FOREWORD Special Issue ‘Biological control of tree and woody plant diseases’

Biological control of tree and woody plant diseases: an impossible task?

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Abstract

The social demand for novel, sustainable and environment friendly approaches, while ensuring the health and productivity of our crops, is increasingly growing. Research on biological control of tree/woody crop diseases is scarce compared to that conducted on herbaceous, annual plants. In addition to their large biomass, complicated anatomy, longevity and perennial nature, peculiarities in the management of tree crops and forestry also contribute to the complexity of the processes of developing effective biological control measures in these agro-ecosystems. Although biological control in woody species poses challenges, difficulties and limitations, its implementation either alone or in combination with other disease management strategies is feasible. As a result, examples of successful application of biocontrol measures based on the use of bacteria, fungi or hypovirulent mycoviruses against tree/woody plant diseases are available. The aim of this Special Issue is to provide interested readers with an overview and updates on the active research field of biological control of tree and woody plant diseases. Such effort includes updates ranging from the generation of fundamental knowledge to examples of successful application of biological control strategies.

Keywords: chestnut blight, citrus (*Citrus sinensis* L.) nematode, Dutch elm disease, endophyte, guava (*Psidium guajava* L.), grapevine (*Vitis vinifera* L.), microbiome, Verticillium wilt of olive (*Olea europaea* L.)

Introduction: Importance of trees and woody plants

Trees and woody crops are crucial for life on Earth. In fact, forests and other wooded lands cover about 40% of the world's land surface (FAO 2010). Crowther and coworkers (2015) have recently estimated that the global number of forest trees is approximately 3.04 trillion, exceeding previous estimates by far and stressing the magnitude of this massive biomass. Besides forests, huge acreages of agricultural soils are devoted to the cultivation of a large variety of trees and woody plants worldwide (*e.g. Camellia sinensis* (L.) Kuntze, *Citrus* spp., *Coffea* spp., *Malus domestica* B., *Olea europea* L., *Phoenix dactylifera* L., *Persea americana* Mill., *Prunus* spp., *Theobroma cacao* L., *Vitis vinifera* L., etc.). Domestication and cultivation of woody species is part of the human history and these commodities became essential to the economy of many countries. Extraction of non-timber products from the forest may be considered as the initial phase of domestication of valuable tree species (Prance 1994). Thus, the first woody plants to be cultivated were those yielding food and other non-timber products, such as olive, edible fig and grapes (around 4,000 BC) in the Mediterranean area, or diverse fruit trees (around 2,000 BC) in Asia (Turnbull 2002). Over the centuries, these activities have shaped particular landscapes, generating outstanding agro-ecosystems in many regions around the world. Trees and woody plants do not only provide edible products essential for human and animal diets, but also important goods (*e.g.*, wood, paper, etc.). Moreover, they play key roles in nutrient and water cycling processes, preventing soil erosion, mitigating the effects of climate change acting as carbon dioxide sink, and supporting microbial, animal and plant biodiversity (Ruano-Rosa and Mercado-Blanco 2015). The health of forests and woody cropping systems is therefore of particular relevance. However, a range of biotic constraints due to the attacks of a

diversity of viruses, phytoplasmas, bacteria, oomycetes, fungi, nematodes, arthropods and parasitic plants continuously compromise the fitness, development and production of trees and woody plants (Fig. 1). For instance, many soil-borne phytopathogens provoke serious losses in economically-relevant tree crops and forestry. Among them, different species of fungi (*e.g. Fusarium, Armillaria, Heterobasidion, Rosellinia, Verticillium*, etc.) and oomycetes (*e.g. Phytophthora, Pythium*, etc.) genera (García-Jiménez et al. 2010), and pathogenic bacteria such as *Agrobacterium tumefaciens* (de Cleene and de Ley 1976) are particularly harmful and may cause great losses. Additionally, many foliar pathogens provoke severe diseases on woody plants, such as fungal-based powdery mildew or cankers (Agrios 2005; Amano 1986; Manion 1991), or the aggressive aerial phytopathogenic bacteria *Erwinia amylovora* (causing fire blight; Vanneste 2000) and *Pseudomonas syringae* (causing bacterial blights; Kennelly et al. 2007). To complete the catalogue of important pathogenic organisms causing relevant diseases on tree and woody plants, we must not forget pathogenic viruses (Cooper 1979) and nematodes (Ruehle 1973).

New emergent diseases are gaining relevance worldwide (Santini et al. 2013). These are usually characterized by the presence of severe symptoms, whose control is challenging. Diseases such as the citrus Huanglongbing (previously known as “citrus greening”, and caused by different “*Candidatus Liberibacter* spp.”; Wang and Trivedi 2013), the oak decline (caused by the oomycete *Phytophthora cinnamomi*; Camilo-Alves et al. 2013) or the olive quick decline (caused by the bacterium *Xylella fastidiosa*; Martelli et al. 2016) are catching the interest of nearly all society and pose new and urgent research challenges. Finally, it is worth mentioning that the development of new cultivation systems (Connor et al. 2014) or either sudden or long-term changes in weather/climate conditions (Ponti et al. 2014) can have an as yet poorly-understood

influence on woody crop diseases, as well as unknown effects on the effectiveness of the disease management strategies traditionally deployed to contain them. These scenarios warrant future in-depth studies that, in our opinion, should be conducted based on a holistic perspective involving multidisciplinary research teams together.

