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The Cypress Canker Disease Pandemic

Cypress Canker Disease affects plants in the cypress family worldwide. This plant health study case describes our current understanding of the disease's history, biology, symptomatology, and control measures. Finally, we will illustrate future research perspectives about this pathosystem.

Authors: **E. Scali[1], M. Garbelotto[1], R. Danti[2] and G. Della Rocca[2]**

Affiliations: **[1]Department of Environmental Science, Policy and Management (ESPM), University of California, Berkeley, California, USA.**
[2]Institute for Sustainable Plant Protection (IPSP), National Research Council (CNR), Sesto, Fiorentino, Italy.

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Abstract

Cypress Canker Disease (CCD) is an infectious disease affecting plants in the family *Cupressaceae*. It is globally caused by various fungal species in the genus *Seiridium*. The causal agents have become invasive in many areas of the world where plants of the cypress family grow under a Mediterranean climate. In this case study, we will focus on how to recognize symptoms of CCD in *Cupressaceae*, and on the management strategies applicable for the control of *Seiridium* fungi with special attention to the epidemiology, disease cycle, and control of *S. cardinale*, the most aggressive among the various CCD agents. We will also provide instructions for best practices for isolating the pathogen from symptomatic cypress tissues. The case study will conclude by explaining the future research framework and experiments that are currently taking place in order to better understand this pathosystem.

Learning Outcomes

1. Understand the epidemiology of CCD.
2. Learn how to recognize symptoms of CCD.
3. Learn how to isolate the pathogen from symptomatic tissues.
4. Understand the main strategies for CCD control.

Introduction: CCD Causal Agents and Spread

Cypress Canker Disease (CCD) is a lethal infectious plant disease of many *Cupressaceae* that has caused several outbreaks over the last century in all continents excluding the Arctic and Antarctica (Graniti, 1998; Danti *et al.,* 2013; Danti and Della Rocca, 2017). Worldwide CCD is caused by seven ascomycetes fungi belonging to the *Seiridium* genus (class Sordariomycetes, order Amphisphaeriales, family Sporocadaceae): *S. cardinale* (W. Wagener) B. Sutton & I.A.S. Gibson, *S. cupressi* (Guba) Boesew.; *S. unicorne* (Cooke & Ellis) B. Sutton; *S. neocupressi* (Bonthond, Sandoval-Denis & Crous);

S. cancrinum (Bonthond, Sandoval-Denis & Crous); *S. pseudocardinale* (Wijayaw., Camporesi, McKenzie & K.D. Hyde); and *S. kenyanum* (Bonthond, Sandoval-Denis & Crous) (Bonthond *et al*., 2018).

Among them, *S. cardinale* is by far the most dangerous and harmful species (at least in the Americas, Europe, and Oceania) and is the most investigated. *S. cardinale* can affect almost all the *Cupressaceae* (*Callitropsis* spp., *Cryptomeria* spp., *Juniperus* spp., *Hesperocyparis* spp., *Cupressus* spp., and *Thuja* spp.). It is particularly severe on Monterey cypress (*Hesperocyparis macrocarpa* (Hartw. ex Gordon) Bartel), Italian cypress (*Cupressus sempervirens* L.), and the intergeneric hybrid Leyland cypress (×*Hesperotropsis leylandii* (A.B. Jacks. & Dallim.) Garland & Gerry Moore [*Hesperocyparis macrocarpa* × *Callitropsis nootkatensis*]).

The *Cupressus sempervirens-Seiridium cardinale* pathosystem is among the most extensively studied forest pathosystems globally, and it is notable for its long-standing research across various regions, particularly in response to epidemic outbreaks. It represents one of the few cases in which it has been possible, through studies of native and invasive population genetics, to trace back the history of the disease, as well as to identify and date the pathways of its spread (Della Rocca *et al*., 2019).

The pathogen is likely to be native to California (Della Rocca *et al*., 2011, 2013) where it was first reported in 1928, and where it gave rise to an initial outbreak in *H. macrocarpa* plantations of the Central Valley, well outside the natural coastal range of this species. Within two decades from its first report, the disease had spread to New Zealand (1933), Europe (1944), South America (1947), while reports from North Africa (1973), and South Africa (1988) came later. A comprehensive map of the disease distribution, available in the CABI Digital Library (Available at: https://www.cabidigitallibrary.org/doi/full/10.1079/cabicompendium.49497), highlights its global reach and impact. CCD is therefore considered a true pandemic as it is present in all regions where cypresses grow. The danger represented by the distribution of the pathogen is due to the fact that infections involve not just planted ornamental trees but also native Cupressaceae hosts. An example of this is the case of native *Widdringtonia* spp. in South Africa that are now getting affected by CCD due to the presence of *Seiridium* species (Wingfield *et al*., 2022).

There is now evidence that the introduction of the pathogen into new areas of the planet has been caused by human activity, through the transfer of infected plants that have been routinely traded and transported by ship between continents. Such trades mainly involved *H. macrocarpa* for ornamental use in the Mediterranean, Oceania, and South America for timber production; and *C. sempervirens* from Mediterranean Europe to the Americas, Oceania, and Africa for ornamental purposes. The trades of ornamental cypresses have been ongoing since the late 1800s (Della Rocca *et al*., 2019), and the introduction of *S. cardinale* in Europe is likely to have started sometime in between the two world wars (Della Rocca *et al*., 2013). In both world regions, the artificial hybrid *xH. leylandii*, widely cultivated as an ornamental plant, is highly susceptible to the disease, further amplifying its spread through the movement of plants (Fig. 1; Table 1).

