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Models of Silviculture for Portuguese Species: Old and New Guidelines

Ana Cristina Gonçalves[1]

Abstract Models of silviculture are used for the selection and scheduling of the silvicultural practices from installation to the end of the production cycle. Most of the published models of silviculture are for even aged stands. Those for mixed and uneven aged stands are scarce. The goal of this study was the development of models of silviculture for Portuguese species; with examples for *Pinus pinea*, *Quercus suber Quercus rotundifolia*, *Pinus pinaster* and *Castanea sativa*. Five stand structures were considered (pure even aged, mixed even aged, temporary mixed even aged, pure uneven aged and mixed uneven aged). For mixed stands were considered two species admixtures and for uneven aged 2, 3 and 4 cohorts. The local level models of silviculture developed in this study are conceptual frameworks where guidelines can be derived to define the model of silviculture for a stand, including target stand structure and production cycle, according to management goals, species and site. Overall, it was intended to stress the importance of defining models of silviculture that are flexible to accommodate a wide range of management options and that should be dynamic in space and time. These models cannot be used directly but have to be adapted to each stand.
Key words: Stand structure; Density; Silvicultural practices; Stand dynamics; Conceptual framework.

Modelos de Silvicultura para Espécies Portuguesas: Velhas e Novas Orientações
Sumário. Os modelos de silvicultura são usados para a seleção e calendarização das práticas silvícolas desde a instalação do povoamento até ao termo de explorabilidade. A maior parte são para povoamentos puros regulares. Os modelos para povoamentos mistos

[1] Departamento de Engenharia Rural, Escola de Ciências e Tecnologia, Instituto Mediterrânico de Agricultura, Ambiente e Desenvolvimento (MED), Instituto de Investigação e Formação Avançada, Universidade de Évora, Apartado 94, 7002-544 Évora, Portugal.
E-mail: acag@uevora.pt

e irregulares são poucos. O objetivo deste estudo foi o desenvolvimento de modelos de silvicultura para espécies portuguesas, com exemplos para *Pinus pinea*, *Quercus suber*, *Quercus rotundifolia*, *Pinus pinaster* e *Castanea sativa*. Foram consideradas cinco estruturas de povoamento (regular puro, regular misto, regular misto temporário, irregular puro e irregular misto). Para os povoamentos mistos consideraram-se misturas de duas espécies e para os irregulares 2, 3 e 4 coortes. Os modelos de silvicultura locais desenvolvidos neste estudo são abordagens conceptuais de onde podem ser derivadas linhas orientadoras para a definição do modelo de silvicultura para um povoamento, incluindo a estrutura de povoamento alvo e o ciclo de produção, de acordo com os objetivos de gestão, espécies e estação. Pretendeu-se destacar a importância de definir modelos de silvicultura que sejam flexíveis de modo a acomodar uma gama ampla de opções de gestão e dinâmicos no espaço e no tempo. Estes modelos não podem ser usados diretamente, mas têm que ser adaptados a cada povoamento.
Palavras-chaves: Estrutura de povoamento; Densidade; Práticas silvícolas; Dinâmica dos povoamentos; Abordagem conceptual.

Modèles de Sylviculture pour les Espèces Portugaises: Anciennes et Nouvelles Lignes Directrices

Résumé: Les modèles de sylviculture sont utilisés pour la sélection et la programmation des pratiques sylvicoles depuis l'installation jusqu'à la fin du cycle de production. La plupart des modèles de sylviculture publiés concernent des peuplements équienne. Celles des peuplements mixtes et inéquiennes sont rares. L'objectif de cette étude était le développement de modèles de sylviculture pour les espèces portugaises, avec des exemples pour *Pinus pinea*, *Quercus suber*, *Quercus rotundifolia*, *Pinus pinaster* et *Castanea sativa*. Cinq structures de peuplement ont été considérées (équiennes pures, équiennes mixtes, équiennes mixtes temporaires, inéquiennes pures et inéquiennes mixtes). Pour les peuplements mixtes, on a considéré les mélanges de deux espèces et pour les inéquiennes de 2, 3 et 4 cohortes. Les modèles de sylviculture au niveau local développés dans cette étude sont des cadres conceptuels où des lignes directrices peuvent être dérivées pour définir le modèle de sylviculture pour un peuplement, y compris la structure du peuplement cible et le cycle de production, selon les objectifs de gestion, les espèces et la station. Dans l'ensemble, on visait à souligner l'importance de définir des modèles de sylviculture qui soient flexibles pour s'adapter à un large éventail d'options de gestion et qui devraient être dynamiques dans l'espace et dans le temps. Ces modèles ne peuvent pas être utilisés directement mais doivent être adaptés à chaque peuplement.
Mots-clés: Structure du peuplement; Densité; Pratiques sylvicoles; Dynamique du peuplement; Cadre conceptuel.

Introduction

The models of silviculture are conceptual frameworks that enable the selection and scheduling of the silvicultural practices from a certain point in time (that can be at regeneration or not) until the end of the production cycle. The models are not static but rather dynamic in space and time, due to the development of trees and stands, which change stand structure. In general, a model of silviculture is specific of a stand and the silvicultural practices can be or not the same for all the stand. Also, their periodical updating is of the utmost importance to make the bridge between the management objectives and stand structure dynamics.

Typically, the models of silviculture can be defined at two levels: the regional and the local (GONÇALVES *et al.*, 2008a). At the regional level they can be considered a tool describing a general framework, which can be or not defined per species and/or stand structure. These models of silviculture cannot be used at local level, but rather be considered a trend to guide the development of the models of silviculture at local level. At the local level the models of silviculture are frequently more detailed than at regional level, including most times a set of silvicultural practices with one or several alternatives that are suited per species and/or stand structure, considering a set of management goals. Again these broad models of silviculture cannot be used to manage a stand rather they serve as guidelines for the construction of the model of silviculture and have to be adapted to the management objectives and stand structure, for one specific stand (SMITH *et al.*, 1997). In other words, the model of silviculture is specific of each stand and has to be updated periodically to accommodate the changes both space and time of tree development and stand structure.

