Harvest Decisions and Spatial Landscape Attributes: The Case of Galician Communal Forests

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Abstract   In recent years, forest management has moved towards a landscape approach reflecting a mix of social, environmental and economic values. In this paper, we evaluate the effect on harvesting decisions of the spatial attributes of communal forests in Galicia. We first model the forest landscape management problem within a bioeconomic framework, which allows the identification of optimal clear-cutting strategies. This framework makes it possible to model a Faustmann-type rotation at the landscape level. The empirical analysis uses data from communal forests in Galicia, Spain. Under communal ownership, members of a rural community have rights to forest resources, but not rights to the forest itself. The management of communal forests integrates multiple forest uses within the decision making process. Given the communal nature of forest rights, and given these multiple uses, we show that landscape patterns—fragmentation, diversity and clumpiness—determine rotation periods.

Keywords   Bioeconomic model · Faustmann–Hartman · Non-timber benefits · Multiple-stand forest · Harvesting decisions

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1 Introduction

One effect of the Millennium Ecosystem Assessment (2005) has been that the analysis and management of environmental goods and services has moved away from a single species, single service approach, and towards a landscape-based approach, in which the effect of spatial structure on the flow of multiple ecosystem services is accounted for Naidoo and Ricketts (2006), Nelson et al. (2009) and Polasky et al. (2009). Landscape structure has long been shown to influence the movement and persistence of particular species, the susceptibility and spread of disturbances such as fires or pest outbreaks, and the redistribution of matter and nutrients (Turner 1989). For instance, the patch structure of the landscape and the rate of dispersal of species between patches influence species survival, and the spread of disturbances. In forest management, a landscape approach goes beyond individual stands, focusing on mosaics of patches and long-term changes in these mosaics to integrate ecological values with the production of an array of ecosystem services (Franklin 1992; Naiman 1992; Baskent and Yolasigmaz 1999; Andersson et al. 2000; Polasky et al. 2005). This approach recognises first, that management at a single stand level impedes the assessment of the implications of management strategies at a landscape scale and second, that a lack of spatial considerations in management activities may result in unanticipated ecological changes, which can have adverse consequences for ecosystem functioning and the provision of ecosystem services.

In this paper, we apply a landscape approach to understanding forest harvesting decisions at the forest level. We combine the traditional Faustmann–Hartman framework with a bioeconomic model of harvest decisions at a landscape level. Following Tahvonen (1998) and Tahvonen and Salo (1999) we account for differences in the ages of multiple forest stands. This contrasts with existing bioeconomic forest models (e.g. Montgomery and Adams 1995; Termansen 2007). Harvesting decisions in multiple stand forests reflect interdependence between stands in the provision of both timber and non-timber benefits (e.g. Bowes and Krutilla 1985; Swallow et al. 1997; Tahvonen and Salo 1999; Amacher et al. 2004). The solution of this problem results in an optimal cutting rule that explicitly accounts for spatial interactions among forest stands. Under this rule, harvesting strategies depend both on stand-specific variables and on variables determined by patterns in the forest as a whole.

Empirically, we test the hypothesis that landscape patterns in multiple-stand, multiple-use forests, have an effect on rotation intervals. That is, dependence among stands in the provision of forest benefits influences the harvesting decisions. The data derived from the Galician communal forests. Galicia is a region of Spain, located on the western edge of Europe, where forest area covers 68.9% of the territory. Although 98% of forest land is privately owned, individual holdings account for only 68%. About 30% is under communal ownership (Consellería de Medio Ambiente 2001). Communal private lands have a mean size of 231 hectares, while individual private holdings are very small, with an average size of 2.3 hectares. These communal forest lands are best described as shared private property. The only other examples of this form of property in Europe are found in north-central Portugal and the Scottish Highlands (GEPC 2002). The responsibility for managing the communal forest is shared by a group of individuals (an assembly) living in the same community. Therefore ownership is determined based on the place of residence. Each member of this assembly represents a family or inhabited house of the community. A group of at least three elected people is responsible for proposing all management decisions following a management plan which must be endorsed by the assembly. They may also be under a management contract with the public forest administration. Under this type of ownership, each individual owns a non-identified part of the property, land access is egalitarian and free for the whole community, and land rights are excluded from either private inheritance or the land market. Moreover, forest

resources are managed collectively in the interests of the whole community. These lands are considered important in the regional policy agenda both because of the large area of land they cover and the array of benefits they provide.

There is an extensive empirical literature on forest management by non-industrial private owners. This paper differs from this literature in three respects. First, much of the literature focuses on individual private landholdings and analyses the role of owner characteristics on harvesting decisions (Amacher et al. 2003; Beach et al. 2005). Most of this work is based on North American and Scandinavian forests. Binkley (1981), for example, estimated the harvest probability as a function of timber price, area managed, and owners' age, education, income and occupation. Jamnick and Beckett (1988), Hyberg and Holthausen (1989) and Dennis (1990) related owner and ownership characteristics to the probability of harvesting. Kuuluvainen et al. (1996) studied the effect of the different owners' objectives (multi-objective owners, recreationists, self-employed owners or investors) on the annual harvest intensity (harvest in m^3/ha). Kuuluvainen and Tahvonen (1999) investigated the inter-temporal change of harvest intensity based on forest and owner explanatory variables. More recently, Bolkesjœ et al. (2007) included economic market, property and owner characteristics to explain round-wood supply in Norway. In this paper, owner characteristics are not considered. This is due to the fact that our analysis focuses on communal forests managed by contract with the public administration, in which harvesting decisions are made by the public administration. The paper also differs from previous studies in that it focuses on rotation intervals as the dependent variable instead of the probability of harvesting, or annual harvest volume/intensity. More importantly, harvesting decisions are hypothesised to depend primarily on the landscape patterns of forest holdings.

