Land allocation between a multiple-stand forest and agriculture under storm risk and recursive preferences

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Abstract

This study aims to characterize steady-state land allocations between a multiple-stand forest and agriculture, when the forest is subject to a storm risk. The landowner is supposed to have recursive preferences, which permits to distinguish between intertemporal preferences and risk preferences. Using a stochastic dynamic programming model, we show that both land allocation and forest management depend on the risk and on both types of preferences at the steady-state. Risk aversion is shown to favor land allocation to agriculture and to reduce the forest average harvest age while the preference for a regular income is shown to favor forestry and to reduce the average harvest age.

Keywords: Land allocation, Forest management, Recursive preferences, Stochastic Dynamic Programming

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1 Introduction

Forest and agriculture are two land-based activities that may be impacted by perturbations such as wind storms. However, wind storms do not have the same impact on both sectors as damages made on forests may be more important and have longer term consequences. Land allocation between forestry and agriculture is therefore a dynamic and stochastic issue in which the two sectors do not relate in the same way to the time and risk dimensions. Forestry requires planning over several decades (or even centuries for certain species) while agriculture is mostly an activity based on annual cycles. In addition, forestry and agriculture are not equally sensitive to given risks. Cropland is for example less exposed and vulnerable than forests to a risk of storms (see Schelhaas et al. (2010)). Therefore, land allocation results from a trade-off that should take into account both time and risk dimensions and corresponding preferences.

The objective of the present study is to characterize steady-state land allocations between cropland (or any other annual activity) and a forest with multiple age-classes when the forest is subject to a risk of perturbation and the landowner has recursive preferences. This raises the parallel question of the relationship between land allocation and forest management. In addition, the study aims at determining the respective impact of intertemporal preferences and risk preferences on steady-states.

Focusing on steady-states in presence of a perturbation risk is particularly relevant when the probability of this risk is low as the land system is then more likely to converge and to remain in a steady-state. However, in any case, the steady-state is a long-term objective to which the producer's decisions tend to lead, and is as such a good indicator on the producer's behavior.

In a dynamic and stochastic context, recursive preferences are more general than expected utility preferences as they take into account preferences on the timing of risk resolution and they permit to distinguish between intertemporal preferences and risk preferences.

As for preferences on the timing of risk resolution, Spence and Zeckhauser (1972) and Kreps and Porteus (1979) show that if a consumer has expected utility preferences on a dynamic flow of consumption and he can arbitrate between consumption and savings, then his "induced" preferences on the dynamic flow of income cannot be properly described by an expected utility framework. Expected utility preferences are indeed indifferent to the timing of risk resolution, that is to say to the points in time when the consumer learns about given random income realizations. In this case, this assumption is unrealistic because prior knowledge of realized incomes enables the consumer to better plan his consumption stream, and should therefore be preferred.

Kreps and Porteus (1978) propose a class of recursive utility functions that are able to represent preferences as to the timing of risk resolution and can then overcome the problems raised by expected utility preferences. Building on this, Epstein and Zin (1989) propose a parameterized sub-class of Kreps and Porteus functions, which allows them to disentangle risk and time preferences, as each of those are represented through distinct parameters. Epstein and Zin (1991) use a function of this sub-class to formulate and estimate a generalized CAPM (Capital Asset Pricing Model). This function is used in the present study.

As for the literature on land allocation, Bell et al. (2006) discuss the main theoretical concepts that underlie land allocation issues. The main point is that land allocation is related to the concept of returns associated to the different land uses. When returns are linear functions of land acreages, the resulting land allocation is a corner solution, which means that all land is allocated to the use presenting the highest return per land unit. On the contrary, diminishing marginal returns (relative to acreages) may result in mixed allocations.

In a deterministic context, Salo and Tahvonen (2004) have developed an analytical model of land allocation and forest management in which both sectors feature diminishing marginal returns. The forest management is flexible and allows for multiple stands. The results show that the rotation age of the forest at the steady-state always follows Faustmann's rule. However, the age-class structure at the steady-state is affected by land allocation. Whenever all land is allocated to forestry, there exists a continuum of steady-state periodic forests around the normal forest. The existence of such steady-state periodic forests have been extensively discussed in Salo and Tahvonen (2002a), Salo and Tahvonen (2002b) and Salo and Tahvonen (2003). However, whenever land allocation is mixed, the forest is normal.

