Spatially explicit farming system modelling for an efficient agri-environmental policy design

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Abstract— **A mathematical programming model is developed and associated to a spatial pattern index (Ripley L function) to analyse the optimal reserve design and implementation for the Little Bustard conservation in *Plaine de Niort*. The model structure corresponds to three spatial levels, fields, farm and landscape. Simple in terms of area representation, it is detailed in terms of farm behaviour and spatially explicit. The model is applied in a normative and in a positive way. The major findings of the normative approach relate to the trade-offs between the reserve pattern and its cost. It was found that the environmentally optimal reserve, which is randomly dispersed across the zone, is the most costly one. Within the positive approach, it is illustrated that the various reserve patterns generated within the normative approach can be obtained through relatively simple uniform contract structures. The most effective contract structure is a degressive set of two payments enabling the farms to enrol at least a small share of their land.**

Keywords— **Biodiversity, spatial optimization, mathematical programming.**

I. INTRODUCTION

Over the last forty years, farmers have increasingly changed the use of their lands, and modified their farming techniques. It appears that these changes have led to an important decrease in biodiversity. Given the lack of standard measurements of biodiversity, one indicator that has been proposed and largely studied is bird population [11]. Agriculture intensification has been pointed out as one of the main reasons for the decline in Europe's farmland bird population [15, 16, 4, 6, 14]. It has been shown that common farmland birds of Europe have declined dramatically over the last two decades (by 25%), whereas woodland birds have not [11].

Until the early 1900s, the Little Bustard (Tetrax tetrax) was commonly found in open fields throughout most of Europe, but it has disappeared from most of its former habitat over the last century. In France, breeding males in agricultural habitats have declined markedly over the last twenty years (by 92% since 1980) due to land use changes and to the intensification of agricultural practices [13]. By 2000, most of the remaining population (420 breeding males) has been limited to the Poitou-Charentes region of France. Our research is focused on a core area of this region covering approximately 350 km^2 in *Plaine de Niort*. *Plaine de Niort* was traditionally dedicated to mixed farming but has recently undergone a rapid specialisation in crop production: the area in meadows and pasture dropped by 60% between 1988 and 2000 [3] and was replaced by annual crops (mainly wheat, maize, and recently, rapeseed). This induced a decrease in insect abundance and an increase in bird nest destruction during harvesting. Today, Little Bustards are seriously in danger.

This specific area was designated a Natura 2000 site to stop the decrease in the Little Bustard population. Within the framework of the CAP Rural Development Regulation, specific agri-environnmental schemes are currently being implemented to encourage farmers to keep grasslands and grow alfalfa using Little Bustard-friendly cropping techniques.

This paper presents a mathematical programming optimisation model called OUTOPIE (*OUTil pour l'Optimisation de PrairIes dans l'Espace)* developed for this specific Natura 2000 site. Mathematical programming farm level models are recognized as a suitable tool for environmental economics research (for discussion of the issue, see e.g. [22], and have been widely applied (e.g. [9, 17, 8]). OUTOPIE differs in that it takes into account, in addition to the farm-level, the field and the landscape spatial levels. Farmers' profit-maximizing behaviour as well as technical and administrative constraints influencing land management are accounted for at the farm level. The field represents the elementary unit which by its characteristics determines to a large extent the actual land use, and the landscape is crucial for our analysis because it is at this level that the protection of the Little Bustard is carried out. The specificity of the landscape pattern that is considered suitable for an optimal Little Bustard conservation, i.e. a percentage of the zone covered with randomly dispersed grassland, obliges us to explicitly take into account the spatial distribution of fields and therefore also requires the use of specific indicators capable to characterize this distribution.

Many studies adopted a normative approach in some form of the optimal reserve design problem, for their comprehensive review see Williams *et al.* [21]. Applications to agricultural landscape are still rare. One of the few examples is the paper by *Wossink et al.* [23], but the latter applies a partial budget method which lacks flexibility in the farm adaptation options. In comparison to these approaches, our model takes explicitly into account farmers' behaviour and is able to assess their response to different policy measures.

