Chapter 1

Multi-Species Stand Classification: Definition and Perspectives

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Additional information is available at the end of the chapter

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Abstract

The increasing demands for products and services from forests enhanced new approaches to stand composition, structure, and management, which encompass multiple use systems, frequently mixed either even aged or uneven aged. Stand classification is frequently based on one density measure (number of trees, basal area, volume or crown cover). As no standard criteria exist, the direct comparison between the different stand classifications is difficult. This created a need for a stand classification that incorporates not only the forest species and composition but also their horizontal and vertical arrangements. The four criteria stand classification incorporates the number of species and their proportion, their horizontal and vertical distribution. The application of this methodology enables an integrated approach, bridging the gap between composition and stand structure. Its use in the National Forest Inventories and in research studies is simple, as shown in the two cases of study presented. It also allows the evaluation of stands in a certain moment in time and their dynamics.

Keywords: density measures, composition, mixture degree index, horizontal distribution, vertical distribution

1. Introduction

Forests occupy vast areas of the world and were able to satisfy the human needs for a long time. They were at the same time a reserve and a resource, which provided shelter, wood, food and have been associated with culture and religion [1]. From the IX century onwards, the increase in human population and agriculture originated a reduction in the forest area. It was during the XIII century and following that an intensive use of wood occurred, which directed several countries in Europe to promote the protection of forests [2]. That gave rise to the development of the forest sciences in the XVII century. In the beginning, due to wood shortage, a pressure was put to create systems that were able to produce large quantities of wood. This led to pure even-aged stands, which were easier to manage. In the XIX century, the conservation issues started to arise. They were not only concerned with the maintenance of the forests and their production but also concerned with other biotic and abiotic components of the systems [1, 3, 4], which originated later the terms biodiversity and sustainability. In this context, it was considered that forests should provide several productions and be managed as multiple use systems. Management was driven to a set of practices that were associated with mimicking the natural development of forests. Many approaches, methods, and techniques are found in literature as well as terms to define them [1, 4–17]. Thought they are not entirely compatible they put a strong emphasis in pure or mixed uneven-aged stands and complex systems. This change of paradigm created new challenges, the first of which being the description of the composition of stands and forests.

Stand classification is constrained by the characteristics and the definition of pure and mixed stands (Section 2) as well as by the criteria used to define them. The most employed stand classifications use as criteria one density measure (number of trees, basal area, volume or crown cover), whereas only two classifications were found that used three criteria. Additionally, different thresholds are associated with each density measure, not enabling a simple and direct comparison between different stands (Section 3).

The aim of this study was the development of a methodology for stand classification with an integrated approach that: bridges the gaps between species composition and stand structure; give a better insight to diversity and stand dynamics; can be used regardless of the species, the stand development stage and the region; and can be implemented with data from National Forest Inventories or research studies. The stand methodology developed encompasses four criteria: species composition, their proportion, and their horizontal and vertical arrangements. Contrary to the other stand classifications, species proportion is evaluated through an index as function of three density measures (number of trees, basal area, and crown cover), enabling it to be independent of the species characteristics while discriminating different classes of mixed stands (Section 4). The application of the four criteria stand classification to both a National Forest Inventory and a research data set highlighted the difference between this classification and those with only one criterion, enabling also the stands dynamics evaluation (Section 5).

2. Pure stands vs mixed stands

The definition of stand composition exists for quite some time. It is based on the number of species and their proportions. Monospecies stands classification does not seem to have any ambiguity. Conversely, multi-species stands can be either pure or mixed, depending on each species proportion in the admixture, usually evaluated with one density measure (number of trees, basal area, volume, or crown cover). Literature puts in evidence the variability of the criteria and thresholds to distinguish stand composition. The number of trees is preferred in young stands, whereas volume, basal area, and crown cover in adult stands. Stands or forests are considered pure when the number of trees, basal area, or volume proportion of one species is equal of larger than 70%, with a varying threshold between 70 and 90%. For crown cover, there seems to be more uniformity with 75% being the most frequent one [18–21].

