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Ecological assessment of *Phragmites australis* wetlands using multi-season SPOT-5 scenes

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ABSTRACT

Ecologists and conservationists need accurate and replicable tools for monitoring wetland conditions in order to develop and implement adaptive management strategies efficiently. The Rhone Delta (Camargue) in southern France encloses 9200 ha of fragmented reed marshes actively managed for reed harvesting, waterfowl hunting or cattle grazing, and holding significant numbers of vulnerable European birds. We used multi-season SPOT-5 data in conjunction with ground survey to assess the predictive power of satellite imagery in modelling indicators of reed structure (height, diameter, density and cover of green/dry stems) relevant to ecosystem management and bird ecology. All indicators could be predicted accurately with a combination of bands (SWIR, NIR) and indices (SAVI, OSAVI, NDWI, DVI, DVW, MSI) issued from scenes of March, June, July, September or December and subtraction between these. All models were robust when validated with an independent set of satellite and field data. The high spatial resolution of SPOT-5 scenes (pixel of 10 X 10 m) permits the monitoring of detailed attributes characterizing the reed ecosystem across a large spatial extent, providing a scientifically-based, replicable tool for managers, stakeholders and decision-makers to follow wetland conditions in the short and long-term. Combined with models on the ecological requirements of vulnerable bird species, these tools can provide maps of potential species ranges at spatial extents that are relevant to ecosystem functioning and bird populations.

KEY-WORDS: Camargue, ecosystem health; GLM modelling; multispectral indices; multitemporal imagery; *Phragmites australis*; vegetation structure, SPOT-5 satellite; state indicators; wetland monitoring.

1. Introduction

Although wetlands support high biodiversity and provide an extensive range of public goods and services to humankind, they are among the most threatened habitats in the world (Williams, 1993; Dudgeon et al., 2006). Their high rate of disappearance has prompted the development of remotely-sensed techniques for mapping their distribution, but little has been done for monitoring their state of health, especially at extensive spatial extents that are relevant to ecosystem functioning and species populations. Ecologists and conservationists need accurate and replicable tools for monitoring wetland conditions in order to develop and implement adaptive-management strategies efficiently (Ostendorp et al., 1995; Kerr & Ostrovsky, 2003).

Common reed *Phragmites australis* (Cav. Trin. ex Steudel) is the most widely distributed flowering plant on earth (Marks et al., 1994; Güsewell & Klötzli, 2000). It typically grows in or near freshwater, brackish, and alkaline wetlands along a gradient from deep water (> 2m) to terrestrial (< 1m below substrate) conditions (Clevering, 1998). It often dominates the area it occupies to form dense stands in floodplains, lowland shallow lakes and along natural river channels or irrigation canals. Reed stands are considered as undesirable invaders in some areas of North America where non-endemic genotypes are proliferating, but have high conservation and socio-economic value throughout in Europe due to specific vulnerable bird species and various traditional, recreational and commercial activities (Güsewell & Klötzli, 2000; Ludwig et al., 2003; Valkamaa et al., 2008).

Common reed can resist fire, frost, high pH, water deficit and salt, but has a low tolerance for wave and current action (Marks et al., 1994; Pagter et al., 2005). Each spring, annual shoots emerge from perennial underground rhizomes, growing up to 3-4 m tall in optimal conditions. These vertical stems produce leaves, flower, and eventually set seed. The stems die in early winter but stand as rigid canes for several months (Burgess & Evans, 1989). Density may reach 200 (wet stands) or 300 (dry stands) shoots per meter square (Hara et al., 1993), leading to a rapid accumulation of decaying matter, which contributes to drying out of the reedbed that eventually evolves towards scrub and woodland (Granéli, 1989; Cowie et al., 1992). Common reed is relatively intolerant of summer mowing and cattle grazing (van Deursen & Drost, 1990), but cutting or burning the dry stems in winter will slow down this hydroseral process (Burgess & Evans, 1989; Bedford, 2005). Common reed can tolerate a constant salinity of up to 22.5 g/L, but shoot height, diameter and density will start decreasing above 5 g /L (Lissner & Schierup, 1997). Decreased reed density and height also result from water deficit (Engloner, 2009). Optimal conditions for reed growth are freshwater bodies exhibiting a seasonal fluctuations of 30-cm in water levels (Deegan et al., 2007). A vigourous reedbed will have homogeneous vegetation cover, tall green stems and a 2:1 ratio of dry to green stems. Permanent flooding without water renewal will result in lower shoots, a higher dry-to-green-stem ratio, and eventually a clumpy distribution of reeds following the death of rhizome buds and roots (Armstrong et al., 1996). Winter burning or cutting will have a positive impact on shoot density and diameter, while reducing shoot height and increasing plant richness the next spring (Granéli, 1989; Cowie et al., 1992). A recent review of the factors influencing reed structure, growth and biomass is provided by Engloner (2009).

