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Regeneration of *Pinus* and *Quercus* After Fire in Mediterranean-Type Ecosystems: Natural Mechanisms and Management Practices

Sandra Oliveira* e Paulo Fernandes**
*Investigadora
Joint Research Centre of the European Commission. Institute of Environment and Sustainability. Land management and Natural Hazards Unit. Via Enrico Fermi, 2749, 21027 Ispra (VA) ITALY
** Investigador Auxiliar
Centro de Investigação e de Tecnologias Agro-Ambientais e Biológicas (CITAB) e Departamento de Ciências Florestais e Arquitectura Paisagista. Universidade de Trás-os-Montes e Alto Douro. Apartado 1013, 5001-801 VILA REAL

Abstract. Fire is a natural and frequent event in Mediterranean-type ecosystems. Changes in land use have altered fire regimes, disturbing the natural processes of post-fire regeneration of vegetation. The management of fire-prone and fire-affected areas can be achieved by combining natural and artificial processes of vegetation recovery.

Pinus and *Quercus* species occur naturally in these areas and are most affected by fire. The contrasting mechanisms used by these species to overcome the effects of fire, mainly different reproduction strategies, are examined and the results obtained in previous studies reviewed. Pines are usually obligate seeders and rely on the surviving seed bank, usually protected in canopy cones, for their regeneration. Oaks are mainly resprouters and have higher resilience capacity, recovering more rapidly, but with time these differences are attenuated because *Pinus* grow faster.

The natural processes of regeneration can be enhanced by targeted management practices. Prescribed burning, applied to modify fuel quantity and structure and prevent high-severity fires, is widely used in Mediterranean-type ecosystems and its potential effects are discussed. The process of seeding and seedling plantation and the application of techniques to improve seedlings performance are described, however further investigation concerning the potential impacts of their application is required.
Key words: Forest fire; obligate seeder; resprouter; post-fire regeneration; management practices

Regeneração de *Pinus* e *Quercus* Após o Fogo em Ecossistemas de Tipo Mediterrânico: Mecanismos Naturais e Técnicas de Gestão

Sumário. O fogo florestal é um evento natural que ocorre com frequência em ecossistemas de tipo mediterrânico. Mudanças recentes no uso do solo alteraram os regimes do fogo, perturbando os processos naturais de regeneração da vegetação após a sua ocorrência. A gestão das áreas mais propícias ou afectadas pelo fogo florestal pode ser alcançada através da combinação de processos naturais e artificiais de restabelecimento da vegetação.

Corresponding Author E-mail: sisoliveira@hotmail.com

Os diferentes mecanismos usados pelas espécies dos géneros *Pinus* e *Quercus* para fazer face ao fogo, nomeadamente as estratégias de reprodução, são analisados e sumariam-se os resultados obtidos em estudos anteriores. Os pinheiros dependem das sementes que sobrevivem ao fogo, usualmente protegidas em pinhas, para se regenerar. Os carvalhos respondem vegetativamente, têm maior capacidade de resiliência e colonizam a área mais rapidamente, mas estas diferenças são atenuadas com o tempo porque as espécies de *Pinus* crescem mais rapidamente.

Os processos naturais de regeneração podem ser reforçados pela utilização de práticas específicas e adequadamente planeadas. O fogo controlado, aplicado com o intuito de modificar a quantidade e estrutura do combustível e prevenir a ocorrência de fogos de maior intensidade, é amplamente aplicado em ecossistemas de tipo mediterrânico e os seus potenciais efeitos são discutidos.

A introdução de vegetação, por sementeira ou plantio, e a aplicação de técnicas para melhorar o desempenho das mesmas são descritas, sendo no entanto necessário investigar em maior pormenor quais os potenciais impactos da aplicação destas técnicas.
Palavras-chave: Fogo florestal; regeneração pós-fogo; regeneração seminal; regeneração vegetativa; práticas de gestão

Régénération de *Pinus* et *Quercus* Après le Feu Dans les Écosystèmes de Type Méditerranéen: Mécanismes Naturels et Techniques de Gestion