Challenges in biocontrol of tree and woody plant diseases

Plant diseases are one of the main limiting factors in modern agriculture, holding potential for a devastating effect on plant health and yield. In addition to agronomic and cultural practices, growers are usually forced to resort to the use of chemical treatments. However, growing public concern about environmental pollution and harmful effects of chemicals in humans and animals, are paving the way for searching new, more environment friendly disease control methods. Mitigation strategies are effective only in some areas, and solutions to woody plant diseases and pests mainly focus on integrating different management approaches. Within this global strategy, biological control is considered as an interesting complement to other management practices. However, the different facets of this scenario have so far been rather poorly explored.

The utilization of biological control agents (BCA) to suppress pathogens has been investigated in a number of pathosystems involving woody hosts (Milgroom and Cortesi 2004; Pliego and Cazorla 2012, and references therein). Nevertheless, a survey in the scientific literature reveals that, overall, the utilization of BCAs as a disease control strategy has been implemented to a lesser extent in trees and woody plants compared to that in herbaceous species, annual crops and seedlings. A number of reasons could explain the lower implementation and/or success of biological control approaches in trees and woody plants. These may include challenges that have not been

encountered so far, or that are not as easily overcome when dealing with annual crops. Factors such as a larger biomass, a more complex anatomy, a greater longevity, the perennial nature, and/or inherent particularities in the management of tree crops and forests (*e.g.* absence of crop rotation aiming to reduce the pathogen inoculum level, etc.), make it more difficult to develop and implement effective biological control approaches. For instance, in the case of soil-borne pathogens, the large root systems of trees and their architecture may facilitate repeated infection events from any given pathogen persisting in soils as dormant, quiescent or resistant propagules (*e.g.* chlamydospores, microsclerotia, etc.). Moreover, infection episodes can take place either in the same season or in successive ones. This fact may contribute to reduce the effectiveness of biocontrol strategies (Pliego and Cazorla 2012). In other cases, such as for vascular pathogens, a tree can only be partially affected by the disease during a growing season. The syndrome is not thus leading to the death of the entire plant but to severe symptoms of individual branches, thereby limiting or stopping tree growth and production. This may pose difficulties when making a decision on which type of disease managing strategy is more appropriate to implement. For instance, López-Escudero and Mercado-Blanco (2011) have highlighted the complexity to control *Verticillium dahliae* in olive (*Olea europaea*) due to, among other factors, the pathogen's location within the vascular vessels, a tissue difficult to be reached either by chemical or biological treatments. Another example is found in Burr et al. (1998) who reported that attempts to control crown gall disease, caused by *A. tumefaciens* have largely failed, except by using the biological control bacterium *Agrobacterium radiobacter* K84 (New and Kerr 1972). However, biocontrol cross-protection is restricted to only certain *Agrobacterium* strains; so these approaches face limitations when they need to be implemented (Anand et al. 2008). In other cases, propagules of pathogens infecting woody hosts (*e.g.*

Uncinula necator causing powdery mildew in grapevine [*Vitis vinifera*], *Rosellina necatrix* causing white root rot on avocado [*Persea Americana*], or *Venturia inequalis* causing apple [*Malus domestica*] scab) overwinter either on plant debris or plant organs/tissues (Pearson and Gadoury 1987; Holb et al. 2004; Pliego et al. 2012; Melnick et al. 2013), making the application of effective control measures difficult. Finally, olive knot caused by the bacterial pathogen *Pseudomonas savastanoi* pv. *savastanoi* (Ramos et al. 2012) can be considered as a model for woody plant diseases in which the causal agent is constantly present in plant tissues. Interestingly, the use of the biocontrol root endophyte *Pseudomonas fluorescens* PICF7 resulted in a reduction of necrotic tumors and confinement of the pathogen at inner regions of the knots, although disease development was not impaired (Maldonado-Gómez et al. 2013).

Biocontrol approaches for woody plant diseases

In spite of these difficulties, a range of biocontrol-based measures have been developed and are practicable for woody plants. So far, however, they mostly focus on the seedling phase, young plants and/or during the nursery propagation stage (Mercado-Blanco et al. 2004; Abraham et al. 2013; González-Sánchez et al. 2013; Vitullo et al. 2013). The question ahead yet to be asked when implementing biocontrol strategies for woody plants, either alone or in combination with other disease management approaches, is whether they can be consistently and effectively used with adult individuals, under field conditions, and on large scales (orchards, forests, etc.). One more relevant question to be addressed is whether the use of biological control measures is feasible from an economical perspective, considering the idiosyncrasy of tree and woody agro-ecosystems. For instance, deep root systems usually developed by trees are less

accessible to chemical- or physical-based disease management approaches, thereby reducing their effectiveness (López-Herrera et al. 2003). It is conceivable to think that deep soil layers will be also less accessible to biologically-based control approaches (e.g. deploying formulations harboring biocontrol agents by irrigation).

Biocontrol approaches to confront tree and woody plants diseases are diverse, encompassing strategies such as the use of hypovirulent viruses and fungi (El Hassni et al. 2004; Milgroom and Cortesi 2004), beneficial bacteria and/or their secondary metabolites to control, for instance, bayoud disease (*Fusarium oxysporum* f. sp. *albedinis*) in date palm (*Phoenix dactylifera*) (El Hassni et al. 2007) or diverse grapevine pathogens (Compant et al. 2012, and references therein), fungi displaying a multiplicity of biocontrol mechanisms such as *Trichoderma* spp. against avocado (*Persea americana*) white root rot (Ruano-Rosa and López-Herrera 2009) or *Phlebiopsis gigantea* against the root and butt rot disease of conifers caused by *Heterobasidion annosum* (Mgbeahurike et al. 2011; 2012), and organic amendments with antagonistic microorganisms (Moreira et al. 2007) which in addition can stimulate soil-resident beneficial microbiota (Bonilla et al. 2015). Thus, the use of organic amendments or mulches has been successfully incorporated into integrated management of certain diseases, such as those affecting avocado trees (Pérez-Jiménez 2008; Bonilla et al. 2012). This is mainly due to the fact that avocado roots are easily accessible since they are mostly in the upper centimeters of the soil (60% of the roots in the first 60 cm of the soil; Salazar-Garcia and Cortés-Flores 1986). An interesting and promising approach, although insufficiently explored, is the use of endophytic microorganisms (Hardoim et al. 2015). Beneficial bacteria and fungi showing effective biocontrol activity and displaying endophytic lifestyle offer the advantage to be adapted and to endure within plant tissues for long periods of time, conferring them great potential in