We find that forest managers opt for shorter rotation periods the smaller the average stand size and the higher the degree of clustering of stands with similar characteristics (i.e. tree species and age structure). Forest managers apply longer rotations in multiple-stand forests that are more heterogeneous in terms of tree species, and age structure. We infer that the managers in such forests attach a higher weight to the non-timber benefits offered by multiple species.

The paper is organised as follows. Section 2 proposes a bioeconomic model of a communal forest involving multiple stands, in which spatial interactions between even-aged stands in the provision of forest non-timber benefits, are endogenous to the harvest decisions. Section 3 then offers an econometric analysis of harvesting decisions in Galician communal forests. A duration analysis is used to examine the impacts of communal forest-specific variables on the length of the rotations. Section 4 discusses the policy implications and concludes the paper.

2 A Bioeconomic Model of Forests Involving Multiple Even-Aged Stands

This section models management of a forest landscape. The model extends Touza et al. (2008)'s single stand approach to a forest with n even-aged stands. Specifically, let $x_i = x_i(t)$ and $F_i(x_i(t))$ be, respectively, the biomass volume (m^3) and timber growth functions of stand i, where $i = 1, \ldots, n$ is the number of stands in the forest. This growth function is assumed concave, such that $F_i(0) = F_i(K) = 0$ and $K > 0$, where K is the maximum volume a given stand can accumulate. Changes in forest biomass due to harvest activities are represented by jumps in the state variables. These jump points occur at discrete moments, and are denoted by $\tau_{i1} \ldots \tau_{ik}$, which represent the time at which stand i is harvest within the planning period $[0, \infty]$. Between harvests the change in the timber stock is given by the growth function. At harvest moments, there is a discontinuous change in the biomass, where

$x_i(\tau_{ij}^-)$ and $x_i(\tau_{ij}^+)$ denote the biomass of any stand i just before and just after jth harvesting moment, respectively.

The sequence of harvesting moments of the different stands determine the stand specific rotation intervals. Thus the rotation interval j of a stand i is denoted $\tau_{ij}^- - \tau_{ij-1}^+$, and the age of the stand along this rotation interval is $t - \tau_{ij-1}^+$, where $t\epsilon\ [\tau_{ij-1}^+, \tau_{ij}^-]$.

It is assumed that the manager's problem is to maximise forest benefits by choice of the optimal harvesting sequence $\tau_{i1} \ldots \tau_{ik}$ for the multiple stands, taking into account both timber and non-timber values (livestock maintenance, hunting, wild fruits harvest, recreation, etc.); i.e. both the timber rewards and the effects of harvest on the provision of non-timber benefits at a forest level. Let x_{pi}, p_i, c_{pi} represent the biomass of the seedlings, the timber price, and the cost of planting of any stand i, respectively, and δ the interest rate. The financial reward from harvesting stand i is the gross timber benefit from harvest, $p_i x_i(\tau_{ij}^-)$, minus the cost of planting, $c_{pi} x_{pi}$. Based on the Faustmann–Hartman framework, replanting activities follow immediately after harvest. The forest non-timber benefits $\pi(x_1(t), \ldots, x_n(t))$ depend on trees biomass of all the stands and how the stands interact to influence the array of non-timber benefits offered by the forest. As the harvest is clear-cut, non-timber benefits are indirectly a function of the stands' ages. Following Tahvonen and Salo (1999), the non-timber function is assumed to be concave where $\frac{\partial^2 \pi}{\partial x_i \partial x_z} \neq 0$ for $i \neq z$. This function is discontinuous, because the vector of ages of the forest stands change as any stand in the forest is clear-cut. Therefore, the values of the forest non-timber benefit function will jump at any harvest point, τ_{ij}, i.e. when any of the stands is harvested.

This problem can be formulated as

$$\max_{\tau_{ij}} \sum_{i=1}^{n}\sum_{j=1}^{k}\int_{\tau_{ij-1}^+}^{\tau_{u,v}^-} \pi\,[x_1(t), \ldots, x_n(t)]\,e^{-\delta t}\mathrm{d}t + \sum_{i=1}^{n}\sum_{j=1}^{k}[p_i x_i(\tau_{ij}^-) - c_{pi}x_{pi}]e^{-\delta\tau_{ij}} \quad (1)$$

subject to

$$\dot{x}_i = F_i(x_i(t)) \quad \text{except at } \tau_{ij}, \quad j = 1 \ldots k \ \ i = 1 \ldots n \tag{2}$$

$$x_i(\tau_{ij}^+) - x_i(\tau_{ij}^-) = -x_i(\tau_{ij}^-) + x_{pi} \quad \forall \tau_{ij}, \quad j = 1 \ldots k \ \ i = 1 \ldots n \tag{3}$$

$$x_i(0) = x_i^0 \quad i = 1 \ldots n \tag{4}$$

When $i = 1$ and $j = 1$, $\tau_{1j-1}^+ = \tau_{10}^+$ is the initial date, and planting of stand 1 is assumed to occur at this date. Let $\tau_{u,v}$ represent the next harvest point in calendar time, and u and v be integers such that $u\epsilon[1, n]$ and $v\epsilon[1, k]$. Equation 2 indicates that between harvests the dynamics of stand biomass is given by their natural growth; Eq. 3 captures the magnitude of the jumps at the harvesting moments; and Eq. 4 is the initial stock constraint. This problem is a special case of the theory of optimal control model with jumps (Seierstad and Sydsaeter 1987). The current-value Hamiltonian is as follows

