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Predicting site index of Douglas-Fir plantations from ecological variables in the Massif Central area of France

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Abstract

Douglas-Fir is the main species used in France for reforesting mid-elevation regions, mostly on former heathlands and coppices. In order to clarify its auto-ecological limits, and to provide forest managers with relevant information for planting, we studied its productivity in a wide range of site conditions. Based on data from 202 Douglas-Fir pure stands at mid-elevation regions, site productivity was assessed using variance analysis with site types, site groups, and multiple regression analysis with ecological variables. Site index, determined from stem analysis data, was used as a species specific measure of site quality. Results show that Douglas-Fir site index is correlated to soil nutrient status, and secondarily to soil moisture regime. Mean stand productivity was generally high, but considerable variation in site index was determined within a study area that was classified by forest managers as uniform. Correlation between site classification and site index was confirmed, because it was based on synoptic factors that are simple and robust indicators of site productivity. Other methods to assess site quality, such as multiple regression on ecological variables and multivariate site groups, appear to be less explicative and robust for predicting site index. The results allow forest managers to predict the site index at parcel scale. Further investigation should be carried out in order to explain the major causes of the unexplained variance of site index by ecological variables, especially genetic variation, and effect of age. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: *Pseudotsuga menziesii* (*Mirb*) Franco; Site productivity; Site classification; Site index

1. Introduction

Douglas-Fir fir [(*Pseudotsuga menziesii*) (*Mirb*) Franco] has been the main species used in France for reforesting since the 1970s. French plantations constitute the widest use of this species (3,30,000 ha^{-1}) outside its natural origin area in North America. It is widely used in France in mid-elevation regions, such as the Massif Central, which represents about 70% of the total surface of plantations. It has been frequently used to reforest former heathlands and coppices, and its use was encouraged by national grants as in other European countries (Tyler et al., 1995; Corona et al., 1998). Douglas-Fir is reputed to be a potentially high yielding species (Tyler et al., 1995), and to be adapted to nutrient-depleted sites with a low water-holding capacity (Décourt and Nys, 1976). Consequently, is has been introduced on a large range of site conditions with an objective of increased timber production. However, French foresters recently observed increasing problems of pests, diseases, and failures in uplands (DSF, 1996). Even if this species is spared serious

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damage, these problems give rise to questioning Douglas-Fir adaptation and productivity according to site conditions.

In spite of the great importance of this coniferous species in the French Massif Central, regional studies on its productivity and auto-ecology are few (De Champs, 1997). The main work on this topic was made by Décourt and Nys (1976) in the western part of the Massif in order to establish height-age curves. A bibliographic survey (Forestry Abstracts 1939–1995, in Marqués et al., 1997) stressed that most of the 245 international studies on Douglas-Fir concern silviculture, pests and diseases, genetics, nurseries, and wood quality. Only a few studies were dedicated to site-yield relationships and auto-ecology. They mainly relate to the North American origin area (Green et al., 1989; Klinka and Carter, 1990; Monserud et al., 1990; Monserud and Rehfeldt, 1990), and secondarily to Scotland (Tyler et al., 1995), and Italy (Corona et al., 1998).

The current survey was integrated in recent efforts in France that focused on linking site index to site classifications, and site quality for the major reforestation species (Becker et al., 1980; Buffet and Girault, 1989). Methods used for assessing site quality and productivity are various (Hills, 1952; Jones, 1969; Pritchett and Fisher, 1987). The first one consists of correlating site index with site types according to a local or a regional site classification system (=synoptic approach). The second one is based on multiple regression analysis between site index and major ecological variables (=analytic approach). More precisely, this last method uses routinely measured site variables, which are indirect indicators of the ecological environment of sites (Wang and Klinka, 1996), instead of the real causative factors that control tree growth. Both methods may be useful for predicting forest yield. Thus, it is interesting to compare the statistical effectiveness, and the practical implications, of different methods for assessing sites and site quality.

Consequently, on the basis of 202 pure and mature Douglas-Fir stands in a mid-elevation region of the French Massif Central, we proposed: (i) to explain the variations in site index among sites, to clarify the auto-ecological limits of these species in Limousin, and consequently, to provide forest managers with relevant information for using this species; and (ii) to validate, and to stress the advantages and limits of using site classification to predict site index, by comparison with other ecological approaches.

2. Materials and methods

2.1. Environmental characteristics

The study area corresponds to metamorphic and granite uplands of Limousin in the northwestern part of the French Massif Central (longitude 45.5°N, latitude 2°E) (Table 1). They were chosen because they are widely reforested with Douglas-Fir. Climate is characteristic of the Atlantic bioclimatic area and favorable to the production of most coniferous species: mean annual rainfall ranges from 1000 to 1600 mm, and annual rainfall regime is uniform. Summer climatic water deficit is about 50 mm. The center of the study area is composed of various granites and gneiss, surrounded by micaschists. Parent materials on granites and gneiss are sandy and gravelly alterites (=arena), partially topped by loamy gelifluidal deposits; materials on micaschists are loamy. Most soils belong to the Brunisolic and Regosolic Orders according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998). Sombric and Dystric Brunisols are predominant on slopes. Most soils are nutrient-depleted, which is due to a combination of detrimental factors (Décourt and Nys, 1976): the poorness of the substratum, the depleting effects of some former silvicultural practices, and the presence of an acidic forest vegetation.

