International Journal of Remote Sensing
Vol. 27, No. 3, 10 February 2006, 535–548

Patterns of irrigated rice growth and malaria vector breeding in Mali using multi-temporal ERS-2 synthetic aperture radar

M. A. DIUK-WASSER†, G. DOLO‡, M. BAGAYOKO§, N. SOGOBA¶, M. B. TOURE, M. MOGHADDAM, N. MANOUKIS, S. RIAN, S. F. TRAORE and C. E. TAYLOR

†Department of Epidemiology and Public Health, Yale School of Medicine, New Haven, Connecticut

‡Department of Organismic Biology, Ecology, and Evolution, University of California, Los Angeles, California

§Malaria Research and Training Center, Faculté de Médecine, de Pharmacie et d'Odonto-Stomatologie, Université du Mali, Bamako, Mali

¶Jet Propulsion Laboratory, Pasadena, California

(*Received 28 May 2004; in final form 25 January 2005*)

We explored the use of the European Remote Sensing Satellite 2 Synthetic Aperture Radar (ERS-2 SAR) to trace the development of rice plants in an irrigated area near Niono, Mali and relate that to the density of anopheline mosquitoes, especially *An. gambiae*. This is important because such mosquitoes are the major vectors of malaria in sub-Saharan Africa, and their development is often coupled to the cycle of rice development. We collected larval samples, mapped rice fields using GPS and recorded rice growth stages simultaneously with eight ERS-2 SAR acquisitions. We were able to discriminate among rice growth stages using ERS-2 SAR backscatter data, especially among the early stages of rice growth, which produce the largest numbers of larvae. We could also distinguish between basins that produced high and low numbers of anophelines within the stage of peak production. After the peak, larval numbers dropped as rice plants grew taller and thicker, reducing the amount of light reaching the water surface. ERS-2 SAR backscatter increased concomitantly. Our data support the belief that ERS-2 SAR data may be helpful for mapping the spatial patterns of rice growth, distinguishing different agricultural practices, and monitoring the abundance of vectors in nearby villages.

1. Introduction

Malaria is one of the most common and devastating diseases in the tropics. The situation is especially acute in sub-Saharan Africa, where 250–450 million clinical cases and over one million deaths occur each year (Greenwood and Mutabingwa, 2002). The disease is transmitted by mosquitoes of the genus *Anopheles*; in sub-Saharan Africa the principal vectors are *An. gambiae* and *An. funestus*. Throughout this region their presence depends largely on suitable habitats and standing water for their larvae to develop. Remote imaging can be used to characterize climates and to identify bodies of water. Accordingly, it shows promise as an important tool for monitoring and potentially controlling vector numbers (Hay *et al*. 2000, Rogers *et al*.

*Corresponding author. Email: maria.diuk@yale.edu

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160500104350

2002). However, vector abundance is just one of the parameters influencing malaria transmission and the effect on vector control on reducing malaria risk is not straightforward (Diuk-Wasser *et al*. 2005). Nearly all such studies to date have used optical satellite data, such as Landsat sensor data.

Our goal in this study was to determine whether radar data, in particular data derived from the European Remote Sensing Satellite 2 Synthetic Aperture Radar (ERS-2 SAR), can be used to identify and monitor environmental factors that influence malaria vector populations. SAR has several advantages over Landsat sensor data. In particular, images from ERS-2 SAR used in this study are available every 35 days and are not affected by clouds. This provides a regular and highly reliable source of satellite data from remote tropical regions. Other studies have shown that SAR is sensitive to a number of features thought to be important for mosquito production, e.g. areas cultivated with rice (Kurosu *et al*. 1995, Kurosu *et al*. 1997, Panigrahy *et al*. 1997, Okamoto and Kawashima 1999), different cultural practices of rice cultivation (Chakraborty *et al*. 1997), local variation in planting dates, and several agronomic parameters of the developing rice (Le Toan *et al*. 1997, Liew *et al*. 1998). In particular, SAR can detect differences in rice plant height and biomass due to growth or variety, factors known to affect larval densities through changes in light, temperature, mechanical obstruction, and nutritional state of the water (Chandler and Highton 1975, 1976, Snow 1983).

Our study site was in the Niger Delta Region of Mali near the city of Niono. Niono is one of the most important rice producing areas of Mali. The irrigated fields there produce very large numbers of anopheline mosquitoes—sometimes exceeding 550 bites per person per night in the villages adjacent to the fields. As a result, malaria prevalence is high (34% of the inhabitants each year). Several large studies of mosquitoes and malaria have been conducted in this area (see Dolo *et al*. 2004, Sissoko *et al*. 2004, Diuk-Wasser *et al.* 2005), so, there is a repository of information about the malaria vectors, although very little work has been done with remote sensing.

Rice fields near Niono are not always suitable for breeding anophelines. *An. gambiae*, the most abundant vector in our study area, thrives in the exposed shallow, inundated fields during ploughing, transplanting, and the first weeks of the growing period. When the rice becomes tall and dense it shades the water so the sun-loving larvae cannot develop, and numbers decline. After harvest the fields are again exposed to sunlight, so if there is any water left, the conditions may become suitable for the mosquitoes once more (Chandler and Highton 1975, 1976, Mather 1984, Snow 1983, Asimeng and Mutinga 1993, Takagi *et al*. 1996, Mutero *et al*. 2000).

In a previous study we explored how Landsat 7 ETM+ data might be used to identify the different stages of rice production in the fields surrounding Niono (Diuk-Wasser *et al*. 2004). Our investigations have built on the pioneering work of Byron Wood and colleagues in Northern California (Wood *et al*. 1991a, b, 1992). Using Landsat sensor data, they found higher anopheline larval production in rice fields that were located near bloodmeal sources (e.g. pastures with cattle) and that showed early season canopy development. That suggested we should find more or less similar phenomena, though in a very different geographical setting, and using not Landsat sensor data, but SAR data. Here we extended those studies to see:

1. How SAR might be used to identify the stages of rice production in an African country.
2. To explore the ability of SAR imaging to capture the abundance of anopheline vectors of malaria in villages situated near these rice fields.