Tree and stand development dynamics have been extensively studied (GONÇALVES, 2022 and references therein). Forest silvicultural practices are anchored in the existing knowledge of the interactions between individual trees, stand structure, management goals, technology and legislation. They should incorporate the existing knowledge when selecting the silvicultural practices and their scheduling. New challenges are required to forest management, including the concerns about the stands' and productions sustainability, mechanisation of silvicultural practices, climate change and diversity of management goals. Most of the published models of silviculture are for even aged stands, more for pure than for mixed. For uneven aged stands the published models of silviculture are scarce. This is related to the specificity of stand structure and thus of the model of silviculture, and due to the difficulty to make generalisations (O'HARA, 2014).

The published models of silviculture for Portuguese species date back to the end of the last century (CORREIA and OLIVEIRA, 2003, 1999; LOURO *et al.*, 1999). Are mainly for on pure even aged stands of artificial regeneration, although permanent and temporary mixed stands are also considered. Moreover, the models are focused on one main production with a rather constraining scheduling. Thus these models have low flexibility to accommodate the changes of the market, new products and services as well as disturbances, such as fire, storms and climate change.

Portuguese forest is composed mainly by pure even aged stands. Yet, mixed even aged and uneven aged have been reported (GONÇALVES, 2017; IFN6, 2019). The variability in site, climate change, and the demand of products and services of the forest stands brings about the need to provide new models of silviculture flexible enough to accommodate those needs. The goal of this study is to develop new models of silviculture. Specifically, the objectives are to discuss the influence of stand structure, production and harvest in stand dynamics and to develop new models of silviculture at local level for Portuguese species, considering different stand structures.

Stand structure influence on the model of silviculture

Most silvicultural practices are common to all forest stands, regardless of stand structure and management goals, namely control of spontaneous vegetation, thinning, pruning, regeneration and harvest (in its broader sense, including fruit harvest and debarking). Yet, they vary in their method, frequency, intensity and scheduling in space and time.

The suitability of the species to the site is of primordial importance to promote stand sustainability and to optimise yield, and influences the model of silviculture. Thus, the knowledge of the species ecological and cultural traits and their suitability to the edaphic and climatic conditions (site) have to be equated. The aptitude maps are of help to evaluate the suitability of the species, productions and yields (ALEGRIA *et al.*, 2021; FERREIRA *et al.*, 2001; PAULO *et al.*, 2015).

Of importance is the *a priori* definition of the target stand structure as function of the management objectives (GONÇALVES *et al.*, 2008a). Three features influence stand structure; density, composition and structure. These features will be analysed in the following sections. Additionally, there are four silvicultural practices that are determined (and determine) stand structure dynamics that will be analysed; thinning, pruning, regeneration (*cf.* Density) and harvest.

Overall it can be said that the model of silviculture depends on stand structure and its dynamics, varying in space and time. Its flexibility enables to reach management goals more efficiently, though it needs skilled and experienced foresters. Also, the periodical revision of the silvicultural practices and their timing should be done to correct the deviations from the target stand structures and productions.

Density

Typically, models of silviculture can be defined for new stands (afforestation or forestation) or existing stands. For the former, initial density and spatial arrangement should be considered while for the latter should be stand structure at the moment of the evaluation.

Initial density has a decisive role on the development of stands. Higher densities promote height growth, but competition starts earlier and derives in lower diameter (volume and biomass) growth per tree (COX *et al.*, 2021; PERACCA and O'HARA, 2008) and frequently lower tree and stand stability (PERACCA and O'HARA, 2008). This results in the need to prescribe thinnings in order to increase growing space to promote diameter growth and increase tree stability and vigour (GONÇALVES, 2021 and references therein). The aforementioned is related to the type of regeneration (natural, seeding or plantation). Natural regeneration has often high plant density, which implies pre-commercial thinnings first and commercial ones after, to reach the target density. Inversely, in the regeneration by plantation, density, as well as spatial arrangement, should be selected in order to get the best possible balance between tree development and the minimisation of the silvicultural practices to reduce costs. Direct seeding initial density depends on how it is implemented. Three main options are available; broadcast seeding, strip seeding and spot seeding (ASHTON and KELTY, 2018). Broadcast seeding (seeds are uniformly scattered over all the area) derives in high densities, if germination and recruitment rate is high, and should be treated similarly to natural regeneration. It can be used for *Pinus pinaster* seeding. Strip seeding derives in a lower density than the former and enables to delay in time the first pre-commercial thinning. It may be applied for *Quercus suber*, *Quercus rotundifolia*, *Pinus pinea* and *Pinus pinaster* seeding. The spot seeding has the lowest density, enables a more efficient control of the spatial arrangement of the individuals and is better suited for large seeds (BOUDRU, 1989). It can be used for *Quercus suber*, *Quercus rotundifolia* and *Castanea sativa*. Natural regeneration is used both in even aged and uneven aged structures while artificial regeneration is more frequent in even aged stands and less commonly in uneven aged ones (SMITH *et al.*, 1997).

The density of the recruited individuals to the main stand as well as their spatial arrangements have strong implications on the silvicultural practices and their timing. In high density stands, pre-commercial thinning enables to reduce competition and increase growth. It should be done early in time so that the trees regain stability (*e.g.*, decrease *hd* ratio, *i.e.*, the quotient between height and diameter at breast height). Moreover, the early thinnings, apart from the abovementioned goals, enable an early selection of the trees with the best potential production (GONÇALVES, 2021).