A frequent stand classification criterion used in research studies is often based on the number of species [22–37] with no reference to the species proportion in the mixture and their spatial arrangement. Few references are found with the proportion of the number of trees and basal area [38–39]. Thus, comparisons between the different stands or forests are rather difficult as one can be comparing different stand compositions and structures. Other question that can arise is the ecological difference between species. A stand of one broadleaved and one conifer specie, as long as the proportion of threshold is met, is considered mixed. The interpretation might be different when a stand is composed by two or more broadleaved species, especially when they belong to the same *genera* or have the same functionality. The stand classification will depend on whether the species or the *genera* or even other parameters are considered, and thus, the same stand can be classified as pure or mixed. A similar pattern is observed for two or more conifer species [40, 41]. Another two aspects to be considered in the classification of multi-species stands are the spatial horizontal and vertical distribution. Regarding the former if two species are individually mingled, the classification as mixed stand is obvious. On the contrary, when they are in groups an area threshold has to be set. Consider the example of a stand of 50 ha composed by two species A and B where the first occupies 30 ha and the second 20 ha. If the stems of the two species are mixed individually, then it is clearly a mixed stand. Conversely, if the spatial arrangement is a group 30 ha of species A and another 20 ha of the B, then it might mean that these groups are two pure stands. In between a wide span of group sizes, smaller or larger, can be found [18]. Thus for the groups' spatial distribution, its dimension has to be used to differentiate the pure and mixed stands. Reference [42] considered a maximum group area of 1 ha. As to the vertical distribution, if the species are casually distributed along the vertical profile, the classification as mixed stand does not seem to cause any doubt. Inversely, when each species mainly occupies one vertical layer, depending on the criteria, the stand can be classified as pure of one species (located in the upper layer) with an accessory stand of another (located in the inferior layer) or as mixed [43].

There seems to be a need to evaluate stand structural diversity not only to differentiate the number of species and their proportion but also to differentiate their horizontal and vertical arrangements. Structural diversity is frequently evaluated with diversity indices, which may or not require spatial information of the individual stems in a stand. Examples of the non-spatial indices are the Simpson, Shannon and Weaver, Sorenson, A profile, and uniform angle. Examples of the spatial indices are spatial mingling species, differentiation, dominance, Clark and Evans and Pielou [44–50] as well as composite stand indices, for example S index [51].

Bearing in mind the aforementioned considerations, there seems to be a need to find clear definitions and a set of criteria to make the clear distinction of stand composition, which enables the comparison between the stands regardless the species or the region of the world.

The advantages of mixed stands include the following: they provide several products [21]; are considered more resilient to disturbances [52, 53]; are more productive [20, 54–58], are frequently associated with positive interactions [55, 58, 59], especially if complementarity [3, 58, 60] and sociality principles are met [3]; have more biodiversity [13, 61–68]; and provide risk attenuation and dispersion [26]. But they are also more complex systems that encompass a wide variability of species (number and proportion) and horizontal and vertical distributions

[20, 43, 54, 69–72]. The different ecological and growth behaviours of a tree and its neighbours, the competitive effects [73–76], the species proportions and how they are calculated [77–79] may originate a reduction in the mixed stands productivity. Many definitions of mixed stands are found in literature as well as attempts to their standardisation. Reference [21] (p. 525) present a comprehensive description and definition. This definition is intended to be integrative of all the previous ones. The authors stress their broad character, underlining that in some situations, it might have to be adapted, considering the forest area, their development stage, the form of mixture, the time frame and the main relations being assessed.

3. Forest inventories and stand classification

Forest inventories had their start more than two centuries ago. Their initial objectives were focused in the evaluation of wood volume and forest planning. As described in the prior section, with the increasing demands for productions other than timber, there has been also an increase of its complexity. On one hand, parameters have to be found to evaluate an increasing number of variables to characterise the forest functions, especially those related with biodiversity for which assessment criteria are not easy to find [80, 81]. On the other hand, sampling designs and intensity for a given accuracy have to be set bearing in mind labour and costs [82] for which sample plot size and type are of crucial importance [83]. In forest stands, two interlinked measures are considered of interest to estimate forest canopies, the sum of the crowns horizontal projection area (in m^2) and the crown cover, which is the relative value of the former (in %) [84–86]. From all the variables assessed in National Forest Inventories, two variables are always assessed: area and crown cover [82, 87]. Two other variables are evaluated in the field plots: the number of trees and the diameter at breast height [36, 82]. Stand areas and crown cover are frequently estimated optical passive sensors. Species can also be identified with high spatial resolution images [82, 88–91].

As already referred, the most frequent criteria to identify mixed stands are using a density measure frequently associated with the identification of the species or *genera* in the mixture. For adult timber, producing stands volume is widely used, with a threshold for the secondary species varying between 10 and 30%. Frequently used is also crown cover for a threshold of 25% for the secondary species. In young stands, the number of trees is preferred for a threshold of 10–30% [20]. Commonly associated with those quantitative criteria, are the names of one to five of the most frequent species. References [40, 43], independently, presented two stand classifications using three criteria: form, type, and degree, which gave a contribution to the better knowledge of the multi-species stands dynamics.

Reference [43] defines texture as the way of the species group and interacts in the stand as function of: type, degree, and form (**Figure 1**). ***Type*** characterises the number of species. ***Degree*** evaluates the species abundance, as function of canopy closure, in four classes: (1) isolated, species individually mixed; (2) sparse, when the secondary species have <10% of canopy closure; (3) accompanying, when the secondary species have 10–40% of canopy closure; and (4) intimate, when the secondary species have more than 40% of canopy closure. ***Form*** refers to the spatial distribution of the individuals of the same species, in four classes: (1) individual,

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when the tree can be differentiated from the adjacent environment; (2) clump, little groups of trees up to a maximum of five trees in the mature stage; (3) group, set of trees that occupy an area of 0.05–0.1 ha; and (4) *bosquet*, set of trees that occupy an area of 0.1–0.5 ha.

