BioControl (2016) 61:233–242
DOI 10.1007/s10526-016-9737-0

FOREWORD

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

Francisco M. Cazorla · Jesús Mercado-Blanco

Received: 18 February 2016 / Accepted: 7 April 2016 / Published online: 18 April 2016
© International Organization for Biological Control (IOBC) 2016

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.)

Handling Editor: Eric Wajnberg.

F. M. Cazorla
Departamento de Microbiología, Facultad de Ciencias, Instituto de Hortofruticultura Subtropical y Mediterránea 'La Mayora', IHSM-UMA-CSIC, Universidad de Málaga, Campus Universitario de Teatinos s/n, 29071 Málaga, Spain

J. Mercado-Blanco (✉)
Departmento de Protección de Cultivos, Instituto Agricultura Sostenible, Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC), Avda. Menéndez Pidal s/n, Campus Alameda del Obispo s/n, 14004 Córdoba, Spain
e-mail: jesus.mercado@ias.csic.es

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 et al. (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 4000 BC) in the Mediterranean area, or diverse fruit trees (around 2000 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, phytoplasms, 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 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 societies 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

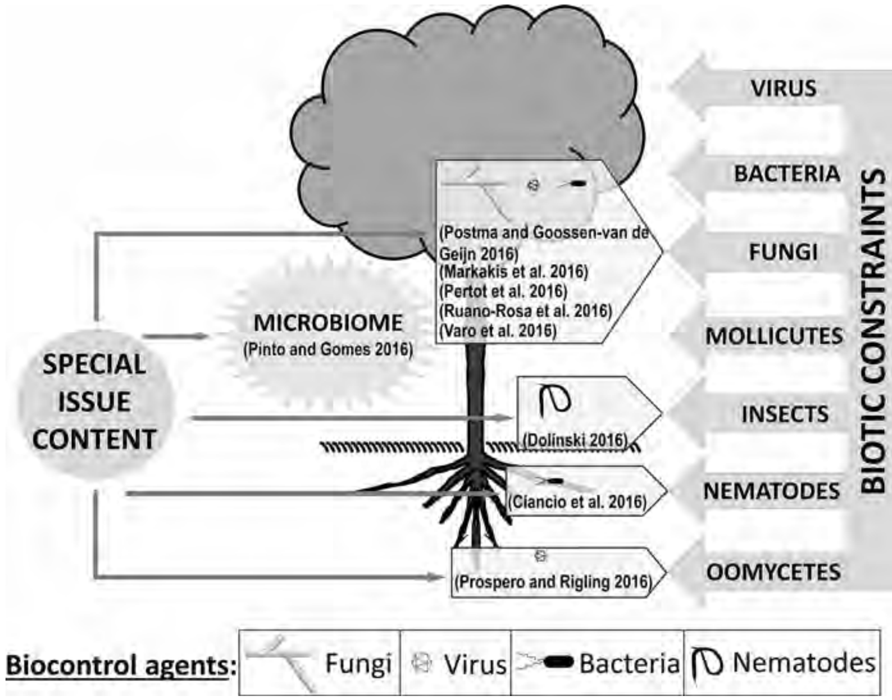

Fig. 1 Approaches to study biological control in different trees and woody plants contained in this special issue. These studies (reference included) use diverse biocontrol agents (represented by *figures* of fungi, bacteria, viruses, nematodes) to fight against some major biotic constraints of trees and woody plants

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 thus not 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 and Otten (1999) 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-González 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* (Mgbeahuruike 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 et al. (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 been 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 constrains 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 et al. (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 et al. (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 suppressive effect of K165 in an established olive orchard naturally infested with *V. dahliae*. Among other interesting observations, this study reports for the first time effective biological control of this disease under field conditions, a scenario not frequently explored in biocontrol research, particularly with woody plants. Finally, Varo et al. (2016) compared diverse pathogen inoculation methods to screen for potential biocontrol agents against *V. dahliae* in olive, addressing one of the major restrictions when developing control measures against this disease: the lack of consistent inoculation methods to evaluate, for instance, the effectiveness of biocontrol agents. The authors eventually propose a promising inoculation method to assess potentially effective BCAs against Verticillium wilt of olive, an important step before evaluation under field conditions.

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

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).

References

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

Agrios GN (2005) Plant Pathology, 5th edn. Elsevier, Academic Press, New York

Amano K (1986) Host range and geographical distribution of the powdery mildew fungi. Japan Scientific Societies Press, Tokyo

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

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

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

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

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

Camilo-Alves CDEP, Esteves da Clara MI, de Almeida Cabral, Ribeiro NM (2013) Decline of Mediterranean oak trees and its association with *Phytophthora cinnamomi*: a review. Eur J For Res 132:411–432

Ciancio A, Roccuzzo G, Ornat Longaron C (2016) Regulation of the citrus nematode *Tylenchulus semipenetrans* by a *Pasteuria* sp. endoparasite in a naturally infested soil. BioControl (this issue). doi:10.1007/s10526-015-9704-1

Compant S, Brader G, Muzammil S, Sessitsch A, Lebrihi A, Mathieu F (2012) Use of beneficial bacteria and their secondary metabolites to control grapevine pathogen diseases. BioControl 58:435–455

Connor DJ, Gomez del Campo M, Rousseaux MC, Searles PS (2014) Structure, management and productivity of hedgerow olive orchards: a review. Sci Hortic 169:71–93

