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Mapping riparian vegetation along rivers: old concepts and new methods

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Abstract

Several objections have been made to the approach of a sliced environment introduced by the Remote Sensing (RS) and Geographic Information System (GIS) tools. There is no evidence that each discipline can be reduced to a set of layers of spatial information. For most botanists, the quality and hence the value of a vegetation map rests more heavily on the selected system of classification than on any other feature. This paper assumes that the knowledge of the historical trends in vegetation mapping concepts may provide useful insights for improving the GIS approach of vegetation. In the first part, a summary of the debates in the scientific community is presented. First taxonomists were opposed to physiognomists. Then, with the development of the ecosystem concept and the landscape concept new questions arose in the debate: what should be mapped, vegetation, ecosystems or landscapes? Controversies opposed botanists to geomorphologists. Today, patterns as well as processes have to be mapped. However, little has been done on riparian vegetation. The second part of the paper focuses on two specific requirements for RS of riparian vegetation, namely high spatial resolution and spatially-oriented classification algorithms. Both have been neglected in the past. By 1998, improvements in satellite data should stimulate studies on riparian vegetation. However, aerial photographs will remain the best medium for analysing riparian vegetation in detail. In the third part, the discussion focuses on the use of GIS for riparian vegetation studies. Obviously, a vegetation layer cannot show the vegetation in all its aspects. However, if it is based on a sound scientific method, much of the information which is stored in an implicit form can be exploited for broader application.

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Mapping vegetation can be considered as a driving element in research, a mean to moderate the subjectivity of conceptual statements and to validate ecological theories. On floodplains the major problem is a Jack of useful data and the high cost for obtaining such data. The challenge is to map flood disturbances and the vegetation dynamic.

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1. Introduction

Riparian vegetation including floodplain forests along rivers is recognized as an important part of river ecosystems (Cummins et al., 1984; Petersen et al., 1987; Décamps, 1996) and there is an increasing demand to include riparian vegetation parameters in conservation, restoration and management projects. Hence the need to develop new methods for mapping riparian vegetation along rivers. A widely-held idea is that the environment can be first described and analysed by independent disciplines or variables, and that data integration or modelling can be undertaken a posteriori using computer facilities. In this perspective, geographic information systems (GIS's) are promising tools, as they handle layers of map information over an area and may capture and process space information (Haines-Young et al., 1993).

Several objections have been made to such an approach. Clearly, there are important conceptual differences in the description of the environment-especially vegetation-as it is perceived by ecologists, geomorphologists, economists, politicians, fishermen or the public, and there is considerable confusion in terminology (Wadeson, 1994). There is also the question of who should integrate the layers of information for decision-making, and how? 'If indeed a GIS is different from a spatial decision support system (SDSS), then should a spatial analytical model coupled to a GIS be called a SDSS, a GIS or a mess?' (Nyerges, 1992). As noted by Petch and Kolejka (1993), 'the capacity of modern computers to handle and display spatial data is no guarantee that what is being displayed is providing the answer that is needed to any particular problem'.

With the recent acceleration of computing performances and the development of software-both at decreasing costs-many of the difficulties for the capture, storage, processing and display of spatial data have been progressively overcome. Therefore, GIS operators may feel ready to enter a new era with unlimited perspectives for environmental analysis and modelling through the processing of multidate / multisource / multiformat geocoded data. However, major problems may arise in finding a vegetation layer to be included in the GIS.

The objective of this paper is to discuss these issues in the particular case of riparian vegetation. The fundamental questions are: 'what data are required for characterizing riparian vegetation?'; 'who should provide the data?'; 'how is it to be collected?'; 'who will use it?'; 'how?', etc.

For vegetation mappers, the quality of a vegetation map-and hence its value-rests more heavily on the selected system of classification than on any other feature (Küchler, 1967, Küchler and Zonneveld, 1988). There is 'a sequence in which the first item (classification) is arrived at more or less arbitrarily, whereas the second item (vegetation map) expresses the first one cartographically' (Küchler, 1967). This distinction between classification and mapping is fundamental but is not really accounted for in the remote sensing and geographic information system approach, where there is semantic confusion between the two terms. Moreover, it is widely admitted that information on vegetation can be more or less automatically derived from remote sensing data and further included in a multilayer GIS (i.e. without intensive field validation).

Today, we know the possibilities and limits of remote sensing quite well. Thorough reviews have been published, from a critical viewpoint, on the efficiency of satellite remote sensing in forestry (Guyot et al., 1989; Iverson et al., 1989), hydrology (Engman and Gurney, 1991), ecology (Roughgarden et al., 1991; Wessman et al., 1991; Green et al., 1993; Garguet-Duport and Girel, 1996) and river environment (Muller et al., 1993; Milton et al., 1995).

This paper will first summarize the evolution of the concept of vegetation mapping. It assumes that the knowledge of historical trends in vegetation mapping and debates in the scientific community may provide useful insights for improving the GIS approach on vegetation. Secondly, it will focus on two specific requirements for remote sensing of riparian vegetation, namely, high spatial resolution and spatially-oriented classification algorithms. Thirdly, it will examine what could be expected from a GIS approach of the riparian vegetation.

2. Historical trends in vegetation mapping concepts

2.1. Taxonomy vs. physiognomy

At the beginning of this century, vegetation was classified according to either taxonomic or physiognomic parameters. Debate within the scientific community produced two main schools. Taxonomists considered that basing vegetation formations on physiognomic parameters was a 'nightmare', while vegetation associations based on floristic parameters were 'banned' by physiognomists (Gaussen, 1927). Such debates have resulted in scientific refinements of vegetation mapping meth- ods.

For many botanists, the floristic composition of vegetation is the natural basis for classifying communities. The most extensively used method is the phytosociological method developed by Braun-Blanquet (1964). It is based on the identification of species and on their frequency within associations and permits a high degree of detail and accuracy for mapping vegetation at scales ranging from 1:25000 to 1:50000. In the Braun-Blanquet method, the major types of vegetation must first be distinguished broadly in the field. Aerial photographs are a great help here. Then the floristic nature of these types is analysed by means of a sampling procedure, typically quadrats. The list of species and their frequency in each

quadrat are recorded. In addition, coverage is estimated as a percentage of the total area of the quadrat. Supplementary data are often recorded (e.g. basal tree area, sociability and distribution of the species, etc..). Braun-Blanquet (1964) said that his classification method was not adapted to mapping, except on very large scales. Eilenberg (1956) showed not only the advantages and the strength of this system but also where subjectivity enters into it and to what degree. Küchler (1967) noted: 'If we compare vegetation maps by Braun-Blanquet and his followers, it becomes at once evident that this strict standardization used in classifying vegetation is not applied on vegetation maps. Men like Emberger, Molinier, Lüdi, Tüxen and even Hueck, the very leaders of European vegetation mapping, ali profess to be followers of Braun-Blanquet. And yet, their maps are not at ali alike'. Obviously, a uniform map representation of vegetation is difficult, as species composition changes through space. Consequently, specialised taxonomists are required not only to compile a vegetation map, but also to understand it.