$$H = \pi(x_1(t), \ldots, x_n(t)) + \sum_{i=1}^{n}\mu_i(t)F_i(x_i(t)) \tag{5}$$

where $\mu_i(t)$ is the current-value shadow price. The first order necessary conditions for the optimal solution include the dynamics of the stands' biomass between harvests

$$\dot{\mu}_i(t) = -\frac{\partial \pi(x_1(t), \ldots, x_n(t))}{\partial x_i} - \mu_i(t)\frac{\partial F_i(x_i(t))}{x_i} + \delta\mu_i(t) \quad i = 1 \ldots n \tag{6}$$

plus the conditions to be met at optimal harvesting moments $\tau_{i1}, \ldots, \tau_{ik}$,

$$\mu_i(\tau_{ij}^-) = p_i \quad i = 1 \ldots n \tag{7}$$

$$H(\tau_{ij}^-) = \delta[p_i x_i(\tau_{ij}^-) - c_{pi} x_{pi}] + H(\tau_{ij}^+) \quad i = 1 \ldots n \tag{8}$$

Condition 6 indicates that the rate at which the value of a unit of stock of stand i is decreasing equals its marginal contribution to the forest returns. Condition 7 states that, along the optimal path, harvests of any stand i will occur only when the current-shadow value of the timber stock equals timber price. In condition 8 the Hamiltonian immediately before harvest, $H(\tau_{ij}^-)$, indicates the marginal contribution to the forest activities' returns of postponing τ_{ij}^-, that is, of postponing the harvest. The Hamiltonian just after the jump, $H(\tau_{ij}^+)$, is the marginal contribution to the objective function of delaying τ_{ij}^+, i.e. of delaying the following rotation. The remaining term is the financial opportunity cost of postponing harvest by one instant. This is the benefit that could be earned if the harvest were to be taken now and the net profits invested elsewhere. Therefore, this cutting condition 8 indicates that the optimal sequence of harvest of any stand i should balance the marginal benefits of delaying harvest and marginal costs of waiting. The later is defined as the opportunity cost of investment of timber revenues and of postponing future benefits. Note that the Hamiltonian just after harvest has an analogous interpretation to the concept of 'site value' in the Faustmann model. The interpretation of condition 8 is thus consistent with the classical Faustmann–Hartman rule.[1]

The solution of the first-order differential equations given by (Eq. 6; see "Appendix A") states that the shadow value of the timber stock at the beginning of each rotation, $\mu_i(\tau_{ij}^+)$, is a function of the timber and non-timber benefits of the following rotation.

In order to evaluate the cutting condition (8) further, we apply the current-value Hamiltonian function (Eq. 5), together with the values of $\mu_i(\tau_{ij}^-)$ and $\mu_i(\tau_{ij}^+)$ (Eqs. 7 and 13, respectively; see "Appendix A" for details)

$$
\begin{aligned}
&p_i F_i\left(x_i\left(\tau_{ij}^-\right)\right) + \pi\left(x_1\left(\tau_{ij}^-\right), \ldots, x_n\left(\tau_{ij}^-\right)\right) \\
&= \delta\left[p_i x_i\left(\tau_{ij}^-\right) - c_{pi} x_{pi}\right] + p_i F_i\left(x_i\left(\tau_{ij+1}^-\right)\right) e^{-\delta(\tau_{ij+1}^- - \tau_{ij}^+)} \\
&\quad + \pi(x_1(\tau_{ij}^+), \ldots, x_n(\tau_{ij}^+)) + \sum_u^i \sum_v^{j+1} \int_{\tau_{ij}^+}^{\tau_{u,v}^-} \pi'(x_1(t) \ldots x_n(t)) F_i(x_i(t)) e^{-\delta(t - \tau_{ij}^+)} dt
\end{aligned} \tag{9}
$$

where τ_{ij}^+ and τ_{ij+1}^- represent the points of time when the next rotation of stand i starts and ends. That is, $\left(\tau_{ij+1}^- - \tau_{ij}^+\right)$ is the next rotation period of stand i. τ_{uv}^- is the next harvest point in calendar time; and u and v are integers. Thus this condition captures the fact that there may be points of discontinuity in the future flow of forest non-timber benefits if (an)other stand/s in the forest ecosystem is/are harvested during the following rotation of stand i.

This harvesting condition gives the rotation period of any even-aged stand i that maximizes the forest timber and non-timber returns. The condition takes into account the effect of the potential harvesting age of any stand i on the provision of the non-timber benefits at the level of the forest. The left hand side is the marginal benefits at the level of the forest of delaying harvest of stand i. The first term is the present value of the marginal timber benefits of stand i; and the second term is the effect on non-timber returns of a potential delay in

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[1] For a single-stand scenario this condition can be reduced analytically to the Faustmann–Hartman rule (Touza et al. 2008).

the harvest of a stand i. The right hand side is the opportunity cost of postponing harvest of stand i: (i) the financial cost; plus (ii) the cost in timber and non-timber benefits of stand i at the next rotation period. The non-timber opportunity costs include, through the integral term, the flow of non-timber benefits derived from the whole forest during stand i's next rotation. This value depends on the age structure of stands across the forest landscape during the following rotation of stand i. So the impact of postponing the harvest is not only the opportunity cost of a delay in timber and non-timber future benefits, but also the value of altering the age of stand i relative to the age of other stands in the forest landscape. Since delaying the harvest decision causes a shift in the distribution of stand ages in the forest, it also alters the interactions between stands, and so affects non-timber benefits in the future.