Habitat selection by breeding birds is tightly related to structural components of the reed ecosystem throughout Europe (Leisler et al., 1989; Boar, 1992; Jedraszko-Dabrowska, 1992; Graveland, 1999; Martinez-Vilalta et al., 2002; Gilbert et al., 2005; Polak et al., 2008). Ecological requirements of reed bird species in southern France have been well identified (Barbraud et al., 2002; Poulin & Lefebvre, 2002; Poulin et al., 2002; 2005; 2009): the great reed warbler (GRW) *Acrocephalus arundinaceus* breeds in harvested or non-harvested reedbeds where shoot diameter is above 6 mm (or 195 cm in height); the moustached warbler (MW) *A. melanopogon* prefers areas with a high proportion of stems with flower head (one-year old reed) intermingled with other emergent plants; the bearded tit (BT) *Panurus biarmicus* is most abundant in reedbeds having high densities of dry and thin shoots, which often reflects a stress response to permanent flooding; the colonial purple heron (PH) *Ardea purpurea* nests in flooded reedbeds having tall and thick shoots with a 2:1 dry:green stem ratio; the Eurasian bittern (EB) *Botaurus stellaris* is either found in harvested areas (no dry stems) with homogeneous vegetation cover or in non-harvested reedbeds characterized by numerous small open-water areas used for foraging, both including small patches of reed cut two winters ago (1:1 dry:green stem ratio).

The Rhone delta (Camargue) in southern France encompasses 145 000 ha including 9200 ha of reed marshes that are actively water managed for various socio-economic uses (Mathevet et al., 2007). These marshes enclose over 50% of the French population of three vulnerable reed birds in Europe: the moustached warbler, the purple heron and the Eurasian bittern. Conflicts over water management among users, the presence of salt in the water table together with the foreseen impacts of climate change justify the development of replicable and robust tools for monitoring the state of health of these reedbeds. Remote sensing appeared as the most appropriate approach for monitoring this quasi monospecific and fragmented habitat spread over a large area and partially located on private properties with difficult access (Davranche et al., 2009b). In this study, we used multispectral and multi-seasonal data in conjunction with ground surveys to assess the predictive power of SPOT-5 scenes in modelling reedbed features that are relevant to bird ecological requirements and management practices. The ultimate goal is to produce replicable maps of reed-stand conditions to orient management and conservation actions over the long term.

2. Methods

2.1 Study area

The Camargue reedbeds are found within water bodies of various types (marsh, pond, lagoon, river, canal), size (from < 1 to > 2000 ha), hydrology (permanent or temporary flooding with stable or fluctuating water levels) and underground salinity (from 0.5 to 30 g/L). Spatial distribution of reedbeds was previously assessed with SPOT-5 scenes and field data using a binary classification-tree algorithm (Fig. 1). The resulting maps for two successive years lead to an overall accuracy of 99% and 98% respectively (Davranche et al., 2009b). Water levels in most of these reedbeds are managed to improve yield of socio-economic activities such as waterfowl hunting, winter-reed cutting, cattle grazing, fishing and nature conservation (Mathevet et al., 2007). For instance, harvested reedbeds are typically flooded during the growing season (March to June) and drained in winter to facilitate access and reduce impact of cutting engines on the rhizomes, whereas hunting marshes are permanently flooded or drained in spring only. These activities have a direct impact on reed structure through the creation of open-water areas for hunting (by cattle grazing or removal of the rhizomes) and the withdrawing of dry stems by cutting. They also affect reed structure indirectly through water management which, combined with rainfall and the presence of salt in the water table, will affect reed growth and the overall state of health of the plant formation. The climate is Mediterranean with mild and windy winters and hot and dry summers. Mean annual rainfall over the last 30 years is 579 ± 158 (SD) mm, being concentrated in spring and autumn, with large intra- and inter-annual variations (Chauvelon, 2009). Total rainfall was 664 and 411 mm in 2005 and 2006, respectively.

2.2 Indicators of reed condition

Hawke & José (1996) have suggested four indicators of reedbed health: height, diameter, and density of reed along with presence of shrubs. We have selected five additional criteria easily measurable in the field that are indicative of stand condition and associated with ecological requirements of birds and reed harvesters (Table 1). Height and diameter of green stems, as well as density of flower heads, can vary on a yearly basis and are tightly related to hydrological conditions (fluctuations in water levels and salinity). Density of reeds and the ratio of dry-to-green reeds are also affected by hydrology, but more directly by management practices such as reed cutting, burning or grazing. Low and high reed density can both reflect ecosystem degradation and this parameter must be interpreted along with reed height or diameter for condition assessment. Reed-cover homogeneity and scrub encroachment are indicative of a degraded reedbed evolving towards open water or woodland, respectively. Two of these criteria, plant richness and shrub encroachment, could not be predicted in this study following their low levels in our study area.

2.3 Field data

Water and vegetation measurements were taken in June and July at 39 reedbed sites (training sample) in 2005 and 21 sites (validation sample) in 2006 (Fig.1). Selection of study sites resulted in a compromise between admittance, accessibility, and getting a representative sample of reedbeds based on aerial photographs and videos collected during aerial surveys. At each site, one sampling plot of 20 X 20 m corresponding to four pixels of a SPOT-5 scene was located within a homogeneous area representative of a larger zone and located at least 70 m from the border to reduce edge effects in spectral responses. Sampling plots were geolocated with a GPS (Holux GR-230XX) of 2-5 m accuracy using the average value obtained from the centre of the plot at three meters above ground to limit the echo caused by tall reeds. Water level, plant cover and floristic composition were estimated along two diagonals 28-m long crossing the entire plot. Water levels were systematically estimated with a rule every 4 m along each diagonal and in the centre of the plot ($N = 17$). We recorded whether this measure was taken above reeds or bare ground and used the proportion of readings taken in reeds as a degree of reed-cover homogeneity. This distinction was not made in 2006, hence we used half the 2005 plots for the training sample and applied the other half on the 2006 scenes for model validation, assuming that this environmental parameter varied little over one year. Reed density, height and diameter were measured within four quadrats of 50 X 50 cm per plot located at seven meters from the centre of the plot in each cardinal direction. Reed density corresponds to the total number of green and dry stems inside the quadrat. Among dry reeds, we distinguished whole stems with flower heads (one-year reed) from flowerless or broken stalks. Whole stems with or without flowers were aggregated during the 2006 field survey, hence we used half the 2005 data for validation on the 2005 scenes. Reed height and diameter were measured on two green and four dry ‘average’ stems inside the quadrats on both years.