The introduction of diminishing marginal returns in Salo and Tahvonen (2004) is *ad hoc* but in reality they can be justified on several grounds, for example the heterogeneity in soil and climate conditions. There is a large empirical literature on land allocation and many articles that deal with soil heterogeneity. For example, Stavins and Jaffe (1990) propose an econometric estimation of unobserved soil quality distribution based on observed land allocation. The econometric model developed by Stavins and Jaffe is structured by a dynamic model of land allocation.

The presence of risk is another factor that can explain mixed land allocations. On the basis of a dynamic and stochastic model of land allocation, Parks (1995) shows that when risks held by two different land uses are not positively correlated and the landowner is risk-averse, then land allocation is mixed. This reflects a diversification behavior.

The aim of this article is to provide clear numerical evidence on the different types of land allocation and forest management at the steady-state and to identify their determinants. In particular, results are aimed to characterize the respective role of intertemporal preferences and risk preferences and to determine the respective roles of land allocation and forest management in adapting to a risk of storms.

In section 2, a model of land allocation and forest management in presence of a storm risk is defined. Section 3 describes how a stochastic dynamic programming approach is used to solve this model and shows the results thus obtained.

2 A stochastic land allocation and forest management program

Consider the problem of a landowner who allocates his land between forest and agriculture uses, and as the case may be manages his forest himself. In the model considered, land allocation and forest management are the two endogenous decisions.

Forest management is even-aged and allows for multiple age-classes. The even-aged management implies that age-classes are spatially separated and there are subsequently no interaction effects between them in terms of biological growth. Even-aged forest management is widespread for growing certain tree species and in certain regions, such as Scandinavia or Southwestern France (see section 3). Moreover, thinning is ruled out, the landowner can only harvest by clear-cutting. However, at a given time, an age-class may be harvested only on a fraction of the total acreage it covers. In addition, a random perturbation may occur at any time. When the perturbation occurs, the age-classes that are impacted are clear-cut and a residual timber value is received by the landowner.

The landowner can also allocate a share of his land to agriculture. In return, he receives a land rent (from a farmer) that is certain and constant over time.

These assumptions ensure that the state of the land system at any given time can be fully described by the land acreages allocated to agriculture and to the different age-classes of the forest, that are respectively noted $x_{agr,t}$ and $x_{a,t}$ with $t \in \mathbb{N}$ the time index and $a \in \mathbb{N}$ the age-class index. The residual value from damaged timber is denoted rv_t. Henceforth, the vector of state variables is noted $X_t = (x_{agr,t}, x_{1,t}, x_{2,t}, ..., x_{a,t}, ..., rv_t)$.

The model is defined in a discrete time setting and the program faced by the landowner is sequential and repeats at every time-step. At time t, the landowner observes the state of his land system, as is defined by the vector X_t. On the basis of this observation, he harvests damaged timber and he makes decisions regarding undamaged timber harvest, forest planting and land allocation to agriculture. These decisions determine the income received at time t, Π_t, as well as the state $X_{t+1} = (x_{agr,t+1}, x_{1,t+1}, x_{2,t+1}, ..., x_{a,t+1}, ..., rv_{t+1} = 0)$ (the "decided state") that is realized at $t+1$ when a perturbation does not occur between t and $t+1$. Π_t is certain from a time t standpoint as decisions are made and executed before a perturbation may occur.

Decisions made between t and $t+1$ can therefore be expressed as functions of "decided" land shares $(x_{agr,t+1}, x_{1,t+1}, ..., x_{a,t+1}, ...)$. The acreage of age-class a that is harvested between t and $t+1$ is denoted $h_{a,t}$ and can be expressed as follows:

$$\text{For all } a \in \mathbb{N}^* \text{ and } t \in \mathbb{N} : \quad h_{a,t} = x_{a,t} - x_{a+1,t+1} \tag{1}$$

The acreage planted with new forest between t and $t+1$, s_t, can be expressed as follows:

$$\text{For all } t \in \mathbb{N} : \quad s_t = x_{1,t+1} \tag{2}$$

The acreage allocated to agriculture at $t+1$, ag_t, is $x_{agr,t+1}$.