Consequently, nutrient status of soils is a major edaphic constraint for forest productivity on granites (Curt et al., 1996) in spite of favorable climatic conditions. Sites on micaschist are often richer and have a higher water storage capacity (WSC) because of the presence of loamy deposits.

In total, climatic and edaphic conditions are unfavorable to cultivation. Heathlands (=rangelands) and coppice forests occupied most of the land before reforestation (respectively, about 40 and 50%, of the study area). Consequently, eventual effects of former vegetation on Douglas-Fir height growth were tested before making correlations with site types or site variables.

Table 1
Summary of site and stand characteristics of the 202 Douglas-Fir stands[a]

	Units	Min.	Mean	Max.
Mean annual rainfall	mm	1000	1350	1600
Mean rainfall from April to September	mm	350	600	700
Mean rainfall in summer	mm	250	285	320
Mean annual temperature	°C	8	10.5	13
Mean temperature of the coldest month	°C	0	2	4
Mean annual temperature of the warmest month	°C	14	16.5	20
Mean summer water deficit	mm	0	45	75
Elevation	m	450	720	977
Topographical exposure (Topex)	°	−50	120	240
Total soil depth	m	45	75	175
Clay	%	0	5	12
Loam	%	15	45	45
Sand	%	45	60	92
pH		3.6	4.5	6.2
Available water storage capacity (WSC)	mm	15	90	180
Rock substratum (% of the 202 stands)	Granites (60), gneiss (24), micaschists (16)			
Soil types (% of the 202 stands)	Sombric Brunisols (40), Dystric Brunisols (35), Orthic Regosols (15), Melanic Brunisols (10)			
Aspect (% of the 202 stands)	N (7.0), NE (5.7), E (2.9), SE (4.0), S (7.9), SW (13.6), O (27.7), NW (4.0), no preferential exp. (27.2)			
Physiographic and geomorphic features (% of the 202 stands)	Crest and summit (11.0), upper part of slopes (10.5), mid part of slopes (34.6), benches (14.0), lower part of slopes (17.3), vales (12.6)			
Crop age	Year	20	25.7	42
Stocking	Stems ha^{-1}	800	1020	1200
Site index, H_{25} (dominant height at 25 year)	m	16.3	21.3	27.8

[a] Numbers in brackets are the percentage of stands corresponding to each class.

2.2. *Sample plan and site classification*

The aim of the study was to take into consideration the major site variables that may be correlated to site index variations. A sampling design was set up in order to form a suitable range of sites supporting the growth of Douglas-Fir. First, we used the regional forest site classification concerning the western border of the French Massif Central (Curt, 1989). Eight site types were represented, which can be regrouped in three classes: medium-rich, poor and very poor. Very rich sites, and wet sites were not sampled because Douglas-Fir stands are rare. This sampling was based only on parcel-scale variables, which were used to classify forest sites (Table 2): (i) the type of substratum and parent materials; (ii) the soil nutrient status (SNS) according to soil type, humus form, and the main indicators of nutrients cycle (pH, S/T, C/N); and (iii) the soil moisture regime according to water storage capacity (WSC) and seepage index (Table 3). Second, the sampling was crossed with a climatic division of the study area in six sub-zones (MeteoFrance, 1989), in order to take into account climate variations. A first sorting out of stands was carried out within each stratum, by selecting stands of more than at least 10 ha^{-1}. The final site selection was made in the field; stands were chosen in order to avoid disturbances, such as pests, windbreaks, and edge effects. In conclusion, at least 13 plots were chosen per site type in order to compute accurate confidence intervals. Site types on waterlogged soils were left aside because they were rarely reforested with these species. Outstanding quality sites with rich (=eutrophic) soils or fresh soils are missing for the same reasons.

In total, 202 sample plots were selected in Douglas-Fir stands [(*P. menziesii*) (*Mirb*) Franco]. Stands are pure (100% Douglas-Fir), even-aged, and closed.

Table 2
Main site and dendrometric variables, and assessment method[a]

