Optimal Regeneration Regime under Continuous Crown Cover Requirements in Cork Oak Woodlands

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Abstract: In the present work the cork oak tree spatial growth simulator CORKFITS is used to create candidate scenarios for generating a large set of regeneration regimes combining both time and intensity factors with the individual tree spatial information. An optimal regeneration regime under continuous crown cover requirements is sought by applying a dynamic programming algorithm. It is shown that the crown cover constraint influences the total cork production potential in a negative way. The target cover constraint of 50% decreases the cork production by 66% from the potential in 40 years in our mature plot, and approximately 43% in our young plot. Higher crown cover constraint of 70% decreases the potential cork production approximately by 54% in the mature plot and does not have any influence on the younger plot. The observed losses in cork production in relation with the potential with the crown cover constrains need to be compensated economically by the higher availability of growing space for the grazing and livestock part of the *montado/dehesa* production system.

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1. Introduction

Cork oak (*Quercus suber L.*) woodlands (*montado/dehesa*) consist of a multifunctional forest system that covers about 713,000 ha in Portugal. Today, its importance relies on cork production, with Portugal producing half of the world cork. As the main economic objectives may change with changes in markets and environment conservation concerns (e.g., biodiversity, water and carbon) there is a need for improving management scheme in order to derive efficient management solutions for sustainable use of cork oak woodlands territories.

Cork oak woodlands system complexity derives from the integration of production activities (forestry, agriculture and growing animal livestock) in the same growing space of a landscape characterized by its site variability especially at the soil/climate/topography levels. The system is based on open stands where trees are responsible for the ecological characteristics fundamental to the sustainability of all activities occurring at the stand level. Balancing these production activities requires a good knowledge of the resilience of the forest component in the particular combination of soil/climate/topography (Ribeiro *et al.*, 2006).

The woodland production system management aims the maintenance of a balanced sustainable land use to cope with the Mediterranean climate variability. Woodland stands (*montado/dehesa*) are managed in agro-silvo-pasture systems, of which sustainability depends on balanced relations between their components (Pinheiro *et al.*, 2008).

The sustainability of these forest structures is closely related with the continuous crown cover management and soil protection, therefore the success of natural or artificial regeneration is the driver for system resilience and elasticity. Cork oak woodlands system resilience is a function of specific stand structures and densities that are supplied with new trees to compensate the natural rates of mortality permitting the maintenance of a stable crown cover (Ribeiro *et al.*, 2003a, 2006, 2010). Managing for a continuous crown cover between 30% and 70% (slope dependent) is essential for the specific ecological conditions created in the woodland ecosystems that enhance the efficient multi-functionality of the system. Furthermore it is reached a sustained protective effect on soil preventing the erosion risk and improving the water and nutrient cycles (Ribeiro *et al.*, 2004).

The sustainability of cork oak woodlands can be solved by seeking an optimal regeneration regime subjected to continuous crown cover management requirements. The optimal management regime must take in account the conflicting activities with the natural/artificial regeneration processes such as agriculture and grazing.

The set of equations of the problem is dependent on the complex integration of constrains that were referred by Ribeiro *et al.* (2010): (1) trees are fully protected by law and legal authorization is needed to cut, thin, prune, debark, etc., (2) the undercover is used to grow crops and/or animal production, (3) the main product is bark (cork) that is extracted every nine years (the minimum period permitted by law).

The spatial explicit tree growth simulator CORKFITS is composed by a set of sub-models for growth, survival and ingrowth (Ribeiro and Surový, 2011), that integrate all the referred complexity constructed based on a wide range of repeated measurements constituted by a set of 87 permanent plots (67 installed in 1995, 5 installed in 2000, and 15 installed in 2003) and on the knowledge acquisition at the site level (soil, management, climate, vegetation, bird population, etc.) as well as at the tree level (growth, cork production, intensity of debark, crown pruning, etc.) (Ribeiro *et al.*, 2003a). The decision model, that composes the model called ECCORK, includes ecological indices (vegetation and animal biodiversity), management risk indices (soil erosion and fire hazard) and economical indices (cork production, cattle production, carbon sequestration, etc.) (Surový *et al.*, 2004, Ribeiro *et al.*, 2007, 2010).