After decisions are made and executed, a perturbation may occur. The perturbation for a given time-period is modelled as a one-trial ($n = 1$) multinomial distribution that is identically and independently distributed for all time-periods. Several outcomes of the perturbation can modify the decided state X_{t+1} (the possible outcomes and the associated probabilities used in the numerical applications are presented in table 2). Thus, actual land shares at $t+1$, as well as the residual value from damaged timber, are stochastic (from a time t standpoint), and their probability distributions are all conditional on decided land shares $(x_{agr,t+1}, x_{1,t+1}, x_{2,t+1}, ..., x_{a,t+1}, ...)$. Therefore, the probability distribution on the state $\tilde{X}_{t+1}$ at time $t+1$ is written as follows :

$$(\tilde{X}_{t+1} \mid X_{t+1}) = (\tilde{x}_{agr,t+1}, \tilde{x}_{1,t+1}, \tilde{x}_{2,t+1}, ..., \tilde{x}_{a,t+1}, ..., \tilde{rv}_{t+1} \mid X_{t+1}) \tag{3}$$

The sequential program is represented on the timeline given in figure 1:

Figure 1: Timeline of decisions and realizations between t and $t+1$

As mentioned above, the income Π_t is certain from a time t standpoint as both components $\Pi_{agr,t}$ and $\Pi_{for,t}$ are certain. $\Pi_{for,t}$ can be expressed in function of the observed state $X_t = (x_{agr,t}, x_{1,t}, x_{2,t}, \ldots, x_{a,t}, \ldots, rv_t)$ and decided land shares $X_{t+1} = (x_{agr,t+1}, x_{1,t+1}, x_{2,t+1}, \ldots, x_{a,t+1}, \ldots, rv_{t+1} = 0)$ as follows:

$$\Pi_{for,t} = \sum_{a=1}^{+\infty} R_a(x_{a,t} - x_{a+1,t+1}) - pc \cdot x_{1,t+1} + rv_t \tag{4}$$

R_a is the income generated by harvesting one land unit of age-class a. Note that timber value results from a pure-aging process, which is a consequence of the even-aged management assumption. pc is the planting cost per land unit. rv_t is the residual value from damaged timber that is harvested anyway. Note that the timber damaged between $t-1$ and t is harvested between t and $t+1$.

$\Pi_{agr,t}$ depends only on the agricultural land share at time t, $x_{agr,t}$ and is written as follows:

$$\Pi_{agr,t} = R_{agr} x_{agr,t} \tag{5}$$

R_{agr} is the income generated during one time-step by one agricultural land unit. R_{agr} is independent from land allocation, which means that we assume constant marginal returns to land. This is the case when the land is rented out to a farmer. This is a major difference from Salo and Tahvonen (2004) who consider the problem in a deterministic context but with decreasing marginal returns to land.

As a consequence, the total income received by the landowner at time t can be expressed as a function of observed land shares X_t and decided land shares X_{t+1}, and we note $\Pi_t = \Pi(X_t, X_{t+1})) = \Pi_{for,t} + \Pi_{agr,t}$.

This sequential problem can be analyzed using the framework proposed by Epstein and Zin (1989), which involves similar temporal lotteries. For such temporal lotteries, Epstein and Zin (1989) define a new preference framework based on recursive utility functions. More precisely, Epstein and Zin (1991) define a recursive utility function, U_t, on the basis of the following recursive relation:

$$U_t = \left((1-\beta)\Pi_t^{\frac{\sigma-1}{\sigma}} + \beta [E(\tilde{U}_{t+1}^{1-\alpha})]^{\frac{\frac{\sigma-1}{\sigma}}{1-\alpha}} \right)^{\frac{\sigma}{\sigma-1}} \tag{6}$$

U_t is the utility brought to the landowner by all possible future income streams following time t. This way of aggregating future possible incomes is an alternative to the use of the standard expected utility framework. Recursive preferences actually generalize expected utility preferences (with constant relative risk aversion), which are obtained as a particular case when $\alpha = \frac{1}{\sigma}$.