Site variables	Abbreviation	Units	Assessment method
Elevation (a.s.l.)	ELEV	m	Taken from the 1:25,000 scale topographic maps
Slope	SLOP	%	Measured by hypsometer
Aspect	ASPE	Degrees	Measured by compass
Topex (topographical exposure)	TOPX	Degrees	Measured by hypsometer in eight directions (N, NE, E, and so on).
Position on slope	POSI	Code	Lower (1), mid (2), upper (3), ridge (4), top of the alveola (5)
Physiographic position	PHYS	Code	Crest and summit (1), upper part of slopes (2), mid part of slopes (3), benches (4), lower part of slopes (5), vales (6), alveola's bottom (7)
Water seepage index (depending on the situation on slope)	SEEP		Classified according to Le Goff and Levy in Baize and Jabiol (1995): water loss>water supply (1), water loss=water supply (2), water loss<water supply (3), water loss≪water supply (4)
Soil group	SOIL	Code	According to the Canadian System of Soil Classification (Soil Classification Working Group, 1998)
Humus form	HUMU	Code	Classified according to Baize and Jabiol (1995): mesomull (1), oligomull (2), dysmull (3), hemimoder (4), moder (5), dysmoder (6), mor (7)
Nature of the parent material	PARM	Code	Sandy-gravely arena (1), gelifluidal loamy deposits (2), colluvium (3)
Texture for each soil horizon	TEXT	Code	Classified according to Jamagne (1960) in Baize and Jabiol (1995): coarse sand (1), sand (2), sandy loam (3), loamy (4), loamy clay (5)
Soil stoniness	STON	%	Estimated according to Baize and Jabiol (1995)
pH for each soil horizon	PH		Estimated by a colorimetric pH-meter
Total soil depth	DEPT	cm	Soil core sampler (three replicates) and observation on soil profile
Maximal apparent rooting depth	MXRD	cm	Observation on soil profile
Available water storage capacity and soil water regime	WSC	mm	Estimated by the texture method (Baize and Jabiol, 1995):<50 mm (1), 50–100 mm (2), 100–150 mm (3), >150 mm (4), seasonal waterlogging (5), permanent waterlogging (6)
Soil nutrient status	SNS		Estimated from pH, C/N, and S/T. SNS=medium-rich (=mesotrophic): pH>5.5; C/N<15; S/T>50; SNS=poor (=oligotrophic): 4.5<pH<5.5; 15<C/N<20; 25<S/T<50; SNS=very poor (=hyper-oligotrophic): pH<4.5; C/N>20; S/T<15
Age of trees	AGET	Years	Using a tree core sampler on three dominant trees
Site index	SI_{25}	m	Measured from the dominant height of three of the 10 largest trees per plot and referred to a reference age using the age-height curves by Décourt in Buffet and Girault (1989)

[a] Numbers under brackets are the codes corresponding to each value of the variables.

These precautionary measures tend to limit the effects of competition and silvicultural practices on height growth (Pritchett and Fisher, 1987; Buffet and Girault, 1989). The age of stands was chosen as close as possible to 25 years, which is the mean age of plantations in Limousin, in order to minimize eventual 'productivity-age' interference (Curt et al., 1996; Corona et al., 1998). An analysis of variance (ANOVA) stressed that there was no effect of planting age on site index at the reference age.

All stands are located on private properties. Silvicultural practices are similar among the 202 stands: most of them have experienced a first thinning, and density is 800–1200 stems/ha^{-1} (Table 2). Forest managers helped us to determine the area of origin in most cases (75%), with the help of silvicultural records. Seedlings mainly come from low elevation (<450 m) areas of the western side of the Cascade Range (Washington and Oregon, USA). This provenance is reputed among French foresters to be productive and adapted to Limousin (Michaud, 1995). It is assumed that the exact provenance of each batch of seedlings is unknown, in spite of investigations of management records. Because it is cost- and time-consuming, it was not possible to determine the tree genetics in order to investigate possible genetic variations among stands, even if they may play a role in variations of initial growth (Michaud, 1995) or site

Table 3
Main ecological features of site types according to the site classification, with the number of stands in parentheses[a]

Soil texture	Sandy					Loamy				
Parent material	Sandy arena					Gelifluidal material Colluvium		Gelifluidal material Gelifluidal material		
Soil nutrient status	Poor (oligotrophic)			Very poor (hyper-oligotrophic)		Rich (mesotrophic)		Poor (oligotrophic) and medium-rich		
Soil types	Orthic Brunisol Dystric Brunisol			Dystric Sombric Brunisol Orthic Regosol Cumulic Regosol Orthic Humic Regosol		Melanic Brunisol		Orthic Brunisol Dystric Brunisol		
Humus form	Oligomull Dysmull			Eumoder Hemimoder Mor		Mesomull Oligomull		Oligomull Dysmull		
Physiographic situation	All			Ridge, top		Plateau, mid- and lower part of slope		All		
Soil moisture regime	Dry	Slightly dry	Fresh	Dry	Slightly dry	Slightly dry	Fresh	Dry	Slightly dry	Fresh
Site types (code)	SOd	SOsd	SOf	SHOd	SHOsd	LMsd	LMf	LOd	LOsd	LOf
Sample size	41	43	37	13	16	-	-	13	26	13

[a] Code: S, sandy material; L, loamy material; M, mesotrophic; O, oligotrophic; HO, hyper-oligotrophic; d, dry; sd, slightly dry; f, fresh. Total number of plots is 202.

index (Monserud et al., 1990; Monserud and Rehfeldt, 1990).

2.3. *Ecological survey*

The surface of each circular sample plot is 400 m^2. Site variables were assessed using a standard protocol for site classification (Table 2); the rationale for the selection of criteria and quantitative classes was discussed in previous works (Curt et al., 1996; Curt, 1999). A soil pit (1 m×1 m×1 m) was opened on each sample plot. Soil horizons were described using a standard protocol (in Baize and Jabiol, 1995), and samples were collected in each soil horizon in order to make complementary physical and chemical soil analyses in the laboratory. Only 60 representative soil profiles gained a complete chemical soil analysis in the laboratory, due to expense. In the end, each plot was joined to one of the site type using information collected in the field and a key for site recognition (Curt, 1989).

