

## FIRST TYPOLOGY OF OAK AND SCOTS PINE MIXED STANDS IN ORLÉANS FOREST (FRANCE), BASED ON THE CANOPY SPATIAL STRUCTURE\*

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### ABSTRACT

In recent years there has been growing interest in uneven-aged or mixed forest stands as a result of new demands of society and of changing forestry practices. Unfortunately, due to their complexity, the dynamics of these stands are more difficult to understand than those of pure and even-aged stands. Thus, new research questions have arisen in terms of stand description, stand dynamics, and growth modelling.

The first step toward better management of such mixed or uneven-aged stands is to describe them precisely — this step corresponds to a classical typological approach. As spatial structure plays a key role in the dynamics of such stands, spatial structure analysis can be used to infer certain types of information based on the biological processes involved in the growth and the dynamics of heterogeneous stands, and thus to build a typology.

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In order to present a first typology of *Quercus petraea* (Matt.) Liebl. (Sessile oak) and *Pinus sylvestris* L. (Scots pine) mixed stands, we analysed the spatial structure in a mixed stand of oak and Scots pine from the French Centre region. We used the classical Ripley function  $L(r)$ , and intertype function  $L_{12}(r)$  to characterise the specific spatial structure of each population, and the structure of the interaction between populations. We then used the results of this analysis to build a typology for these stands, with four main types. These four types may have resulted from ecological processes and historical management, and a typology could be used to simulate realistic virtual stands when real data are unavailable.

**Keywords:** spatial structure; mixed stands; Ripley functions; Orléans Forest; forest management; *Quercus petraea*; *Pinus sylvestris*.

## INTRODUCTION

For a few years, there has been renewed interest in uneven-aged and mixed forest stands (Buongiorno *et al.* 1995; Otto 1997; Pretzsch 1997; Hanewinkel 2001; Johansson 2003; Götmark *et al.* 2005). This interest stems from changes both in the needs of society and in forest management practices. Indeed, there is a general social demand that environmental considerations be taken into account in forest management. Thus, single-species forest management, widely used in France and in several temperate countries, has been put into question. More precisely, mixed and uneven-aged stands are seen as a better answer to the objectives of ecological diversification. They are also perceived to be more resistant to catastrophic climatic events or parasitic attacks (Lygis *et al.* 2004; Simard *et al.* 2005). Forest managers may also see value in these types of stands: better use of poor sites, no clearfelling with resulting periods of bare soil, more even balance between income and expenditure.

However, there is a need for specific new tools to manage these complex stands. Indeed, the description and modelling tools usually used for pure even-aged stands cannot easily be applied to mixed stands, because they are composed of very different trees with highly variable characteristics and growth conditions (Spellmann 1992; Hanewinkel & Pretzsch 2000).

The first step toward better management of such mixed or uneven-aged stands is to describe them precisely, and especially to take into account their variability by defining different types of stands. This step corresponds to a classical typological approach, which may better encompass the variability and the functioning of complex systems (Tomassone *et al.* 1993). In forest management, site typology is often used to describe environmental factors, and to optimise the choice of tree species, as well as to predict the potential production of a forest stand (Arnould & Simon 1988). Moreover, stand typology is used both to globally describe a forest stand for management purposes, and to define optimal silvicultural practices (Lacombe 2001). However, classic stand typologies are based on simple stand-

level variables such as total basal area or diameter distribution (Renaud 1995) and do not take into account individual variability or spatial structure. Therefore it is difficult to use them directly on mixed or uneven-aged stands, that are composed of very different trees, with highly variable characteristics (species, size, age), and that have complex spatial structures.

Spatial structure analysis can be used to adapt some dendrometrical tools, and especially the typological approach, to complex stands (Goreaud 2000; Seynave 1999). Spatial structure plays a crucial part in the functioning of ecosystems (Begon *et al.* 1990). For a forest stand, spatial structure represents the organisation of trees in space, and describes the neighbourhood relations between individuals, possibly taking into account their dimensions (Matern 1960; Bouchon 1979). As the dynamics for each individual tree are strongly influenced by its interactions with the other elements in the ecosystem (Begon *et al.* 1990), spatial structure influences the dynamics of the whole stand. Stand spatial structure results from history, past biological processes (birth, recruitment, and mortality of trees), and past interactions between individuals. It also defines the variety of local neighbourhoods around each tree, which in turn influence future processes such as competition and mortality. Consequently, studying the spatial structure enables us not only to describe the stands, but also to establish some links with the various processes implied in their operation and dynamics (*see* for example Moeur 1997; Batista & Maguire 1998; Barot *et al.* 1999; Hoshino *et al.* 2001, 2002; Goreaud *et al.* 2002; Park 2003). What is more, the analysis of spatial structure is now commonly used in plant ecology (e.g., Tomppo 1986; Haase 1995; Pélissier & Goreaud 2001; Wiegand & Moloney 2004).

The aim of this paper is to present a first typology of oak and Scots pine mixed stands, based on the spatial structure of canopy trees.

Our study focused on mixed stands of Sessile oak and Scots pine in Orléans Forest in France. We describe these stands in the first section of this paper, and then present the method used to analyse the spatial structure. We applied our method to 24 plots of mixed stands, and used the results to define four types, which we organised into a typology. Finally, we discuss how the four types may have resulted from ecological processes and historical management, and how such a typology could be used to simulate realistic virtual stands when real data are unavailable.