Π_t is the certain (from a time t standpoint) income received at time t, $\tilde{U}_{t+1}$ is the uncertain recursive utility brought to the landowner by all possible incomes received from $t+1$ onwards, and E the expectation operator corresponding to our Bernoulli trial. This uncertainty reflects the fact that the sets of possible income streams as of $t+1$ do not need to be the same whether a perturbation occurs between t and $t+1$ or not. $\sigma \in \mathbb{R}^{+*}$ is the parameter that represents preferences for a regular income over time (the greater σ, the more flexible intertemporal substitutions), $\alpha \in \mathbb{R}^{+}$ is the risk aversion parameter (the greater α, the more risk-averse the producer), and β is the subjective discount rate.

Epstein and Zin (1989) have proven that it is possible to maximize U_t by adjusting, subject to constraints, all possible future incomes for all possible perturbation scenarios. As the program is sequential, they have also shown that it is possible to determine a stationary optimal decision rule at time t given the observed state at time t. In the context of our model, this decision rule, noted d, gives optimal decided land shares X_{t+1} for any observed state X_t and we have $X_{t+1} = d(X_t)$.

In addition, Epstein and Zin (1989) have demonstrated that this optimal decision rule can be determined using a modified Bellman equation. In the context of our model, this modified Bellman equation, as introduced by Epstein and Zin (1991), is given in equation 7:

$$V(X_t) = \max_{X_{t+1} s.t. \mathbb{D}(X_t)} \left\{ \left((1-\beta)\Pi(X_t, X_{t+1})^{\frac{\sigma-1}{\sigma}} + \beta [E(V((\tilde{X}_{t+1} \mid X_{t+1}))^{1-\alpha})]^{\frac{\frac{\sigma-1}{\sigma}}{1-\alpha}} \right)^{\frac{\sigma}{\sigma-1}} \right\} \tag{7}$$

The value function $V(X_t)$ that verifies equation 7 gives the maximum value of U_t when the initial state at time t is X_t and when all subsequent decisions are optimal regardless of the perturbation scenario that will be realized.

Decisions X_{t+1} must belong to the feasible set $\mathbb{D}(X_t)$. Decided land shares $X_{t+1} = (x_{agr,t+1}, x_{1,t+1}, x_{2,t+1}, \ldots, x_{a,t+1}, \ldots)$ are indeed subject to two types of constraints. On one hand, the acreages of forest that are harvested from the different age-classes are by definition positive. On the basis of equation 1, these constraints can be expressed as follows:

$$\text{For all } a \in \mathbb{N}^* \text{ and } t \in \mathbb{N}: \quad x_{a,t} \geq x_{a+1,t+1} \tag{8}$$

On the other hand, the total land acreage (normalized to 1) available for both agricultural and forest production is without loss of generality limited and constant :

$$\text{For all } t \in \mathbb{N}^*: \quad x_{agr,t} + \sum_{a=1}^{+\infty} x_{a,t} \leq 1 \tag{9}$$

The Bellman equation 7, as well as constraints 8 and 9, define the optimization program faced by the landowner.

This optimization program can be solved numerically using dynamic programming methods as performed in section 3.

3 Stationary land allocation and forest management: a numerical application

The aim of this section is to characterize steady-states in land allocation and forest management and the role of its determinants. A state is steady if it is optimally perpetuated as long as no perturbation occurs. The steady state rotation age provides a good indicator of the landowner's behaviour. For example, risk aversion may induce smaller rotation ages as it enables to reduce both the exposure and the vulnerability to risk.

3.1 A stochastic dynamic programming model

The numerical model is based on the stochastic dynamic programming model introduced in section 2. The parameter values used in the simulations are chosen to correspond to current conditions and practices that prevail in the forestry of maritime pine (*Pinus pinaster*) in Southwestern France.