2.4. *Dendrometrical survey and site index characteristics*

The protocol to assess site productivity and site index is common to most comparable studies (e.g. Buffet and Girault, 1989; Wang and Klinka, 1996). The final objective was to relate sites with an index estimating the yield of Douglas-Fir forest stands. To this end, foresters use the 'site index' which is the most commonly used species-specific approach for assessing forest site productivity (Pritchett and Fisher, 1987; Buffet and Girault, 1989; Monserud et al., 1990; Wang and Klinka, 1996). Site index is the height of dominant trees of a stand projected to some particular reference age, using specific tables and equations for each forest species. It is commonly assumed that the influence of genetic and silvicultural effects on forest height growth remain small when working in monospecific, even-aged and closed plantings (Wang, 1998), especially for low thinning treatments.

In practice, the method consisted in according to the French methodology (Duplat, 1989) consisted in measuring dbh (1.30 m) of all trees on a circular plot (400 m^2). Then, we pointed out the 10 largest trees, which are supposed to be representative of the 100 largest trees per ha. These 10 trees were sorted according to their dbh (decreasing order), and the age and height of no. 1, 3, 5 were measured. The height was measured with the help of a Suunto dendrometer, and the age at breast height (1.30 m) was measured using an increment borer. Duplat (1989) indicated that the dominant height of an n acres plot can be computed from the $n-1$ biggest trees. Site index was calculated for each stand at the reference age of 25 years (called below SI$_{25}$) using the model by Décourt (in De Champs, 1997).

2.5. *Investigation of former practices and vegetation*

Most of our Douglas-Fir stands were settled on former heathlands, forests, and coppices. Although this situation is widespread over Europe, site-yield surveys generally pay no attention to the effects of former practices and history of parcels. A preliminary test was carried out to test these effects, using silvicultural records. They were compared with other information sources: direct evidence from forest managers, composition of ground vegetation, edaphic features like marks of stubble-burning, and chemical analyses of soils. In particular, multivariate analyses (CA, and HCA) were performed in order to assess ground vegetation groups, and coupled with soil analysis. We assume that these indicators do not constitute absolute evidence of former land use. However, we considered the information was reliable when at least two indicators were in agreement, for example when silvicultural records and vegetation composition indicate that the plot was formerly covered with a beech acidic forest.

In total, reliable information was found for only 115 of the 202 stands. Six former land uses were distinguished (Table 4); distinction between poor (=acidic) and medium-rich (=mesotrophic) oak-beech forests or coppices was done using ground vegetation, and chemical analysis. Two major former land uses, on which Douglas-Fir plantations can be found in mid-elevation regions (De Champs, 1997), were not taken into account in this study: (i) former cultivated lands, because they are rare in the study area, and because it was difficult to establish the former cultivation practices with reliability. Most of these lands were abandoned in the 1950s, and colonized by immature pioneer vegetation like *Salix*, *Betula*, and *Pinus sylvestris*; and (ii) old coniferous woodlands (*P. sylvestris*), which

Table 4
Variance of site index explained by former land-use in 115 of the 202 Douglas-Fir stands

Former land-use	Sample size	SI_{25} (median) m	SI_{25} (confidence interval) m
Calluna heathland (*C. vulgaris*)	13	18.3	17.7–18.9
Bare soil and wet land	3	19.2	17.9–20.5
Poor (=acidic) beech-oak forest and coppices (*Fagus sylvatica, Quercus* sp.)	63	21.0	20.7–21.3
Broom moorlands (*Genista* sp.) and ferns	5	21.6	20.6–22.6
Medium-rich (=mesotrophic) beech-oak forest and coppices (*F. sylvatica, Quercus* sp.)	21	24.5	24.0–25.0
Chestnut coppices (*Castanea sativa, Quercus* sp., *Betula* sp.)	10	24.3	23.6–25.0
Total/median	115	21.3	

were not found in the above-mentioned silvicultural records.

2.6. Data analysis

Analysis of variance (ANOVA) was carried out to compare site types with site index. Differences between groups were assessed using the *F*-Ratio and the *P*-Value tests. *F*-Ratio is the ratio of the between-group estimate to the within-group estimate. Confidence interval (confidence level 95.0%) is calculated using the Least Significant Differences (LSD) method, which is the best fit for making comparisons when the *F*-Ratio is significant.

Multivariate classification methods (correspondence analysis, CA, and hierarchical clustering, HCA) were performed to assess homogeneous site groups according to their site conditions. The objective was to reassemble site types and to simplify the regional site classification. A database (202 stands) was set up with active variables (physiographic and edaphic), and supplementary variables (former use, site index). Variables were coded as indicated in Table 2. Inertia of the two main axes of the CA is respectively, 10.7 and 7.1%: results are significant but they must be considered only as indicative. Stands were attributed to five site groups according to the results of HCA (Table 5). These groups were compared with site types determined in the field with the help of the regional site classification and the key for site determination. Comparisons were made by contingency tables.