In opposition to this taxonomic approach of vegetation, other botanists considered physiognomy as 'the most important of the features to be defined in describing a plant community' (Salisbury, 1931). Two reasons explained this importance given to physiognomy (Beard, 1944): 'first, structure and lifeforms are capable of exact measurement and record in the field, and secondly, can be mathematically defined'. According to Küchler (1967), who developed its own
method, physiognomic maps could be compiled at any scale, over any region with a clear and unequivocal terminology for comparative studies. His method did not require taxonomic knowledge but neither did it provide the list of species of which the vegetation was composed. Each physiognomic category was assigned a formula with a combination of letters and numbers for describing life forms (e.g. broadleaf evergreen, broad leaf deciduous, graminoids), leaf characteristics, height and coverage.

It also became evident to most authors that the taxonomic and physiognomic approaches were complementary. As noted by Dansereau (1961) 'the application of the physiognomic system to very different types of vegetation from the humid tropics to the Arctic bas convinced me that structure characteristics vegetation quite as significantly as does floristic composition ... 1 have never thought that one could do without the other'.

Since the 1970s, field investigation and photointerpretation have been supplemented by multispectral satellite images which facilitated a more quantitative approach to vegetation. For example, in the Garonne valley, France, if one considers the reflectances of the three dominant woodland types, important differences can be clearly observed in the seasonal variation (Fig. 1). The Normalized Difference Vegetation Index shows contrasted phenophases, particularly the late leafing of oaks and the early leaf-fall of poplar. Unfortunately, the coarse resolution of satellite data does not make it possible to obtain information on individual riparian communities. Remote sensing of vegetation, based on satellite data, had great development for the mapping of broad landcover classes and biomass on large areas. Such an approach of vegetation is too reductionist and cannot be
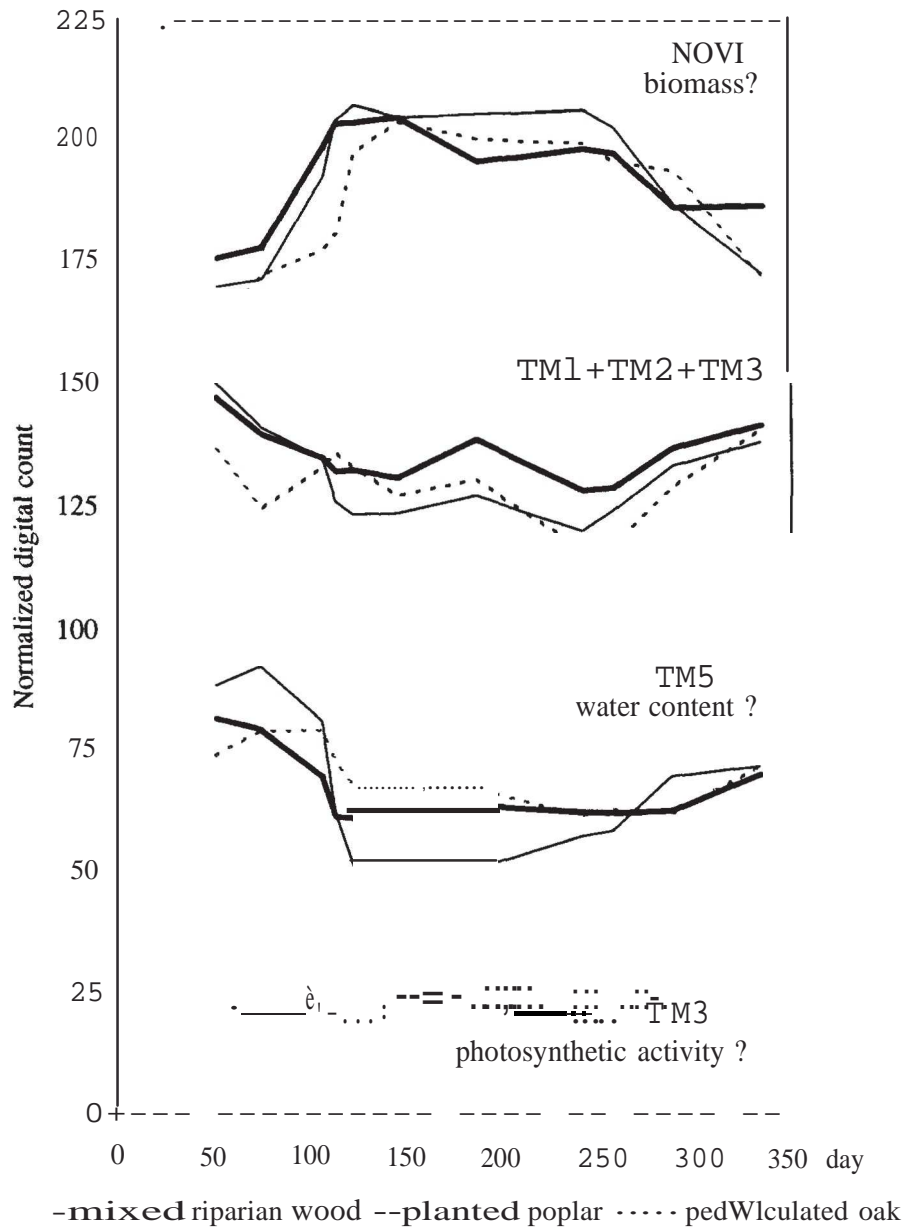
Fig.1. Comparison of the seasonal variation of TM spectral data for the dominant woody species in the Garonne valley, France.

considered satisfying. As noted by Wessman et al. (1991) 'little can be derived from reflectance measurements with regard to detailed species composition and distribution'.

In recent studies, the radiative transfer was modelied in 3D-Vegetation in order to retrieve biophysical parameters (e.g. crown diameter, tree height, tree row, leaf area index). One promising example, which has been tested for pines and for poplar plantations in the Garonne valley, is provided by the Discrete Anisotropie Radiative Transfer-DART model (Gastellu-Etchegorry et al., 1996; Pinel, 1996).

2.2. Mapping vegetation us. mapping environment

With the development of the ecosystem concept (Tansley, 1935; Rowe, 1961) and the landscape concept (Troll, 1950), new questions arose in the debate: what should be mapped, vegetation, ecosystems or landscapes? The initial answer was unambiguous: 'vegetation should be primarily characterised by its own features, not by habitat. It is the structure and composition of a plant community that we must first ascertain and record as the secure basis of all subsequent knowledge' (Richards et al., 1940). The fundamental question was to know if vegetation should be (or could be) objectively described with absolute impartiality and independent of its environment. Ambiguity comes from the fact that the environment can be considered as an indicator of the vegetation and the vegetation as an indicator of the environment. Botanists considered (and still consider today) that vegetation is the best integrator of environmental parameters. Therefore, they have tried to use environmental factors for improving the classification of vegetation, e.g. exposure and altitude (Troll, 1939), temperature and rainfall (Gaussen, 1948), water table level fluctuation (Walther, 1957), soil moisture (Wagner, 1961). Consequently, vegetation maps became 'ecological' and were often considered by their authors as 'the most comprehensive, the most reliable, and the simplest tool in analysing the site qualities of the landscape' (Krause, 1955).