In the present work the cork oak tree spatial growth simulator CORKFITS is used to generate candidate scenarios for generating a large set of regeneration regimes combining both time and intensity factors with the individual tree spatial information. An optimal regeneration regime under continuous crown cover requirements is sought with the use of one of the dynamic programing algorithm called MS-PATH algorithm (Yoshimoto *et al.*, 1988, 1990, Yoshimoto and Marusák, 2007).

2. Material and Methods

For the present study a set of permanent plots was used. Its dendrometrical characteristics are described on Table 1. The plots were selected according to stand age and structure: Plot 101 (young plot) uneven-aged with young trees cohort; Plot 317 (mature plot) even-aged without young trees cohort. The 2,000 m^2 plot statistics are presented in Table 1.

CORKFITS was used for simulation. It was constructed with data generated with the monitoring system installed in 1995. The simulator was built assuming the potential increment modifier principle:

[1] $$z = z_{pot} \times M + \varepsilon$$

where z is exact growth, z_{pot} is the potential growth as function of site, and M is a modifier to adjust the amount which changes with a spatial competition index and the intensity of debark, ε is an error term. CORKFITS consists of sub-models (cork, stem, tree height and crown), cork production models and mortality models (Ribeiro *et al.*, 2003a, 2003b, 2006, Ribeiro and Surový, 2011, Surový *et al.*, 2011). MS-PATH algorithm was utilized in the dynamic programming search

Table 1. Descriptive statistics of permanent plots 101 and 317.

		cbh^b	h	cdw	e
Plot 101	Mean	138.9	8.8	29.7	3.65
number of trees=10	Standard error	15.7	0.6	7.5	0.11
	Minimum	87.5	6.5	9.0	3.26
	Maximum	191.5	11.5	55.9	3.98
Plot 317	Mean	155.9	10.4	42.3	3.26
number of trees=15	Standard error	20.4	0.7	12.6	0.15
	Minimum	86.0	7.4	7.2	2.71
	Maximum	236.0	13.0	107.9	3.90

cbh^b : perimeter at breast height before debark (cm), h : tree height (m), cdw : cork dry weight (kg), e : caliper (cm)

technique. The dynamic programming network is shown in Figure 1 for the five-stage case.

To seek an optimal regeneration intensity and spatial distribution of regeneration, the positions for future regenerated trees are assumed to be in the (1m x 1m) grid. For every candidate tree for regeneration in this grid, the value of so-called "competition index", I^c is calculated based on following formula:

$$I^c = \sum_{i=1}^{n} \frac{C_i}{D_i} \qquad [2]$$

where n is the number of trees within the circle of the 20 meter distance from a candidate tree, D_i is the distance between the i-th tree and a candidate tree in the circle, C_i is the circumference with the search radius, r_i for competitors at breast height for the i-th tree observed in the circle of 20 meters. This index is used to decide the order for regeneration. The lower values of the index, sets the the earlier placement of a candidate tree will be placed for regeneration. In this sense, our

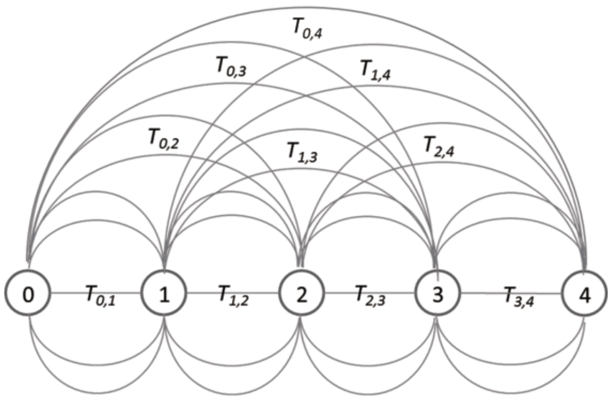

Figure 1. Dynamic programming networks for the five stage case with MS-PATH algorithm.

dynamic programming approach is rather classified as the stratified one to avoid numerical burden. There remains a problem of adjustment for this index on the positions at the edge of the circle. Modification for this adjustment is to use geometrical correctors.