Tahvonen and Salo (1999) illustrate the steady-state policy for a simplified two stand forest with identical timber growth function, and symmetric contributions to non-timber values. Under this scenario, the system converges to a heterogenous age structure with equal rotation lengths and constant intervals between harvests. However, if the stands have initially the same age and are treated as one unique stand, the optimal rotations may differ or it may be optimal to give up harvesting. Fragmentation may decrease rotations periods. When stands make asymmetric contributions to non-timber values (i.e., their contribution is allowed to differ), the solution of the integral term is cumbersome. Recall that this integral term shows that each harvesting decision of stand i involves the projection of the non-timber benefits for the next rotation. When the stands are not symmetric due, for example, to location-specific characteristics, the forest manager must account for the impact of any current harvesting decision on the spatial relationships of the focal stand and its surrounding stands in the next rotation. Each potential current harvest changes the forest conditions and the contribution of the multiple stands to the non-timber benefits. In this case, optimal rotation periods may differ for each stand in the forest; and the evaluation of this cutting condition should be done on stand-specific basis.[2] We explore these issues more thoroughly in the context of an empirical study of harvesting decisions.

3 Harvest Decisions and Forest Landscape Structure

We now consider the relationship between harvesting decisions and landscape structure in the Galician communal forests. The general characteristics of forestry activities in these forests include even-aged management of multiple stands and a collective decision process, making a theoretical framework that extends Faustmann-type rotation decisions to the landscape level appropriate. Interdependence between stands is captured via the effect of landscape patterns in the forests. Our analysis focuses on an area known as Baixo-Miño, located in South-West Galicia. It covers 32,441 hectares, 67.7% of which are formally described as forest land (DGCN 2001, 2002). The most abundant tree species are maritime pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus*). More particularly,[3] maritime pine and eucalyptus cover 38% and 17% of the wooded-land, respectively. Mixed forests dominated by conifers and eucalyptus represent 21% of the wooded-land, while 9% is covered by mixed woodland dominated by native species such as oaks (*Quercus robur*, *Quercus suber*) and other broadleaves.

The study area contains 40 parishes and all except one of these parishes have communal forest lands. Indeed, communal forests cover around 49% of the Baixo-Miño and comprise

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[2] See Swallow et al. (1997) for another numerical illustration of the Faustmann cutting condition on a two-stand forest.

[3] Calculations are based on Digital Forest Map of Spain, 1 : 50.000 (DGCN 2002) using Arc/Info software.

Table 1 Descriptive statistics of the data used in the estimation

Variable	Mean	SD	Min.	Max.	N
Rotation period	31.14	10.77	15	60	94
Species DV = one if conifer, zero otherwise	0.48	0.50	0	1	94
Reported reserve net price per m^3 (Euros)	31.98	6.44	12.14	46.16	94
Market stumpage price index per m^3 (Euros)	49.48	7.49	31.25	64.28	94
Annual difference in interest rate ($IR_t - IR_{t-1}$)	−0.40	1.01	−2.45	1.08	94
Mean wooded patch size index	0.04	0.06	0.01	.33	94
Percentage of 'mixed' patches	0.35	0.15	0.01	0.55	94
Habitat contagion metric	0.26	0.14	0.09	0.58	94

73% of forest land. More than a third of forest communities have a management agreement with the public forest administration for all or part of their forest area. The public administration tends to focus on the largest forests, and in fact manages more than half (56%) of the communal lands in this area. Timber production is the main service provided by communal forests. Traditional uses, such as support for cattle raising and agriculture are relevant secondary uses (Vence et al. 1995), and amenities provided by forests are increasingly recognised (Lage 2001) with an growing number of plots set aside for recreational purpose. Moreover, eolic (wind) power plants are increasingly located in communal forests.

3.1 Data Sources and Methodology

The data come from the regional forest administration database, which contains information on harvests undertaken on communal forests managed under agreement. Before harvest, forest rangers report details to inform the timber auctions carried out by the administration. Our sample includes the harvests carried out in communal forests in the study area from 1995 to 2001.[4] The average number of stems per harvesting report is small, around two thousand.

Since the goal of this research was to examine the determinants of the rotation intervals, the 14% of reports that did not provide information about the age at which the stand was clear-cut were excluded from the analysis. Furthermore, 16 reports include harvests containing both eucalyptus and conifer trees. When one of these tree species contributed less than 10% to the reported total volume of harvest, it was deleted from the sample (this reduced the sample size from 108 to 94 harvests). Nevertheless, the econometric results are presented for both sample sizes.

Table 1 presents descriptive statistics for the variables used. The rotation period is the time elapsed between planting and harvest. Our sample shows a mean of 31 years, with a range from 15–60 years. All harvests undertaken involve eucalyptus and conifers, which is not surprising given the tree species in the study area. A dummy variable was created to represent the predominant species harvested (1 if conifer, zero otherwise).

Although community members own the forest land, as explained above, forest rangers make all day-to-day decisions about the intensity of harvesting and the selection of the stands to be harvested, based on professional and market considerations. The effect of stumpage prices and interest rates on rotation intervals is examined. The stumpage price variable used

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[4] Harvests undertaken for 'extraordinary' reasons were excluded. These include harvests of land affected by fire, or harvests to enable the conversion of land to other uses—e.g. to build community facilities.

here corresponds to the reserve net price detailed in the administration reports, which takes into account quality, location and potential uses. In addition, a market stumpage price index for pine and eucalyptus was also constructed as an average of the prices in the wood industries based on the Galician Forest Association Reports. These provide a time series for regional net prices for pine and eucalyptus saw, board and pulp wood between 1994 and 2001. There is annual and per species variation in this proxy of stumpage price.