2.4 SPOT-5 data

SPOT-5 scenes centred on the Rhone delta were acquired on 30 December 2004, 17 March, 19 May, 18 June, 31 July and 21 September 2005 through the SPOT Image Programming Service (Copyright CNES). These periods were selected based on key events in the phenology and water management of reedbeds (Davranche et al., 2009b). For model validation, we used images from

18 December 2005, 16 March, 29 May, 23 June, 24 July and 15 October 2006, as no scene was available in September. SPOT-5 scenes have 10-m pixel resolution and four spectral bands: B1 (green: 0.50-0.59 μ m), B2 (red: 0.61-0.68 μ m), B3 (near infrared NIR: 0.79-0.89 μ m) and B4 (short-wave infrared SWIR: 1.58-1.75 μ m). Radiometric corrections were performed using, the Second Simulation of the Satellite Signal in the Solar Spectrum (6S), developed by Vermote et al. (1997). This atmospheric model predicts the sensor signal assuming cloudless atmosphere, taking into account the main atmospheric effects (gaseous absorption by water vapour, carbon dioxide, oxygen and ozone; scattering by molecules and aerosols) and lead to a mean error of 0.7% per band (Davranche et al., 2009a). The corrected scenes were projected to Lambert conformal conic projection datum NTF (Nouvelle Triangulation Française) using a second-order transformation and nearest-neighbour re-sampling (Davranche et al., 2009a), and georeferenced to a topographic map at 1:25 000 scale using ground control points (RMSE < one pixel). Mean reflectance values at the locations of the field plots were extracted for each band using the 'Spatial Analyst' of ArcGIS version 9.2 (Environmental Systems Research Institute). Eleven multispectral indices among the most commonly found in the literature (Table 2) were calculated for each scene, as well as multitemporal indices obtained by subtracting two monthly values from a same indice.

2.5 Model calibration and validation

The six scenes provided 15 possible combinations of subtractions between two dates and yielded 315 explanatory variables when multiplied by the four bands and 11 indices. A pre-selection of conceptually meaningful explanatory variables based on environmental resilience of reeds was made based on the following assumptions: (1) under similar abiotic conditions, reed parameters should not vary annually and the remotely-sensed data useful for describing these parameters should have a similar constancy; (2) reed parameters are mostly influenced by human intervention, which is site specific and unlikely to affect distinctly a large number of marshes on a given year. We compared the degree of relationships (R^2) and the mean value (*t*-test) of each predictive variable from the 39 study plots in 2005 and 2006, and conservatively used $P > 0.01$ as threshold value for variable selection with both tests.

We built Generalized Regression Models with a forward-stepwise procedure in *Statistica* version 8.0 (StatSoft Inc.) to predict reed parameters from the remotely-sensed data. For each computed model, the regression analysis was rerun excluding any selected variable, one by one, to verify that model fit was not improved when the variables selected automatically were replaced by two or more other variables. Goodness-of-fit of the model was assessed by calculating the coefficient of determination (R^2) and the normalized root-mean-square error (NRMSE) between the predicted and observed 2005 values (training sample). Predictive accuracy of the model was assessed by calculating R^2 and NRMSE between the predicted and observed 2006 values when applying the 2005 model. This validation approach, based on a dataset independent from the training sample, is considered as the most compelling demonstration of model usefulness (Mac Nally & Fleishman, 2004; Thomson et al., 2007). Means of predicted and observed values from the validation sample were further compared using Student's *t*-tests (or Welch's t-test if unequal variances) to determine whether field calibration would be required in future model application.

3. Results

3.1 Pre-selection of predictive variables

Fifty-three variables did not differ significantly between 2005 and 2006 and were selected for model building. Their distribution according to each month and band/index is shown in Figs. 2-3. March and July were the most frequently selected months, followed by June and December with May showing the least consistent value (Fig. 2). The NIR and SWIR bands and the DVI, SAVI, OSAVI were the most stable, with many multispectral indices showing less consistent reflectance values than single bands (Fig. 3).

3.2 Modelling of reed indicators

All seven reed indicators were modelled with two bands and six indices issued from three to five scenes (dates), involving subtraction of bands and/or indices between these (Table 3). SAVI and NDWI were the most commonly selected indices, with NIR and SWIR being the only selected bands. DVI was selected for modelling dry- and green-reed density and DVW for modelling reed-cover homogeneity. All these models were accurate when applied to the 2006 independent dataset (Table 3, Fig. 4-6). Reed height was particularly easy to predict, as revealed by the high correlation between the predicted and observed values (Fig. 4) and by the numerous significant single- and two-date models that arose during the model selection process. Density of green and dry stems and their ratio showed significantly or nearly significantly different means in 2006, suggesting that these parameters might require a field calibration (Table 3, Fig. 5). Actually, a similar reed density can exhibit different spatial patterns from the regular distribution of shoots to sparsely-distributed dense tussocks, which probably explains the lower predictive power of these models. Reed-cover homogeneity could be accurately and repeatedly predicted, in spite of the low sample size and the fact that these data were originally meant to reflect bathymetric variation rather than vegetation coverage (Fig. 6). Modelling of this parameter would, however, certainly benefit from an increased sampling effort with measurements taken every meter.