Résumé. Le feu forestier est un événement naturel et cyclique dans les écosystèmes de type méditerranéen. Des changements récents de l'usage du sol ont modifié les régimes du feu, en dérangeant les processus naturels de régénération de la végétation après son occurrence. La gestion des surfaces les plus propices ou affectées par le feu forestier peut être atteinte par la combinaison de processus naturels et artificiels du rétablissement de la végétation. Les espèces *Pinus* et *Quercus* sont affectées par les feux forestiers. Les différents mécanismes utilisés par ces espèces pour survivre aux effets du feu, notamment les stratégies de reproduction, sont analysés suivant les résultats obtenus lors des études précédentes. *Pinus* dépendent des semences qui survivent au feu, usuellement protégées dans des cônes, pour se régénérer. *Quercus* repoussent, ont une plus grande capacité de résilience et colonisent le secteur plus rapidement. Ces différences sont, néanmoins, atténuées au cours du temps parce que les espèces de *Pinus* grandissent plus rapidement.

Les processus naturels de régénération après les feux forestiers peuvent être renforcés par l'utilisation de pratiques spécifiques et appropriément planifiées. Le feu contrôlé, appliqué pour modifier la structure et quantité de végétation et empêcher des feux forestiers plus sévères, utilisé extensivement pour les écosystèmes de type méditerranéen et ses potentiels effets, sont discutés. L'introduction de végétation, par semis ou plantation, et l'application de techniques pour améliorer leur performance sont décrites, mais il est nécessaire d'une plus grande recherche sur les impacts de l'application de ces techniques.
Mots clés: Feu forestier; régénération par semence; régénération végétatif; régénération après le feu; pratiques de gestion

Introduction

Fire is a widespread phenomenon that can cause highly damaging ecological, economic and social effects (FAO, 2001; KONSTANDINIDIS *et al*., 2005). Fire affects the biogeochemical properties of the soil, the hydrology and geomorphology of the area, influencing the vegetation cover and, consequently, the characteristics of subsequent fires (WHELAN, 1995).

In Mediterranean-type ecosystems, fire is a natural and ancient occurrence

that plays an important role in shaping vegetation communities and landscapes, controlling age, structure and species composition (TRABAUD, 1994; NE'EMAN *et al*., 2004). The Mediterranean eco-region is defined by climatic and bioclimatic similarities: the climatic conditions define a pattern of rainy and mild winters, which allow the growth of vegetation, followed by relatively long and dry summers, when the vegetation grown during winter becomes more flammable due to the dry period (CALVO *et al*., 2003). In these ecosystems, fires tend to occur from late spring to early autumn, at intervals of 5 to 50 years (WHELAN, 1995).

The present vegetation of Mediterranean-type ecosystems results from many years of evolution, during which plants evolved mechanisms to overcome the effects of fire (TRABAUD, 1994; CALVO *et al*., 2003). In fire-prone ecosystems, many plants are adapted to fire (ESCHEL *et al*., 2000) and are able to resist to the exposure to fire and its effects, plant recovery after fire is rapid and pre--fire communities are restored mainly from endogenous sources (MORENO and OECHEL, 1994).

During the last few decades, changes in land use have altered the characteristics of fire, human-caused fires are becoming more frequent and in many areas the fire regime has changed (PAUSAS and VALLEJO, 2004). In the Mediterranean Basin, fires have been mainly of anthropogenic origin (NE'EMAN *et al*., 2004). According to FERNANDES and BOTELHO (2004), wild-fires burn each year 700.000 to 1.000.000 hectares of land in the Mediterranean Basin alone. In the other areas where Mediterranean-type ecosystems occur, fire is also a major disturbance (Figure 1).

The management of affected and fire-prone areas requires the understanding of both the beneficial and adverse effects of fire, which depend on the type of ecosystem considered and in the characteristics of the fire itself and the fire regime. Moreover, the maintenance of life forms, specifically vegetation, in these areas, requires research into the ecological characteristics that enable the survival or regeneration of species in fire-disturbed environments.

