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How Timber Harvesting and Biodiversity are Managed in Uneven-Aged Forests: A Cluster-Sample Econometric Approach

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1. Introduction

Nonindustrial private forest (NIPF) landowners have been shown to be more multi-objective by nature than industrial landowners: they give more importance to standing timber and forestland for the amenity values they provide (Newman & Wear, 1993). Among analyses of forest landowner behaviour, the household production framework recognises the benefits associated with forest amenities, as first applied by Binkley (1981). These non-market services are jointly produced with timber and are a determinant in the landowner's utility function.

NIPF landowners comprise close to 70% of land ownership in many U.S. states and significant land holdings throughout Europe (Amacher et al., 2003). In France, almost 75% of the total forestland is privately owned, and 96% of private landowners are nonindustrial. In this article, we investigate the joint production of timber and biodiversity for NIPF landowners using a micro-econometric household production model.

Even though our model is situated within a standard framework where a non-marketed good is jointly produced with timber products, we consider here that biodiversity is not totally disconnected from market strategies. Biodiversity is measured by the diversity of tree species. This assumption is based on the theory of coevolution introduced by Ehrlich & Raven (1964). Coevolution acts as an evolutionary engine and a vehicle for biological diversification. Thus, the diversity of trees or plants may not only tend to increase the diversity of insects and animals, but the converse may also be true. In our model, tree diversity is a determinant of consumer satisfaction and a joint product in the profit-maximisation problem. Tree diversity has an additional impact: it is closely related to some market aspects since the different species have different monetary values. The forest landowner can decide to favour one tree species over another, depending on its value on the market. Conversely, he can make the choice of species diversification to cope with the volatility of timber prices.

We focus on a complete set of forest landowners' decisions in uneven-aged forests where landowners are assumed to value the tree diversity of their forests, as well as timber harvesting. Our economic model is based on the maximisation of their utility that depends on the revenues from harvesting and tree diversity with respect to technological and budgetary constraints. The global objective of the paper is to explain the links between some of the harvest strategies of forest owners, unit price variability and the observed diversity of trees.

More precisely, we analyse: (1) their demand for species diversity and their timber supply; and (2) the joint production of timber and species diversity. Timber supply and amenity demand functions are derived using first-order conditions of the maximisation problem for the landowner.

The behaviour of the forest owner is also strongly dependent on the characteristics of the forest blocks in question. Moreover, his/her harvesting strategy should differ according to the tree species and its value (depending itself on the quality and the diameter of the trees). The issue of heterogeneity in this case is crucial and its omission may result in consequent biases in the estimation stage. The estimation of timber supply and diversity demand is made using a database on uneven-aged forests in France for which several economic and ecological variables are regularly collected. This database typically concerns several forest blocks within which different tree species cohabit. This makes it possible to consider the forest owner within a multi-product framework where each product corresponds to a particular tree species.

2. Methods

2.1 Biodiversity and the economic model

In the literature on NIPF landowners, recent models of timber supply have included non-monetary returns or amenities (Binkley, 1981; Hyberg & Holthausen, 1989; Max & Lehman, 1988; Pattanayak et al., 2003; 2002). The idea is to better understand the trade-off between timber harvesting and amenity benefits.

In this study, we attempt to understand forest owners' decisions concerning timber harvesting and biodiversity. Indeed, different tree species have different monetary values, and the forest landowner has several alternatives: to favour one tree species over another, depending on its market value, or to diversify the tree species in order to cope with the volatility of timber prices.

Our definition of biological diversity may appear to be restrictive due to the sole inclusion of trees (instead of global biodiversity). Nevertheless, tree diversity accounts for a large part of biodiversity: it is generally accepted that the mixture of species is the guarantee of a certain degree of diversity of other living communities (for invertebrates, see Greatorex-Davies et al. (1993), and for bats, see Mayle (1990)). This is the principle of coevolution (Ehrlich & Raven, 1964). The diversity of trees or plants may not only tend to increase the diversity of insects and animals, but the converse may also be true.[1] Even if the extrapolation of tree diversity to global biological diversity is still in debate, this makes it possible to take both biodiversity and strategies on the timber market into account with only one indicator. Furthermore, there is no consensus about the choice of the diversity indicator. This is why several measures were tested in our model.