3.1.1 Data and model parametrization

Timber revenue and agricultural land rent

Timber revenue dynamics used in the model are calibrated based on figures from Couture and Reynaud (2011), which give the final timber revenue in function of the rotation age of a forest of maritime pine. Couture and Reynaud (2011) make the distinction between saw timber and pulpwood, both in term of price and relative growth. The data on biological forest growth they use is adapted from Vannière (1984).

Couture and Reynaud (2011) also propose to use a 1000 euros/ha planting cost taken from Guo (1994). This cost is in line with the technical literature on maritime pine forestry (see ONF (2013))

Timber revenue dynamics are recalibrated so as to fit market prices for maritime pine forestland in Southwestern France. More precisely, relative dynamics computed by Couture and Reynaud (2011) are kept but timber revenues are shifted so that series of discounted revenues (for the Faustmann rotation) fit with forestland prices given a 1000 euros/ha planting cost. Market prices for maritime pine forestland are around 2000 euros/ha for bare land and 8000 euros/ha for a mature forest (45 to 50 years), see *Forêt Privée Française*.

The timber revenue data used in our model is presented in table 1:

(Table 1 here)

We assume a 3% annual discount rate, which is a value commonly found in the academic (see Couture and Reynaud (2011) and professional literature.

As for agricultural land rents, we consider regulated prices for 2016. In the *Département des Landes*, land rents for marginal agricultural land had to be between 40 and 90 euros/ha/year. The values used in the simulations are in this range or slightly above (up to 95 euros/ha/year, see figure 7).

Storm Risk

A perturbation risk on forest is defined by three components (see Schelhaas et al. (2010)): i) its probability of occurrence, ii) the exposure of the forest to the perturbation, that is the total timber value that can potentially be affected by the perturbation, and iii) the vulnerability of the forest to the perturbation, that is the probability that a given forest is damaged if the perturbation occurs.

The perturbation introduced in the numerical model is aimed to be a risk of storm. Information on storm probabilities and consequences is scarce as storms are by definition rare events. However, we assume, as in many articles from the literature (e.g. Reed (1984), Couture and Reynaud (2008)), that the risk of storm is independently and identically distributed over time.

There are estimations of storm probabilities on the national (French) level, for example Picard et al. (2002) but no specific value for Southwestern France. However, seven important storms have hit Southwestern France since 1976. This corresponds to a 0.17 probability that a storm occurs in the region every year. However, whenever a storm occurs, only some parts of the region are impacted. The storm Klaus in 2009 impacted 63% of the *Landes de Gascogne* forest area (see *Inventaire Forestier National*) but this was an exceptional event. We assume a lower value of 10%, which means that any spot in Southwestern France has a 0.1 conditional probability to be impacted by a storm whenever a storm occurs. Therefore, the unconditional annual probability that a storm impacts a given spot is 0.017. This probability is larger than the figure proposed by Picard et al. (2002), 0.0031 on the national level. This reflects the specificities of the region.

In addition, we know that the vulnerability of a forest to wind storms increases with its age (see Schelhaas et al. (2010)). So as to represent this characteristic, we consider a set of storms with different effects, which are presented in table 2 below. The first type of storm (#1) destroys completely the age-class 8 (the oldest possible one), the second type (#2) destroys completely age-classes 7 and 8 (the two oldest ones), and so on. The different events are supposed to be mutually exclusive. In addition, agriculture is assumed not to be affected by storms.

(table 2 here)

This way of modelling the storm risk ensures that the relative increase in vulnerability over the age fits with the data estimated for spruce by Dhôte (2000) and given in Couture and Reynaud (2008) while the total annual probability of occurrence of a storm is 0.017.

This approach also ensures that if a given age-class is damaged by a storm, all older age-classes are also damaged. This is consistent with the mechanism of action of the wind. In this regard, this approach is more realistic than the more usual conditional probability approach based on the assumption that damages are independently distributed over the different age-classes.

Recovery function

When an age-class is impacted by a storm, a given proportion of the prior standing value can be recovered by the landowner. This proportion is lower when the forest is older. Indeed, older trees are destined as a priority to saw timber production for which mechanical damages are more problematic than for pulpwood production. The recovery coefficients that are used in the model are presented in table 3. They are specific to maritime pine forests and are derived from Piton (2002).