## STUDY AREA AND DATA COLLECTION

Orléans State Forest is one of the largest public woodlands in France (350 km<sup>2</sup>). It is located a few kilometres north of the Loire River. It is a typical flat, lowland forest, stretching from Gien to Orléans (Fig. 1). Our experimental network was set up in the southern part of the forest, characterised by alluvial deposits of sand upon clay. The absence of natural drainage and the non-permeable substratum both



FIG. 1—Location of Orléans Forest (indicated in the map on the right), a few kilometres north of the Loire River. Source: [www.geoloiret.com](http://www.geoloiret.com)

contribute to the development of groundwater tables. Soils are often acidic and characterised by successive water-logging and dry periods.

The ancient oak forest was heavily over-harvested from the Middle Ages to 1850 (ONF 1992). By that time, the oak stands had been decimated, and the numerous gaps accounted for 30% of the total surface area. Between 1870 and 1890, the openings were reforested by either seeding or planting of Scots pine. In this way, the administration intended to reclaim soils and to restore the forest ecosystem. Since that time, oak and pine have been managed together. Today, foresters wish to continue to manage as mixed stands the large area that originated from second-generation pine. These stands are the object of our surveys.

In 2003, our research team started a project aimed at analysing these mixed stands of oak and pine, in collaboration with the National Forest administration. We set up 1-ha experimental plots in each compartment with homogeneous site conditions and containing more than 10% of mixed canopy. A first study (unpubl. data) showed wide variations in the mixture rate and tree-size distribution in these stands. For the study reported here we chose 24 plots representative of these various mixture rates and tree-size distributions, located throughout the southern part of the forest.

We mapped these 24 plots in order to study the spatial structure of the oak/pine mixed stands. Within each 1-ha plot, we measured the exact location of each tree (diameter >7.5 cm) using a theodolite. Measurements were taken from four points, each located at the centre of one 2500-m<sup>2</sup> quarter section of the plot. For the occasional trees that may have been obscured by other trees, the direction was assumed to be the same as the direction of the obscuring tree, and the distance was estimated in a slightly modified direction. For each tree located, we noted its species, circumference, and whether it formed part of the forest canopy or was in the understorey. One of our 24 maps (plot 20) is illustrated in Fig. 2 which shows the position (obtained by the x, y co-ordinates) of all the different tree species represented by different symbols; the size of the symbols indicates whether the tree belonged to the canopy (bigger symbols) or to the understorey (smaller symbols).

These plots showed a wide variety of tree species, heights, and circumferences, which led us to define various sub-populations corresponding to homogeneous groups of trees—mainly oak and pine, but also birch, chequer-tree, and hornbeam. We also distinguished the trees in the canopy from the trees in the understorey, which were not present in all plots.

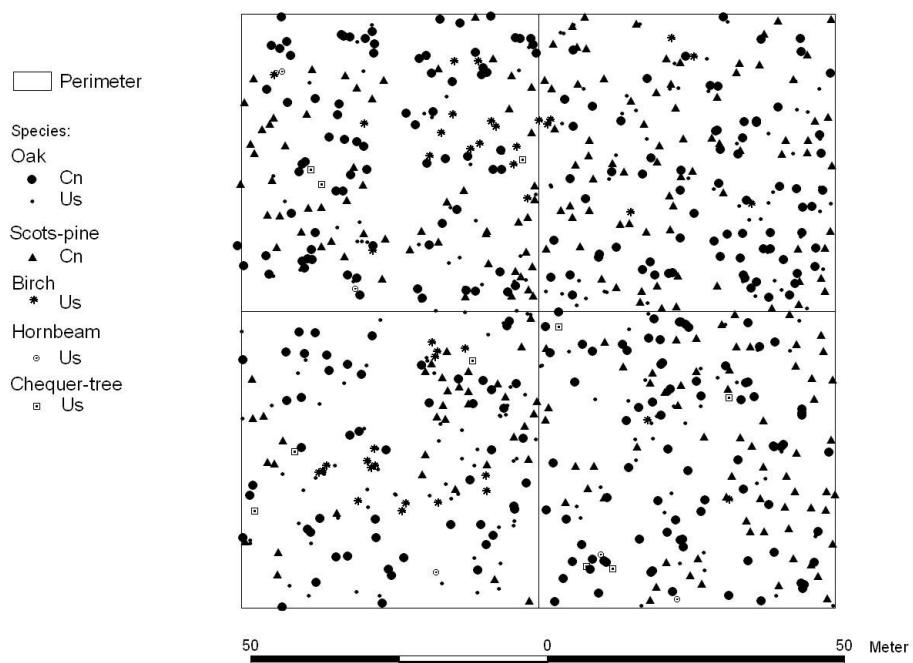


FIG. 2—Location of trees in plot 20 in Orléans Forest. The different species are represented by different symbols (oak are circles, Scots pine are triangles). Larger symbols indicate that the tree belongs to the canopy (Cn); smaller symbols indicate that the tree belongs to the understorey (Us).