We, in fact, used two notions, richness and diversity, the latter being the Shannon diversity index computed as $H = -\sum_h p_h \ln p_h$, where h represent a species. Three diversity indices were calculated:

1. Tree richness, designated by $RICH$, is computed as the number of species in the forest compartment. This is the simplest and the most intuitive index used to measure biodiversity. However, this measure strongly depends on the area surveyed.

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[1] Many references exist on this topic, see Lähde et al. (1999), Barbier et al. (2008), Schuldt et al. (2008), McDermott & Wood (2009), among others.

2. The Shannon diversity index on the basis of number, designated by $SHANN$, is computed from the number of stems (n_h) with $p_h = \frac{n_h}{\sum_h n_h}$.

3. The Shannon diversity index on the basis of volume, referred to as $SHANV$, is expressed in volume v_h: $p_h = \frac{v_h}{\sum_h v_h}$. The Shannon diversity index based on number is often used by ecologists, but the Shannon diversity index based on volume is more effect for characterising the crown size of different species.

In our model, tree diversity is a determinant of consumer satisfaction and a joint product in the profit-maximisation problem. The landowner i is represented in the framework of the household production function by a utility function that depends on the total income and non-pecuniary attributes:

$$U_i = U(I_i, z_i), \tag{1}$$

where I_i represents the total income of the landowner i and z_i is the forest biodiversity.
The forest landowner faces a budget constraint where the total income is the sum of timber production profit π and exogenous income E:

$$I_i = \pi_{ij} + E_i. \tag{2}$$

The timber profit π_{ij} depends on timber production y_{ij} sold at the price p_{ij}, where the subscript j designates the tree species. The profit function is the difference between the timber revenue and the multi-product cost function related to the production of the (marketable) timber output y_{ij} and the tree diversity z_i conditional on some exogenous variables x_{ij} (including forest capital and ecological variables). It can be written as:

$$\pi_{ij} = p_{ij} \times y_{ij} - C(y_{ij}, z_i, x_{ij}). \tag{3}$$

Timber production y_{ij} and tree diversity z_i are linked by the following transformation function:

$$T(y_{ij}, z_i, x_{ij}) = 0. \tag{4}$$

The forest landowner has to choose the level of decision variables (i.e., y, z and I) that maximizes the utility function (1) subject to constraints (2) and (3). This utility maximisation problem can be solved by substituting these constraints into the utility function. The resolution is done in two steps: the household first selects the optimal level of I and z and then chooses the level of production y. In order to obtain explicit solutions to this problem, we have imposed some simple functional forms on our model. We chose a Cobb-Douglas form for the utility and cost functions. With these particular functional forms and by deriving with respect to y, we obtain the timber supply function that depends on timber price p, non-timber product z and other variables x. Expressing the first-order condition in log-linear form, we find the following timber supply function:

$$\ln y_{ij} = \alpha_0 + \alpha_1 \ln p_{ij} + \alpha_2 \ln z_i + \alpha_3 \ln x_{ij}, \tag{5}$$

where the unknown parameters α are to be estimated. Note that α_1 represents the price elasticity of supply. If α_1 is respectively $<, =$ or > 1 then the supply is price inelastic, unit-elastic or price-elastic. α_2 measures the trade-off between tree harvesting and diversity

in terms of elasticity. If α_2 is negative, there is a substitution effect, whereas a positive sign is synonymous with complementarity.

Entering the equation (5) in the utility function and deriving it with respect to z give us the diversity demand. Transforming it into log-linear form, we have:

$$\ln z_i = \beta_0 + \beta_1 \ln p_{ij} + \beta_2 \ln x_{ij}, \tag{6}$$

where β are the unknown parameters of the demand function to be estimated. β_1 represents the elasticity of diversity demand with respect to timber price. If β_1 is respectively $<, =$ or > 1 then the diversity is inelastic relative to the timber price, unit-elastic or price-elastic.

2.2 The econometric approach

A two-step estimation procedure is implemented by first estimating the diversity demand equation (at the forest level), followed by the timber supply equation in which the predicted value of diversity is entered as a regressor.

