not sufficient to provide enough food to the 100 larvae of An. gambiae VKPR and the addition of NPK in the water did not increase the food resources. When the environments were treated with deltamethrin, paradoxically more adults emerged than in untreated breeding sites with a cumulative emergence of 24 % at D12 in PM1 + \( \Delta \), 56 % in (PM1 + NPK1) + \( \Delta \) and 59 % in (PM1 + NPK2) + \( \Delta \). Adding NPK1 or NPK2 concentrations to PM1 + \( \Delta \) favored the larval growth and the adults emergence, without any significant difference between both fertilizer doses.

- **PM2**: 5 g/l – NPK1: 8-12-8 mg/l – NPK2: 17-23-17 mg/l – \( \Delta \): 0.015 mg/l (Fig. 3)

Doubling the dose of plant matter (PM2) allowed the larvae of An. gambiae VKPR to have a normal growth and after 8 to 11 days following the beginning of the test to induce 74 % emergence in PM2, 84 % in PM2 + NPK1 and 93 % in PM2 + NPK2. In these experiments, the treatment of breeding sites with deltamethrin reduced the percentage of adult emergence to 23 % in PM2 + \( \Delta \) (similar to PM1 + \( \Delta \)), 47 % in (PM2 + NPK1) + \( \Delta \) and 69 % in (PM2 + NPK2) + \( \Delta \). A dose effect of NPK on the nutritive qualities was observed in both untreated and treated environments. Also it is worth noticing that (PM2 + NPK2) + \( \Delta \) treated environment gave adult emergence rate almost as high as with untreated plant matter (PM2) alone (74 and 69 % respectively).
Deltamethrin at the concentration of 0.015 mg/l killed 100 % of the larvae of An. gambiae KIS susceptible to pyrethroids whatever the environment.

DELTAMETHRIN SUSCEPTIBILITY OF FEMALES OF AN. GAMBIAE VKPR AND KIS STRAINS

The bioassays were carried out with adult females from untreated habitats. Due to the very small individuals collected in PM1 environments, the tests were only performed with the adults emerging from PM2, PM2 + NPK1 and PM2 + NPK2 environments (Table I). Compared to susceptible KIS, VKPR strain confirmed its high level of resistance to pyrethroids (0.0003 < P < 0.01). VKPR females from PM2 + NPK1 and PM2 + NPK2 demonstrated a susceptibility to deltamethrin similar to PM2 (respectively P = 0.98 and P = 0.27).

AVERAGE WEIGHTS AND PROTEIN CONTENTS OF FEMALE AN. GAMBIAE VKPR (Table II)

The average weight and the dosage of soluble proteins were measured on the females emerging from
the environments treated with deltamethrin. Doubling the quantity of plant matter in the water (MV1: 2.5 g/l versus MV2: 5 g/l) led to the emergence of larger females, containing more soluble proteins \((P < 0.0001)\).

The females of \((PM1 + NPK1) + \Delta\) and \((PM1 + NPK2) + \Delta\) showed average weights and protein contents greater than in adults emerged from \((PM1 + \Delta)\) \((P < 0.0001)\). The addition of NPK to an environment lacking organic matter is enough to raise larger mosquitoes with more proteins.

The females of \((PM2 + NPK1) + \Delta\) and \((PM2 + NPK2) + \Delta\) showed average weights greater than the females collected in \((PM2 + \Delta)\) \((P < 0.001)\) while having barely significant more proteins \((P = 0.027)\) for \((PM2 + NPK1) + \Delta\) and non-significant ones \((P = 0.16)\) for \((PM2 + NPK2) + \Delta\). Therefore the addition of NPK to an organic matter filled habitat favors the emergence of bigger females of \(An.\ gambiae\) not necessarily richer in soluble proteins.

**DISCUSSION**

Rice fields are environments favorable to the proliferation of \(An.\ gambiae\) and it is now well established that the levels of proliferation of this mosquito is in relation with the cultivating techniques adopted by the farming communities. With our laboratory study we attempted to identify some of the physico-chemical factors favoring the larval development of pyrethroid-resistant \(An.\ gambiae\) VKPR whether the breeding sites contained plant matter alone or in association with NPK fertilizer. Half of the environments studied were not exposed to selection pressure (control) whereas the other half was submitted to deltamethrin treatment.