Composition

A target composition (characterised by the number of species, their proportion and spatial arrangement) should be promoted early in the production cycle, to reach the defined target admixture. The choice is basically between pure and mixed stands (SCHÜTZ, 1997). The pure stands are easier to manage and more information is available to help the forester to make decisions. Yet, mixed stands are equally productive, more resilient to many abiotic and biotic disturbances and have higher diversity. In terms of management in the pure stands the interactions are between trees with the same traits. Inversely, in mixed stands species traits, their proportion and spatial arrangement have to be considered. The target species, proportion and spatial arrangement should be defined *a priori* as function of the species traits and site. The silvicultural practices enable to reach the defined target (GONÇALVES, 2022). Special care should be taken when the species in the admixture are shade intolerant (*Quercus suber*, *Quercus rotundifolia*, *Pinus pinea* and *Pinus pinaster*) and/or in sites prone to drought where growing space per tree should be larger to minimise or avoid stresses (GROSSIORD *et al.*, 2014). The spatial arrangement of the species (form of mixture) is frequently grouped in three classes; individual mingling, per group or per strip/line. Yet, the former two can coexist and the groups can be of the same or of different sizes. Spatial arrangement per strip/line is frequently associated to artificial regeneration. In practice, the identification of the more suitable niche per species will have a strong influence on the form of mixture. The type of mixture is related to the arrangement of species in the vertical plane and can be either a horizontal one or a vertical stratification. The former is better suited for admixtures of shade intolerant species while the latter is for species that are more tolerant to shade (ASHTON and KELTY, 2018; SCHÜTZ, 1997).

Structure

The structure (characterised by the number of cohorts, their proportion and spatial arrangement) is frequently divided in even aged and uneven aged, depending on the number of cohorts (1 or two or more, respectively). Although theoretically structures from 1 to n cohorts can be defined, some are more frequent than others. The even aged stands (one cohort) have canopy arranged in a single layer, in which the silvicultural practices are focused. The species traits, density, stability and spatial arrangement of the individuals' constraint the thinning method (O'HARA, 2014; SCHÜTZ, 1997). This means, in practice, that one or several thinning methods, with the same or different intensities, can be applied. The uneven aged stands (two or more cohorts) have a more or less continuous canopy in the horizontal and vertical plane. Silvicultural practices aim attaining and maintaining a target stand structure during all production cycle, that is a certain frequency per cohort, in number of trees, basal area, volume or crown cover (GONÇALVES, 2021; O'HARA, 2014).

Thinning and pruning

Thinning is a silvicultural practice that maintains or promotes a certain stand structure, with the removal of trees. It is characterised by its method, intensity and frequency. Several methods are available. The most frequently used are thinning from below and thinning from above, yet selective or Schädelin, free and variable density thinning are gaining importance. In the thinning from below, trees with low social status (supressed and dominated) are removed. It is suited for shade intolerant species. In the thinning from above, trees of the upper canopy (dominant and codominant) are removed to release the trees with the best potential traits and growth. Selective (or Schädelin), free and variable density thinning methods are based on the selection of the future trees (the individuals with good vigour, stability and productive traits) and periodically release them from competition so that they are in free growth (corresponding to isolated trees with crowns of contiguous trees having a mean distance equal or larger than half of the average of the crown radii of neighbouring trees) during all production cycle, regardless their social position. These thinning methods are especially interesting for the stands of fruit and bark production. When selecting future trees, criteria should be included to evaluate fruit production, such as past production trend, crown dimension and symmetry, and bark characteristics, such as cork cracking, cork thickness and, when possible, cork quality. Thinning from below and from above are frequently used in even aged stands. The thinning methods, Schädelin, free and variable density, in all of which future trees are selected, are more flexible, enable the maintenance of the stand structure variability, and are better suited for uneven aged stands. Yet, thinning from below and from above can also be applied (GONÇALVES, 2021). The main goal for fruit and cork production stands is that the trees are in free growth during all production cycle to enhance stem and crown growth and thus bark and fruit production. For timber oriented stands, at least in the early development stages, the goal is to reduce competition between individuals while in the later development stages, especially in uneven aged stands is to guarantee that the future trees are in free growth. In practice due to the variability of the stand structure more than one thinning method is frequently needed.

Thinning intensity and frequency should be guided by stand development and not by an inflexible timeframe. For stands for fruit and bark production, free growth should be maintained and promoted along all production cycle, which corresponds to an overall crown cover between 40% to 60% (JOBLING and PEARCE, 1977; NATIVIDADE, 1950). For timber oriented stands, in uneven aged stands the future trees should be in free growth from the moment of the selection of the future trees until the end of the production cycle while in even aged stands the goal is to maintain or promote high growth rates of the trees from stem exclusion stage until the end of the production cycle. Thinnings of light intensity are preferable to avoid reducing too much crown cover, yet in young stands moderate or heavy intensity can be considered when trees are vigorous and are expected to react to release with increased growth rates. The timing of the first thinning should be when crown cover is equal or higher than 60% in agroforestry systems and/or the crown neighbouring trees touch each other. If trees are in free growth it is better to delay thinning until it is possible to evaluate which trees will have the best potential in productive terms.

Pruning, which can be natural or artificial, is a silvicultural practice, consisting in the removal of live or dead branches, which usually accompanies thinning. Its main goal is to increase the quantity and quality of timber, enabling debarking only in the stem (*Quercus suber*) and increase the efficiency of mechanical fruit harvest (*Pinus pinea*). For timber production pruning should originate a stem without branches of at least 4-6 m and for bark and fruit production of 2-4 m (CORREIA and OLIVEIRA, 2003, 1999). Due to its costs, whenever possible natural pruning should be promoted (SMITH *et al.*, 1997; BOUDRU, 1989).

Approach for the definition of the novel models of silviculture

The models of silviculture developed in this study encompass a set of alternatives based on a suite of criteria, namely composition, structure, production and management options. As already referred it is a conceptual framework that cannot be implemented directly but rather be used as a set of guidelines that help to develop the model of silviculture for one specific stand.

The ***composition*** of forest stands can be grouped in three broad classes: pure, permanent mixtures and temporary mixtures. ***Pure*** stands are constituted by one main specie and are adapted to all forest species. The ***permanent mixtures*** are suited to species with complementary interactions. Many admixtures can be considered for the Portuguese forest species. Examples are *Pinus pinea* x *Quercus suber*, *Pinus pinea* x *Quercus rotundifolia*, *Quercus suber* x *Pinus pinea*, *Quercus rotundifolia* x *Pinus pinea*, *Pinus pinea* x *Pinus pinaster*, *Quercus suber* x *Quercus rotundifolia*, *Quercus rotundifolia* x *Quercus suber*, *Pinus pinaster* x *Quercus suber*, *Pinus pinaster* x *Castanea sativa*, and *Castanea sativa* x *Pinus pinaster*. The ***temporary mixtures*** are of interest as one specie provides shelter to another specie and as the shelter specie can provide some income when it is removed (prior to full production of the main specie) as well as for soil, water, habitat, flora and fauna conservation. Examples of temporary mixtures are *Quercus rotundifolia* x *Pinus pinea*, *Quercus suber* x *Pinus pinea*, *Quercus suber* x *Pinus pinaster*, *Pinus pinea* x *Pinus pinaster*, and *Castanea sativa* x *Pinus pinaster*.

