Quantitative diachronic spatial analysis using GISs to assist farming and forest land management in periurban areas. As applied to two French periurban districts included in the Aix-Marseille conurbation.

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The process of low-density urbanisation in periurban areas has lead to the emergence of complex spatial structures in which patches of farming, forest and urban land are mixed together [Antrop 00]. Several issues are at stake in this development. The first, in the Mediterranean area, is an increase in the risk of forest fire, firstly because the probability of fires breaking out is higher where there is a large amount of human activity within forestland, and secondly because what is threatened by a possible fire (persons and goods) is highly valuable. The second main spatial problem is the defacing of the landscape, which reduces the appeal of the area both for tourists and inhabitants. The third issue is that agriculture is disappearing as urbanisation eats away the farming land. Besides the economic and social consequences, which are usually small, the disappearance of agricultural activity leads to farming land being deserted but not being built on, and this increases the risk of fires breaking out and spreading, as well as the landscape being defaced. These three issues are closely related to the ratio of the different kinds of land cover, but also to their appearance and the relationship between them.

The urbanisation of French rural districts surrounding large towns is partly controlled by local decision-makers. By defining the "Land Use Plan"[1], the town council decides which part of the district space will be used for farming, forest or urban activities. However, decision-makers have to arbitrate between various lobbies as well as plan the development of the local economy and assess the major problems of land management in the district. If they are to give more importance to the necessity of long-term land management than to satisfying the lobbies, they need quantitative information and maps depicting the state and transformation of the space which makes up their district.

Town mayors of periurban districts included in the Aix-Marseille conurbation asked us for tools to assist them in managing the process of urbanisation through the "Land Use Plan". They were interested in depicting and measuring the spatial development of their district so that they could better manage the landscape and the upkeep of the land through farming as well as control the risk of forest fire.

In response to their request, we used GISs to produce maps and indicators characterising spatial transformation. GISs having become widespread over the past twenty years, quantitative spatial analysis tools have been developed by geographers and experts in other disciplines [Geoghegan 97]. In particular, vector-based indicators have been developed in landscape ecology in order to relate the topological structure of land to the functioning of ecosystems [Baudry 82, Lefeuvre 88,]. This research has lead to the development of computer applications, some linked with GISs and some not, to calculate structural indicators of varying complexity. We have attempted to adapt some simple indicators in order to respond to more general land management issues, especially those related to forest fire risk, landscape defacement and the functioning of farming systems [Maillé 00].

Two periurban districts included in the Aix-Marseille conurbation

The Aix-Marseille conurbation is located in the southeastern Mediterranean area of France. It is a network of large towns (Marseille, Aix-en-Provence, Vitrolles/Marignane, Istres, etc.) linked by several routes (roads, highways, railways, etc.) and separated by periruban areas with varying levels of urbanisation density and some patches of

[1] " Plan Local d'Urbanisme ", former " Plan d'Occupation du Sol (POS) "

farming and forest land. The districts studied, although quite close to each other, are located in very different spots. District 1 (3682 ha) is at the centre of the triangle formed by the three main urban nuclei (Marseille, Aix-en-Provence, Etang de Berre). This district mostly covers the “Plateau d’Arbois”, a large stretch of natural land with vegetation quite damaged by past human activity, but where urbanisation is still quite moderate. However, this natural land is not considered to have great worth as heritage. District 2 (1086 ha) is located just between the urban area of Aix-en-Provence (east side), and the “Sainte Victoire Mountain”. This large piece of natural land is considered to be of great patrimonial and cultural value, notably due to the activities of famous impressionist painters such as Paul Cezanne at the end of the XIXth century. The urbanisation policies of the two districts have also greatly differed : since the seventies, decision-makers in district 1 have furthered the development of residential and commercial areas while those in district 2 have promoted the district’s cultural heritage and natural land by developing residential areas of very low density.