In such a situation is displayed when for the given tree at the point C2 the search radius for competitor's r goes beyond the circle with a candidate tree in the center C1 and radius R (Figure 2). The geometrical corrector would be defined as the area of a circle with radius r from center C2, divided by the overlapped segment of two circles based on C2 and C1.

Let us consider the following: in the case of a circle being inside the plot, the coefficient is 1 (the value of competition will be multiplied by one) in the case of a searching circle being on the edge of plot let us consider the value of coefficient be equal to 2. So we can use linear

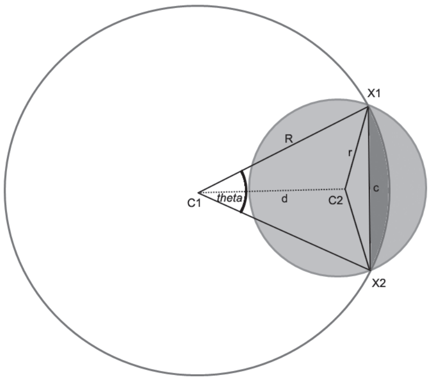

Figure 2. Overlapping of searching radius (smaller circle) with plot radius (larger circle).

estimation for corrector by following formula:

[3] $$y = \frac{1}{r}\mathrm{x}+1$$

where r is the radius of searching cycle. The resulting value of corrector is shown in Figure 3. In the left part of the figure the geometrical corrector is displayed, while in the right part the values of the index of competition for Plot 101 are displayed. High values close to large trees are the least probable for regeneration.

MS-PATH starts recursive searching an optimal regeneration regime in the present year while CORKFITS simulates the growth over every period of 10 years up to 40 years with different regeneration amounts from 0 to 320 trees per ha. The best solution with maximum cork production meeting the crown cover constraint is stored for every period for the final comparison. Then the same process is completed for the second period (20 years) until the fourth period. In each period the best solution is saved as potential future candidate. Next step starts in period 1 (10 years). In this moment the initial point is taken from the

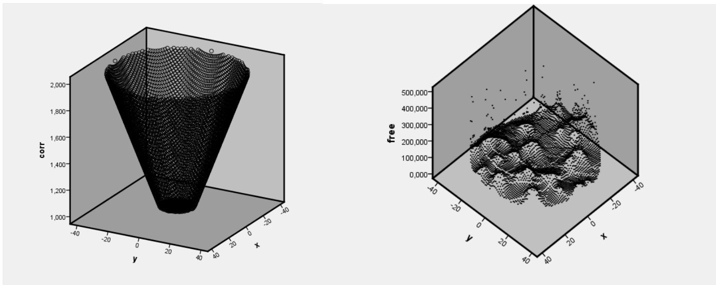

Figure 3. The value of corrector (left) with increasing distance from center the corrector is closer to value 2, in the right part the value of so-called freedom index lowest in the places with no trees around highest in close distance to trees for plot 101.

best regeneration in period 0 and all regeneration amounts (0-320 per ha) are generated. In period 2 (20 years) there are two possible initial points to be chosen from period 0 to 2, or from period 0 to period 1and then to period 2 (in the latter case, the best regeneration in period 1 takes place for generating candidates in period 2). The best of these two options is chosen for the next searching for period 3 and so forth.

Mathematically the process can be described as follows: The objective is to maximize the amount of biomass from debarking for cork production over time, where the optimal solution $(\mathbf{R}^*, \mathbf{H}^*)$ is expressed by

$$[4] \qquad (\mathbf{R}^*, \mathbf{H}^*) = \arg\max_{R,\, H}\{z\,(R, H)\}$$

where $\mathbf{R}$ and $\mathbf{H}$ are $(N^r \times 3)$ and $(N^d \times 3)$ matrices describing the regeneration regime and describing debarking regime by specifying the x-y coordinate location of all target trees with the period to implement actions during the planning horizon, respectively. The total number of regenerated trees is expressed by N^r, while N^d is for debarked trees during the planning horizon.

These consist of individual regime at each period by appending submatrices.