The permanent mixture of *Pinus pinea* x *Quercus suber* and *Quercus suber* x *Pinus pinea* can increase diversity both ecological and of production, and complement a periodical income (cork) with an annual one (pine cones). The mixed stands of *Quercus rotundifolia* x *Pinus pinea*, are interesting especially in the areas with low cone production, as temporary mixtures where *Pinus pinea* provides shelter for *Quercus rotundifolia*, or as permanent mixtures when soil, water, habitat, flora and fauna conservation is one of the target management goals. The *Pinus pinea* x *Pinus pinaster* mixture balances an annual production and income (cone) and a medium to long term production (timber), while *Quercus suber* x *Pinus pinaster* balances a short term production (cork) and a medium to long term production (timber). The admixture *Quercus suber* x *Quercus rotundifolia* and of *Quercus rotundifolia* x *Quercus suber*, are interesting in areas where both species have good aptitude for cork and fruit production or where site has niches for both species, increasing diversity and enabling to balance an annual production (fruit) with another periodical (cork). The mixed stands of *Pinus pinaster* x *Castanea sativa* and *Castanea sativa* x *Pinus pinaster* enable the diversification of timber products and reduce fire risk.

The most frequent ***structure*** in the Portuguese stands is the ***even aged*** (pure mainly and mixed to a lesser extent), which has advantages in terms of management (including timber harvest, cork debarking and fruit harvest). Yet, even aged stands have the disadvantage of the interruption of the production (and income) during a long period, because full production for fruit and bark stands (*Quercus suber*, *Quercus rotundifolia*, *Pinus pinea*) is reach at about 30-40 years or longer (potentially less if *Pinus pinea* trees are grafted); and for timber oriented stands *circa* 30-60 years (*Pinus pinaster*, *Castanea sativa*). Inversely, ***uneven aged*** stands production tends to be continuous in time. The stands are characterised by a periodical regeneration, depending on the number of cohorts and the duration of the harvest cycle. The proportion of the different cohorts has to be defined (LUNDQVIST *et al.*, 2019; O'HARA, 2014; SCHÜTZ, 1999). These systems have been developed mainly with shade tolerant species (SCHÜTZ, 2002). Yet, as long as the number of cohorts is not high they can be adapted to species less tolerant to shade (O'HARA, 2014; SMITH *et al.*, 1997), like *Quercus suber*, *Quercus rotundifolia*, *Pinus pinea* or *Pinus pinaster*, with 2 to 4 cohorts.

The target ***species proportion*** for a mixed stand should be defined when developing the model of silviculture (*prior* to its implementation), either in number of trees, basal area and/or crown cover. The minimum threshold for the secondary species is 25% of the number of trees and of crown cover, or 20% of the basal area, while the maximum threshold for the main species is 80% of the number of trees and crown cover or 75% of basal area (GONÇALVES, 2017). The silvicultural practices will progressively approach the stand structure to the target composition and species proportion. Similarly, for uneven aged stands the target ***cohort proportion*** has to be defined at the development of the model of silviculture. Recruitment of the individuals per cohort should ensure at least the minimum threshold defined. Silvicultural practices will enable a gradual approach to the target proportion of individuals per cohort (LUNDQVIST *et al.*, 2019; O'HARA, 2014; SCHÜTZ, 1997, 2002).

The ***spatial arrangement*** of the species in mixed stands and the cohorts in uneven aged systems can be by individual mingling or per group or per strip/line, or even the combination of the former two (O'HARA, 2014; SCHÜTZ, 1997). In practice, management is easier with per group or per strip/line spatial distribution and more cost-effective. Furthermore, in mixtures if natural regeneration is used, species tend to regenerate in the most favourable niches, thus rather than imposing a spatial arrangement it is advantageous to promote the recruitment of the advanced regeneration. Site and topography determines, at least partially, the type of mingling. In the temporary mixed stands is of primordial importance to adequate the spatial arrangement of the species to the removal of the temporary species, so that the damages on the individuals that will remain on the stand are minimised.

For forestations or afforestations the type of ***regeneration***, natural or artificial (seeding or planting) or the combination of both has to be equated. The type of regeneration is linked with the initial density, composition and structure and determine the silvicultural practices in time and space. For existing stands, its characterisation enables to evaluate which silvicultural practices are needed and their scheduling in the short time, which, in function of the target stand structure, will enable to evaluate their necessity at the medium and long term.

When a forestation or afforestation target structure is the uneven aged structure a gradual approach has to be considered. In a first step is planting or seeding or recruiting advanced regeneration the first cohort. An accessory stand (of other species, corresponding to a temporary mixed stand) can be installed to occupy the growing space and to generate some income. The second cohort, if possible of natural regeneration, is settled sometime after (determined for example by dividing the duration of the production cycle by the number of cohorts) and the accessory stand is cut.

New models of silviculture developed

Five general models of silviculture will be presented as function of stand structure: i) pure even aged, ii) permanent mixed even aged, iii) temporary mixed even aged, iv) pure uneven aged, and v) mixed uneven aged.

For the definition of the models of silviculture a set of assumptions was made: i) target crown cover for adult stands for fruit production is 40-60%, and for timber and protection 40-80%; ii) stem height between 2-4 m for fruit and bark production, and equal or larger than 4-6 m for timber production; iii) thinning method, intensity and frequency depends on stand structure and can vary both spatially and temporally; iv) pruning should remove about 1/3 of the length of the crown in mature trees and up to ½ in young vigorous trees; v) regeneration can be natural or artificial; vi) cuttings at the end of production cycle can be clearcut, clearcut with standards or uniform shelterwood system for even aged stands, and irregular shelterwood or selection system for uneven aged stands; vii) salvage cuttings can be considered to remove dead and diseased trees, whenever needed; viii) annual cone harvest, either manually or mechanically; ix) cork debarking in cycles of 9 or 10 years; x) production cycle ends when there is an accentuated decrease of cork (*Quercus suber*) or fruit (*Quercus suber*, *Quercus rotundifolia*, *Pinus pinea*) production, for *Pinus pinea* with mechanical harvest for a target diameter, and for timber when trees reach the target diameter or age.