The bioassays showed that 2.5 g/l plant matter were not enough to feed the hundred of larvae. Treating the breeding sites with deltamethrin (0.015 mg/l) reversed the situation as it decreased the competition for food resources and allowed the surviving larvae to share the small amount of food enabling them to pursue their development into adults. If adding NPK (8-12-8 mg/l and 17-23-17 mg/l) did not improve the nutritive quality of untreated habitats, it significantly impacted the quality of treated ones by multiplying by 2.5 the number of emerging adults (23.5 % versus 56 and 59 %). The addition of NPK in a poor environment treated with deltamethrin also noticeably impacted the average weight of the females and their soluble protein content.

On the other hand the environments containing 5 g/l of plant matter (PM2) provided enough food (proteins, glucids and lipids) for the larvae and allowed an emergence rate of 74 %. Both NPK concentrations brought nutritional supplement compared with plant matter alone and resulted in the emergence of a greater number of adults (74 % versus 84 and 93 %). Actually, nitrogen, phosphorus and potassium are not directly assimilated by the mosquito larvae. However the three minerals enhance the development of bacteria, algae and fungi, increasing the food biomass of the breeding sites. Insofar as MV2 environments alone or in combination with NPK did not generate feeding competition, the impact of treatment went along a more traditional selection scheme by decreasing the number of adult emergences. Also if the females from those sites were characterized by the greatest average weights of the study, quite paradoxically the protein contents of the females PM2 + NPK1 and PM2 + NPK2 mixtures were not more important than for those emerging in PM2 alone. In such environments, rich in organic matter, mosquito larvae produce the protein amount they need, the rest of the food being turned into lipids (fatty acids, phospholipids and sterols) that can constitutes up to 50 % of the insect body (Gilbert & Chino, 1974). In any case the gain of proteins and/or lipids in VKPR \(An.\ gambiae\) females does not show any significant incidence on the expression of resistance to deltamethrin.

The carbon (C) and potassium (K) concentrations in water where 5 g of plant matter were added were high whereas mineral nitrogen contents \((\text{NH}_4^+ + \text{NO}_3^-)\) and phosphorus (P) remained low (Darriet et al., 2010a). A mixture made of plant matter and NPK fertilizer adds up the supplies each part brings into an organic-mineral complex rich in nutrients. Nitrogen is the most abundant atom next to carbon in the chemistry of the living. Among most insects, the fertility of females is often correlated with the amount of nitrogen in the ingested food (Scriber & Slansky, 1981; Ridsdill-Smith, 1991). Phosphorus is absorbed by the cells for the synthesis of the nucleic acids, and phospholipids whereas potassium is more specifically involved in the making of proteins (Madigan & Martinko, 2007). Mosquito larvae ingest large quantities of organic matter in their diet, which results in a reduction of turbidity in the water and allows organic nitrogen to proceed to mineralization \(via\) the nitrifying bacteria (Darriet & Corbel, 2008b).

In sites lacking organic matter and unable to ensure the feeding of a great number of mosquito larvae, the addition of NPK is not enough to compensate the nutritional deficit. Paradoxically, treating these unfavorable sites – by eliminating only part of the larvae of \(An.\ gambiae\) VKPR – allows the surviving ones to consume the food available and keep growing into adult stages. This selective pressure generated by the insecticide, making breeding sites formerly improper to mosquito development into a productive one, can be only observed in regions where \(An.\ gambiae\) is resistant to pyrethroids. Indeed, in our study we have observed that treating similar breeding sites at the
same dosage of deltamethrin eliminated all the susceptible larvae from Kisumu strain. In the place where *A. gambiae* shows limited susceptibility to conventional insecticides (pyrethroids, organophosphorus and carbamates), it is now necessary to use, at least in rice fields, insecticides that are active on new targets, or combinations of insecticides with different modes of action, that can eliminate resistant mosquitoes (Darriet et al., 2010b; Darriet & Chandre 2011).

Finally this study shows us how the not so well thought-out use of pesticides and fertilizers in agriculture could impact the mosquito environment and even generates new ecological systems beneficial to the proliferation of mosquitoes. They cause a growing eutrophication of the natural breeding sites and select for resistance mechanisms to insecticides, already widespread among nuisance and disease vectors mosquitoes.

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