[5] $$R = [R^1, \cdots, R^T]$$

[6] $$H = [H^1, \cdots, H^T]$$

where R^t and H^t are regeneration and debarking regimes at time t, T is the last period and [ ] is the appending operand for matrices. The first and second columns of the matrices are x-y coordinates, while the third column is the period for the corresponding action. Since debarking takes place for the existing trees, its regime becomes a subset of the location matrix of all trees at the corresponding period.

[7] $$H^t \in N^t$$

After regeneration, the number of the existing trees increased, so that we have the following relationship among the existing and regenerated trees. The number of the existing trees at time t without considering dead trees, $\hat{N}^t$, becomes the summation of that at time (t-1) and regenerated trees, expressed by the appended matrix of N^{t-1} and R^{t-1} with the survival vector, $I^S_{n_t}$.

[8] $$\hat{N}^t = \text{diag}(I^S_{n_t})[N^{t-1}, R^{t-1}]$$

where $I^S_{n_t}$ is $(n_t \times 1)$ vector with elements of 1 to identify survival trees and those of 0 for dead trees among the existing trees during the interval of time from t-1 to t, and diag(A) is a diagonal matrix with diagonal elements by vector A. Any zero row vector of the above matrix for existing trees is removed to create the updated matrix for the next period. For instance, let assume that the i-th row vector of $\hat{N}^t$is zero vector, then we have the updated matrix by removing the i-th row vector from $\hat{N}^t$ as follows.

[9] $$N^t = (\tilde{N}^t_1, \ldots, \tilde{N}^t_{i-1}, \tilde{N}^t_{i+1}, \ldots, \tilde{N}^t_{n_t})'$$

where $\tilde{N}_i^t$ is the i-th row vector of $\hat{N}^t$. For more dead trees, the same removing operation takes place. Note that

[10] $$R^0 = \mathbf{0}, H^0 = \mathbf{0}$$

Trees set to die are determined randomly on the threshold basis using a logistic regression survival model, where the explanatory variables for the i-th response include circumference at breast height, height of debark, competition index of the i-th debarked tree at time t, and site quality index.

The initially existing trees are expressed by its number of n_0, so that we have the following.

[11] $$N^0 = \begin{pmatrix} x_{0,1} & y_{0,1} & 0 \\ \vdots & \vdots & \vdots \\ x_{0,n_0} & y_{0,n_0} & 0 \end{pmatrix}, \qquad (n_0 \times 3)$$

The matrices R^t and H^t are defined by the following.

[12] $$R^t = \begin{pmatrix} x_{t,1}^r & y_{t,1}^r & t \\ \vdots & \vdots & \vdots \\ x_{t,n_t^r}^r & y_{t,n_t^r}^r & t \end{pmatrix}, \qquad (n_t^r \times 3)$$

[13] $$H^t = \begin{pmatrix} x_{t,1}^h & y_{t,1}^h & t \\ \vdots & \vdots & \vdots \\ x_{t,n_t^h}^h & y_{t,n_t^h}^h & t \end{pmatrix}, \qquad (n_t^h \times 3)$$

where n_t^r is the number of regenerated trees at time t and n_t^h is the number of debarked trees at time t, and $n_t = n_{t-1} + n_t^r - n_t^d$ with $n_t^d (= n_{t-1} - 1'_{n_t} \cdot I_{n_t}^S)$ as the number of trees to die from period t-1 to t.

The objective function is expressed by

[14] $$z\,(R, H) = \sum_{t=1}^{T} B_t^{cork}(R^t, H^t)$$

where

[15] $$B_t^{cork}(R^t, H^t) = \sum_{i \in row(H^t)} f(cbh_{t,i}, hd_{t,i},\ c_{t,t})$$

The index function, $row(H^t)$ is the index set of row-vectors of H^t, so that $i \in H^t$ indicates the i-th row vector of H^t, or the i-th debarked tree at time t. Elements of the function $f(\cdot)$, $(cbh_{t,i}, hd_{t,i},\ c_{t,i})$ are circumference at breast height, height of debark and competition index of the i-th debarked tree at time t, $(i \in H^t)$, respectively. The competition index is a function of the location of existing trees, N^t and CBH^t at time t,

[16] $$c_{i,t} = g(N^t, CBH^t)$$

[17] $$CBH^t = (cbh_{t,1}, \ldots, cbh_{t,n_t})$$

where n_t is the number of existing trees at time t including regenerated trees. We applied one constraint by crown cover over the area.