All the models of silviculture include the following practices: control of spontaneous vegetation (CSV), thinning (T), pruning (P), regeneration (R) and cuts (C). For mixed stands it is included the number of species, proportion of each specie, the form and type of mixture (M) and for uneven aged stands the number of cohorts, proportion of individuals per cohort and their spatial arrangement (PIC).

As most stands of *Pinus pinea*, *Quercus rotundifolia* and *Quercus suber* are managed in agroforestry systems with fruit and bark as main productions, it was considered a target crown cover of 40-60%, a density between 80-150 trees/ha and a production cycle of 100-120 years. For timber oriented stands it was considered a target density at the end of the production cycle of 250-500 trees/ha, crown cover between 40-80% and production cycles depending on the target diameter (≥ 30 cm) or age (≥30 years). Stands with the main function of protection and/or conservation a target crown cover of 40-80%, density of 200-500 trees/ha and production cycles of 100-150 years can be considered.

Control of spontaneous vegetation should be done whenever needed, with the methods suited to management goals, site and legal restrictions (for details see (ALVES *et al.*, 2018)).

One or more thinning methods, intensity and frequency can be used, depending on stand structure and its dynamics (*cf.* Thinning and pruning).

Pruning should be done early in the production cycle (at the age of 3-10 years) to promote a straight stem, free of branches or forks up to 2-4 m for bark and fruit production and 4-6 m for timber production. This will enable to minimise the damages in the crown by mechanical equipment, facilitate mechanical fruit harvest, make cork debarking mainly in the stem, and improves quality and quantity of timber. Frequently, and especially in species with low epinastic control, formation pruning is needed. It should be done early in the production cycle (at an age of 10-30 years) so that the branches have small diameter, which enable a faster cicatrisation of the wounds.

The model of silviculture for *pure even aged* stands (Figure 1) considers an initial density of 100-300 trees/ha for fruit and cork oriented stands and 800-2500 trees/ha for timber oriented stands. This density is a compromise between having the highest possible crown cover at the early stages of development (and thus soil protection), a number of individuals that allows the selection of the individuals with the best productive potential traits and minimise costs with thinning, pruning and stump destruction of the species that sprout (*Quercus rotundifolia*, *Quercus suber* and *Castanea sativa*).

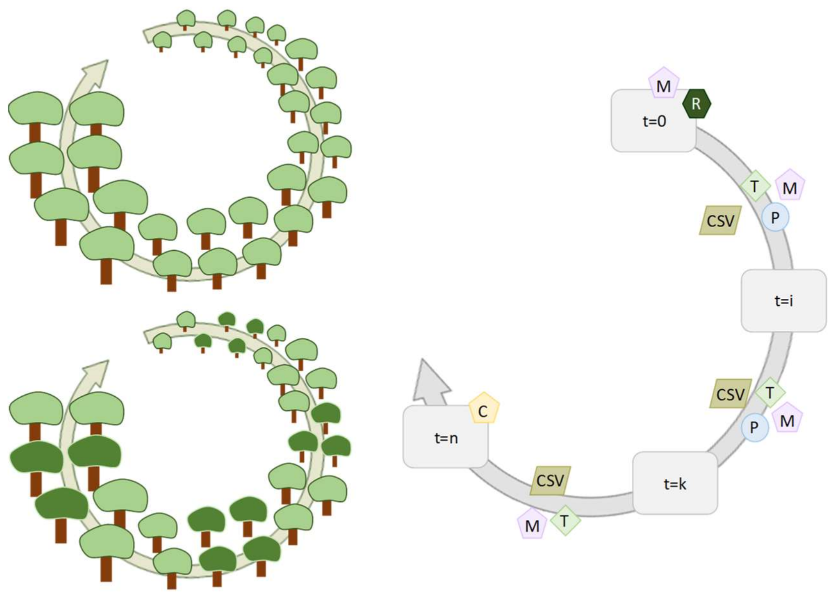

Figure 1 – Model of silviculture for even aged (right) pure (top left) and permanent mixed (bottom left) stands (where R is regeneration, CSV control of spontaneous vegetation, T thinning, P pruning, C cuts, M number of species, their proportion and spatial arrangement, t is time and 0, i, k and n moments in time)

The model of silviculture for *permanent mixed even aged* stands (Figure 1) is similar to the former, except in what regards the species and their proportions, form and type of mixture, which as to be defined. The mixture proportions per species encompass a wide range of options. Yet, considering the species traits and sites in Portugal, indicative proportions for admixtures of two species, for the main and secondary species are: 50:50, 60:40, 70:30 and 80:20. Other options are available. In any case the main specie should have a proportion between 50-80% and the secondary species among 20-50%. For mixtures of three or more species the proportion per specie is a compromise between species traits, regeneration and potential productions. The form of mixture can be individual mingling, per group, per strip/line (only for artificial regeneration) or a combination of the former two. In practice mixture per group is easier to manage. Also, if natural regeneration is used it is better to promote its form of mixture, rather than imposing a form difficult to achieve. As most Portuguese species are shade intolerant horizontal mixture type seems better suited than the vertical stratification, except for *Castanea sativa* as it is shade tolerant, so vertical stratification can be considered.