For example, Gaussen's system developed for the vegetation map of France at the scale of 1:200000 (Gaussen, 1948), was qualified as 'ecological' by Küchler (1967) and was based on the concept of series of vegetation and on the description of growth forms of vegetation. As vegetation develops, the same area becomes successively occupied by different plant communities. In Gaussen's terminology, this plant succession is a 'series' and the progressive stages in a series are 'formations' corresponding to physiognomic categories, identifiable on aerial photos (i.e. barren soil, herbaceous, under shrub, shrub, wooded shrub, forest). Each series gives an immediate indication of essential ecological factors, such as temperature and humidity, and has its own specific colour on the maps. The occurrence of the same series (same colour) in two distant areas implies that essential ecological factors are analogous. It took 35 years to compile the 80 sheets that cover France. The small scale of the maps makes it impossible to obtain detailed information on riparian vegetation. However, planted poplar, artificial meadows, cultivated fields, and several physiognomic stages within the 'aider series' can be identified on floodplains, because vegetation patches were derived from aerial photos at 1:50000

and later mapped at 1:200000. For Forsberg (1961), Gaussen's maps were 'excellent examples of maps of ecosystems' but were 'misnamed vegetation maps'.

In the 1960s, there were controversies between botanists and geomorphologists. For most geomorphologists, landforms were better integrators of environmental parameters than vegetation (Christian, 1963). Integration was also considered to be above all a matter of team work and photointerpretation was seen as an arm for integration (Christian and Stewart, 1968). At the same time, many phytosociologists proposed an 'integrated' or 'ecosystemic' approach for mapping vegetation (Long, 1974). The approach was also qualified as 'holistic', since the ward was introduced by Zonneveld (1968). For any given organization level, this approach requires a priori selection of significant environmental variables as well as the integration of the variables ('integration is not mixing up'; Zonneveld, 1968). However, studying individual factors of the environment may be a very hard task (71 factors were identified by Billings, 1952) and identifying significant factors was considered hazardous (Ellenberg, 1956).

On floodplains, the geomorphological postulate bad a very accurate sense because the morpho-dynamic processes of flows, erosion, sedimentation and water table fluctuation clearly play a primary role in structuring vegetation (Zolyomi, 1954; Karpati, 1958; Pautou, 1984; Décamps et al., 1988; Carbiener and Schnitzler, 1990; Johnson, 1994). A single morphological unit may encompass a range of flow environments and substratum conditions and therefore may be composed of one or more objectively definable biotopes (Wadeson, 1994).

The typology of floodplains, introduced by Amoros et al. (1982) and recently reactivated by Ward and Stanford (1995), distinguished two principal domains on a floodplain: superficial and underground. There are three 'spaces' in the superficial domain: the permanent aquatic space, the semi-aquatic space and the terrestrial space. Each space is subdivided into 'functional ensembles' and each ensemble into 'functional units'. In the permanent aquatic space, the 5 functional ensembles were named eupotamon, pseudopotamon, parapotamon, plesiopotamon and paleopotamon, depending on the connection type with the main channel. In the semi-aquatic space, Amoros et al. (1982) distinguished four functional ensembles, according to the mean yearly duration of floods. In the terrestrial space (i.e. a space not influenced by the river and it's water table), three functional units were distinguished and lastly, in the underground space three units, as well. This classification was used for interdisciplinary purposes (Amoros et al., 1982, 1986), especially for mapping riparian vegetation using aerial and space remote sensing data (Girel, 1986; Girel et al., 1986).

In the Netherlands, the ITC system-based on pedons and polypedons, morphons and polymorphons, and on terrain, soil, land caver and land use map units-has reached a high degree of conceptualization and application (Meijerink, 1988; Zinck and Valenzuela, 1990; Meijerink et al., 1994). For the intensive use of remote sensing and map data, a specific GIS, the Integrated Land and Watershed management Information System (ILWIS), was developed with a strong orientation towards landform, sail, vegetation and hydrological studies (ITC, 1988). In the United Kingdom, aerial cameras and other airborne sensors have also been

intensively used for mapping channel bed changes and floodplain morphology
(Gilvear, 1993; Watson et al., 1993; Gilvear et al., 1995; Milton et al., 1995).

2.3. Mapping patterns vs. processes

With the development of landscape ecology, the spatial and temporal patchiness
of the environment has been explicitly recognized as a driving force in ecological
processes. As explained by Krummel (1986), while ecosystem analysis attempts ta
create black box explanations of spatial heterogeneity, landscape ecology must
accept spatial patterns as a driving force in determining system function. Today, there
are increasing interests in scale, hierarchies and heterogenities in vegetation studies.
This heterogeneity may include social, cultural, economic and aesthetic factors,
together with physical and biotic parameters.

These considerations are central in riparian vegetation studies. The instability of
The riparian environment explains the high complexity of the vegetation caver. For
a given vegetation stand, flood disturbances can modify or interrupt the sequence of
successional stages and provoke a rejuvenation of the communities (see Décamps,
1996, for a review). Consequently, riparian vegetation is generally distributed in an
unstable mosaic of stands. Recently Wadeson (1994) explained that stream ecologists
not only subdivided morphological features into smaller spatial units, but also
recognized temporal changes in biotope definitions. Such concerns are not totally
new. Vegetation dynamics have been an early and central problem in vegetation
mapping. As vegetation changes continuously over the same area (seasonally, yearly,
secularly), the temporal dimension of vegetation can be considered as an intrinsic
characteristic of class definition. Several Vegetation mappers tried to produce
dynamic vegetation maps rather than static maps and tried to explain the causes of
these changes. For that purpose they developed new con- cepts, e.g. successions
(Lüdi, 1921), phases of vegetation (Saxton, 1924), series of vegetation (Gaussen,
1948), association rings (Schwickerath, 1954), potential natu- ral vegetation (Tüxen,
1956), vegetation sequences (Godron and Poissonet, 1973). Mapping the dynamism
of vegetation was criticized by several authors because it introduces elements of
interpretation in addition to elements of observation, especially if a single map is used,
rather than a series of successive maps. For example, Fosberg (1961) explained that
the mapper is recording what he observes and 'what he thinks is going to happen or
bas happened'. Long (1974) considered that under European conditions, field
observations of two or three annual cycles were necessary to start understanding
vegetation dynamics and their relation to soil and climate. As the environment is
unstable, ecologists have often great difficulties in distinguishing allogenic and
autogenic processes.