Methodology

The first stage in this work was creating a diachronic cartographic depiction of land cover transformation on a GIS by interpreting aerial photographs taken at different periods: 1968, 1985 and 1999 for district 1, 1964 and 1996 for district 2. For early periods (1964, 1968 and 1985) we used small-sized photographs (24cm x 24cm or smaller for the earliest ones), with scales between 1/30,000 and 1/17,000. These were scanned, rectified and assembled, then interpreted and digitised directly on the screen. For recent periods (1999 and 1996 respectively for the first and the second district) large-sized (A0) aerial photographs were printed. The photograph interpreter traced a plan which was first digitized on a digitizer (table), then the cover obtained was rectified. In both cases, a vectorial rectified GIS cover for each period was obtained.

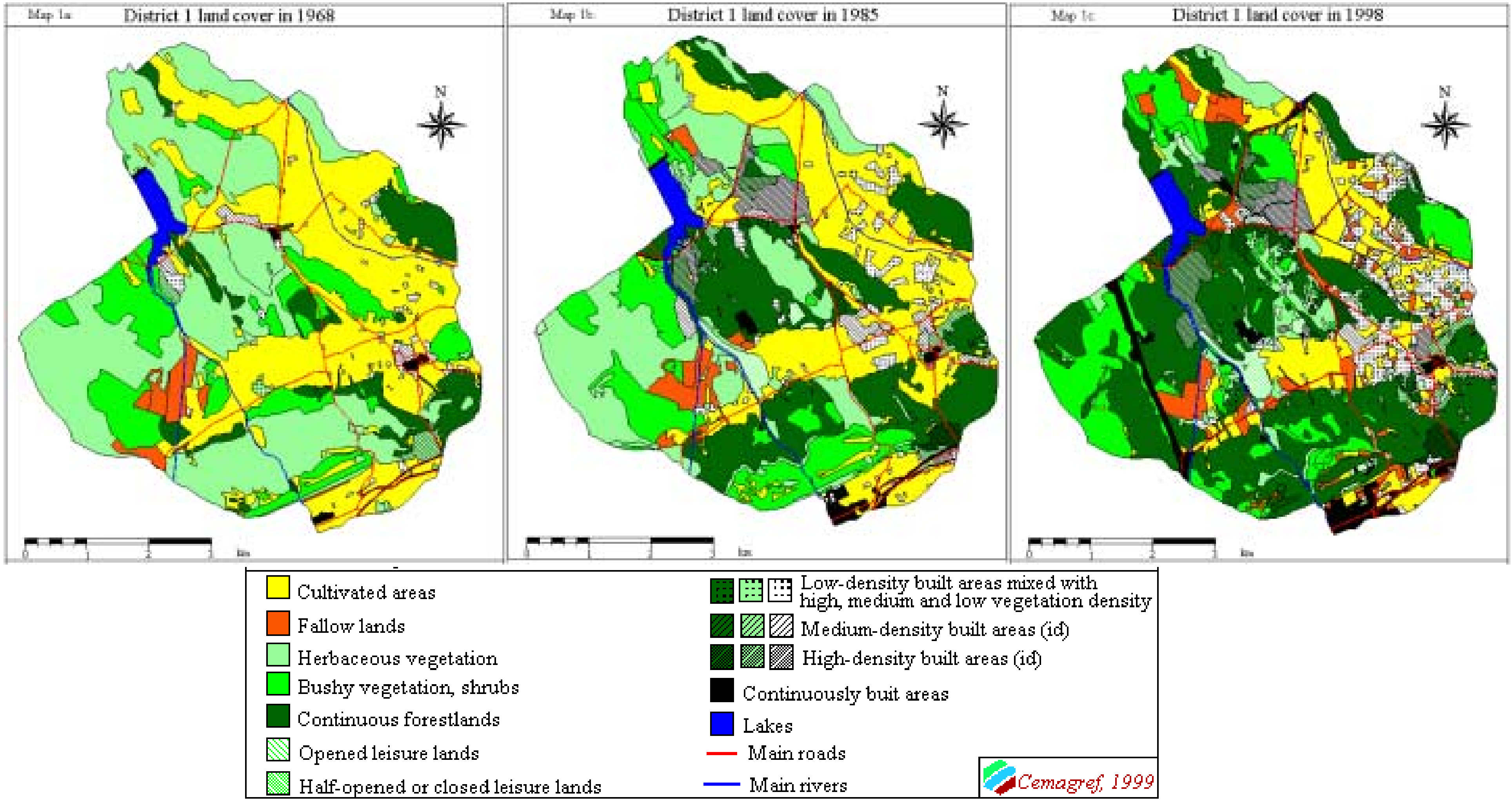
The interpretation of the photographs was based on a specifically defined three-part nomenclature. Firstly, the three main categories of land use were distinguished, i.e. farming, natural and urban, without any reference to their appearance. Secondly the appearance of each land use category in relation to its hypothetical effect on forest fire risk, landscape and spatial constraints for farming activities was described. Thus, a distinction was made between farming land, annual plants and grassland, small shrub plants (vines) and tree plants (olive trees and other tree plants). Recently deserted land (fallow land) was also classified as farming land because of its potential use for farming. Among the different types of natural land a distinction was made between open and half-open uncultivated land and forestland. Types of urban land included residential areas with non-stop construction, industrial and commercial areas, wide roads and highways, and complex land with a mixture of vegetation and construction. Thirdly, a three-class indicator of the density of construction was given to complex land (low, medium and high), and an indicator of vegetation density was given to natural land and complex land (from 0 for totally open land to 5 for unbroken forestland).

