Forest Ecology and Management 429 (2018) 384–393

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Quercus suber cork as a keystone trait for fire response: A flammability analysis using bench and field scales

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ARTICLE INFO

Keywords:
Fire severity
Fire vulnerability
Corkback roughness
Cork quality
Porosity

ABSTRACT

Quercus suber (cork oak tree) is an excellent epicormic resprouter that can keep cambium alive after high-intensity fires because of its plan traits, mainly its thick cork. Although tree bark harvesting is an important source of income, it may reduce protection against wildfires. This study aims to identify stem and cork characteristics that affect the probability of reaching lethal cambial temperature and hence the probability of survival of living tissues. Cork flammability was analyzed using a sample set comprised of 120 cork specimens and 120 cork pieces. Five experimental fires were used to test the results obtained at bench scale.

Bench-scale flammability experiments could not simulate the real heat spread and presence of highly volatile isoprenoids. The results revealed differences in cambial temperature and lethal temperature rate (LTR) at both scales according to corkback roughness and cork quality. Peak cambial temperature and LTR show an increase in stems characterized by maximum roughness and worse cork quality. The LTR measurements showed a 30% difference between bench and field scales (0.35 mm s^{-1} and 0.5 mm s^{-1}, respectively). The findings indicate that corkback roughness, cork thickness, cork porosity and cork quality could influence the vulnerability of cork oak forests to wildfires. A negative correlation was found between total thickness and cambial temperature. A total thickness of over 3.7 cm prevented reaching lethal cambial temperature. Forest managers can use this information to define silviculture and design forest treatments with a view to reducing fire severity and mitigating the ecological and socioeconomic impacts of fire in cork oak forests.

1. Introduction

Forest fires are an active element in the configuration and shaping of a wide variety of fire-prone ecosystems (Abrams, 1992). Therefore, fire has played a keystone role in the shaping of the heterogeneous Mediterranean landscape (Pausas and Verdu, 2005). Although low-severity wildfires could be beneficial for natural regeneration, climate change and anthropic factors have increased the frequency and severity of large fires (Cardil et al., 2014) and ecological and socioeconomic impacts on natural resources (Rodríguez y Silva et al., 2012; Chuvieco et al., 2014). In this sense, catastrophic wildfires have ravaged large areas of Chile, Portugal, Spain and the United States, causing important impacts at landscape scale (Molina et al., 2017a, 2018).

Bark is one of the most important non-timber forest products in many Mediterranean countries (Catry et al., 2012). The cork oak tree (*Quercus suber* L.) is the only European tree used for the commercial exploitation of bark (cork) (Moreira et al., 2007). However, wildfires are an increasing concern in the Mediterranean Basin (Pausas and Fernández-Muñoz, 2012) as they cause a range of social, economic and ecological impacts. Burned cork oak forests have a negative economic impact because the charred bark loses its value and bark productivity decreases (Catry et al., 2012). The cork cycle or periodical removal of cork from the cork oak stem takes place every 9–12 years depending on cork productivity. There is a significant difference between the first harvest (virgin cork) and subsequent harvests. While virgin cork is irregular in structure, thickness and density, first reproduction cork is of insufficient quality for cork stoppers and second and subsequent reproduction cork can be employed to manufacture natural discs and stoppers (Pereira, 2007). For many centuries, cork has proved to be the most effective closure for wine, as it protects its qualities and allows it to develop and improve over time (Silva et al., 2005).

Fire regime does explain a very important proportion of bark thickness variance (Pausas, 2017). In spite of being considered a highly fire-resilient species, some studies suggest that *Q. suber* responses to fire vary depending on the characteristics of the bark and tree and fire behavior (Catry et al., 2012; Pausas, 2015). The resistance of cork trees

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https://doi.org/10.1016/j.foreco.2018.07.041
Received 29 May 2018; Received in revised form 19 July 2018; Accepted 22 July 2018

to wildfire depends on several factors, such as species-characteristics (e.g., cork thickness, depth of sapwood), tree-variables (e.g., diameter at breast height, age, growth rate) and abiotic factors (e.g., topography, meteorology) (Whelan, 1995; Pinard and Huffman, 1997; Frejaville et al., 2013). Therefore, brush clearing from understory could greatly reduce fire severity, the probability of living tissues reaching lethal temperature and cork losses, as well as promote cork regeneration, particularly in the most susceptible areas. According to regional legislation (Law of 26 September 1988 in Andalusia, Spain), brush must be cleared in an area of at least 2 m around the tree stem just before debarking. Trees located in sites with a higher proportion of south-facing slopes are also more vulnerable to fire (Catry et al., 2012) and infestation by *Coroebus undatus* Fabr. (Du Merle and Attié, 1992).

Bark thickness is a major factor affecting the resistance of trees to fire as thick cork is a clear mechanism for protecting phellogen and cambium from the heat generated by fires (Pausas, 1997; Catry et al., 2010; Dehane et al., 2015). Moreira et al. (2007), for example, identified significant differences in bark thickness after fire between dead trees (1.86 ± 0.09 mm) and live trees (2.65 ± 0.04 mm). The most important factor in the survival of *Q. suber* is the number of years after harvesting. The vulnerability of debarked trees is at its highest immediately after harvesting (Rosa and Fortes, 1987; Catry et al., 2012). Other factors influencing survival are careful harvesting operations and number of strippings (Moreira et al., 2007). In a forest fire with temperatures above 200 °C, carbonization depth usually ranges from 20% to 25% of the total thickness, independently of tree size (Cardillo et al., 2007). The thermal decomposition of cork starts at temperatures above 200 °C and increases with increasing temperatures until ashing at approximately 485 °C. The thermal degradation of phloem is similar to that of cork although the exothermal peak temperatures are higher (Sen et al., 2014).

