Czech University of Life Sciences Prague

Faculty of Forestry, Wildlife and Wood Sciences

Department of Forest Management

Management Framework for Selected Stands of Cork Oak Woodlands in South Portugal

Diploma thesis

Author: Bc. Martin Janík

Diploma Thesis Supervisor: Priv. – Doz. Ing. Peter Surový, Ph.D.

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Bc. Martin Janík

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Management framework for selected stands of cork oak woodlans in south Portugal

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Objectives of thesis

The objective of the thesis is to analyze the current situation in study region; estimate future evolution scenarios of the stands and propose management actions to achieve sustainable productivity including the ecological aspects as crown cover.

Methodology

- Acquire data from inventory plots with necessary parameters to obtain prediction scenarios

- Literature research of available growth predictors (including yield tables, simulators) describe positives/negatives and select one

- Preparation of simulation scenarios showing the natural evolution (without management) of the selected stands.

- Preparation of different management scenarios and simulating the evolution of the selected stands.

- Description of the best selected scenarios including positives and possible threats to the objectives of management

The proposed extent of the thesis

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Keywords

management, cork oak

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The Diploma Thesis Supervisor

Ing. Peter Surový, PhD.

Supervising department

Department of Forest Management

Advisor of thesis

Nuno Almeida Ribeiro

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Ing. Peter Surový, PhD.

Head of department

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prof. Ing. Marek Turčáni, PhD.

Dean

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Affirmation

Hereby I declare that I have written the Diploma thesis “Management Framework for Selected Stands of Cork Oak Woodlands in South Portugal” on my own, under supervision of Priv. – Doz. Ing. Peter Surový, Ph.D. and I have used only the sources which are marked in the list of references.

I am aware that by releasing of this bachelor thesis I agree with its publication according to the law number 111/1998 Sb. about universities as amended regardless of the result of its defense.

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……………………………

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Abstract

Cork is a renewable natural resource which is periodically harvested from the cork oaks (*Quercus suber L.*). Portugal produces half of the world's cork and most of the cork oak woodlands (*montado*) are situated in Portuguese region Alentejo. *Montado* is characterized by low tree density and it combines cork production with agriculture or pastoral activities. Cork oaks have been facing several mortality events in the last century and recent cork oak decline is believed to be associated with wrong management of cork oak woodlands and subsequent pest attacks. Adaptive management concepts associated with growth models and decision-support systems are needed to keep the *montado* system sustainable and prevent it from further decline. The present work uses growth simulator CORKFITS to analyze situation in the selected stands in Alentejo, Portugal, and to propose management actions to achieve productional and ecological sustainability.

Keywords: management, cork oak

Abstrakt

Korek je přírodní obnovitelný zdroj, který je opakovaně sklízen z dubu korkového (*Quercus suber L.*). Portugalsko v současné době produkuje polovinu světové produkce korku a většina jeho korkových lesů (*montado*) se nachází v portugalském regionu Alentejo. *Montado* se vyznačuje nízkou hustotou zalesnění a kombinací produkce korku se zemědělstvím a pastevectvím. Dub korkový čelí od začátku minulého století vysoké úmrtnosti, současný pokles stavů dubu korkového je často spojován se špatným hospodařením v korkových lesích a následným útokem škůdců. Adaptivní management ve spojení s užitím růstových modelů je potřeba k dosažení udržitelnosti tohoto systému a k zabránění vymírání dubu korkového. Tato práce využívá růstového simulátoru CORKFITS k analýze situace ve vybraných stanovištích v portugalském regionu Alentejo a navrhuje hospodářské opatření k dosažení jejich produkční a ekologické udržitelnosti.

Klíčová slova: management, dub korkový

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3 Introduction

Cork is natural, renewable, reusable and recyclable material which is periodically harvested from cork oaks (*Quercus suber L.)*. Roughly 50% of world's cork is produced in Portugal. Cork oaks in Portugal are often grown in open woodlands called *montado*. *Montado* is an agro-silvo-pastoral system which is in Portugal most abundant in Alentejo – 84% of Portuguese *montado* is situated in this region. This anthropogenic system is typical for its low tree density which allows its multifunctionality as the under-canopy is used for grazing of cattle and grain production. *Montado* is a complex agroforestry system which combines large number of activities such as cork production, agriculture, grazing, pasture, animal stock etc., that share the growing space in the landscape which is characterized by its site variability.

Cork oaks have been facing several mortality events since the beginning of the 20^{th} century. Recent cork oak decline is believed to be associated with wrong management of cork oak woodlands, recent extreme climatic conditions and subsequent pest attacks.

Adaptive management concepts associated with growth models and decision-support systems, based on good monitoring, are needed to maintain the cork oak woodlands sustainable and to prevent it from further decline. In the present work, growth simulator CORKFITS is used to analyze selected set of stands in Alentejo, Portugal, to examine their current situation, create different scenarios and select one.

4 Goals of the Work

The aim of this thesis is to analyze current situation in the study region (Alentejo, Portugal), to gather information and estimate future evolution scenarios of the selected stands and propose management actions to achieve sustainable productivity including ecological aspects as crown cover.

5 Literature Review

5.1 Cork

Cork is renewable natural resource produced from the bark of a tree – Cork oak (*Quercus suber L.*). It is a valuable and versatile material which can be used for many different products, however wine bottle stoppers are economically the most important (Catry et al. 2012).

Cork – the bark of a cork oak is periodically harvested from the tree, starting when the tree is about 25 years old and has at least 70 cm circumference measured 1.3 meters above ground (refers to roughly 22cm DBH) (APCOR, 2018). Portuguese law prohibits to debark a tree with smaller circumference. From then on, the cork can be harvested from the tree for average of 150 years while the minimal interval between the harvests must not be shorter than 9 years, as ordered by Portuguese law (Ribeiro et al. 2010). This interval differs in different culture regions (Duarte and Bordado, 2015).

Figure 1 – Cork harvesting

The first harvest, so-called “desbóia” or “virgin cork”, has very irregular structure, it is considered the lowest quality cork and therefore it is used for application other than cork stoppers, for instance flooring or insulation. After nine years the second harvest is produced, it is called “secundeira” or secondary cork. It has regular structure but it is still unsuitable for cork stoppers. The third and subsequent harvests called “amadia” or “reproduction cork” produce cork with good properties suitable for production of quality cork stoppers (APCOR, 2018), however, the first “amadia” cork is still porous and irregular and the quality of the cork in each tree improves over the time (Duarte and Bordado, 2015). The best quality cork is used for bottle stoppers production (Pinheiro et al. 2008). There are many aspects influencing the quality of the harvest (mainly porosity and structure) such us annual climatic conditions, pests or the performance of the workers who debark the tree. The harvesting of cork is done in traditional way by trained experts (*descortiçadores*) who use special axe to peel of the bark off the tree. The procedure of debarking has changed only a little over last thousands of years. Harvesting of cork is performed between middle of May until the middle of August because it is the time when the tree is the most active in terms of cork growth and has the highest water content in the trunk, thus it is possible to remove the cork layer from the trunk without damaging the cambium layer, so the tree can continue growing and regrow a new layer of cork. The trunk of a freshly debarked cork oak has typically bright orange color, which continuously fades until it becomes black.

You can often read that harvesting of cork does not harm the tree, however debarking is the main stress factor of the cork oak, affecting water balance and tree productivity (Correira et al. 1992), it reduces the tree vigour and resistance against external agents such as fire (Catry et al. 2012, Oliveira et al. 2012).

Figure 2 – Cork oak cross section with virgin cork

Annually 201,000 tons of cork are produced world-wide of which 100,000 tones are produced in Portugal. Portugal produces 49.6% of world cork production (APCOR, 2018). 72% of the Portuguese harvested cork is produced into wine stoppers followed by construction sector with 28% - including floors, insulation, blocks, plates, sheets, strips and decorations. Within cork stopper segment, natural cork stoppers represent 60% followed by technical stoppers with 20% and champagne stoppers with 20%. Natural cork stoppers are punched from one piece of cork, technical stoppers are made of agglomerated cork granules, to the ends of which a natural cork disc is often applied so the wine is not in direct contact with the glue used to stick the cork particles together. The top quality cork is used for natural cork stoppers and all the leftovers together with the virgin and secondary cork are used for the manufacture of the products for constructions and other application like sports equipment, clothing, decorations and many others (APCOR, 2018).

Cork chemical composition depends on many factors such as geographic origin, climate and soil conditions, genetic origin, age (virgin or reproduction cork) and growth conditions (Silva et al. 2013). In general, cork is composed of suberin (ca. 40%), lignin (ca. 22%), polysaccharides (cellulose and hemicellulose, ca. 18%), extractables (ca. 15%) and others (Silva et al. 2013).

Cork has unique physical properties. Presence of suberin results in high elasticity and low permeability. Its low density (high gas content) and low thermal conductivity makes it a good insulating material. Low sound transmission and acoustic resistivity allows its usage as sound insulator. Its friction property and high damping capacity are important for the use as handles of tools and sports equipment. Cork can be also used as electric insulator. All these properties together make cork optimum (in many cases the only) material for variety of applications (Silva et al. 2013). The physical properties of this material have not yet been artificially imitated by human (APCOR, 2018), moreover cork is natural, renewable and recyclable material (Duarte and Bordado, 2015). All the by-products of wine stopper production are used in other applications – mainly for general purpose agglomerates and agglomerates for wall and floor coverings (Silva et al. 2013).

Society's growing interest in natural, renewable and sustainable materials opens new market opportunities for the cork. New cork products such as jewelry, fashion accessories, clothing or souvenirs have emerged in recent years. These products might help to spread the awareness of cork and induce new researches to study this versatile material and find new applications for it.

Cork is one of the most important marketable non-timber forest product in the western Mediterranean (Catry et al. 2012).

There has been a wild debate going on among the wine makers on the topic whether to use natural cork stoppers or synthetic alternatives to seal the wine. Some wine producers claim that the cork can spoil the wine because it contains some undesirable chemicals, however other wine makers say, that synthetic wine stoppers can impart a slight chemical flavor to the wine. Screw caps form a very tight seal and do not let any oxygen in the bottle even after a long time, so it might be the best option for aging wines, although other wine makers say that the aging wine needs to “breath” through the cork and it gets spoiled when sealed completely. Plus, alluminium is not very environmentally friendly material – it is almost impossible to recycle it and a lot of harmful substances are produced during its manufacture. The biggest disadvantage of real cork wine stoppers is its price as it is way more expansive than its synthetic alternatives. In my opinion, the problem is the fact that most of the people do not know where cork comes from or they think that trees have to be cut down to harvest the cork so by buying wine with alternative stoppers they save the environment. But the opposite is true because alternative wine stoppers are mostly not biodegradable or recyclable and harmful substances are produced during their manufacture. The prevailing opinion is that fine wine should be sealed with real cork and the good wine producers still prefer to use real cork stoppers to seal their wine although it is more expensive than its alternative substitutes. Therefore, demand for cork, whose main application is for wine stoppers, is correlated with demand for good wine. In Europe wine consumption is declining while demand for good wine is increasing (Pinheiro et al. 2008).

5.2 Cork Oak


Figure 3 – Cork oak after debarking

Cork oak is a slow growing, evergreen tree with sclerophyllous leaves which can grow up to 20 m and commonly lives for more than 200 years. It is native to Mediterranean Basin and thrives only in specific regions of Western Mediterranean (Portugal, Spain, Southern France, Italy, North Africa) because it needs relatively high amount of sunlight and unusual combination of low rainfall and high relative humidity (Duarte and Bordado, 2015, Pausas, 1997, Silva et al. 2013). Cork presence has been evolutionary linked to fire, its purpose is to protect the cambium layer from the heat generated by fire and it can grow to the thickness of up to 30 cm (Pausas, 1997). In the Mediterranean, the wildfires are a natural phenomenon and many Mediterranean species have evolved strategies thanks to which they are able to survive periodic fires. But while most of the other fire-resistant species have evolved a strategy to resprout after a fire from subterranean structures, the bark (cork) of *Q. suber* with its excellent insulation properties protects the whole trunk and all the branches of the tree so after the fire it resprouts through epicormic buds which are present under the bark (Catry et al. 2012). Cork oak is highly fire-resistant species and it is the only European tree species with above-ground resprouting capability (Pausas, 1997).

Thick bark is a fire adaptation which can be also found in other plants around the world living in ecosystem with occurrence of natural wildfires (Catry et al. 2012). Mortality of cork oak due to fire is very low due to insulating capacity of its bark (Pausas, 1997), but it depends very much on the bark thickness (Catry et al. 2012).

Periodical bark extraction of *Q. suber* sp.: (1) is main stress factor affecting water balance and tree productivity (Correira et. Al 1992), (2) reduces tree vigour and protection against external agents (Catry et al. 2012, Oliveira et al. 2012), (3) reduces resistance of

Q. suber to fire (Catry et al. 2012) and (4) produces natural, renewable and recyclable material with unique physical properties (Silva et al. 2013, Duarte and Bordado, 2015, APCOR, 2018).

Cork oak is in Portugal protected by law which prohibits to cut it down. Only dead trees can be cut down and it is only possible after consent of the authorities (Ribeiro et al. 2010).

Cork oak creates forests or open woodlands where it is the main tree species, or it grows together with other Mediterranean trees, e.g. *Q. ilex, Q. rotundifolia, Pinus pinea* and *P. pinaster*. The natural distribution of *Q. suber* is in the west and northeast of the Iberian Peninsula, north Africa, a small area in south France, Italian coast and some Mediterranean islands, e.g. Corsica, Sardinia and Sicily (Figure 4). All these areas have dense populations and high pressure from tourism. Cork oak stands are mainly managed for cork produced from the bark, 52% of the World's cork oak forests are in Iberian Peninsula (Pausas, 1997). The cork oak forests where periodical tree bark harvesting is a major economic activity may be particularly vulnerable to disturbances such as fire, since debarking reduces tree vigour and protection against external agents (Catry et al. 2012).