CCD Epidemiology and Impact

The CCD epidemiology has been extensively studied in California. In this region, the disease outbreaks mostly occur in the inland areas where the pathogen is likely native and the main host, *C. macrocarpa,* is planted. Another relevant area where the disease has been extensively studied is the Mediterranean basin, where the main host, *C. sempervirens* is native, but the pathogen is not (Danti and Della Rocca, 2017). The impact of the disease has been devastating at times, especially in areas where epidemic outbreaks have been favored by the density of susceptible hosts, and by cool-wet autumns and springs. These factors were particularly present during the 1930s and 1940s, therefore CCD devastated Monterey cypress plantations intended as windbreakers and grown in nurseries for sale as plant stock in California's Central Valley. This outbreak severely impacted and limited the economic use of the species ever since. In the Mediterranean area, the situation has been even more severe. Since the 1970s, CCD has caused the death of millions of trees in Southern Europe, the Near and Middle East, and North Africa, leading to heavy economic losses in woods, ornamental plantations and plant nurseries. Beyond the economic impact, the ornamental and cultural loss has been profound. Cypress is an integral part of the Mediterranean cultural and historic heritage, playing an iconic ornamental role, and serving as a distinctive and irreplaceable feature of the landscape. Italy and Greece were the hardest-hit countries in Europe, with disease incidence rates exceeding 50% in several areas. However, North America and the Mediterranean Basin were not the only affected regions. Similar CCD outbreaks have been reported in New Zealand on *H. macrocarpa*, *H. lusitanica*, and *Chamaecyparis lawsoniana*.

Fig. 1. CCD symptoms on cypress trees. The image on the left shows a Leyland cypress affected by CCD. We can observe that many twigs in the canopy of this young specimen are necrotic. On the right, we see an adult common cypress impacted by the disease. The plant exhibits symptoms of dieback, indicating that the disease is in an advanced state and that the necrosis has girdled the entire trunk, albeit relatively close to the top.

Table 1. Distribution and host associations of different *Seiridium* species. This table summarizes the geographic regions, host plant species, and reported non-hosts in the *Cupressaceae* family for the seven *Seiridium* species currently recognised based on the literature: *S. cardinale*, *S. cancrinum, S. cupressi*, *S. kenyanum*, *S. neocupressi*, *S. pseudocardinale* and *S. unicorne*. While *the formers* are restricted to specific host genera within *Cupressaceae*, the letter *S. unicorne* is pathogenic on a broader range of plant families, including *Cupressaceae*.

Seiridium species	Continent/region	Host	Note
S. cancrinum	Kenya, South Africa	*H. macrocarpa, H. lusitanica.*	
S. cardinale	Africa, Asia, Australia, Europe, New Zealand, North and South America	*Cupressus, Hesperocyparis, Chamaecyparis, Cryptomeria, Juniperus, Thuja, Callitropsis Cupressus x leylandii.* Highly susceptible: *H. macrocarpa; Thuja plicata, C. x leylandii;* resistant*: H. bakeri, C. torulosa, C. funebris, C. cashmeriana,* and other Asiatic species of *Cupressus*	No non-hosts reported in Cupressaceae
S. cupressi	East Africa, Greece,	*Cupressus spp., Hesperocyparis (including H. macrocarpa and H. forbesii)*	No non-hosts reported in Cupressaceae Produces toxins such as Cyclopaldic acid and Seiricuprolide.
S. kenyanum	Kenya	*Juniperus procera*	
S. neocupressi	Australia, Italy, South Africa	*C. sempervirens; C. x leylandii; Widdringtonia nodiflora*	
S. pseudocardinale	Italy, Portugal	*Cupressus spp.; C. glabra*	
S. unicorne	New Zealand, South Africa, USA	*Cupressaceae (Chamaecyparis, Cupressus and Juniperus), Anacardiaceae, Caprifoliaceae, Cornaceae, Hamamelidaceae, Rosaceae, Vitaceae.* Wider range of affected plant families compared to other *Seiridium* species	Considered pathogenic on various plant families, including Cupressaceae

Over the past 20 years, a slowdown in new infections has been observed in Italy, likely due in part to the loss of the most susceptible portion of the host population. Although the disease has reached an endemic phase, it still affects 20% to 25% of cypress trees in regions like Tuscany. In California's inland valleys, disease incidence is correlated with: (a) density of susceptible hosts growing inland, outside of their natural range, and (b) the presence of Leyland cypress (Danti and Della Rocca, 2017), but large outbreaks are no longer present mostly because CCD prevents the growth of susceptible hosts, which are no longer planted.

As aforementioned, Leyland cypress deserves special attention. Although trees of this species are widely used, fast-growing and aesthetically appealing, only a few clonal varieties of Leyland cypress are available on the market and all are highly susceptible to the disease. It is estimated that the extensive and widespread cultivation of this horticulture hybrid may have contributed to the spread of the disease. In Italy, for example, the incidence of CCD in Leyland cypress remains over 55%.