Reference [40] presents a stand classification based in Langhammer scheme. The stands are classified using three criteria: type, degree, and form (**Figure 1**). ***Type***, the stand vertical pattern, is function of the vertical distribution of the species that is if each species is located in one or several layers; horizontal crown mixture and vertical species stratification, respectively. ***Degree***, the relative proportions of each species (defined as the percentage of the total volume (basic criterion), basal area, number of trees (especially in young stands) or crown size), considers three classes where the secondary species represent the following: (i) <10%, (ii) 10–20%, and (iii) more than 20%. ***Form***, the species horizontal spatial pattern, is defined in three classes: (1) isolated, species mixed individually; (2) line, species are arranged in lines or strips; and (3) group, species are arranged in groups of variable forms and sizes.

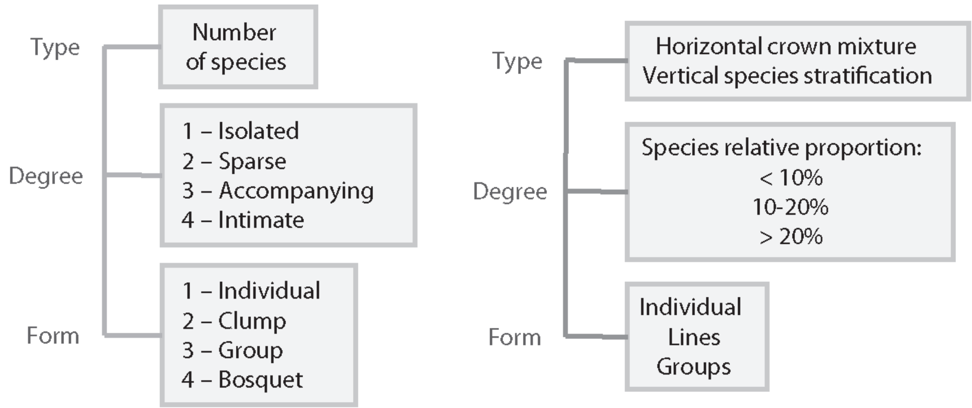

Figure 1. Representation of Schütz (left) and Leikola (right) stand classification.

4. Four criteria stand classification

Having stand composition defined the challenge is to develop a set of criteria that enables its evaluation. As already referred, especially in Europe, several methods to classify stands are found. The majority is based on one of the following density measures, number of trees, basal area, volume or crown cover, frequently associated with the species names or indicating only that the stands are composed by broadleaved and/or conifer species [19, 20]. The large number of methodologies associated with the wide span of forest species does not enable a straightforward comparison between different mixed stands. Also, no consideration is given to the horizontal and vertical distribution of the forest species in the stand, and these methods can hardly enable the analysis of the stand dynamics.

The four criteria stand classification will allow the differentiation of pure and mixed stands while discriminating different classes of the latter. The objectives are to give a better insight into the number of species, their proportions as well as their horizontal and vertical distribution in the stand. Thus, developing a tool enables stand classification with standard criteria that bridges the gap between existing ones and which gives a better insight into multi-species stands diversity as well as their dynamics. It is addressed to both National Forest Inventories and research studies. It can be easily implemented in the latter as frequently all parameters are evaluated as well as in the former with a very reduced, if any, increase in labour and costs. The stand classification was developed considering four criteria: composition, degree, form, and type (**Figure 2**). Composition evaluates the main species present in the mixture; degree their proportions, with three density measures (number of trees, basal area, and crown cover); form the species horizontal distribution; and type their vertical distribution.

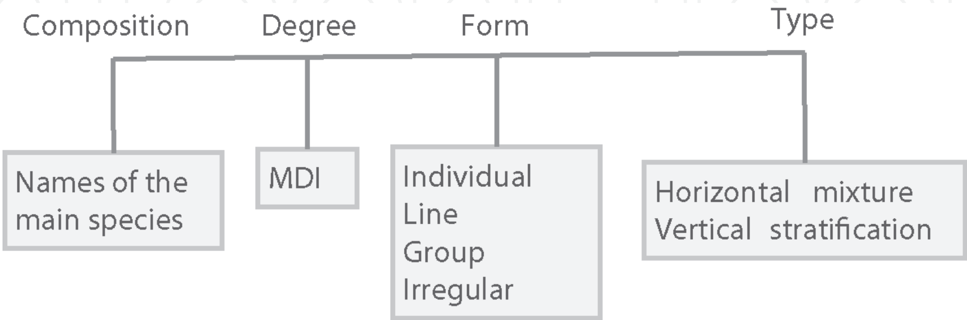

Figure 2. Representation of the four criteria stand classification.