On European floodplains, a typical successional sequence starts with pioneer
herbaceous communities. They are replaced by softwood communities and by
hardwood communities at the final stages (Carbiener, 1970; Pautou, 1984; Werner,
1985; Carbiener and Schnitzler, 1988, 1990; Décamps et al., 1988). In the Peruvian
Amazon, the disturbance due to lateral erosion and channel migration of meander-
ing rivers, provokes a high site turnover and maintains a high between-habitat

species variability which can be identified with satellite data (Salo et al., 1986; Kalliola et al., 1992; Puhakka et al., 1992; Mertes et al., 1995). A full successional sequence may last 300-500 years in the upper Amazon basin (Terborgh and Petren, 1991) and 1000 years in Europe (Naiman et al., 1989). Human disturbances (flood regulation, channelization, gravel extraction, farming practice, tree plantation, urbanization) typically disrupt the dynamic patterns and processes that structure river floodplain ecosystems, yet it is possible to assess vegetation changes through the use of historical aerial photos and maps (Johnson, 1994; Otahel et al., 1994; James, 1996).

Classifying riparian vegetation therefore requires a full understanding of species distribution and succession, in relation to environmental parameters and disturbance factors over a large area. In addition, mapping requires an exhaustive interpretation of the area under study as well as a spatial representation of it. Unfortunately, current satellite data 'does not yet provide adequate resolution for the purpose of modelling vegetation succession' (Green et al., 1993). Moreover, despite the versatility of GIS as a powerful analytical tool, the general problem of data availability is a major barrier to the wider use of these tools (Haines-Young et al., 1993). It is clear that until quite recently, the analytical tools available did not match the scale of questions we needed to ask about landscapes (Haines-Young et al., 1993). The lack of spatially distributed data on floodplains (e.g. detailed flood frequency maps, soil maps and water table fluctuation maps) and the lack of appropriate tools to collect them may explain why, in the past, conceptual studies were considered more important than mapping activities.

3. Specific requirements for remote sensing of riparian vegetation

3.1. High spatial resolution

The scale factor is of prior importance for studying riparian vegetation. The spatial resolution of remote sensing data imposes a scale for the analysis of vegetation. In forest studies, White and Mac Kenzie (1986) considered that the 'goal was to find a scale at which the signature of one pixel integrates the relevant heterogeneity within a unit to be mapped, without causing blurring across boundaries of major cover types'. They considered that the optimum scale of resolution depends on the objectives of the study and on inherent characteristics of the landscape, i.e. size of tree crowns, canopy roughness, number of species within vegetation types, shape and extent of patches in a forest type, spectral contrast with the matrix around the forest type, and heterogeneity produced by patchiness within the forest type. Ali these intrinsic vegetation parameters vary within and between vegetation types and sites. For White and Mac Kenzie (1986), 'no one scale of resolution will be perfect for even a single vegetation mapping goal'.

In order to find optimum spatial resolution, Woodcock and Strahler (1987) proposed to compute the local variance of images as a function of spatial resolution. The local variance was defined as the mean value over the entire image of the standard deviation of a 3×3 pixels moving window. Woodcock and Strahler (1987)

observed peaks in local variance in the range of $1/2$ and $3/4$ of the size of the objects to be detected in the scene, i.e. not at the exact size of the objects. For example, the peak was at a resolution of 6 m for tree canopy diameters of 8 m. The usefulness of local variance in remote sensing studies had already been stressed by Lowitz (1983) and was confirmed by James (1996) for the identification of riparian species in riparian woodlands along the Garonne river (France), using 0.8 m airborne data in three Spot XS bands.

Another approach was proposed by Marceau et al. (1994). This method consists in identifying the spatial resolution which induces minimal intraclass spectral variance, for each forest class. Results showed that with a low density of trees, coarse resolution is necessary to integrate the canopy, soil and shadow but that for dense pine plantations, tree height, rather than tree density, determines optimum resolution. Both methods necessitate the acquisition of images at high spatial resolution and the progressive reduction of this resolution for the purpose of forest studies, i.e. from 0.75 m to 50 m in Woodcock and Strahler (1987) and from 0.5 m to 30 m in Marceau et al. (1994). Unfortunately, the lack of high resolution satellite images definitely limits the study of small patches of riparian vegetation on a floodplain. Satellite remote sensing is better adapted for mapping broad landcover categories rather than vegetation communities.

As suggested by White and Mac Kenzie (1986), boundary pixels can also be used as a gross evaluation of optimum spatial resolution according to the size of the objects to be analysed. For this purpose, objects are assumed to be internally homogeneous with the edges of one pixel. To illustrate this approach, let us consider 6 quality levels in the perception of circular objects, according to the percentages of boundary pixels computed as a function of spatial resolution and of diameter (Fig. 2). The quality of the perception refers to the amount of pure information in the objects. Results provide a quick evaluation of the possibilities and limits of any data. For example, with pixels of 10 m, a forest stand of 80 m in diameter can be fairly monitored (i.e. half of the pixels are boundary pixels). A good perception (i.e. with 1/4 of boundary pixels or less) would require either a larger forest stand (160 m) or smaller pixels (5 m). For large-scale riparian vegetation studies, the size of the objects to be analysed is small and the efficiency of remote sensing data is primarily a function of spatial resolution. If the spatial resolution is too coarse, it will act as a limiting factor and the information extracted from the image will have at best statistical, but not cartographic, value. Therefore, the multispectral or multidate resolutions of remote sensing data are Jess critical than the spatial resolution.

It is interesting to notice that the specific requirements for large-scale vegetation studies are not fundamentally different from military requirements. In a utility comparison of sensors at different ground resolutions, Heric et al. (1996) considered that the poorest acceptable resolution for military surveillance was 10 m and that at 10 m, there were exponential advantages associated with finer spatial resolutions. Furthermore, results showed that spectral domains could be ranked by decreasing order of utility for a given resolution (i.e. multispectral, panchromatic, thermal, r adar). The Open Skies Treaty, which was signed in 1992 by Nato
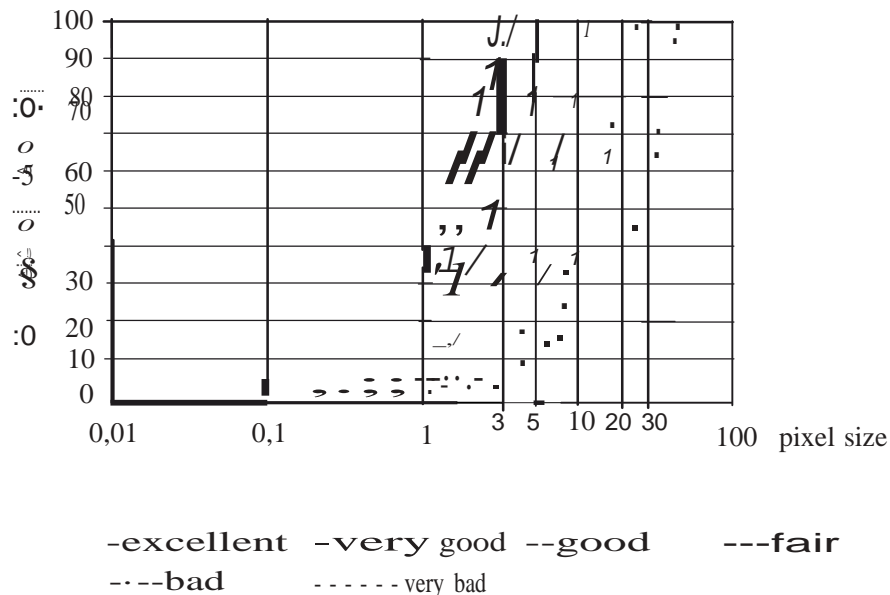
Fig.2. Quality of the perception of circular objects as a function of diameter and pixel size. The diagram can be read in any unit (e.g. in centimetres, in metres). Quality refers to the proportion of boundary pixels in the object: excellent < 10%, very good = 14%, good = 24%, fair= 47%, bad= 75%, very bad= 100%.