3.3 Model application

Height of reed stem is a good indicator of stand condition. It is correlated with stem diameter and leaf size (respectively $R = 0.82$ and 0.72, d.f. = 39, $P < 0.001$), as well as flower production and resistance to breakage (van der Toorn & Mook 1982; Boar, 1992). It evolves rapidly following modifications in water management, especially under brackish conditions. The largest continuous reed area in the Camargue, the Charnier-Scamandre site, is located along a salinity gradient in its northernmost part, with mean underground salinity varying from 27 to 3 g/L from west to east (Fig. 7). Mapped reed height in 2005 covaries with this salinity gradient. Predicted reed height ranged from 29 cm to 309 cm per pixel, and from 132 to 222 cm per hydrological unit. Overall, these values were relatively similar in 2006 (respectively 19-309, 117-220), although some hydrological units exhibited a different pattern between years owing to a different water management (Fig. 7). This spatio-temporal variation in reed height can help orient management options whether in terms of defining optimal hydrological regimes, protecting areas for vulnerable birds (e.g. great reed warbler and purple heron) or selecting areas for reed harvesting.

4. Discussion

We demonstrate that multi-spectral and seasonal imagery can be a powerful tool for monitoring fine-scale variations in reedbed attributes relevant to bird ecology and habitat management. Studies using scenes from multiple dates often rely on a single value (eg: mean reflectance or principal-component axes) for model building (Suárez-Seoane et al., 2002; Wiegand et al., 2008). Monthly subtraction between bands and indices issued from different images associated with specific phenological stages of reed was a key feature of the models developed in this study, allowing these bands and indices to carry a lot more information than what they were originally created for.

Although SPOT-5 scenes were radiometrically corrected, many bands and indices showed inconsistent values between years. Their pre-selection, based on their reliability for describing the selected reed parameters under different environmental and hydrological conditions, appears as a necessary step of model development. For instance, NDVI was stable in July only and was not selected in any of the final models, highlighting the usefulness of exploring the potential of other, less well-known indices. This statement certainly holds for any remote-sensing application in ecological studies that are currently largely restricted to the use of NDVI (Pettorelli et al., 2005). The most useful indices for modelling reed attributes in this study were the SAVI, NDWIs (NDWIF, MNDWI), and DVI for height, diameter and density of green reeds, in addition to MSI for the ratio dry/green reeds and DVW for reed-cover homogeneity. SAVI accounts for the spectral contribution of soil and is recommended for predicting biomass when soil exposure is high relative to vegetation cover (Zhang *et al*, 1997). This index, designed to eliminate soil-induced variation, was mostly selected in December and March when vegetation coverage of reed stands is minimal. SAVI was always combined with indices (NDWIs and MSI) or bands involving the NIR and/or SWIR in our models. These bands provide a pigment-independent quantitative estimate of vegetation water content, and are influenced by leaf structure, leaf dry matter, canopy matter, canopy structure and leaf area index (Ceccato et al, 2002; Cheng et al, 2006). DVI has been shown to be a good predictor of deciduous plantations and is considered more sensitive to vegetation density than other indices (Franklin, 2001). In our model, DVI was most useful for predicting density of green and dry stems and their ratio. DWIs and MSI probably reflect dry matter and water content, with the advantage of the NDWI not being saturated during the growing period like other vegetation indices. Gao (1996) suggests that the NDWI, which increases from dry soil to free water, should be used in combination with NDVI. The DVW combines both indices to reinforce the perception of free water bodies (Gond *et al*, 2004), and is then particularly well-suited to model reed-cover homogeneity which reflects the proportion of open-water areas inside reedbeds.

Thorough field campaigns to develop accurate and robust remote-sensing tools that do not require field sampling when re-applied (or limited field work for calibration), is a desirable approach for ecosystem long-term monitoring. Application of the models developed in this study will allow detecting local or regional reedbed degradation in order to orient stakeholders toward more sustainable management practices. In cases of conflicts around the water resource among landowners, users and nature conservationists, they will provide an unbiased source of information to address the impact of various management options for collective-decision making. Combined with models on the ecological requirements of vulnerable-bird species, they have the potential to provide precise estimates of potential species ranges and their evolution in the long term. Human activities are increasing in intensity and extent, ensuing habitat loss and degradation that impair ecosystem function and reduce the value of ecosystem services for humans. The need to detect and predict changes in natural ecosystems in general and wetlands in particular has never been greater.

5. Conclusion

Our study shows that stand condition of reed marshes can be mapped accurately over a major river delta, providing a powerful and robust monitoring tool for evidence-based habitat management. This study highlights the potentialities of multiseasonal and multi-spectral data in ecological applications. The increased availability of powerful statistical techniques, geographic information systems (GIS) and satellite sensors is opening a new field for monitoring the health of ecosystems across large geographic areas (Guisan & Zimmermann, 2000; Kerr & Ostrovsky, 2003). The high spatial resolution of SPOT-5 scenes makes it possible to obtain detailed attributes of ecosystem characterization that can be modelled across large spatial extents (Wulder et al., 2005) abolishing the recurrent scale mismatch between field and remotely sensed-data.