Composition, characterising the species in the mixture, is a reflection of the site and the ecological and cultural characteristics of the species, thus a differentiating factor. In mixtures with many species, their full enumeration might be misleading as some species might have little significance in the mixture. Thus, for composition, it was considered that the two to six most representative species, considering the three density measures, should be indicated.

Degree was defined by the *mixture degree index* (*MDI*, Eq. (1)), incorporating the number of individuals as well as their dimensions. Three density measures were used as follows: number of trees (*N*), basal area (*G*), and crown cover (*CC*). Their thresholds are the most frequently used (**Table 1**). Each density parameter was reclassified as a binary variable (*Nrec, Grec, CCrec*), in which zero represents the pure and one represents the mixed stand (**Table 1**) [92]. Volume was not considered as a criterion as not all forest stands have timber as its main production, but other productions like bark (*Quercus suber*) or fruit (*Quercus ilex, Pinus pinea*). Nonetheless, an indirect evaluation of volume can be inferred from basal area and crown cover, as there is a positive relation between the former and the latter two.

$$MDI = 100 \times Nrec + 10 \times Grec + CCrec \tag{1}$$

	Main species			Main species	
Density measure	**Pure (%)**	**Mixed (%)**	**Reclassified density measure**	**Pure**	**Mixed**
N	75–100	0–75	*Nrec*	0	1
G	80–100	0–80	*Grec*	0	1
CC	75–100	0–75	*CCrec*	0	1

Table 1. Thresholds for the density measures used in *MDI*.

The evaluation of degree considering one density measure does not behave in the same way for the different stand compositions and structures. To illustrate the differences consider the examples of **Table 2**, for stands composed by two species (A and B), where the *N*, *G*, and *CC* are presented in percentage of the total. In case i using *N*, both stands are pure, while using *G* or *CC*, stand 1 is mixed and 2 is pure. In case ii for *G*, both stands are pure, whereas for N or *CC*, stand 1 is mixed and stand 2 is pure. In case iii for *N* and *G*, both stands are mixed, whereas for *CC*, stand 1 is pure and stand 2 is mixed. In case iv for *CC*, both stands are mixed, whereas for *N* or *G*, stand 1 is pure and stand 2 is mixed.

From the examples, it can be said that each density measure refers to the specie proportions, either in number or dimension, not allowing an integrated analysis. *N* evaluates only the number not giving any information about tree dimensions, thus not integrating the differences of the species development stages (young vs adult). *G* evaluates the tree dimensions yet it does not allow the distinction between species with different morphologic characteristics (large vs narrow crowns). *CC* evaluates the species-specific crown development but does not differentiate stem dimension (small vs large diameter). Though there is a direct relation between basal area and crown horizontal projection for individual trees, it varies per species and in a stand

	Stand				**Stand classification**	
	1		**2**			
Density measure	**A**	**B**	**A**	**B**	**1**	**2**
Case i						
N (%)	80	20	80	20	Pure	Pure
G (%)	40	60	80	20	Mixed	Pure
CC (%)	50	50	80	20	Mixed	Pure
Case ii						
N (%)	60	40	80	20	Mixed	Pure
G (%)	80	20	80	20	Pure	Pure
CC (%)	70	30	90	10	Mixed	Pure
Case iii						
N (%)	60	40	60	40	Mixed	Mixed
G (%)	50	50	50	50	Mixed	Mixed
CC (%)	80	20	50	50	Pure	Mixed
Case iv						
N (%)	80	20	50	50	Pure	Mixed
G (%)	80	20	40	60	Pure	Mixed
CC (%)	70	30	70	30	Mixed	Mixed

Table 2. Examples of stand classification with *N*, *G*, and *CC*.

due to competition phenomena, high and low shade, and branch abrasion might induce crown shyness resulting in a smaller crown when compared to individuals of the same species in open or free growth [3, 52]. *MDI* combines the three density measures and gives a better insight of different structures of mixed stands and their dynamics. It enables to distinguish the pure and mixed stands and in the latter differentiates in seven classes (**Table 3**). When *MDI* is 000 or 111, the classification is obvious; in the first case, it is a pure stand, and in the second case, it is a mixed one. If *MDI* = 001, the secondary species have high *CC* but low *N* and *G* indicative of adult or young trees with large crowns. When *MDI* = 010, the secondary species have high *G* but low *N* and *CC* indicative of secondary species adult trees with narrow crowns or subjected to strong competition. *MDI* = 011 corresponds to mixed stands where the secondary species proportion is low in *N* but high in *G* and *CC*, that is adult trees with large crowns. When *MDI* = 100, the secondary species have a high *N* but low *G* and *CC*, indicating young trees in the initiation development stage, thus with small diameters and crowns. *MDI* = 110 represents a stand where *N* and *G* of the secondary species are high but with low CC, as these species have narrow crowns or as a result of a strong competition. For *MDI* = 101, the secondary species have a high *N* and *CC* but low *G* indicating young stems with large crowns. *MDI* can be evaluated with inventory plot data, calculating the proportion of *N* and *G*. *CC* can be evaluated with the passive optical sensors either visually or with remote sensing classification methods. *MDI* can also be evaluated visually in the field by experienced foresters.