In this paper, we focus only on the trees that are included in the forest canopy, because canopy trees are known to play a major role in the stand dynamics. Indeed, the structure of the canopy greatly influences the penetration of light inside the stand (e.g., Schütz 1999; Ricard *et al.* 2003), which then becomes a constraint on the regeneration and growth of the understorey. Moreover, canopy trees represent most of the biomass and define the economic value of the stand. We have therefore considered two sub-populations of canopy trees for each plot, oaks on the one hand and pines on the other. We verified that each sub-population is composed of trees with similar characteristics: the same species, the same height class, and mostly similar circumferences.

## METHODS

### Spatial Structure Analysis

There are many methods used to analyse the spatial structure of ecosystems. For instance, geostatistics focus on the spatial structure of continuous variables, whereas point processes are more relevant for analysing sets of points (e.g., Diggle 1983; Cressie 1993). Therefore, point processes are typically used to analyse the spatial structure of trees in forest stands (Tomppo 1986). Among the possible tools for point process analysis, Ripley's  $K(r)$  and  $L(r)$  functions are increasingly being used in ecological studies (*see* Batista & Maguire 1998; and Goreaud 2000 for a summary). While these statistics require a complete map of the area to be characterised, they are able to describe the spatial structure of point patterns at different scales (Cressie 1993).

In this study, we used the classical  $K(r)$  and  $L(r)$  functions (Ripley 1977) to characterise the specific spatial structure of each sub-population, and the  $K_{12}(r)$  and  $L_{12}(r)$  intertype functions (Lotwick & Silverman 1982) to characterise the structure of the interactions between sub-populations (i.e., between oaks and pines in the canopy).

The  $K(r)$  function is based on the average value of the number of neighbours at various distances  $r$  from an arbitrary tree in the stand (Equation 1).  $\lambda$  is the density of the sub-population, considered to be homogeneous all over the plot, and estimated as the ratio of the number of trees in the sub-population to the area of the plot.  $E()$  is the expectation operator.

$$\lambda K(r) = E(\text{number of trees within a circle of radius } r \text{ centred in one tree}) \quad \text{Eqn 1}$$

When analysing spatial point patterns, the classic null hypothesis corresponds to Complete Spatial Randomness (CSR), which means that the location of each tree is completely random and completely independent from the location of the other trees (Diggle 1983; Cressie 1993). For this null hypothesis, the expected value of  $K(r)$  is  $\pi r^2$ , i.e., the area of a circle of radius  $r$ , at every range  $r$ . In order to simplify

the comparison with the null hypothesis and to stabilise the variance, we used the classic  $L$ -function transformation (Besag 1977) (Equation 2). It follows that  $L(r) = 0$  for CSR,  $L(r) > 0$  for clustering, whereas  $L(r) < 0$  indicates regularity.

$$L(r) = \sqrt{\frac{K(r)}{\pi}} - r \quad \text{Eqn 2}$$

Considering the classic null hypothesis of CSR, we computed the confidence intervals for  $L(r)$ , and for each range  $r$  at the  $\alpha = 1\%$  level using Monte Carlo simulations. More details on the methods and programs used to estimate these functions and their confidence intervals have been given by Goreaud & Pélissier (1999, 2003). We considered that there is significant aggregation (clustering or clumping) for significant positive values (outside the confidence interval) of the  $L(r)$  function at different ranges  $r$ , and significant regularity for significant negative values (outside the confidence interval) of the  $L(r)$  function at different ranges  $r$ . The different spatial patterns and corresponding  $L(r)$  curves are illustrated in Fig. 3. The more positive or negative (outside the confidence interval) the values of  $L(r)$ ,

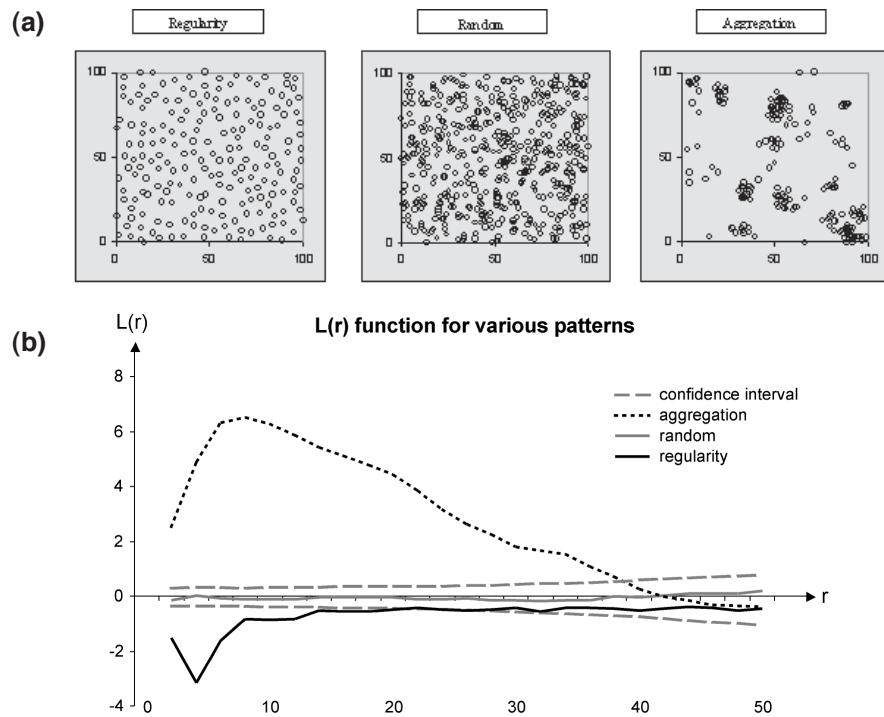


FIG. 3—(a): illustration of regular, random, and aggregated distribution, and (b): corresponding  $L(r)$  (from Goreaud 2000). In Fig. 3(b), we have the  $L(r)$  curves for aggregation (dashed black line), regularity (black line), and random structure (grey line). The CSR curve is between the corresponding confidence interval for the CSR null hypothesis (dotted grey line).