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Table 1

Selected indicators of reed conditions and their relationship (+ or −) with reedbed health, requirements of birds and reed harvesters, and management practices. See text for bird species' abbreviations.

Indicator	Reedbed health	Ecological needs		Ecosystem impacts		
		Bird	Harvester	Cutting	Burning	Grazing
Green reed height	+	+ *PH*	+	−	−	−
Green reed diameter	+	+ *GRW, PH*	+	+	+	−
Green reed density	+/−	− *EB*	+	+	+	+
Dry reed density	−	+ *BT*	−	−	−	−
Flower head density	+	+ *MW*	+	−	+	−
Ratio dry/green shoots	−	*EB ,PH*	−	−	−	−
Reed cover homogeneity	+	+ *EB*	+			−
Plant richness	−	+ *MW*	−	+	+	+
Scrub encroachment	−		−	−	−	−

Table 2

Multispectral indices used in this study.

Index	Formula	References
SR - Simple Ratio	B2/B3	Pearson & Miller, 1972
VI - vegetation index	B3/B2	Lillesand & Kiefer, 1987
DVI - Differential Vegetation Index	B3-B2	Richardson & Everitt, 1992
MSI - Moisture Stress Index	B4/B3	Hunt & Rock, 1989
NDVI - Normalized Difference Vegetation Index	(B3-B2)/(B3+B2)	Rouse et al., 1973
SAVI - Soil Adjusted Vegetation Index	1.5*(B3-B2)/(B3+B2+0.5)	Huete, 1988
OSAVI – Optimized SAVI	(B3-B2)/(B3+B2+0.16)	Rondeaux *et. al.*, 1996
NDWI – Normalized Difference Water Index	(B3-B4)/(B3+B4)	Gao, 1996
NDWIF – Normalized Difference Water Index of Mc Feeters	(B1-B3)/(B1+B3)	Mc Feeters, 1996
MNDWI – Modified Normalized Difference Water Index	(B1-B4)/(B1+B4)	Hanqiu, 2006
DVW – Difference between Vegetation and Water	NDVI - NDWI	Gond *et al*, 2004

Table 3

Best models for each reed indicator with their goodness-of-fit (2005) and predictive accuracy (2006) estimated from the correlations between predicted and observed values (*: $P \leq 0.05$, **: $P \leq 0.01$, ***: $P \leq 0.001$) and the normalized root-mean-square error. P values from *t*-tests comparing the predicted and observed mean values are also provided for 2006. Variables are labeled as follow: B4/09 = reflectance of the SWIR band in September; SAVI/12-03 = difference between the SAVI of December and March.

Indicator	Best model	2005		2006		
		R^2	NRMSE	R^2	NRMSE	*t*-test
Green-reed height	141.71 + 414.50 * SAVI/12-03 – 224.01 * B4/03-07 – 145.43 * MSI/06 + 613.57 * B4/09	0.67***	12%	0.56***	16%	0.611
Green-reed diameter	4.02 + 10.60 * OSAVI/12-03 + 4.91 * MNDWI/06 + 7.26 * SAVI/06	0.45***	19%	0.28*	23%	0.722
Green-reed density	310.45 - 2258.65 * DVI/12 + 1356.02 * B3/03-06	0.50***	15%	0.18*	29%	0.001
Dry-reed density	-83.10 + 1885.33 * B3/12-07 - 826.50 * DVI/03-06 - 1054.36 * NDWIF/03-07 - 3247.56 * B3/03-07	0.67***	17%	0.35**	28%	0.052
Dry/green-reed ratio	-2.01 + 52.39 * SAVI/12-03 – 19.48 / OSAVI/12-07 – 9.02 * DVI/03-06 – 24.67* NDWIF/03-07	0.71***	13%	0.52***	32%	0.017
Flowered-reed density	-13.05 + 168.62 * SAVI/12 - 233.99 * B3/03-06	0.56***	22%	0.56***	22%	0.829
Reed-cover homogeneity	152.81 - 103.79 *B4/12-03 + 117.85 * DVW/03-07 + 202.70 * NDWIF/06	0.88***	10%	0.23*	22%	0.645