3. To examine the relationship between ERS-2 SAR backscatter and biophysical parameters known to affect anopheline breeding from previous reports.

2. Materials and methods

2.1 *Study area*

It is located in the Northern Sudan region of Mali, at 14°18′ N and 5°59′ W, about 330 km north-east of Bamako. The Office du Niger in the Niono district of Mali constitutes the largest rice irrigation project in Mali, overseeing irrigation from a dam on the Niger river. The climate of Niono is typical of the Sahel, with a wet season of about three months (July to September), a cold dry season (October to February), and a hot dry season (March to June). The average annual precipitation is 400 mm. The short rainy season normally restricts mosquito breeding in the region, but the introduction of irrigation schemes and construction of dams provides additional semi-permanent water surfaces, which can serve as mosquito breeding sites.

2.2 *Rice cultivation*

The schedules of rice cultivation near Niono differ a bit from one group of fields to another, largely because the beginning of each cropping cycle is scheduled according to the water distribution scheme (see, for example, Klinkenberg *et al.* 2003.). Most fields are cultivated once a year, during the rainy season, though some farmers cultivate a second crop during the dry season (between January and May). Breeding sites for anopheline mosquitoes are therefore available throughout most of the year (Klinkenberg *et al.* 2003. Dolo *et al.* 2004).

The International Rice Research Institute (IRRI, 2002) has proposed that nine standard growth stages of rice maturation can be identified. We were able to distinguish only four of them (plus the pre-cultivation and after-harvest periods) with remote sensing. We categorized the typical cycle into: (0) fallow or ploughed fields; vegetative period (45–60 days), which can be subdivided into (1) early vegetative stage—including seedling transplanting and tilling and (2) late vegetative or stem elongation stage; (3) reproductive stage (20–30 days)—during which plants stop growing and orient towards the development of the panicles and grains; (4) ripening stage (35–65 days), when plants senesce and their water content drops; and (5) an after-harvest period when the fields lie fallow.

In the autumn 2001 cropping season we recorded information on rice growth stages in 164 basins near nine different villages. Basins are subdivisions of rice fields. Each basin is approximately 1500 m^2 in size, is managed more or less independently and shows a single (or clearly dominant) rice growth stage. In the spring 2002 season we re-sampled 47 of the basins that had been sampled earlier (those with double cropping) and added 31 basins from four additional villages. There was a sensor malfunction in the ERS-2 SAR satellite during March 2002, so only two ERS-2 SAR acquisitions matched our spring larval collections.

2.3 *Satellite data pre-processing*

We acquired nine ERS-2 SAR precision corrected images (PRI), four during autumn 2001, four during spring 2002, and one on 9 September 2002. The ERS-2

SAR sensor acquires SAR data at C-band (5.3 GHz), VV polarization and at an incidence angle of 23°. Pixel size of the PRI product was 12.5m. We re-sampled all ERS-2 scenes by a factor of 2 to reduce speckle noise, using a nearest neighbour algorithm. We calibrated the ERS-2 images by converting the digital number (DN) values to normalized cross sections in dB units using equation (1):

$$\sigma^o = 10 \log 10\left(DN^2/K\right) \tag{1}$$

where σ^o is the backscatter coefficient, and K is a calibration constant, equal to 9,440,000 for the Italian Processing and Archiving Facility that supplied our images (Appendix D in Laur *et al*. 2002).

We then co-registered all ERS-2 SAR images to a reference Landsat 7 ETM+ image from 18 September 2000 (RMS between 0.3 and 0.6) using a nearest neighbour algorithm. This base image had been previously geometrically calibrated by registration to ground reference data using 80 ground control points, with a root mean square (RMS) error of 0.1 pixels.

2.4 *Ground data collection*

We recorded larval numbers and rice growth stages coincident with the 2nd, 3rd and 4th ERS-2 SAR acquisitions in the autumn of 2001 and spring of 2002. The first ERS-2 SAR acquisition was scheduled before the first larval collection in order to observe whether backscatter had a generally increasing or decreasing trend when we started collecting larvae. A larval sample consisted of the total numbers collected in 20 dips evenly spaced around each basin, using a standard Bioquip mosquito larvae dipper (350 ml white plastic container with a wooden handle), as recommended by Service (1993). In a sub-sample, we discriminated among the anopheline species collected (*An. gambiae* s.l., *An. funestus, An. pharoensis* and *An. rufipes*) using descriptions from the keys in Gillies and DeMeillon (1968). We collected a total of 7330 anopheline larvae during both seasons. Due to poor preservation of some specimens, we were only able to distinguish among species in a sub-sample of 3567 larvae, yielding 89.7% *An. gambiae* s.l., 7% *An. pharoensis*, 3% *An. rufipes* and 0.3% *An. funestus*. We present here the results for all anopheline species pooled (numbers were insufficient to analyse each separately). Therefore, the patterns we observed are mostly representative of *An. gambiae*. Data presented are the average of two larval collections per ERS-2 SAR acquisition, one obtained three days before, and a second, three days after, the date of the satellite overpass.

We performed an additional study in the autumn of 2002 to provide more detail on how rice growth stages and ERS-2 backscatter relate to agronomic parameters associated with larval production. We selected 23 sites at different rice growth stages that were homogenous over a large area (at least 2500 m^2) and mapped them using GPS. In each site, we randomly selected a location away from the site's borders and delimited a 1 m^2 plot in which we measured the height of the rice plants, the depth of the water at the centre and collected the aerial portion of all rice plants. We measured fresh biomass immediately after harvest and dry biomass after oven-drying for three days.