the more significant the resulting structure. When the values of  $L(r)$  are within the confidence interval, we can conclude that the structure is not significantly different from CSR. Since the  $L(r)$  function characterises the spatial structure at different ranges  $r$ , we can describe the spatial structure at many scales: for high resolution (small scale, range, or distance; for  $r < 10$  m), medium scale (for  $10 \text{ m} < r < 20$  m), and low resolution (high scale; for  $r > 20$  m).

The  $L_{12}(r)$  intertype function, which characterises the structure of the interactions between two sub-populations, is based on the same principle as the  $L(r)$  function, but used when two sub-populations (1 and 2) occur in the same plot. The function  $K_{12}(r)$  is based on the number of trees in sub-population 2 within a radius  $r$  of an arbitrary tree from sub-population 1. As for the  $L(r)$  function, the  $L_{12}(r)$  function is a transformation of the  $K_{12}(r)$  function (Equation 3).

$$L_{12}(r) = \sqrt{\frac{K_{12}(r)}{\pi}} - r \quad \text{Eqn 3}$$

When analysing the relative location of our two sub-populations, corresponding to oaks and pines in the canopy, we used the null hypothesis of population independence (Lotwick & Silvermann 1982; Goreaud & Pélissier 2003). Indeed, our two sub-populations correspond to *a priori* different patterns. For this null hypothesis of population independence, the expected value of  $K_{12}(r)$  is again  $\pi * r^2$ , and the expected value of  $L_{12}(r)$  is 0. Hence, for  $L_{12}(r) > 0$ , we have attraction between the populations, and for  $L_{12}(r) < 0$ , we have repulsion of the populations. The confidence interval is built using the same approach as previously explained.

### **Building a Typology Based on the Spatial Structure of the Stand**

We used a hierarchical cluster analysis (Tomassone *et al.* 1993; Everitt 1974, cited by R Development Core Team 2005) to determine groups of plots with similar spatial structure.

For each plot, we considered the values of the  $L(r)$  function computed for the two sub-populations (oaks and pines in the canopy) at ranges  $r=2,4,\dots,30$  m. Indeed, we wanted to take into account only the short- and middle-range spatial structure, corresponding to inter-tree interactions, not the long-range structure that usually corresponds to soil heterogeneity whose results are difficult to interpret. We obtained 30 values characterising the specific spatial structure for oaks (15 values) and pines (15 values) in the canopy at short and middle distances. We also considered the 15 values of the intertype function  $L_{12}(r)$  between these two sub-populations, at the same ranges ( $r=2,4,\dots,30$  m).

We then computed the matrix of spatial structure distances between all 24 plots, using the classic Euclidean distance between the 45 values characterising the spatial structure of each plot: the square distance between two plots  $i$  and  $j$  was

defined as the sum of the squares of the differences between the corresponding values of  $L(r)$  or  $L_{12}(r)$  (Equation 4). It should be noted that weighting factors could have been used to give more importance to some ranges or functions. However, as we had no statistical or ecological reasons to give preference to certain ranges or functions, we first gave the same weight to each measure (as done by Diggle 1983) (Equation 4).

$$D_{i,j}^2 = \sum_{r=2}^{30} (L_{oak}^i(r) - L_{oak}^j(r))^2 + \sum_{r=2}^{30} (L_{pine}^i(r) - L_{pine}^j(r))^2 + \sum_{r=2}^{30} (L_{12}^i(r) - L_{12}^j(r))^2 \quad \text{Eqn 4}$$

Lastly, we applied the classic hierarchical clustering algorithm to this distance matrix, grouping together the plots whose spatial structure distances were the smallest. We used the corresponding “*hclust*” function in the R software (R Development Core Team 2005). As all the plots corresponding to the same cluster have, by construction, a similar spatial structure, we interpreted the different clusters as different types in our typology.

## RESULTS

We will first detail the results obtained for one of the plots (plot 20; Fig. 2), then present the main spatial characteristics of the oak-pine mixed stands in this study that we have used to build our first typology of the spatial structure.

### One Example: Plot 20

Plot No.20 (Fig. 2) was composed of 239 pines all within the canopy, and 492 oaks of which 284 were in the canopy. We also located 41 birches, 10 chequer-trees, and 11 hornbeams. For this first study, we considered only oaks and pines within the canopy that were also the biggest in terms of diameter.

The results of the  $L(r)$  and  $L_{12}(r)$  functions, estimated for the two sub-populations, are presented in Fig. 4. Canopy oaks have a structure not significantly different from randomness, while canopy Scots pines have a clumped spatial structure (significant positive values of the  $L(r)$  function at all ranges  $r > 4\text{ m}$ ). The two sub-populations present an interspecific repulsion at short distances (significant negative values of the  $L_{12}(r)$  function up to  $r = 4\text{ m}$ ).