The vectorial GIS covers obtained were topologically crossed over so that it was possible to measure and locate every kind of land transformation and to produce diachronic maps. However, a quantitative structural analysis was made by comparing each synchronic cover before crossing them over. In this paper, we give examples of quantitative analysis results only fort the first part of the nomenclature.

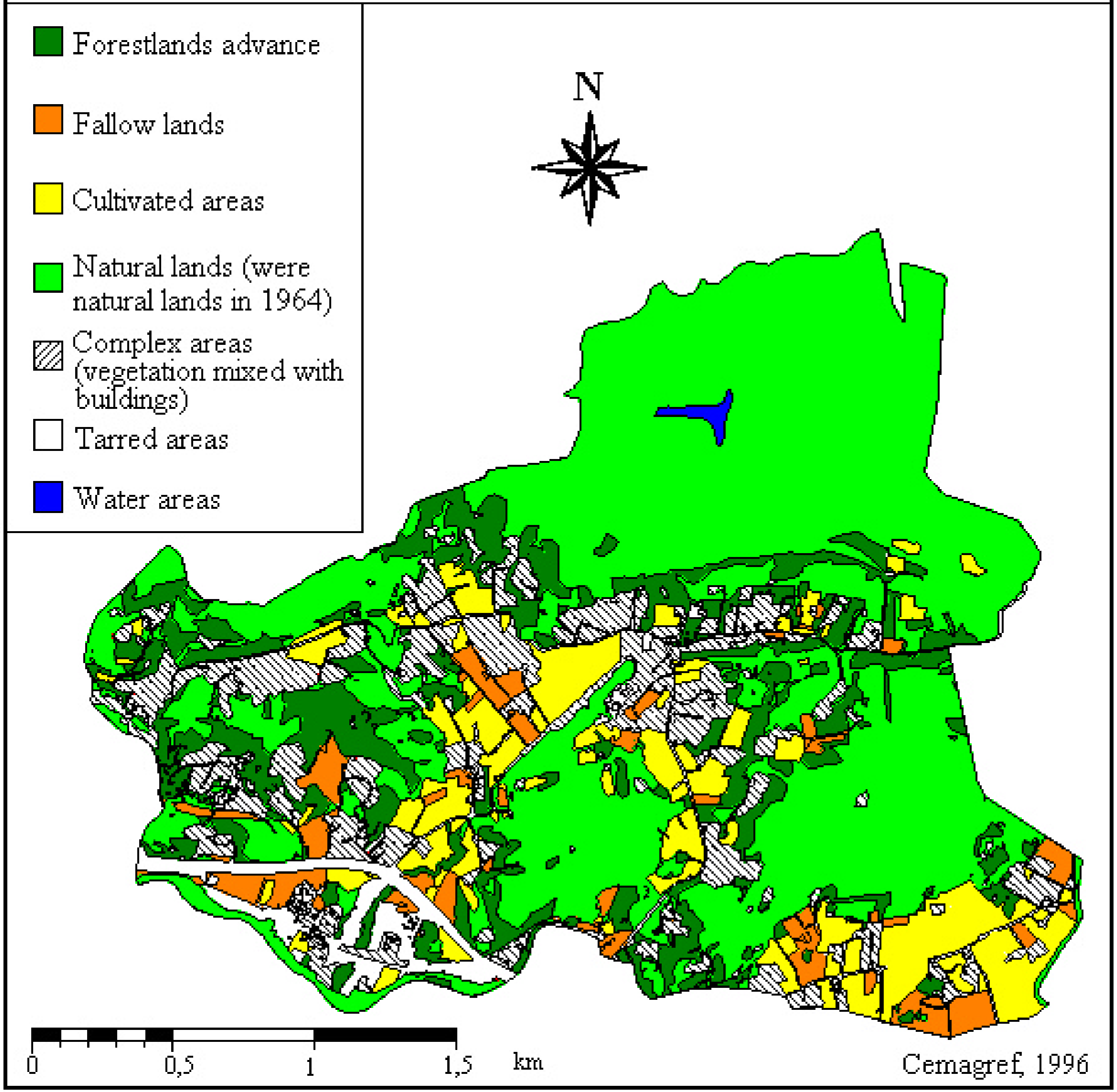
Cartographic products: from GIS covers to maps