[18] $$c_t^R \leq \ \alpha, \qquad \text{for } t = 1, \ldots, T$$

where α is a given value and

[19] $$c_t^R = h(N^t,\ CBH^t)$$

3. Results and Discussion

It was decided to select two case studies according to stand age and structure. Case study 1 uses plot 101 (young plot) that corresponds to an uneven-aged stand with a young trees cohort, while case study 2 uses plot 317 (mature plot) that corresponds to an even-aged without a young trees cohort. The initial stand status of the case study 1 for the plot 101 is shown in Figure 4.

The initial stand has the total crown cover of 24.50% and its initial cork production is 1,000 kg ha^{-1}.

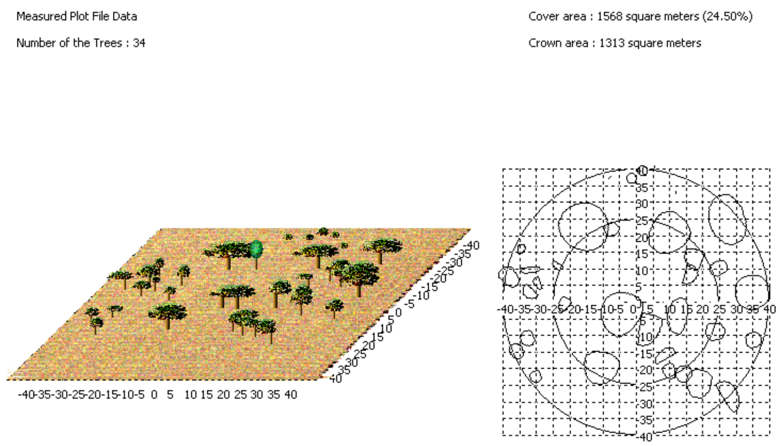

Figure 4. The initial stand status of the case study 1 for the plot 101 with 3D view (left) and crown map (right).

The evolution of crown cover displayed in Figure 5 (left), for a period of 100 years shows a steady increase of crown cover until the year 90, indicating that the selected regeneration intensity did not drive to a continuous constant crown cover. The same behavior can be observed for cork production (see Figure 5 right) due to the allometry. The solution for a constant continuous crown cover must then be based in optimal regeneration regime solutions by MS-PATH with crown cover constrains.

The optimized management by MS-PATH with no crown cover constraint is shown in Figure 6. As it can be seen by the simple maximization of the cork production, the cover grows to the threshold of 100% due to no constrain in crown coverage. In a practical sense, however the forest managers prefer to keep lower crown coverage due to the cattle presence under the trees which can only have enough pasture with light availability on the ground (e.g., crown cover lower than 100%).

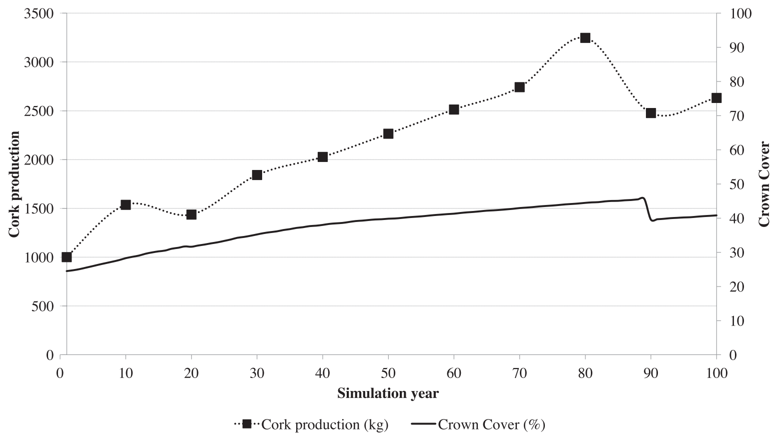

Figure 5. Evolution of crown cover % (left) and cork production in Kg (right) in plot 101 years (right).