### First Typology for Spatial Structure of our Oak - Pine Mixed Stands

The analysis of the spatial structure performed on all 24 plots showed that there was a high variability in the spatial pattern of the plots, concerning both the specific spatial structure of each sub-population, and the intertype structure between sub-populations.

The result of the hierarchical clustering allowed us to summarise this variability and to define four main types of spatial structure. Indeed, the dendrogram corresponding

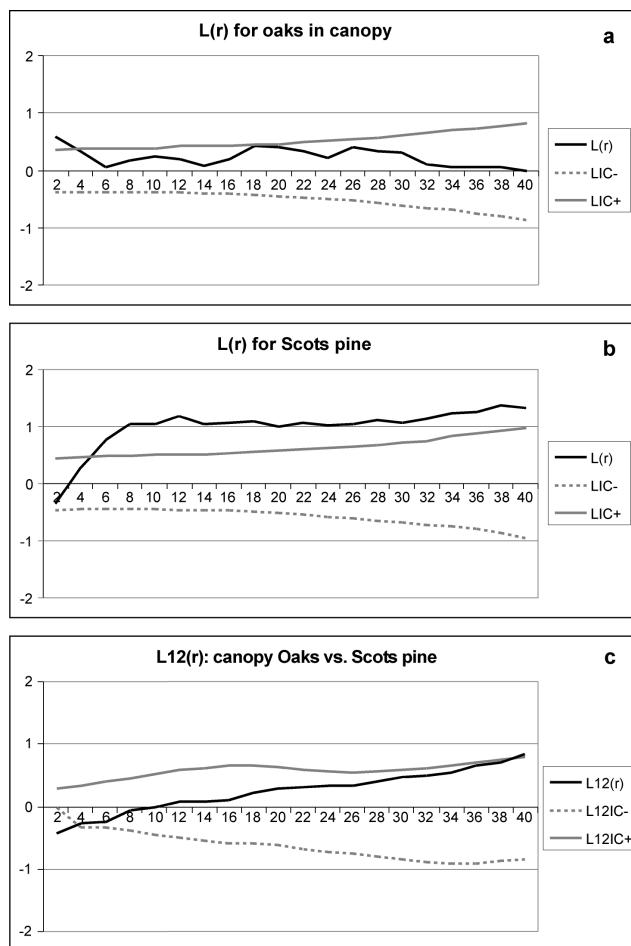


FIG. 4—Analysis of the spatial structure of Plot 20 in Orléans Forest:  $L(r)$  function (black line), and the corresponding confidence interval for the CSR null hypothesis (grey line), for oak and pine in the canopy: (a) oak, (b) Scots pine. Intertype  $L_{12}(r)$  function (black line), and the corresponding confidence interval for the Population Independence null hypothesis (grey line), for (c) oak vs Scots pine in the canopy.

to our 24 plots (Fig. 5) shows four very clear clusters, that we identified as four types for our typology. These types highlight a form of gradient, from random (type 1) to strong aggregation (type 3) of the two species, with the others falling between these two. The intertype structure also ranges from independence (type 1) towards clear interspecific repulsion (type 3).

#### Type 1

The first type is characterised by a relatively similar structure for oaks (Fig. 6a) and pines (Fig. 6b), not differing significantly from randomness or only slightly

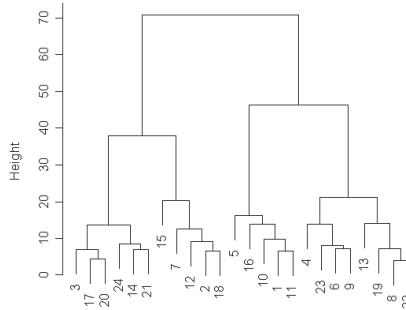


FIG. 5—Dendrogram of plots. We can identify four main clusters of plots corresponding to four types of spatial structure.

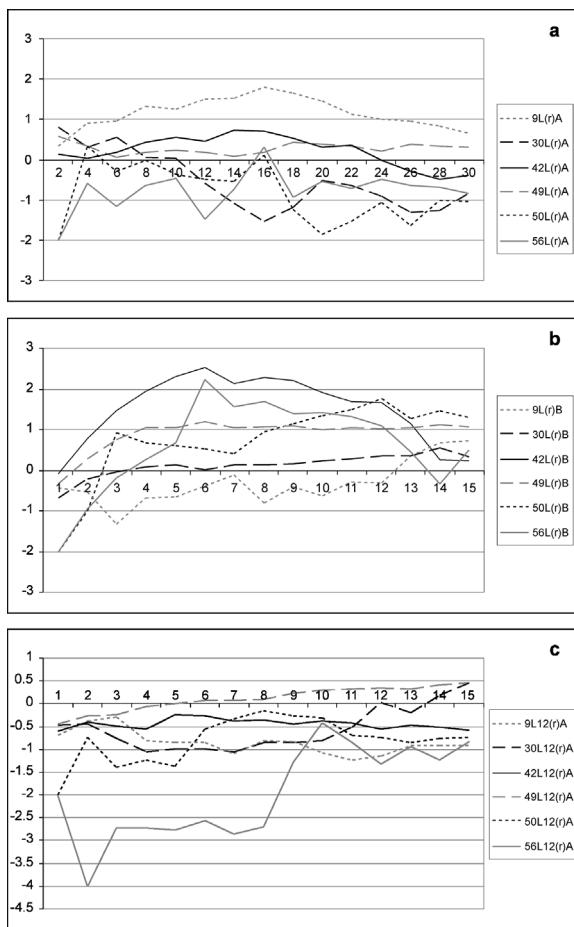


FIG. 6— $L(r)$  function for oak and pine in the canopy for type 1: (a) oak, (b) Scots pine, and (c) intertype  $L_{12}(r)$  function. In Fig. 6a we can see the first subtype with a random structure of oak (grey brackets) and the second type where oak are slightly clustered (black brackets).