Table 5
Main ecological features of site types according to the site groups assessed by multivariate analyses[a]

	Group 1	Group 2	Group 3	Group 4	Group 5
Physiographic and topoclimatic variables	Crest upper part of slope Lost by seepage	Ridge Aspect: N, NE, NW		Plateau	Vale
Edaphic variables	TSD<45 cm	Dystric Sombric	Orthic Brunisol	Colluvium on granite	Gelifluidal material and colluvium on metamorphic rocks
	WSC<50 mm Regosols	Brunisol TSD: 45–75 cm	Dystric Brunisol Sombric Brunisol	TSD: 80–105 cm WSC>100 mm	Melanic Brunisol Humus form: mesomull
	Humus form: moder, mor	Humus form: dysmoder	WSC: 50–100 mm Humus form: dysmull	Humus form: oligomull	
Complementary observation (supplementary variables)	Former *Calluna* heathlands		Former acidic beech-oak forests	Former mesotrophic beech-oak forests	Former chestnut coppices
Sample size	70	17	14	62	40

[a] Only the main variables were indicated.

3. Results

3.1. *Effects of former practices and history of parcels*

About 36.8% of site index variance was explained by former land use. Former *Calluna* heathlands, and former bare soils or wet lands are the least favorable to Douglas-Fir height growth. The most favorable conditions to settle this species are former oak-beech forests or coppices, and chestnut coppices (Table 5).

It is noteworthy that Douglas-Fir site index is high on sites previously occupied by chestnut coppices, although most of them were subjected to soil and vegetation degradation by old silvicultural practices, such as stump extraction and clearing of soil litter (Verger et al., 1985). An artifact in sampling may explain this: Douglas-Fir plantations are missing on depleted chestnut coppices, which are reputed to be unproductive. Most plantations were established on medium-rich soils, which are productive, and which correspond to LOf sites.

3.2. *Site index versus regional site classification*

Site type explains 51.6% of variance of site index (*F*-Ratio: 20.44; *P*-Value: 0.0000). A multiple range test indicated three levels of productivity among sites. A group of sites is clearly highly productive (LOd, LOsd, LOf), and corresponds to loamy soils developed on metamorphic substrate (Fig. 1). Within this group, the presence of a dry soil (LOd) leads to a decrease of site index. The lowest site index corresponds to harsh site conditions, with strongly nutrient-depleted soils (SHOd and SHOsd). The increase of WSC among site types within this group does not have a significant influence on site index. Medium site index was observed on oligotrophic sites on sandy materials. As observed in the first group, a reduction of soil moisture regime results in a reduction of site index.

3.3. *Site index versus site groups*

The five site groups assessed with the help of multivariate analysis explained 37.2% of site index variance (*F*-Ratio: 29.22; *P*-Value: 0.0000). Fig. 1 stresses that group 1 experiences a very low site index because of a combination of unfavorable ecological factors, both topoclimatic and edaphic. Conversely, group 5 is highly favorable to Douglas-Fir production. Groups 3 and 4 present comparable levels of productivity.

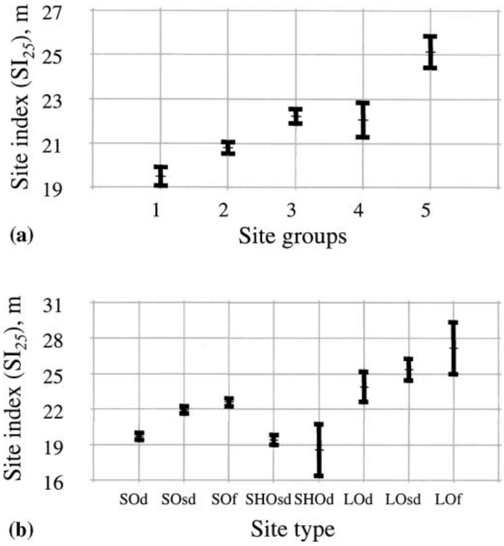

Fig. 1. Means and confidence intervals of Douglas-Fir site index according to site types (Fig. 1A) or site groups (Fig. 1B).

Comparison of stand allocation either to site types or to site groups (Table 6) was performed by cross-tabulation. The results stress that the two classifications are not independent (χ^2-test=306.6; *P*-Value=0.000). Two situations can be distinguished. First, some site types may be attributed for the most part to only one site group (=well sorted) because they present distinctive ecological features. Second, they may be allocated among several site groups (=not well sorted) when they have common ecological characteristics. For example, in the first case, site types on loamy parent material (L) are mostly grouped in site group 5 because the soil texture favors their meso-oligotrophic nutrient status. Very nutrient-depleted sites with dry soils (SHOd) are grouped for the major part in group 1, which is characterized by a very low nutrient status. Conversely, about half of sites SHOsd with slightly dry soils belong to group 2 which corresponds effectively to a variant with a higher WSC, and about half to group 1. Oligotrophic sites that are widespread and common (SOd, SOsd, SOf) are distributed in groups 1–4 according to ecological features of secondary importance.

Table 6
Correlation matrix between site groups according to multivariate analysis of the 202 stands database and site types according to site classification[a]

Site groups	1	2	3	4	5	Row total (number of stands)
Site types						
SOd	31 (75.7)	8 (19.5)	2 (4.8)	0 (0.0)	0 (0.0)	41
SOsd	18 (41.8)	2 (4.6)	2 (4.8)	20 (46.5)	1 (2.5)	43
SOf	5 (13.5)	7 (18.9)	0 (0.0)	25 (67.5)	0 (0.0)	37
SHOsd	0 (0.0)	0 (0.0)	7 (53.8)	6 (46.2)	0 (0.0)	13
SHOd	16 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	16
LOd	0 (0.0)	0 (0.0)	3 (23.0)	2 (15.4)	8 (61.6)	13
LOsd	0 (0.0)	0 (0.0)	0 (0.0)	9 (33.0)	13 (67.0)	26
LOf	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	13 (100.0)	13
Column total	70 (34.7)	17 (8.4)	14 (6.9)	62 (30.5)	40 (19.6)	202

[a] Values are numbers of plots, with the cell's percentage of the row in which it falls (in parentheses).