So the constraint for crown coverage was redefined. It is arbitrarily determined by the decision maker based on the slope (driver for erosion control) and the grazing needs of animal livestock. Usually in slopes above 15% the lower threshold for crown cover should be 56% (Ribeiro *et al.*, 2003a). Below slope of 15%, all combinations for crown cover in the range between 25% and 100% are possible.

For case study 2 Figure 7 shows the initial stand status for the plot 317. In this case, with older trees and no young tree cohort, Figure 8 shows the evolution of crown cover and cork production. An impact of regeneration on crown development became apparent at the peak in the middle of the cycle. Nevertheless, due to the old age of the majority of the trees, higher reduction in crown coverage was observed when compared with case study 1 for plot 101 (see Figure 8). This shows the importance of initial stand structure in the results for optimizing regeneration moment and intensity on the response variables (cork production and crown cover). Evolution of crown cover in stand

Figure 6. Development of cork production and cover under regime aiming to maximize the cork production (regeneration moment – year 0, regeneration amount 320 trees ha^{-1}).

317 is displayed in Figure 8. In the year of 60 the crown cover started to go down.

An optimal solution of cork oak stands management by regeneration scheduling using MS-PATH with and without crown cover constraints is shown in Table 2 considering only the number of regenerated trees per hectare and the total cork production per hectare to permit a clear view of the forest system responses to management.

Table 2 displays the different regeneration regimes for each plot with the crown cover constraint planned for different target years (e.g., crown cover not exceeded in 10 years from now, 20 years from now). However, all optimal regimes suggested regeneration only in the first year for these plots, while zero regeneration took place for all the remaining years. The maximum regeneration in the first year is usually possible if no cover constraint is set, or decreasing with both: lower cover constraint and later target year for the constraint. The solution for year 10 is always 0 because young trees do not enter into production. It is

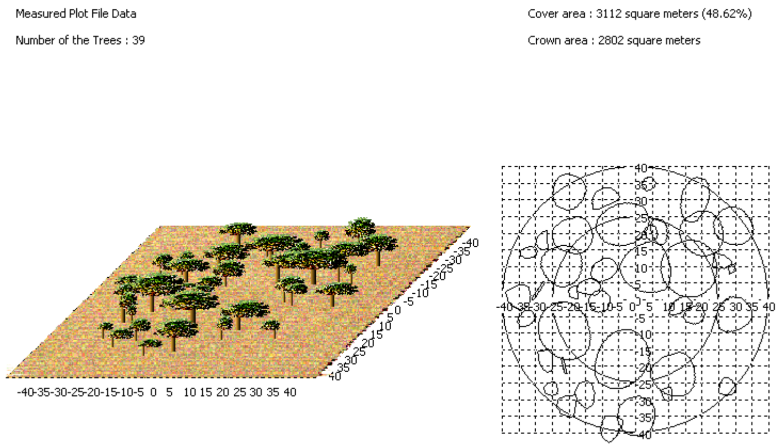

Figure 7. The initial stand status of the case study 1 for the plot 317 with 3D view (left) and crown map (right).

also observed that the crown cover constraint has a significant impact in potential production. In the case of crown cover of 50% in 40 years, approximately half of the potential cork production was lost because of the constraint.

In Figure 9 it can be observed that the maximum cork production will be influenced by initial stand structure (Case study 1: uneven-aged with young trees cohort; Case study 2: even-aged without young trees cohort). The higher the cover constraint, the lower the final production will be in the initial 40 years after regeneration management. This can be a measure for the costs of regeneration management on short period analysis. It must be referred that in the cork woodland production system, crown cover constrains are set by the landowners in order to create the necessary growing space for the grazing/livestock component. Therefore the referred losses need to be partially compensated by the revenues coming from annual animal production.