agricultural biotechnology (Mercado-Blanco and Lugtenberg 2014). Adaptation to inner tissues and endurance within them make endophytes good candidates as biocontrol agents of long-living, woody plant diseases. Indeed, tree endophytes have been proposed as an excellent tool aiming to sustain forest health (Pautasso et al. 2015). Examples of effective and/or promising use of bacterial endophytes to control diseases in trees are already available, such as in olive against the soil-borne vascular pathogen *V. dahliae* (Maldonado-González et al. 2015), against poplar (*Populus* spp.) canker caused by *Cytospora chrysosperma*, *Phomopsis macrospora* and *Fusicoccum aesculi* (Ren et al. 2013), diverse cacao (*Theobroma cacao*) pod diseases (Melnick et al. 2011), or against *Xylella fastidiosa* sbsp. *pauca* causing citrus variegated chlorosis (CVC) disease of sweet oranges (*Citrus sinensis* L) (Lacava et al. 2004; 2007). Noteworthy, this pathosystem poses an additional interest. Indeed, the vector of CVC, the sharpshooter insect *Bucephalogonia xanthophys*, also transports the endophytic biocontrol bacterium *Methylobacterium mesophilicum* (Gai et al. 2009). This offers stimulating perspectives to develop innovative biocontrol approaches for this pathogen. Overall, while some results have been obtained using endophytes in different pathosystems under controlled conditions, yet the actual challenge is to develop appropriate strategies for their formulation, application and efficient use in woody agro-ecosystems and forestry.

Aim and content of this Special Issue

In this volume, several examples of on-going research on biocontrol approaches in different pathosystems involving trees and woody plants are presented (Fig. 1). They confirm that even though challenges and difficulties are encountered when confronting woody plant diseases by biocontrol approaches, fundamental knowledge is

progressively gathered and promising results are obtained. Moreover, successful application of biocontrol measures is a reality in some cases.

Microbiomes of plants have a strong impact on their health, growth and productivity. Likewise, several factors influence the abundance, diversity and composition of the plant-associated microbial communities. The complexity of the plant microbiome is not yet fully understood, and several attempts to unravel its influence on the host have been performed in different crops of interest, such as grapevine (Pinto et al. 2014; Zarraonaindia et al. 2015). In this Special Issue, two studies deal with different aspects of biocontrol in grapevine. Pinto and Gomes (2016) review how basic research on grapevine microbiome could lead to new technological developments to improve agriculture productivity and sustainability. This can be achieved by exploiting microorganisms harboring beneficial traits for the plant, identifying new genes and enzymes with potential to be used in novel strategies for crop protection. In this work, it is proposed that the knowledge gathered about the plant-associated microbiome can assist in the elucidation of plant-microbial interactions taking place, thus revealing microorganisms that could be involved in plant protection processes. By this basic knowledge, and facing a possible disease scenario, different microbial-based tools could be developed thanks to the previous research performed on the plant microbiome. Pertot and coworkers (2016) present one of the few works focused on the promising use of the well-known biocontrol agent *Trichoderma* spp. during the grapevine nursery process. *Phaeoacremonium aleophilum* and *Phaeomoniella chlamydospora* are pathogens commonly associated with wood discoloration symptoms in tracheomycotic syndromes of esca, and are thus considered the causal agents of this phaeotracheomycotic complex. Infections commonly occur in vineyards or derive from infected mother plants. However, the grafting process in nurseries can also pose an additional risk of infection.

The analysis of different *Trichoderma* spp. biocontrol agents applied during this special stage of the plant revealed that although new approaches to reduce the risk of fungal pathogen infection in nurseries can be proposed, the preventive use of strain SC1 of *Trichoderma atroviridae* could be a feasible and relatively cheap control measure.

Verticillium wilt is one of the most threatening biotic constraints for olive cultivation in many areas where this tree is cultivated. So far, the best approach to confront the disease is by implementing an integrated disease management strategy (López-Escudero and Mercado-Blanco 2011), in which biological control measures can play a role, mainly when applied in a preventive way. In this Special Issue, three studies devoted to the biocontrol of this disease are included. Ruano-Rosa and co-workers (2016) describe in detail the behavior of *Trichoderma harzianum*, a widely-used BCA, once released in the olive rhizosphere. Using a fluorescently-labeled derivative of *T. harzianum* CECT 2413 and confocal laser scanning microscopy, they observed for the first time events related to mycoparasitism of *V. dahliae* by *T. harzianum* *in vitro*. Moreover, they found that most of the biomass of CECT 2413 was mainly visualized as chlamydospores, a resistant structure, soon after being released in the olive rhizosphere, regardless of the experimental conditions used and the absence or presence of the pathogen. This observation suggests that this BCA seems not to be able to persist in a metabolically-active form when applied as a spore suspension, raising interesting questions about the way this BCA should be formulated and deployed to reach full effectiveness. In another study, Markakis and associates (2016) evaluated the biocontrol efficiency of the bacterium *Paenibacillus alvei*, strain K165, against the same pathogen under both greenhouse and field experimental conditions. While bioassays conducted in greenhouse revealed that strain K165 significantly decreased disease development in a susceptible olive cultivar, a major step forward of this study was to confirm the

253 suppressive effect of K165 in an established olive orchard naturally infested with *V.*
254 *dahliae*. Among other interesting observations, this study reports for the first time
255 effective biological control of this disease under field conditions, a scenario not
256 frequently explored in biocontrol research, particularly with woody plants. Finally, Varo
257 and coworkers (2016) compared diverse pathogen inoculation methods to screen for
258 potential biocontrol agents against *V. dahliae* in olive, addressing one of the major
259 restrictions when developing control measures against this disease: the lack of
260 consistent inoculation methods to evaluate, for instance, the effectiveness of biocontrol
261 agents. The authors eventually propose a promising inoculation method to assess
262 potentially effective BCAs against Verticillium wilt of olive, an important step before
263 evaluation under field conditions.