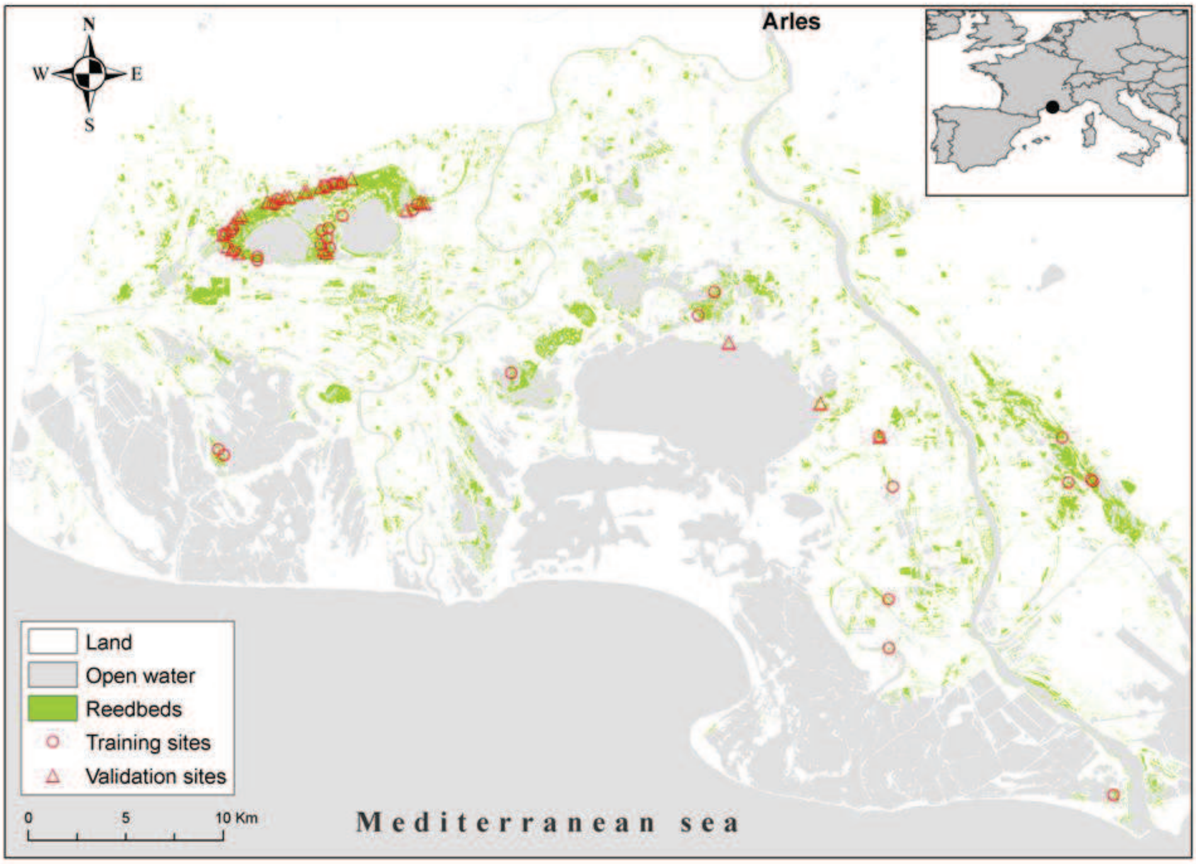

Fig 1. Reedbed distribution in the Camargue with the location of the training (2005) and validation (2006) field plots.

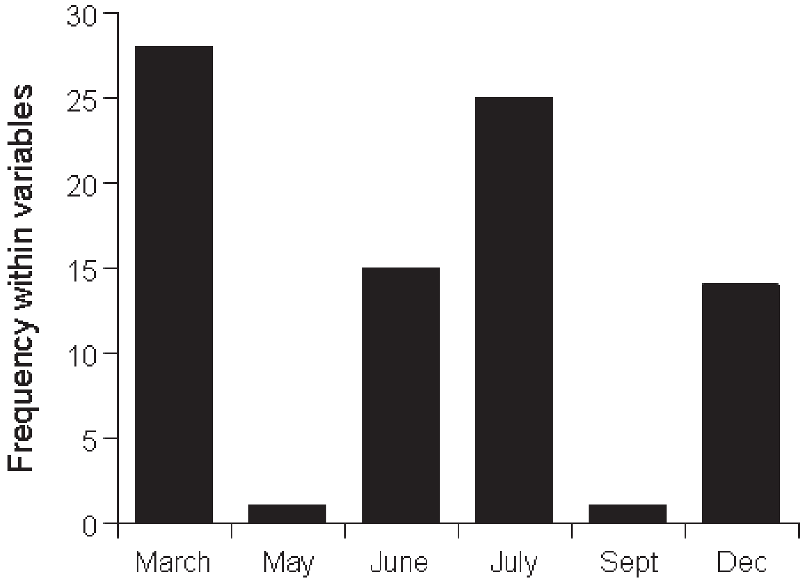

Fig.2. Contribution of each scene to the 53 pre-selected predictive variables.

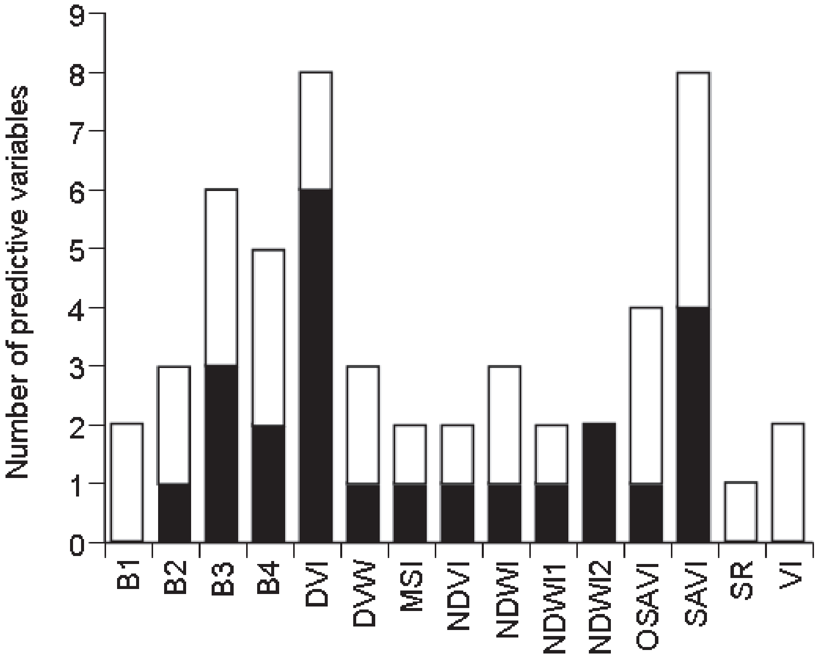

Fig. 3. Contribution of each band and indice to the 53 pre-selected predictive variables. Black columns refers to single-date variables and white columns to two-date variables.