The model of silviculture for *temporary mixed even aged* stands (Figure 2) main goal is that the secondary species provide shelter to the main one and promote soil protection. The secondary species is cut when shelter is no longer needed, frequently at stem exclusion stage, providing an anticipated harvest. Interesting temporary admixtures are *Quercus suber* x *Pinus pinea*, *Quercus rotundifolia* x *Pinus pinea*, and *Pinus pinea* x *Pinus pinaster*, *Castanea sativa* x *Pinus pinaster*. For the former two an initial density of 300-400 trees/ha can be considered while for the two latter may be 300-600 trees/ha and 800-2500 trees/ha, respectively, with a proportion of 30% for the main specie and 70% for the secondary. However, other species and/or densities could be used. The management is focused on the main specie and no thinning and pruning is considered for the secondary one, except if the goal is attaining timber of small and medium dimensions for pines, in which case, if needed, it can be prescribed one thinning from below and one pruning. The secondary species is removed when the main species does not need shelter and/or the crown of the main specie starts to be confined (to avoid crown regression and to promote growth), which corresponds broadly to an age between 20 and 40 years, depending on the species and site quality.

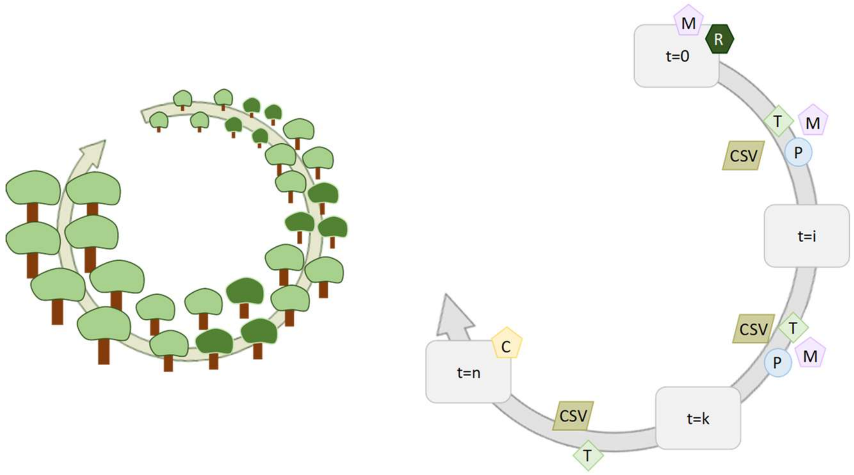

Figure 2 – Model of silviculture for even aged (right) temporary mixed (left) stands (where R is regeneration, CSV control of spontaneous vegetation, T thinning, P pruning, C cuts, M number of species, their proportion and spatial arrangement, t is time and 0, i, k and n moments in time).

For *pure uneven aged* stands the models of silviculture (Figures 3, 4, 5) were developed as function of the number of cohorts. Since the mature individuals of most species are shade intolerant and under a climate with periodical drought (summer) and with a wide variability of annual precipitation, it was considered that the number of cohorts better suited were 2, 3 and 4. Uneven aged stands are based on natural regeneration, which for the target crown cover and density should ensure a recruitment ≥ 50 trees/ha for the regeneration cohort for agroforestry systems and ≥ 250 trees/ha for timber oriented stands. Artificial regeneration can be considered especially when the number of individuals of natural regeneration is low or when conversion or transformation of the stand composition is the goal (for details see GONÇALVES *et al.*, 2008b). Examples of equilibrium frequencies per cohort in terms of crown cover and number of individuals for agroforestry systems and timber oriented stands are presented in Table 1. The frequency of each cohort should be equated as function of the management and production goals, species traits and site. The regeneration effort is dependent on the duration of the production cycle and the number of cohorts. For example, considering a production cycle of 120 years, the periodicity of regeneration will be about 60 years, 40 years and 30 years for uneven aged structures of 2, 3 and 4 cohorts, respectively while for a production cycle of 45 years will be around 22 years, 15 years and 12 years for 2, 3 and 4 cohorts, respectively. The longer the production cycle and lower the number of cohorts the wider the periodicity of regeneration. The spatial distribution of the individuals of the several cohorts can have an individual mingling or a per group arrangement, or even a combination of both. Though a per group distribution is easier to manage, it is better suited to promote the spatial arrangement of the natural regeneration and recruitment, rather than trying to impose a specific spatial distribution. Of importance is also to release the advanced regeneration cohort from competition of trees from oldest cohort which are at the end of the production cycle. The timely removal of the oldest cohort promotes the growth of the advanced regeneration individuals as well as the recruitment of the new cohort.

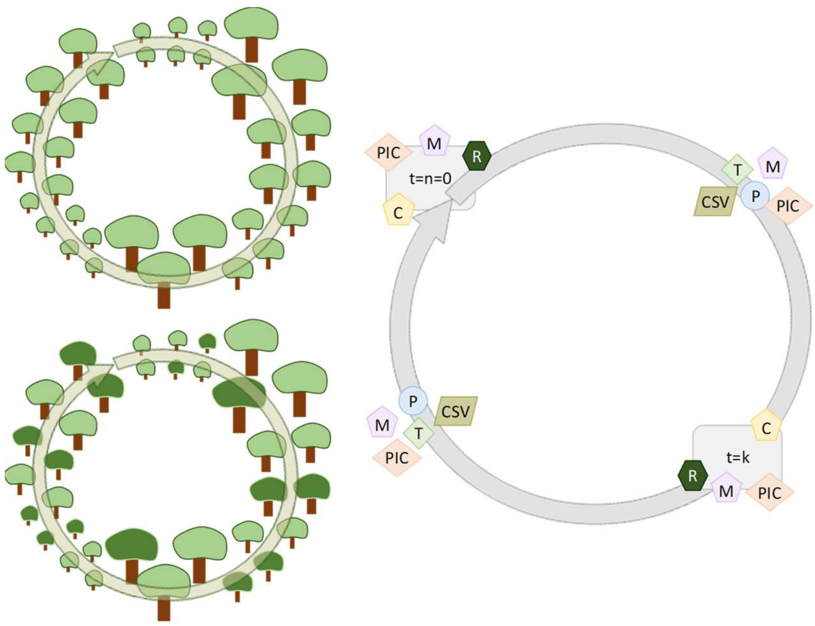

Figure 3 – Model of silviculture for uneven aged stand with 2 cohorts (right) pure (top left) and permanent mixed (bottom left) (where R is regeneration, CSV control of spontaneous vegetation, T thinning, P pruning, C cuts, M number of species, their proportion and spatial arrangement, PIC number of cohorts, proportion of individuals per cohort and their spatial arrangement, t is time and 0, i, k and n moments in time).