The aim of our model is to explore where the Little Bustard compatible grasslands should be located so that the cost in terms of the foregone farm income is the lowest. It also investigates what agri-environmental policy should be implemented so that the target farms really participate in the programme and thereby contribute to achieving the desired landscape pattern. First we explore the Little Bustard optimal landscape pattern and the trade-off between a deviation from the latter and the corresponding cost change, using the normative approach. Secondly, we investigate different payment schemes susceptible to provide these landscape patterns. We evaluate them in terms of the landscape pattern quality and the budgetary expenditure due to compensation payments incurred, using the positive approach. The methodology aspects concerning the analysis of the landscape pattern are covered in section 2. The studied zone and the model are described in section 3. The results of simulations are analysed in section 4. To conclude we discuss the adopted approach and the findings as well as suggestions for further research.

II. SPATIAL PATTERN ANALYSIS: METHODOLOGY

According to ecologists, the Little Bustard needs at least 15 % of the site under study covered by extensively managed grassland, 3 ha being the ideal size, randomly or regularly located within any radius between 100 and 1000m if the bird is to recover a normal productivity level[1]. We will refer to the plots of alfalfa and temporary or permanent grassland, managed in a Little Bustard-friendly (LBF) way, as to the *reserve*. This LBF management corresponds to the restrictions imposed by the existing agri-environmental programme (AEP) on livestock density, fertilisation, pesticides and mowing dates. To carry out a quantitative analysis of the optimal reserve design and implementation, we need to measure not only the size but also the shape of the reserve generated by the model. The former being straightforward, we will focus here on the measurement of the reserve shape.

A Potential landscape pattern measures

According to Ripley [20], methods to analyse spatial point patterns can be classified into two broad categories: quadrat counts and mapped data. Quadrats are sample plots in a given area where measurements or "counts", such as population abundance or density, are made. However, this first category does not efficiently account for the spatial pattern of points, since different patterns can lead to the same index value. The second category of methods is based on distance measurements between (all) individuals (bird nests, trees, etc.) on a map. Indices are generally based on the nearest neighbour distance, e.g. Clark and Evans [5], and as a consequence do not account for spatial structures at different scales.

The Ripley K and L functions [19, 20] combine both types of methods, i.e. quadrats (density counts) and distances, and account for spatial structures at different scales. They are widely used in plant ecology and can be used to study sedentary animals or stationary constructions [12]. They seem to be the most appropriate indices for the present study.

B The Ripley K and L functions

The K function counts the number of neighbour reserve plots located within a circle of radius r centred on each reserve plot in the study zone, takes the average and divides it by the reserve plot density in the study zone as shown in equation 1:

$$\hat{K}(r) = \frac{A}{N^2} \sum_i \sum_{j \neq i} (w_{ir} * I_r(d_{i,j})) \quad (1)$$

where A is the area of the zone studied, N the number of observed reserve plots, λ the density ($\lambda = N / A$), d_{ij} the distance between two reserve plots, I_r a counter equals to 1 if $d_{i,j} \leq r$ or to 0

[1] Information provided by V. Bretagnolle, CEBC, CNRS.

otherwise, and w_{ir} an edge effects correction weighting factor[2] (c.f. equation 2).

$$w_{ir} = \frac{circle\ area\ (\pi r^2)}{circ.\ area\ within\ studied\ zone\ boundaries} \quad (2)$$

$\hat{K}(r)$ is an unbiased estimator of $K(r)$ and $\lambda * K(r)$ can be interpreted as the expected number of further reserve plots within a radius r of any arbitrary plot. If the fields dedicated to the reserve are randomly located, following a Poisson distribution, then the expected value of $K(r)$ equals πr^2. According to Haase [12], $\hat{K}(r)$ is calculated for the relevant values of r and is tested against the null hypothesis of Complete Spatial Randomness (CSR of Diggle,[7]). Like many others, we apply the normalised form L(r) ([2][20]), which has an expected value of zero under the null hypothesis of CSR (see equation 3).

$$L(r) = \sqrt{\frac{K(r)}{\pi}} - r \quad (3)$$

Once the $\hat{L}$ function is assessed for the spatial distribution of the reserve in a scenario, it has to be tested against the null hypothesis of CSR. We used the Monte Carlo method to create a 95% confidence envelope[3].