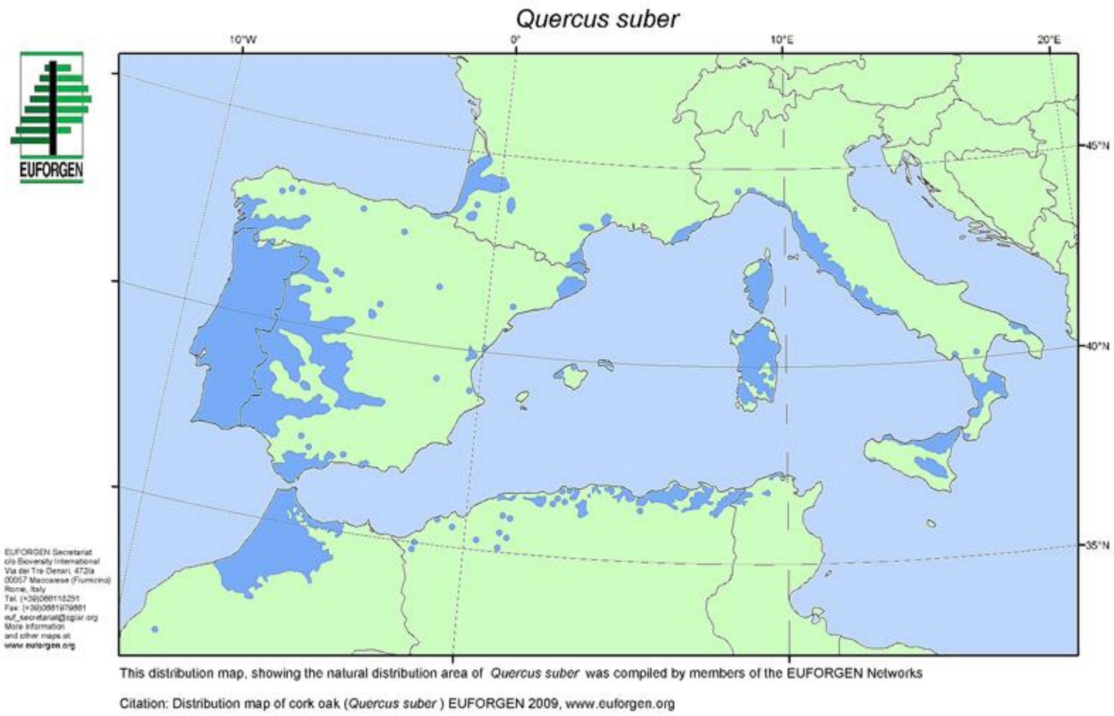

Figure 4 – The distribution map showing natural distribution area of Quercus suber L. Source: EUFROGEN 2009

The occurrence of wildfires in Mediterranean basin has recently increased due to human impact and global climate change and it may continue to increase in the future (Pausas, 1997).

Cork oaks are often grown in open woodlands which are managed like agro-silvo-pastoral systems which combine cork production with agriculture and pasture for grazing animals (Ribeiro et al. 2012). This system is called *Montado* in Portugal and *Dehesa* in Spain.

5.3 Montado

Figure 5 – *Montado* with grain fields in under-canopy

Montado is a complex agroforestry system which combines large number of activities such as cork production, agriculture, grazing, pasture, animal stock etc., that share the growing space in the landscape which is characterized by its site variability, especially at soil/climate/topography levels. *Montado* is mostly dominated by Mediterranean evergreen oaks such us cork oak (*Quercus suber L.*) and holm oak (*Quercus ilex*) which are kept in low stocking of about 40 trees per hectare (Pulido et al. 2001). This system is mainly known for production of cork but also for its savanna-like appearance, diversity of ecosystem services and biodiversity (Pinto-Correira et al. 2011).

Cork oak forests are very important to the economy and ecology of several Mediterranean countries. Worldwide it covers area of 2,139,942 hectares and in Portugal 736,775 hectares, which represents 34% of world cork oak forest and 23% of total area of Portuguese forest. Another important countries in terms of cork oak forest are Spain with 27%, Morroco with 18%, and Algeria with 11% of world cork oak forest. Most of the Portuguese cork oak forest is situated in the south of Portugal, 84% of it is situated in the province Alentejo (APCOR, 2018).

Montado is also acknowledged for its biodiversity, specificity, aesthetic and identity values, attractiveness for recreation and environmental balance. Typical characteristic of the *montado* system is its savanna-like appearance with changing densities of evergreen oak trees. The cork oak ecosystems are, among the others, recognized for their remarkable ecological value providing habitat to many endangered species (Catry et al. 2012), in terms of biodiversity, *montado* landscape reaches levels of up to 60-100 flowering plant species per 0.1 ha. *Montado* also offers a rich biological diversity that evolved from ingenious and dynamic adaptation of humans to their environment. It is good habitat for wild ungulates as red deer (*Cervus elaphus hispanicus*) and wild boar (*Sus scrofa*). In addition, small and medium mammals are abundant as a consequence of low human disturbance including endangered cabrera's vole (*Microtus cabrerae*). The wild rabbit (*Oryctolagus cunniculus*) abundant in the *montado* is the basic prey of many predators such us endangered Iberian imperial eagle (*Aquila adalberti*) Iberian lynx (*Lynx pardinus*) or black vulture (*Aegypius monachus*) (Pinto-Correira et al. 2011). A lot of the plant and fungi species in the *montado* landscape are valued as non-timber forest products for human use, many of them with aromatic, culinary or medical properties.

Montado represents one of the best examples of multi-functional forest system which has been maintained for thousands of years. In these landscapes high conservation forests alternate with multipurpose farmland systems. The main source of income of *montado* is cork which can be of varying degrees of quality that determines its selling price and final utilization (Pinheiro et al. 2008). In Portugal, *montado* system is mainly owned by private owners. Most of the private landowners see forest primarily as a way of earning money. They are aware of the forest by-products which benefit the society, but they mostly receive nothing for them (Pinheiro et al. 2008).

Figure 6 – A bull in misty morning *Montado*

The *montado* system results from integration of conflicting activities in the same space so it is necessary to constantly search for balance among its components in order to achieve sustainability. Sustainable management of the combination sets of production activities requires a good knowledge of the resilience and elasticity of the forest components, in each particular situation (Pinto-Correira et al. 2011).

5.4 Management of Cork Oak Woodlands in Portugal (*montado*)

There is a significant difference between management of conventional forestry systems and multi-functional system *montado*. Ordinary middle Europe forest management plan has some mandatory components such as total allowable cut, plan of thinning, harvesting plans and rotation period. None of these activities can be applied for *montado* management plans because there is no final harvest nor thinning, as the trees are protected by law and they can only be cut down when they are dead and even than only with a permit from authorities. There is no rotation period neither, as the crown cover in *montado* is continuous. The only management practice conducted in *montado* is regeneration of the stand and shrub control (to decrease wildfires hazard). From economical point of view, conventional forestry systems have long-term investments and the main profit is generated with the final harvest of the stand in roughly 100 years intervals, with some minor incomes from thinning few times during the forest's lifetime. *Montado* system generates the first significant earnings 25 years after establishing of the stand when the first "virgin cork" is harvested. Then the cork is harvested every 9 years where every next harvest produces more and higher quality cork so the income is bigger every period. Moreover, there are some other profits from agriculture activities conducted in the under-canopy of the cork oak trees (cattle, grain production).

Figure 7 – *Montado* after debarking with ploughed soil

Portugal and Spain failed to negotiate EU's forestry measures in the Common Agriculture Policy (CAP) in 1992 and 1999 reform, which would help to mitigate the low regeneration rate. Unfortunately, *montado* and *dehesa* were never officially considered as a whole, and only partial measures were financed from EU's budget which resulted in increasing of the conflicts in the production and unbalanced livestock numbers which is incompatible with regeneration of cork and holm oak whether artificial or natural (Pinheiro et al. 2008).

Management of the *montado* system aims to the balanced sustainable land use to cope with the Mediterranean climate variability. The economically most important outcome of *montado* is and for centuries has been cork production (Portugal currently produces half of the world cork) but its sustainability depends on maintenance of all its components. The forest component is managed to sustainably produce cork, acorns, fire-wood and to provide environment which supports production of natural pasture, habitat for game, honey, mushrooms and many more. The agriculture component is based on livestock (cows, sheep, goats and Iberian pig) feeding on acorns and grass and cereal culture production. Associated activities in *montado* are bee-keeping and mushroom picking (Pinheiro et al. 2008, Ribeiro et al. 2010). The sustainability of these forest structures is closely related to its continuous crown cover management and soil protection, so the success of both natural and artificial regeneration is the key factor of keeping the system's multi-functionality. Keeping the continuous crown cover between 30% and 70% (dependent on slope) is important in order to keep the specific ecological conditions necessary for all the functions of the system. The optimal management regime must take in account the conflicting activities – regeneration is not compatible with agriculture and grazing (Ribeiro et al. 2012).

The management objectives which aim to sustain all the function of the system may be negatively influenced by intensification of the undercover activities which can lead to lack of regeneration and consequent disappearance of the crown cover and soil erosion. On the other hand, neglecting the maintenance of undercover can lead to shrub invasion and subsequent increase of the risk of forest fire, so it is necessary to constantly search for the equilibrium between all the functions of the *montado* system. In fact, Portuguese *montado* is currently facing a gradual dye-back of the trees because the tree recruitment is insufficient to compensate high tree mortality (Pulido et al. 2004).

The goal of regeneration planning is to continuously keep the stocking of 30-40 trees per hectare in order to keep all the functions of the system. One of the challenges of regeneration planning is its cost (purchase of seedlings, planting, labor). To successfully regenerate the cork oak, the manager must refrain from the other under-canopy activities in order of seedlings survival. If the regenerated area is fenced, cork oak can start to regenerate naturally but the owner loses incomes from cattle and grains production for at least 20 years. Also, if the undercover is not managed, the shrub layer expands, which increases the hazard of wildfires and it brings up the necessity of the second management activity – shrub control. Shrub control is very important in order to prevent forest fires during the regeneration period. Forest fires are common in Mediterranean and recently their occurrence increased due to human impact and possibly it might continue rising due to global climate change (Pausas, 1997). The two most common ways of shrub-control are by mechanical destruction with soil disking (which includes soil mobilization) or by shrub cutting (with minimum impact on soil). These two techniques have different costs and impacts on cork production and other services of *montado* (multifunctionality). The two techniques were compared by Pinheiro et al. (2008) and the results showed that while soil disking is more profitable, shrub cutting has better results if carbon sequestration is considered. This means that besides economic sustainability, which is dependent on cork production, one should also consider other functions of the natural environment, which are on the other hand hard to evaluate financially.

5.5 Current Dieback Events of Cork Oaks and Threats of the *Montado* System

The cork oak woodlands in Mediterranean basin have been facing a significant decline since the beginning of the twentieth century, the severity of this dieback has increased during the last three decades. The pathogen *Phytophthora cinnamomi* was often recovered from the declining stands and it has been considered the main factor associated with decline. (Brasier, 1992, 1996; Cobos et al. 1992, Camilo-Alves et al. 2013). *Phytophthora cinnamomi* is an oomycete which transmits in soils and parasitizes on living roots. It causes rot of fine roots and the secondary symptoms of the infestation resemble those of drought: the foliage starts to dry off and epicormic buds turn brown until the tree dies (Camilo-Alves et al. 2013). In 1951, about 246,000 dead or injured cork oaks were cut down in Portugal (Natividade, 1958) and between 1990 and 1992, there was a stable increase in the cork and holm oak defoliation and authorization of the land owners for cutting down dead or injured cork trees increased by about 70% (Sousa et al. 2007). One possible reason for this decline might be the increase of annual temperature and decrease of average annual precipitation (possibly associated with global warming) which could lead to physiological decline of the trees and increase of tree vulnerability to insects and pathogens (Kim et al. 2017). Camilo-Alves et al. (2013) suggests, that tree mortality is a result of interaction of pathogen attack with abiotic factors such as drought events or unintentional root pruning by ploughing. Therefore, the initial reason of the last dieback events could be the intensification and mechanization of the agriculture in the half of 20th century, deep-ploughing of farmland in the *montado* under-canopy which damaged the root system, in

Figure 8 – A dying cork oak tree

combination with droughts and consequent attack of the pathogen *Phytophthora cinnamomic.*

Also, the owners of the cork oak stands prune the trees so they have one main trunk about 3 meters long and 2-4 main branches. This tree structure has advantages when debarking the tree, but the pruning should only be carried out on young trees which can withstand the associated stress. Unfortunately, the trees are often pruned in advanced age, maybe in good faith, as this procedure is based on the tradition. Also, tree pruning provides some firewood, which could be another aspect driving the owner to do it. In any case, if the pruning is not done correctly, it cannot change the tree structure and only acts like additional stress, as if there were not enough stress factors as it is.

Figure 9 – An example of wrong tree pruning

Overall, the situation does not seem very well for the cork oak woodlands. Beginning with alternative wine stoppers negatively influencing cork prices through soil erosion and all the disturbances weakening the trees, leading to the massive dye-back of cork oak or the hazard of forest fires, all these factors affect the *montado* production system sustainability, multi-functionality, and its economical feasibility for its owners. In these hard times, adaptive management concepts associated with growth models and decision support systems based on good monitoring are needed to maintain the cork oak woodlands sustainable and to prevent it from further decline. It is necessary to use management practices focused on long term objectives. Present study suggests management practices for selected set of stands located in Portuguese region Alentejo, with focus on both ecological and economical sustainability of the cork oak woodlands.