The success of *S. cardinale* does not appear to be explained by its high virulence on susceptible hosts, a phenotype or outcome hypothesized for many non-native pathogens. Rather, it appears that intermediate virulence associated with good or high sporulation and a trend to successfully decrease its spore size may be the key to its great invasive potential. Above all, the success of this pathogen is invariably associated with its great demographic plasticity in most traits associated with infection and disease (Garbelotto *et al*., 2015). Although native populations of the pathogen in California include genotypes with a diverse thermal tolerance, in line with the rugged topography of the natural range of the pathogen in the State, including hot desert sites, cold mountain tops and cool coastal shrublands, the restricted thermal tolerance of *S. cardinale* introduced elsewhere may be a factor limiting its distribution. In New Zealand, where at least two genetically distant genotypes were introduced decades apart, novel and significant tree mortality was associated with the second introduction, suggesting that all predictions and trends of disease incidence and severity may need to be reevaluated if new introductions were to occur (Della Rocca *et al*., 2019).

Disease Cycle

S. cardinale is a necrotrophic pathogen that infects, kills, and feeds on host bark tissues, specifically targeting the area from the cribro-vascular cambium outward, including parenchymal tissues and the cork cambium. The pathogen potentially affects every epigeal woody organ of the plant. Although *S. cardinale* can secrete cell wall-degrading enzymes (Graniti, 1998), it is unable to independently penetrate the epidermis or outer bark of the host and is therefore termed a wound pathogen. Notably, *S. cardinale* reproduces exclusively asexually in those regions of the world where it has been introduced. However, the population genetic structure in California suggests that sexual reproduction has occurred historically and thus may be cryptically occurring. We also note that there is a partial description of the sexual stage from California. The pathogen releases airborne conidia serving as the source of inoculum for new infections. Wind and rain are the main means of dispersing conidia, which results in primary infections predominantly occurring on the youngest, most succulent organs located in the highest and most distal parts of the crown. These areas are more exposed to the fungal inoculum and typically have a less thickened periderm making it easier to infect. In contrast, in Leyland cypress, many infections have been observed to occur directly on larger branches or the trunk, possibly due to micro-cracks resulting from the species' rapid growth. An additional peculiarity of Leyland cypress is that it seems that the impact of the disease is milder in younger plantations, i.e., it is quite difficult to find young symptomatic plants. This is a problematic trait because, based on observations in plantations, one may grossly underestimate both the presence of the pathogen and the susceptibility of the plants.

S. cardinale is a primary pathogen that infects and thrives in vigorous plants, characterized by living bark tissues well supplied with nutrients. New infections generally start on mechanically damaged host tissues, caused by abiotic factors such as strong winds or frost. Biotic factors, such as damage caused by insects, birds nesting in cypress trees, pruning, and other human-induced damage can also be a source of infection of the disease. As mentioned above, natural cracks in the bark associated with rapid growth or with branching are also susceptible to infection.

Although wounds are the primary infection courts, infection can also be caused by conidia vectored by insects in the genera *Phloeosinus* (bark beetles), *Orsillus* (seed bugs), and *Cydia* (moths).

A spindle-shaped bark lesion can normally be seen around the infection point and is the result of the necrosis of the living inner bark. As the necrosis progresses within the cambium, noticeable cankers form on the surface of the bark cork tissue, leading to depressions and cracks in the bark, typically accompanied by resin emission. *Seiridium cardinale* generates asexual reproductive structures called acervuli on the

surface of the infected tissues, which will release conidia (Fig. 2). Acervuli production is interrupted during hot and dry weather conditions and is halted when the bark tissue is too dry due to further progression of the disease. Cankers can develop further than the area that was originally infected, thus enlarging and girdling the twig, branch, or trunk of the host tree causing diebacks on numerous of the infected shoots or causing general decline. Cankers developing on the stem or on primary branches eventually lead to the death of the infected plant, however, some plants can survive for decades with dieback limited to the canopy. The growth of *S. cardinale* within the bark parenchyma of the host can occur at varying rates, especially in the longitudinal direction, where it can expand up to 5–10 cm in 6–8 months under favorable conditions and in the presence of susceptible hosts. A twig with an axis of 1–3 cm in diameter can be killed in 6–24 months. However, for branches of larger diameters, the time required for mortality is longer, with adult plants potentially taking anywhere from a few years to even decades to succumb to the infections. In contrast, seedlings infected with CCD have a much shorter survival time, which can be as little as 1 month after infection by *S. cardinale*.