Harvest observations collected for different tree species in different forests lead to the use of methods specific to cluster sampling (Wooldridge, 2003). However, the diversity of tree species is observed at the forest compartment level and is therefore cluster-invariant. Supposing that all variables are exogenous, the tree diversity demand equation (6) is estimated by the Ordinary Least Squares (OLS) method.

Cluster specificity is taken into account in the estimation of the timber supply equation (5). The units within each cluster (or forest) may be correlated, whereas independence across clusters is assumed. Specific methods applied to Fixed Effect (FE) and Random Effect (RE) models make it possible to control for unobserved forest heterogeneity while studying the effects of factors that vary across species and forests (e.g., price), and others specific to forests (e.g., tree species diversity). Moulton (1986) shows the consequences of inappropriately using OLS estimation in the presence of random group effects. In particular, he demonstrates that the OLS standard errors that are not adjusted in this case are biased.

Consider the following timber supply cluster-sample equation:

$$y_{ij} = \alpha + X_{ij}\beta + Z_i\gamma + u_{ij}, \qquad i = 1, \ldots, N, \quad j = 1, \ldots, J_i, \tag{7}$$

where i indexes the "cluster" (or forest), j indexes individual observations within the cluster (or tree species). There is a total number of N clusters. The number of species is not the same throughout the different forests i, so that J (i.e., the number of species in the case of balanced data) is indexed by i. The total number of observations is $n = \sum J_i$. Harvest in the forest i of the tree species j is designated by y_{ij}. X_{ij} is a $(1 \times K)$ vector of explanatory variables that vary with respect to i and j. Z_i contains L explanatory variables that only depend on the cluster i. u_{ij} is the error term. α is the constant, and β and γ are the parameter vectors associated with the X and Z to be estimated, respectively.

We consider the following unbalanced one-way error component:[2]

$$u_{ij} = \mu_i + \epsilon_{ij}, \qquad i = 1, \ldots, N, \quad j = 1, \ldots, J_i, \tag{8}$$

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[2] Only five species are observed and not within all forests. We can therefore not implement a two-way error component regression model. Moreover, each forest is observed only once since we only have cross-section data.

where μ_i is the cluster specific effect, and ϵ_{ij} represents the remaining unobservables. μ_i and ϵ_{ij} are assumed to be independent and respectively i.i.d. $(0, \sigma_\mu^2)$ and $(0, \sigma_\epsilon^2)$. In matrix form, the one-way cluster model can be written as:

$$y = \alpha \iota_n + X\beta + Z\gamma + u$$
$$= R\delta + u,$$

(9)

where $u = R_\mu \mu + \epsilon$, with $R = (\iota_n, X, Z)$ and ι_n a vector of n ones. y and R are of dimensions $n \times 1$ and $n \times (1 + K + L)$. $\delta' = (\alpha', \beta', \gamma')$ is the vector of parameters to be estimated. Finally, $R_\mu = diag(\iota_{J_i})$ with ι_{J_i} is a vector of ones of dimension J_i.

Supposing that all variables are exogenous, the equation can first be estimated by pooled OLS from the unbalanced data. The OLS estimator is trivially given by $\hat{\delta}_{OLS} = (R'R)^{-1}R'y$. It is unbiased and consistent. However, according to the method proposed by Pepper (2002), we use an estimate of the asymptotic variance matrix that is robust to heteroscedasticity and within-cluster correlation of arbitrary forms: $Var(\hat{\delta}_{OLS}) = (R'R)^{-1} \left(\sum_{i=1}^{N} R_i' \hat{u}_i \hat{u}_i' R_i \right) (R'R)^{-1}$, where $\hat{u}_i$ is the $N \times 1$ vector of OLS residuals $(Y_i - \hat{\delta}_{OLS} R_i)$.

Other consistent methods exist (some of which are more efficient), which make it possible to take the presence of unobserved effects in the error term into account. Cluster samples and panel data sets (where i represents individuals and j time periods) can be treated with similar methods (FE and RE models). In our case, the database has the same structure as an unbalanced panel data set. This is why we based our estimation method on the work of Baltagi & Chang (1994).