Results can be interpreted as follows (c.f. Figure 1 for two spatial distributions of the reserve and Figure 2 for the associated values of L): a) if $L(r)$ remains within the confidence envelope (dotted lines in Figure 2) then the spatial pattern of the reserve is significantly (Poisson) random; b) if the deviation from zero is significantly positive, i.e. $L(r)$ is above the upper limit of the confidence envelope, then the spatial pattern is clustered or aggregated.

The scale of interest and the intervals between radii depend on the specie and on the issue which is addressed. In our case, the analysis of the Ripley L function should be limited to the Little Bustard relevant radii ranging from 100 to 1 000 metres, and to intervals equal to the distance between two fields.

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[2] This weighting factor is inspired from the one of Getis and Franklin (1987) cited in Haase (1995). It is based on the assumption that the density and distribution pattern of neighbouring areas outside and inside the site boundary are the same

[3] For more details on the confidence envelope generation, please ask the authors.

a) b)

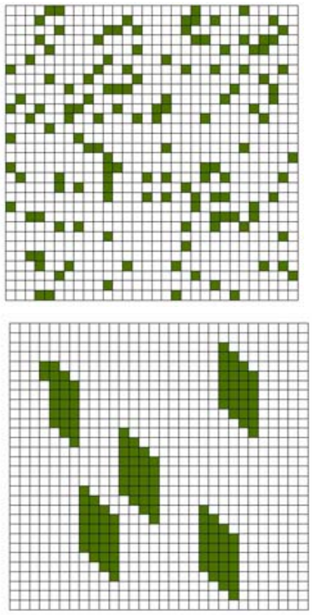

Figure 1. Examples of the spatial distribution of 135 reserve plots on a 900 plots grid: a) random, b) aggregated.

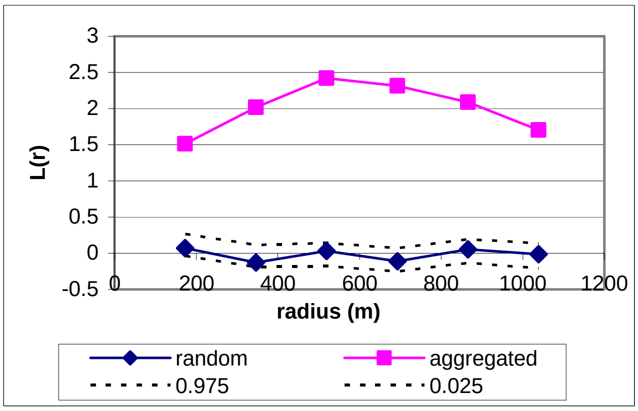

Figure 2. Ripley L function for an aggregated and a random spatial distribution of the reserve, c.f. Figure 1.

III. MODEL DESCRIPTION

C *Studied zone*

The site under study is part of *Plaine de Niort*, it extends over 35000 ha and is composed of 450 farms and 11000 fields. In our study, we have chosen to implement the model with a simplified map (c.f. Figure 3) of the site because we found it more relevant to study farms' behaviour and the reserve formation process on a stylized zone rather than on the real site with a complex structure. We considered a 2,700 hectares zone divided into 900 fields, each of 3 hectares which corresponds to the ideal size of plots for the Little Bustard. The three main groups of soils -calcareous valley, deep and shallow plain soils- were represented on the map, according to the ratio and layout observed. We represented 12 crop growing farms and 6 mixed dairy farms, 150 hectares each, both types being located on all types of soils. Some of the farms have the possibility to irrigate a fixed set of contiguous fields.

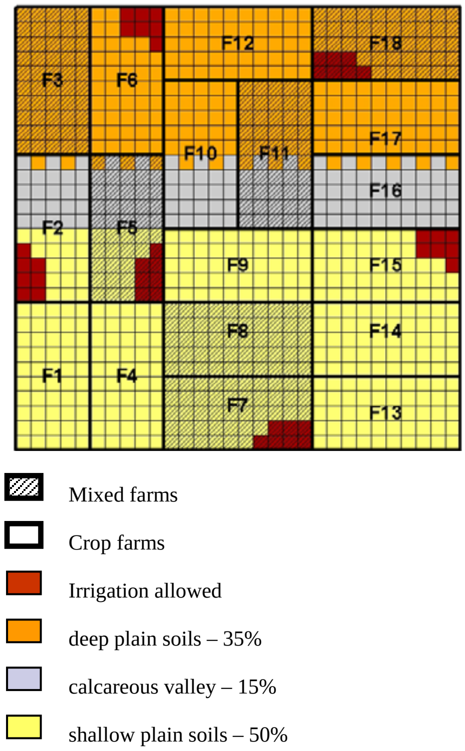

Figure 3. Model representation of the study area.