(table 3 here)

For a storm occurring between t and $t+1$, the recovered value is received as an income between periods $t+1$ and $t+2$, ensuring that the income received between t and $t+1$ is certain from a time t standpoint (that is independent from storms that may occur between t and $t+1$). This is important with regard to the use of the recursive preferences framework.

3.2 The solving algorithm

The program is solved using a value function iteration algorithm (see Judd (1998)) that is computed using the GAMS language and solvers. This algorithm supposes an infinite time horizon, which is necessary as the focus is put on steady-states. The convergence of the algorithm is ensured by the Contraction Mapping Theorem (see Judd (1998)).

More precisely, the purpose of this algorithm is to compute the value function V corresponding to the optimization program defined by equations 7, 8, and 9. The computation is parametric and the value function is given a third order polynomial form, as expressed in equation 10:

$$V(X) = rv + \alpha_{agr} \cdot x_{agr} + \sum_{i=1}^{10} \sum_{j=i}^{10} \sum_{k=j}^{10} \alpha_{i,j,k} \cdot x_i \cdot x_j \cdot x_k + \sum_{l=1}^{10} \sum_{m=l}^{10} \alpha_{l,m} \cdot x_l \cdot x_m + \sum_{n=1}^{10} \alpha_n \cdot x_n + \sum_{o=1}^{10} \sum_{p=o}^{10} \alpha_{agr,o,p} \cdot x_{agr} \cdot x_o \cdot x_p + \sum_{q=1}^{10} \alpha_{agr,q} \cdot x_{agr} \cdot x_q \quad (10)$$

The algorithm requires a discretization of the space of possible states. In this case, we consider 1315 different states, which is a good compromise between the precision of the algorithm and its execution time. This level of discretization allows V to be given a third order polynomial form but not a fourth order. However, in many studies, a less precise second order polynomial is deemed sufficient. The convergence criterion for the algorithm is set at 1%, which means that the algorithm is considered to have converged after i iterations when $\| \mathbf{V}_{i+1} - \mathbf{V}_i \| \leq 0.01 \cdot \| \mathbf{V}_i \|$, where $\mathbf{V}_i$ is the vector of 1315 values for the value function obtained after i iterations of the algorithm. For all results presented in this article, the algorithm had converged within 30 iterations. This threshold value was chosen as it was a good compromise between precision and computation time.

Once the value function is known, that is once the parameters from its polynomial form are known, steady-states can be computed. To this purpose, a sequence of optimal decisions is constituted starting from bare land or any other arbitrary state. The convergence of this sequence is checked on the basis of the producer's objective, which must show less than 1% variation, between the last two time-steps for constant equilibria and between the same two phases of a cycle for periodic equilibria (see section 3.3), checked on the last two cycles. For all results presented in this article, the convergence was observed within a 200 time-step sequence. The last time steps of this sequence are then considered as a steady-state.

3.3 Results

The model is solved for different values of the exogenous parameters: preference parameters, recovery coefficients, agricultural income, and discount rate. The aim of this section is to characterize steady-states and to assess their sensitivity to these exogenous parameters.

As for forest management, the results reveal the existence of three types of steady-states: i) periodic forests with unique harvest ages, and ii) forests with constant age-class structures but with several harvest ages, and iii) constant mixed land allocations between a forest with a constant age-class structure, with one or several harvest ages, and agriculture.

The existence of steady-state periodic forests in a deterministic context is well documented (see for example Salo and Tahvonen (2002b)) and is shown to be related to the discrete time setting. The same reason applies in the stochastic case.

In case of periodicity, the age-class structure is shown to be dependent on the arbitrary initial state that is used to compute the steady-state but the harvest age is independent from it. When the steady-state forest has a constant age-class structure and several harvest ages, this structure is shown to be independent from the arbitrary initial state. In this case, it is possible to associate a unique average harvest age weighted by the acreages respectively harvested from the different age-classes. In both cases, it is possible to associate a unique average harvest age to a given set of values for the exogenous parameters. Therefore, it is possible to assess the sensitivity of the average harvest age to exogenous parameters.