For ***form***, four classes were considered as follows: individual, line, group, and irregular. The first is similar to a chessboard; theoretically is the more elementary form of mixture of a community of plants [40]. The second, especially common in plantations, where species' spatial arrangement is in lines or strips. The third is defined by groups of variable forms and sizes. The fourth corresponds to a spatial distribution where individual and group distributions, or even line, have similar proportions. This criterion can be evaluated visually in the field or with optical sensors where the vegetation mask is attained per species. In research plots, where tree locations are known, diversity indices can be used for example the Pielou.

		Secondary species	
MDI	**Degree**	**Proportion**	**Characteristics**
000	Pure		
001	Mixed	Low	Young or adult with wide crowns
010	Mixed	Low	Adult with narrow crowns
011	Mixed	Low	Adult with wide crowns
100	Mixed	High	Young with narrow crowns
110	Mixed	High	Young or adult with narrow crowns
101	Mixed	High	Young with wide crowns
111	Mixed	Low/High	Young or adult with narrow or wide crowns

Table 3. *MDI* classes and secondary species proportion and characteristics.

Regarding ***type***, two classes were considered, the horizontal mixture and the vertical stratification, allowing the distinction between stands with one or more layers, thus even-aged from uneven-aged stands. This criterion can be evaluated visually in the field or with height distribution histograms. Though frequently total height is not measured in all trees in the field plots of the National Forest Inventories, it can be easily calculated with hypsometric functions that exist for almost all forest species. Again, in research plots, type can be evaluated with diversity indices, for example the profile A.

5. Application of the four criteria stand classification

5.1. Materials and methods

The four criteria stand classification was applied to two sets of data, the plots of the fifth Portuguese National Forest Inventory (NFI5) and to a set of research plots with two measurements to evaluate whether this classification can detect the stands' dynamics. *MDI* was also compared with *N, G*, and *CC*.

The NFI5 data set used is composed of 5435 plots, where the species were identified, diameter at breast height (1.30 m) was measured, and vertical distribution was evaluated visually. Crown cover was evaluated in aerial photographs. The representative forest species in Portugal are *Pinus pinaster, Eucalyptus* spp., *Quercus suber, Quercus ilex, Pinus pinea, Castanea sativa* and *Quercus robur* [93]. The second data set is composed of 28 research plots, with two measurements, one in Serra da Lousã (LO) and another in Herdade da Machoqueira do Grou (HM). LO is a mountain in central Portugal, about 250 km northeast from Lisbon (40°04′51″ N and 8°14′44″ W), where 16 plots were installed in adult stands of *Pinus pinaster*, located predominantly in the superior and intermediate layers, and broadleaved (mainly *Castanea sativa* and *Quercus robur* but also *Quercus rubra, Prunus avium, Fagus sylvatica*) and several conifers (*Pinus pinaster, Pseudotsuga menziesii*, C*hamaecyparis lawsoniana*) of natural regeneration in the intermediate and inferior layers. HM, located in Coruche, about 120 km east from Lisbon (39°06′59″ N and 8°21′05″ W), is mainly composed of *Quercus suber* and *Pinus pinea* with some *Pinus pinaster* individuals. The surveys took place in 2001 and 2009 in LO and in 1998 and 2008 HM. In these plots, diameter at breast height, total height and crown radii (North, South, East, and West directions) were measured for all trees with diameter at breast height ≥5 cm, and the tree coordinates recorded. The equality between each pair of density measures (*N, G, CC*, and *MDI*) was evaluated with McNemar test [94], implemented in R statistical software [95], for $\alpha = 0.05$.

5.2. Results and discussion

The plots of NFI5 have one to six species. Those with one species account for 63.8%, whereas two or more species represent 36.2%. In the latter, the most frequent have two (28.1%) and three (6.2%) species. In the two species plots, 113 combinations were found. The most frequent are *Pinus pinaster* × *Eucalyptus* spp. (15.7%), *Eucalyptus* spp. × *Pinus pinaster* (14.2%), *Quercus suber* × *Quercus ilex* (11.7%), *Quercus suber* × *Pinus pinaster* (10.9%), and *Quercus ilex* × *Quercus suber*