members and former Warsaw Pact States for verification of arms limitation agreements, specifies how member states are allowed to overfly the territory of other members using aircraft fitted with a variety of treaty-specified sensors. Currently, the minimum allowed ground resolution for optical sensors is 0.3 m, O.S m for thermal infrared scanners and 3 m for side-looking radars (Heric et al., 1996). One would expect the same sensor performances for ecological studies...

In the next few years, the needs of the scientific community for high spatial resolution will be partly satisfied by improvements in satellite sensors and platform characteristics (Baudoin et al., 1995; Crépeau and Pierre, 1996). By 1998, best resolutions should be 1 m in the panchromatic domain, 4 m in the visible and near infrared domains and 20 m in the short-wave infrared domain (Table 1). These improvements should stimulate studies on riparian vegetation although the radio-metrie quality of the data cannot be anticipated. For technical reasons, no progress is expected in terms of additional spectral bands unless airborne missions are programmed with spectrometers or military derived technology (Gabrynowicz, 1996).

For Naithani (1990) and Light (1996), aerial photographs produce the best resolution attainable of all remote sensing schemes and represent a very dense storage medium. With panchromatic aerial photos at scales of 1:10000 to 1:25000, the majority of the vegetation types of interest, defined in a classification scheme,

Table 1
Characteristics of existing and future high resolution satelite data (existing data is bold)

Pixel size (rn)	Spectral bands								Available	Satellite	Sensor	Origin
	Visible				Infared		Microwave					
30		B	G	R	NIR	SWIR			1982	LANDSAT-4	TM	USA
30	—	B	G	R	NIR	SWIR	—		1999	LANDSAT-7	ETM	USA
25	—	—	—		—		C		1991	ERS-1,-2	SAR	Europe
25			—	—			C		1995	RADARSAT-1	SAR	Canada
25				—	—		C		1998	ENVISAT	SAR	Europe
25			—				C		1999	RADARSAT-	SAR	Canada
23.5			G	R	NIR				1995	IRS-lC	LISS-3	India
23.5			G	R	NIR		—		1996	IRS-lD	LISS-3	India
20			G	R	NIR	SWIR			1998	SPOT-4	HRVIR	France
20			—	—		SWIR			2002	SPOT-S	HRG	France
20				—	—		L		1992	JERS-1	SAR	Japan
16		B	G	R	NIR				1997	ADEOS-1	AVNIR	Japan
15		B	G	R	NIR	—		—	1996	Earth Watchj Early Bird		USA
15	P	—	—						1999	LANDSAT-7	ETM	USA
10	P								1986	SPOT·1,-2,-3,	HRV	France
10	P		—	—					1998	SPOT-4	HRVIR	France
10			G	R	NIR				2002	SPOT-S	HRG	France
10		—	G	R	NIR				2002	ALOS-1		Japan
8	P				—		—		1997	ADEOS-1	AVNIR	Japan
5.8	P								1995	IRS-1C	PAN	India
5.8	P	—		—	—				1996	IRS-lD	PAN	India
5	P								2002	SPOT-5	HRG	France
5	P	—		—					2002	ALOS-1		Japan
4		—	G	R	NIR	—		—	1998	Space1S		USA
4	—		G	R	NIR				1998	Orbview 1		USA
4			G	R	NIR				1998	Earth Watchj Quick Bird		USA

Table 1   (*Continued*)

Pixel size (rn)	Spectral bands								Available	Satellite	Sensor	Origin
	Visible			Infared		Microwave						
3	Ρ	—	—		—	—	—	—	1996	Earth Watch/ Early **Bird**		USA
2	Ρ	—	—	—	—	—	—	—	1998	Orbview 1		USA
1	**p**	—	—	—	—	—	—	—	1998	Earth Watch/ QuickBird		USA
	p	—	—	—	—	—	—	—	1998	Space1S		USA
1	**p**	—	—	—	—	—	—	—	1999	OrbviewjBaseline		USA

could be recognized for vegetation successions (Green et al., 1993). This confirmed conclusions made by other authors who used multidate aerial photographs for the specific mapping of riparian vegetation (e.g. Girel, 1986).

The last thirty years have been characterised by a dramatic improvement in airborne cameras. The resolving ability of a film camera system is measured by the area weighted average resolution (AWAR), in line pairs per millimetre (lp/mm). The improvement went from 60 to more than 95 lp/mm. However, final film resolution is reduced during flight surveys, due to atmospheric disturbances and to image blur resulting from the forward and angular motion of the airplane (roll, pitch and yaw). With today's best aerial cameras, a system resolution of 39 lp/mm for low contrast scenes and 54 lp/mm for high contrast scenes can be reasonably expected (Light, 1996). One lp corresponds on film to 25 and 19 μm, respectively. At a scale of 1:40 000, this corresponds to 1 m and O.7 m on the ground, respectively. This scale can be obtained at an altitude of 6 000 m with a Leica-Wild RC 30 camera or a Zeiss Top-15 camera, using a focal length of 152 mm and a 230x X 230 mm film (e.g. as in the U.S. National Aerial Photography Program).

Converting this film to pixels requires precise scanning to minimize resolution losses. The appropriate pixel sizes for preserving film resolution was evaluated in the range of 9-13 μm (i.e. with an average of 11 μm) by Light (1996). Scanning a 230 X 230 mm film frame at this density, will require storage capacity of 0.4 Gbytes for a panchro photograph and 1.2 Gbytes for a colour photograph, assuming 8 and 24 bits/pixel, respectively. In comparison, the array size of a digital camera would need approximately 21000 X 21 000 detectors to preserve this resolution. However, today staring array sizes are more in the range of 5 000 by 5 000 detectors (Light, 1996). They can rival 35-mm films but cannot challenge large format 230-mm films. With a linear array used in a push-broom scan mode, 21 000 detectors would be necessary and data rate acquisition would be very high, e.g. 60 Mbits/s assuming an acquisition velocity of 140 m/s (270 knots) and 8 bits/pixel for panchromatic images. Such a sensor does not yet exist. lt is feasible but would be expensive as regards data transmission and storage. By comparison, in the SPOT-1, -2 and -3 satellites, basic detector arrays of 1728 elements were mounted to reach 6000 detectors per line. Spot data rate of acquisition is 25 Mbits/s, magnetic storage capacity is twice 120 Gbits, and transmission rate to the ground is 50 Mbits/s. For Landsat TM, the acquisition rate was 85 Mbits/s. For the future SPOT-5 satellite, it will be 150 Mbits/s.