The first set of products provided to local land managers to help them to make decisions was maps. The aim was to show changes in land cover and identify places where transformation is particularly strong and where it might be necessary to intervene. For local organizers, maps are also important aids in helping local participants to become aware of the changes in their own area.

Between the simple covers and the maps, two main operations were carried out: land categories were grouped together and a choice of graphic symbols was made. Grouping together land categories makes it possible to choose the appropriate level of detail to be depicted on the map so that local participants can read and understand it. A choice in graphic symbols was made, namely that of colour, with three main aims in view : giving an idea of the meaning of the objects depicted, giving an idea of the landscape, especially as to how open it is, and underlining the


Map 1a
District 1 land cover in 1968
Map 1b
District 1 land cover in 1985
Map 1c
District 1 land cover in 1998
N
Cultivated areas
Fallow lands
Herbaceous vegetation
Bushy vegetation, shrubs
Continuous forestlands
Opened leisure lands
Half-opened or closed leisure lands
Low-density built areas mixed with high, medium and low vegetation density
Medium-density built areas (id)
High-density built areas (id)
Continuously buit areas
Lakes
Main roads
Main rivers
Cemagref, 1999

Map 2: Forestlands advance between 1964 and 1996 on district 2



most important features. Two kinds of maps were produced: synchronic ones, stemming from simple vectorial covers, and diachronic ones stemming from topologically crossed GIS covers. Synchronic maps can show general spatial transformation by placing different periods side by side. Diachronic maps are used to show and precisely locate a few specific transformations.

Synchronic maps 1a, 1b and 1c mainly reveal three general changes in the land cover of district 1 between 1968 and 1998: farming land eaten away by urbanisation, the tendency of natural land to become "closed in" by vegetation (open land developing into forest), and a global tendency towards a greater complexity in spatial structure. Different categories of farming land were grouped together, excepting fallow land, since land desertion was an important phenomenon to underline. Thus, quite a bright colour was used to represent it. Vegetation and construction density was also depicted, each grouped into three classes, using increasingly darker colours (green and grey respectively). Diachronic map 2 shows how forestland has overtaken farming land in district 2.

Maps are not only one of the main products provided to local decision-makers, but a starting-point in quantitative analysis, particularly for structural analysis. They are used to detect different kinds of structures to be analysed and offer significant and useful indicators. Moreover, indicators have to be interpreted on the basis of some hypothesis, which can be validated by the visual analysis of maps [Maillé 01].

Comparative quantitative analysis of area changes

Although in each case the period of comparison is slightly different, the surface variation figures of each main land category (farming, forest and urban) reveal small differences between the land transformation of the two districts in terms of surface variation (table 1).