5.6 Forest Modeling

A model is simplified display of a system, which makes it easier to understand and explore it. It is a representation of certain object conceived from certain point of view. Model is built based on collected known information and it should verify correctness of known facts. Real forest ecosystem represents original, which we are trying to imitate in the form of abstraction (model). Before we try to imitate it, we need to collect the information about structure and behavior of the original. In forest modeling, we mostly talk about so called dendrometric characteristics of trees or of stands. Basic tree dendrometric characteristics are: diameter, height, basal area, volume, age, increment, crown height, crown diameter, biomass. Basic dendrometric characteristics of a stand are: area, number of trees, basal area, volume, increment, mean diameter, mean height, mean basal area, mean tree volume, mean tree increment, total volume production etc. This information can be collected either from long-term experimental plots or compilation of information from previous researches. A model can also be created based on verified regularities in form of mathematical rules, physical or chemical formulas, or knowledge from generally known theories. A model is created by putting all the information together and giving it a system with required behavior. Model is almost always relatively closed system because high complexity can distract the viewer from the functions which are in his interest. Model behavior can be then used to verify known facts based on match of the model and original behavior. Good models allow us to use them to create predictions from different data sets (Fabrika and Pretzsch, 2011).

Forest is system with multi-criteria output variables because it performs a variety of functions within multipurpose sustainable forest management. Therefore, when modeling a forest, we should not only quantify its dendrometric values, but also the values of biomass and binding of chemical elements, economical and ecological parameters, eventually also biodiversity characteristics and value of non-market forest functions (Šebík and Polák, 1990).

Growth values are characteristics of a tree or stand, whose values grow with their age. Growth function is used for their modeling and prediction of future evolution. There are several important growth functions based on which the models are created. The most famous creators of growth functions are: Korf, Chapman-Richards, Hossfel (Fabrika and Pretzsch, 2011).

The models used for simulation of growth and production can be divided into several levels: from cell, through organs, tree individuals, up to the stand or landscape (Fabrika and Pretzsch, 2011). Every level of modeling attempts to take into account many different input parameters and produce a lot of different outputs, so using any model without computer support is nearly impossible (Surový et al. 2011). Modern software tools have been introduced into forestry management relatively recently, firstly in 90ties in the United States, in last decades also in Europe (Hasenauer, 2006). Let's mention at least some of the forest models: SILVA (Pretzsch et al. 2002) in Germany, Prognaus (Sterba and Moser, 1995) in Austria, BWINPro (Nagel and Schmidt, 2006) in Germany and SIBILA (Fabrika, 2005) in Slovakia. Many others can be found online.

The future of the forest models lays in its accessibility, so ordinary forest manager can use it in forest practice, in ideal case online through a web browser. In order to achieve it, it is necessary to (1) simplify its interface and allow to create simulations based on inventory data or on plot description with reduced level of detail (number of trees per hectare, diameter structure etc.), (2) make the software flexible, so it can be used on any platform, (which can be fulfilled by web application) and (3) to unify the software output format, so it can be used in forest practice (Surový et al. 2010).

5.7 Cork Oak Woodlands Modeling Review

Sustainable forest management has nowadays become very actual topic both in sense of forest production and environmental policy, since the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in June 1992. The basic principle of sustainable forest management lays in maintaining both environmental and socio-economical function of the forests in present as well as for the future generations. Three main aspects must be taken in account in sustainable forest management: natural, social and economical sustainability. Forest is a resource with multiple functions and forest managers are challenged to balance many, often conflicting, outcomes and at the same time to meet economical requirements (Sánchez-Gonzáles et al. 2005). This goal is especially difficult to achieve in Cork oak woodlands where the conflicting outcomes are essential part of the management system. Cork oak stands currently need an immediate solution for their main silvicultural problems: ageing of cork oak woodlands, low regeneration, intense pruning and increasing cork oak decline.

To achieve this goal, adaptive management techniques are required – growth models and decision support systems constructed in knowledge-based monitoring systems. Economic objectives of management may change according to new market balances, social demands and related public policies (Pinto-Correira et al. 2011).

Montado is characterized by low stand density and high variability in the size and age classes of tree individuals. Such heterogeneity makes it particularly difficult to inventory these stands, yet forest managers need accurate estimations of potential cork harvest to optimize the harvest operations (Surový et al. 2015). The vast majority of cork oak woodlands in Portugal is owned by private owners. In many cases, the cork is sold to the processing facilities before it is extracted from the trees, so the private owner has enough resources to finance the harvesting operations which are quite expensive, because (1) usually the private owners in Portugal own large areas of woodlands and (2) the workers performing the debarking are highly valuated – debarkers are the highest payed forest workers in the World. To train a good debarker usually takes about 10 years of training before he is experienced enough to debark a tree on his own. The debarkers usually work in crews of three pairs with three more people loading the cork on a trailer.

Before the cork is sold, an evaluator from the cork processing facility samples the cork in the stands to be sold, calculates some estimation of cork harvest amount and quality, and offers the owner a price for which the cork is sold. Then the owner manages the cork harvest. In the case that the owner has enough resources to finance the cork harvest, he can do the harvesting on his own expanses and he can than keep the cork stored and speculate when to sell it. Essentially, the prices of cork differ throughout the year, because it is harvested only between May and August. It is usually more expensive in the spring before the cork harvest, because the facilities are running out of their cork storage and they need raw cork material to maintain the facility running. On the other hand, if the owner finances the harvest and keeps the cork for speculation, he has to face the associated risks such us unpredictable market prices, risk of theft of the cork or degradation of quality of the stored cork.

The figure 10 shows a cork tree which has been recently sampled for the harvest evaluation. You can see the number written on the bark of the tree. All the trees of Portuguese *montado* have a such numbers on them, it represents the year in which the cork was harvested last time, in this case number 8 means that it was harvested in 2008 and because the cork is harvested every 9 years, next harvest should be done in 2017 and that is why this tree was sampled in spring 2017.

Figure 10 – A sampled tree

In any case, estimating of the cork production is an important part of the *montado* management and it essential part of decision making and planning of the harvest. In the following pages, I will describe some of the ways of cork oak production prediction systems.

5.7.1 Yield Tables for Cork Production Estimation (Montero et al. 1996)

Yield tables for estimation of standing cork weight were created by Montero et al. (1996). The yield tables are based on the measurements of the 75 sample plots located in different zones of cork production in Spain. Based on the correlation of each variable with the production of cork, following values were chosen for model creation: AB (basal area in square meters), IDM (debarking intensity), PCM2 (weight of extracted cork in kilograms per square meter of uncorked basal area).

IDM = 30

AB	PCM2								
	6	7	8	9	10	11	12	13	14
4	720	840	960	1080	1200	1320	1440	1560	1680
5	900	1050	1200	1350	1500	1650	1800	1950	2100
6	1080	1260	1440	1620	1800	1980	2160	2340	2520
7	1260	1470	1680	1890	2100	2310	2520	2730	2940
8	1440	1680	1920	2160	2400	2640	2880	3120	3360
9	1620	1890	2160	2430	2700	2970	3240	3510	3780
10	1800	2100	2400	2700	3000	3300	3600	3900	4200
11	1980	2310	2640	2970	3300	3630	3960	4290	4620
12	2160	2520	2880	3240	3600	3960	4320	4680	5040
13	2340	2730	3120	3510	3900	4290	4680	5070	5460
14	2520	2940	3360	3780	4200	4620	5040	5460	5880

IDM = 31

AB	PCM2								
	6	7	8	9	10	11	12	13	14
4	744	868	992	1116	1240	1364	1488	1612	1736
5	930	1085	1240	1395	1550	1705	1860	2015	2170
6	1116	1302	1488	1674	1860	2046	2232	2418	2604
7	1302	1519	1736	1953	2170	2387	2604	2821	3038
8	1488	1736	1984	2232	2480	2728	2976	3224	3472
9	1674	1953	2232	2511	2790	3069	3348	3627	3906
10	1860	2170	2480	2790	3100	3410	3720	4030	4340
11	2046	2387	2728	3069	3410	3751	4092	4433	4774
12	2232	2604	2976	3348	3720	4092	4464	4836	5208
13	2418	2821	3224	3627	4030	4433	4836	5239	5642
14	2604	3038	3472	3906	4340	4774	5208	5642	6076

Figure 11 – Cork yield tables – cork production in kg/ha (Montero et al. 1996)

Simplicity of this model makes it a valid instrument to estimate cork production which can be applied in cork oak woodlands management.

5.7.2 Fonseca-Parresol Cork Production Equation (2001)

Despite the cork industry is economically quite important in some regions of Mediterranean basin, only few models have been developed for estimation of tree cork weight yield (Fonseca and Parresol, 2001). There have been several equations developed mainly for Southern Portugal throughout last century, but as stated by Ferreira and Oliveira (1991), they do not work well in other regions than in the region of their origin due to polymorphism across the species geographical distribution. The authors also state that stands in several regions of Portugal could be grouped according to the mean tree dimensions but for example the north part of Portugal should be considered separately.

Therefore, Fonseca and Parresol (2001) created a new cork weight equation for Northern Portugal. The equation is based on dendrometric values of 205 sample trees in four locations in Northern Portugal. The values collected were: circumference at breast height before and after bark extraction (the thickness of harvested cork was calculated from these two values), trunk height, debarking height (if some branches were also debarked, sum of their lengths was added up to this value) crown height, weight of the harvested cork, crown projection and subsequently crown diameter. They tried to apply different linear regressions with all above mentioned variables and they found out that two values: tree circumference before debarking and debarking height, account for most of the variation of their results, so they created an equation based on these two values. Their new model is a regression function which provides a point estimate which has some variance, so when evaluating a group of trees, prediction confidence intervals need to be applied. Estimating of a cork oak stand yield is a straight forward summarization of the predictions for the individual trees.

5.7.3 Estimation of Cork Production Using Aerial Imagery (Surový et al. 2015)

This method is based on the correlation between crown geometrical information of the cork oak trees obtained from aerial imagery and their productivity. The work is based on the assumptions mentioned in other researches: (1) cork production correlates with net primary production (NPP), which is also well correlated with a tree leaf area index (LAI) and, (2) LAI directly correlates with net ecosystem carbon dioxin exchange and ecosystem productivity (Zhang et al. 2005). They proposed a cork prediction model based on the remote sensed data about spectral reflectance and they used the ground measurements from permanent sample plots to verify the model's accuracy.

They created a simplified model without spectral information and their results showed that there is a strong correlation between dry cork weight per tree and its crown projection area, which suggests that the cork production can be easily estimated using the geometrical information of crown. The horizontal crown projection is also well correlated with the stem cross section, which is the primary value for most cork production models and it is a dendrometric value which can be very easily measured. The model, in which they also used spectral information was more accurate because it decreased the variance of residuals by ca 15%.

This method of cork oak production estimation uses only the remotely sensed aerial imagery which is commonly available in Portugal with quite good results. This model can help during decision-making processes about the cork oak woodlands management, but also to understand the distribution of cork oak production in space and the influence of site factors on cork production.

5.7.4 Cork Oak Growth Simulator CORKFITS

Growth simulator CORKFITS is based on the distance-dependent individual tree growth model (Ribeiro et al. 2010). It is used to create possible scenarios for generating a large set of regeneration regimes combining both time and intensity factors with the individual tree spatial information. The growth simulation of diameter and height is calculated based on the stand quality (soil), the potential production is derived from stem circumference and debark height derived from legislation (3x the circumference at 1.3 meter height) (Surový et al. 2010).

An optimal regeneration regime under continuous crown cover requirements is sought by applying a dynamic programing algorithm. The set of equations used in CORKFITS is dependent on the integration of the three basic constraints of *montado* system: (1) trees are protected by law, legal permission is needed to cut, thin, prune, debark, etc., (2) undercover is used to grow crops and/or grazing of cattle (3) the most important product of the system is cork, which is extracted every nine years (the minimum period permitted by law) (Ribeiro et al. 2010).

The growth simulator CORKFITS is composed by a set of sub-models for growth, survival and ingrowth, and it integrates the referred complexity based on wide range of repeated measurements in the set of 87 permanent plots in south of Portugal and on the knowledge acquisition at the site level (soil, management, climate, etc.) and tree level (growth, cork production, crown pruning) (Ribeiro and Surový, 2011).

6 Materials and Methods

Set of permanent plots in Alentejo, Portugal was used for this work. 84% of Portuguese cork oak woodland (*montado*) is situated in this province, and because Portugal produces half of world's cork (Ribeiro et al. 2010), we can say without question, that this area is very important in terms of cork production on worldwide level. The permanent plots in this area are measured every 10 years by the people from the University in Évora and they served, among the others, as a base for the growth simulator CORKFITS.