2.5 *Data analysis*

We used a generalized estimating equation (GEE) algorithm (STATA 6.0, Stata Corporation 1999) to examine the relationship between larval samples, rice growth stages and ERS-2 SAR backscatter over three subsequent months and two seasons. GEEs are based on generalized linear models (GLM), which are a unified framework that allows a relaxation of the assumptions of linear models by restructuring the relationship between the linear predictor and fit. GEE models or 'panel data' analyses look at a sampling unit, the 'panel,' on more than one occasion, allowing the user to specify the within-group correlation structure for the panels (Hardin and Hilbe 2003). In our study, the sampling units were the rice basins and the time intervals were the 35 days between ERS-2 SAR acquisition dates. We treated rice stage as a categorical variable and used a forward coding system to compare the mean larval counts in one rice stage to the mean in the next (adjacent) level.

Because there were no ERS-2 SAR data acquired on 18 March, we only fit the regression models to the autumn 2001 data. In addition, some of the basins were drained prematurely due to channel maintenance work at the end of the spring 2002 cropping season, when most of the rice was in the ripening phase. We used this as an opportunity to evaluate whether ERS-2 SAR data is sensitive to the presence/absence of water under the canopy of plants in the later developmental stages, by comparing the radar response of flooded and drained rice paddies.

3. Results

3.1 *Rice stage and larval production*

Larval counts were significantly different among rice growth stages for both the autumn 2001 and spring 2002 seasons ($X^2 = 109.14$, df = 5, $p < 0.0001$ in the autumn, $X^2 = 90.53$, df = 5, $p < 0.001$ in the spring) (figure 1). There was high within-stage variability, with stage 1 (early vegetative) the most productive and variable stage. Using forward difference coding, we then compared each stage with the adjacent one. Stages 2, 3 and 4 were not significantly different from each other in the autumn and only stages 0 and 5 could be significantly distinguished from the intermediate ones in the spring.

ERS-2 SAR responses varied significantly with rice growth stage ($X^2 = 182.93$, df = 5, $p < 0.0001$) for the autumn 2001 season, with all stages significantly different from the adjacent ones (figure 2). Ricefields at stage 2 (late vegetative) showed the lowest response. During spring 2002, there was a sensor malfunction in March 2002. We could therefore not obtain backscatter data for rice at stage 1. We showed the resulting backscatter for the others stages in figure 2, although the lack of data on rice stage 1 and high variability of stage 0 precludes clear interpretation.

In the spring, basins suffering from water shortage during the ripening stage ($n = 42$) showed a significantly lower radar response than normally flooded ones ($n = 19$) in a one-tailed *t*-test with unequal variances ($t = 2.66$, df = 44.44, $p < 0.01$). These basins also showed significantly lower larval counts (one-tailed *t*-test with unequal variances, $t = 4.37$, df = 18.8, $p < 0.001$).

Although adjacent rice stages could generally be distinguished by their radar responses, rice fields at early stages were sometimes indistinguishable from those at later ones (e.g. stage 0 with stage 3 or 4 in figure 2). To overcome this limitation, we examined temporal profiles of mean backscatter to distinguish between rice planted at different times or 'cohorts' (as in Diuk-Wasser *et al.* 2004). Since we did not have information on the exact planting dates, we labelled the basins that were at stage 1 on 20 August as 'late' ($n = 38$); those at stage 2 as 'on time' ($n = 90$) and those

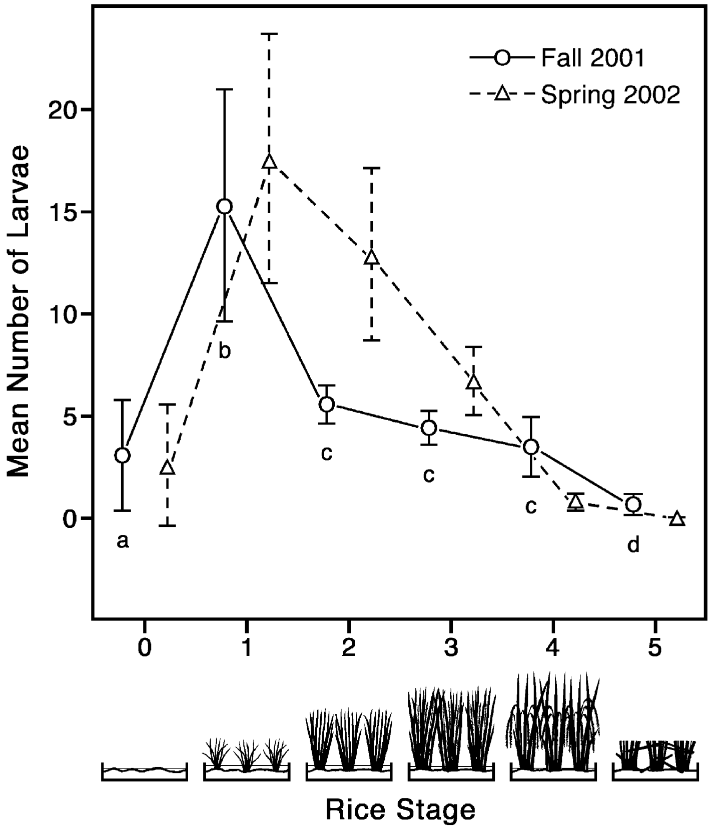

Figure 1. Mean number of anopheline larvae collected during the autumn 2001 and spring 2002 rice cropping seasons. Rice stages are: 0 (fallow or ploughing); 1 (early vegetative); 2 (late vegetative); 3 (reproductive); 4 (ripening); 5 (harvested). Rice stages not significantly different from the adjacent stage(s) are labelled with the same letter (fall 2001). In the spring 2002 season, only stages 0 and 5 were significantly different from the intermediate ones (see details in text). Error bars show 95% confidence interval (CI) of the mean.

already at stage 3 as 'early' ($n = 25$) (figure 3). Both 'on time' and 'late' basins reached the lowest backscatter when they were at stage 2 (in 20 August and 24 September, respectively).