In a similar fashion, mixed land-use allocations are constant over time and do not depend on the arbitrary initial state, so it is possible to allocate a unique land allocation to a given set of values for exogenous parameters.

Note that the coexistence of several harvest ages as well as the existence of mixed land allocations at the steady-state are permitted only in a stochastic context. Salo and Tahvonen (2002b) have shown that in a deterministic context, a multiple age-class forest has a unique harvest age that follows Faustmann's rule. As for land use, Bell et al. (2006) have shown that in a deterministic context and in presence of constant returns to scale from land, mixed land allocations are not possible. However, Parks (1995) has shown that risk and related preferences can explain mixed land allocations.

The figures below present the results obtained with our model for a series of sensitivity analyses, in particular on preference parameters. For comparison purposes, Brunette et al. (2014) had estimated experimentally the coefficient of relative risk aversion of French forest producers and obtained a result close to 1 (precisely 1.1527), which is in accordance with previous estimations that can be found in the references. The value of a preference parameter is specific to a functional form but the recursive form we use in this article is equivalent to expected utility preferences with constant relative risk aversion when $\alpha = \frac{1}{\sigma}$. This is the case if we set $\alpha = \sigma = 1$. Moreover, these values correspond to a coefficient of relative risk aversion of 1, which is in line with the figures proposed by Brunette et al. (2014). On the basis of these values, our model gives a rotation age of 40 years, which is consistent with current forestry practice for the maritime pine in Southwestern France.

Figure 2 shows the impact of risk aversion (parameter α) on both land allocation and the average harvest ages when it is not possible to recover any value from damaged timber ($\sigma = 100$ so that the preference for a regular income is very low):

Figure 2: Risk aversion, land allocation and forest management - No recovery

Figure 2 reveals that risk aversion tends to decrease the average rotation age to favor land allocation to agriculture. Lowering the average rotation age indeed reduces the exposure and the vulnerability of the forest to the risk of storm and is as such a precautionary behavior. Similarly, allocating land to an agricultural use provides a certain income to the landowner and is therefore a precautionary behavior as well.

Figure 2 reveals that both strategies can be used jointly but that when risk aversion is too high, all land is allocated to agriculture.

Figure 3 shows that when value recovery from damaged woods is possible, the impact of risk aversion is similar although somewhat different:

Figure 3: Risk aversion, land allocation and forest management - With recovery

In this case, land allocation is the only lever used as a precautionary behavior. It emphasizes the fact, also apparent in figure 2, that land allocation is the main endogenous lever to respond to risk aversion, at least when the landowner does not have preferences for a regular income.

The effect of the preference for a regular income (parameter σ) is more contrasted as shown in figure 4 ($\alpha = 0$ so that the landowner is not risk averse):

Figure 4: Preference for a regular income, land allocation and forest management

Figure 4 shows that the preference for a regular income (that increases when σ decreases) leads to agricultural land allocations only when it is very strong (when σ is very low) and when timber recovery is not possible, at least in the context of our model. As for the impact on forest management, when recovery is not possible the preference for income regularity seems to increase the average rotation age, except for really low values of σ.

This could be explained by two antagonistic effects: i) increasing the average rotation age increases the total timber value in the forest, which constitutes a kind of precautionary savings that could be used to smooth down the consumption stream, ii) decreasing the average rotation age reduces the exposure of the forest to the storm risk, which in turn reduces the variations in the income stream in case a storm occurs.

In the absence of recovery value, the first effect dominates, except for low values of σ. However, when there is a recovery value, the second effect dominates. This seems to show that despite the existence of antagonistic effects, the preference for a regular income has overall a similar effect as risk aversion on the average harvest age; but not on land allocation.