(7.3%), which correspond to 59.8% of their total number of plots. As to the three species plots, 261 combinations were found being the more frequent those of *Quercus suber* × *Pinus pinea* × *Pinus pinaster* (4.4%) and *Pinus pinaster* × *Eucalyptus* spp. × *Quercus robur* (3.0%). The number of plots of NFI5 classified has mixed vary according to the criterion used for degree (**Table 4**). *N* detects less 3.9% mixed stands than *G*, less 5.4% than *CC* and less 19.4% than *MDI*. *G* and *CC* detect less 15.5 and 14.0% plots than *MDI*. These results are confirmed by the significant differences between *N* and *G* ($\chi_1^2 = 69.5$, $p < 0.001$), *N* and *CC* ($\chi_1^2 = 71.2$, $p < 0.001$), *G* and *CC* ($\chi_1^2 = 4.5$, $p = 0.033$), *N* and *MDI* ($\chi_1^2 = 1052.0$, $p < 0.001$), *G* and *MDI* ($\chi_1^2 = 839.0$, $p < 0.001$), and *CC* and *MDI* ($\chi_1^2 = 760.0$, $p < 0.001$).

The analysis of *MDI* (**Table 5**) reveals that the most frequent class is 001, that is, where the secondary species have large crowns, but has a low number of individuals with small basal area. The second and third more frequent mixed plots are 010 and 110, respectively, and correspond to secondary species with large basal area and small or large number of individuals. From the above results, it can be said that *N* and *G* seem to detect less mixed plots, conversely to *CC* and *MDI*. One of the reasons might be that stands of species with large crowns (e.g. *Quercus* sp.) have frequently <200 tree ha^{-1} [96], and only a few trees are needed to reach the minimum threshold for *CC*, but not for *N* or *G*. From the plots classified as mixed with *N*, 44.5% were classified as mixed by *CC* (*MDI* 101 and 111) and from those mixed with *G* 38.3% were classified as mixed with *CC* (*MDI* 011 and 111). *MDI* has the advantage of being a flexible index enabling their use regardless the species ecological characteristic and growth habits. These results suggest that the NFI data sets [36, 82, 83, 87] can be used to enhance further detail on stand classification using *MDI* and they can be of help during regeneration phases or during transformation processes [4, 7].

As form was not evaluated in the NFI5, all mixed plots detected by *MDI* were surveyed in the corresponding ortophotomaps to evaluate form visually. Form was irregular for 63.1%, in

	Pure		Mixed	
Density measure	**Number**	**Proportion (%)**	**Number**	**Proportion (%)**
N	4626	85.1	809	14.9
G	4334	79.7	1022	18.8
CC	4334	79.7	1101	20.3
MDI	3572	65.7	1863	34.3

Table 4. Stand classification with different density measure criteria.

MDI	001	010	011	100	101	110	111
Number	624	313	117	131	86	318	274
Proportion (%)	33.5	16.8	6.3	7.0	4.6	17.1	14.7

Table 5. *MDI* mixed classes, number and proportion (in %) of the IFN5 plots.

groups for 22.3%, individual for 14.4%, and only residual (0.2%) for lines. The more frequent form varies according to *MDI* classes (**Table 6**). The irregular form prevails for 001, whereas for 010 group, irregular distributions occur with similar frequencies. Not considering line form, 011, 110, and 101 have predominantly an individual distribution. In the 110 predominates, the group distribution (not considering the line) as for 111 individual is the most frequent one. These results are expectable for two main reasons. Many forest species have heavy fruits (such as *Quercus* sp., or *Castanea sativa*), so it is expected that fruits fall near the seed bearer [96] and also as some forest species coppice very easily (*Eucalyptus* sp. and *Castanea sativa*) [69, 96] thus increasing the tendency to form groups. Contrary, other species have light fruits (*Pinus pinaster*) with fruit dispersal in large areas [52, 97]. Inversely, individual and group forms seem to be linked to management practices.

Type detected that more than half of the plots classified as mixed had vertical stratification (**Figure 3**), 62.4% with *N*, 57.8% with *G*, 61.5% with *CC*, and 52.9% with *MDI*. This is indicative of a successful natural regeneration for *MDI* classes 100, 101, and 111, in number of individuals,

Form	001	010	011	100	101	110	111
Group	26.4	17.8	7.7	7.5	4.8	19.0	16.8
Individual	24.3	12.3	10.1	9.0	7.1	17.9	19.4
Irregular	38.2	17.5	4.9	6.3	4.0	16.2	12.9
Line	0.0	0.0	0.0	66.7	0.0	33.3	0.0

Table 6. Form per *MDI* classes (in %).