We then enquired whether we could distinguish between those fields producing high vs. low larval numbers at stage 1 by their temporal profile of mean backscatter. After ranking all the basins at stage 1 ('late' basins) by their larval production, we calculated separate means for the top seven basins (producing 50% of all larvae) and the lower 31 ones. The high producing basins had a different temporal profile than the low producing ones (figure 4). Similarly to 'on time' basins, high producing 'late' basins showed the lowest radar response at stage 2, while low producing ones reached their lowest at stage 1.

Radar response values extracted from 23 sites showed a positive relationship with fresh biomass ($F = 8.13$, df = 22, $p = 0.01$, $R^2 = 0.28$) (figure 5) and rice plant height ($F = 20.53$, df = 22, $p < 0.001$, $R^2 = 0.49$) (figure 6). Lower response from maturing vs. reproductive plants could be explained by their lower relative water content (figure 7).

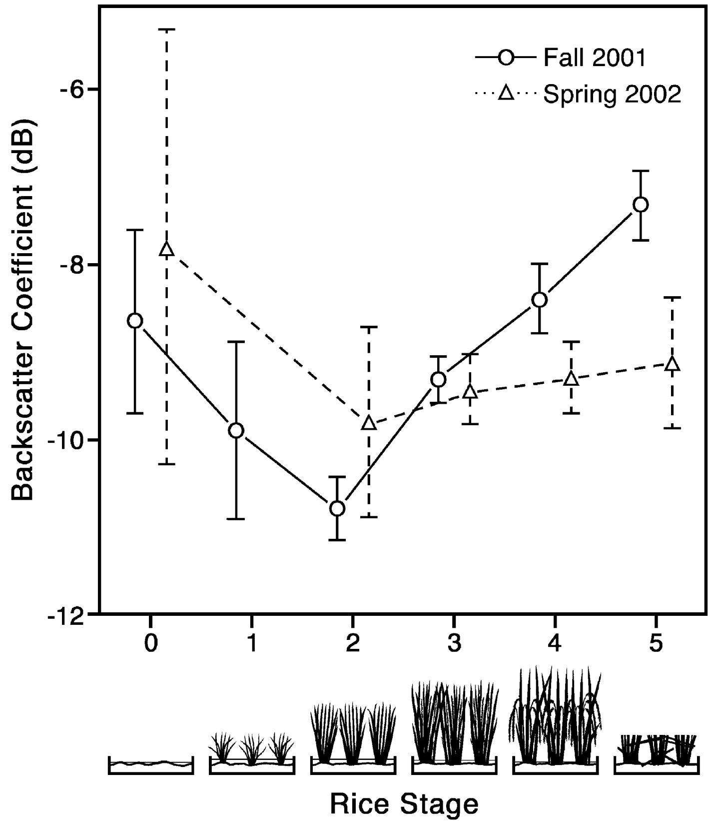

Figure 2. Mean ERS-2 synthetic aperture radar (SAR) backscatter of the rice growth stages present at the time of the ERS-2 SAR acquisition, during the autumn 2001 and spring 2002 cropping seasons. Due to sensor malfunction, no ERS-2 SAR backscatter data were collected during March 2002, when all records of rice at stage 1 occurred.

4. Discussion

ERS-2 SAR was sensitive to differences in rice growth stages relevant to anopheline larval production, with the early vegetative stage being both the most productive and variable. We were able to further discriminate a group of basins with very high mosquito numbers within those at the early vegetative stage based on their temporal profile of their radar response. Rice biomass and height were positively correlated to radar response. We discuss below the changes occurring at each rice growth stage, focusing on the autumn 2001 data, with a more complete dataset.

Before transplanting (stage 0), fields laid fallow or were being ploughed, with very low larval counts. From stage 0 to 1 (flooding and transplanting), there was a sharp drop in the radar response, most likely caused by the flooding of the fields, since the dielectric rough surface represented by the non-flooded fallow land or pasture would produce a higher backscatter than the smooth flooded surface. Our results agreed with previous studies that found larger numbers of *An. gambiae* larvae during the early stages of the rice growth cycle, which later decreased with canopy development (Chandler and Highton 1975, 1976, Snow 1983, Asimeng and Mutinga 1993, Mutero *et al.* 2000).