3.2. Spatially oriented classification algorithms

With image processing systems, one expects the images to be classified in vegetation categories using automatic (more objective?), supervised or non supervised algorithms, based on digital spectral data. Many authors have noted that finer spatial resolution does not necessarily improve per-pixel image classification (Latty and Hoffer, 1981; Irons et al., 1985; Green et al., 1993; Muller, 1993). The classification accuracy of images is the result of a trade-off of two main factors: class boundary pixels and within-class variances (Markham and Townsend, 1981).

Boundary pixels between classes are generally unwanted for classification purposes. However, they may provide useful information on the structure and the diversity of landscapes in an ecotone perspective (Fortin, 1992; Metzger and Muller, 1996). The within-class variance is often considered to be a 'noise' in image classification. With higher ground resolutions, the amount of boundary pixels decreases but the within-class variances increase. For ecologists, within-class variance is an intrinsic characteristic of vegetation patches. Unfortunately, common classification algorithms do not take the local structure or the heterogeneity of patches into consideration in the classification. Another factor limiting the accuracy of a result is the low between-class variance and the poor representativity of conventional statistical parameters such as the mean values and the standard deviations (White and Mac Kenzie, 1986; Muller, 1993). This problem can be simply illustrated by comparing the spectral responses of homogeneous patches, such as planted poplar groves on a floodplain (Table 2). In the example, no significant difference existed in the spectral bands between the two dominant poplar clones, whatever their age (Fig. 3). Up to 4 years, the difference in spectral responses was statistically significant although it could not be considered to be characteristic for the two clones because the variance of data was totally uncontrolled due to haphazard farming practices, but not to intrinsic poplar characteristics.

In most cases, when image classification methods rely on no more than spectral data and a priori vegetation class definition, it is just a stroke of good fortune to end up with satisfying image classification results. Improving the classifications necessitates either the use of additional spectral bands (e.g. a short-wave infrared
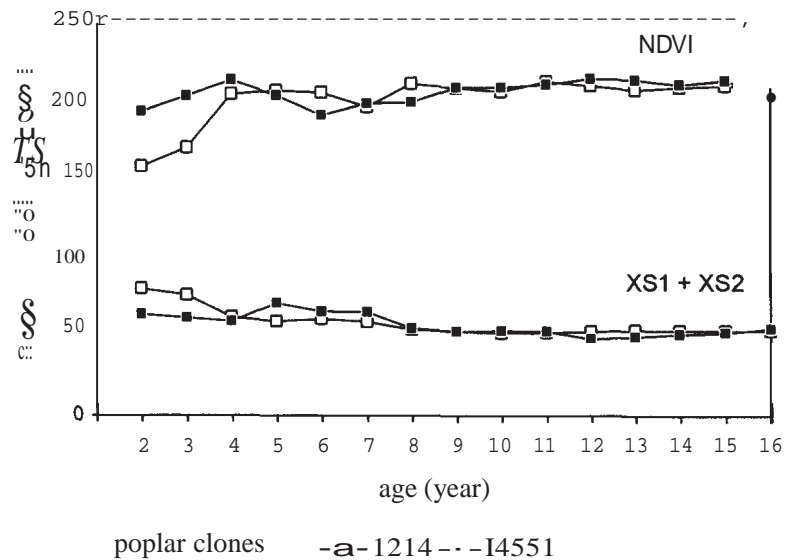

Fig.3. Comparison of the spectral responses of two poplar clones as a function of age (same data as in Table 2 for land parcels).

Table 2

Spectral variability of poplar clones in a SPOT simulated image at a spatial resolution of 5 rn over the Garonne ftoodplain on May 6, 1993. Statistics were computed over 95 poplar sites using three sampling levels: the pixels (25 m^2), square plots of 900 m^2 and land parcels (ranging from 1.5 to 8.2 ha) (in Normalized Digital Count)

	Poplar clones	XS1			XS2			XS3		
		Pixels	Plots	Parcels	Pixels	Plots	Parcels	Pixels	Plots	Parcels
Mean	1214	33.5	33.7	33.7	31.0	31.3	31.4	95.9	95.4	95.1
	14551	30.8	30.8	31.1	25.9	26.0	26.6	105.2	105.4	103.6
	ali clones	31.7	31.8	32.0	27.6	28.0	28.5	100.9	99.9	98.9
Standard	1214	3.6	3.8	3.6	7.3	7.3	7.2	21.5	19.6	20.2
deviation	14551	3.0	2.6	2.7	4.8	4.5	4.9	15.2	16.2	14.6
	ali clones	3.4	3.6	3.4	6.1	6.5	6.4	17.7	17.8	17.1
Max-min	1214	33.0	13.9	12.9	43.0	25.1	24.9	105.0	68.3	o7.3
	14551	34.0	10.6	10.4	57.0	17.7	22.5	115.0	75.4	72.8
	ali clones	34.0	14.4	13.8	57.0	25.5	25.3	116.0	78.0	74.0

band in addition to the three SPOT bands) or the selection of optimum dates for the acquisition of images (Muller, 1995). The ultimate solution is to change the initial class definition. But this may seem intolerable to many ecologists, as it leads to accurate (i.e. statistically correct) but inappropriate (i.e. useless) vegetation classes. As noted by Iverson et al. (1989), 'using satellite imagery to classify forest types is still a subjective procedure and as much an art as a science'. For Green et al. (1993), 'even with currently available image-processing algorithms, satellite data are at best only a supplementary/complementary source of information to standard aerial photo-interpretation'.

If more importance were given to the improvement of image classification methods based on the form, context and internal structure of spectral patterns in images, one could expect to obtain not only better classification results for heterogeneous objects, but new findings on significant scales of phenomena as well. In ecology, different processes and structures exist on different scales. The scales of phenomena are not arbitrary but tend to concentrate around discrete states which cannot always be defined a priori (Klemes, 1983; Meentemeyer, 1989; O'Neill et al., 1989; Burel et al., 1992). In other words, images could be analysed without a priori class definition as well. However, as mentioned above, coarse spatial resolution restricts the exploration of scales and prevents the detection of significant scales.

4. The GIS approach to riparian vegetation

Clearly, vegetation can be analysed under many aspects and a vegetation map cannot show vegetation in all its aspects. It just focuses on some aspects of reality. Therefore, it should not be judged in terms of right or wrong, but in terms of insight and use. Is the map comprehensive, adequate, useful for the purpose for which it was created? A vegetation map cannot solve all possible issues concerning vegetation. However, if it is based on a sound scientific method, i.e. on clear objectives with a classification system and a cartographic method to represent it, much of the information which is stored in an implicit form can be exploited for broader applications.