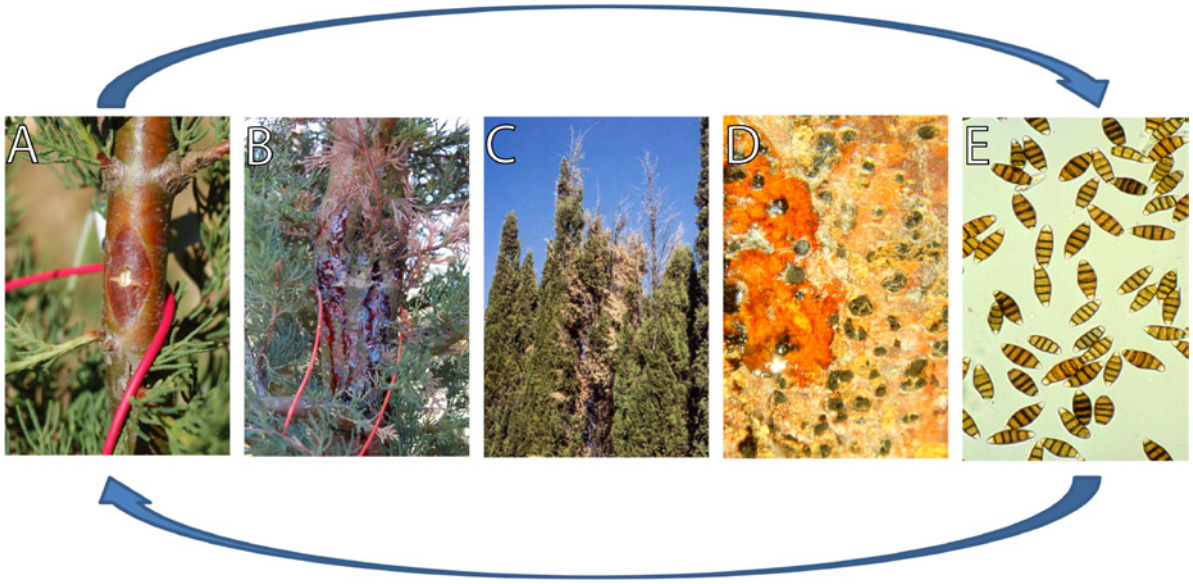

Fig. 2. CCD cycle. This image illustrates the five stages of the disease cycle. Panel A shows the initial phase of infection and depicts an artificially inoculated plant on which a diamond-shaped lesion is observable on the stem. A canker has formed, and the plant tissues appear sunken. Panel B reveals the presence of copious resin exudates leaking from cracks in the bark in advanced stages of the cankers. Note how some twigs appear desiccated above the area affected by the canker. Panel C shows the decline of the canopy, which exhibits symptoms of dieback. This condition is lethal for the affected plant when cankers are on the main stem or primary branches. Panel D displays the acervuli, structures of asexual reproduction, which form on the surface of cankers at an advanced stage of development. Panel E shows a microscope image of the conidia, the mitospores that *S. cardinale* uses to spread in the environment. Once these spores land on wounded plants and under optimal environmental conditions, the disease cycle begins a new infection.

Symptoms

Macroscopic symptoms

Canopy desiccation levels depend on the affected portion of the plant (twig, branch, trunk). Death on girdled stems occurs due to the destruction of the plants' phloem and cambium. Symptoms include a gradual change in color of the foliage which initially turns pale green, then straw yellow, light brown, reddish brown, and then ashy grey due to leaf decay, until the leaves fall off completely (Fig. 3). In such cases, the completely bare woody structure of the affected stem or branch remains visible for many years. Moreover, the fungus persists in the bark of the affected portions of the tree and continues to grow downward, leading to continuously enlarging cankers.

Another macroscopic diagnostic feature is the frequent occurrence of asynchronous infections on the same plant, characterized by multiple infections of varying ages (Fig. 4). It is not uncommon to observe plants, particularly susceptible host genotypes, with portions of crowns of various sizes already dead and others in the dying phase, exhibiting different colors and shades.

Fig. 3. Typical sequence of colors assumed by cypress foliage after CCD has girdled the corresponding vegetative axis of the plant (twig or branch).

Fig. 4. This image depicts symptoms displayed by plants affected by multiple infections. The left image illustrates this phenomenon on Leyland cypress, while the right image shows how it can appear on common cypress. In both cases, we can observe that the decline of the canopy is widespread and dieback advanced. Although symptoms can appear simultaneously on plants, a useful diagnostic element is the presence of initial symptoms that lack a directional or homogeneous distribution over the canopy, and which are typically few and never synchronous.

As shown in the disease cycle (Fig. 2), propagules often spread to other plant organs after the initial infection, typically moving downward and leading to secondary infections.

Microscopic symptoms

Microscopic symptoms refer to the development of the canker lesion, which can be recognized by examining the affected organ. Initially, at the infection point, if the infected organ has not yet developed

a thick suberous bark, the epidermis turns red-brown, with a well-defined margin that often assumes a spindle shape, indicating the underlying fungal development in the bark. As the host-pathogen interaction progresses, it leads to the formation of cankers on wooded organs, active lesions that exhibit depressions and cracks in the bark, with resin exudation occurring more frequently on younger trees.

Signs of *S. cardinale* can be observed as scattered black pustules, called acervuli, which develops on the surface of the cankers. These acervuli, range from 0.3 to 1.5 mm in diameter, emerge from the bark surface and from openings in the bark during wet weather. When the bark is moist, conidia exude from acervuli in black drop-shaped masses, resembling toothpaste squeezed from a tube (Fig. 5). Conidia are six-celled asexual spores, measuring 18–30 µm by 6–12 µm. The terminal cells are hyaline without appendages, an important diagnostic trait to distinguish them from *S. unicorne* and *S. cupressi*; the four central cells are melanized having an olive-brown to dark-brown coloration (Fig. 5).