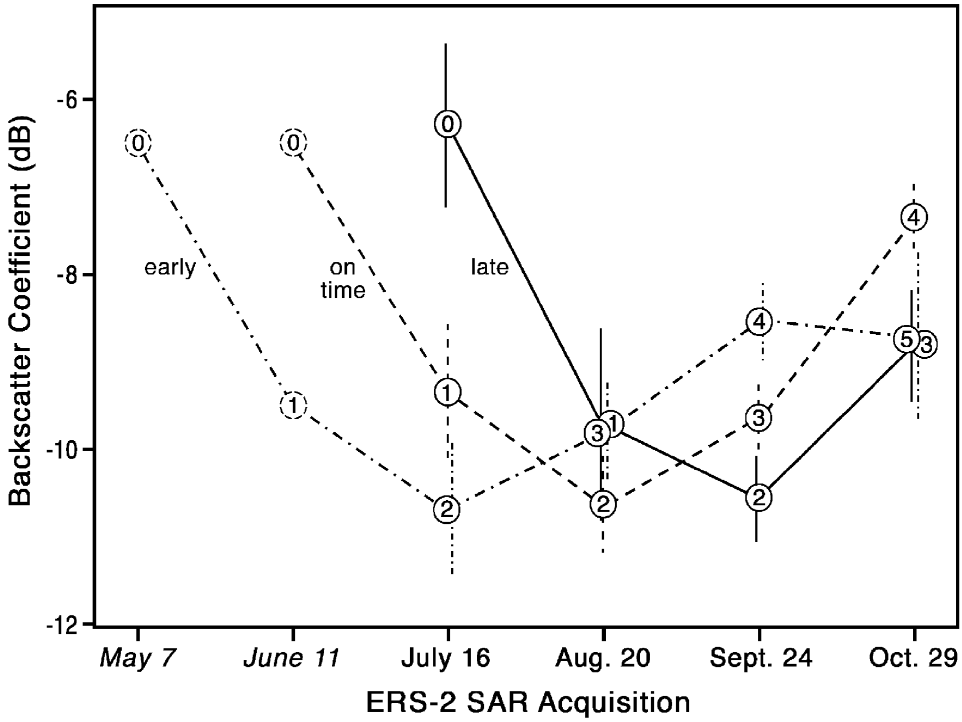

Figure 3. Multitemporal radar response of basins starting cultivation at different times during the fall 2001 season. Rice stages at each date are indicated in the grey boxes. The basins were classified according to the stage recorded on 20 August—rice labelled as 'late' ($n = 18$) was at stage 1 on 20 August; 'on time' ($n = 90$) was at stage 2 and 'early' rice ($n = 25$) was at stage 3. Greyed out are estimated trajectories for earlier stages of the 'on time' and 'early' rice, based on the signature observed for the 'late' rice.

Unlike other reports in the literature (e.g. Le Toan 1996), we found that mean backscatter continued to decrease in most fields after transplanting. This was probably due to the draining of some fields between stages 1 and 2, a procedure used by some farmers to stimulate the production of side-shoots or tillers. Draining the fields would reduce the reflectivity of the surface that caused the double-bounce effect, reducing the overall response. Typically, double bounce from water surface is much stronger than volume scattering alone, even if volume scatterers are getting denser in more advanced rice stages. Volume, or diffuse, scattering, causes the microwave energy to be scattered in all directions, and so a small portion makes it back to the radar receiver. Conversely, double bounce is the result of two specular reflections, in which all of the energy is focused in a given direction (backscatter). So even if the total scattered power in the diffuse case is larger, the portion of it in the backscatter direction is still small compared to double bounce.

Draining of the fields would result in a large number of sunlit pools and puddles, which form ideal breeding habitats for *An. gambiae* s.l. (Mogi and Miyagi 1990, Mogi 1993). It was then important to distinguish the fields that were drained from those that were not. Although we did not have field data to distinguish these two groups, high- and low- larval producing fields had very different temporal profiles of their radar response, which may indicate differences in their cultivation patterns. High producing fields showed an initially higher radar response, which decreased

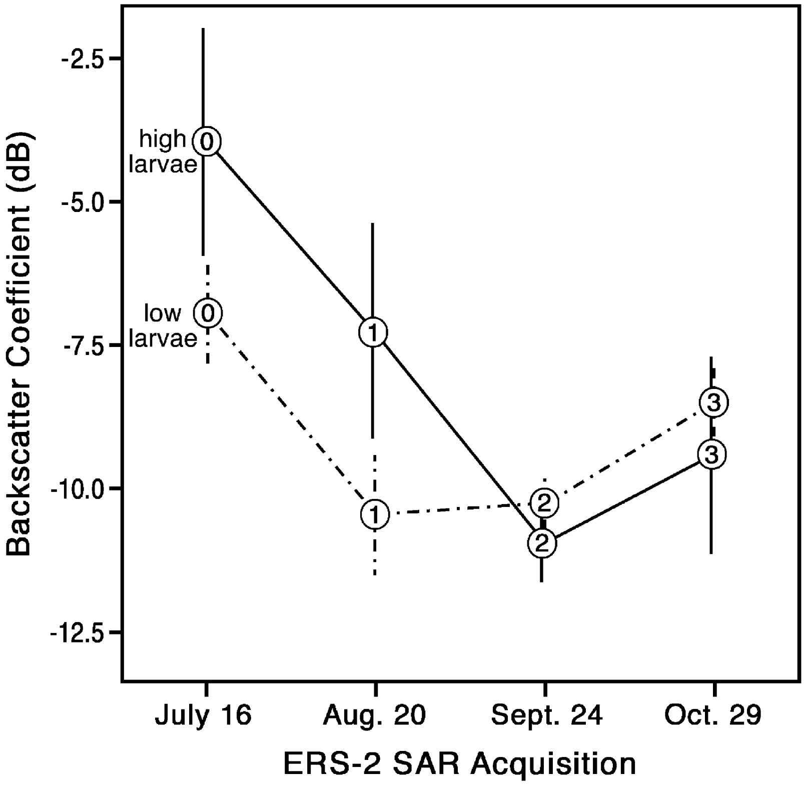

Figure 4. Multitemporal signature of 'late' basins showing high or low numbers of larvae when at stage 1 (20 August). Rice stages at each date are indicated in the grey boxes. The high production group is the mean of the seven top-ranking basins that concentrate 50% of the larval production during the peak production stage, while the low production one is the mean of the remaining 31 basins.

steadily up to stage 2. In contrast, low producing fields showed a drop in the response at stage 1 and then steadily increased (figure 4). The drop in radar response at stage 2 may indicate that those high producing fields were drained and therefore hosted large number of larvae in the remaining pools. Further study is necessary including field data on drainage status of the paddies.

Differences in cultivation practices may partially explain the lower dynamic range in this study compared to that of Le Toan *et al.*'s (1997) study, due mainly to different minimum backscatter values (−11 dB in our study, −18 dB in Le Toan's). In our study area, fields were only flooded for a very short time before transplanting, which resulted in a combination of flooded and non-flooded pixels in any one basin or group of basins from which we extracted SAR values. In contrast, to rice was sowed rather than transplanted in Le Toan *et al.*'s (1997) study, which would extend the time of very low radar backscatter due to a calm water surface.