Table 1

Hectares	District 1				District 2			
	1968	**1998**	**Variation**	**Variation Rate**	**1964**	**1996**	**Variation**	**Variation Rate**
Farming land	1310	703	-607	-46%	472 (43%)	157	-316	-67%
Natural land (including forest)	2174	1987	-186 *(5%)*	-9%	595 (55%)	716	+121	+20%
Urban land	149 *(4%)*	936	+786	+526%	19 (2%)	205	+186	+979%
Other (water land cartographic	*49 (1%)*	*56 (2%)*	*+6*		*0*	*8 (1%)*	*+8*	
TOTAL	3682	3682			1086	1086		

Percentage figures indicated in brackets are relative to the total surface of the district. The variation rate is the percentage of new land relative to the initial surface of each land category.

The rate of urban land increase is notably higher for district 2 than for district 1. However, relative to the total district surface, the proportion of new urbanised land is lower in district 2, and notably lower for absolute surfaces. The rate of urbanisation is quite similar for both districts.
On the other hand, the rate of farming land variation is higher in district 2. Within this district, the disappearance of farming land cannot be due to urbanisation alone. Natural land surface has increased whereas that of district 2 has slightly decreased. We can suppose part of the farming land was deserted and developed from fallow land into forest.

To clarify these figures, we need to have a better knowledge of land transformation. Topological crossing reveals not only the surface changes in each land category but also their origin (what current land patches were covered with years ago). Results of topological crossing are given in table 2.

Table 2

Hectares	District 1 (1968-1998)					District 2 (1964-1996)			
	farming land	**natural land**	*Crossing errors*	**Total**		**farming land**	**natural land**	*Crossing errors*	**Total**
New urban area on…	521 (65%)	281 (35%)	*-16*	786 (100%)		167 (83%)	32 (17%)	*-13*	186 (100%)
Increase in natural land	> +79 *(crossing errors maximised)* > +3.6% of the initial natural land surface					> +140 *(crossing errors maximised)* > +23% of the initial natural land surface			

In both districts 1 and 2 most of the urbanisation process has occurred on farming land, but part of it has occurred on natural land. The totality of new natural land was, of course, farming or fallow land in the sixties. This means that forest land has taken over deserted farming land while another part of it has been used for urbanisation. The phenomenon of forestland overtaking deserted farming land is significant in district 2 but relatively insignificant in district 1. However, natural land in district 1 has grown more and more closed due to vegetation, as shown on map 1, and can be measured through changes in the respective surfaces of open, half-open and closed natural land (chart 1). This change is interpreted as follows: almost all of the natural land was used as pastoral land up to the middle of the last century. When this activity virtually came to an end, the forest started to grow progressively denser. In district 1, this development is not apparent because a large forest fire opened natural land in 1989.

Landscapes produced by low-density urbanisation on farming land are open, with high visibility of buildings (whence its “urban” character) and a low risk of fire spreading. However, bushy fallow land mixed with construction and farming land, sometimes in contact with dense forestland, might increase the risk of fires breaking out. Fallow land is also considered to reduce the aesthetic quality of the landscape. On the contrary, newly built areas on former natural land are closed due to vegetation, with a high risk of fires breaking out and spreading. Visibility of buildings is low and this kind of landscape has a more “natural” character.

The disappearance of farming land is mainly due to land being taken up by urbanisation. However, there are still some farmers, and the high rate of fallow land and the phenomenon of forestland overtaking natural land leads us to believe that other parameters are involved in the desertion of farming land. Spatial structures change too, and we need to quantify this change to relate it to farming activity and to compare the two districts. The same goes for the character of the landscape and the risk of forest fire which are not only related to the surface, but also to spatial structure.

Topological spatial analysis : spatial complexity assessment

Visual analysis of the maps reveals a tendency for spatial structures to become more and more complex. One hypothesis is that spatial complexity has a major influence on forest fire risk, the quality of the landscape, and the possible uses of farming land :

- On complex land, people and goods often share space with highly combustible forestland, and are thus seriously threatened by forest fire. Moreover, as most forest fires are the result of human error, the risk of one breaking out is higher in these kinds of spaces.
- Landscapes studies reveal that it is easier to make sense of a simple, well-arranged landscape than of an overly complex space (simple landscapes are said to be more “readable”).
- When space becomes too complex, plots of farming land become smaller and more scattered, so that it is difficult (and costly) to use them for farming. Barriers such as highways or other urban areas are very difficult to cross over with farming equipment, which increases the difficulties entailed in making use of farming land.