3.4. *A prediction model for site index*

Multiple linear regression methods were used to assess a model predicting site index (SI_{25}) versus quantitative site variables. The best-fit model was:- where SNS is soil nutrient status (index), ELEV is elevation (meters), SEEP is the water seepage index, WSC is the soil water storage capacity (mm), and TOPX is the Topex index (Table 7).

This model explains a relatively small portion of the variance of SI_{25} (adjusted R^2=0.40). The standard error of estimate of the model for the 202 stands is 1.72 m (Fig. 2). Analysis of residuals shows no particular trend due to structural or distributional problems, or to hidden factors (Fig. 3).

The main variables regressed with site index are in agreement with expectations based on correlation and ANOVA on isolated variables, and on previous studies (notably Décourt and Nys, 1976; Tyler et al., 1995). The variable having the greatest effect on site index are: distance to the nearest ridge (39.7%), elevation (39.0%), Topex (33.9%), position on slope (30.0%), soil water storage capacity (29.4%), soil nutrient

Table 7
Estimates, standard error and *t* values for the multiple regression model

	b estimate	Standard error	*t*
Constant	27.27	1.72	22.05
SNS	+1.95	0.34	−6.64
ELEV	−0.0052	0.001	−4.32
SEEP	+0.78	0.20	4.10
WSC	+0.0083	0.004	1.20
TOPX	−0.0031	0.0019	−1.29

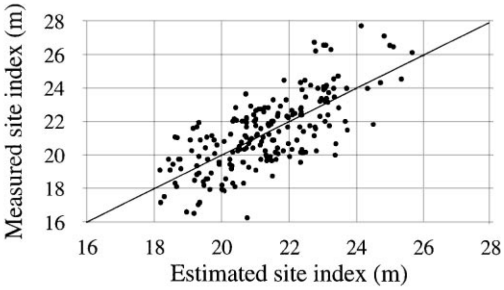

Fig. 2. Regression analysis for the prediction model of Douglas-Fir site index: estimated site index vs. measured site index.

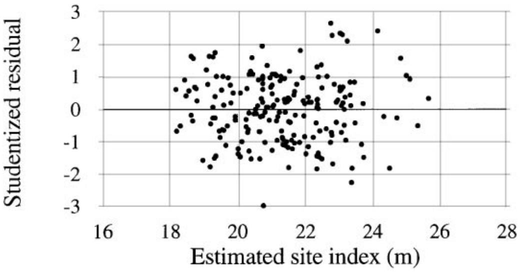

Fig. 3. Residual analysis for the prediction model of Douglas-Fir site index: studentized residuals vs. measured site index.

status (25.0). Physiographic variables are important to explain both topoclimatic effects and dynamics of water on slopes (Curt, 1999).

4. Discussion

More than 36% of site index variance was explained by former land use. Comparable results (32% for SI at 40 year) were observed for 202 Norway spruce stands in the same area (Curt et al., 1996). Former *Calluna* heathlands, and former bare soils or wet lands are the least favorable to Douglas-Fir height growth; this result is in agreement with previous observation by Décourt and Nys (1976). The effect of former land use on site index may be explained by various causes: (i) the absence of suitable mycorrhizal associations under heathlands, and their presence under broadleaves (Décourt and Nys, 1976). Phosphorous and potassium deficiencies are common under former heathlands, and fertilization leads to significant increase in tree growth; (ii) the remnants of former practices, such as fertilization and enrichment, or planting techniques; and (iii) differences in competition between Douglas-Fir seedlings and various pre-existing species.

Consequently, we conclude that former land use still influences present height growth of Douglas-Fir, even if they are insufficient to predict site index with accuracy. Former land use is partially correlated with forest sites, but the above results stress that they remain inadequate to replace site classification. Whether silvicultural practices (e.g. plantation techniques) according to different former land use may influence Douglas-Fir height growth remains to be determined using a specific study plan. For example, clear cutting and stump extraction were generally carried out on coppices before planting Douglas-Fir, and former heathlands were generally subjected to chemical refining or stubble-burning. Old practices remain unknown, although they may influence present day forest growth (Koerner et al., 1997).

4.1. Advantages and drawbacks of tested methods

The most accurate method to predict site index was to use site types, which were assessed with the help of a regional site classification. This classification was based on two major synoptic variables: SNS and WSC, which integrated an indirect evaluation of major causative factors that control tree growth (i.e. light, heat, and nutrients) (Hills, 1952; Wang and Klinka, 1996). Our results on Douglas-Fir confirm previous works (Green et al., 1989; Klinka and Carter, 1990; Wang and Klinka, 1996), stressing that this approach is relevant to assess both site quality and site productivity. The main advantage of regional site classification is to set up a comprehensive and common inventory of forest ecosystems within a large area, and to identify a wide range of sites presenting specific ecological characteristics, and productivity.