As a proxy for the alternative rates of return affecting the cutting decisions, we use the annual real interest rate on long term loans (10–15 years). These data were provided by the Capital Market Department of a regional bank (Caixanova). Annual differences in the real interest rate (i.e. real interest rate this year minus the value of last year) was used to account for the impact of short-term variation in this variable. However, most of the theoretical literature on optimal rotation periods (and the model above), assume constant interest rates; and the effect of a variable interest rate on Faustmann-type rotation is unclear (Alvarez and Koskela 2003). The effect of this variable is, then, an empirical question.

Landscape patterns expected to have an influence on rotation intervals, are controlled by including a set of landscape metrics to assess the level of fragmentation, diversity and clumpiness in the wooded part of these forests[5] (O'Neill et al. 1988; Turner 1990; Botequilha-Leitao and Ahern 2002). The calculation of these metrics is based on forest inventories and 1 : 10.000 paper maps of Baixo-Miño communal forests compiled in 1995 (Vence et al. 1995). Note that these maps have a polygonal format which provides a series of vectors describing the boundaries enclosing a patch (i.e. area under a single land cover category). Therefore they contain neither geographical information (such as latitude/longitude data) nor information on areas and perimeters, and had to be digitized using Arc/Info software. The digitization process produced the areas and perimeters for digital patch data for each of the communal lands. The associated holding's uses/vegetation characteristics were tabulated and linked to the digital patches to create a GIS polygon formatted data base.

Fragmentation is evaluated by the mean wooded patch size index. This index indicates the percentage that the mean size of the wooded patches occupy in the total wooded area of the holding. Lower values of mean patch size index reflect a more fragmented landscape. Forest diversity is measured by the percentage of wooded area not occupied by monoculture stands. Following The Spanish Forest Inventory, the indicator of biodiversity in forestry plantations is defined as the percentage of wooded lands occupied by at least two species, i.e. areas in which neither tree species cover more than 90% of the canopy (DGCN 2001). This indicator can also be interpreted in this study as the probability that the harvested trees are located in mixed tree-species forest patches. In order to control for the spatial configuration of the forests, we use a habitat contagion metric. First, communal forest patches were classified by habitat type. Seven forest habitat categories were considered following the classification established by the Forest National Inventory in the area of study (DGCN 2001) (Table 3, Appendix B). Then, the habitat contagion index was calculated to assess the existence of clusters of patches of identical habitats, i.e. to measure the extent to which patches of the same habitat are aggregated (O'Neill et al. 1988; Li and Reynolds 1993). This index is explained in Appendix B. Large values of this index indicate high levels of aggregation of patches of identical habitats.

A duration analysis is then applied to deal with these data. In duration analysis the key notion is the hazard function, which gives the probability that the stand is clear-cut after

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[5] In the theoretical model above $\frac{\partial^2 \pi}{\partial x_i \partial x_z} \neq 0$ for $i \neq z$, which allows for the stands to be substitutes or complements in the provision of the forest non-timber benefits due to spatial patterns (Amacher et al. 2004). One may expect that higher fragmentation and clustering leads to the stands to act as substitute sources of forest non-timber values; while higher diversity may implies complementary sources.
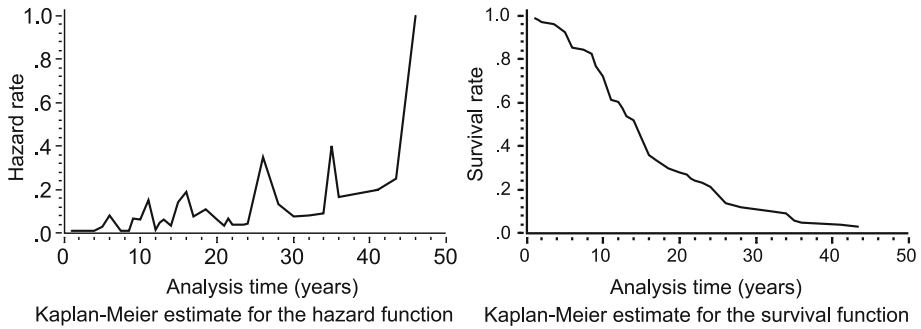
Fig. 1 Non-parametric hazard and survival functions for harvesting decisions

an interval of t, conditional upon it remaining uncut to that point. The hazard function, $\mu(t) = \frac{f(t)}{S(t)}$, can be written in terms of the density function—the probability that a stand is harvested at time t—and the survival function—the probability that the rotation is of length at least t—(Cox and Oakes 1984; Greene 2003). Notice that the data contain no stands that were not cut when the harvesting data were collected, therefore there are no censored observations. The shortest rotation observed was 15 years (see Table 1). This means that the sample is restricted to stands which were not being cut at or before the age of fourteen. Based on Hammar and Martinsson (2001), the duration variable to be estimated was defined as 'rotation age-14', which implies that the analysis is conditional stands not being harvested up to age fourteen. There are several parametric models that assume a given distribution function for the hazard rate, and so for the density function and the survival function. Kaplan-Meier non-parametric estimates of the survival and hazard rates were used to provide some guidance on the distribution of the hazard function.