The purpose of this paper is to identify valuable methods for regenerating native vegetation after fire, and discuss the success of the practices already in use in Mediterranean-type ecosystems affected by fire, based on previous studies. In order to understand the results of these methods, it is necessary to analyse the major effects of fire in soil and nutrients, hydrology and vegetation. The maintenance and recovery of vegetation in areas affected by fire are related either to the survival of species during the passage of fire, or by their tolerance to the post-fire environmental conditions (WHELAN, 1995). Thus, the study of the natural regeneration mechanisms and the application of artificial ones require the understanding of the different strategies used by plant species to persist in face of fire. *Pinus* and *Quercus* genera often dominate the natural plant communities found in the Mediterranean-type ecosystems of the Northern Hemisphere and are among the plants most affected by fires (FAO, 2001). The strategies of *Pinus* and *Quercus* species are compared, taking into consideration that the vegetative characteristics of some of these species are correlated with the fire regime and the post-fire regeneration strategies (NE'EMAN *et al*., 2004).

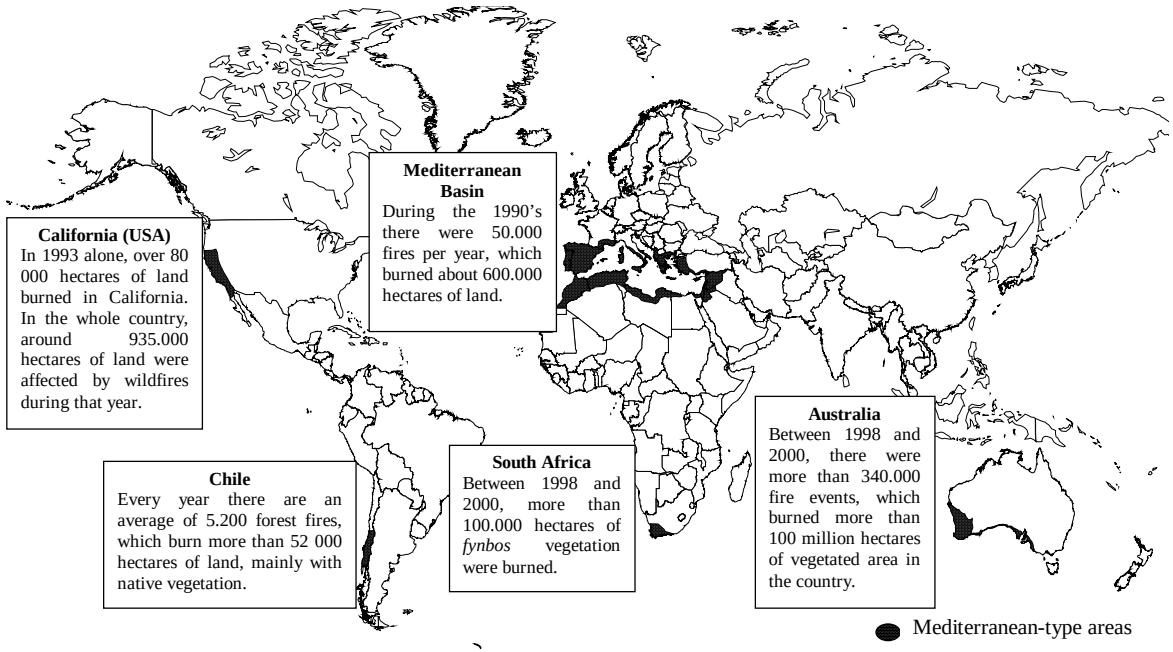

Figure 1 – Location of Mediterranean-type areas and fire statistics. Source: FAO (2001)

Effects of fire on vegetation

The effects of fire on vegetation are the most obvious impacts of burning (CALVO *et al.*, 2003). Plant material constitutes a major component of the combustion process and living tissues are affected in several ways by the heat caused by fire, specifically by cell and tissue death, disruption of metabolism and disruption of nutrient and water transport (WHELAN, 1995). Plants can survive the direct effects of fire, or they may tolerate the post-fire environmental conditions through several protective mechanisms, as described in table 1.

Regardless of the changes in soil characteristics, nutrient resources, hydrology and vegetation, individual plants may increase their productivity, flowering, establishment of seedlings and seed-dispersal distances after fire (WHELAN, 1995). However, this is dependent on fire characteristics and on the conditions of the vegetation by the time the fire occurs, which varies in space and time.

Mechanisms of regeneration and management practices

Natural strategies of vegetation regeneration, when it is possible to develop them, can bring ecological advantages and prove beneficial for the process of post-fire recovery. KRUSE *et al.* (2004) suggest that long-term stabilization of forest soils and the protection of streams from siltation require the re-establishment of the native plant community.