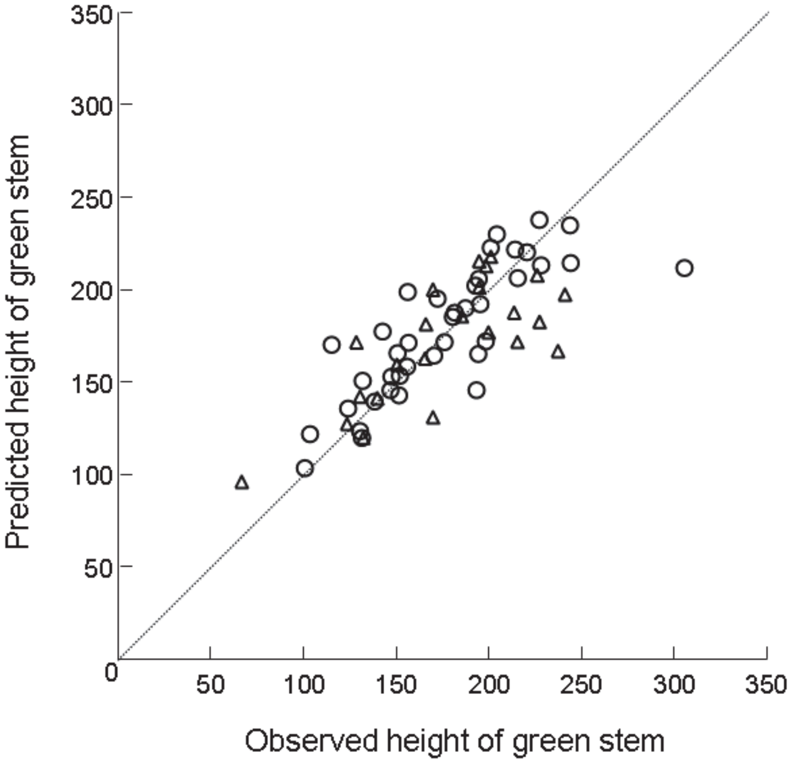

Fig. 4. Correlation between the predicted and observed values for green-stem height in 2005 (o) and 2006 (Δ) using the best 2005 model.

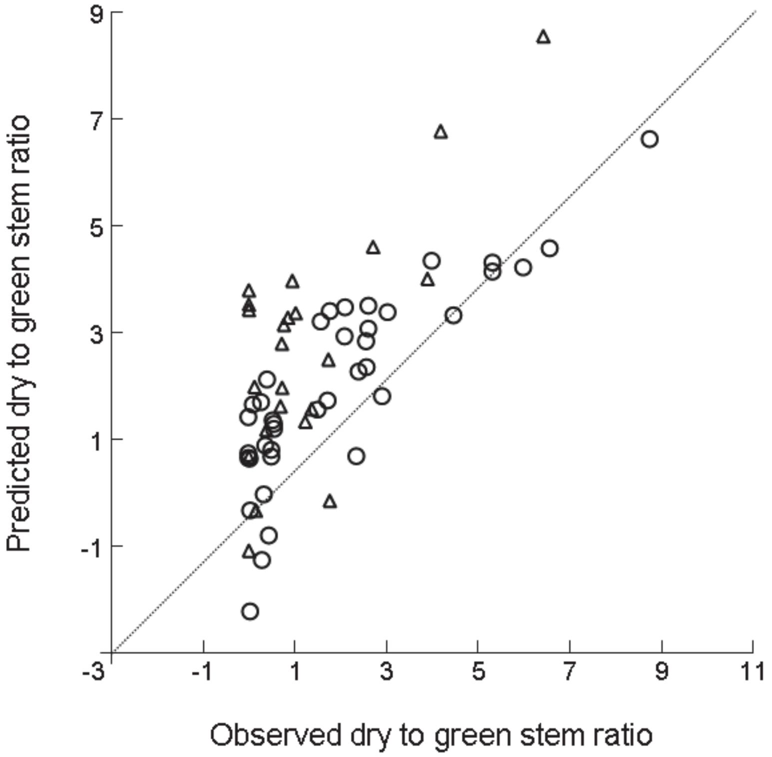

Fig. 5. Correlation between the predicted and observed values for the dry/green-stem ratio in 2005 (O) and 2006 (Δ) using the best 2005 model.