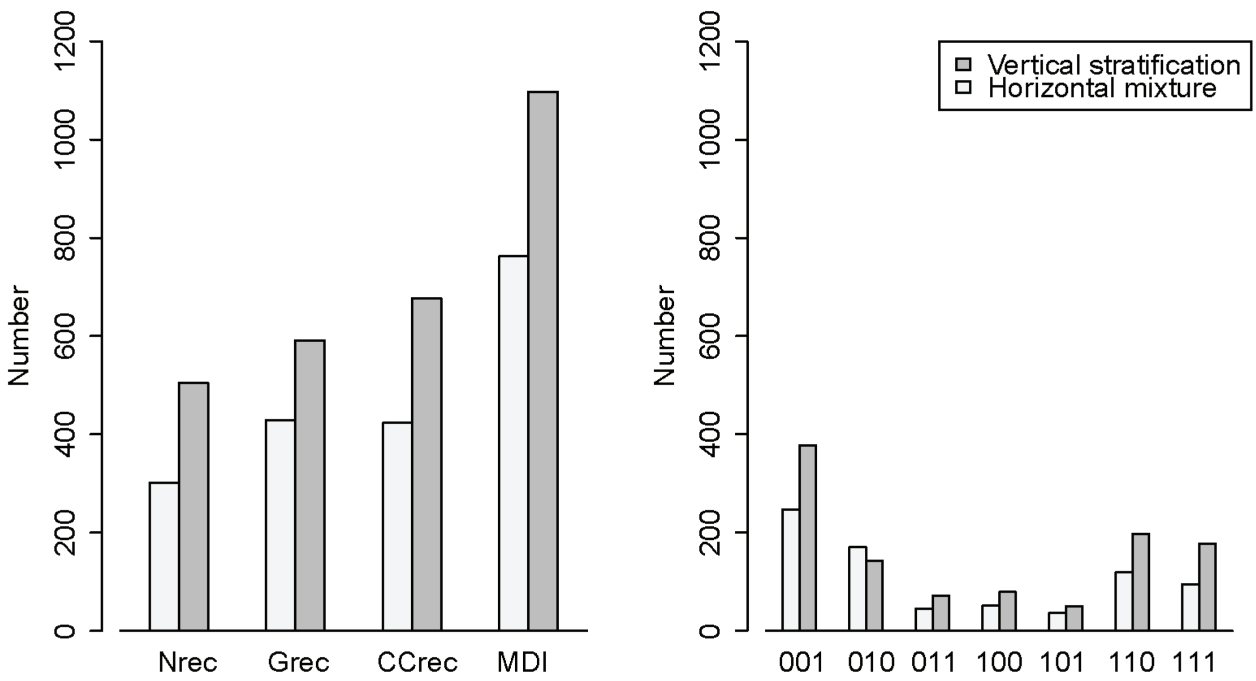

Figure 3. Number of plots per density measure (left) and per *MDI* classes for the total of *MDI* mixed plots (right).

which is one of the principles of uneven-aged silviculture [4, 7]. *MDI* classes 001, 010, and 011, with vertical stratification, correspond also to establish regeneration of species with large crowns (001), and for adult individuals with narrow crowns (010) or large crowns (011). This can be, at least partially, explained by the periodic recruitment [3, 4, 7, 52]. The horizontal mixture is frequent for 001 (32.2%) and 010 (22.2%). The former corresponds to stands where the secondary species have few individuals with large crowns and the latter to stands where the secondary species have few adult individuals with large stems.

In LO, the number of species per plot varies between 2 and 7. In all plots, *Pinus pinaster* and *Castanea sativa* are present, in 14 *Quercus robur*, and the other species occur in reduced numbers in one or two plots. In HM, three species are present in the plots; *Quercus suber* and *Pinus pinea* are present in all plots and *Pinus pinaster* is present in five plots. In these research plots, there seems to be a trend to a similar classification with *CC* and *MDI* for LO and all the density measures for HM (**Table 7**). The latter is not surprising as the plots are composed by adult stems with *Quercus suber* as main species and *Pinus pinea* and *Pinus pinaster* with *N*, *G*, and *CC* always higher than the threshold. Contrary, LO plots have adult *Pinus pinaster* stems and recruitment mainly of *Castanea sativa* and *Quercus robur*, two species of large crowns, thus it is not surprising that *CC* and *MDI* detected the same number of mixed plots. The largest difference is observed when *G* is used as a criterion, as the secondary species have quite small diameters. Conversely, *N* reflects a successful regeneration. The results for LO are confirmed by the statistical differences observed *N* and *G* ($\chi_1^2 = 10.5625$, $p < 0.001$), *N* and *CC* ($\chi_1^2 = 4.1667$, $p = 0.041$), *G* and *CC* ($\chi_1^2 = 18.05$, $p < 0.001$), *N* and *MDI* ($\chi_1^2 = 4.1667$, $p = 0.041$), and *G* and *MDI* ($\chi_1^2 = 18.05$, $p < 0.001$). For HM, no significant differences were found between each pair of the density measures (*all*, $p > 0.05$).