The sample plots are situated north-east to the town Coruche, as seen in the figure 12. As the sample plots were often hard to access, we used a 4x4 pickup truck to get to the plots and we stayed in the field for the whole day to collect the data. The climatic conditions in this part of the world are extreme and although we have done the measuring in the middle of April, the temperatures often exceeded values of over 30°C. This area is also full of desolate animals that are often poisonous such as snakes, scorpions or

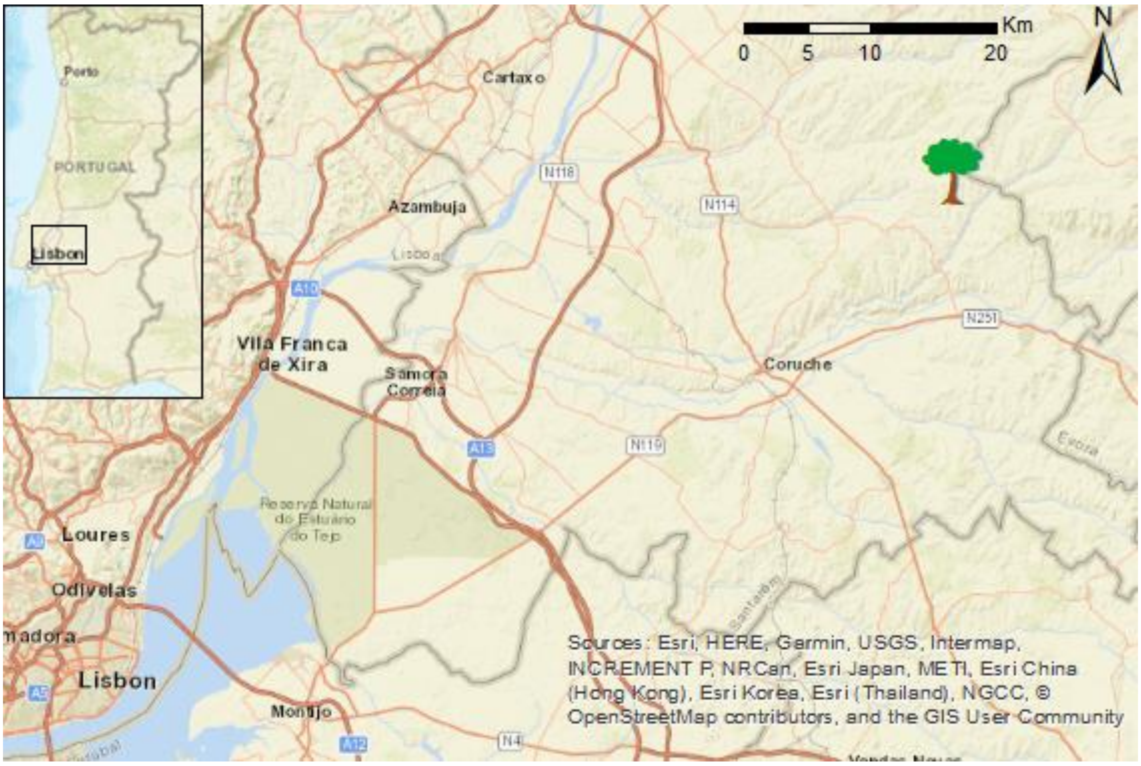

Figure 12 – Situation of the study area. Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, ESri Japan, METI, Esri China, Esri Korea, Esri Thailand, NGCC © OpenStreetMap contributors and GIS User Community

centipedes, so it is advisable to wear high boots and long-sleeved pants despite the extremely hot weather conditions. I once found a poisonous Mediterranean banded centipede (*Scolopendra cingulata*) climbing up inside my pants and was very careful ever since.

We usually measured two plots in one day. We gathered following dendtrometric values: tree circumference at breast height, tree height, stem height, crown height and crown dimensions – distance of the crown from middle of the tree in four directions and the azimuth of these measurements. Circumference is used in case of cork oak rather than diameter because its trunk has very irregular horizontal shape.

Figure 13 – Data acquisition

For present work, I have chosen plots 114, 118 and 320. The first digit of the plot numbers represents the stand crown cover rate in the time of the first measurement: 1xx means stand with the crown cover of 25% and smaller, 2xx means stand with crown cover rate between 25% and 50%, and 3xx meant that the stand used to have the crown cover rate of 50% and higher. As I will mention in the individual stand description, these numbers do not apply anymore due to high tree mortality in last decades - all of the stands have currently the crown cover rate under 25%, some of them way bellow this value.

In order to keep the specific ecological conditions which are necessary for sustaining all the functions of the *montado* system, it is necessary to keep the crown cover between 30% and 70% (Ribeiro et al. 2012).

The plots have circular shape with diameter of 40 meters and area of 1256.637 square meters (0.126 ha).

After the field work, the data was rewritten into the excel tables and included into the database with the historical measurements in the University of Évora. I was only provided with the data I helped with measuring.

The software CORKFITS was used for the simulations of the individual stands and for the proposal of different management practices.

6.1 Description of CORKFITS for Windows Desktop Client

At the beginning the user creates the stand by putting in all the necessary variables: crown dimensions and direction of the first measurement (azimuth), circumference in breast height, coordinates in the sample plot, stem height, tree height and crown height. If some of the data is missing (only simplified inventory method was used), it is necessary to generate the missing parameters. It is also possible to input a dataset table in .txt format which makes it simpler when the user has a plot with large number of trees as shown in the Figure 12.

dendext martin 101-3 – Poznámkový blok

Soubor Úpravy Formát Zobrazení Nápověda

ptnr	r1	r2	r3	r4	r1dir	x	y	cbh	d	sh	th	ch	sp	hdt
101001	792	900	669	586	189	6.69715341	3.697382346	274	87.21690881	581	9.52	3.71	1	7.31
101002	491	238	0	126	210	-8.670838012	4.588318665	84	26.73803044	341	6.35	2.94	1	4.91
101003	161	334	224	308	123	-25.0940013	-12.99687265	106.5	33.90000288	254	5.75	3.21	1	4.04
101004	467	264	173	139	120	4.98278754	3.553340447	100	31.83098862	582	8.83	3.01	1	7.32
101005	0	626	116	0	162	1.876923465	-8.894113689	237.5	75.59859797	777	11.3	3.53	1	9.27
101006	425	155	338	188	279	-8.754579962	6.011799205	138	43.92676429	710	11.82	4.72	1	8.6
101007	385	290	357	184	171	5.246417505	23.81905127	101.5	32.30845345	296	5.61	2.65	1	4.46
101008	264	286	156	227	225	9.752329213	-24.69401901	117.5	37.40141163	351	6.08	2.57	1	5.01
101009	241	135	218	127	351	19.88453292	-23.02133251	81	25.78310078	294	5.3	2.36	1	4.44
101010	277	157	68	224	18	20.50283379	-23.31815401	83	26.41972055	370	6.79	3.09	1	5.2
101011	430	394	148	246	261	-31.32299326	-7.925035865	106.5	33.90000288	383	6.38	2.55	1	5.33
101012	447	356	423	391	162	1.300838045	-6.16423721	183.6	58.4416951	767	11.22	3.55	1	9.17
102001	620	730	610	570	111	-3.934922019	-6.769437843	196	62.38873769	536	9.21	3.85	1	6.86
102002	570	440	350	400	166	-11.18837189	6.176466184	187	59.52394872	595	9.5	3.55	1	7.45
102003	545	490	280	480	178	-9.751784493	17.84988233	159	50.6112719	378	7.7	3.92	1	5.28
102004	490	440	240	210	191	-18.66408259	13.8137765	138	43.92676429	453	8.53	4	1	6.03
102005	710	335	340	330	167	-21.29726082	-11.51307002	182	57.93239929	604	10.86	4.82	1	7.54

Figure 14 – Input table for CORKFITS

After the stand is created, its management has to be defined, which includes: shrub control (soil disking or shrub cutting), pasture (cattle, sheep or none) and economics of debarking (work productivity, payments, regeneration costs, worker payments). All these variables are later used to calculate stand economy in the values of costs and profits. In the present work, the economical part of CORKFITS is not used, because this part of the software is out of date, the data it is based on are unreliable and would create misleading results. I only used charts with cork weights and crown cover.

When all these settings are prepared, the user can define simulation interval, simulation length and start the simulation itself. The maximum simulation length is 100 years. The stand is debarked every nine years, starting with the ninth year of the simulation. Heights and diameters of the trees, crown expansion and tree mortality are calculated, and the simulation stops when the final year is reached. The charts about tree cover, cork production and economics throughout the simulation can be viewed. It is possible to "jump to year" of the simulation and propose regeneration, after which it is necessary to run the simulation again from the year of this intervention. Now the charts have two sets of values – without intervention and with intervention. The forest manager can use this client to try different times and intensities of regeneration and compare the stand's outcomes in terms of cork production, tree cover, economy and finally he can choose the best scenario for his actual stand.

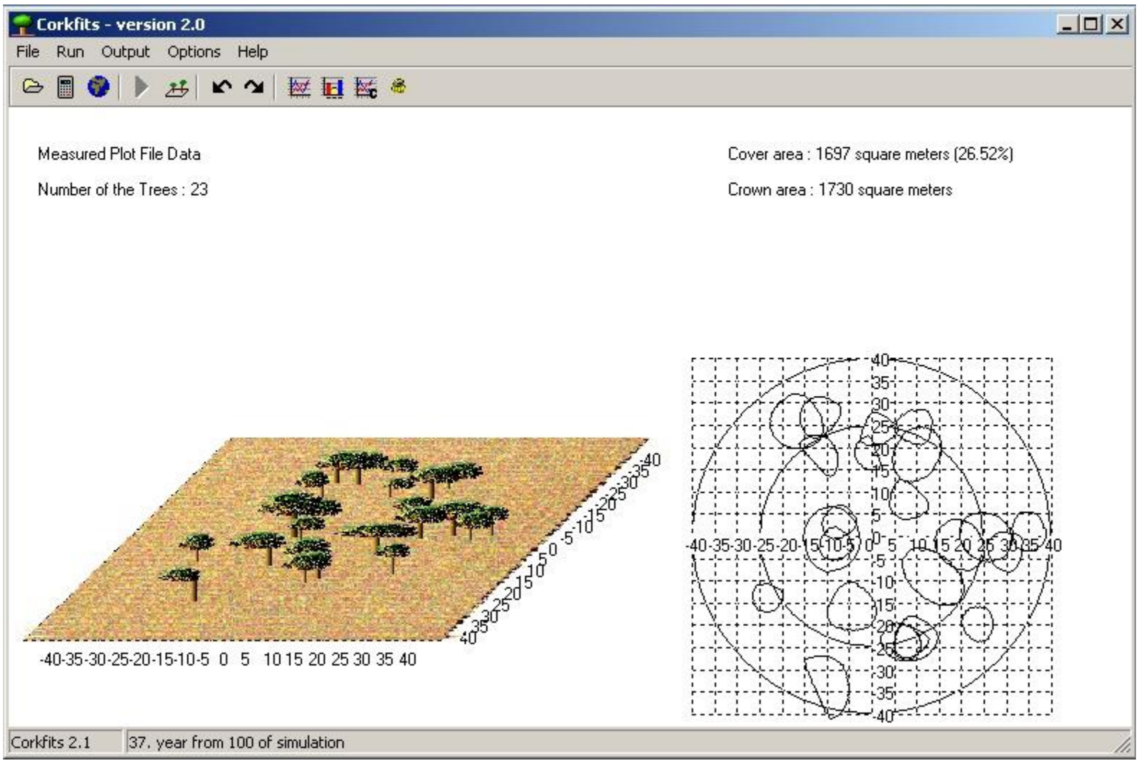

Figure 15 – CORKFITS client (screenshot from CORKFITS)

The advantage of this client is, that it is simple and usable by people with minimum computer education and that the input data can be partially generated by the program. However, the program still has some bugs, sometimes it crashes and its calculations of predictions of cork production are not realistic, as I found at the very beginning of my work, which I will mention later. The economical part (mainly under-canopy management and cork prices) was not used in this work, because I do not know the real cost values of regeneration, nor I know how much income is generated by cattle etc. The economical situation can change very fast, actually cork prices differ every year due to market demand and annual cork supply which depends on many factors, such as climatic conditions, pests, debarkers performance, labor prices etc. If the *montado* owner wants to use the economical of the CORKFITS, he needs to know all the above mentioned values and input them into the software when creating the stand. However, in my opinion, even when the economical part of the software CORKFITS is not used, it can still offer orientation predictions which can be useful for the decision making about regeneration timing and intensities, despite that the actual values of production and economy generated by the software are not calibrated and might have misleading values.

6.2 Sample Plot 114

6.2.1 Plot Description

The plot number 114 has had small crown cover rate ever since it has been measured, as the first digit of its code "1" means that when it was measured for the first time (probably in 2007), it had the lowest crown cover rate category – less than 25%. In the time of the measurement in April 2017, it had the crown cover of only 8.91%. In the table 1 you can observe that the mortality rate was very high in last ten years: eight out of twenty one trees in the stand died in past ten years (31% of the trees). Majority of the reminding trees were concentrated in one patch, creating a group of about 8 trees.

Figure 16 – Plot 114

Table 1 – Dendrometric values of trees in the plot 114

Tree ID	Species	CBH	Azimuth1	R1	R2	R3	R4	Tree height	Crown Height	Notes
114001	*Q. suber*	274	189	792	900	669	586	952	371	
114002	*Q. suber*	84	210	491	238	0	126	635	294	
114003	*Q. suber*									dead
114004	*Q. suber*									dead
114005	*Q. suber*	106.5	123	161	334	224	308	575	321	
114006	*Q. suber*									dead
114007	*Q. suber*									
114008	*Q. suber*	100	120	467	264	173	139	883	301	
114009	*Q. suber*	237.5	162	0	626	116	0	1130	353	
114010	*Q. suber*	138	279	425	155	338	188	1182	472	
114011	*Q. suber*									dead
114012	*Q. suber*	101.5	171	385	290	357	184	561	265	
114013	*Q. suber*	117.5	225	264	286	156	227	608	257	
114014	*Q. suber*									dead
114015	*Q. suber*									dead
114016	*Q. suber*									dead
114017	*Q. suber*	81	351	241	135	218	127	530	236	
114018	*Q. suber*	83	18	277	157	68	224	679	309	
114019	*Q. suber*	106.5	261	430	394	148	246	638	255	
114020	*Q. suber*									dead
114021	*Q. suber*	183.6	162	447	356	423	391	1122	355	

6.2.2 Evaluation of the Current Regeneration in the Plot 114

The forest manager decided to regenerate this stand, which came through severe mortality events in last decades and the number of trees in the stand fell rapidly. The regeneration is not included is not involved in the table above. We do not know in which year the trees were planted, but they were from three to five meters high, so I assume they have been in the stand for at least 5 years. When we measured the plot, there were only 31 saplings left which is not much, given the current tree mortality. It was a surprise to encounter such a low intensity of artificial regeneration, not only because the stand which is regenerated in *montado* cannot be used for other under-canopy activities for at least twenty years if the trees should survive, so the owner is losing incomes during this time no meter how many trees he plants. I assume that (1) there was big mortality of saplings in past years, perhaps due to extremely dry climatic conditions or (2) the manager did not plant enough trees to ensure successful regeneration.