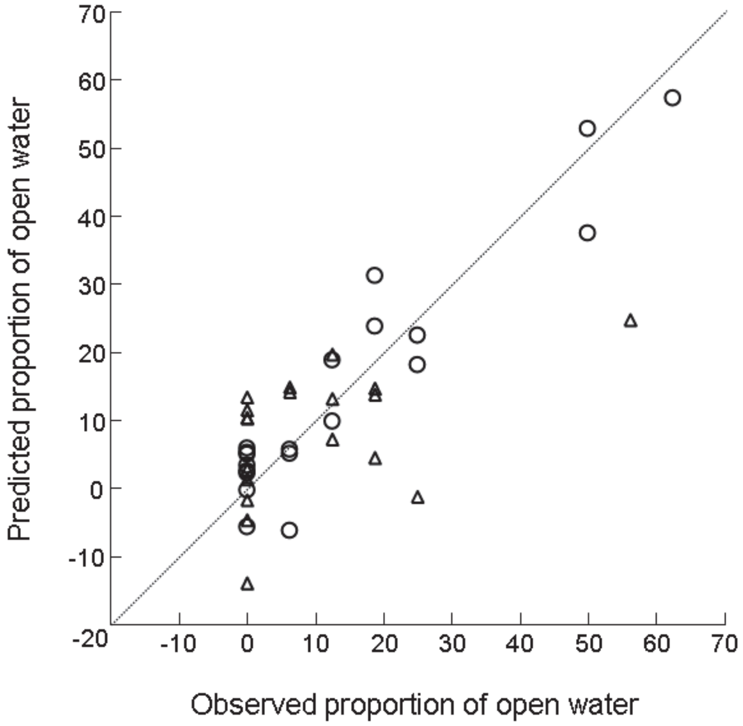

Fig. 6. Correlation between the predicted and observed values for reed-cover heterogeneity in 2005 (O) and 2006 (Δ) using the best 2005 model.

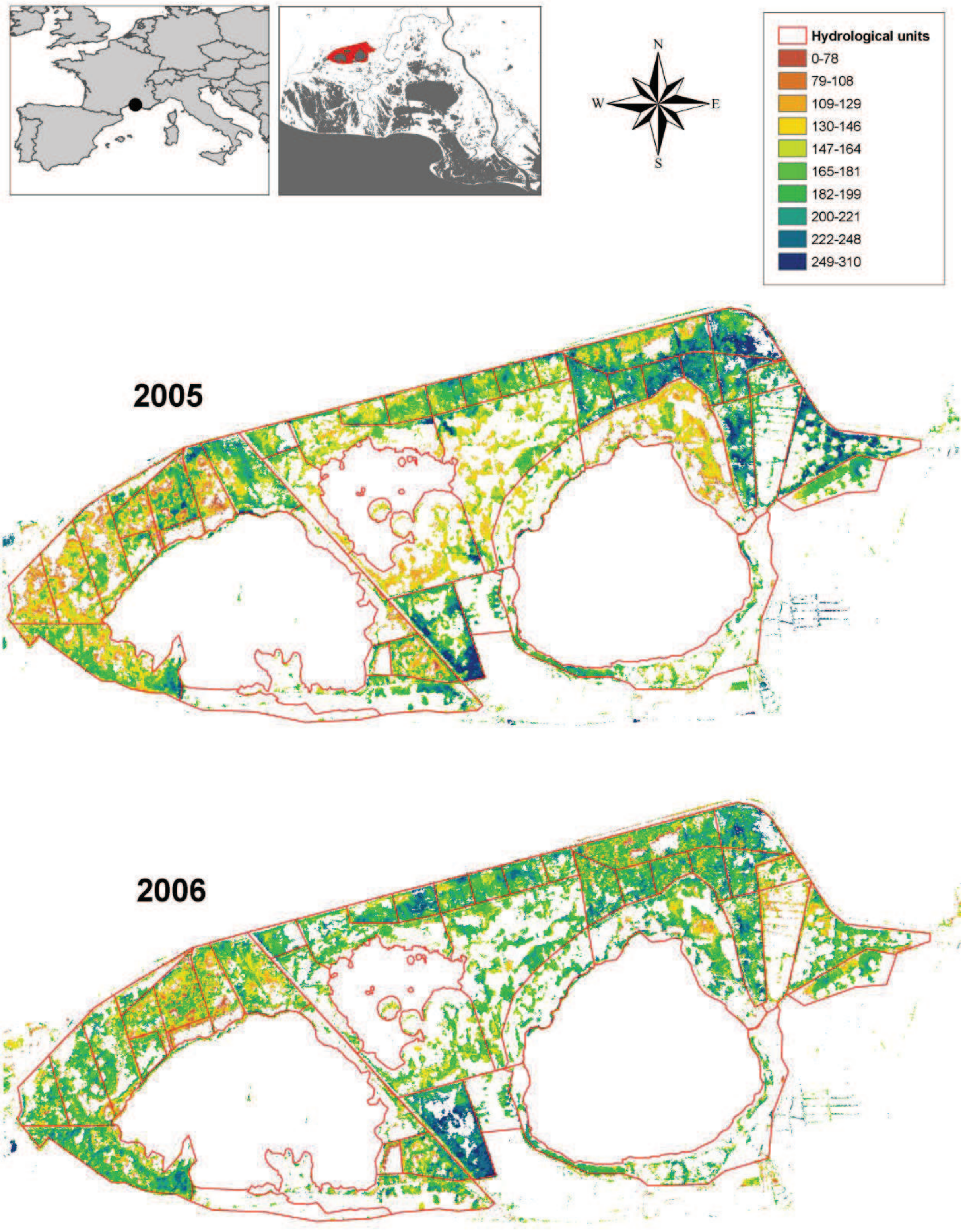

Fig. 7. Mapping of green-reed height (in cm) at the Charnier-Scamandre site in 2005 and 2006 using natural breaks for color scheme. Water or land areas free of reed are shown in white. Hydrological units either refer to large water bodies or to embanked reed marshes having independent water management.