D OUTOPIE

OUTOPIE is a mixed integer linear programming model. The model maximizes the sum of all farms' gross margins, subject to resource availability, technical and policy constraints. Prices are exogenous and there is no interdependence between the individual farms.

The model accounts for three *spatial levels*: field, farm and landscape/region. The field represents the elementary unit of the model. Field characteristics, such as soil, climate and slope, determine the potential agricultural activities and cropping techniques that can be chosen by the farmer as well as the resulting yield and gross margin. In our model fields are characterised by their soil type, irrigation equipment (or not), and the farm to which they belong. The farm is the level at which decisions concerning land allocation are made, taking into account regulation and policy constraints (milk quotas, obligatory set aside etc.), and technical constraints such as feed requirements. Finally, spatial relationships between fields constituting the landscape are accounted for at the regional level.

On a crop farm, the basic decision variable is the share of each field allocated to a specific crop rotation. The model accounts for the major crops (wheat, winter barley, sunflower, rapeseed, maize, and sorghum), for permanent as well as temporary grasslands, including alfalfa, and for set aside land. Crops are declined in different cropping activities i) depending on the preceding crop, ii) on crop use, iii) on the duration of perennial crops (e.g. alfalfa cultivated for 3 or 4 years) or iv) on the cropping technique (rain fed, irrigated or LBF). These crops are combined in 52 crop rotations on the basis of information about the current practice, or new rotations are constructed so that they could be eligible for agri-environmental programmes or used to diversify the cattle feedstock, on each of the soil types. Crop rotations were provided by agronomists and local experts involved in the PRAITERRE project. Apart from alfalfa and grassland4, yields were evaluated for each type of soil, taking into account the preceding crop effect, with a tool named PERSYST[5].

Mixed dairy farms optimize crop rotations as well as the herd size and composition, the choice of feed rations, the purchase of concentrates, and the purchase or sale of forage crops. They are subject to constraints such as milk quotas and cattle demography. The link between the herd size and milk production is made through feed rations. The dairy cattle breeding module of the model is derived from the Opt'INRA model, initially developed for suckler cow breeding [18] and adapted to dairy cows in Poitou-Charente by LEE INRA Clermont-Theix. The module accounts for 18 animal types (differentiated by age, state and feed requirements), 7 forage types (grazed grass, grass hay, grass silage, alfalfa hay, maize silage, cereals, and cattle-cake) and 80 feed rations[6].

We implemented the 2003 reform of the CAP in the model, with a 10% set aside rate. Single payments and decoupled premium for animals were calculated with

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[4] Information on alfalfa and grassland management was provided by M. Laurent, UEFE, INRA-Lusignan.
[5] Persyst is developed by L. Guichard, UMR Agronomie INRA-Grignon,
[6] They are based on local practices or composed with the use of INRATion software.

local references. Crop prices and production costs are based on data from the 2005 FADN, the regional Centre d'Economie Rurale and experts. Production costs and prices for milk and animals were provided by Institut de l'Elevage, Poitou-Charente, for 2005.

The aim to analyse precisely the spatial pattern of the reserve requires two adjustments of the model structure presented so far. First, the decision variables which express the share of each plot enrolled in the reserve are to be binary. Second, in order to observe the reserve location over time, we add an index to each reserve relevant rotation, indicating at which stage the rotation starts.

IV. ILLUSTRATIVE APPLICATION

The strength of the presented model consists in its suitability for both normative and positive applications. The normative application is used to find the cost-efficient solution given the environmental constraints for the reserve design problem. This supposes that we have complete information about each farm and thus we can go to each farmer and propose him a contract which determines the area he should enrol into the reserve, as well as the payment which would compensate him precisely for the cost of the reserve. The administrative cost due to information gathering and negotiation would probably make the implementation of the normative approach too costly on the real site. Therefore, agri-environmental schemes usually propose a uniform, non-differentiated across farms, payment per hectare of the reserve to all farmers and let them choose the area they want to enrol. The positive application is used to test the agri-environmental schemes against the farmers' responses and thus to set up the schemes in a way which ensures that the desired reserve size and shape will be obtained. The purpose of the present section is to illustrate these two possible applications.