3.2 Results

The Kaplan–Meier estimates of the survival and hazard functions are shown in Fig. 1. The shape of the hazard function suggests that the probability of a stand being cut at time t, conditional on its duration up to time t, is monotonically increasing in t. Both Weibull and the generalized Gamma models allow for this type of behaviour. The Gamma model encompasses the Weibull function; i.e. if the extra parameter of the Gamma model, Θ, equals 1 then the Weibull model results. Given that these distributions are nested, the log likelihood ratio can therefore be used to search for the preferred model. The extension of the Weibull model to the gamma generalisation (Greene 2002, E271-1-E27-6) provided no estimates for the additional parameter, Θ, (absence of convergence). A grip search over Θ showed that the log likelihood was still increasing at values of this parameter equal to forty, suggesting that the data do not support a gamma generalisation. The Weibull model was thus chosen as the preferred specification. Note that this model defines the hazard function as: $\lambda(t) = \lambda p t^{p-1} \cdot exp(\beta'x)$, where λ and p are the parameters to be estimated and x is a vector comprising the covariates. The value of p indicates whether the hazard rate is increasing, decreasing or constant.

Table 2 presents parameter estimates for the determinants of rotation length. As expected, the results show that the dummy for tree species is statistically significant and conifers are expected to have longer rotations (compared to the reference observations: eucalyptus stands). Turning now to the effect of the logarithm of the net reserved prices, the results

Table 2 Parameter estimates from the Weibull distribution

Covariate	Coefficient $N = 108^a$	p-value	Coefficient $N = 94$	p-value
DV Conifer	0.543***	0.000	0.580***	0.000
Log of reserved timber prices	0.582***	0.003	0.607*	0.060
Annual difference in interest rate	−0.132**	0.006	−0.119**	0.032
Log of mean wooded patch size index	0.465***	0.005	0.427**	0.018
Log of percentage of 'mixed' patches	0.436***	0.000	0.401***	0.001
Log of habitat contagion metric	−0.192**	0.033	−0.206**	0.044
Constant	2.528	0.020	2.215	0.106
λ	0.059	0.000	0.058	0.000
p	2.788	0.000	2.663	0.000
Log Likelihood	−61.799		−57.417	
Wald test (p-value)	0.764		0.766	
p-value[b]	0.000		0.000	

*** Significant at 1% level; ** Significant at 5% level; * Significant at 10% level

[a] This estimation was computed with several dummy variables for those harvesting reports which contained several tree species but the p-values suggested omitting them from the model

[b] p-value is from a test of the null hypothesis that the coefficients of the three landscape metrics are jointly zero

show that prices have a positive effect, which is fairly significant (10% level) even with the smaller sample. The sign of the coefficient indicates that higher stumpage prices imply longer rotation periods. Note that this reserved timber price variable may be acting as a proxy for the percentage of harvested logs with high thin-end diameter. It is reasonable to expect that longer rotations produce a higher percentage of logs with high thin-end diameters. A similar estimation in which the reserved price variable is substituted for a market stumpage price index was also computed. Recall that this index was constructed as an average of the regional prices in the different wood processing industries. The coefficient for this variable was also positive, and significant at the 1% level. This suggests some responsiveness of harvesting behaviour to timber price dynamics in the market. The coefficient for the annual difference in the interest rates was negative and significant at the 5% level. An increased rate of interest would increase the opportunity costs of delaying the harvest, hence lower harvesting ages.[6]

The three landscape metrics included in the estimation capture differences in landscape-level aspects of communal forests. The coefficient of the mean wooded patch size index is positive and significant at the 5% level. This suggests that the smaller the wooded patches in the holding, the longer the rotation. The percentage area occupied by mixed tree-species patches is also significant at the 1% level, and also positively associated with harvesting age. This means that communal forests with a higher percentage of wooded area of at least two tree species have longer rotation intervals. The habitat contagion metric is significant at the 5% level and it has a negative sign. Thus, lower levels of this index, i.e. lower levels of aggregation of patches of identical habitats, imply higher harvesting ages. A test of the null hypothesis that the coefficients on the three landscape metrics are jointly zero shows that

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[6] The effect on optimal rotations of a fluctuating interest rate is studied in Alvarez and Koskela (2003). Kuuluvainen and Tahvonen (1999) provide an empirical analysis of inter-temporal effects of interest rate.

Table 3 Habitat classification used in the calculation of landscape metrics

Habitat	Tree species–Occupation–Age structure
Habitat 1: Oak	A pole/mature native deciduous forest of which at least 70% of stems are Quercus and the canopy crown is at least 20%
Habitat 2: Conifer	A pole (between 16–24 years) or mature (more than 25 years old) conifer forest of which at least 70% of stems are *Pinus pinaster* –*Pinus radiata* and the canopy crown is at least 20%
Habitat 3: Eucalyptus	A pole (between 6–9 years) or mature (more than 10 years old) forest with 70% or more of the canopy as *Eucalyptus globulus* and at least 20% percent tree cover
Habitat 4: Mixture of oak with conifers, eucalyptus or both; or with chestnuts, acacia or other decidious trees	A mixed forest with *P. pinaster-radiata-Q. robur-E. globulus* or with *Q. robur-Betula spp.-Castanea sativa-E. globulus*, with less than 70% of the canopy under one single species and irregular age structure and canopy crown of at least 20%
Habitat 5: Mixture of conifers or conifers and eucalyptus	Young conifer (1–15 years) or eucalyptus (1–5 years) forest; or mixed pole/mature forest of conifers and eucalyptus of which less than 70% of the canopy is *P. pinaster–P. radiata* or *Eucalyptus globulus* and canopy crown is at least 20%
Habitat 6: Scrub forest	Land with scrubs and disperse trees with crown cover between 5 and 20%.
Habitat 7: Riparian trees	Riparian zones with trees species such as alders (*Alnus glutinosa*) gray willow (*Salix atrocinerea*), buckthorn (*Rhamnus frangula*), etc

Source: DGCN (2001)

they are jointly statistically significantly different from zero at the 1% level and rejects the null hypothesis.