Table 1 - Protection mechanisms of plants in face of fire, implications for their efficacy and examples of species that exhibit these mechanisms. Based on WHELAN (1995)

Protection Mechanisms	Implications	Species (e.g.)
Bark and Vegetative insulation	Depends on thickness, which varies proportionally to plant size, and thermal properties. Fire intensity, fire frequency (related to bark recovery) and season (related to degree of hydration) influence the efficiency of this mechanism.	*Quercus suber* *Eucalyptus cypellocarpa*
	Certain parts of the plant (living cambium) are protected from heat by insulation (e.g. through bark).	*Xanthorrhoea* *Protea laurifolia*
Roots and underground stems	Plant species with lignotubers, which protect buds and store energy required for sprouting. It depends on the size of lignotuber, the depth of lignotuber beneath soil surface and fire frequency (related to the replacement of energy spent and buds).	*Eucalyptus*
Height above ground	Peak temperature decreases with height. Taller plants are less susceptible to suffer direct effects of understorey fire.	
Seeds	The protection of seeds by burial in soil or enclosure within fruits in canopy. Depends of fire intensity.	*Conifers*

In some cases, the purpose of the regeneration of vegetation is the economical exploitation of the land and, thus, plantations of fast-growing trees are preferred.

It is possible to combine both ecological and economic benefits of regeneration, either natural or artificial, of these groups of species. PAUSAS *et al.* (2004) described the use of pine and oak species as potential restoration tools for degraded areas in Spain, based on the complementary features of both groups. BARTON (1999) analysed the effects of fire in pine and oak communities in Arizona and concluded that these species exhibit contrasting mechanisms to persist in the face of fire and the uneven fire regimes that currently occur strongly influence the balance between the two groups of species. Even if in some cases the natural regeneration of these species doesn't accomplish all the requirements of land recovery, these processes should still be the starting point of the practices applied, which can be improved by artificial methods.

Natural regeneration of vegetation

The response of vegetation to fire depends on its characteristics before fire, the season when fire occurs, the intensity of fire and the concentration of ash, weather parameters, the physical-chemical alterations of soil due to fire and the animal populations associated with the habitat (WHELAN, 1995; BARTON, 1999; CALVO *et al.*, 2003; SILVA and REGO, 2007, TSITSONI, 1997). Even though the natural regeneration of vegetation varies significantly among areas and with time of the year as a result of these factors, the capacity and speed of recovery of a burned area greatly depends on the regeneration strategy of the species present before the occurrence of fire (CALVO *et al.*, 2003). Plant species have evolved contrasting strategies for persisting in fire-prone environments, which can be by seedling establishment, resprouting or a combination of both (FUENTES *et al.*, 1994; BARTON, 1999). The post-fire survival and recovery of plants is also linked to their morphology (FERNANDES and BOTELHO, 2004). *Pinus* and *Quercus* species display contrasting reproductive strategies to deal with the impacts of fire, which influence the post-fire succession of these species and the evolution of plant communities (PAUSAS *et al.*, 2004), which have in turn evolved, at least partially, as an adaptation to specific fire regimes, revealed by its vegetative characteristics (NE'EMAN *et al.*, 2004).

Most pines are obligate seeders, and often their post-fire regeneration relies on the seed bank contained in serotinous cones, which protect the seeds and open only after fire (FUENTES *et al.*, 1994; HABROUK *et al.*, 1999; TORRES *et al.*, 2006). The protection of seeds in cones and their release after a fire facilitate the re-colonisation of the burned area (VERKAIK and ESPELTA, 2006). In the case of *Pinus pinaster*, the seeds contained in the cones are released at fire-induced temperatures of about 50ºC (FERNANDES and RIGOLOT, 2007). In *Pinus halepensis*, the seeds from serotinous cones germinate naturally in post-fire environments (NE'EMAN *et al.*, 2004). However, cone serotiny is usually absent from pine species under low-severity fire regimes that rely on tree survival through tissue insulation (KEELEY and ZEDLER, 1998).