We can also speculate why he planted the mixture of pines and cork oaks. He probably wanted to have some trees to provide him with firewood as current trend tries to reduce cork oak pruning to improve the tree's resistance, and the owners might lack this by-product. However, cork is economically the most important product of the multifunctional system *montado* and if the regeneration is looked at as an investment, planting cork oaks has better long-term return.

Following charts represent the crown cover evolution of the stand 114 without the regeneration (Figure 17) and with the regeneration which was done by the owner roughly 5 years ago (Figure 18).

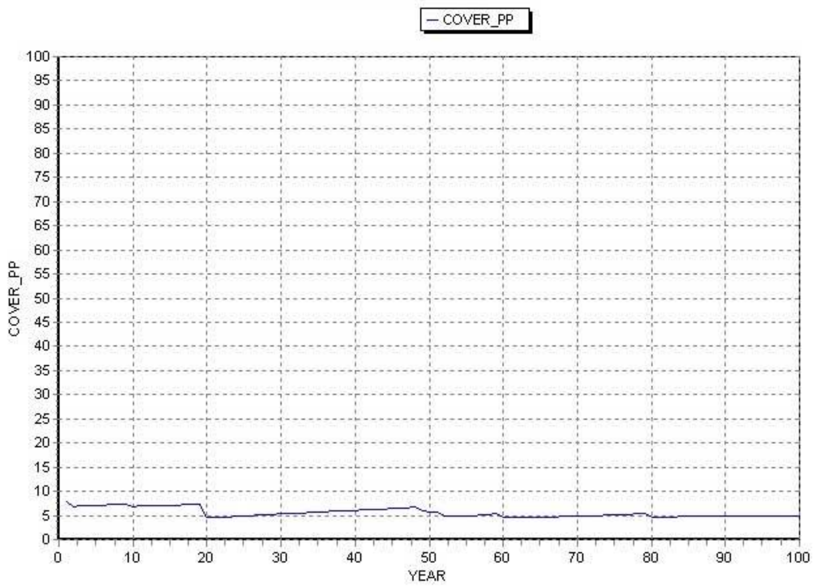

Figure 17 – Crown cover development of the plot 114 with no intervention (screenshot from CORKFITS)

We can observe, that the regeneration which was performed in the stand by the owner increased the crown cover by about 10% to its maximum of 15% in about 50th years of the simulation. This increase is not sufficient because as I mentioned before, in order to keep all the functions of the *montado* and at the same time to have good incomes from the cork, the owner's goal is to keep the crown cover between 30% and 70% (Ribeiro et al. 2012).

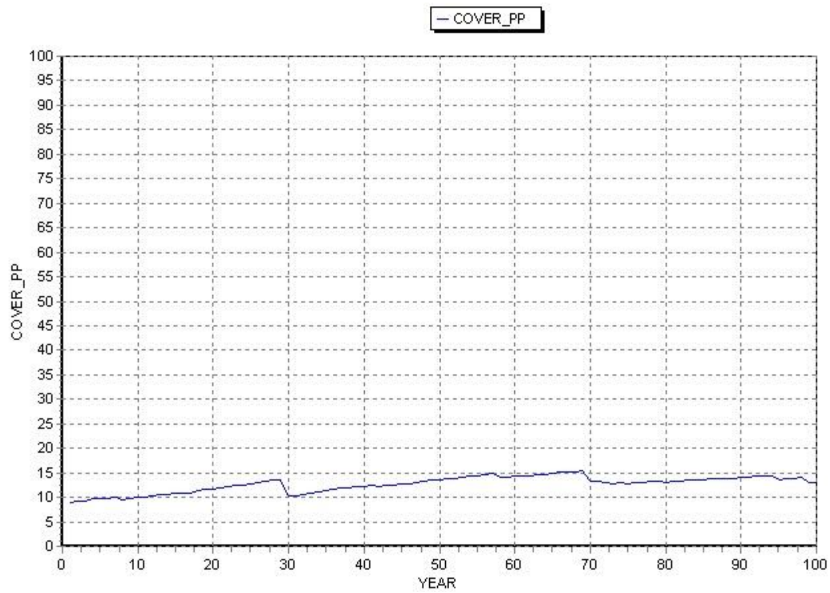

Figure 18 – Crown cover development of the plot 114 with the present regeneration (screenshot from CORKFITS)

6.2.3 Scenario 1: Planting 200 Cork Oaks in Year 1

My proposal is to take advantage of the situation, and as the stand is already fenced, plant another 200 cork oaks. The following charts (Figures 19 and 20) show results of this intervention in terms of crown cover and cork production.

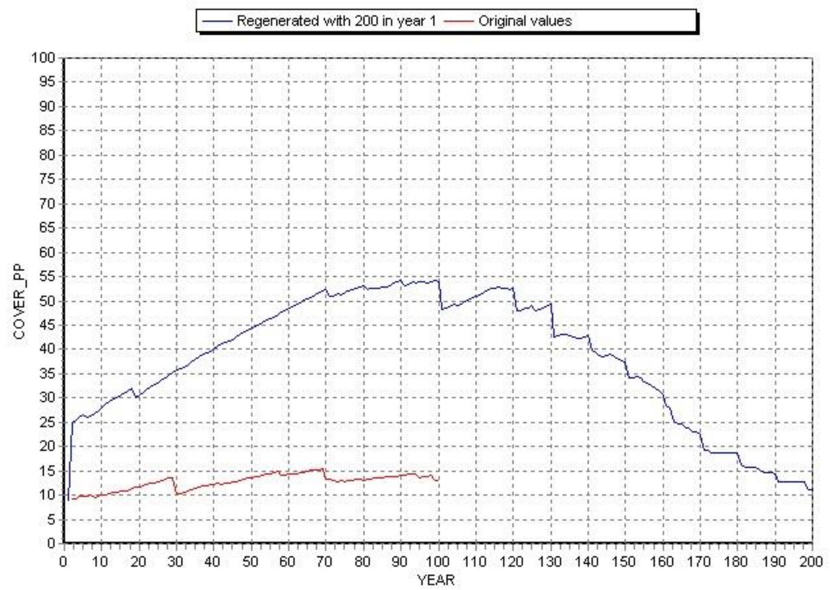

Figure 19 – Crown cover development of the stand 114 – 200 cork oaks per hectare planted in year 1 (screenshot from CORKFITS)

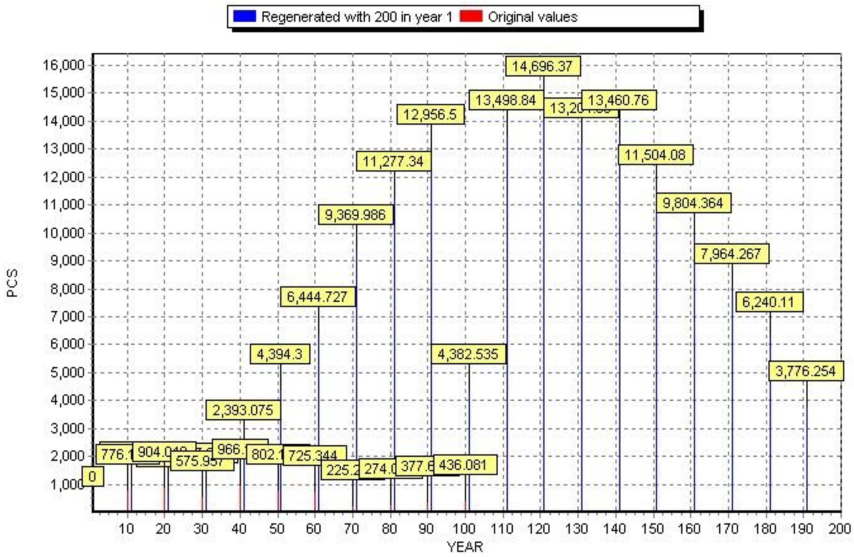

Figure 20 – Cork production development (in kg per harvest) of the stand 114 – 200 cork oaks per hectare planted in year 1 (screenshot from CORKFITS)

CORKFITS is designed to perform the simulations only for 100 years, but as the cork oaks can live for up to 200 years and it takes about 40 years after regeneration before it influences cork production, I quickly realized that this time interval is not enough. In this case, in the year 100, the crown cover culminates, but we cannot see what happens next. So, I tried and found a way how to see the further stand development, though I am still unable to perform any intervention after the year 100.

After the plantation, the crown cover continuously increases until it starts to culminate between 50% and 55%, 70 years after the plantation, and it keeps similar values for another 50 years when it starts to decline (Figure 19).

The cork production has different tendency: it takes about 40 years before the new trees start to produce harvestable cork and then the production grows quite steeply until the year 90, from when on it reminds more or less stable for about 50 years. Then it decreases with similar tendency as it grown (Figure 20).

By planting 200 cork oak trees into the plot 114 we achieved: (1) an increase of the maximum stand crown cover from 15% to 55% and (2) its cork production from the maximum of 966kg to the maximum of 14,696kg (more than 1500% increase). I would like to mention again that the values are unrealistic and according to my estimate, the values of the cork production are 3-4 times higher than they would be in reality.

There is an irregularity in the cork production chart in the year 100 when the cork production drops by about 60% for one harvest. This drop occurs in all the scenarios I tried when I visualize the prognosis for more than 100 years. I think it is just another flaw of the program because the cork harvest goes back to its trend the next harvest.

The target crown cover of *montado* should be between 30%-70% (Ribeiro et al. 2012), so we can try and plant even more trees into the stand and see what happens.

6.2.4 Scenario 2: Planting 350 Cork Oaks in Year 1

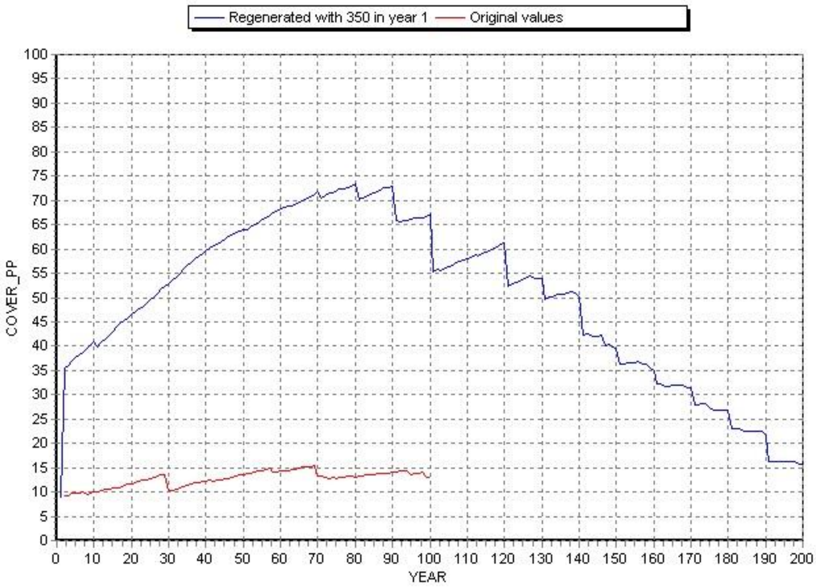

Figure 21 – Crown cover development of the stand 114 – 350 cork oaks per hectare planted in year 1 (screenshot from CORKFITS)

The trend of the stand crown cover development is very similar to the previous one only with slightly different values. In year 60 it reaches the value of the 70% crown cover and stays close to this value for about 40 years, then it again continuously decreases.

Also, the harvested cork weight development has similar tendency as in the previous scenario, but the top values culminate at about 5,000 kg of harvested cork higher.

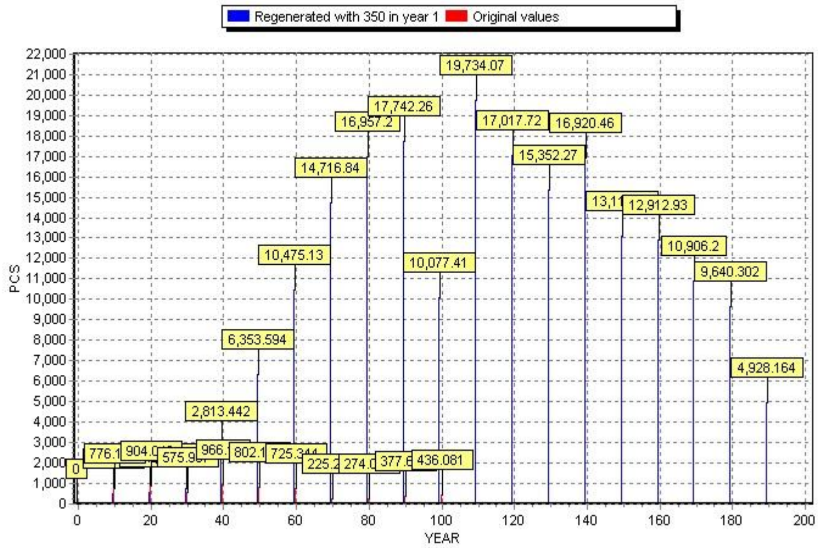

Figure 22 – Cork production development of the stand 114 – 350 cork oaks per hectare planted in year 1 (screenshot from CORKFITS)

6.2.5 Scenario Selection in the Plot 114

Different intensities of regeneration were presented. At first, I thought I would go for the last situation with highest regeneration intensity, because it produced the highest amount of cork and cork is economically the most important part of the *montado* multiple outcomes. Cattle and grains will never produce such high incomes as cork. This could be demonstrated if the economical part of the software was involved in my simulations. On the other hand, under-canopy products generate revenues every year, while cork is harvested every 9 years, so one has to manage his finance situation in long term. Moreover, there is a higher risk in cork production, especially in recent years when the cork oak dieback events occurred, there are pests, previously unknown extreme weather oscillations and huge forest fires, or alternative wine stoppers influencing cork price. The future of cork production is uncertain and for that reason the manager should maybe think of a back door for the worst scenarios of the *montado* future. It is also necessary to consider the fact, that no cork oaks cannot be cut down until they dye so once the regeneration is done, there is no way of reducing the stand density, except to natural mortality of the trees. This decision has to be made by each manager individually but considering all these negative prospects, it would maybe be advisable to go for the scenario with less intense regeneration (200 trees in first year) to keep more space for under-canopy activities.