To assess complexity, structural spatial analysis can use various spatial models. Because our methodology is based on aerial photographs, manual analysis directly produces vectorial covers [Muraz 00], and because our analysis objectives are, by hypothesis, highly related to the relationship existing between land patches, we have chosen the vectorial model. This model describes the interfaces between different land categories in terms of lines. The topology of complete lines and polygons performed by the GIS application used (ESRI ArcInfo) informed us of the attributes (surface and category) of both polygons separated by each interface, as well as the length of this interface.

Spatial complexity, perceived through the visual analysis of maps, can first be related to the average shape complexity of each patch of land comprised in the GIS covers. The complexity in shape of the land patches can easily be assessed through the ratio between their perimeter and their surface [Haggett 73]. A disk has a minimum ratio, thus the ratio necessarily increases for any other shape. The Patton shape indicator (P) is, moreover, equal to 1 for any disk [Roy 90].

$$P = \frac{Perimeter}{2\sqrt{p} * Surface}$$

However our aim is to assess the complexity of the relationship between the different land categories, rather than the shape complexity of each patch of land separately. From the Patton indicator, indicators can be constructed which represent the level of interlocking amongst land categories taken two by two [Baudry 85]. We chose the following indicator of “interlocking”:

For 2 polygons with S_1 and S_2 surfaces, joined by the interface length L_{1-2}

$$I = L_{(1-2)}\sqrt{\frac{2}{S_1 + S_2}}$$

This equals 1 for 2 squares of equal surfaces, joined on one side. This is applied to the whole cover as follows:

$$I_{(AB)} = \sum_{i(AB)=1}^{n_{i(AB)}} L_{i(AB)} \times \sqrt{\frac{n_A + n_B}{\sum_{p_A=1}^{n_A} S_{p_A} + \sum_{p_B=1}^{n_B} S_{p_B}}}$$

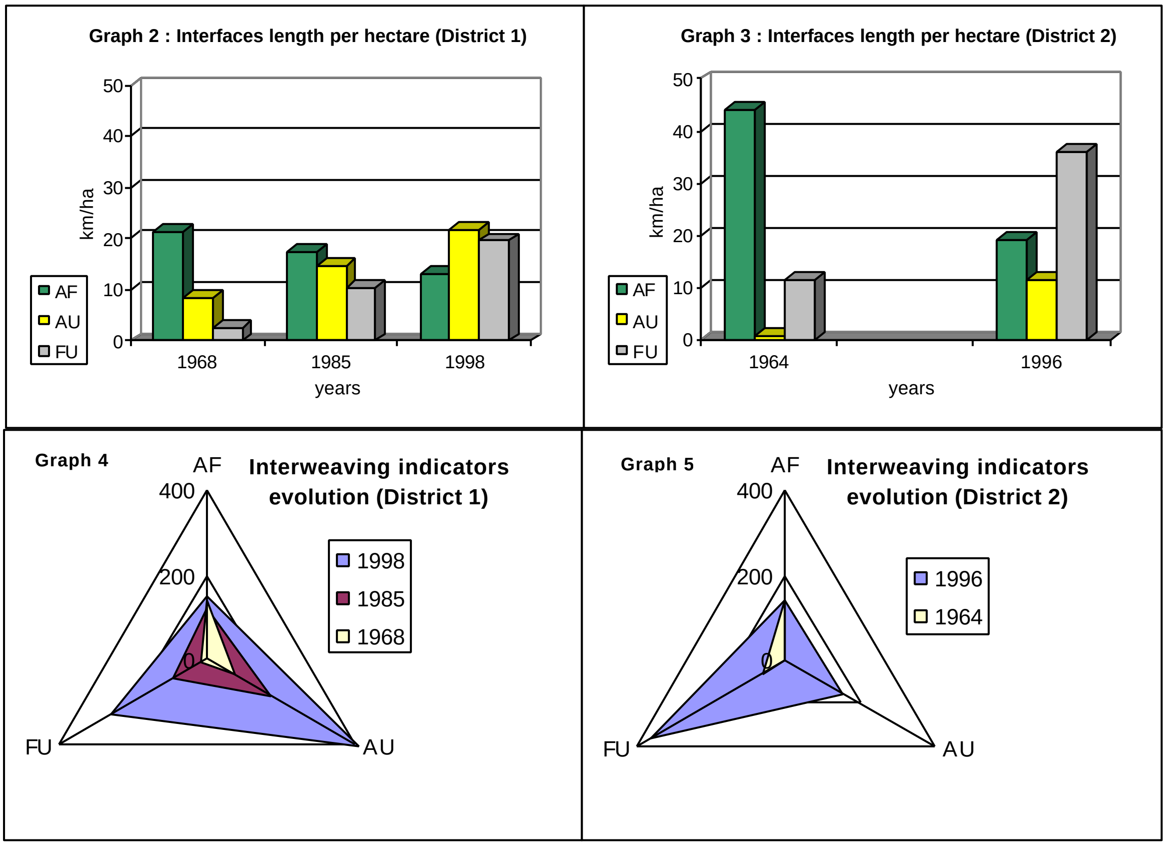
$I_{(AB)}$: *indicator of interlocking between category A land and category B land*
$n_{i(AB)}$: *number of arcs separating patches of category A land from patches of category B land*
$L_{i(AB)}$: *length of arcs number $i_{(AB)}$ separating one patch of category A land from one patch of category B land*
n_A: *number of patches of category A land*
n_B: *number of patches of category B land*
S_{pA}: *surface of patch number p_A of category A land*
S_{pB}: *surface of patch number p_B of category B land*