Site types were assessed using some simple field tests: (i) type of parent material according to their texture and stoniness; (ii) soil nutrient status according to soil type, humus form, and complementary soil analysis; and (iii) soil moisture regime according to SWC, rooting depth, and seepage index. This classification is only based on abiotic variables. The reason is that it was difficult to relate ground vegetation in young Douglas-Fir plantations to that of mature forest ecosystems, which are generally used to classify forest sites. Ground vegetation was very poor and homogeneous because of acidic soils, and disturbance resulting from the former agricultural practices and recent plantation of exotic species.

It is noteworthy that site classification is based on parcel-scale variables, such as soil nutrient, and soil moisture status. Correlation between climatic subzones and site index was low. This may be explained by two major causes: (i) variation of climatic variables remains low within the study area, which is favorable to this species and rather uniform; and (ii) lack of reliable climatic information and data at medium scale in mid-elevation forest Massif: only three meteorological stations were available. Data extrapolated with the help of simple climatic models were assessed but they were not sufficient to explain site index variation. Topoclimatic indices assessed at parcel-scale were more valid.

Site groups assessed by multivariate analysis were not as accurate as site types according to site classification. This specific outcome is in agreement with previous works on Norway spruce in three mid-elevation regions of the French Massif Central (Curt et al., 1998). Variance explained by site groups ranges from 30 to 76% according to study areas, while variance explained by site types is 50–80%, respectively. This may be explained by the fact that site groups are composed of a great number of plots, and they are consequently subject to a large range of SI_{25} variation. Regrouping sites tends to increase ecological variability among groups. In, e.g. group 5 is composed of sites of different levels of productivity, like SOsd (mean SI_{25}=22 m) and LOf (mean SI_{25}=26.5 m).

Nevertheless, reassembling site groups according to ecological variables at a local scale has advantages: (i) eliminating variables that are of secondary importance, and regrouping sites. For example, the regional classification (Curt, 1989) overemphasized the role played by soil stoniness. Consequently, a large number of site types (12) were present in the study area. Four or five types should be enough to predict the variations of site index for Douglas-Fir; (ii) taking into account physiographic and topoclimatic variables that were left aside because site classification was only based on edaphic variables. Correlation on isolated variables stresses the major importance of such variables to explain the productivity of Douglas-Fir (Curt, 1999); (iii) giving an area-specific diagnosis to managers: site groups were built with a local database, and make local features stand out that may be important to experts of a specific area; and (iv) a species-specific classification may be especially fitted to predict the productivity of a particular species. Regional site classifications are assessed to describe forest ecosystems in a large area, and to provide advice to forest managers when choosing species adapted to local site conditions among a large range of possibilities. Different tree species may perform differently in the same site type because their needs and resource use efficiency are different. Consequently, a site classification may be adapted to predict site index for some species, but not be effective for some others. For example, 165 pure Douglas-Fir stands were studied on the eastern border of the French Massif Central (Curt et al., 1998). Comparison between the two classifications stressed that the local and specific classification based on multivariate analysis was considered more convenient and more relevant by forest managers to predict site index for Douglas-Fir, even if the explained variance (34%) was less than the variance explained by regional site classification (52%). The main reason is that it is suited for Douglas-Fir, which is the main objective of local owners, and managers.

Site index of Douglas-Fir and Norway spruce was correlated with landscape-soil units (=morphopedological units) in granite areas in the same area (Curt, 1999). Each morphopedological unit is a distinct and replicable association between a landform (ridge, slope, bench, and vale), a type of parent material (arena, gelifluidal deposits) and a soil type (i.e. within Brunisolic or Regosolic Orders). These factors explain 42% of variance of site index, because they take into account physiographic and edaphic variables that play an important part in forest productivity.

Predicting site index using the multiple linear regression is not very accurate because standard error is 1.72 m. Multiple regression explains <40% of SI_{25} variance, and standard error of estimates is 1.72 m. This corresponds to a relative value of 8.2% (S.E. divided by mean site index), which is comparable to the results gained by Klinka and Carter (1990) or Wang and Klinka (1996), with a value of 7.4 and 7.1%, respectively. In Scotland, Tyler et al. (1995) predicted Douglas-Fir site index on better quality sites at 20–60 year. Their model was based on temperature, topoclimate, and crop age of plantations (R^2=0.46). In central Italy, Corona et al. (1998) established statistical correlation between site variables and site index of 15–61 years old plantations. A model combining climatic and edaphic variables explained about 58% of site index variations.

Our results give indication but may not be used as a common tool for predicting site index because of the residual variability of the model. Nevertheless, it confirms the major role played by some ecological variables as predictors of site index, such as elevation, topoclimate according to geomorphic features, seepage, and water storage capacity of soil (Curt, 1999). Furthermore, using this model to assess site index is rather simple for the forest managers because criteria and measurements can be performed easily in the field. However, this approach remains non-satisfactory because it mixes different families of site variables (edaphic and physiographic), and because it is based on the hypothesis that these variables are linked linearly with site index. It may not be realistic because: (i) it is known that some of them act together, and some are concerned with threshold effects and non-linear relationships. For example, correlation between site index and elevation is non-linear; a logarithmic curve fits better. The combined effects of elevation and WSC are complex. Under 500 m elevation, site index remains low for all the values of WSC because summer drought is harmful to Douglas-Fir. It is also a poor index above 900 m because climate is too cold. The influence of WSC on site index is linear between 500 and 900 m. Comparable effects of ecological compensation and non-linear correlation were found with elevation and aspect; and (ii) practical application in the field often comes up against this problem. Forest managers may encounter practical difficulties to use such regression models on variables of different families. Linking a great number of site variables that are non-linearly correlated remains difficult.