clustered. The intertype structure is (Fig. 6c) not different from interspecific independence, or shows only a slight interspecific repulsion. In this type, we can subdivide the different plots into two subtypes: the first where oaks and pines present a random spatial pattern , and the second where oaks are slightly clustered while pines have a random or only slightly clumped pattern (*see* the brackets in Fig. 6a). Plot 20 (Fig. 4) belongs to this type.

#### Type 2

The second type is characterised by a spatial pattern more clumped than the previous type for oaks (Fig. 7a) and a slightly clumped spatial pattern for pines (Fig. 7b), with the two populations showing an interspecific repulsion (Fig. 7c) over a shorter distance.

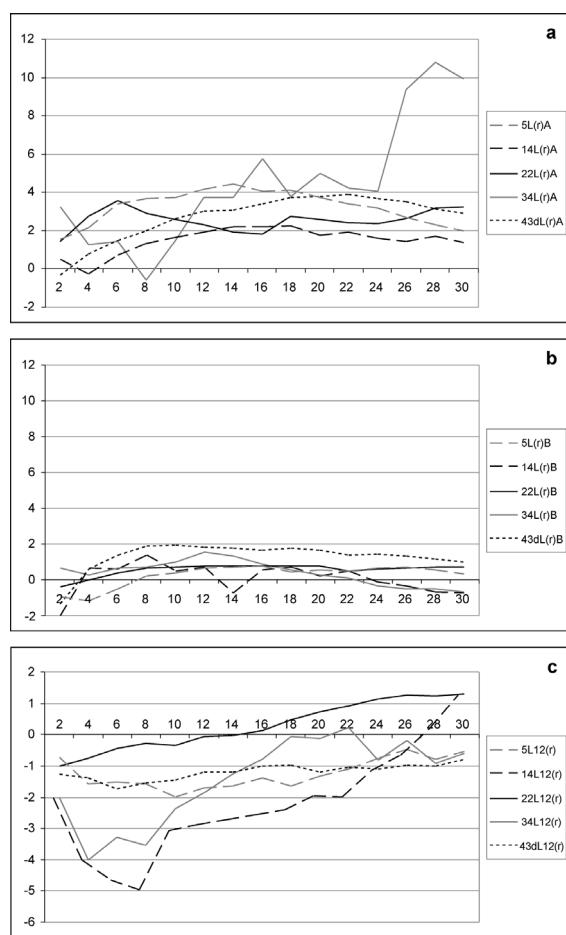


FIG. 7— $L(r)$  function for oak and pine in the canopy for type 2: (a) oak, (b) Scots pine, and (c) intertype  $L_{12}(r)$  function.

### Type 3

The third type is characterised by a clustered pattern for both oaks (Fig. 8a) and pines (Fig. 8b) that is more significant than types 1 and 2. The intertype structure is characterised by interspecific repulsion at the medium and high distances (Fig. 8c). Compared to the first two types, we see a more clustered spatial structure and more significant repulsion.

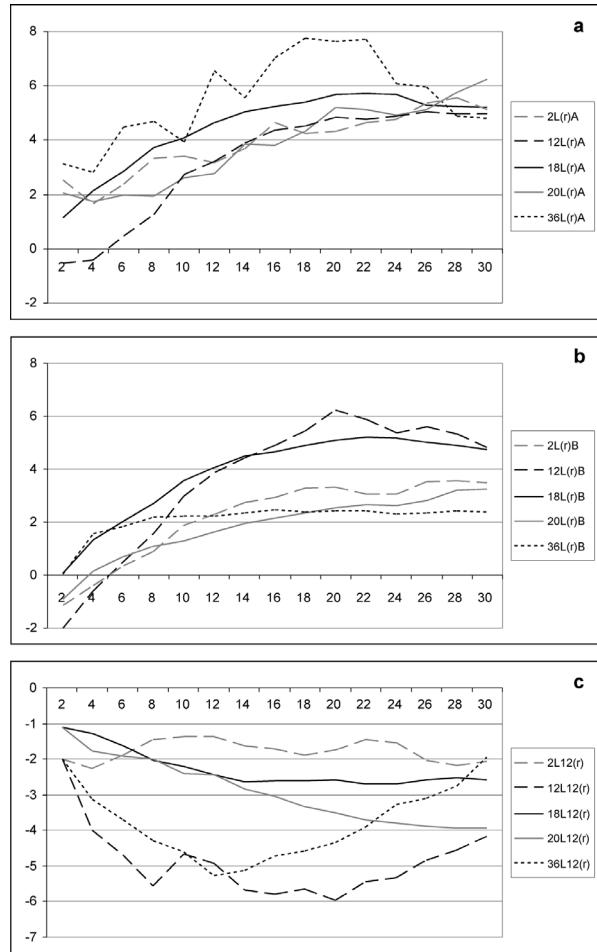


FIG. 8— $L(r)$  function for oak and pine in the canopy for type 3: (a) oak, (b) Scots pine, and (c) intertype  $L_{12}(r)$  function.