MDI classified 21 plots as mixed (**Table 8**), and four different classes of degree were identified as follows: 001, 011, 101, and 111. *MDI* = 001 identifies stands where the individuals of the secondary species have large crowns, and this was observed in one plot of LO, where a small number of *Castanea sativa* stems recruited developed large crowns [92]. *MDI* = 010 occurs in one plot of HM where the *Pinus pinaster* adult individuals have large basal area but, characteristic of the species, have narrow crowns [97]. *MDI* = 011 occurs in HM in four plots of *Quercus suber* and *Pinus pinea* where the latter are adult, with large basal area and crowns [96].

		N		*G*		*CC*		*MDI*	
Local	**Survey**	**Mixed**	**Pure**	**Mixed**	**Pure**	**Mixed**	**Pure**	**Mixed**	**Pure**
LO	2001	9	7	1	15	11	6	11	6
	2009	10	6	3	13	14	2	14	2
HM	1998	10	2	11	1	11	1	11	1
	2008	11	1	11	1	11	1	11	1

Table 7. Stand classification per density measure, local and survey.

MDI = 101 was observed in eight plots of LO with a large number of recruitment individuals with large crowns, mainly of *Castanea sativa*. *MDI* = 111 corresponds to established mixed uneven-aged (LO, HM) and even-aged (HM) stands. The proportion of plots classified as mixed in LO was 56.3% for *N*, 6.3% for *G*, and 62.5% for *CC* and *MDI*; and for HM, 83.3% for *N* and 91.7% for *G, CC*, and *MDI*. From the first to the second survey, some changes occurred in the former but not in the latter. In LO, four pure plots in 2001were classified as mixed in 2009 (**Table 8**). In fact, six plots have changed *MDI*, three moved from 000 to 001, one moved from 000 to 101 and two moved from 101 to 111. These dynamics can be explained by two factors. First, due to the growth of the secondary species individuals. Second, from the first to the second survey selection, cuttings were carried out to remove mainly *Pinus pinaster* individuals [98], which increased the relative proportion of *N, G*, and *CC* of the secondary species. In HM, one plot passed from 011 to 111 for the aforementioned reason due to the removal of some individuals of *Quercus suber* and *Pinus pinaster*. These small changes show a trend towards mixed stands, though no significant differences were found between *MDI* classes between the two surveys for both LO and HM (*all*, $p > 0.05$).

Local	Survey	000	001	011	010	100	101	110	111
LO	2001	6	1	0	0	0	8	0	1
	2009	2	4	0	0	0	7	0	3
HM	1998	1	0	1	0	0	0	0	10
	2008	1	0	0	0	0	0	0	11

Table 8. Stand classification per *MDI* classes, local and survey.

Form was evaluated using the crown maps and revealed for both surveys that for LO species, spatial arrangement was individual in eight plots, irregular in five and in groups in three, and for HM, irregular in eight plots and in groups in four. The results of LO are in accordance with Ref. [99] that refer that Pielou index showed for *Pinus pinaster, Castanea sativa* and *Quercus robur* a tendency to segregation.

Type was evaluated with profile A index. For all plots, the index was greater than zero indicative of species in several height layers. In LO, it is indicative of the presence of *Pinus pinaster, Castanea sativa*, and *Quercus robur* in three, two (inferior and intermediate), and one (inferior) layer, respectively. From the first to the second survey profile A index increased, corresponding to the presence of *Castanea sativa* in the superior layer and *Quercus robur* in the intermediate, which is in accordance to the results of Ref. [99]. In HM, the profile A index values for *Quercus suber* and *Pinus pinea* are indicative of their presence in two (inferior and intermediate) height layers, while for *Pinus pinaster* in one (superior) layer. The analysis of the height distribution histograms confirmed the trend attained with the diversity index. In HM in seven plots, there was a slight reduction of the profile A index values. This can be explained, at least partially, by the removal of *Pinus pinaster* that was predominantly in the superior layer, confirmed by the height distribution histograms.

6. Conclusions

In the four criteria stand classification, composition characterises the most representative species, degree their relative proportions, form their horizontal distribution and type their vertical distribution. Stand classification with *N*, *G* or *CC* makes it dependent on the species and their morphological patterns. For *MDI* 111 and 000, stand classification is similar whatever density measure is used. For the other *MDI* classes, the selection of the density measure influences stand classification. *MDI* advantage is that it aggregates, in a simple way, *N*, *G*, and *CC* can be used regardless the stand structure or the species morphological patterns. The analysis of each density measure suggests that *N* is suited for uneven-aged stands, where diameters and crowns have the same morphological pattern; *G* for even-aged stands; and *CC* for even-aged and uneven-aged stands for species with different morphological patterns. Also, *MDI* can provide further detail on the stands' dynamics, as shown in the LO plots from the first to the second survey. The four form classes enable the evaluation of the horizontal distribution of the species, and the two type classes enable the evaluation of their vertical distribution. These criteria are especially useful to prescribe silvicultural practices, such as the control of competition pressure between individuals as well as to promote growth both in stem and crown diameters, especially important for stands with bark (the former) and fruit (the latter) as their main production.

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