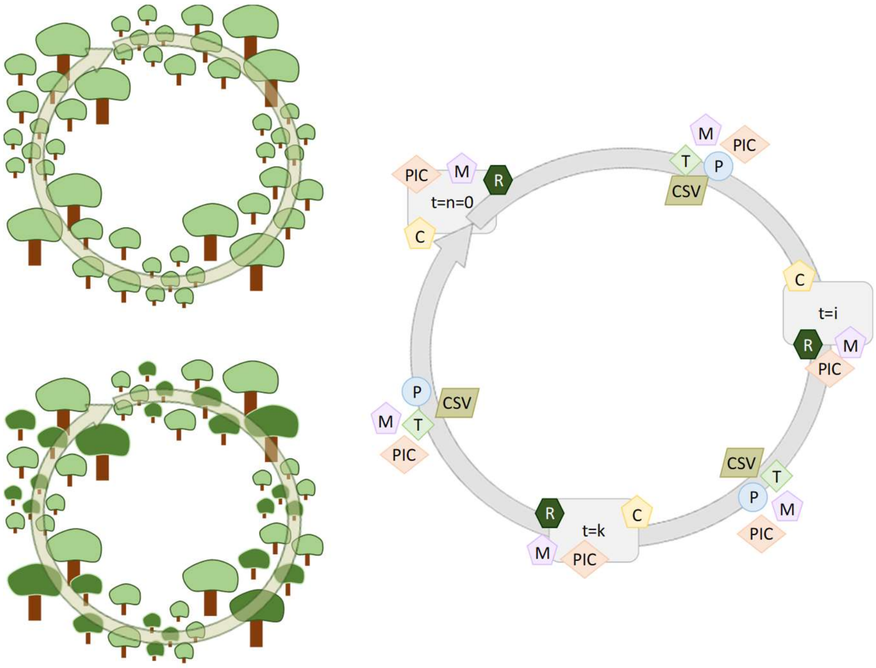

Figure 4 – Model of silviculture for uneven aged stand with 3 cohorts (right) pure (top left) and permanent mixed (bottom left) (where R is regeneration, CSV control of spontaneous vegetation, T thinning, P pruning, C cuts, M number of species, their proportion and spatial arrangement, PIC number of cohorts, proportion of individuals per cohort and their spatial arrangement, t is time and 0, i, k and n moments in time).

The mixed uneven aged stands models of silviculture (Figures 2, 3, 4) are similar to those of the pure ones, except in what concerns the composition, species proportion per stand and per cohort, form and type of mixture. The distribution of the cohorts presented for pure uneven aged stands can also be applied to the mixed ones (Table 1), yet the distribution of the species per cohort has to be considered. Two broad options can be considered: one where each cohort has all the species of the admixture and another where each cohort has only one specie.

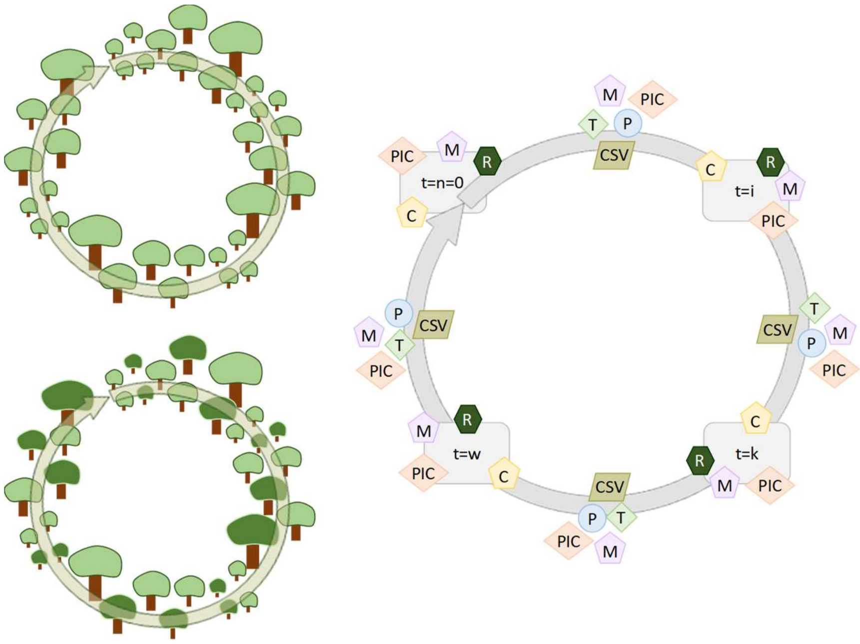

Figure 5 – Model of silviculture for uneven aged stand with 4 cohorts (right) pure (top left) and permanent mixed (bottom left) (where R is regeneration, CSV control of spontaneous vegetation, T thinning, P pruning, C cuts, M number of species, their proportion and spatial arrangement, PIC number of cohorts, proportion of individuals per cohort and their spatial arrangement, t is time and 0, i, k and n moments in time).

Examples of both options are presented in Figure 6 for uneven aged stands of 2, 3 and 4 cohorts. Moreover, a combination of both options can occur in practice due to the spatial distribution of natural regeneration. The distribution of species per cohort determines the form of mixture, either individual mingling, per group or a combination of both. Again it is better to promote the natural regeneration distribution pattern and with silvicultural practices, especially thinning, to promote a slow and gradual approach to the target spatial distribution.

Table 1 – Target proportion of crown cover (TCCc) and number of individuals per hectare for agroforestry systems (Ncaf) and timber oriented stands (Ncti) per cohort (where 1 is the oldest cohort and 4 the newest).

Number of cohorts	Ratio per cohort	Cohort	TCCc (%)	Ncaf (trees/ha)	Ncti (trees/ha)
1	1	1	100	80-150	250-500
2	2:1	1	67	27-50	167-335
		2	33	53-100	83-165
3	3:2:1	1	50	13-25	125-250
		2	33	27-50	83-165
		3	17	40-75	42-85
4	4:3:2:1	1	40	8-15	100-200
		2	30	16-30	75-150
		3	20	24-45	50-100
		4	10	32-60	25-50
	2:2:1:1	1	33	13-25	83-165
		2	33	13-25	83-165
		3	17	27-50	42-85
		4	17	27-50	42-85

The horizontal mixture seems better when compared with the vertical stratification for the type of mixture for most Portuguese species. The mixture proportion and/or the cohort frequency may, and sometimes is, not the target one. The approach to the target one is better achieved in thinning operations, and to a lesser extent with cuts, that promote the gradual, and many times slow, approach to the target composition and structure.