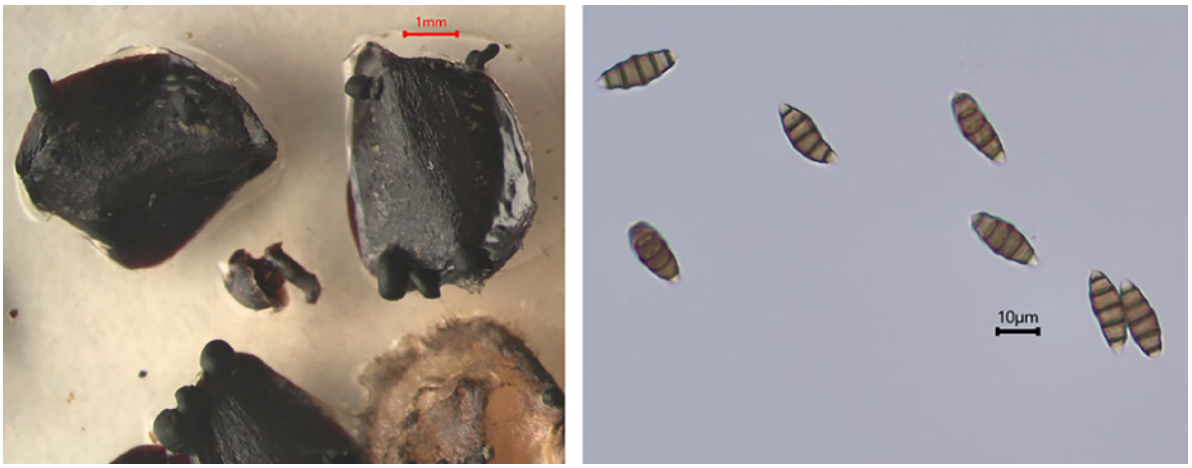

Fig. 5. The image on the left illustrates the acervuli of *Seiridium cardinale* produced *in vitro*, growing on 1% Malt Extract Agar amended with cypress seeds. The cypress seeds are colonized by the mycelium of *S. cardinale*, which finds a favorable environment for asexual reproduction. The conidia that form appear as black, globular masses, resulting from an aggregation of individual conidia. The image on the right displays the conidia of *S. cardinale* observed under a light microscope. Notably, one can see the hyaline terminal cells, which appear as the white tips of the conidia located at both ends, as well as the melanized cells positioned at the center of the conidia. Another diagnostic characteristic observable in these conditions is the number of septa, which in *S. cardinale* is five.

Gently removing the outer bark at the margins of a canker using a pen knife or scalpel reveals the infected bark tissues. These tissues are easily identifiable thanks to their reddish-brown coloration often referred to as cardinal red, hence the pathogen's name *S. cardinale*. Additionally, infected tissues often have a pasty, translucent appearance due to the resin impregnating the infected bark (Fig. 6).

Fig. 6. The left image shows the trunk of a cypress plant that has been inoculated with *S. cardinale*. The plant has responded to the inoculation on the bark by creating a ring of new tissue around the inoculation point. On the right, a lesion has developed beneath the plant's bark. Thirty days post-inoculation, the cambium and bark of this plant were removed to examine the development of necrosis. It is evident that the necrosis is developing mostly in a vertical direction. Additionally, the woody tissues near the cambium are affected by the necrotizing activity of the fungus.

Isolation of the Pathogen

To isolate the pathogen, it is essential to collect a branch or twig from a symptomatic tree, ensuring that the entire canker is included in the sample. If the branch or twig is already partially killed by the pathogen, it is important to include at least 10 cm of tissue that is still alive, characterized by white healthy bark tissue and green leaves below the lower limit of the infection (Fig. 6). After sample collection, isolation of the fungus must be conducted in a clean and sterile environment, under a laminar flow hood. A sterile scalpel, 70% ethanol, and Petri dishes with Potato Dextrose Agar (PDA) are all required to isolate the fungus. The isolation procedure begins with exposing the necrotic lesion. While working under the laminar hood, the scalpel must be used to remove the outer bark and reveal the inner bark tissues of the infected branch. It is essential to find the boundary zone of the lesion, marked by the point of contact between infected brownish tissues and still healthy yellowish-white tissues (Fig. 7). At this juncture, small portions of tissue between the necrotized and healthy bark will be excised and plated in Petri dishes containing PDA. These plates must be incubated at 20–25°C for a few days. As the mycelium begins to grow from the plated fragments, the developing mycelium must be transferred individually to new Petri dishes with PDA and stored in the same condition as before. On PDA, the appearance of *S. cardinale* is characterized by a dense, floccose cotton texture with grey-olive green shades in the center and off-white color at the margins of the colony, accompanied by a salmon-orange hue on the reverse side.