### Type 4

The fourth type is characterised by slight aggregation for oaks (Fig. 9a) and strong aggregation for pines (Fig. 9b). The two populations show either an intertype structure of independence or a tendency toward repulsion (Fig. 9c). In this type, we

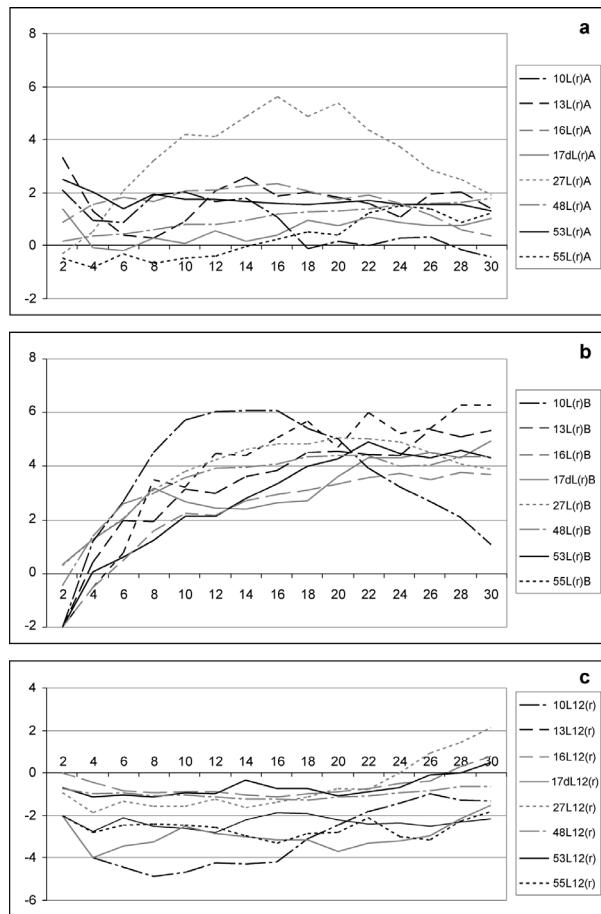


FIG. 9— $L(r)$  function for oak and pine in the canopy for type 4: (a) oak, (b) Scots pine, and (c) intertype  $L_{12}(r)$  function. In Fig. 9c, we can see the first subtype with independence or slight repulsion between oak and pine (black brackets) and the second type were the repulsion is more significant (grey brackets).

can define one subtype where oak show interspecific repulsion with pine and a second subtype where interspecific repulsion is less pronounced, sometimes even showing independence (see brackets in Fig. 9c).

The difference between this type and type 3 is the slight aggregation of oaks, while pines always show a significant aggregation.

## INTERPRETATIONS OF RESULTS

The analysis of the spatial structure of oak-pine mixed stands has led us to demonstrate two main characteristics of these stands. Firstly, aggregation is the most common structure. Secondly, there is high variability in the spatial structure

of our stands with a gradient from random structure (type 1) to strong aggregation (type 3).

These spatial characteristics can help us to better understand how the ecological and anthropic processes have influenced the dynamics of the ecosystems. Many studies have used spatial analyses to characterise the structure of different populations and spatial patterns to infer information on ecological processes that play a part in the dynamic of stands studied (for example, Moeur 1993, 1997; Batista & Maguire 1998; Barot *et al.* 1999; Goreaud 2000; Hoshino *et al.* 2001, 2002; Goreaud *et al.* 2002; Park 2003; Zenner *et al.* 2000; Szwagrzyk 1991). Indeed, the spatial structure of a stand results from different processes that lead to the death of older trees and to regeneration at any given position. For instance, the regeneration of species with heavy seeds is considered to induce aggregates, whereas competition for light or soil nutrients is considered to induce regularity and interspecific repulsion (e.g., Collinet 1997; Goreaud *et al.* 2002).

However, as we are dealing with managed stands, we can hypothesise that the main factor influencing the spatial structure is past management of the stand. Indeed, Orléans Forest is a former oak grove, deforested by excessive cutting at the end of the eighteenth century. Later (between 1870 and 1890), gaps were filled in with Scots pine, chosen for its adaptation to difficult climatic and soil conditions. Thus, we can assume that at the end of that period the spatial structure was mainly characterised by aggregates of oak and pine in interspecific repulsion. This same spatial structure can still be found in our present-day mixed stands, especially in the third type.

For both oak and pine, the presence of more or less aggregated patterns and the fact that regularity is rare lead us to two assumptions: (i) intraspecific competition is not the main factor in stand dynamics, (ii) silvicultural thinnings have not been too intense. The latter is linked to the fact that there are no clear guidelines for thinning in these mixed stands.

We can assume that these aggregated structures are also the result of localised regeneration. Indeed, regeneration in our stands (and more generally in broad-leaved/coniferous mixed stands) is known to be highly dependent on quantity of light, and this leads to the creation of aggregates within gaps (Mosandl & Kleinert 1998; Hoshino *et al.* 2001, 2002, 2003; Park 2003; Paluch & Bartkowicz 2004). Clustering may also be explained by the limited seed dispersal of some species (Menaut *et al.* 1990; Collinet 1997; Barot *et al.* 1999), particularly for sessile oak in our study. With these oaks, seedlings are found in clusters around the mother trees.