E Normative approach

Within the normative approach, we introduce the conservation requirements into the model as additional constraints. We impose a minimum of 15% of LBF managed grassland in the zone to control the size of the reserve. We did not constrain explicitly L(r) in the model to avoid a considerably increased complexity of the solution procedure, due to non-linearities, and thus looked for a proxy constraint. We found that in the studied case, the environmentally optimal spatial distribution can be obtained through a constraint requiring that all farms contribute equally to the reserve, enrolling 15 % of their land. The resulting landscape and L function are depicted in Figure 4a and Figure 5; they provide a benchmark for further analysis[7] scenario will be referred to as *1N*.

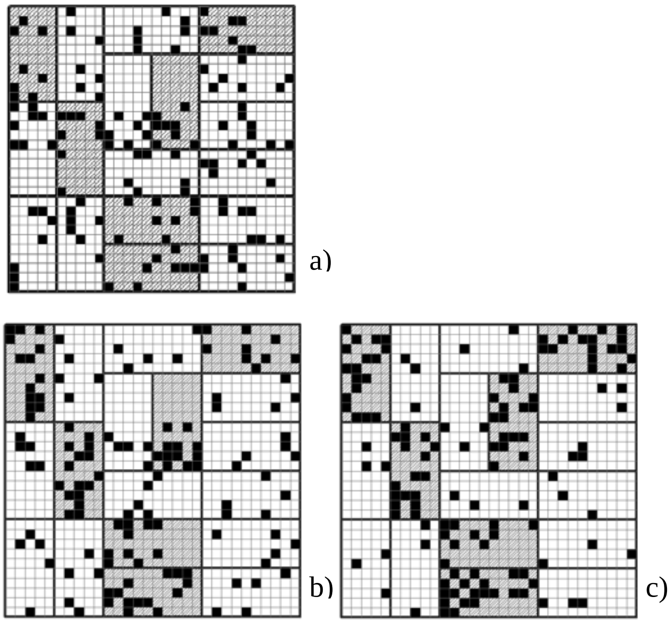

Figure 4. Environmentally optimal reserve location (a); and reserve location when the minimum share of each farm enrolled into the reserve is set at: b) 10 %, c) 5 %.

The cost of the reserve - calculated as the difference between the total gross margins obtained without and with reserve size and shape requirements - is 258 000 €, which represents 10 % of the total unconstrained gross margin. The reserve cost is then 640 €/ha on average, but differs from farm to farm. Mixed farms on shallow plain soils have the lowest average cost: 35 €/ha. They manage a part of their grassland in a LBF way even if the reserve is not imposed. The expansion of this management on a few additional hectares does not require any changes in the dairy herd size or structure; there is only a small decrease in the cropland area (around 5 %) and an increase in purchases of concentrated feedstock, by 1.5 tons per farm. At the

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[7] More precisely, Figure 5 represents the solution for the first year of the controlled period (11 years). The reserve will change its shape within each farm over the time. However, tests carried out for the other years show that the L-values for all of them are close to each other.

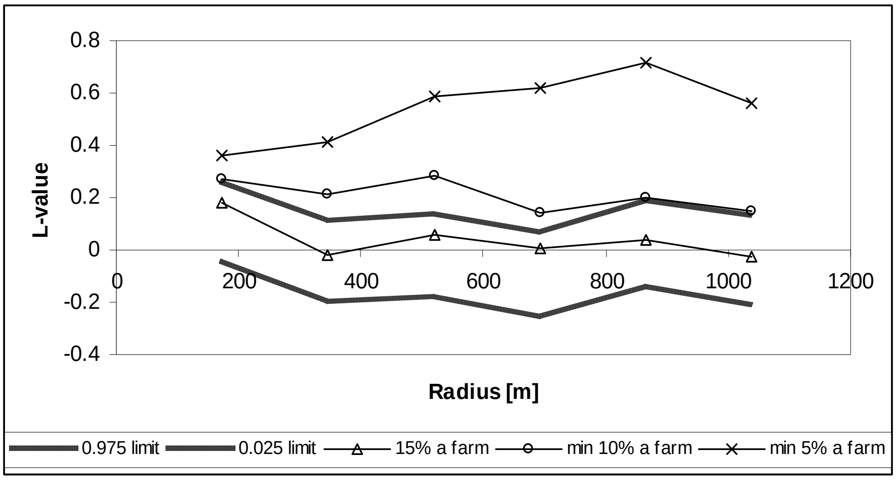

Figure 5. L-function values of the environmentally optimal (random) reserve pattern and for different minimum shares of each farm obliged to be enrolled into the reserve.