We can first consider that μ_i represents the unobserved heterogeneity related to the forest, and treat it as a constant parameter to be estimated for each cluster i. If the fixed effects are correlated with the explanatory variables, there is an endogeneity problem that implies a biased estimator of parameters α, β and γ. We can obtain a consistent estimator of β by removing these effects with a suitable transformation (within-group transformation). However, an important drawback is that the parameters (γ) associated with cluster-invariant variables cannot be identified. The within-group transformation matrix for the (unbalanced) cluster-sample case is $Q = diag(E_{J_i})$. $E_{J_i} = I_{J_i} - \frac{\iota_{J_i} \iota_{J_i}'}{J_i}$, where I_{J_i} is an identity matrix of dimension J_i. The Within (or FE) estimator of β is:

$$\hat{\beta}_{FE} = (X'QX)^{-1}X'Qy,$$

(10)

under the assumption of non correlation between ϵ and X. A drawback of this method is that γ cannot be identified because the variables Z disappear after within transformation.

In order to take any possible autocorrelation or heteroscedasticity into account, Arellano (1987) proposes the following variance-matrix estimator:

$$Var(\hat{\beta}_{FE}) = (X'QX)^{-1} \left(\sum_{i=1}^{N} QX_i' e_i e_i' QX_i \right) (X'QX)^{-1},$$

with $e_i = Qy - QX\hat{\beta}_{FE}$, which is fully robust.

If the specific effects are assumed to be non-correlated with the explanatory variables, then a random effects (Generalised Least Squares, GLS) estimation can be used. Even if OLS

estimators provide consistent parameters, a heteroscedasticity-consistent variance matrix is necessary. The effect μ_i is now treated as a (cluster-specific) error term and assumed to be i.i.d. $(0, \sigma_\mu^2)$. In this model, we can identify all coefficients related to all variables (including those that are cluster-invariant). Hence, the matrix of explanatory variables is now $R = (\iota_n, X, Z)$. The vector of parameters $\delta' = (\alpha', \beta', \gamma')$ and the variance components $(\sigma_\mu^2, \sigma_\epsilon^2)$ are estimated. The variance-covariance matrix of error terms u is $\Omega \equiv E(uu') = \sigma_\epsilon^2 \Sigma$, where $\Sigma = I_n + \rho Z_\mu Z_\mu'$, with I_n an identity matrix of dimension n and $\rho = \frac{\sigma_\mu^2}{\sigma_\epsilon^2}$. The GLS (or RE) estimator is:

$$\hat{\delta}_{RE} = (R'\Omega^{-1}R)^{-1}(R'\Omega^{-1}y). \tag{11}$$

The variance of the RE estimator is: $Var(\hat{\delta}_{RE}) = \sigma_\epsilon^2 (R'\Omega^{-1}R)^{-1}$. Several methods of estimation of variance components $(\sigma_\mu^2, \sigma_\epsilon^2)$ exist. However, the solution the most often chosen is the method of Swamy & Arora (1972) by using the Within and Between residuals.

The RE estimator is asymptotically more efficient than pooled OLS under the usual RE assumptions. However, if the cluster effects are correlated with μ_i are correlated with X or Z, this estimator is not consistent. This possible endogeneity can be tested for by performing a Hausman test. The Hausman test statistic is: $(\hat{\beta}_{FE} - \hat{\beta}_{RE})'[Var(\hat{\beta}_{FE}) - Var(\hat{\beta}_{RE})]^{-1}(\hat{\beta}_{FE} - \hat{\beta}_{RE})$. Under the null hypothesis, this statistic has an asymptotic chi-square distribution with a number of degrees of freedom equal to the number of cluster-variant variables (K).

3. Results and discussion

3.1 Data sources and characteristics

The database of the AFI network (*Association Futaie Irrégulière* - Uneven-aged forest network) was used. Uneven-aged forest management is characterised by two fundamental principles: the use of natural dynamics of the ecosystem and the individual treatment of each tree. The first principle implies the use of all tree species on the site: forests are always mixed-species (with variations depending on the acidity of the soils). The second principle means that each tree is examined in order to assess its different functions (e.g., value-added wood, aesthetic aspect). Hence, the decision of tree harvesting or conservation does not result from the stand age but rather from its functionality: Does this tree "pay" for its place? (Bruciamacchie & de Turckheim, 2005). Uneven-aged forest management is practised in numerous forests worldwide with a multitude of variations in terms of species composition and stand structures under local ecological, social and economic constraints.