264 Dutch elm (*Ulmus* spp.) disease, caused by species of the fungal genus
265 *Ophiostoma*, is a devastating disease affecting elms in Europe and North America.
266 Infections mostly occur by pathogen transmission by several species of bark beetles,
267 mainly from the genus *Scolytus*, although infection by means of root contact between
268 infected and healthy trees can also take place. Biological control of Dutch elm disease
269 under field conditions has already a long history (Scheffer et al. 2008). In this issue,
270 Postma and Goossen-van de Geijn (2016) report on the successful use of a biological
271 control approach to protect a tree over a long period of time (> 20 years) and under
272 natural (and urban) conditions. Moreover, this is an interesting case on the use of a
273 pathogenic fungus (*Verticillium albo-atrum* strain WCS850) behaving as a protective
274 agent in a non-host species. While the product under study does not protect already-
275 infected elm trees or trees connected with diseased individuals via root grafts, it does
276 prevent healthy trees from pathogen infection through elm bark beetles.

The ascomycete *Cryphonectria parasitica* is a wound parasite that causes lethal bark lesions on the stem and branches of chestnut (*Castanea* spp.), developing chestnut blight (Prospero and Rigling 2013). The consequences of this disease are less dramatic in Europe on the European chestnut (*Castanea sativa* Mill.) than in North America on the American chestnut (*Castanea dentata* (Marshall) Borkh.) due, among other factors, to the spontaneous appearance and spread of natural hypovirulence caused by an unencapsidated RNA virus (Heiniger and Rigling 1994). This made chestnut blight as one of the few tree diseases in Europe for which biological control is possible. In this Special Issue, Prospero and Rigling (2016) revealed that therapeutic canker treatment with a virus is mostly effective. However, *Cryphonectria* virus could yield contradictory results, due to competition with naturally-occurring viruses. This study also emphasizes the usefulness of molecular markers to track biological control agents and to evaluate the success of their application.

Another hot topic in biological control of trees and woody plants are the pests which severely affect plant performance and yield. Even though this volume is focused on diseases, we also aimed to include an example illustrating biocontrol strategies implemented to manage tree pests. One study model is the common guava (*Psidium guajava* L.), where different insect pests can be found, such as the fruit fly (*Bactrocera* spp.), the fruit borer (*Deudorix Isocrates* Fab.) or different types of Lepidoptera, Hemiptera and Homoptera (Souza et al. 2003). Management of insect pests involves several applications of chemicals, mainly targeting the adult form. To avoid the environmental concerns caused by the effects of pesticides, alternative measures are being developed, including those based on biological control. Dolinski (2016) presents in this Special Issue a review on how natural pathogens of insects, such as the entomopathogenic nematodes, often play an important role in regulating insect pest

populations, and proposes them as components of Integrated Pest Management (IPM) programs.

Another model to study biocontrol on woody plants is the citrus phytopathogenic nematode *Tylenchulus semipenetrans*, which causes heavy attacks on young feeder citrus roots. Moreover, its pathogenicity can be enhanced by stress related to soil and/or water availability (Duncan and Noling 1987). In this issue, Ciancio and co-workers (2016) confirm the potential of the bacterium *Pasteuria* spp. to effectively control the citrus nematode. Moreover, by modeling obtained data, a clear relationship between *T. semipenetrans* and *Pasteuria* sp. is shown, making it possible to have a management strategy of this nematode based on the use of this bacterium.

Concluding remarks

Research conducted on biological control of woody plant diseases, including the examples compiled here are stimulating and encourage further research in all aspects related to the use of biological control in these agro-ecosystems, particularly as a preventive measure. Moreover, biocontrol approaches, or more particularly the use of BCAs, can be complementary to other disease control measures (e.g. the use of pathogen-free certified planting material, the use of tolerant/resistant cultivars, their combined use with organic amendments, etc.) and/or integrated with appropriate agronomical or forestry practices. Nevertheless, our knowledge on the mechanisms underlying biocontrol, on the influence of environmental factors on the effectiveness of BCAs, on the interaction between a given BCA and the plant-associated microbiome once the former is released in the target host, on the colonization ability of the BCA, or on how the plant respond to the presence of the BCA, are still scant. The

implementation of currently-available, powerful ‘-omic’ technologies will definitively boost our understanding on woody plant-BCA-pathogen interactions (Massart et al. 2015). So far, these approaches have been used in trees and woody plants to a lesser extent than in herbaceous species, although examples are increasingly available (Sun et al. 2011; Palmieri et al. 2012; Mgbeahuruike et al. 2013; Gómez-Lama Cabanás et al. 2014; Calderón et al. 2015; Martínez-García et al. 2015), and many more will be on hand soon. Likewise, proper understanding of the causes behind inconsistencies observed with BCAs is urgent, particularly when they are released under field conditions and a multiplicity of (a)biotic factors is dynamically interacting. Working with trees and woody plants, and considering the peculiarities of these plants which have been briefly described above, can accentuate these inconsistencies. In spite of these difficulties, the use of biocontrol measures, either alone or complementary to other actions within IPM frameworks, is feasible and should have a promising future as sustainable and environmental-friendly approaches.