other extreme, crop farms on the very fertile deep plain soils have an average cost of the reserve higher than 1 100 €/ha, as they substitute cash crops by alfalfa and temporary grassland; this makes them loose 18 % of their gross margin[8]. In general, the average reserve cost does not exceed 220 €/ha on livestock farms, and it does not fall below 850 €/ha on crop farms.

If the "low-cost" farms were allowed to provide a larger part of the reserve and the "high-cost" farms could decrease the part of the reserve on their land, then the total reserve would cost less. We consider here one option to relax the reserve pattern optimality constraint by setting up the minimum share to be enrolled into the reserve by each farm below 15 %. The rest of the reserve can then be provided by the "low-cost" farms. Figure 4b-c shows how the cost-efficient reserve location changes when we oblige a farm to enrol at least 10% (scenario *2N*) or 5 % of its land in the reserve. Figure 5 shows how the reserve pattern deteriorates (aggregates) as the minimum share to be enrolled by each farm decreases. The cost of the reserve decreases to 204 000 euros and to 171 000 if the minimum participation constraint is set to 10 and 5 % of each farm, respectively.

F Positive approach

In this sub-section, we search for the contract schemes which would enable to obtain, or approach, the environmentally optimal reserve *1N* presented in section 4.1.

The simplest payment scheme would consist in proposing a uniform payment for each hectare enrolled into the reserve. Using the model, we calculated that a payment of 860 €/ha would be necessary for the farmers to enrol all together 15 % of the zone into the reserve and that this programme would cost 348 300 euros (scenario *3P*). However this reserve is not acceptable because of its highly aggregated pattern (see Figure 6). This scenario is equivalent to a "normative" scenario *3N*, where only the reserve size is constrained, at the zone level.

The contract scheme able to ensure the nearly optimal reserve *2N* would require a slightly more complex structure. We found that a payment of 1 125 €/ha up to 10 % of a farm, and another payment of 400€/ha above this limit, are necessary (scenario *2P*). The cost of this programme, which leads to a nearly optimal reserve pattern (see Figure 6), is then 357 750 €.

Finally, even the environmentally optimal reserve *1N* can be obtained when paying 1 125 €/ha up to 14% of each farm and 170 €/ha above this limit (scenario *1P*), for a programme cost of 429 840 €.

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[8] We make here the assumption, that the grassland product from crop farms is not commercialised, as it is the case in the studied zone.

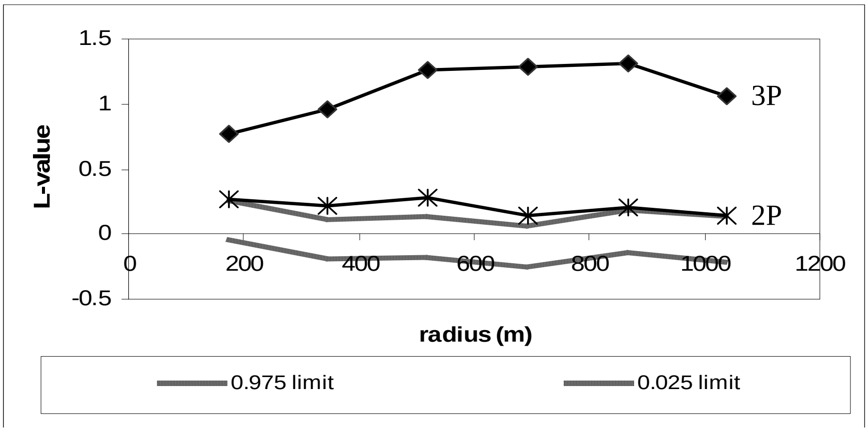

Figure 6. L-function values for uniform (*3P*) and degressive (*2P*) payment schemes

The cost of the reserve under the normative approach and the cost of the equivalent AEP using the positive approach are compared in Figure 7. We can see that the latter is always at least 65% higher than the former, this because payments were not differentiated between farmers and thus "low-cost" farmers were overcompensated. The sum of total payments necessary to obtain the second best reserve pattern *2P* is only by 3 % higher than the sum of the uniform payments in *3P*. The difference is of 29% within the normative approach for the corresponding reserve patterns *2N* and *3N*. This means that the way a reserve is implemented is also to be considered when weighting the costs against the environmental benefits. Depending on the institutional arrangement, the difference in costs can be considerably different for the same change in the environmental outcome.