The AFI network consists of 68 compartments in the northern part of France. The compartment is the management unit for uneven-aged forests (whereas the whole forest is the unit considered for even-aged forests) and corresponds to a block that varies from 5 to 15 ha. One compartment is made up of ten permanent plots that make it possible to monitor the individual growth of approximately 200 trees per compartment. These compartments also make it possible to monitor poles, coppice and regeneration. Some of them are good examples of successful transitions between even-aged and uneven-aged stands. Our sample is made up of forests whose stands are well-balanced in terms of forestry (consistent harvesting), which makes it possible to handle economic data that are uniform on the long term.

As mentioned above, we consider a forest owner who maximises his utility that is a function of total income and diversity. The forest owner decides on the main orientations of his/her

forest management (e.g., level of revenues, distribution of species, risks concerning species management). However, we wanted to introduce an important characteristic of forest management into the empirical model: in practice, forests are managed by the "owner/forest manager" pair. Indeed, the owner often delegates the management to a forest manager who implements the owner's choices and can thus have an influence on the harvesting decision and the distribution of species. This is why we include dummies that proxy the identity of the manager (see below).

Among the 68 compartments, 39 were selected because all of the information in all of the categories of variables was available. We classified tree species into five classes: oak, beech, precious broad-leaved trees, other broad-leaved trees and conifers. These five classes of species are not observed in all of the compartments, so that the total number of observations in our sample is 102.[3]

However, the number of species is greater and we compute the diversity for each compartment from the total number of species (varying from 2 to 14 in our sample). As presented above, we calculate three diversity indices. The first index used is tree richness, designated by $RICH$, simply computed as the number of species in the forest compartment. The last two are Shannon diversity indices computed as $H = -\sum_h p_h \ln p_h$, where h represent a species.[4] We compute a Shannon diversity index on the basis of number ($SHANN$) and a Shannon diversity index on the basis of volume ($SHANV$), already defined above.

The variables used in the model are the following:

- Variables observed per compartment and broken down by species: harvested volume (y), unit price (p),[5] stock inventory (INV), volume increment ($VOLINCR$).

- Percentage of quality ($QUAL\%$) and average diameter ($DIAM$) are measured for standing timber.

- At the compartment level, seven dummy variables (from $ST1$ to $ST7$)) are built for seven different ecological conditions ranging from the more basic to the more acid soils. In fact, this set of dummies represents an ecological indicator built from the variables, pH and moisture.[6]

- The type of owners is represented by four dummy variables: institution ($DUMO1$), individual ($DUMO2$), group of owners ($DUMO3$) or joint ownership ($DUMO4$).

- The owner often delegates the management to a forest manager. He/she implements the owner's decisions but can have an influence on the distribution of species. Dummies $DUME1$ to $DUME10$ are used for the manager. $DUME10$ is the remaining sum of managers that are in charge of only one forest compartment.

Descriptive statistics are reported in Table 1.

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[3] In a complete data cluster, the number of observations would be 195.

[4] We use two different subscripts in our article. Subscript j refers to the (five) classes of species, whereas h refers to the species alone (the total number of species varies from 2 to 14 in our sample).

[5] Unit price refers to the market price depending on species, diameter and quality. In the empirical model, we use the average unit price, i.e., the unit price for one species in one compartment.

[6] In reality, a more in-depth ecological study would take pH, moisture and altitude into account. There is actually no significant variation in altitude since all forests observed in our sample are located at altitudes below 500 meters.