By contrast, oaks are resprouters and regenerate from shoots on the rhizome or

the stem of subterranean roots (CALVO *et al.*, 2003). Oaks are known for their ability to dieback and resprout (FRANKLIN *et al.*, 2003) and show very high resilience (PAUSAS *et al.*, 2004). Nevertheless, resprouting may be delayed for several months, depending on the season, the intensity of fire and on the size of the plants (MORENO and OECHEL, 1994; QUINTANA *et al.*, 2004); besides, the resprouting success is dependent on the mortality of adult plants due to fire (ESCHEL *et al.*, 2000). The post-fire environment provides better conditions for seedling establishment, such as light, soil resources and less competition with other plants (MORENO and OECHEL, 1994). According to PAUSAS *et al.* (2004), high fire severity increases post-fire nutrient concentration and benefits pines regeneration. Nonetheless, the canopy seedbank takes between 10 to 15 years to build up. In the case of high frequency of fires, the seed bank has no time to form and post-fire regeneration is not possible by seeding (TSITONI, 1997; CALVO *et al.*, 2003; ZAGAS *et al.*, 2004). Pines are often more resistant to fire (BARTON, 1999) but the establishment of seedlings requires more time, thus their regeneration is slower. Additionally, the number of seeds can be reduced by predation of birds and rodents (FRANKLIN *et al*, 2003; ZAGAS *et al.*, 2004).

Resprouters dominate the first phase of recolonisation after fire, but subsequently lose dominance in favour of obligate seeders (MONTES *et al.*, 2004); this means that *Quercus* communities recover more rapidly than *Pinus* communities, but these differences are attenuated within few years after the occurrence of fire (CALVO *et al.*, 2003). The authors also report that in the first post-fire year the proportion of bare soil decreases with time and it is higher in *Pinus* communities than in *Quercus* communities. In oak communities, understorey species (herbaceous) are more abundant and species richness is high, while in pine communities herbs are practically inexistent, and therefore there is no significant competition between understorey and woody species (FRANKLIN *et al.,* 2003). In pine populations, the ratio of small to large stems decreases slightly, while oak populations evidence higher skewness towards small stems (BARTON, 1999).

The success of regeneration of different *Pinus* species will depend to a great extent of the resistance of seeds to fire, on the effects of fire severity on seed viability and on the seeding phenology (HABROUK *et al.,* 1999). *Quercus* species must resist to fire by protecting living tissues from which resprouting will be possible (SILVA and REGO, 2007), besides the influence of the environmental post-fire conditions.

The different post-fire regeneration strategies of *Pinus* and *Quercus* can complement each other and are a potential resource for the successful recovery of burned areas.

Other management practices

The natural regeneration of vegetation may not fulfill all the ecological and economic requirements for the recovery of certain areas affected by fire. It is acknowledged that high-severity fires and the slow establishment of certain plant species cause severe modifications of the environmental conditions (PAUSAS *et al.*, 2004), which play a decisive role in the early phase of establishment of a plant after it

germinates (QUINTANA *et al.,* 2004). Furthermore, the characteristics of the soil, specifically the amount of organic matter, and the position of the hillside can affect natural regeneration (TSITONI, 1997). When there is an important risk of soil loss by erosion, artificial methods can be applied to assist the regeneration of vegetation after the occurrence of fire (FERNANDEZ-ABASCAL *et al.*, 2003). The application of management tools prior to the occurrence of fires is also widely used, specifically prescribed burning in fire-prone areas. This practice will be presented first, considering its importance and extensive use.

Prescribed burning

Prescribed burning is one of the most common practices applied in fire-prone areas (CARTER and FOSTER, 2004) to reduce fuel loads and, thus, the occurrence of high-intensity fires (FERNANDES and BOTELHO, 2003; MOREIRA *et al.*, 2003). Prescribed fires in forests are usually low intensity fires that burn primarily in surface fuels and leave a high percentage of overstorey trees alive. These are normally set in the dormant season of the vegetation, when moisture levels are higher and the fires are easier to control (BAKER and SHINNEMAN, 2004; CARTER and FOSTER, 2004). The use of prescribed burning after tree harvesting to eliminate woody debris and forest floor can help natural regeneration or site preparation for planting or seeding.

Previous studies reveal contrasting results for the use of fire as management tool. MOREIRA *et al.* (2003) showed that prescribed burning in *Pinus pinaster* stands in Northern Portugal increases understorey regrowth after fire but doesn't affect significantly the vegetation structure in the long-term. CARTER and FOSTER (2004) concluded that the use of this management practice in southern pine forests brings beneficial effects, such as the removal of logging debris, the reduction of wildfire risk and the increase in the abundance of certain understorey plant species. This is due to increases in available nutrients that result from low-severity fires and these, in turn, are captured by understorey vegetation and help restore ecological conditions. However, burning also releases carbon to the atmosphere and may alter, in the long-term, the available nutrients in the soil, influencing negatively the overall productivity of the forests.