Finally, we would like to express our sincere gratitude to all researchers who collaborated by submitting their latest results in the field of biological control of tree and woody plant diseases. Their works demonstrate that the biocontrol of tree and woody plant diseases is not an impossible task. We are also in debt to Dr. Eric Wajnberg for his continuous encouragement and enthusiasm to make this Special Issue a reality.

References

350 Abraham A, Philip S, Jacob SK, Jayachandran K (2013) Novel bacteria endophytes
 351 from *Hevea brasiliensis* as biocontrol agent against Phytophthora leaf fall
 352 disease. BioControl 58:675-684

353 Agrios GN (2005) Plant Pathology, 5th ed. Elsevier, Academic Press, New York. 922 p.

354 Amano K (1986) Host range and geographical distribution of the powdery mildew
 355 fungi. Tokyo: Japan Scientific Societies Press. 741 p.

356 Anand A, Uppalapati SR, Ryu C-M, Allen SN, Kang L, Tang Y, Mysore KS (2008)
 357 Salicylic acid and systemic acquired resistance play a role in attenuating crown
 358 gall disease caused by *Agrobacterium tumefaciens*. Plant Physiol 146:703-715

359 Blakeman JP, Fokkema NJ (1982) Potential for biological control of plant diseases on
 360 the phylloplane. Ann Rev Phytopathol 20:167-190.

361 Bonilla N, Gutiérrez-Barranquero JA, de Vicente A, Cazorla FM (2012) Enhancing soil
 362 quality and plant health through suppressive organic amendments. Diversity
 363 4:475-491

364 Bonilla N, Vida C, Martínez-Alonso M, Landa BB, Gaju N, Cazorla FM, de Vicente A
 365 (2015) Organic amendments to avocado crops induce suppressiveness and
 366 influence the composition and activity of soil microbial communities. Appl
 367 Environ Microbiol 81:3405-3418

368 Burr TJ, Otten L (1999) Crown gall of grape: biology disease management. Annu Rev
 369 Phytopathol 37:53-80

370 Calderón CE, Ramos C, de Vicente A, Cazorla FM (2015) Comparative genomic
 371 analysis of *Pseudomonas chlororaphis* PCL1606 reveals new insight into
 372 antifungal compounds involved in biocontrol. Mol Plant-Microbe Interact
 373 28:249-260

374 Camilo-Alves CDEP, Esteves da Clara MI, Cabral de Almeida Ribeiro NM (2013)
 375 Decline of Mediterranean oak trees and its association with *Phytophthora*
 376 *cinnamomi*: a review. Eur J For Res 132:411-432
 377 Ciano A, Roccuzzo G, Ornat Longaron C (2016) Regulation of the citrus nematode
 378 *Tylenchulus semipenetrans* by a *Pasteuria* sp. endoparasite in a naturally
 379 infested soil. BioControl (this issue) DOI: 10.1007/s10526-015-9704-1
 380 de Cleene M, de Ley J (1976) The host range of Crown gall. Bot Rev 42:388-466
 381 Compant S, Brader G, Muzammil S, Sessitsch A, Lebrihi A, Mathieu F (2012) Use of
 382 beneficial bacteria and their secondary metabolites to control grapevine
 383 pathogen diseases. BioControl 58:435-455
 384 Connor DJ, Gomez del Campo M, Rousseaux MC, Searles PS (2014) Structure,
 385 management and productivity of hedgerow olive orchards: A review. Sci Hort
 386 169:71-93
 387 Cooper JJ (1979) Virus diseases of trees and shrubs. Institute of Terrestrial Biology,
 388 Cambridge, p 74
 389 Crowther TW, Glick HB, Covey KR, Bettigole C, Maynard DS, Thomas SM, Smith JR,
 390 Hintler G, Duguid MC, Amatulli G, Tuanmu MN, Jetz W, Salas C, Stam C,
 391 Piotto D, Tavani R, Green S, Bruce G, Williams SJ, Wiser SK, Huber MO,
 392 Hengeveld GM, Nabuurs GJ, Tikhonova E, Borchardt P, Li CF, Powrie LW,
 393 Fischer M, Hemp A, Homeier J, Cho P, Vibrans AC, Umunay PM, Piao SL,
 394 Rowe CW, Ashton MS, Crane PR, Bradford MA (2015) Mapping tree density at
 395 a global scale. Nature 525:201-205
 396 Dolinski C (2016) Entomopathogenic nematodes against the main guava insect pests.
 397 BioControl (this issue) DOI: 10.1007/s10526-015-9695-y

398 Duncan LW, Noling JW (1987) The relationship between development of the citrus root
 399 system and infestation by *Tylenchulus semipenetrans*. Revue Nématol 10:61-66

400 El Hassni M, El Hadrami A, Daayf F, Cherif M, Barka EA, El Hadrami I (2007)
 401 Biological control of Bayoud disease in date palm: Selection of microorganisms
 402 inhibiting the causal agent and inducing defense reactions. Environ Exp Bot
 403 59:224-234

404 El Hassni M, J'Aiti F, Dihazi A, Ait Barka E, Daayf F, El Hadrami I (2004)
 405 Enhancement of defence responses against Bayoud disease by treatment of date
 406 palm seedlings with an hypoaggressive *Fusarium oxysporum* isolate. J
 407 Phytopathol 152:182-189

408 Food and Agriculture Organization of the United Nations (2010) Global forest resources
 409 assessment 2010: global tables.
 410 <http://foris.fao.org/static/data/fra2010/FRA2010GlobaltablesEnJune29.xls>.