Variable	Definition	Unit	Mean	Standard deviation	Minimum	Maximum
Dependent						
RICH	Richness index		7.80	2.84	2.00	14.00
SHANV	Shannon index (in volume)		1.17	0.42	0.07	2.16
SHANN	Shannon index (in number)		1.39	0.41	0.00	1.98
Y	Timber harvest	$m^3/ha/year$	1.02	1.86	0.03	15.03
Independent						
P	Timber price	$euros/m^3$	31.34	31.53	3.00	170.20
DIAM	Tree diameter	centimeters	30.40	12.17	9.50	58.93
QUAL%	Percentage of quality		0.25	0.16	0.00	0.62
INV	Stock inventory per species	m^3/ha	48.23	72.14	0.75	667.52
INVD	Stock inventory (sum of species)	m^3/ha	131.55	81.71	59.00	677.00
VOLINCR	Volume increment (of stock)		4.31	2.27	1.90	17.90
	Type of owners (Dummies)					
DUMO1	Institution		0.1078			
DUMO2	Forest owner		0.3333			
DUMO3	Group of owners		0.4216			
DUMO4	Joint ownership		0.1373			
	Manager (Dummies)					
DUME1			0.0686			
DUME2			0.1667			
DUME3			0.2157			
DUME4			0.0980			
DUME5			0.1176			
DUME6			0.0490			
DUME7			0.0490			
DUME8			0.0392			
DUME9			0.0392			
DUME10			0.1568			
	Ecological conditions (Dummies)					
ST1	Calcareous		0.2059			
ST2	Calcareous clay		0.0490			
ST3	Silt and clay		0.1961			
ST4	Hydromorphic		0.3333			
ST5	Sand		0.1176			
ST6	Sandstone		0.0784			
ST7	Acid		0.0196			

Table 1. Descriptive statistics, 102 observations

3.2 Estimation results

We first estimate the tree diversity demand equation (6). The diversity of tree species is observed for each forest compartment and is cluster-invariant. Since some explanatory variables vary according to the forest compartment as well as to the species (such as the price), the diversity equation is estimated by a (between-type) OLS method. All variables can be considered as exogenous in this estimation (at least, on the short term). In particular, the price is determined by the market. Hence, there can be no doubt about the direction of the cause-effect relationship. For example, it is the timber price that explains the tree diversity in a compartment and not vice versa.

As mentioned above, there are three different indices to proxy diversity. Three regressions were successfully run with the three different indices as dependent variables. The estimated coefficients are similar. However, the goodness of fit as well as the significance of parameters are better with the logarithm of the number of species (i.e., the richness index). The richness varies as soon as an individual of a new species is added or removed. Shannon indices are preferred by ecologists because they take the richness as well as the distribution of species into account at the same time. However, according to the managers, taking biodiversity into account tends to favour minority species. Estimation results are presented in Table 2.

Variable	Coefficient	s.e	Variable	Coefficient	s.e.
Dependent variable: $\ln z = \ln RICH$					
Constant	-4.1585**	1.7642	*DUME6*	-0.3070***	0.0837
$\ln p$	0.3110*	0.1781	*DUME8*	1.2389***	0.2417
$\ln DIAM$	0.7357**	0.2985	*ST1*	2.4252***	0.4362
QUAL%	-2.4432***	0.6085	*ST2*	2.3281***	0.3816
$\ln INVD$	0.0645	0.2351	*ST3*	2.2615***	0.3882
VOLINCR	0.4216***	0.1398	*ST4*	1.8120***	0.4080
DUME2	0.3974***	0.0970	*ST5*	1.7468***	0.4016
DUME3	0.1129	0.1259	*ST6*	1.8774***	0.4155

Notes: $n = 102, N = 39$. Adjusted $R^2 = 0.602$. Heteroscedasticity-consistent s.e.

***: significant at 1%, **: significant at 5%, *: significant at 10%.

Table 2. Demand estimation - OLS method

The overall performance of the demand equation is good since the adjusted R^2 is equal to 0.602. The estimated parameters are all significantly different from zero, except for the stock inventory (i.e., the standing timber per ha) and a dummy variable that proxies a forest expert. However, other variables related to the state or trend of forest capital such as the average diameter of trees, the share of qualitative stand wood and the volume increment of forest are significant in our model. In particular, the negative sign for the coefficient associated with the percentage of quality (*QUAL%*) has an interesting interpretation. Forests with the highest percentage of quality correspond to ones with the lowest diversity. Since a high percentage of quality increases the revenues over time, this result would mean that in this case, species

diversity is less favoured, showing a trade-off between quality and diversity. Moreover, the coefficient associated with the variable $DIAM$ is significantly positive. In order to favour diversity, some trees were harvested early to diminish natural competition between species.