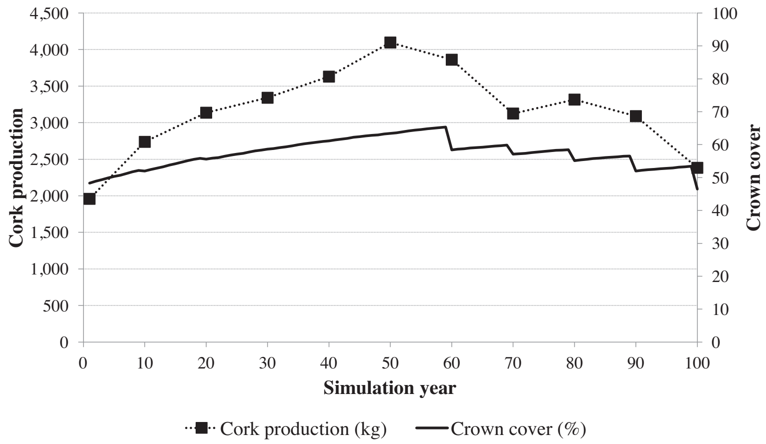

Figure 8. Evolution of crown cover (left) and cork production (right).

4. Concluding Remarks

We found that constrains in crown cover in the simulation, influences negatively the total cork production. If the target cover constraint is set to 50%, it will decrease cork production by 66% in 40 years in plot 317 (mature plot), and by 43% in plot 101 (young plot). Higher crown cover constraint (70%) decrease the potential cork production by 54% in plot 317 and have no influence in plot 101. This observation emphasizes the importance of initial stand structure in the optimization results with strict crown cover constrains and suggests that not all the crown cover constrains are suitable for each case.

On the other hand the regeneration required for maximizing the crown cover is lower when crown constraint is set. In plot 317 the regeneration required to achieve maximum cork production with no constraint was 320 trees per hectare while with constraint of 50% no regeneration is required. In plot 101 the regeneration required for maximum cork production with no crown cover constraint is 320 trees per

Table 2. Optimized management for maximum cork production with different crown cover constraints MS-PATH.

	Year	No constraint tree ha^{-1}(kg ha^{-1})	Constraint 70% tree ha^{-1}(kg ha^{-1})	Constraint 50% tree ha^{-1}(kg ha^{-1})
Case Study 1 (101)	10	0 (1000.47)	0 (1000.47)	0 (1000.47)
	20	320 (1550.42)	320 (1550.45)	200 (1548.42)
	30	320 (1449.51)	320 (1449.58)	180 (1447.55)
	40	320 (8421.99)	320 (8421.99)	140 (4722.22)
Case Study 2 (317)	10	0 (1958.35)	0 (1958.35)	0 (1958.35)
	20	320 (2764.25)	160 (2758.88)	0 (2757.85)
	30	320 (3167.17)	100 (3161.62)	0 (3161.43)
	40	320 (9959.97)	60 (4611.55)	0 (3379.54)

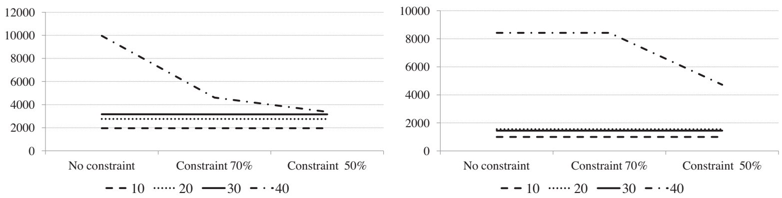

Figure 9. Impact of different constraints on production in 40 years (left plot 101, right plot 317).

hectare, however with the crown cover constraint of 50% only 140 trees per hectare becomes necessary.

It was concluded that for the specific problem of optimization of regeneration regimes for continuous crown cover management in cork oak woodlands, the MS-PATH optimization framework is more suitable due to its handling capacity for multi-period effects than other algorithms such as PATH. This is because in the cork production, multi-period effects should always be considered in the solution search process since the evaluation period's size can have significant influence on the best selected scenario (as shown in Table 2)

With the presented results, it can be suggested to stakeholders that the crown cover constraint has certain cost incurred by loss of potential cork production. The lower the cover constraint, the higher the losses would be compensated. The observed losses in cork production in relation with its potential after crown cover constrains should be economically compensated with higher availability of growing space for livestock grazing in the *montado/dehesa* production system. Inclusion of the grazing/livestock components in the optimization framework could be the next step toward efficient regeneration management in order to allow the longest possible period of animal presence without damage to the young trees cohort.

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