A significant advance in the capability to distinguish between different land cover types and rice stages is expected with a new generation of polarimetric satellites (ENVISAT and RADARSAT-2). RADARSAT-1 has been successfully used to study rice (Shao *et al.* 2001) and malaria (Kaya *et al.* 2004). Although Ribbes and Le Toan (1999) found that RADARSAT-1 data had lower dynamic range than

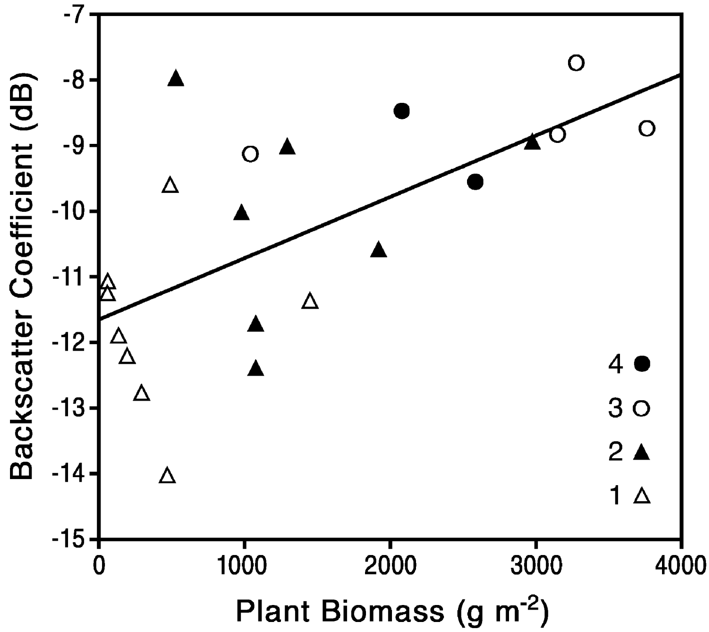

Figure 5. ERS-2 SAR backscattering coefficient as a function of fresh biomass in 21 samples collected on 9 September 2002 around Niono, Mali. Symbols represent rice stages. *Note*: Two outliers are excluded from the graph for clarity: one was at stage 3 and had a fresh biomass of 5665.1 g/m^2 and the other one was at stage 2 and had a dry biomass of 1617.4g/m^2.

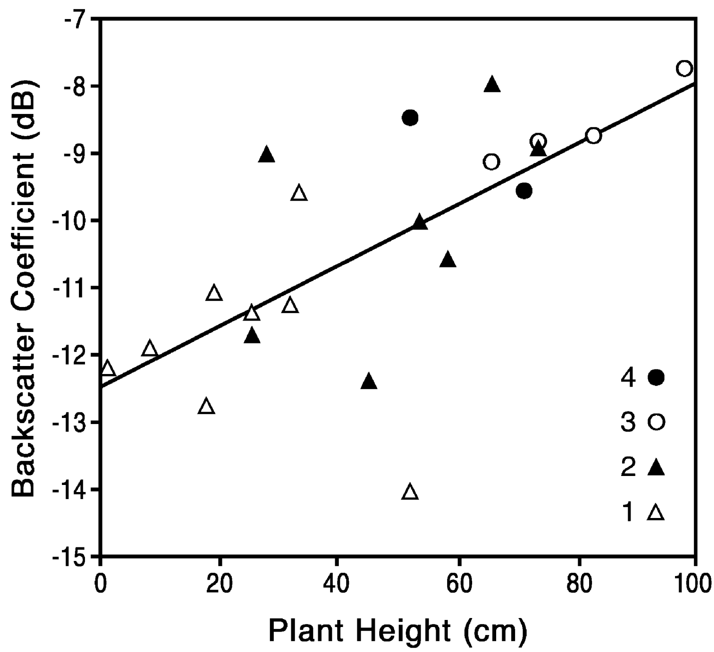

Figure 6. ERS-2 SAR backscattering coefficient as a function of above-water plant height in 21 samples collected on 9 September 2002 around Niono, Mali. Symbols represent rice stages. *Note*: Two outliers are excluded from the graph for clarity: one was at stage 3 and had a fresh biomass of 5665.1 g/m^2 and the other one was at stage 2 and had a dry biomass of 1617.4g/m^2.

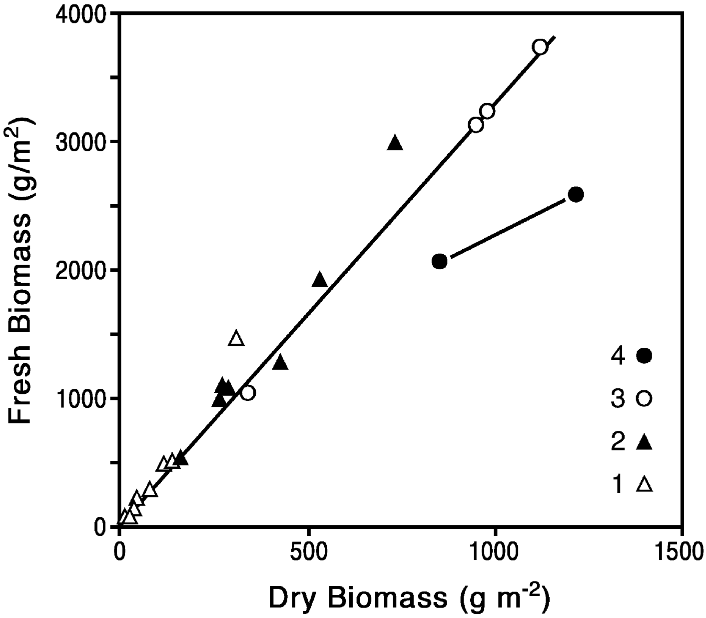

Figure 7. Fresh vs. dry biomass. The regression line was fitted only to samples at stages 1 to 3. The two samples at stage 4 were not included since rice plants had already partially dried out before being sampled and they are therefore not expected to fit the same relationship. Symbols represent rice stages. *Note*: Two outliers excluded from the graph for clarity: one was at stage 3 and had a fresh biomass of 5665.1 g/m^2 and the other one was at stage 2 and had a dry biomass of 1617.4g/m^2.