As expected, the site context has a significant impact on the diversity. Coefficients associated with dummies from $ST1$ to $ST6$ are all significant with positive signs (decreasing from 2.43 to 1.88, respectively) with respect to acid soils ($ST7$), confirming a decrease in richness when the context is acid. Furthermore, the estimated coefficients allow a classification of the site conditions that is in agreement with the observed ecological link between the chemical characteristics of the soil and tree (and flora) diversity.

Some forest managers have a significant positive impact on tree diversity, while other ones have a negative impact that supports a short-term view. The variables for the type of forest owner have been removed because their coefficients were not significantly different from zero. The unit price has a significant and positive influence on the diversity. Its value (0.3110) means that a 10% decrease in timber price implies a 3.11% decrease in tree diversity. This result highlights the effect of timber price on the abandonment of species. For example, in the ecological context where diversity is the highest (14 species in our sample), a 23% decrease in price could lead to the loss of one species. Unit prices for timber are exogenous. However, average unit price (for one species in one compartment) can vary according to the distribution in the stand with respect to its quality and its size. The forest owner can therefore adjust his/her revenues by acting on these variables. One of the principles in uneven-aged forest management is to concentrate the volume increment on the high-quality trees. Hence, low-quality trees are progressively cut and, at the same time, the unit price of standing timber as well as that of harvested timber increase. Once this unit price has increased, forest managers and owners are more inclined to maintain the minority species. The objective is to reduce economic risks by finding an optimal distribution among the different species.

Using the estimates of the demand equation, the fitted value of diversity was computed and used as an explanatory variable in the timber supply equation (5). The use of generated regressors may produce non-consistent estimated standard errors. This is why a vector of regressors was used that includes some or all exogenous variables already in the first regression (Pagan, 1984). This second-step OLS leads, in fact, to a two-stage least squares procedure since the regressors are variables used in the first-step estimation (of the demand equation), and gives correct standard errors. Because the predicted diversity $\ln \widehat{RICH}$ can be approximated by a linear function of the explanatory variables in the demand equation and leads to a problem of collinearity, several exclusion restrictions were used in the supply equation. Some variables that do not appear to be significant to explain harvesting have thus been excluded, including the volume increment of stock ($VOLINCR$) and some dummies that proxy the forest manager. Finally, this estimation procedure is implemented with a robust variance-covariance matrix.

Within and GLS methods (for FE and RE models, respectively) are implemented as described in the econometric method section. They are also conducted in two steps like the OLS method. A Hausman test was then computed to check for the exogeneity of explanatory variables. The value of the statistic is 3.217 (with a P-value of 0.5222) and is below the $\chi^2(4)$ critical value at the 1% level. This result confirms the exogeneity of variables. Hence, the GLS method is the best adapted here for dealing with the cluster feature of our sample. R^2 is equal to 0.606

and indicates a good fitting of our model. Estimation results of (second-step) OLS, Within and GLS methods are reported in Table 3.

	OLS (Pooled)		Within (FE - Fixed Effects)		GLS (RE - Random Effects)	
Variable	Coef.	Robust s.e.	Coef.	Robust s.e.	Coef.	s.e.
Dependent variable: $\ln y$						
Constant	-1.2893*	0.7816	-3.3204***	0.2433	-1.3713**	0.5866
$\ln p$	0.5735***	0.0955	0.3467***	0.1089	0.4659***	0.0699
$\ln DIAM$	-0.0368***	0.0089	-0.0424***	0.0072	-0.0387***	0.0066
$QUAL\%$	-1.4822**	0.6484	-1.1813	0.7142	-1.3775***	0.4515
$\ln INV$	0.7178***	0.0771	0.9054***	0.0756	0.8085***	0.0630
$\ln \widehat{RICH}$	-0.8651**	0.3456	–		-0.7797***	0.2610
$DUME2$	-0.8210*	0.4226	–		-1.0129***	0.2387
$DUME3$	-0.3628	0.2651	–		-0.4820**	0.2119
$ST4$	-0.5238**	0.2433	–		-0.5008**	0.1980
$ST5$	-0.8125**	0.3761	–		-0.7456**	0.3018
$\hat{\sigma}_\epsilon^2$					0.5065	
$\hat{\sigma}_\mu^2$					0.2861	
Hausman test (P-value)					3.217 (0.5222)	
R^2		0.613		0.460		0.606

Notes : n=102, N=39. ***: significant at 1%, **: significant at 5%, *: significant at 10%. Robust s.e. for OLS and FE estimation are respectively computed following Pepper (2002) and Arellano (1987).