Three successive steps can be identified in a traditional vegetation mapping process: conceptualization, classification and mapping. They correspond to three modelling levels: conceptual (explanation of the real world), logical (systemic representation of vegetation) and physical (the map sheet or the map layer). At each level, subjectivity cannot be entirely avoided for the partition of a continuum into 'objects' (i.e. concepts, vegetation classes and map units respectively).

The primary advantage of a GIS is that it gives considerably more importance to the physical level, with possibilities of direct manipulation in the database depending on computer and software capabilities. The risk is to restrict analysis at this level. The challenge is to improve the logical and conceptual levels. As noted by Petch and Kolejka (1993), 'there is a great danger that the power of the digital display may divert attention away from the central issue of pursuing scientific environmental analysis'. In landscape ecology, according to Wiens et al. (1993),

'existing theory needs to be reformulated in explicitly spatial terms and new theory must be developed to integrate spatial patterns and processes and to consider scaling functions'. The question is to know if vegetation can be objectively analysed without a mapping phase. For example, in riparian environments disturbances arc often seen as a temporal phenomenon but have an important spatial dimension as well (Minshall, 1988). The rate and dynamics of recovery, particularly the mechanisms by which new communities are derived, depends on the size of the disturbed area relative to the broader universe of which it is a part. As noted by Pinay et al. (1990), subsystem instability maintains the metastability of the whole riparian ecotone. Therefore changes or processes cannot be evaluated without this spatial dimension.

The spatial representation of the environment requires an exhaustive interpretation of the area under study and must take into account all existing situations (extremes as well as intermediate cases, well defined units as well as fuzzy transition units). With the expected developments in remote sensing and geographie information systems, it must be considered that mapping riparian vegetation could be a driving element in research, a means to moderate the subjectivity of conceptual statements and to validate ecological theories. If the traditional way is to classify first and then to map, with a GIS it can be easy to map first and then to classify. The two approaches are actually complementary, helping to obtain new developments in landscape ecology.

In that perspective, one of the prior steps is to facilitate easy and efficient access to existing spatial information. Over many areas, spatially oriented information systems have been developed to assist in research and in spatial decision support activities. For example, in France, several regional administrative entities have already developed such systems, i.e. SIGALE for the Nord-Pas-de Calais region, SIGR for the Île-de-France region, SIGMIP for the Midi-Pyrénées region (Crépeau, 1995). The SIGMIP system is one of the most advanced examples. It covers 45 000 km^2 and works as a regional server for SPOT data, for the CARTO and ALTI databases created by the French survey (Institut Géographique National), for geological maps, for the European Corine landcover and for several other local databases (land use, statistics). Such data correspond roughly to maps with scales ranging from 1:25 000 to 1:100 000. In Switzerland, for the Vaud state, a 'système d'information du territoire' (SIT-VD) bas been developed using an advanced systemic approach of the territory (Prélaz-Droux, 1995; de Sède, 1995; de Sède et al., 1995).

However, for floodplain environments, more detailed information is required but generally does not exist unless large-scale mapping programs have been devel- oped. When data are available, an Environmental Data Atlas (EDA) can be developed like for the 777 km^2 of the River Savannah Site of the U.S. Department of Energy (Cowen et al., 1995). The EDA system takes advantage of the latest progress in geographical data browsing systems, fourth generation procedural programming languages and network communications between Macintosh, UNIX and DOS platforms and uses spatial keys to link ail data sources to a common geographical data base. Data layers are stored on the server and each user can

easily combine these layers into customized views without physically transferring them between machines. The EDA system has three customized applications. (1) The spatially oriented bibliographic search and retrieval system is based on a hyper-media hot-link, capable of attaching geographic features to various kinds of data (i.e. bibliographic listings, texts, images, data sets, metadata). (2) The image browse and retrieval system is based on tabular, hypertext or spatial searches. Browse images have been scanned at 100 DPI (254 µm). Archive images have been stored at 2,000 DPI (12.7 µm). For example, for an aerial photo at 1:20000 scale, the spatial resolution is $5m^2$ for the browse image and $0.25m^2$ for the archive image. (3) The site selection and modelling system was designed for localizing landfills, waste disposals, power facilities and other new activities. Because overlay and buffer operations are performed much more quickly in raster-based GIS, as compared to their vector counterparts, raster analysis was used in the site selection component of the EDA.

On floodplains, for the understanding of riparian vegetation distribution, the challenge is to map disturbances, especially flood disturbances. For example, to avoid confusion between the riparian woods and the upland woods in a Thematic Mapper image, a buffer zone along the river can be used. However, in the GIS, the overlay should not be based on a proximity analysis (Fig. 4a) but on a flood frequency maps (Fig. 4b and 4c). In the example, 15.0% of the river corridor was occupied by woodlands (12.2% on the terraces and 17.3% on the floodplain). On the floodplain, the proportion of wooded areas was 48.3%, 25.8% and 8.1% on areas with flood occurrences of 1, 10, and 100 years, respectively.