A RESET test was used to test the null hypothesis of misspecification in the estimation. This involved including the squares of the predicted values as an extra covariate in the Weibull model. The log likelihood ratio and the Wald tests indicate that the null hypothesis can not be rejected (*p*-values, 0.764 and 0.766, Table 2). The sensitivity of the results to heterogeneity problems was also considered. A Weibull model with heterogeneity can be estimated assuming that the unobservable variables have a gamma distribution (Greene 2003). In this analysis, the Weibull model with gamma heterogeneity fails to converge. This suggests that it is not a feasible model, hence there are no problems due to unobserved heterogeneity.

Notice that this econometric analysis has used a retrospective data set, which may lead to problems due to rounded-off durations. The fact that in a few cases a range of ages with 1, 3 or 5 year differences were reported, instead of a certain rotation age, seems to confirm this possibility. Problems of this type may result in 'heaps' of the duration variable at certain values. An analysis of the sensitivity of the results to this issue, with dummy variables coding for those rotations which were, or were suspected of being, rounded off, suggests that the signs and significance of the variables presented above are robust to these heaping effects in the data set.

4 Discussion and Conclusions

This paper investigates harvesting decisions in forest landscapes composed of even-aged stands. We developed a bioeconomic model based on Faustmann–Hartman forest management decisions. The simplicity of the theoretical framework used provides a coherent and tractable analytical understanding of the optimal solution. Furthermore, its flexibility will enable further research into environmental conservation issues in forest management. A basic conclusion is that 'optimal' harvesting strategies at a single-stand scale are not necessarily optimal when a larger spatial scale is adopted, and when spatial interactions are included in management decisions. When a single stand is managed independently, the Faustmann–Hartman rule indicates that the flow of the stand's non-timber benefits influences when the stand should be harvested (Hartman 1976). At a landscape level, the optimal harvesting age of any stand is a function of the importance of the stand's non-timber benefits relative to the non-timber benefits derived from the entire forest, and reflects the role of each stand in determining forest benefits over space and time.

The empirical estimation suggests that higher stumpage prices are related to longer rotation durations. This result is contrary to what one would expect from the basic forest model, but is not unusual. Early empirical studies note that the sign of the price variable in the individual private harvest decisions may be ambiguous (Binkley 1981; Dennis 1989). This is consistent with an utility maximization approach. An increase in timber prices may lead to shorter or longer rotations due to income and substitution effects (Tahvonen 1999; Tahvonen and Salo 1999).[7] A higher price increases the opportunity cost of reserving the stand for non-timber outputs, which may lead to an increased harvested volume and shorter rotations. However, the higher income derived from increased stumpage prices may also reflect higher demand for non-timber outputs. A recent review has also shown that timber prices are among the least likely factors to be significant determinants of non-industrial individual private forest management behavior (Beach et al. 2005). In the Galician case, harvesting decisions are taken by public foresters, and the results seems to suggest that as stumpage fees increases, increased timber income for the rural communities implies less pressure on forest resources, which allows public foresters to use longer rotations. In Galicia, where rotation periods are shorter than in other European countries (harvesting ages of 12–14 years for the eucalyptus and less than 30 years for conifers are common), the application of longer rotation intervals is recognized to be one way to improve the quality of timber (Bermúdez and Touza 2000). Publicly-managed communal forests may be playing an important role in this direction.

These factors aside, we are able to show that fragmentation, diversity and clumpiness are determinants of harvesting behaviour in Galician communal forests managed by the public administration. Our findings suggest that in communal forests with small patches, and clusters of patches that share tree species, occupation and age structure, the impact of harvesting on forest non-timber benefits is perceived to be small, and shorter rotation periods are used. However, in more diverse communal forests, where there is a more heterogeneous patch structure, rotation lengths are longer. This result reinforces the idea that the role of an

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[7] An utility maximization approach was not adopted here because decisions are taken collectively, and there is no a direct link between collective timber income and personal wealth of the members of the community. Forest rural communities are forced by law to reinvest at least 15% of the forest income on the social values of their forest, and some communities reinvest the 100% on their forests and on community services (e.g. cultural center; Diario Oficial de Galicia 1989; GEPC 2006). Furthermore, forest lands used in the empirical analysis are under contract with the public administration, which takes the forestry decisions (e.g. harvesting, sivicultural treatments, etc.).

individual stand in the non-timber benefits offered by the whole forest is higher the more heterogeneous the structure of the forest.

In Galicia, communal lands were traditionally used to support agricultural and cattle grazing activities in the rural economy. This secondary function of forests may help to explain the historical lack of forest management plans in Galicia. The regional government established a programme called 'Fomento de ordenación de montes' to provide incentives to forest owners to develop management plans. The success of this programme has been limited for several reasons (Balboa 1990; Fernández 1990; Bermúdez and Touza 2000; Valdés and Gil 2001) including the aging of the rural population, and the absence of a forestry culture or tradition among forest owners. Only 9% of the total forest land (AFG 2005) and less than 2% of the communal forest land (Consellería de Medio Ambiente 2001) are subject to a management plan or forest inventory. Future research should encompass the analysis of organisational issues in the communities, and their relationship to the socio-economic, environmental and institutional factors surrounding the management of community lands (Marey et al. 2002; Chas et al. 2002).