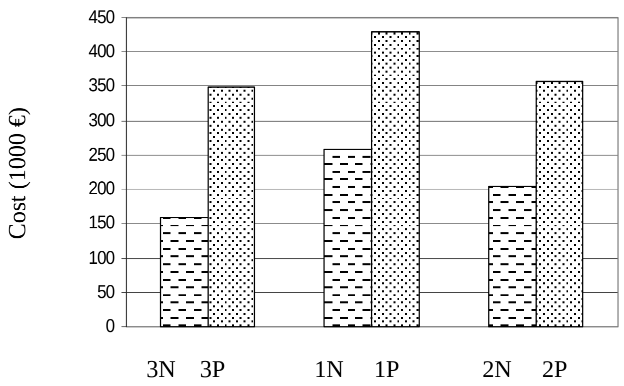

Figure 7. Cost of the reserve (normative approach "N") and of the equivalent agri-environmental programme (positive approach "P") for different schemes.

V. CONCLUSION

A mathematical programming model has been developed to analyse the optimal reserve design and implementation for the Little Bustard conservation in *Plaine de Niort*. Simple in terms of the zone representation – 18 farms regularly distributed on a square of 2 700 hectares – but detailed in the farming systems description and spatially explicit, OUTOPIE, connected to an efficient spatial pattern index (the Ripley L function), showed that it is possible to give valuable insight into the conservation economics by means of mathematical optimisation models.

It was illustrated that the model can be applied both in a normative way as well as in a positive way. Within the normative approach, the major findings relate to the trade-offs between the reserve quality and its cost. It was found that the environmentally optimal reserve, which is randomly dispersed across the zone, is the most costly one because it requires equal participation of all, "low-cost" as well as "high-cost", farmers. Allowing higher concentration of the reserve on the "low-cost" mixed dairy farms enables to decrease the cost of the reserve, but the spatial pattern of the reserve deteriorates. Depending on how the concentration of the reserve within a farm is restricted, the pattern and cost of the reserve change. A better reserve pattern for lower cost can be obtained if each farm is required to enrol at least a small area into the reserve.

The positive approach illustrated that the various reserve patterns generated within the normative approach can be obtained through relatively simple uniform contract structures, which do not require complete information about, and negotiation with, the individual farms. The most effective contract structure, which was able to encourage all farms to enrol at least a small share of their land into the reserve, is a set of two payments where one of them is guaranteed up to a certain share of the farm and the second, much lower, remunerates all the land enrolled above this limit. In terms of budgetary expenditure, this option costs nearly the same as a simple uniform payment scheme but can provide considerably better reserve patterns.

Finally, the simultaneous application of both normative and positive approaches enables us to evaluate the cost-efficiency of the proposed contract schemes. In the presented scenarios, we have seen that the sum of the payments necessary to obtain a given reserve within the positive approach was always much higher than the actual cost of the same reserve calculated within the normative approach. This is because, in the contract schemes we tested, the payment levels were not differentiated between "low-cost" and "high-cost" farmers, thus the "low-cost" farmers were overcompensated.

Although, or because, the model seems to be able to advice the conservation reserve design both in terms of its location and implementation, further research is desirable. We see two prominent directions which should be explored. First, supplementary scenarios concerning the distribution of the farms across the zone should be investigated, so that the robustness of the results in terms of the reserve size and shape resulting from different contract schemes could be tested with respect to this parameter and the conclusions generalised. Second, a simple spatial pattern index able to account for the reserve characteristics in a coherent way should be incorporated into the model, so that not only the desired reserve size but also its pattern can be controlled explicitly through a constraint or even through the objective function. This second feature would further increase the domain of applicability of the presented approach.

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