ERS, more work need to be done with the complementarity of C-HH and C-VV polarization. Multi-frequency and multi-polarization SAR will certainly offer the best rice discriminating capability and reduce the number of data acquisitions required for accurate discrimination accuracy (Shao *et al.* 2001).

We designed our research to look at changes in larval numbers with rice development. The significant (although weak due to small sample size) relationship between SAR backscatter and structural features of the rice plants (biomass and height) provide evidence that we are measuring a biologically significant parameter that affects larval habitat preferences (Chandler and Highton 1975, 1976, Snow 1983). Future research should more explicitly address the effects of draining the fields in both larval numbers and radar response. Intermittent irrigation has been proposed as a method of larval control. A recent review (Keiser *et al.* 2002) concluded that this could be effective if the fields are drained of all surface water. This requirement may be relaxed if the large numbers of larvae in leftover puddles have low survivorship due to regular disturbance (as in Mutero 2000). Keiser *et al.* (2002) found no negative effects on yield of intermittent irrigation, and proponents of the System of Rice Intensification (SRI) even claim that it can greatly increase rice yields. This is subject to current debate (Surridge 2004).

Our findings agreed with the studies of Wood *et al.* (1991a, b, 1992) using Landsat, in that it is easier to discriminate between differentially-producing rice fields early in the cropping season. These studies, however, focused on discriminating high and low producing fields in California, which were all planted at about the same date. In their case, spectral differences were mainly related to different early developmental rates. Our work in Africa showed an additional level of complexity, i.e. inter-field differences in cultivation schedule, due to the spatial variability in developmental patterns, rice variety and growing conditions. In order to identify rice growth stages using ERS-2 SAR in such a system, it was first necessary to separate the fields into cohorts, which we achieved by using multi-temporal ERS-2 SAR data.

Our studies relate two traditionally separate lines of research—studies of African rice field mosquitoes, based mostly on fieldwork, and studies with remote sensing of rice plants using Landsat or SAR. The latter have been conducted primarily in Asia. Our results should provide background for mapping high anopheline producing fields, to explore the potential of intermittent irrigation, and to validate these methods in other irrigation schemes.

Acknowledgments
We would like to thank the collaboration of the Niono Health Center, the Office du Niger, the Institute d'Economie Rurale, Niono supervisors and village guides, and Yeya Touré, Robert Gwadz and the members of the MRTC GIS Laboratory in Bamako for their support. Special thanks to Dr.Yongkang Xue, Dr. Seydou Doumbia and Dr. Sassan Saatchi for their very productive comments and Gina Hendricks for help with image registration.

Financial support
This work was supported by the National Institute of Health (NIH), the National Aeronautic and Space Administration through an Interagency Agreement Y3-AI-5059-03 with the National Institute of Allergy and Infectious Diseases and WARDA Africa Rice Center. The ERS-2 SAR scenes were provided by the European Space Agency as part of the ESA EO Exploitation Project # C1P.1089.

References

Asimeng, E.J. and Mutinga, M.J., 1993, Effect of rice husbandry on mosquito breeding at Mwea rice irrigation scheme with reference to biocontrol strategies. *Journal of the American Mosquito Control Association*, **9**, pp. 17–22.

Chakraborty, M., Panigraphy, S. and Sharma, S.A., 1997, Discrimination of rice crop grown under different cultural practices using temporal ERS-1 synthetic aperture radar data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **52**, pp. 183–191.

Chandler, J.A. and Highton, R.B., 1975, Succession of mosquito species (Diptera: Culicidae) in rice fields in the Kisumu area of Kenya, and their possible control. *Bulletin of Entomological Research*, **65**, pp. 295–302.

Chandler, J.A. and Highton, R.B., 1976, Breeding of Anopheles-Gambiae Giles (Diptera-Culicidae) in Rice Fields in Kisumu Area of Kenya. *Journal of Medical Entomology*, **13**, pp. 211–215.

Diuk-Wasser, M.A., Bagayoko, M., Sogoba, N., Dolo, G., Touré, M.B., Traoré, S.F. and Taylor, C.E., 2004, Mapping rice field anopheline breeding habitats in Mali, West Africa, using Landsat ETM+ sensor data. *International Journal of Remote Sensing*, **25**, pp. 359–376.

Diuk-Wasser, M.A., Toure, M.B., Dolo, G., Bagayoko, M., Sogoba, N., Traore, S.F., Manoukis, N. and Taylor, C.E., 2005, Vector abundance and malaria transmission in rice-growing villages in Mali. *American Journal of Tropical Medicine and Hygiene*, **72**(6), pp. 725–731.

Dolo, G., Briet, O.J.T., Dao, A., Traore, S.F., Bouare, M., Sogoba, N., Niare, O., Bagayogo, M., Sangare, D., Teuscher, T. and Toure, Y.T., 2004, Malaria transmission in relation to rice cultivaton in the irrigated Sahel of Mali. *Acta Tropica*, **89**, pp. 147–159.

GILLIES, M.T. and DEMEILLON, B., 1968, *The Anophelinae of Africa South of the Sahara (Ethiopian Zoogeographical Region)*, 2nd edition (Johannesburg: South African Institute for Medical Research).

GREENWOOD, B. and MUTABINGWA, T., 2002, Malaria in 2002. *Nature*, **415**, pp. 670–672.

HARDIN, J.W. and HILBE, J.M., 2003, *Generalized Estimating Equations* (Florida: Chapman and Hall/CRC.).

HAY, S.I., OMUMBO, J.A., CRAIG, M.H. and SNOW, R.W., 2000, Earth observation, geographic information systems and *Plasmodium falciparum* malaria in Sub-Saharan Africa. In *Remote sensing and geographic information systems in epidemiology*, S.I. Hay, S.E. Randolph and D.J. Rogers (Eds), pp. 173–215 (London: Academic Press).

KAYA, S., SOKOL, J. and PULTZ, T.J., 2004, Monitoring environmental indicators of vector-borne disease from space: A new opportunity for RADARSAT-2. *Canadian Journal of Remote Sensing*, **30**, pp. 560–565.