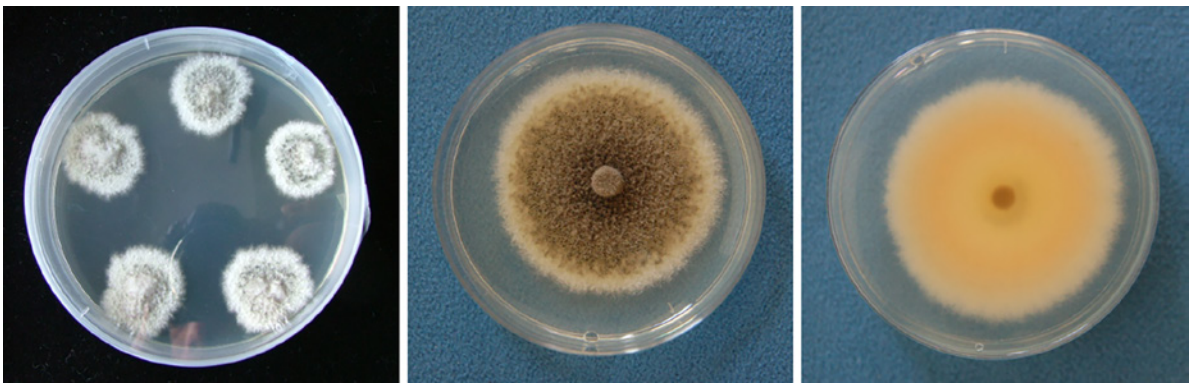

Fig. 7. The left image illustrates colonies of *S. cardinale* outgrown from five necrotic bark fragments. The mycelial tissue appears cottony in texture. The outer edges of the colonies remain light in color, while the inner portions begin to melanize. The central and right images show a PDA Petri dish with pure cultures of *S. cardinale* grown for 15 days, viewed from above and below, respectively. The surface of the mycelium exhibits light-colored outer margins, while the center of the colony takes on a dark, melanized coloration. The underside of the Petri dish reveals the characteristic salmon pink color of *S. cardinale* grown on PDA.

To confirm the presence of *Seiridium cardinale*, qPCR or sequencing can be utilized as precise diagnostic tools. Given that the genome of *S. cardinale* has been published (Scali *et al*., 2024), qPCR primers can be designed based on specific genomic regions to detect the pathogen in infected tissues. Additionally, sequencing techniques can be used to confirm pathogen identity at a molecular level, ensuring accurate detection of *S. cardinale*. Such methods offer high sensitivity and specificity, allowing for the detection of the pathogen even in the early stages of infection or in cases where visual symptoms are not yet prominent. Further research is recommended to optimize these techniques for routine diagnostic use, as they could complement traditional isolation methods, improving overall disease management strategies.

Control

Controlling CCD is challenging and complex due to the aggressiveness of the fungus, its ability to spread rapidly, and its development in plant tissues that are not easily accessible. CCD control can be achieved through three approaches: (1) chemical control, (2) sanitation, or (3) genetic improvement of resistant hosts. Biological control of CCD has also been tested.

1. *Chemical control*: Primarily preventive, chemical control is particularly advisable for young plants in nurseries. However, market restrictions on certain environmentally hazardous pesticides have

significantly reduced the possibilities of chemical control against CCD in many world regions. Thiophanate-methyl (70%, contacticide and systemic, at a concentration of 1.5 g L^{-1}) is considered the most effective fungicide; however, it has not been available on the European market for several years. Several new-generation products were tested, among which Boscalid (50%, contacticide and translaminar, at 1.2 g L^{-1}), and Azoxystrobin (22.9%, contacticide and systemic, at 1ml L^{-1}) demonstrated moderate efficacy (Della Rocca *et al*., 2011).

2. *Sanitation*: This direct control of CCD relies on management strategies aimed at reducing the amount of inoculum. Sanitation involves the careful mechanical removal of infected organs and tissues from affected plants: this method can be effective only if implemented promptly, systematically, and continuously. Given that infected portions of the plant may not always be visible, timely sanitation is crucial. Sanitation is particularly recommended for monumental trees or plants of special significance, where the purpose is preserving the individual specimens. A well-performed pruning allows an affected tree to recover and is the only therapeutic measure available. Interventions can be technically complex and require specialized and trained personnel. It is imperative to disinfect cutting points and tools such as scissors and chainsaws before moving from one plant to the next to avoid transmitting the disease.
3. *Genetic improvement*: This strategy involves the planting of host genotypes selected for their resistance to CCD, specifically through the use of plant clones that are vegetatively propagated by grafting or cutting. These agamically reproduced plants have been developed as part of an ongoing genetic improvement program for Italian cypress started in the 1970s at the IPSP-CNR in Italy. They have been patented and six clones are available for purchase on the European market: 'Bolgheri', 'Agrimed No. 1', 'Italico', 'Mediterraneo', 'Le Crete 1', 'Le Crete 2' (Panconesi and Raddi, 1991; Danti *et al.,* 2006, 2013). Resistant cypress expresses resistance to *S. cardinale* infections by forming a ligno-suberized boundary zone in the infection site. This boundary zone is made by four to six layers of cells with suberized walls that are capable of containing the activity of *Seiridium* preventing it from expanding into adjacent healthy tissue (Danti *et al*., 2018). Additional factors contributing to resistance include rapid activation of signal molecules, including hormones, following infection (Scimone *et al*., 2024). Furthermore, there is *ex novo* synthesis of terpenoids as phytoalexins (Achotegui-Castells *et al*., 2015, 2016) in phloem axial resin ducts, which are produced by the host as a defense mechanism against infection, along with other anatomical mechanisms at the phloem level (Della Rocca *et al*., 2021, 2022). Inoculation studies have also shown that resistant clones support significantly less sporulation by the fungus than susceptible clones, hence their use is not likely to increase the overall amount of inoculum present in one area (Della Rocca *et al*., 2018), a concern associated with the use of tolerant genotypes of a host for any pathosystem.
4. *Biological control*: Promising results have been obtained, both in mesocosm and in the field, with the application of *Pseudomonas chlororaphis* subsp. *aureofaciens* strain M71. The bacterium, through the production of Phenazine-1-carboxylic acid, is apparently able to control the growth of *S. cardinale in vivo* following artificial inoculations and remains viable on cypress phyllosphere for more than 3 months (Raio *et al*., 2011).