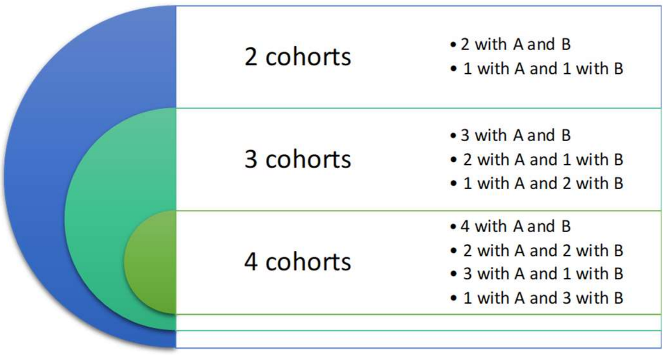

Figure 6 – Examples of the possible combinations of two species per cohort in uneven aged stands of 2, 3 and 4 cohorts (where A and B are forest tree species).

Discussion

The models of silviculture published are frequently for pure even aged stands, while those for mixed and uneven aged are scare. On one hand, for pure even aged stands is easier to make generalisations whereas for mixed and uneven aged ones is difficult due to its diversity and specificity. On the other hand, though there are some examples of models of silviculture for mixed and/or uneven aged stands it is not viable to develop all the possible alternatives, or even the most frequent, stand structures due to their wide number (O'HARA, 2014).

For Portuguese forest species several models of silviculture were published for pure even aged stands (CORREIA and OLIVEIRA, 2003, 1999; LOURO *et al.*, 1999). Those for permanent mixed and uneven aged developed by GONÇALVES *et al.* (2008a) have less details regarding mixture proportions, form and type of mixture, number of cohorts and the spatial arrangement of the species and cohorts than those of this study.

In Portugal the national forest inventory (IFN6, 2019) and several studies (ALEGRIA and TOMÉ, 2013; GONÇALVES and OLIVEIRA, 2010) indicate that mixed and uneven aged stands exist in a significant area. Thus, there is the need to define models of silviculture for those stand structures. The published models of silviculture follow the traditional rather inflexible frameworks and timeframes for the silvicultural practices and have somewhat high initial densities for stands managed as agroforestry systems (CORREIA and OLIVEIRA, 1999; LOURO *et al.*, 1999), which makes it difficult to accommodate other productions, climate change and diversity.

The models of silviculture at local scale developed in this study, under a conceptual framework, had the main goal of providing flexible and broad models that are able to accommodate a wide range of stand structures, sites and management goals. They were focused on the main Portuguese forest species under agroforestry and timber oriented systems, though they can be easily used for other functionalities and/or species. They were developed considering a set of assumptions (*cf.* New models of silviculture developed) which are flexible enough to be generalised to all stand structures considered. The silvicultural practices are presented as a suite of options that enable to accommodate the stand structure dynamics as well as the management goals. The stand structure changes deriving in different interactions between trees (FORRESTER, 2014) can be accompanied by the models due to its flexibility. Also, the target stand structure can be attained by a gradual and continuous approach with a set of silvicultural practices (O'HARA, 2014; SCHÜTZ, 2002) as the models are flexible enough to implement changes in the silvicultural operations methods, techniques, intensity and periodicity.

The number of species in a stand is linked to their complementarity (FORRESTER and BAUHUS, 2016). For the sake of simplicity, the models of silviculture for mixed stands were presented for two species. Yet, they can be easily defined for three or more species, as long as target composition is defined. However, considering that most forest species in Portugal are shade intolerant (CORREIA and OLIVEIRA, 1999; FERREIRA *et al.*, 2001) care should be taken in what regards density and structure to avoid stresses, especially those linked to drought (GROSSIORD *et al.*, 2014). Similarly, the models of silviculture for uneven aged stands were defined for 2, 3 and 4 cohorts. According to several authors (LUNDQVIST, 2017; O'HARA, 2014) these number of cohorts are better suited for shade intolerant species, especially in sites with periodical drought.

The novelty of the models of silviculture presented in this study is that they were developed for the main Portuguese forest species focused on agroforestry or timber oriented systems under a conceptual framework. The advantages are that it enables to define the model of silviculture for one stand after target stand structure is chosen. Its flexibility in what concerns silvicultural practices, timing, methods, intensities and frequencies, is able to accommodate the dynamics of stand structure in space and time. The main disadvantage that can be pointed out is the need of skilled foresters to define and update the model of silviculture.

Conclusions

The models of silviculture developed in this study were based on five stand structures: pure even aged, mixed even aged, temporary mixed even aged, pure uneven aged and mixed uneven aged, with composition of one or two species and structure with 2, 3 or 4 cohorts. The assumptions for agroforestry systems of *Pinus pinea*, *Quercus suber* and *Quercus rotundifolia* were a target crown cover of 40-60%, density between 80-150 trees/ha and a production cycle of 100-120 years while for timber oriented stands were crown cover of 40-80%, density 250-500 trees/ha and a production cycle for a target diameter equal or larger than 30 cm or a target age equal or larger than 30 years. These baselines were chosen for the sake of simplicity, yet many other target thresholds can be used.

The choice between the pure and mixed stands is related to dispersal of yield per one or more productions while between even aged and uneven aged stands is related to the interruption or not of the production. Both mixed and uneven aged stands promote diversity and protection against abiotic and biotic disturbances.

The model of silviculture better suited to a stand has to be equated as function of the management and production goals, species and site. There are no good or bad models of silviculture, rather some are better suited than others. Moreover, the models of silviculture developed in this study cannot be used directly rather they should be used as guidelines to develop the model of a silviculture to a specific stand, which should be flexible to accommodate stand structure dynamics in the periodical revisions that have to be made.

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