6.3 Sample Plot 118

6.3.1 Plot Description

Figure 23 – Plot 118

The plot 118 belongs to the same crown cover category as the previous plot 114 – crown cover under 25% - but the actual crown cover as measured in April 2017 is quite higher than in the plot 114: 17.37%. This stand is also doing better in terms of tree mortality, because as you can observe in the Table 2, only 5 out of 31 trees in the plot died in past ten years, which represents 16.3%. In overall, the trees in this plot are quite old, so the mortality might have been natural. There has been no under-canopy activity going on recently as the shrub layer in this plot is slowly expanding and there is even some natural regeneration. The young trees are already over 3 meters high, so I suppose they could have emerged shortly after the last plot inventory in 2007. Although this plot is not fenced to ensure the successful regeneration development, the two saplings have still survived for quite long time, which means that the manager did not use this stand for any under-canopy activities since the seedlings emerged.

Given the dimensions of the majority of standing trees, one could deduce that this stand is already ageing and it is about time to regenerate it.

Table 2 – Dendrometric values of trees in the plot 118

Tree ID	Species	CBH	Azimuth	R1	R2	R3	R4	Tree height	Crown height	Notes
118001	*Q. suber*	196	111	620	730	610	570	921	385	the whole plot was pruned
118002	*Q. suber*	187	166	570	440	350	400	950	355	
118003	*Q. suber*	159	178	545	490	280	480	770	392	
118004	*Q. suber*	138	191	490	440	240	210	853	400	
118005	*Q. suber*	182	167	710	335	340	330	1086	482	
118006	*Q. suber*	163.7	140	0	500	480	280	832	378	
118007	*Q. suber*	113.5	200	470	190	330	260	684	365	
118008	*Q. suber*	110	187	530	440	190	330	764	460	
118009	*Q. suber*	96.5	187	340	280	220	170	747	375	
118010										dead
118011	*Q. suber*	82	280	360	280	60	270	875	355	
118012	*Q. suber*	109.1	158	430	300	320	450	882	425	
118013	*Q. suber*	118.5	212	630	290	220	400	875	335	
118014	*Q. suber*	169.2	81	590	450	260	460	1011	269	
118015	*Q. suber*	160	144	640	560	470	290	1066	363	
118016										dead
118017	*Q. suber*	212.3	153	250	670	470	490	1242	477	
118018	*Q. suber*	90.5	162	220	340	390	0	632	265	
118019	*Q. suber*	108.5	198	360	390	300	170	777	333	
118020	*Q. suber*	111	36	480	250	270	345	737	355	
118021	*Q. suber*	80.6	72	130	270	30	180	550	120	
118022	*Q. suber*	135.2	216	360	110	310	90	903	462	
118023										dead
118024	*Q. suber*	206	122	455	140	360	260	861	367	
118025										dead
118026										dead
118027	*Q. suber*	123.5	189	200	340	230	220	850	278	
118028	*Q. suber*	133	153	470	170	380	300	1035	363	
118029	*Q. suber*	76.8	342	290	200	260	190	695	291	
118030	*Q. suber*	175.4	9	150	440	520	620	931	381	
118031	*Q. suber*	135.6	162	400	440	430	300	1000	347	
118032	*Q. suber reg.*	24.4	0	80	70	70	59	353	80	close to the tree 16
118033	*Q. suber reg.*	18	0	61	75	60	68	320	40	close to the tree 16

6.3.2 Evaluation of the Current Situation in the Plot 118

In the figures 24 and 25, you can see similar trend as in the previous stand: while the crown cover is presently at the end of its culmination period and it will start to decrease in following years, the cork production will be increasing for another 2 harvests and then it will settle at similar values for about 50 years. Crown cover increases continuously after the new trees are planted, cork production follows similar trends, but is delayed by approximately 40 years.

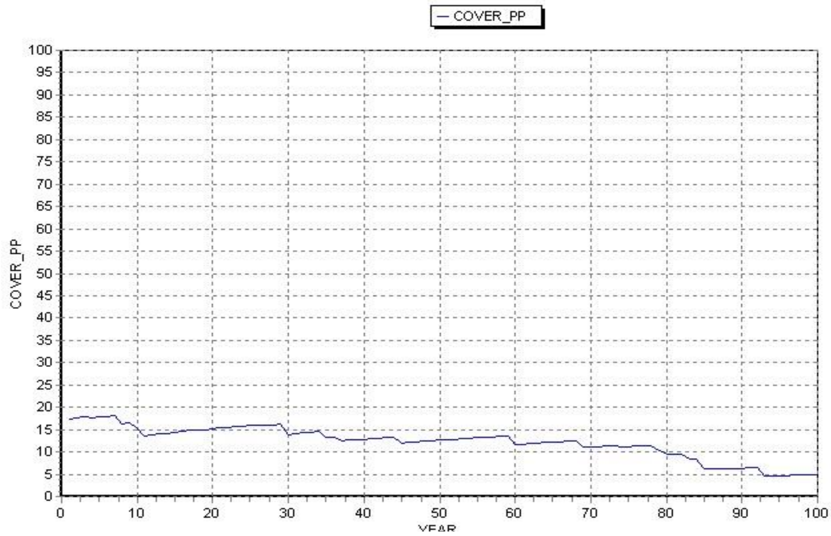

Figure 24 – Crown cover development of the plot 114 without intervention (screenshot from CORKFITS)

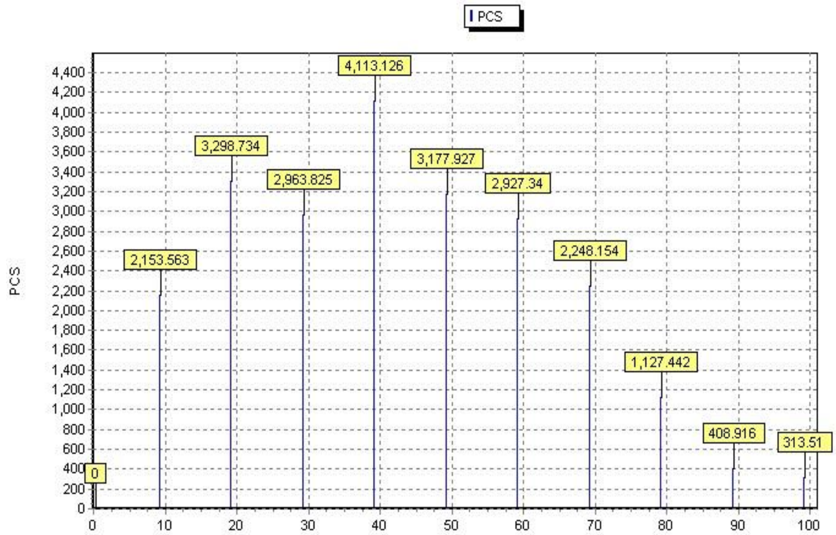

Figure 25 – Cork production development of the plot 114 without intervention (screenshot from CORKFITS)

If the crown cover was sufficient, present time would be perfect to regenerate it in order to sustain stable cork production, because newly planted trees would be able to start producing the cork before the cork production of the trees already in the stand starts to decrease. But the stand crown cover is only around 18% and our target cover is 30%-70% (Ribeiro et al. 2012). For this reason, I propose to start with intense regeneration immediately.

6.3.3 Scenario 1: Planting 300 Cork Oaks in Year 1

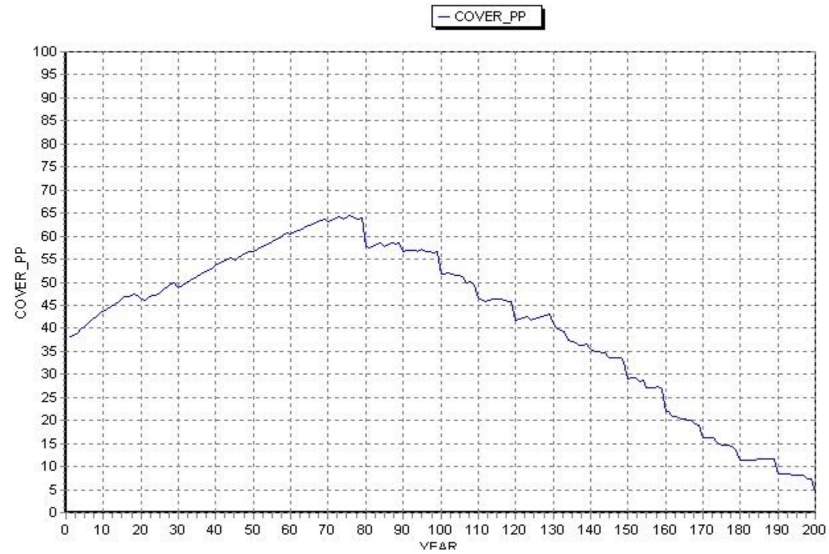

Figure 26 – Crown cover development of the plot 114, regeneration of 300 trees per hectare in year 1 (screenshot from CORKFITS)

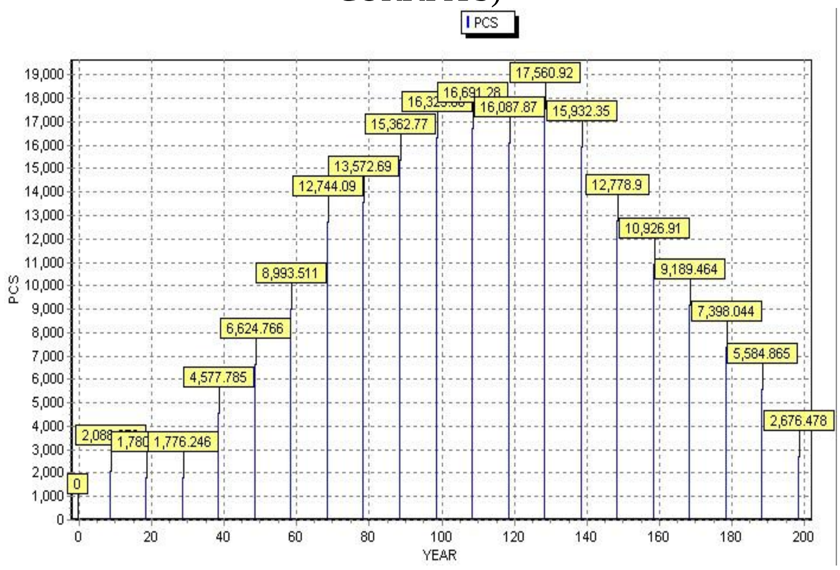

Figure 27 – Cork production development of the plot 114, regeneration of 300 trees per hectare in year 1 (screenshot from CORKFITS)

In this case, we can again observe the delay of cork production development after the development of the crown cover rate. In the year of its maximum, the crown cover reached the value of about 65%, which is sufficient to ensure the multifunctionality of the stand and sufficient cork production.

6.3.4 Scenario 2: Planting 150 Cork Oaks in Year 1 and 150 Cork Oaks in Year 50

In this scenario, I wanted to try what influence has dividing the previous regeneration into two interventions.

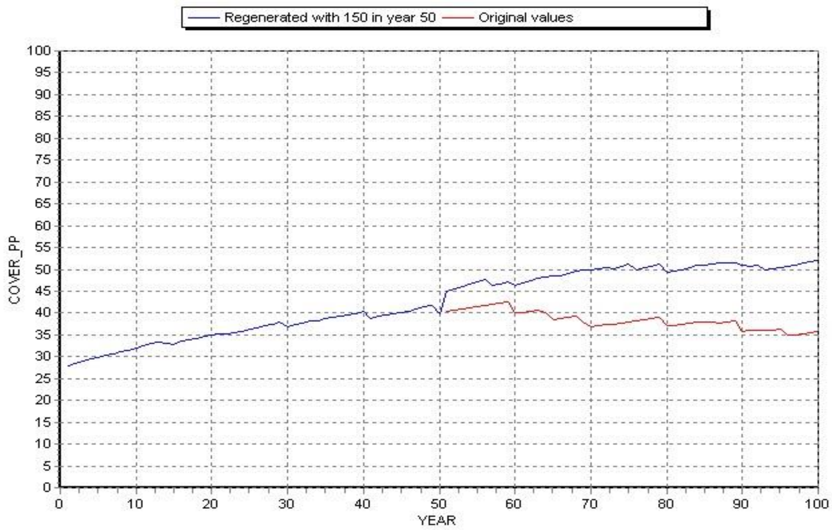

Figure 28 – Crown cover development of the plot 114 - regeneration of 150 trees per hectare in year 1 and another 150 trees per hectare in year 50 (screenshot from CORKFITS)

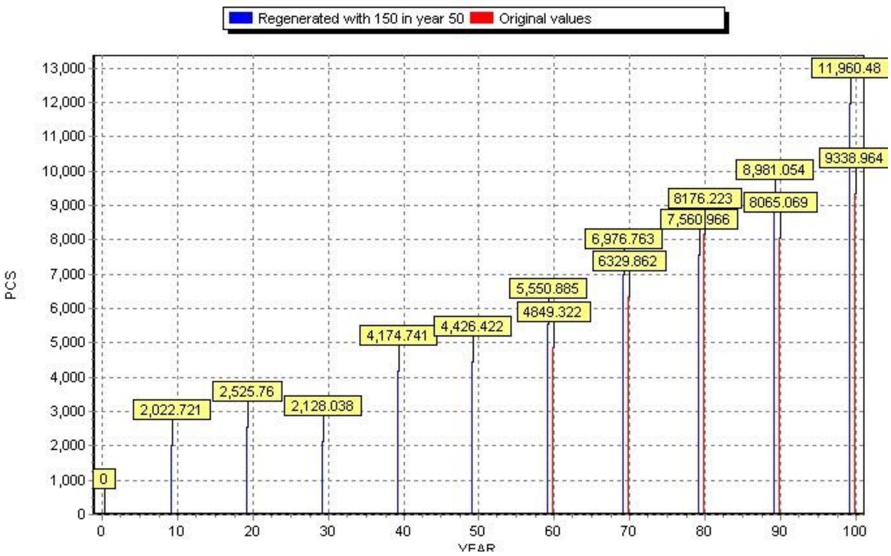

Figure 29 – Cork production development of the plot 114 – regeneration of 150 trees per hectare in year 1 and another 150 trees per hectare in year 50 (screenshot from CORKFITS)

The red color in the Figures 28 and 25 represent the development if only 150 trees were planted in first year of the simulation, blue represents the scenario when 150 trees were regenerated in the year 1 and another 150 trees in year 50. Unfortunately, I was not able to view the development of the stand for longer period but based on previous observation I can more or less predict how the stand would behave.