Future Research

This pathosystem provides a unique setting for the investigation of host-pathogen interactions thanks to the presence of genetically identical plant clones that can be easily propagated and have a well-defined level of disease tolerance/susceptibility and also thanks to the mitotic nature and easy *in vitro* growth of the pathogen, with pathogen genotypes also well characterized in terms of virulence. Clonal replication is thus possible for host and pathogen thus providing a wonderful model system to study host-pathogen interactions in a tree disease. Current cutting-edge research efforts involving UC Berkeley and IPSP-CNR in Italy, are focused on understanding the dynamic of host-pathogen interaction (*S. cardinale* vs. *C. sempervirens*) at the molecular level. The dual-RNA seq technique is employed to characterize the genes involved during the infection process and those associated with host resistance. Identifying the molecular pathways and genes linked to resistant plants could facilitate the selection of new resistant clones of cypress that exhibit resistance to a broader range of isolates of the pathogen than that currently present in Europe (Della Rocca *et al*., 2018). Given the current issue of climate change, researchers are further investigating how temperature may modulate disease tolerance, thus greatly increasing our predictive power regarding disease progression of current and future outbreaks. Finally, the comparative analysis of entire genomes will allow us to determine the virulence of various populations growing in different world regions, without necessarily testing such virulence in plants. Findings in these areas might help further understand the disease and interaction between *Seiridium spp.* and their hosts. Furthermore, it might provide essential knowledge for the regulamentation of the worldwide movement of plant materials potentially infected.

Besides the molecular interaction between host and pathogen, important coevolutionary investigations might reveal fundamental knowledge for disease management. The understanding of how coevolutionary dynamics shape resistance and virulence in host and pathogen populations respectively is still an uninvestigated aspect of CCD.

Lastly, another relevant research question involves the characterization of different populations of *Seiridium* at the genomic level. Genomes of *Seiridium* species have recently been published (Scali *et al*., *2024*). By comparing the genomes of these different species, important questions regarding why *Seiridium* became such a lethal pathogen upon its introduction to Europe from California might be investigated. In this epidemiological context, the pathogen displayed remarkable adaptability, and genome comparison among different populations will help us understand the evolutionary dynamics that facilitated these ecological successes.

Discussion Points

1. Discuss the history of CCD from its first report to today, and explain the factors that contributed to its spread worldwide.
2. Indicate what are the principal characteristics of CCD symptoms at both macroscopic and microscopic levels.
3. How many and what are the means of CCD controls? In what contexts is one means of control more suitable than another?
4. Describe what you think are the future research prospects on this topic and why they are critically important.

Conflict of interest

The authors have no conflicts of interest to declare.

Further Reading

Danti, R., Della Rocca, G., Faini, A. and Perulli, D. (2007) *La Selvicoltura delle cipressete in Toscana*. ARSIA Regione Toscana.

Danti, R., Della Rocca, G., Di Lonardo, V., Panconesi, A. and Raddi, P. (2011) *Cypress: An Essential Tree of Landscape, Economy and Tradition of the Mediterranean Countries*. DOI: 10.13140/RG.2.1.5065.6249.

Danti, R., Di Lonardo, V., Pecchioli, A. and Della Rocca, G. (2013) 'Le Crete 1' and 'Le Crete 2': two newly patented *Seiridium cardinale* canker-resistant cultivars of *Cupressus sempervirens*. *Forest Pathology* 43(3), 204–210.

Della Rocca, G. and Danti, R. (2011) *Cypress: Mainspring of Economic and Sustainable Development in the Mediterranean Countries*. IPSP-CNR; DEISTAF-UNIFI. Available at: https://www.researchgate.net/publication/305307462_Cypress_mainspring_of_economic_and_sustainable_development_in_the_Mediterranean_Countries.

Della Rocca, G., Di Lonardo, V. and Danti, R. (2011) Newly-assessed fungicides for the control of cypress canker caused by *Seiridium cardinale*. *Phytopathologia Mediterranea* 50(1), 66–74.

Guidotti, A. (2003) *La Bonifica Fitosanitaria a tutela del cipresso*. ARSIA Regione Toscana. Available at: https://www.regione.toscana.it/documents/10180/11270546/6_Arsia_Manuale_Cipresso.pdf/5780ec50-7016-0800-57af-7148a6a33543?t=1715762762842.

Olembo, T.W. (1983) Further studies on cypress canker disease in east Africa caused by *Monochaetia unicornis* (Cookie & Ellis) sacc. *Forest Ecology and Management* 5(2), 119–131.

Panconesi, A. (2007) *Il Cipresso. Dalla leggenda al futuro*. Centro Promozione Pubblicità, p. 454.

References

Achotegui-Castells, A., Danti, R., Llusià, J., Della Rocca, G., Barberini, S. and Peñuelas, J. (2015) Strong induction of minor terpenes in Italian Cypress, *Cupressus sempervirens*, in response to infection by the fungus *Seiridium cardinale*. *Journal of chemical ecology* 41, 224–243.