This indicator depends on the length of the interfaces and the surface of the land, but also the total number of patches in each land category. This means that interlocking will be higher if there is a greater number of patches for the same ratio between an interface length and the total surface of patches affected by this interface. However, it is important to quantify the parcelling phenomenon alone, without any reference to interlocking. There has been a great amount of parcelling in farming land, as access to and size of plots of farming land are determining factors in possibilities of farming use. For each land category, changes in parcelling can be assessed by the number of patches and their average surface. But these are not relationship indicators. It is necessary to know the parcelling of each land category, in relation to the others: for example, constraints involved in isolated plots of farming land within forestland are different from isolated farming land within urban land. To form an idea of relative parcelling we have to identify “islands”, i.e. patches of land sharing interfaces with only one other land category. Although they usually represent only a part of the total number of patches, the number and average surface of these “islands” can reveal the level of parcelling in each land category in relation to the others.

Examples of results

The change in the relationship between the different land categories is first estimated through the length of the interfaces and changes in interlocking indicators. The different lengths of the interfaces of both districts are shown on charts 2 and 3. So that they can be compared, they have been divided by the total surface of the district.

Interlocking indicators are represented on polar charts 4 and 5, where each axis represents an interface. The area of the triangles gives an idea of the global complexity.



AF: interface between farming and forest (natural) land
AU: interface between farming and urban land
FU: interface between forest (natural) and urban land

These charts indicate two different situations in the two districts: increase in global complexity seems to be the same (or a bit lower for district 2), but the more complex interface, in the nineties, is the farming land/urban land (AU) one for district 1 and the forestland/urban land (FU) one for district 2. This is due to the fact that the FU interface is very long in district 2 whereas in district 1, urban land has a longer line of contact with farming land. Although in district 2 the urbanisation process has occurred mainly on farming land, the major complex relationship in this district today is between urban land and forestland. This fact is necessarily related to forestland overtaking farming land, at the same time that urban land was moving onto farming land.

However, a similar situation already existed in the sixties: although the interface between forest and farming land (AF) was very long in district 2, interlocking between farming land and forestland was equivalent in districts 1 and 2: the shape of the patches was quite simple and geometric, generating a quite “well-ordered” landscape. But while the main contact with urban land was farming land in district 1, in district 2 it was already forestland. In district 1, built-up areas were surrounded by farming land, separating them from forestland as shown by the length of the AU interface and the shortness of the FU interface. In district 2, built-up areas were surrounded by natural land. These structures seem to have been “retained in the memory” of the district space, although complexity has increased considerably and the proportions of the land categories have considerably varied.