When cork is removed from the tree, the outer layer of the stem is exposed to the atmosphere. This layer then dries up and dies, and becomes the external surface of the new cork, which is known as "corkback" (Silva et al., 2005; Pereira, 2007). Corkback has a ligneous composition and is denser and harder than the cork tissue, and must be considered in assessing tree response to fire. Other technological characteristics that may influence cork response to fire are cork quality, porosity and the presence of defects, insects or diseases. Cork quality is an indicator that serves to determine if the cork is apt for the manufacture of stoppers (Moreira et al., 2007). The principal indicator of the visual quality of cork is porosity. In the strict sense of the term, porosity is due to the presence of lenticular channels or pores that cross the cork in a radial direction. In a broad sense, the term also takes into account the presence and extent of certain defects (Sanchez-González et al., 2016). The defects that affect cork quality are of very different origins such as the formation of sclerenchyma and the presence of *C. undatus* (Prades et al., 2017; Du Merle and Attié, 1992). Although cork provides protection against fire, in light of current changes in climate and fire regimes, knowledge of the effects of bark conditions on tree vulnerability to fire plays a keystone role in forest management (Catry et al., 2012; Oliveira and Augusta, 2012).

Flammability analysis is an effort to address these gaps in our knowledge of fire-related traits in plant species, as it provides scientific explanations for the relationship between cork response and cork characteristics and fire behavior. However, no single definition captures the variability of plant flammability and various authors have used this concept in different ways (Pausas et al., 2017). The results obtained by the different vegetation flammability assessment methods depend on the scale considered (Etlinger and Beall, 2004; Ganteaume and Jappiot, 2014). The assessment of flammability in the laboratory is limited by the scale of experimentation because plant exposure to heat is frequently not comparable to wildfire conditions (Fernandes and Cruz, 2012), while field experiments in cork oak forests are often limited by landscape and economic impacts. Therefore, research that integrates laboratory and field experiments should be explored as it can provide a more realistic representation of how cork is affected by fire.

Flammability analysis has three major dimensions: ignitability (ability to start a fire), flame spread rate and heat release (Pausas et al., 2017). The first dimension is related to the corkback and cork characteristics, while the second and third dimensions are associated with fire behavior. This paper aims to identify, for the first time, the effect of corkback and cork characteristics on flammability and the probability of survival of living tissues based on the lethal cambial temperature. One of the most difficult aspects of measuring bench-scale devices is to provide the most realistic representation of the position of the fire and the bark affected by natural fire spread. To address this issue, this study extends the traditional bench-scale approach in flammability analysis and proposes a bench-scale protocol based on flame fire spread and residence flame time using a butane gas burner. With this aim, we have incorporated five field experiments in order to test the reliability of laboratory experiments. This paper proposes a technique for the integration of both scales of tree vulnerability using real burnings. Furthermore, a new measure of cork vulnerability was developed that integrates cork thickness, corkback roughness, cork quality and porosity, and fire severity. The result is an estimate of potential vulnerability based on lethal cambial temperature in two fire severities. This information can be useful to simulate the effects of forest treatments on fire behavior and potential fire impacts on cork oak forests. From a management viewpoint, effective silvicultural treatments could also be identified in order to increase the quantity and quality of cork and reduce the impact of fire in more vulnerable areas.

2. Material and methods

2.1. Experimental material

The cork planks were provided by La Almoraima SA (Cadiz, Spain) and were extracted from Los Alcornocales Natural Park located in the provinces of Cadiz and Malaga, Spain, in the Mediterranean area. This protected area spans 167,767 ha of alternating dense and sparse cork oak forests. Annual precipitation in the study area ranges from 800 to 1400 mm, most of which occurs during the winter season and rarely during the summer months. The area is characterized by a continental Mediterranean climate with Atlantic Ocean and Mediterranean Sea influence and has daytime summer temperatures of about 30 °C which are conducive to fire ignition and propagation. Fire statistics for the provinces of Cadiz and Malaga for the period 2006–2016 show an average of 46.5 forest fires (> 1 ha) per year, which burn 1731 ha of woodlands.

The cork planks were randomly selected from a pile after removal from the tree, ensuring that all quality classes were present. The sample set comprised 65 cork planks measuring 60–120 cm in length and 20–45 cm in the transverse direction. Each plank was divided into two subplanks (120 subplanks). Two subsets of samples, which we refer to as specimens and pieces, were obtained from each subplank. A total of 120 specimens measuring 10 × 10 cm^2 in size were extracted from the top corner of the plank and used to study industrial quality and porosity coefficient. A total of 120 pieces measuring 50 × 50 mm^2 in size were extracted at a depth of 10 cm from the top section of the plank (top position of the plank in the tree) and used to measure cork thickness, corkback thickness, total thickness and corkback roughness, as well as for the bench-scale analysis. A conventional jig saw (Black & Decker) and a circular saw (Emco Swing) were used to prepare the experimental samples.

- Cork thickness, corkback thickness, total thickness (cork thickness plus corkback thickness), corkback roughness, porosity coefficient, cork quality and the presence of *C. undatus* were identified as follows:
- Cork thickness (radial bark dimension expressed as millimeters): thickness was measured as the average value at the center of the