4.2. Unexplained variance

In total more than 50% of SI_{25} variance remains unexplained, whatever the method used to assess site productivity. This may be due to a reduced number of plots in some site types, and especially in some site groups. This unbalanced sampling nevertheless reflects the field pattern of sites. Oligotrophic sites are over-represented within the study area, but this may be also to due to some of the classic causes listed notably by Corona et al. (1998) or Monserud and Rehfeldt (1990): (i) measurement and sampling errors in the field; (ii) failure to measure the true causes of site productivity because of missing variable or inconsistent descriptors. In particular, accurate and robust relationship should be established between synoptic variables used for the site classification, and direct causative factors of forest growth, such as light, heat, moisture, and nutrients (Wang and Klinka, 1996). Using simple field-tests, such as evaluation of WSC is convenient for giving advice to forest managers, but remains a rough estimate of the complexity of ecosystem functioning (Curt et al., 1996). Furthermore, site types result from a cutting-out of an ecological continuum, and ecological features that are subjected to a range of variation within a site type may cause variation in site index; and (iii) failure to adequately sample the ecological complexity of the study area.

Assessing site productivity should require further investigation on genetics and silvicultural practices. It is noteworthy that the older the reference age of stands, the higher the variance of site index explained by site types (Curt, 1999). A hypothesis could be that differences in site productivity are more evident when stands are older, because possible problems in initial growth (due to silvicultural practices) are mitigated. Moreover, errors in estimation of site productivity may result from the method used to assess site index (Wang, 1998).

Nevertheless, our findings are sound and convincing as compared with most results of site-yield studies (e.g. Monserud et al., 1990) that predict about 30% of the total site index variation. Sites may be of practical interest for foresters at medium scale; it is only indicative for assessing site productivity for single observations at parcel scale.

4.3. Practical application: is Douglas-Fir adapted to site conditions?

Douglas-Fir is reputed among forest managers to be adapted to acidic sites in mid-elevation regions of the French Massif Central. The Limousin area is reputed as one of the most productive for Douglas-Fir in France: the mean annual yield increment is 21 m^3 ha^{-1} per year in the first productivity class, while the mean value for France is 18.61 (De Champs, 1997). This may be due to favorable ecological conditions, especially climatic.

Our results confirm the adaptability of Douglas-Fir to most of the sites existing in acidic and wet climatic mid-elevation regions of the French Massif Central, in agreement with Décourt and Nys (1976). They also revealed some information on the Douglas-Fir autoecology in this area. Because of geochemical characteristics of granites and gneiss, soils of the Limousin area are generally acidic and nutrient-depleted, especially in potassium, calcium, and phosphoric acid (Décourt and Nys, 1976). For example, deficiencies were observed for the above-mentioned cations, in respectively, 50, 90, 90, and 98%, of the 60 stands. Consequently, locating and identifying sites with mesotrophic soils at landscape scale is helpful to forest managers (Curt, 1999). The productivity of this species is high on oligotrophic soils on metamorphic substrata that are common in the provenance area. Despite its reputation of adaptation to any soils, Douglas-Fir is sensible to extreme cation depletion. When soils are strongly nutrient depleted, the increase of soil moisture regime has no real influence on site index because lack of nutrients is a limiting factor.

Conversely, the increase of WSC is favorable for oligotrophic and medium-rich soils. This analysis confirms the assumption of Wang and Klinka (1996) who stressed that growth-limiting factors vary within site groups.

Correlation between site index and chemical analyses for 60 stands stress that the major chemical variables to explain site index variation are those related to dynamics of organic matter and mineralization (total carbon, organic matter, carbon: nitrogen ratio), and those indicating the podzolization process like exchangeable aluminum.

5. Conclusion

In acidic, mid-elevation regions of the northwestern part of the French Massif Central, we conclude that Douglas-Fir site index is correlated to soil nutrient status, and secondarily to soil moisture regime. Douglas-Fir stands are generally very productive, but this study highlighted variations in site index within the study area, which was nevertheless reputed as uniform. Correlation between site classification and site index was confirmed, because it was based on synoptic factors that are simple and robust indicators of site productivity. Other methods to assess site quality, such as multiple regression on ecological variables, and multivariate site groups, appear to be less explicative and robust to predict site index.

Results are accurate enough to help forest managers to predict site index at medium scale. Research is needed to explain the major causes of unexplained variance of site index by ecological variables, especially genetic variation, and age effect. Understanding the consequences of former agricultural practices on differences in productivity of current reforested areas is a major problem in France. Koerner et al. (1997) stressed that long-term effects (about 100 year) of these practices can persist in ground vegetation and soil's cation dynamics, and should be taken into account in forest management.

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