The maximum crown cover of this scenario reaches values of about 50% (compared to 65% in the previous scenario) and cork production in year 100 of almost 12,000 kg (compared to 17,560 kg in previous scenario).

It is interesting to observe the cork production chart as it behave exactly as I would expect based on the previous experiments: In the scenario only with 150 planted trees in year 1 (the red line), the cork production starts to rise in year 40 (when the cork oak produces first good quality cork). The second wave of the regeneration starts to have effect on cork production in last years of the simulation, for the same reason. We can again observe the delayed tendency of increase of cork production behind the crown cover increase.

In further development, we can expect the decrease of the crown cover to come later than in the first scenario, because the second wave of regeneration should increase its crown cover roughly until the year 150.

6.3.5 Scenario Selection in the Plot 118

It is hard to make any conclusions when we cannot view longer development than 100 years. From the point of view of revenues, the first scenario seems to reach higher incomes sooner, so economically it seems to be more feasible. However, we do not know the regeneration costs so again the software limits us. The second scenario might be more feasible in the point of view of continuous crown cover as the goal is to continuously keep the crown cover on similar percentage.

So, from the data acquired from the simulations, the first simulation only with one intervention looks better from economical point of view. However, if it was possible to perform more interventions for longer time period than 100 years, it could bring out new facts which might challenge this statement.

6.4 Sample Plot 320

6.4.1 Plot Description

Figure 30 – Sample plot 320

The last plot of my work was the first cork oak plot I have ever helped with measuring. The shrub layer in this plot was well developed and mainly composed by species with thorns and spikes, so it was quite hard to access individual trees. This stand belongs to the category with highest crown cover (3), which means that when it was measured for the first time, the crown cover rate was above 50%. Current crown cover in spring 2017, as calculated by CORKFITS, was 22.9%, which indicates that the stand came through a massive mortality events. One can only speculate what happened here but from the first sight it is obvious, that the tree pruning here was done too intensely as the trees are obviously deformed (Figure 30). Also, the picture showing too intense pruning (Figure 10) in the chapter 4.4 (Management of cork oak woodlands in Portugal) was taken here. Therefore, pruning could had been the main stress factor decreasing the vigour of the trees which might have been subsequently killed by pest or dry out because of the recent extremely dry summers. This scenario is just a hypothesis, but based on the knowledge gathered in the theoretical part of this work, it seems the most probable.

In Table 2, you can see that 31 out of 60 trees died since the last inventorying of this stand, which represents more than 50% mortality in last ten years. This mortality rate is the highest of all the stands rom this work.

The occurrence of the strong shrub layer indicates that the owner did not use this stand for under-cover activities, which allowed the spread of the shrubs. Despite this strong competition, we have found some natural regeneration. There were 7 small seedlings, which probably emerged in last years. This regeneration is not included in the following table.

Table 3 – Dendrometric values of trees in the plot 320

Tree ID	Species	CBH	Azimuth	R1	R2	R3	R4	Tree height	Crown height	Notes
320001	Q. suber									dead
320002	Q. suber	134.5	130	595	412	233	415	950	450	
320003	Q. suber	110	345	648	422	670	383	912	378	
320004	Q. suber	65	278	320	315	83	263	417	264	
320005	Q. suber	134	157	536	402	420	386	896	456	
320006	Q. suber	151.2	133	363	458	414	536	918	435	
320007	Q. suber	82	188	386	266	237	158	753	349	
320008	Q. suber									dead
320009	Q. suber	143	225	502	487	268	198	1202	510	
320010	Q. suber	83	285	318	314	210	191	770	354	
320011	Q. suber									dead
320012	Q. suber	79	309	450	210	163	370	590	364	
320013	Q. suber									dead
320014	Q. suber	68.1	211	290	260	159	210	669	364	
320015	Q. suber	129.6	247	363	184	357	420	862	400	
320016	Q. suber									dead
320017	Q. suber	102.5	81	264	200	240	364	841	366	
320018	Q. suber	144.5	266	552	505	340	463	813	484	
320019	Q. suber	92.5	201	472	252	211	336	659	378	
320020	Q. suber									dead
320021	Q. suber	63								dead
320022	Q. suber	154	174	708	514	423	0	1039	385	
320023	Q. suber									dead
320024	Q. suber									dead
320025	Q. suber									dead
320026	Q. suber									dead
320027	Q. suber	73	254	346	203	224	285	720	357	
320028	Q. suber									dead
320029	Q. suber									dead
320030	Q. suber									dead
320031	Q. suber	103	51	130	376	435	300	474	320	
320032	Q. suber									dead
320033	Q. suber	192	288	459	467	617	487	1100	473	
320034	Q. suber	207.5	311	663	456	515	524	954	476	
320035	Q. suber									dead
320036	Q. suber	97	153	467	393	316	90	738	378	
320037	Q. suber									dead
320038	Q. suber	80	225	419	333	100	212	702	350	
320039	Q. suber	200	198	470	622	343	408	982	300	
320040	Q. suber	70	338	348	313	344	278	743	376	
320041	Q. suber	130	333	522	433	437	396	966	479	
320042	Q. suber									dead
320043	Q. suber	96.5	234	505	422	73	112	575	360	
320044	Q. suber									dead
320045	Q. suber									dead
320046	Q. suber									dead
320047	Q. suber									dead
320048	Q. suber									dead
320049	Q. suber	96	0	429	244	255	312	859	363	
320050	Q. suber									dead
320051	Q. suber									dead
320052	Q. suber									dead
320053	Q. suber									dead
320054	Q. suber									dead
320055	Q. suber	80	261	330	213	186	306	524	330	
320056	Q. suber	182	198	676	614	647	520	1300	666	
320057	Q. suber									dead
320058	Q. suber									dead
320059	Q. suber	88	288	400	277	187	250	839	368	
320060	Q. suber									dead

6.4.2 Evaluation of the Current Situation in the Plot 320

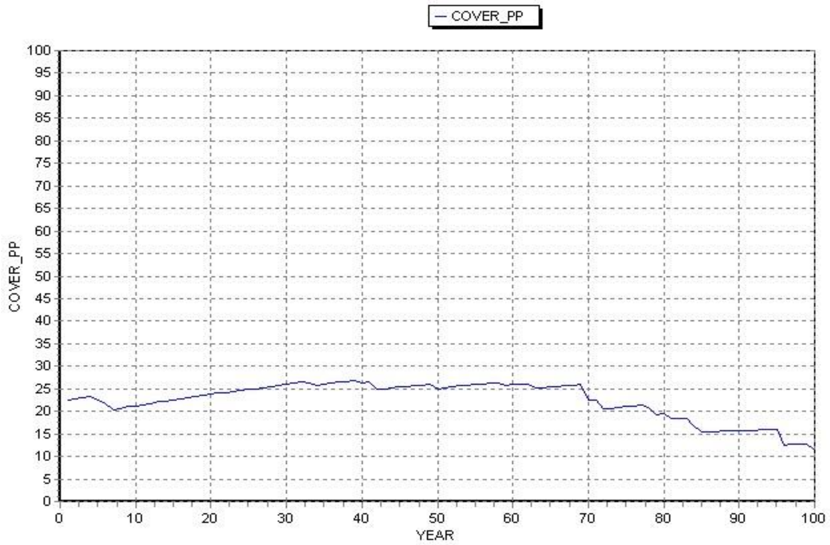

Figure 31 – Crown cover development of the plit 320 with no intervention (screenshot from CORKFITS)

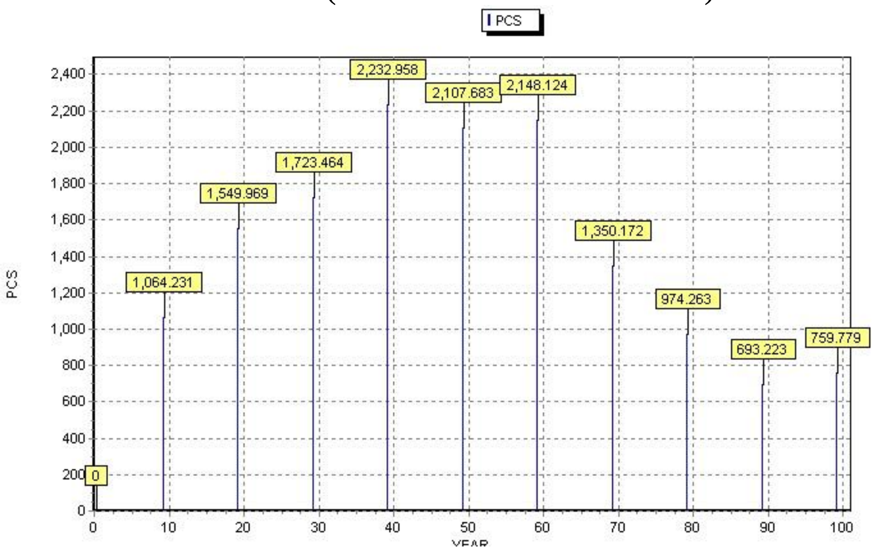

Figure 32 – Cork production development of the plot 320 with no intervention (screenshot from CORKFITS)

As shown in the figures 31 and 32, this stand has slightly different development tendencies than the previous ones – the crown cover starts to decline later than cork production, which is opposite than in the previous situations. Why CORKFITS predicts this development I cannot explain. In any case, the software does not know about the presently weak health status of the trees due to intense pruning, nor he knows about the mortality events in the past, so I would not rely on this prediction and concentrate on the new regeneration of the stand.

6.4.3 Scenario 1: Planting 350 Cork Oaks in Year 1

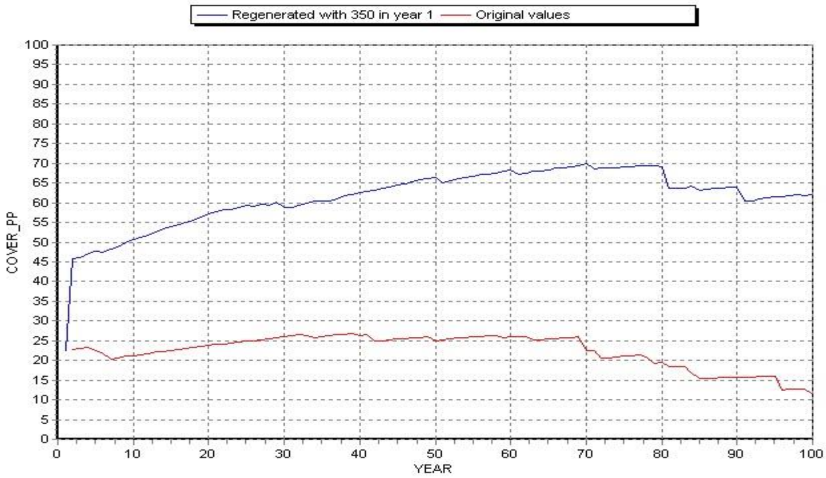

Figure 33 – Stand crown cover development of the plot 320 when regenerated with 350 trees per hectare in year 1 (screenshot from CORKFITS)

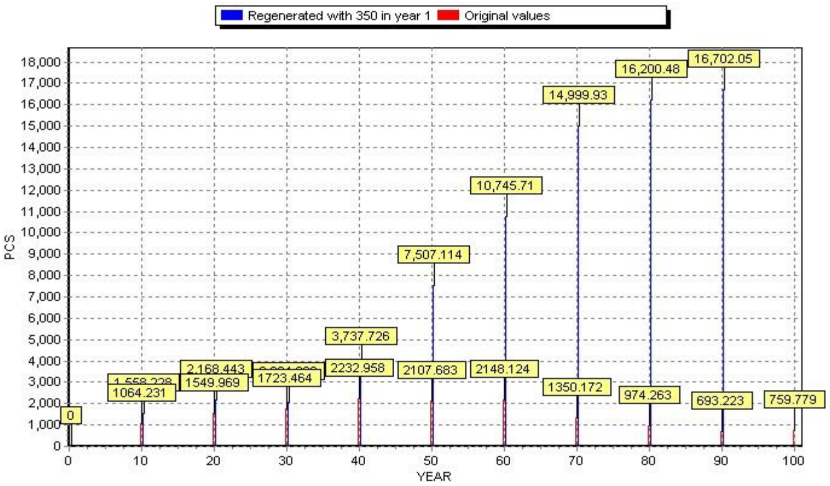

Figure 34 – Stand cork production development of the plot 320 when regenerated with 350 trees per hectare in year 1 (screenshot from CORKFITS)

In this scenario, I was looking for the regeneration intensity which ensures the highest recommended crown cover rate of 70% (Ribeiro et al. 2012), which was reached by planting 350 seedlings in the stand. According to CORKFITS prediction, the stand exhibits similar tendencies as the simulations of previous stands. The stand reaches more or less stable crown cover after 40 years from regeneration and keeps it for roughly 40 years. The cork production culminates roughly in the year 80 at values over 16,000 kg per harvest.