Table 3. Supply estimation - Cluster-sample econometric methods

As explained above, OLS is less efficient than GLS since it does not fully take the cluster feature of our sample into account, even if a robust variance-covariance matrix makes it possible to alleviate this problem. OLS coefficients are rather similar to those estimated by specific cluster methods. However, some interest coefficients such as those associated with price and diversity are slightly overestimated. For example, the coefficient associated with the price is 0.57 with OLS, compared to 0.43-0.47 with GLS. For the diversity, it is equal to 0.87, compared to 0.75-0.78 (in absolute value).

The coefficients associated with the variables $QUAL\%$ and $DIAM$ are significantly negative (with estimates of -1.38 and -0.04, respectively). This means that high-quality trees with big diameters are harvested to be sold. Hence, the actual standing timber is characterised by a lower percentage of quality and a lower average diameter. Moreover, it is not surprising to

see that whereas forest managers have a positive impact on tree diversity, this is not the case for timber harvest.

Results also show a positive and significant impact of both timber inventory and unit price. As expected, timber harvest increases with the standing volume of trees. The coefficient associated with the price (or price elasticity of timber supply) is estimated at 0.47, meaning that a 10% increase in price implies a 4.7% increase in harvesting.

The diversity is negatively and significantly correlated to the timber harvest, all things being equal. The estimated coefficient can be directly interpreted as a measure of substitution between tree diversity and the volume of timber harvested. The point estimate is equal to -0.78. This value is rather high. However, based on the standard error estimate, we can reject the hypothesis of a unitary elasticity substitution. An explanation for this negative sign is that when the site context is acid, the forest manager cannot influence the unit timber price interval per species. In this case, under acid soil conditions, the forest manager can only act on timber volume. On the contrary, the basic context allows for a greater variety of species. However, in order to favour all species, the forest manager cannot increase the standing volume and in some cases, may be forced to reduce it. Hence, the forest stock is low on the long term and this trend leads to a lower timber harvest.

4. Conclusion

In this study, a household production approach was used to model the behaviour of the NIPF owner in order to derive the structural econometric equations of timber supply and diversity demand and to estimate substitution and price elasticities. In the empirical application, a definition of diversity was chosen solely on the basis of the number of tree species. This diversity is simple to calculate and positively correlated with the diversity in flora and fauna. Moreover, the richness of data related to harvested species and the cluster-sample methods used in this context make it possible to deal with heterogeneity and variability within clusters. In addition, Within and GLS estimation methods make it possible to test for the possible endogeneity problem of some variables.

This study revealed that diversity demand and timber supply are negatively linked, meaning that an increase in tree diversity will lead to a decrease in timber harvesting. This result confirms that these two forest outputs are substitutes. Estimation also shows that timber price and tree diversity evolve in the same direction: the positive and significant coefficient associated with the timber price in the demand equation indicates that a price decrease has a negative effect on diversity. This result is certainly the consequence of the characteristics of uneven-aged forests and the strategies used to manage them. This could be explained by the fact that a part of the diversity not only procures some satisfaction for the forest owner, but that the price paid for this diversity is a decrease in timber production. Management strategies should therefore be aimed at finding a trade-off between timber production and tree diversity in a given ecological context.

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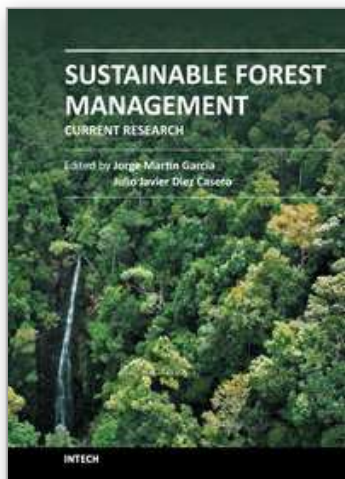
Sustainable Forest Management - Current Research

Edited by Dr. Julio J. Diez

Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.

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