For interspecific spatial structure, the trend is sometimes toward independence, and sometimes toward repulsion. We therefore hypothesise that interspecific competition is higher in some plots (type 3), and lower in others.

Interspecific interaction can have a considerable influence on regeneration. In these plots we have found (unpubl. data) that: (i) oak can regenerate under a canopy of pine, but (ii) the opposite situation is very rare (pine regeneration is generally rare under shelter), (iii) in certain plots, no oak regeneration occurred under pine, which could be the result of too great a distance from mother trees, poor soils, or competition with herbaceous vegetation. These remarks are recurrent in many studies on mixed broad-leaved/coniferous stands (Mosandl & Kleinert 1998; Hiura & Fujiwara 1999; Lookingbill & Zavala 2000; Takahashi *et al.* 2003; Paluch & Bartkowicz 2004).

We can therefore suppose that, when oak does regenerate under pine, the spatial structure will evolve towards less aggregation and less interspecific repulsion (types 1 and 4), whereas when no oak regeneration occurs under pine, the spatial structure will remain aggregate with repulsion (type 3).

This difference in spatial structure from one type to another may be explained by differences in soil conditions. Soil heterogeneity has a great influence on regeneration and stand dynamics by creating favourable or unfavourable conditions for individual tree growth. Soil heterogeneity is often the outcome of the spatial distribution of soil resources, resulting either in favourable zones where aggregates will be found, or in less favourable or unfavourable zones which will be more or less empty (Barot *et al.* 1999). Certain species may also use environmental resources better than others, following the ecological niche theory (Hutchinson 1957, cited by Begon *et al.* 1990). This could be the case in our mixed stands, as broad-leaved and coniferous trees may not have the same environmental needs, which could also lead to a structure with aggregates and the two species in repulsion.

## DISCUSSION

In this paper, we have presented a typology of mixed oak and pine stands, based on spatial structure. We have showed clearly that the spatial structure of such stands can be highly variable, and we have identified four types, that can be interpreted as a gradient from random (type 1) to strong aggregation (type 3) of the two species, and from independence (type 1) towards clear interspecific repulsion (type 3). Such results on the variability of the spatial structure can be obtained only because we analysed many plots in the same stands. It is complementary to previous work, usually focusing on one or two plots only (e.g., Paluch & Bartkowicz 2004) We used spatial structure in two important steps. Firstly, we built a typology with four types of spatial structures that helped us to describe the stands. Secondly, we used the generally observed spatial structure to link the present structure with the history of the stand, and to make hypotheses about the ecological processes which had influenced the dynamics of these stands.

Our study was applied to a mixed oak and Scots pine forest, but the method described in this paper can, of course, be used in any other mixed stands.

### **Interest and Limit of Such a Typology**

Such a typology appears to be very important, because the precise description of stand structure should allow forest managers to set out forestry guidelines and to adjust them according to the different types identified. In the current context where knowledge of heterogeneous stands is lacking, this approach based on spatial structure supplies a clear description of mixed stands, a preliminary condition for an appropriate management policy.

Such a typology could also be helpful in simulating realistic virtual stands, that could be used as the initial state for a simulation to proceed with an individual-tree-based growth model. Individual-tree-based models are often used for growth modelling in mixed or irregular stands, in order to take into account the strong individual variability inside these stands (Houllier *et al.* 1991; Spellman 1992; Pretzsch 1997). Such models simulate the evolution of each individual tree according to its particular characteristics and its local environment. There are many models of this type, with a great diversity of competition index — for example, Botkin *et al.* (1972), Ek & Dudek (1980), Schütz (1989), Pukkala *et al.* (1994), Murphy & Shelton (1996), Moeur (1997), Cescatti & Piutti (1998), Nagel (1999), Gourlet Fleury & Houllier (2000), Dube *et al.* (2001), Courbaud *et al.* (2001), Ménard *et al.* (2002), and Chertov *et al.* (2003). However, this kind of model cannot easily be used by forest managers because an initial state with the description and the location of each tree must be provided in order to run simulations. Typically, these data are not commonly available.

However, our typology of mixed oak-pine stands identifies the main spatial characteristics of the stands in terms of spatial types. Furthermore, for each type we can measure many stand-level characteristics such as the rate of mixing in the canopy, the tree density in the canopy and in the understorey, the presence or absence of species in the understorey, the basal area, the diameter classes, and possibly a few inter-tree distances. For a given real stand whose spatial pattern has not been mapped, we could easily measure the stand-level characteristics and the resulting variables could be used to identify its corresponding type in our typology. Then, the main spatial characteristics of the identified type could be used to simulate a realistic stand, using specific point processes.

Our typological approach depends, of course, on the number of plots used to build the typology. We do have a few reservations concerning the representative character of our typology. To evaluate this aspect, we hope to create additional maps in other mixed oak-pine stands (possibly outside Orléans Forest), in order to compare the structure with our typology, and maybe to define new types.

Our approach also depends on the variable that we chose to build the typology. We used the spatial structure of oaks and pines in the canopy. It would be interesting to investigate the influence of understorey spatial structure on our typology; and also possibly the influence of the other significant species present.

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