Obviously a larger-scale flood disturbance map is essential for identifying riparian vegetation. Unfortunately, conventional flow models are not spatially oriented and existing Digital Elevation Models (DEM) are too coarse. To create a detailed flood frequency map and a flood duration map, more accurate digital elevation data are necessary. This can be derived from large-scale base maps when they exist (Fig. 5). On the floodplain of the Garonne river, base maps at 1:5000 were compiled in 1994. The maps were scanned in a raster format and geocoded in the Lambert III projection over a test site of 2 km X 2.5 km. Each pixel in the scanned map corresponded to $1m^2$ on the ground. The contour lines (metric precision) and the spot heights (centimetric precision) were vectorised manually and further rasterised in order to apply a conic search grid interpolation algorithm for the creation of a DEM. Floods were simulated with the DEM by considering a progressive immersion of the site, by steps of 25 cm (Fig. 5). The simulation was based on three mechanisms which work simultaneously during floods: (1) dawn-stream filling of side-channels, (2) overbanks flood discharges, (3) run-off. Dawn-stream filling was simulated by progressive thresholds on the DEM from the lowest points of each side-channel. Points where the water progressively poured outside the channel for overbanks flood discharges, were located in the vicinity of the river channel by the difference between the DEM and a proximal map, created with Theissen polygons, where each pixel outside the channel had the elevation of the nearest point in the channel. Water run-off on the site was derived from the DEM using the three-step method developed by Jenson and Domingue (1988). A depres-
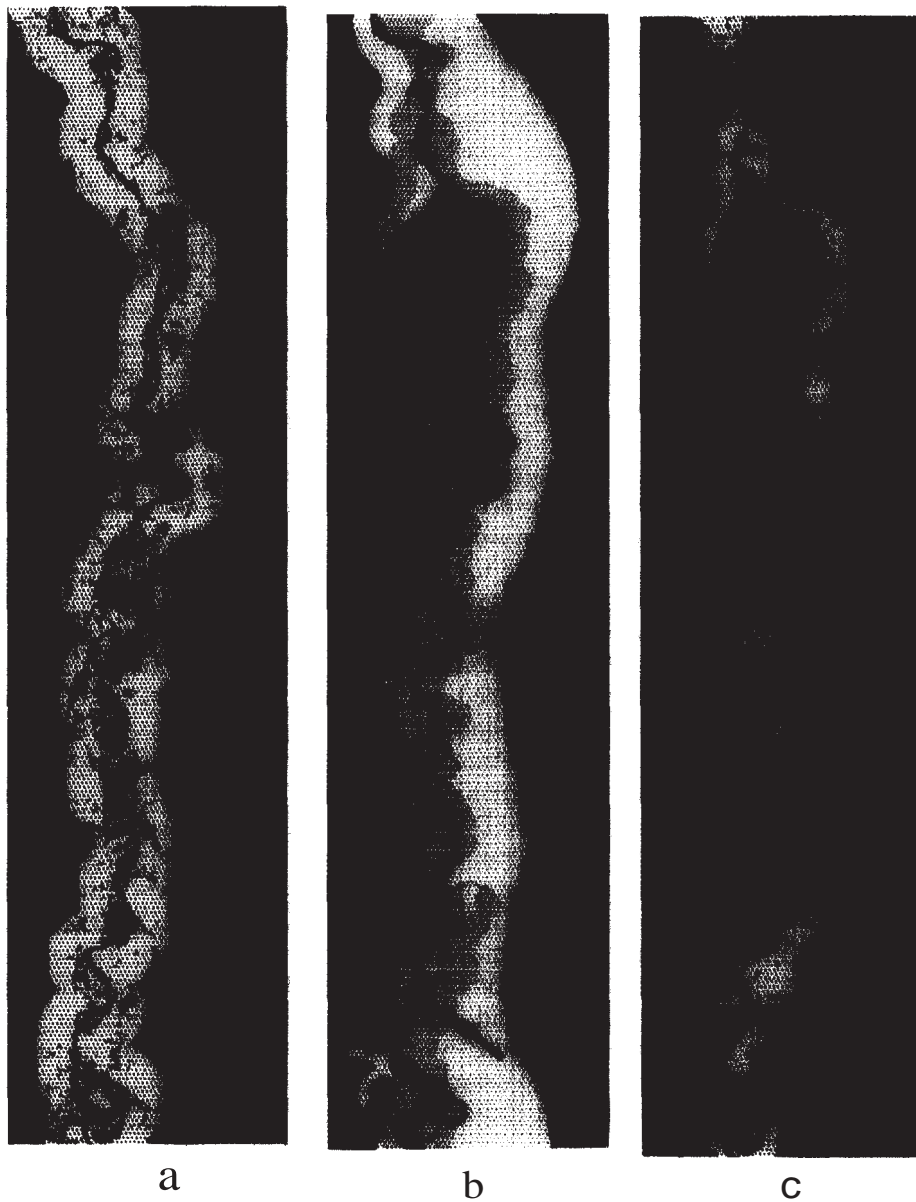
Fig.4. Localization of the riparian woodlands in the Garonne valley, over a stretch of 30 km using TM data and other environmental data (scale 1: 200000); (a) undifferentiated woodlands in a buffer strip of 1 km from the river; (b) flood frequency map (with occurrences of 1 year, 10 years. lOO years in dark blue, light blue and yellow, respectively); (c) riparian woodlands in the decennial floodplain. The arrow corresponds to the study site in Fig. 5.

sionless DEM was first created. Then a flow direction data set was computed by considering that the water at any given pixel could flow into only one of its eight adjacent neighbouring pixels. In the third step, a flow accumulation data set was created, where each pixel was assigned a value which represents the number of the pixel whose water flows into it. For each water level in the river, an immersion map was created. Finally, a synthetic map corresponding to increasing water levels from 0-3 m, by steps of 25 cm, was compiled to show the spatial distribution and dynamic of the floods.

This example of the mapping of flood disturbances shows that the major problem is not just the lack of data but the lack of useful data and the high cast for obtaining such data. In France, funding should be available, following new regulations on risk prevention and water management with explicit requirements for large-scale mapping on floodplains (Garry, 1994, 1996).

5. Conclusion

In the last years, spatial data quality has been evaluated under many aspects (Guptill and Morrison, 1995). This paper has tried to remind that in vegetation studies, data quality rests primarily on the selected system to classify vegetation and that remote sensing or GIS are just tools to facilitate it, not a substitute for it. With Zonneveld (1990) we agree that 'remote sensing (including the unsurpassable aerial photographs) and any other modern means, is just one of the many handy tools which would be unwise and inefficient not to use'. The danger with GIS is that decision-makers on environmental projects accept impact analysis or any other type of study from any company whose sole positive feature is to have bought the latest upgrade of GIS software. Zonneveld (1990) has said it already many times: 'integration is essential, but integration is not to mix, or whip or whisk'. Obviously, the production (or the use) of a vegetation layer without a clear classification system and a cartographic method to represent it should be rejected. From a broader point of view, the quality of environmental data should be evaluated similarly.

Early debates on vegetation mapping clearly showed that vegetation cannot be described in a unique and absolute way. The use of multispectral images acquired by earth observation satellites with a digital format cannot avoid such evidence. De facto the old controversy which opposed physiognomists and taxonomists still exists between teams working on the physical modelling of vegetation and teams working on the biodiversity of vegetation. For example, in the French remote sensing community there is a dichotomy between the self-proclaimed 'scientific teams' (i.e. those who can model 'ecosystems' on different scales) and the 'application teams' (i.e. ecologists, geographers and other old-fashioned ground data collectors who still have scruples about modelling the environment). Similarly, in the GIS community, concepts are discussed mainly by computer specialists and not by thematic cartographers who are considered to be 'potential users' or 'map-layers producers'.

The use of satellite remote sensing data for vegetation mapping, especially

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Fig.5. Flood disturbance map in the Garonne valley, over an area of 5 km^2 The distribution of floods in the valley varies according to the local microtopography and to the in-channel flow. The increasing water levels are ranging from 0 (in white) to 3 m (in dark grey), by steps of 25 cm. This range of floods can be observed every year and can better explain the local diversity of the riparian vegetation than usual flood frequency maps like in Fig 4b.

riparian vegetation, was considerably more limited than aerial photographs, yet it facilitated a more quantitative approach to vegetation. Limitations were mainly due to the coarse spatial resolution of data and to the absence of spatially oriented classification algorithms. However, in the near future, progress is expected in both domains.

For understanding the distribution and the dynamic of riparian vegetation, disturbances maps are necessary. The solution is the development of multi-organisational information systems where botanists are fully contributing operators, providing information on riparian vegetation and participating in the conceptual approach of the GIS. No discipline can create its own spatially oriented information system independently from the others. Especially in floodplains where the official environmental approach is often restricted to an hydraulic vision. Would it not be more justified to give botanists a little more leeway in environmental studies?

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