These results are made more explicit by the degree of parcelling as shown in the following table :

Table 3

Number of patches (mean area, ha)	**District 1**		**District 2**	
	1968	**1998**	**1964**	**1996**
Farming land	*31 (42.3)*	*96 (7.3)*	*4 (118.0)*	*88 (1.8)*
Natural land	*16 (135.8)*	*27 (73.6)*	*30 (19.8)*	*35 (20.5)*
Urban land	*58 (2.6)*	*67 (14.0)*	*40 (0.5)*	*186 (1.1)*
"Islands" of urban land inside farming land	36 (0.6 ha)	18 (0.5 ha)	1 (1.2 ha)	13 (0.1ha)
"Islands" of farming land inside urban land	1 (1.8 ha)	24 (3 ha)	1 (3.9 ha)	16 (1.3ha)
"Islands" of urban land inside natural land	1 (1.7ha)	26 (1.3 ha)	14 (1.4 ha)	119 (0.1ha)

Overall parcelling has increased on both districts for all the land categories. The increase is particularly strong for farming land, and especially in district 2. Parcelling of urban land has also increased, although the mean area of patches has become greater: while new urban nuclei have appeared, a tendency exists for urban patches to merge.

To simplify the analysis, we have presented only 3 of the 6 possible types of relative parcelling on table 3. In 1968, in district 1, urban nuclei had already appeared inside farming land whereas in 1964, it was not really the case for district 2. Before 1998, urban patches had begun to merge in district 1, and these patches entered into contact with forestland so that their number has decreased, but their mean area has not increased. Whereas in the sixties, urban patches were included in farming land, it is now the opposite. In district 2, it is not possible to detect the merging of urban patches in 1996. In both districts, urbanisation has lead to farming land being greatly parcelled out. In the nineties, the plots of farming land totally included in urban land represented 9% and 13% of the total farming surface respectively for district 1 and 2. Access to these plots of land can be difficult and the risk of their being deserted is high: this part of farming land might be given up to fallow land or to construction.
Lastly, there has been a great amount of parcelling of urban land within forestland, specially in district 2 (119 plots of built-up land inside forestland). These are very small patches with one or a few buildings, which were set up within forestland. Although the total surface involved is very low, they are factors in forest fire risk and are threatened in the case of fire.

Finally, in district 1, the urbanisation of farming land has led to low-density complex open areas where patches of urban land are mixed with plots of farming land very difficult to use for farming activity. In the future, to save farming land, improve the quality of the landscape and limit the risk of fires breaking out in fallow land, it will be necessary to limit low-density urbanisation, if necessary by increasing the density of construction in present urban areas. In district 2, priority will be given to limiting the risk of fire by trying to reduce the complexity of the urban land/farming land interfaces. One way could be to avoid small patches of built-up land within forestland.

Conclusion

There are many limits to the use of quantitative indicators of structural spatial transformation in land management. In particular, although they are based on a quantitative reference (for example, the chosen interlocking indicators equal 1 for the simplest possible relation between patches), they only make sense in comparative processes. Moreover, they represent a particular definition of a given spatial characteristic, which is not the only one possible: interlocking could be measured by other indicators than the one we have chosen, for example some indicators not dependent upon the number of patches. Lastly, indicators have to be interpreted together with the cartographic representations.

The next step will be to extend the work scale, to get more general results. We've begun to map spatial transformations of a group of 33 districts using recent and old satellite remote sensing images. Then, it would be interesting to quantify the influence of spatial organisation on farming activity and the risk of forest fire (the landscape issue remains qualitative), that is to correlate the indicators to quantitative models. We have already used them to assess the influence of spatial structures on farming activity, using systemic modelling tools to analyse the functioning of farming systems. These are not quantitative models, but it is conceivable to use spatial indicators to assess the cost of spatial organization for farmers using micro-economic models. Moreover, in the future, spatial indicators could be introduced into quantitative fire risk models developed in our research unit.

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