411 Gai C, Lacava P, Quecine M, Auriac M-C, Lopes J, Araújo W, Miller T, Azevedo J
 412 (2009) Transmission of *Methylobacterium mesophilicum* by *Bucephalogonia*
 413 *xanthophis* for paratransgenic control strategy of Citrus variegated chlorosis. J
 414 Microbiol 47:448-454

415 García-Jiménez J, Monte E, Trapero A (2010) Los hongos y oomicetos fitopatógenos.
 416 In: Jiménez Díaz R, Montesinos Seguí E (eds) Enfermedades de las plantas
 417 causadas por hongos y oomicetos. Naturaleza y control integrado, Phytoma,
 418 España, pp 23-50 (in Spanish)

419 Gómez-Lama Cabanás C, Schilirò E, Valverde-Corredor A, Mercado-Blanco J (2014)
 420 The biocontrol endophytic bacterium *Pseudomonas fluorescens* PICF7 induces
 421 systemic defense responses in aerial tissues upon colonization of olive roots.
 422 Front Microbiol 5:427

423 González-Sánchez MA, de Vicente A, Pérez-García A, Pérez-Jiménez R, Romero D,
 424 Cazorla FM (2013) Evaluation of the effectiveness of biocontrol bacteria against
 425 avocado white root rot occurring under commercial greenhouse plant production
 426 conditions. *Biol Control* 67:94-100

427 Hardoim PR, van Overbeek LS, Berg G, Pirttilä AM, Compant S, Campisano A, Döring
 428 M, Sessitsch A (2015) The hidden world within plants: ecological and
 429 evolutionary considerations for defining functioning of microbial endophytes.
 430 *Microbiol Mol Biol Rev* 79:293-320

431 Heiniger U, Rigling D (1994) Biological control of chestnut blight in Europe. *Annu Rev*
 432 *Phytopathol* 32:581–599

433 Holb IJ, Heijne B, Jeger MJ (2004) Overwintering of conidia of *Venturia inaequalis* and
 434 the contribution to early epidemics of apple scab. *Plant Dis* 88:751–757

435 Kennelly MM, Cazorla FM, de Vicente A, Ramos C, Sundin GW (2007) *Pseudomonas*
 436 *syringae* diseases of fruit trees – Progress toward understanding and control.
 437 *Plant Dis* 91:4-17

438 Lacava PT, Araújo WL, Marcon J, Maccheroni W, Azevedo JL (2004) Interaction
 439 between endophytic bacteria from citrus plants and the phytopathogenic bacteria
 440 *Xylella fastidiosa*, causal agent of citrus-variegated chlorosis. *Lett Appl*
 441 *Microbiol* 39:55-59

442 Lacava P, Li W, Araújo W, Azevedo J, Hartung J (2007) The endophyte
 443 *Curtobacterium flaccumfaciens* reduces symptoms caused by *Xylella fastidiosa*
 444 in *Catharanthus roseus*. *J Microbiol* 45:388-393

445 López-Escudero FJ, Mercado-Blanco J (2011) Verticillium wilt of olive: a case study to
 446 implement an integrated strategy to control a soil-borne pathogen. *Plant Soil*
 447 344:1-50

448 López-Herrera CJ, Perez-Jiménez RM, Basallote-Ureba MJ, Zea Bonilla T, Melero-
 449 Vara JM (2003) Effect of soil solarization on the control of *Phytophthora* root
 450 rot in avocado. *Plant Pathol* 46:329-340
 451 Maldonado-González MM, Prieto P, Ramos C, Mercado-Blanco J (2013) From the root
 452 to the stem: interactions between the biocontrol root endophyte *Pseudomonas*
 453 *fluorescens* PICF7 and the pathogen *Pseudomonas savastanoi* NCPPB 3335 in
 454 olive knots. *Microbial Biotechnol* 6:275-287
 455 Maldonado-González MM, Schilirò E, Prieto P, Mercado-Blanco J (2015) Endophytic
 456 colonization and biocontrol performance of *Pseudomonas fluorescens* PICF7 in
 457 olive (*Olea europaea* L.) are determined neither by pyoverdine production nor
 458 swimming motility. *Environ Microbiol* 17:3139-3153
 459 Manion PD (1991) Tree disease concepts, 2nd ed. Prentice-Hall, Englewood Cliffs, NJ,
 460 402 p.
 461 Markakis EA, Sotirios ET, Antoniou PP, Paplomatas EJ, Tjamos EC (2016) Biological
 462 control of *Verticillium* wilt of olive by *Paenibacillus alvei*, strain K165.
 463 *BioControl* (this issue) DOI: 10.1007/s10526-015-9669-0
 464 Martelli GP, Boscia D, Porcelli F, Saponari M (2016) The olive quick decline syndrome
 465 in south-east Italy: a threatening phytosanitary emergency. *Eur J Plant Pathol*
 466 144:235-243
 467 Martínez-García P, Ruano-Rosa D, Schilirò E, Prieto P, Ramos C, Rodríguez-
 468 Palenzuela P, Mercado-Blanco J (2015) Complete genome sequence of
 469 *Pseudomonas fluorescens* strain PICF7, an indigenous root endophyte from
 470 olive (*Olea europaea* L.) and effective biocontrol agent against *Verticillium*
 471 *dahliae*. *Stand Genomic Sci* 10:10

472 Massart S, Perazzolli M, Höfte M, Pertot I, Jijakli MH (2015) Impact of the omic
473 technologies for understanding the modes of action of biological control agents
474 against plant pathogens. *BioControl* 60:725-746