So far, the effects of risk aversion and of the preference for a regular income have been considered independently. Instead, figure 5 shows the effect of risk aversion (parameter α)

on the average harvest age and land allocation for different levels of regularity preferences (parameter σ):

Figure 5: Effects of risk aversion for different levels of preference for a regular income

When the landowner has preferences for a regular income (that is when σ is sufficiently small), land allocation to agriculture seems to vanish, even when the landowner is very risk averse. As an illustration, when $\sigma \leq 9$, no land is allocated to agriculture, even when risk aversion α is as high as 5. As land allocation to forest constitutes a kind of precautionary savings, the preference for regular income prevents land to be allocated to agriculture. In this case, lowering the average harvest age seems to become the only lever to respond to risk aversion. However, risk aversion always reduces the average harvest age regardless of the level of σ.

Similarly, figure 6 shows the effect of the preference for a regular income (parameter σ) for different levels of risk aversion (parameter α):

Figure 6: Effects of the preference for a regular income for different levels of risk aversion

Figure 6 confirms the effect of σ on preventing land allocation to agriculture (when timber recovery is possible) and shows in addition that preferences for a regular income (the smaller σ the stronger preferences for a regular income) reduces the average harvest age regardless of the level of risk aversion.

Although risk preferences and intertemporal preferences have a significant influence on steady-state land allocation and forest management, other determinants also have a crucial role.

Figure 7 shows the impact of the agricultural land rent on land allocation:

Figure 7: Sensitivity of land allocation to the agricultural income

Figure 7 reveals that relatively small variations in the agricultural income can shift land use from a total allocation to one use to a total allocation to the other. It also shows that the impact of preferences is visible only in a narrow range for agricultural land rent.

The same two conclusions apply to the discount rate. For a 2.5% discount rate, all land is allocated to forest regardless of the preferences (at least for the simulated ranges), and for a 3.5% discount rate, all land is allocated to agriculture.

Relative incomes and the discount rate are undeniably important determinants of land use and forest management. However, it is shown that in standard economic and climate conditions, risk and preferences can also have a significant impact on those two issues.

4 Discussion

It is shown that in a stochastic context, mixed land allocations as well as forests with several harvest ages can be steady-states and that both land allocation and harvest ages depend on the risk, and on both risk preferences and time preferences.

Land allocation and forest management are shown to be complementary levers in the response to preferences. As far as the risk of wind storms is concerned, risk aversion tends to favor land allocation to agriculture and to decrease the average harvest age of the forest, as precautionary behaviors. The preference for a regular income also reduces the average harvest age so as to reduce the income variability in case a storm occurs. However, it favors land allocation to forestry so as to constitute precautionary savings in the form of a timber stock.

Although relative land rents and the discount rate remain the most important determinants of land allocation, risk and preferences are also shown to have a significant influence in usual economic and climatic conditions.

This study extends the deterministic approach presented in Salo and Tahvonen (2004) to a stochastic setting, and demonstrates and clarifies the joint role of risk and preferences in allocating land. In parallel, it also extends studies such as Parks (1995) that are based on stochastic models of land allocation but that do not take into account the dynamic nature of forestry.

This study also shows that recursive preferences are essential in the understanding of land allocation between a dynamic activity such as forestry and an alternative use. Risk aversion and intertemporal preferences are indeed shown to have different effects on land allocation and should therefore be distinguished.

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Age-class	Age (years)	Timber revenue (euros/ha)
1	5	0
2	10	22
3	15	58
4	20	194
5	25	780
6	30	2756
7	35	5834
8	40	8166
9	45	9564
Agricultural land rent (euros/ha)		
40-95		

Table 1: Timber revenue in function of the age and land rent

#event	Destroyed age classes	5-year prob of occurrence
0	None	0.918
1	9	0.012756
2	8+9	0.012756
3	7+8+9	0.012756
4	6+7+8+9	0.021867
5	5+6+7+8+9	0.020409
6	4+5+6+7+8+9	0.000583
7	3+4+5+6+7+8+9	0.000437
8	2+3+4+5+6+7+8+9	0.000292
9	All	0.000146

Table 2: Storms and probabilities

Age-class	Age (years)	Residual value after destruction (in proportion)
1	5	0.65
2	10	0.55
3	15	0.48
4	20	0.44
5	25	0.4
6	30	0.35
7	35	0.33
8	40	0.31
9	45	0.3

Table 3: Proportion of residual timber value after destruction in function of the age