Achotegui-Castells, A., Della Rocca, G., Llusià, J., Danti, R., Barberini, S. and e al. (2016) Terpene arms race in the *Seiridium cardinale–Cupressus sempervirens* pathosystem. *Scientific Reports* 6(1), 18954.

Bonthond, G., Sandoval-Denis, M., Groenewald, J.Z. and Crous, P.W. (2018) Seiridium (Sporocadaceae): an important genus of plant pathogenic fungi. *Persoonia-Molecular Phylogeny and Evolution of Fungi* 40(1), 96–118.

Danti, R. and Della Rocca, G. (2017) Epidemiological history of cypress canker disease in source and invasion sites. *Forests* 8(4), 121.

Danti, R., Panconesi, A., Di Lonardo, V., Della Rocca, G. and Raddi, P. (2006) 'Italico' and 'Mediterraneo': Two *Seiridium cardinale* Canker-Resistant Cypress Cultivars of *Cupressus sempervirens*. *HortScience* 41(5), 1357–1359.

Danti, R., Della Rocca, G. and Panconesi, A. (2013). In: Gonthier, P. and Nicolotti, G. *Cypress Canker. Infectious Forest Diseases*. CAB International, Wallingford UK, pp. 359–375.

Danti, R., Rotordam, M.G., Emiliani, G., Giovannelli, A., Papini, A. *et al.* (2018) Different clonal responses to cypress canker disease based on transcription of suberin-related genes and bark carbohydrates' content. *Trees* 32, 1707–1722.

Della Rocca, G., Eyre, C.A., Danti, R. and Garbelotto, M. (2011) Sequence and simple-sequence repeat analyses of the fungal pathogen *Seiridium cardinale* indicate California is the most likely source of the Cypress canker epidemic for the Mediterranean region. *Phytopathology* 101(12), 1408–1417.

Della Rocca, G., Osmundson, T., Danti, R., Doulis, A., Pecchioli, A. *et al.* (2013) AFLP analyses of California and Mediterranean populations of *S eiridium cardinale* provide insights on its origin, biology and spread pathways. *Forest Pathology* 43(3), 211–221.

Della Rocca, G., Danti, R., Popenuck, T., Di Lonardo, V. and Garbelotto, M. (2018) Resistance to Cypress Canker Disease in Italian cypress has desirable effects on disease epidemiology but may fail against novel genotypes of the pathogen *Seiridium cardinale*. *Forest Ecology and Management* 424, 259–266.

Della Rocca, G., Danti, R., Williams, N., Eyre, C. and Garbelotto, M. (2019) Molecular analyses indicate that both native and exotic pathogen populations serve as sources of novel outbreaks of Cypress Canker Disease. *Biological Invasions* 21(9), 2919–2932.

Della Rocca, G., Posarelli, I., Morandi, F., Tani, C., Barberini, S. *et al.* (2021) Different polyphenolic parenchyma cell and phloem axial resin duct-like structure formation rates in *Cupressus sempervirens* clones infected with *Seiridium cardinale*. *Plant Disease* 105(10), 2801–2808.

Della Rocca, G., Papini, A., Posarelli, I., Barberini, S., Tani, C., Danti, R. and Moricca, S. (2022) Ultrastructure of terpene and polyphenol synthesis in the bark of *Cupressus sempervirens* after *Seiridium cardinale* infection. *Frontiers in Microbiology* 13, 886331.

Garbelotto, M., Rocca, G.D., Osmundson, T., di Lonardo, V. and Danti, R. (2015) An increase in transmission-related traits and in phenotypic plasticity is documented during a fungal invasion. *Ecosphere* 6(10), 1–16.

Graniti, A. (1998) Cypress canker: A pandemic in progress. *Annual Review of Phytopathology* 36(1), 91–114.

Panconesi, A. and Raddi, P. (1991) Agrimed No. 1 and Bolgheri: Two new cypress varieties resistant to canker. *Cellulosa e Carta* 42(1), 47–52.

Raio, A., Puopolo, G., Cimmino, A., Danti, R., Della Rocca, G. and Evidente, A. (2011) Biocontrol of cypress canker by the phenazine producer *Pseudomonas chlororaphis* subsp. *aureofaciens* strain M71. *Biological Control* 58(2), 133–138.

Scali, E., Rocca, G.D., Danti, R. *et al.* (2024) Genome assembly of two California isolates of *Seiridium cardinale* (BM-138-000494 and BM-138-000479). *Journal of Plant Pathology* 106, 1389–1392. DOI: 10.1007/s42161-024-01665-5.

Scimone, G., Pisuttu, C., Cotrozzi, L., Danti, R., Nali, C. *et al.* (2024) Signalling responses in the bark and foliage of canker-susceptible and-resistant cypress clones inoculated with *Seiridium cardinale*. *Physiologia Plantarum* 176(2), e14250.

Wingfield, M.J., Marincowitz, S., Pham, N.Q., Roets, F., Paap, T., Wingfield, B.D. and Aylward, J. (2022) Cypress canker: An important disease discovered for the first time on a native South African tree. *Plant Pathology* 71(8), 1735–1742.