475 Melnick RL, Bailey BA, Backman PA (2013) Bacterial Endophytes of Perennial Crops
476 for Management of Plant Disease. In: Maheshwari DK (ed) *Bacteria in*
477 *Agrobiological: Disease Management*, Springer-Verlag, Berlin Heidelberg, pp 49-
478 76

479 Melnick RL, Suárez C, Bailey BA, Backman PA (2011) Isolation of endophytic
480 endosporeforming bacteria from *Theobroma cacao* as potential biological
481 control agents of cacao diseases. *Biol Control* 57:236-245

482 Mercado-Blanco J, Rodríguez-Jurado D, Hervás A, Jiménez-Díaz RM (2004)
483 Suppression of *Verticillium* wilt in olive planting stocks by root-associated
484 fluorescent *Pseudomonas* spp. *Biol Control* 30:474-486

485 Mercado-Blanco J, Lugtenberg B J J (2014). Biotechnological applications of bacterial
486 endophytes. *Curr Biotechnol* 3: 60–75

487 Mgbeahuruike AC, Karlsson M, Asiegbu FO (2012) Differential expression of two
488 hydrophobin genes (*Pgh1* and *Pgh2*) from the biological control agent
489 *Phlebiopsis gigantea*. *Fungal Biol* 116: 620-629

490 Mgbeahuruike AC, Kohler A, Asiegbu FO (2013) Expression analysis of the impact of
491 culture filtrates from the biocontrol agent, *Phlebiopsis gigantea* on the conifer
492 pathogen, *Heterobasidion annosum* s.s. transcriptome. *Microb Ecol* 66: 669-681

493 Mgbeahuruike AC, Sun H, Fransson P, Kananen R, Daniel G, Karlsson M, Asiegbu FO
494 (2011) Screening of *Phlebiopsis gigantea* isolates for traits associated with
495 biocontrol of the conifer pathogen *Heterobasidion annosum*. *Biol Control* 57:
496 118-129

497 Milgroom MG, Cortesi P (2004) Biological control of chestnut blight with
 498 hypovirulence: a critical analysis. *Annu Rev Phytopathol* 42:311–338

499 Moreira AC, Domingos AC, Fontes AM, Semedo J, Melo E, Machado H, Reis M, Horta
 500 M, Cravador A (2007) Evaluation of cork and holm oak seedling viability to
 501 *Phytophthora cinnamomi* infection treated with compost and mycorrhizae fungi.
 502 *IOBC/wprs Bull* 57:73–76

503 New PB, Kerr A (1972) Biological control of crown gall: field measurements and
 504 glasshouse experiments. *J Appl Bacteriol* 35:279-287.

505 Palmieri MC, Perazzolli M, Matafora V, Moretto M, Bachi A, Pertot I (2012) Proteomic
 506 analysis of grapevine resistance induced by *Trichoderma harzianum* T39 reveals
 507 specific defence pathways activated against downy mildew. *J Exp Bot* 63:6237-
 508 6251

509 Pautasso M, Schlegel M, Holdenrieder O (2015) Forest health in a changing world.
 510 *Microb Ecol* 69:826-842

511 Pearson RC, Gadoury DM (1987) Cleistothecia, the source of primary inoculum for
 512 grape powdery mildew in New York. *Phytopathology* 77:1509-1514

513 Pérez-Jiménez RM (2008) Significant avocado diseases caused by fungi and oomycetes.
 514 *Eur J Plant Sci Biotechnol* 2:1-24

515 Pertot I, Prodorutti D, Colombini A, Pasini L (2016) *Trichoderma atroviride* SC1
 516 prevents *Phaeomoniella chlamydospora* and *Phaeoacremonium aleophilum*
 517 infection of grapevine plants during the grafting process in nurseries. *BioControl*
 518 (this issue) DOI: 10.1007/s10526-016-9723-6

519 Pinto C, Gomez AC (2016) *Vitis vinifera* microbiome: from basic research to
 520 technological development. *BioControl* (this issue) DOI: 10.1007/s10526-016-
 521 9725-4

522 Pinto C, Pinho D, Sousa S, Pinheiro M, Egas C, Gomes AC (2014) Unravelling the
523 diversity of grapevine microbiome. PLoS ONE 9:e85622

524 Pliego C, Cazorla FM (2012) Biocontrol of tree root diseases. In: Bruijn FJ (ed)
525 Molecular microbial ecology of the rhizosphere, vol 2. Wiley Blackwell, New
526 Jersey, pp 655–663

527 Pliego C, López-Herrera C, Ramos C, Cazorla FM (2012) Developing tools to unravel
528 the biological secrets of *Rosellinia necatrix*, an emergent threat to woody crops.
529 Mol Plant Pathol 13:226-239

530 Ponti L, Gutierrez AP, Ruti PM, Dell'Aquila A (2014) Fine-scale ecological and
531 economic assessment of climate change on olive in the Mediterranean Basin
532 reveals winners and losers. Proc Natl Acad Sci USA 111:5598-5603

533 Postma J, Goossen-van de Geijn H (2016) Twenty-four years of Dutch Trig®
534 application to control Dutch Elm Disease. BioControl (this issue) DOI:
535 10.1007/s10526-016-9731-6

536 Prance GT (1994) Amazonian tree diversity and the potential for supply of non-timber
537 forest products. In: Leakey RRB, Newton AC (eds), Tropical trees: the potential
538 for domestication and the rebuilding of forest resources, HMSO, London, UK,
539 pp 7-15

540 Prospero S, Rigling D (2013) Chestnut Blight. In: Gonthier P, Nicolotti G (eds),
541 Infectious Forest Diseases, CAB International, Wallingford, UK, pp 318–339