Finally, the analysis presented here has focused on rotation periods. Investigating the effects on forest management of other practices for maintaining ecological forest values (i.e. enhancing aesthetic values, opening ecological corridors, controlling damaging invasive species, carrying out less systematic thinning, etc.) is an important area for future research. In addition, examining restrictions on harvest practices, such as the requirement that part of the stand to be left uncut to decay, would offer an interesting extension to the work. Nguyen (1979) and Koskela et al. (2007) analysed such harvest restrictions in the traditional Faustmann–Hartman static framework. Studying these issues in a dynamic model would allow the implications of adding a temporal dimension to the analysis of environmental incentives for forest owners to be examined. Furthermore, note that management of the forest at an ecologically and economically significant scale involves multiple owners' decisions and may operate within a structure of mixed property rights which introduces requirement for coordination and cooperation among adjacent landowners (Sample 1994; Ellefson et al. 1997; Blumenthal and Jannink 2000). Expansion of the analysis here to address these issues would undoubtedly assist forest policy design at the landscape level.

Appendix A

In Sect. 2, the first-order differential equation associated with the dynamics of the current-value shadow price between harvests, condition 6, is solved as follows

$$\mu_i(t) = e^{\int_{\tau_{ij}^+}^{t} [\delta - F_i'(x_i(t))] dt} \left(\mu_i(\tau_{ij}^+) - \int_{\tau_{ij}^+}^{t} \frac{\partial \pi(x_1(t) \ldots x_n(t))}{\partial x_i(t)} e^{-\int_{\tau_{ij}^+}^{t} [\delta - F_i'(x_i(t))] dt} dt \right) \quad (10)$$

Note that the exponential function above $e^{-\int_{\tau_{ij}^+}^{t} F_i'(x_i(t))\mathrm{d}t}$ can solved by integrating twice by substitution,

$$e^{-\int_{\tau_{ij}^+}^{t} F_i'(x_i(t))\mathrm{d}t} = e^{-\int_{x_i(\tau_{ij}^+)}^{x_i(t)} \frac{F_i'(x_i(t))}{F_i(x_i(t))}\mathrm{d}x} = e^{-\int_{F_i[x_i(\tau_{ij}^+)]}^{F_i[x_i(t)]} \frac{1}{F_i(x_i(t))}\mathrm{d}F(x_i(t))}$$

$$= e^{-ln[F_i(x_i(t))]+ln[F_i(x_i(\tau_{ij}^+))]} = \frac{e^{ln[F_i(x_i(\tau_{ij}^+))]}}{e^{ln[F_i(x_i(t))]}} = \frac{F_i(x_i(\tau_{ij}^+))}{F_i(x_i(t))} \quad (11)$$

Now we can apply this to Eq. (11)

$$\mu_i(t) = \mu_i(\tau_{ij}^+)e^{\delta(t-\tau_{ij}^+)}\frac{F_i(x_i(\tau_{ij}^+))}{F_i(x_i(t))}$$

$$-\frac{1}{F_i(x_i(t))}e^{\delta(t-\tau_j^+)} \int_{\tau_{ij}^+}^{t} \frac{\partial \pi(x_1(t)\ldots x_n(t))}{\partial x_i(t)} F_i(x_i(t))e^{-\delta(t-\tau_{ij}^+)}\mathrm{d}t \quad (12)$$

At $t = \tau_{ij+1}^-$, i.e. at the end of next rotation of stand i, this implies

$$\mu_i(\tau_{ij}^+) = \mu_i(\tau_{ij}^-)e^{-\delta(\tau_{ij+1}^- - \tau_{ij}^+)}\frac{F_i(x_i(\tau_{ij+1}^-))}{F_i(x_i(\tau_{ij}^+))}$$

$$-\frac{1}{F_i(x_i(\tau_{ij}^+))} \sum_{u}^{i} \sum_{v}^{j+1} \int_{\tau_{ij}^+}^{\tau_{uv}^-} \frac{\partial \pi(x_1(t)\ldots x_n(t))}{\partial x_i(t)} F_i(x_i(t))e^{-\delta(t-\tau_{ij}^+)}\mathrm{d}t \quad (13)$$

Therefore, the shadow value of the timber stock at the beginning of each rotation, $\mu_i(\tau_{ij}^+)$ is related to the timber and non-timber benefits generated during stand i's next rotation period, that is, $(\tau_{ij+1}^- - \tau_{ij}^+)$. Given that there may be points of discontinuity if (an)other stand/s in the forest ecosystem is/are harvested during the following rotation of stand i. We express in equation (13) the forest non-timber benefits at stand i next rotation as a sum over time periods where this function $\pi(x_1(t)\ldots x_n(t))$ is continuous. Where τ_{uv}^- is the next harvest point in calendar time, and u represents the stand being harvest during stand i next rotation period, and v is its corresponding harvesting number.

Appendix B

The contagion habitat index is given by O'Neill et al. (1988) and Li and Reynolds (1993):

$$C = \frac{nln(n) + \sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}ln(P_{ij})}{nln(n)} = 1 + \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}ln(P_{ij})}{nln(n)} \quad (14)$$

where $P_{ij} = \frac{N_{ij}}{N_i}$ represents the probability of patches of habitat type i being adjacent to patches of habitat type j. This is calculated by dividing the number of patches of habitat type i that are adjacent to patches of habitat type j, N_{ij}, by the total number of adjacencies between patches of habitat type i and all other patch types (including type i itself), N_i. In this equation, $nln(n)$ expresses the maximum possible contagion, when adjacency probabilities between all habitat types are equal (i.e. when, for any random patch in the forest holding,

there is an equal probability of any habitat type being adjacent to the patch). The summation, $\sum_{i=1}^{n} \sum_{j=1}^{n} P_{ij} ln(P_{ij})$ is negative, so large values of contagion indicate high levels of aggregation of patches of identical habitats.

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