KEISER, J., UTZINGER, J. and SINGER, B.H., 2002, The potential of intermittent irrigation for increasing rice yields, lowering water consumption, reducing methane emissions, and controlling malaria in African rice fields. *Journal of the American Mosquito Control Association*, **18**, pp. 329–340.

KLINKENBERG, E., TAKKEN, W., HUIBERS, F. and TOURÉ, Y.T., 2003, The phenology of malaria mosquitoes in irrigated rice fields in Mali. *Acta Tropica*, **85**, pp. 71–82.

KUROSU, T., FUJITA, M. and CHIBA, K., 1995, Monitoring of rice crop growth from space using the ERS-1 C-Band SAR. *IEEE Transactions on Geoscience and Remote Sensing*, **33**, pp. 1092–1096.

KUROSU, T., FUJITA, M. and CHIBA, K., 1997, The identification of rice fields using multi-temporal ERS-1 C band SAR data. *International Journal of Remote Sensing*, **18**, pp. 2953–2965.

LAUR, H., BALLY, P., MEADOWS, P., SANCHEZ, J., SCHAETTLER, B., LOPINTO, E. and ESTEBAN, D., 2002, Derivation of the backscattering coefficient σ^{o} in ESA ERS SAR PRI products. Available online at: http://earth.esa.int/ESC2/0_esc.html (accessed 20 April, 2004).

LE TOAN, T., RIBBES, F., WANG, L.F., FLOURY, N., DING, K.H., KONG, J.A., FUJITA, M. and KUROSU, T., 1997, Rice crop mapping and monitoring using ERS-1 data based on experiment and modeling results. *IEEE Transactions in Geosciences and Remote Sensing*, **35**, pp. 41–56.

LIEW, S.C., KAM, S.P., TUONG, T.P., CHEN, P., MINH, V.Q. and LIM, H., 1998, Application of multitemporal ERS-2 synthetic aperture radar in delineating rice cropping systems in the Mekong River Delta, Vietnam. *IEEE Transactions in Geosciences and Remote Sensing*, **36**, pp. 1412–1420.

MATHER, T.H., 1984, *Environmental management from vector control in ricefields* (Rome: Food and Agriculture Organization of the United Nations).

MOGI, M., 1993, Effect of intermittent irrigation on mosquitos (Diptera, Culicidae) and larvivorous predators in rice fields. *Journal of Medical Entomology*, **30**, pp. 309–319.

MOGI, M. and MIYAGI, I., 1990, Colonization of rice fields by mosquitos (Diptera, Culicidae) and larvivorous predators in asynchronous rice cultivation areas in the Philippines. *Journal of Medical Entomology*, **27**, pp. 530–536.

MUTERO, C.M., BLANK, H., KONRADSEN, F. and VAN DER HOEK, W., 2000, Water management for controlling the breeding of Anopheles mosquitoes in rice irrigation schemes in Kenya. *Acta Tropica*, **76**, pp. 253–263.

OKAMOTO, K. and KAWASHIMA, H., 1999, Estimation of rice-planted area in the tropical zone using a combination of optical and microwave satellite sensor data. *International Journal of Remote Sensing*, **20**, pp. 1045–1048.

RIBBES, F. and LE TOAN, T., 1999, Rice field mapping and monitoring with RADARSAT data. *International Journal of Remote Sensing*, **20**, pp. 745–765.

ROGERS, D.J., RANDOLPH, S.E., SNOW, R.W. and HAY, S.I., 2002, Satellite imagery in the study and forecast of malaria. *Nature*, **415**, pp. 710–715.

SERVICE, M.W., 1993, *Mosquito Ecology: Field Sampling Methods*, 2nd edition (London and New York: Elsevier Applied Science).

SHAO, Y., FAN, X., LIU, H., XIAO, J., ROSS, S., BRISCO, B., BROWN, R. and STAPLES, G., 2001, Rice monitoring and production estimation using multitemporal RADARSAT. *Remote Sensing of Environment*, **76**, pp. 310–325.

SISSOKO, M.S., DICKO, A., BRIET, O.J.T., SISSOKO, M., SAGARA, I., KEITA, H.D., SOGOBA, M., ROGIER, C., TOURE, Y.T. and DOUMBO, O.K., 2004, Malaria incidence in relation to rice cultivation in the irrigated Sahel of Mali. *Acta Tropica*, **89**, pp. 161–170.

SNOW, W.F., 1983, Mosquito production and species succession from an area of irrigated rice fields in the Gambia, West Africa. *Journal of Tropical Medicine and Hygiene*, **86**, pp. 237–245.

SURRIDGE, C., 2004, Feast or Famine? *Nature*, **428**, pp. 360–361.

TAKAGI, M., SUGIYAMA, A. and MARUYAMA, K., 1996, Effect of rice plant covering on the density of mosquito larvae and other insects in rice fields. *Applied Entomology and Zoology*, **31**, pp. 75–80.

WOOD, B.L., BECK, L.R., WASHINO, R.K., PALCHICK, S.M. and SEBESTA, P.D., 1991, Spectral and spatial characterization of rice field mosquito habitat. *International Journal of Remote Sensing*, **12**, pp. 621–626.

WOOD, B.L., BECK, L.R., WASHINO, R.K., HIBBARD, K.A. and SALUTE, J.S., 1992, Estimating high mosquito-producing rice fields using spectral and spatial data. *International Journal of Remote Sensing*, **13**, pp. 2813–2826.

WOOD, B., WASHINO, R., BECK, L., HIBBARD, K., PITCAIRN, M., ROBERTS, D., REJMANKOVA, E., PARIS, J., HACKER, C., SALUTE, J., SEBESTA, P. and LEGTERS, L., 1991, Distinguishing high and low anopheline-producing rice fields using remote sensing and GIS technologies. *Preventive Veterinary Medicine*, **11**, pp. 277–288.