542 Prospero S, Rigling D (2016) Using molecular markers to assess the establishment and
543 spread of a mycovirus applied as a biological control agent against chestnut
544 blight. BioControl (this issue) DOI: 10.1007/s10526-015-9713-0

545 Ramos C, Matas IM, Bardaji L, Aragón IM, Murillo J (2012) *Pseudomonas savastanoi*
546 pv. *savastanoi*: some like it knot. Mol Plant Pathol 13:998-1009

547 Ren JH, Li H, Wang YF, Ye JR, Yan AQ, Wu XQ (2013) Biocontrol potential of an
548 endophytic *Bacillus pumilus* JK-SX001 against poplar canker. Biol Control
549 67:421-430

550 Ruano-Rosa D, López-Herrera CJ (2009) Evaluation of *Trichoderma* spp. as biocontrol
551 agents against avocado white root rot. Biol Control 51:66-71

552 Ruano-Rosa D, Mercado-Blanco J (2015) Combining biocontrol agents and organics
553 amendments to manage soil-borne phytopathogens. In: Meghvansi MK, Varma
554 A (eds), Organic Amendments and Soil Suppressiveness in Plant Disease
555 Management, Soil Biology 46, Springer International Publishing, Switzerland,
556 pp 457-478

557 Ruano-Rosa D, Prieto P, Rincón AM, Gómez-Rodríguez MV, Valderrama R, Barroso
558 JB, Mercado-Blanco J (2016) Fate of *Trichoderma harzianum* in the olive
559 rhizosphere: time course of the root colonization process and interaction with the
560 fungal pathogen *Verticillium dahliae*. BioControl (this issue) DOI:
561 10.1007/s10526-015-9706-z

562 Ruehle JL (1973) Nematodes and forest trees – types of damage to tree roots. Ann Rev
563 Phytopathol 11:99-118

564 Salazar-Garcia S, Cortés-Flores JI (1986) Root distribution of mature avocado trees
565 growing in soils of different textures. California Avocado Soc Yearbook 70:165-
566 174

567 Santini A, Ghelardini L, De Pace C, Desprez-Loustau ML, Capretti P, Chandelier A,
568 Cech T, Chira D, Diamandis S, Gaitniekis T, Hantula J, Holdenrieder O,
569 Jankovsky L, Jung T, Jurc D, Kirisits T, Kunca A, Lygis V, Malecka M, Marcais
570 B, Schmitz S, Schumacher J, Solheim H, Solla A, Szabo I, Tsopelas P, Vannini
571 A, Vettraino AM, Webber J, Woodward S, Stenlid J (2013) Biogeographical

572 patterns and determinants of invasion by forest pathogens in Europe. New
573 Phytol 197:238-250

574 Scheffer RJ, Voeten JGWF, Guries RP (2008) Biological control of Dutch elm disease.
575 Plant Disease 92:192-200

576 Souza JC, Haga A, Souza MA (2003) Pragas da goiabeira. Tech Bull no. 71, 60 pp.

577 Sun H, Paulin L, Alatalo E, Asiegbu FO (2011) Response of living tissues of *Pinus*
578 *sylvestris* to the saprotrophic fungus *Phlebiopsis gigantea*. Tree Physiol 31:438-
579 451

580 Turnbull JW (2002) Tree domestication and the history of plantations. In: Squires VR
581 (ed) The role of food, agriculture, forestry and fisheries in human nutrition –
582 Vol. II. Encyclopedia of Life Support Systems developed under auspices of
583 UNESCO. EOLSS Publishers, Oxford, UK, pp 48-74

584 Vanneste JL (2000) Fire Blight: the disease and its causative agent, *Erwinia amylovora*.
585 CAB International, Wallingford, UK, 375 p

586 Varo A, Moral J, Lozano-Tóvar MD, Trapero A (2016) Development and validation of
587 an inoculation method to assess the efficacy of biological treatments against
588 *Verticillium* wilt in olive trees. BioControl (this issue) DOI: 10.1007/s10526-
589 015-9710-3

590 Vitullo D, Altieri R, Esposito A, Nigro F, Ferrara M, Alfano G, Ranalli G, De Cicco V,
591 Lima G (2013) Suppressive biomasses and antagonist bacteria for an eco-
592 compatible control of *Verticillium dahliae* on nursery-grown olive plants. Int J
593 Environ Sci Technol 10:209-220

594 Wang N, Trivedi P (2013) Citrus Huanglongbing: A newly relevant disease presents
595 unprecedented challenges. Phytopathology 103:652-665

Zarraonaindia I, Owens SM, Weisenhorn P, West K, Hampton-Marcell J, Lax S,
Bokulich NA, Mills DA, Martin G, Taghavi S, van der Lelie D, Gilbert JA
(2015) The soil microbiome influences grapevine-associated microbiota. mBio
6:e02527-14

Figure captions

Fig. 1

Approaches to study biological control in different trees and woody plants contained in
this Special Issue. These studies (reference included) use diverse biocontrol agents
(represented by figures of fungi, bacteria, viruses, nematodes) to fight against some
major biotic constraints of trees and woody plants.

Acknowledgments

We are grateful to two anonymous reviewers for their comments and suggestions to improve an earlier version of the manuscript. Research on Verticillium wilt of olive in Jesús Mercado-Blanco's lab supported by grants P07-CVI-02624 and P12-AGR-667 (Junta de Andalucía, Spain), AGL2009-07275 (Spanish MICINN/MINECO), and RECUPERA 2020 (MINECO-CSIC agreement), all co-funded by ERDF from EU. Research on bacterial biocontrol of avocado white root rot was supported by grant AGL2014-52518-C2-1-R (Spanish MINECO).