FRANKLIN *et al.* (2003) suggest that prescribed burning is not an effective management tool in *Quercus* forests that already have strong succession processes. The relationship between bark thickness and stem diameter is quite variable in oaks (HENGST and DAWSON, 1994), which has implications on the possibility and conditions of using prescribed burning. BARTON (1999) concluded that in combined forests of *Quercus* and *Pinus,* repeated prescribed burning should reduce the dominance of oaks in the short-term. WHELAN (1995) refers the extinction of obligate seeders in case of too frequent fires and the introduction of weeds as possible consequences of prescribed burning. On the other hand, fire exclusion, extensively practiced in North America in the past, increases fuel loads and stand structure and alters subsequent fire behaviour, with negative effects in forests (BARTON, 1999).

RIGGAN *et al.* (in MORENO and OECHEL ed., 1994) argued that the

consequences of "managing fire with fire" in Southern California chaparral can alter the impacts of the fire regime and reduce the risk of catastrophic events caused by high severity fires. FERNANDES and BOTELHO (2004) concluded that prescribed fire reduced by 96% the potential intensity of wildfires occurring under extreme weather conditions in pine forests of northwestern Portugal, contributing to fire hazard reduction without causing damaging effects to the ecosystem. The results of the use of prescribed burning to reduce fire hazard vary considerably by vegetation type and are affected by weather conditions during and after the fire (FERNANDES and BOTELHO 2003).

The ecological impacts implied by the use of fire as a management tool to reduce the potential impacts of wildfires in fire-prone areas must be investigated for the specific areas where it can be applied.

Artificial techniques

Seedling is an attractive technique because of its low impact, low cost and easy application in extensive areas (PAUSAS *et al.*, 2004). Nevertheless, sowing can have a negative influence on the natural recovery of species through competition (FERNANDEZ-ABASCAL *et al.*, 2003). Seed predation, usually by birds and rodents, can reduce the efficacy of this method, which can in turn be overcome by over doubling the quantity of seeds (ZAGAS *et al.*, 2004).

The use of mulch can increase the germination rate and plant establishment when seeding occurs, or even increase seedling density without seeding (PAUSAS *et al.*, 2004). Nevertheless, it is possible that mulch contains seeds of non-native species, which can outcompete native ones (KRUSE *et al.*, 2004).

The plantation of seedlings has different rates of success, depending on the species used. PAUSAS *et al.* (2004) concluded that *Pinus* evidence higher survival and earlier growth than *Quercus*, and suggested it was probably due to higher water use efficiency of pines. In this case, it is possible to improve performance of oak seedlings through water harvesting and irrigation techniques (increasing water availability). Other restoration techniques can be used to assist the introduction of vegetation in fire-affected areas, such as fertilisation and soil amendments (reducing the limitation of underground resources and increasing soil water holding capacity), tree shelters (reducing evaporative demand), nurse plants, seedling preconditioning (avoiding transplantation shock) and controlled grazing (TSITONI, 1997; PAUSAS *et al.*, 2004). According to VERKAIK and ESPELTA (2006), thinning can also be recommended in pine forests to reduce fire occurrence and intraspecific competition, in areas overstocked and threatened by the occurrence of new fire events. Finally, one must not forget that species characteristics and site conditions influence the regeneration ability of plants (ESPELTA *et al.*, 2003) and must be taken into account when planning management techniques.

Conclusion

The effects of fire in Mediterranean-type ecosystems vary considerably. The recovery of these areas requires the understanding of the effects of fire in each specific area, in order to apply the most appropriate methods.

The natural regeneration of vegetation in areas affected by fire brings evident benefits, considering the intrinsic relation between the characteristics of the vegetation and the environmental conditions. Furthermore, the different mechanisms used by species, specifically obligate seeding and resprouting, can be combined to achieve better results.

Anthropogenic intervention may be required to support natural processes, however further investigation of potential impacts of the application of artificial techniques is required.

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