6.4.4 Scenario 2: Planting 850 Cork Oaks in Year 1

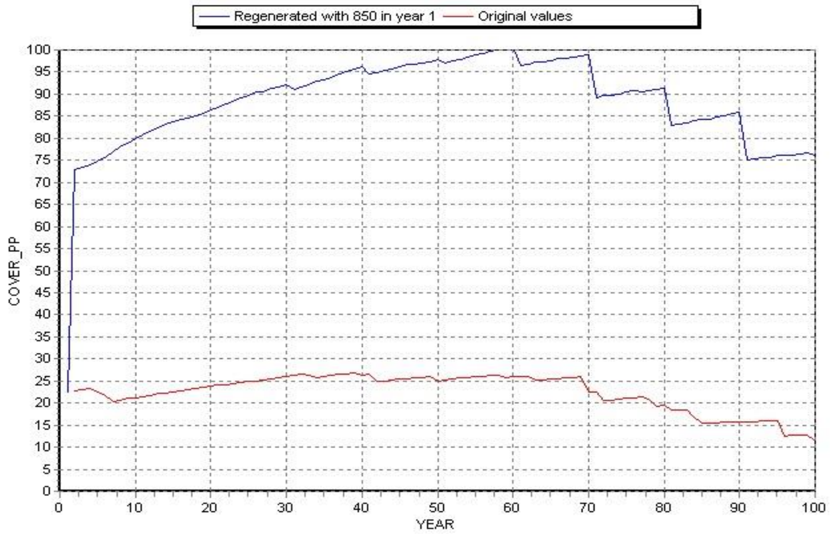

Figure 35 – Crown cover development of the plot 320 when 850 trees per hectare are planted in the year 1 (screenshot from CORKFITS)

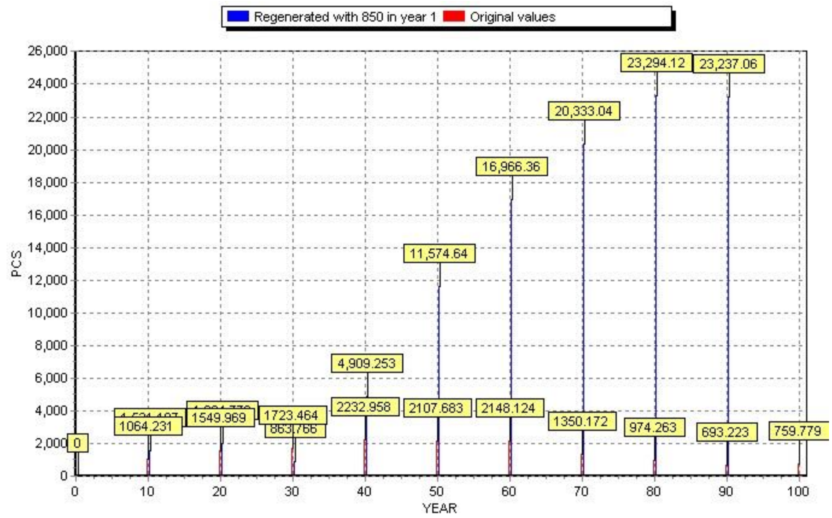

Figure 36 – Cork production development of the plot 320 when 850 trees per hectare are planted in the year 1 (screenshot from CORKFITS)

In the second scenario, I was looking for the regeneration intensity which results in maximum possible crown cover (100%), which means that the stand has closed canopy. It is necessary to plant 850 trees into this plot (which is roughly 6,750 trees per hectare) to reach closed canopy in about 40 years from the plantation. The cork production is also maximized at more than 23,000 kg of cork per harvest, 80 years after the plantation. This management would probably also maximize the incomes of the stand as cork is the most valuable outcome of all the *montado's* multiple products, but it is just a hypothesis as we do not know the actual costs of regeneration and incomes of agriculture products.

6.4.5 Scenario Selection in the Plot 320

The second scenario reports higher cork production, so if incomes are the manager's priority, he should try to keep maximal crown cover of the stand, then he would produce maximal possible cork amounts and he would probably earn maximal incomes. But open canopy is the main characteristic of the *montado* and it is the prerequisite not only for diversity of its functions, but also for its environmental qualities as biodiversity. If the crown cover is closed, it is not possible to perform the under-canopy activities and we cannot talk about *montado* anymore, it is rather cork oak plantation.

Stand with 70% crown cover produced the maximum of roughly 17,000 kg of cork and stand with crown cover of 100% produced maximum of roughly 23,000 kg of cork. 17,000 represents roughly 70% of 23,000. From this we can conclude that cork production is directly proportional to crown cover. Again, I would like to note that these numbers are not realistic as the software CORKFITS is not correctly calibrated.

So, in order to produce maximum cork amounts, the owner should consider converting his montado into cork oak plantation as shown in the second scenario, but he would have to completely refrain from the other activities in the under-canopy, as grain production or grazing of cattle because the closed canopy would not allow much undergrowth. From ecological point of view, this would totally change this special environment which represents the symbol of Portugal.

In this stand, I just wanted to compare the cork production in *montado* system and cork oak plantation and I found out, that the cork production is correlated with crown cover even in higher crown densities. This work is about *montado* management, so I would recommend to select the first scenario in order to maintain all the function of this special agro-forestry system.

7 Results

The existence of the recent decline of cork oaks, mentioned in the theoretical part of this work, was confirmed in this work as all the sample plots exhibited high mortality rates in last decade.

The first stand had the lowest crown cover of the tree plots. The soil was recently ploughed there, and it looked as it has been ploughed periodically. Deep ploughing is believed to be one of the main stress factors of cork oaks, weakening their root system, which can be consequently attacked by the root parasite *Phytophthora cinnamomic*, which, in most cases, kills the tree.

The second stand had quite low crown cover, but also lower tree mortality than the other plots. The mortality might be natural as the trees looked quite old, but relatively healthy. The under-canopy activities were neglected here which has led to occurrence of intermediate shrub layer and weak natural regeneration represented by two saplings.

The third stand had the highest mortality of all three plots (51% trees died in last decade). This mortality rate is believed to be caused by intense pruning, as the trees did not look good from the first sight. The stand under-canopy management practices were also neglected here, which was deduced from the strongly expanding shrub layer. The presence of strong shrub layer increases the risk of forest wildfires. Despite the strong shrub layer, natural regeneration represented by 7 seedlings was found in the under-canopy.

Management practices were proposed for the stands. Given the low crown cover, high tree mortality and low natural regeneration rates, I suggested intense regeneration which should, according to the simulations created by CORKFITS, lead to maximization of the cork production, while sustaining the ecological stability of the stands. Maintaining the ecological stability and multifunctionality of the stands was achieved by keeping the maximal crown cover rate under 70%. Low crown cover rate is a crucial characteristic of the *montado* system which is typical for its wide variety of outcomes from under-canopy.

Based on my observations, the development of cork production can be divided into four stages (Figure 37): the first stage takes roughly 40 years, in this stage the newly planted trees do not produce harvestable cork. The second stage takes again roughly 40 years, in this time interval the cork production continuously rises each harvest, until it reaches the third stage, in which the cork production reaches its maximum. The third stage of stable cork production takes about 60 years. In the last stage, decline of cork production can be observed, this stage of stand degradation takes roughly 60 years. So, based on the CORKFITS experiments, the cork oak stand “rotation period” takes about 200 years.

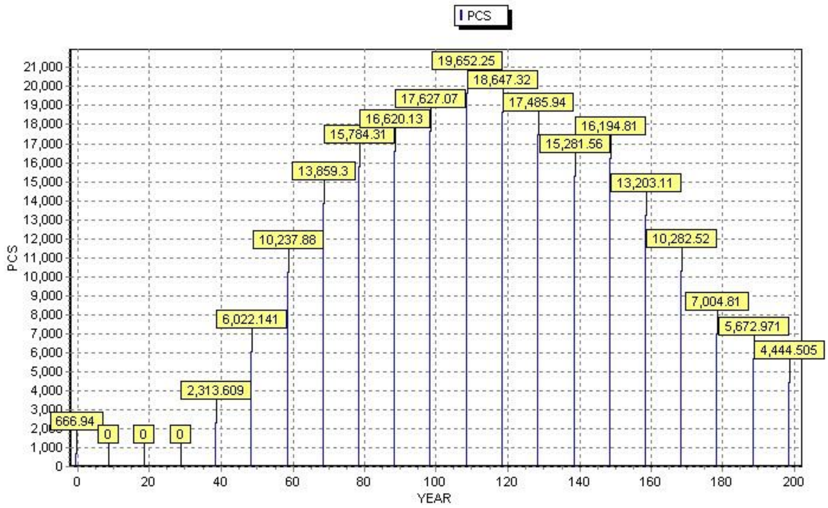

Figure 37 – Cork production development of an empty stand when 400 cork oaks per hectare are planted in year 1 (screenshot from CORKFITS)

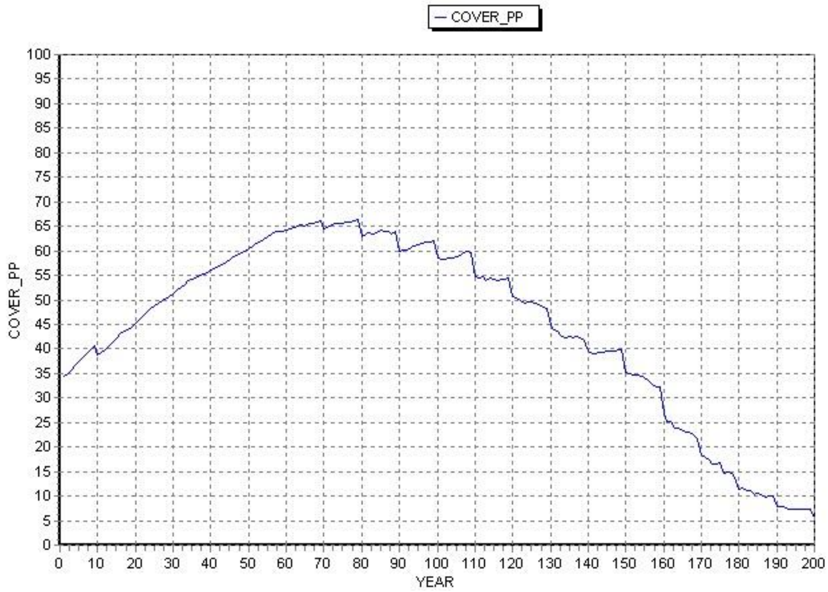

Figure 38 – Crown cower development of an empty stand when 400 trees per hectare are planted in year 1 (screenshot from CORKFITS)

In my opinion, the best time to regenerate the stand is 40 years before the cork production starts to decrease, so the newly planted trees would compensate the cork production decrease and the cork production would become more or less stable. This timing is also perfect in terms of keeping the continuous crown cover at stable level, as it starts to decrease sooner after the regeneration then cork production and the newly planted trees would compensate the continuously decreasing crown cover (Figure 38).

I am not able to demonstrate my proposed ideal regeneration regime of the cork oak stands, as the software CORKFITS is designed to perform the simulations only for 100 years. The results of this work are slightly limited by the software. It was found that the cork production predictions do not fit the real values from the last year's cork harvest – the cork weight production estimation in CORKFITS is about 3-4 times higher than the real values measured during the cork harvest in summer 2017. The economical part of the software was not used, because the actual costs connected to under-canopy activities are not known, nor I know the actual cork selling price, which in reality changes every year.

8 Discussion

The plot 118 had low pruning and low under-canopy activities and it exhibited the best tree vitality of the three stands. On the other hand, the plot 114 was regularly ploughed and the trees in the plot 320 were intensely pruned in the past and their mortality was significantly higher. This fact might confirm the assumptions that intense pruning and intense agricultural activities represent some of the practices which have negative impacts on tree health status and can subsequently lead to pest attacks and death of the trees. Generally speaking on a larger scale, we might say that periodical ploughing and intense tree pruning are some of the reasons for the recent cork oak decline.

It was found that, according to growth simulator CORKFITS, the cork production is directly proportional to crown cover, so keeping the crown cover at 100% would produce higher amounts of cork. The cork is economically the most important outcome of the *montado,* so by converting the open cork oak stands to cork oak plantation would probably lead to maximization of owner's incomes. But *montado* is characterized by open crown canopy and it is crucial to maintain all its multiple outcomes and functions including ecological stability and biodiversity.

In Portugal, it is prohibited to cut down cork oak trees and even when they are dead, it is necessary to apply for permission to remove it. This fact leads to impossibility of thinning of the stands in order to remove deformed or unhealthy individuals. Doesn't it lead to genetical degradation of the species from productional point of view? In Czech forestry 10,000 seedlings per hectare are often planted (differs with species) and 5,000 of them are removed in first ten years because they have deformed shape. Only the promising individuals are left in the stand. Multiple more interventions are performed in the stands during its life in order to leave only the "good" individuals and only about 5% of the initially planted trees stay in the stand until the harvest. This process results in the fact that only the "good" individuals are allowed to reproduce, and next generations bear the characteristics which are desired by forest managers. This management practice improves genetical value of the stand – from productional point of view. Cutting down any cork oak tree is prohibited in Portugal, so it allows the deformed trees to reproduce.

9 Conclusion

The theoretical part of the work analyzed the current situation in the study region and pointed out the main problems and threats of the cork oak woodlands. The data for this work was collected in the permanent plots situated in Alentejo, Portugal. Each of the studied stands was analyzed, their future development scenarios were created with the help of the growth predictor CORKFITS and management practices were proposed. All the stands exhibited high mortality rates, which are believed to be caused by wrong management practices. For that reason, quite intensive regeneration regimes were proposed for all the stands in order to achieve sustainable productivity of the system with emphasis on cork production and crown cover. The results of the work would be even better if the software CORKFITS was more extensively calibrated.

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