Cooper JI (1979) Virus diseases of trees and shrubs. Institute of Terrestrial Biology, Cambridge

Crowther TW, Glick HB, Covey KR, Bettigole C, Maynard DS, Thomas SM, Smith JR, Hintler G, Duguid MC, Amatulli G, Tuanmu MN, Jetz W, Salas C, Stam C, Piotto D, Tavani R, Green S, Bruce G, Williams SJ, Wiser SK, Huber MO, Hengeveld GM, Nabuurs GJ, Tikhonova E, Borchardt P, Li CF, Powrie LW, Fischer M, Hemp A, Homeier J, Cho P, Vibrans AC, Umunay PM, Piao SL, Rowe CW, Ashton MS, Crane PR, Bradford MA (2015) Mapping tree density at a global scale. Nature 525:201–205

de Cleene M, de Ley J (1976) The host range of Crown gall. Bot Rev 42:388–466

Dolinski C (2016) Entomopathogenic nematodes against the main guava insect pests. BioControl (this issue). doi:10.1007/s10526-015-9695-y

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

López-Herrera CJ, Perez-Jiménez RM, Basallote-Ureba MJ, Zea Bonilla T, Melero-Vara JM (2003) Effect of soil solarization on the control of Phytophthora root rot in avocado. Plant Pathol 46:329–340

Maldonado-González MM, Prieto P, Ramos C, Mercado-Blanco J (2013) From the root to the stem: interactions between the biocontrol root endophyte *Pseudomonas fluorescens* PICF7 and the pathogen *Pseudomonas savastanoi* NCPPB 3335 in olive knots. Microbial Biotechnol 6:275–287

Maldonado-González MM, Schilirò E, Prieto P, Mercado-Blanco J (2015) Endophytic colonization and biocontrol performance of *Pseudomonas fluorescens* PICF7 in olive (*Olea europaea* L.) are determined neither by pyoverdine production nor swimming motility. Environ Microbiol 17:3139–3153

Manion PD (1991) Tree disease concepts, 2nd edn. Prentice-Hall, Englewood Cliffs

Markakis EA, Sotirios ET, Antoniou PP, Paplomatas EJ, Tjamos EC (2016) Biological control of Verticillium wilt of olive by *Paenibacillus alvei*, strain K165. BioControl (this issue). doi:10.1007/s10526-015-9669-0

Martelli GP, Boscia D, Porcelli F, Saponari M (2016) The olive quick decline syndrome in south-east Italy: a threatening phytosanitary emergency. Eur J Plant Pathol 144:235–243

Martínez-García P, Ruano-Rosa D, Schilirò E, Prieto P, Ramos C, Rodríguez-Palenzuela P, Mercado-Blanco J (2015) Complete genome sequence of *Pseudomonas fluorescens* strain PICF7, an indigenous root endophyte from olive (*Olea europaea* L.) and effective biocontrol agent against *Verticillium dahliae*. Stand Genomic Sci 10:10

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

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

Melnick RL, Bailey BA, Backman PA (2013) Bacterial endophytes of perennial crops for management of plant disease. In: Maheshwari DK (ed) Bacteria in agrobiology: disease management. Springer, Berlin, pp 49–76

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Prospero S, Rigling D (2013) Chestnut Blight. In: Gonthier P, Nicolotti G (eds) Infectious forest diseases. CAB International, Wallingford, pp 318–339

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

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

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

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

Ruano-Rosa D, Mercado-Blanco J (2015) Combining biocontrol agents and organics amendments to manage soil-borne phytopathogens. In: Meghvansi MK, Varma A (eds) Organic amendments and soil suppressiveness in plant disease management, soil biology, vol 46. Springer International Publishing, Cham, pp 457–478

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

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

Salazar-Garcia S, Cortés-Flores JI (1986) Root distribution of mature avocado trees growing in soils of different textures. Calif Avocado Soc Yearb 70:165–174

Santini A, Ghelardini L, De Pace C, Desprez-Loustau ML, Capretti P, Chandelier A, Cech T, Chira D, Diamandis S, Gaitniekis T, Hantula J, Holdenrieder O, Jankovsky L, Jung T, Jurc D, Kirisits T, Kunca A, Lygis V, Malecka M, Marcais B, Schmitz S, Schumacher J, Solheim H, Solla A, Szabo I, Tsopelas P, Vannini A, Vettraino AM, Webber J, Woodward S, Stenlid J (2013) Biogeographical patterns and determinants of invasion by forest pathogens in Europe. New Phytol 197:238–250

Scheffer RJ, Voeten JGWF, Guries RP (2008) Biological control of Dutch elm disease. Plant Dis 92:192–200

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

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

Turnbull JW (2002) Tree domestication and the history of plantations. In: Squires VR (ed) The role of food, agriculture, forestry and fisheries in human nutrition, vol II. Encyclopedia of life support systems developed under auspices of UNESCOEOLSS Publishers, Oxford, pp 48–74

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

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

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

Wang N, Trivedi P (2013) Citrus Huanglongbing: a newly relevant disease presents 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

Francisco M. Cazorla is associate professor in the Department of Microbiology, Faculty of Science, Málaga University, Spain (Institute for Mediterranean and Subtropical Horticulture "La Mayora", IHSM-UMA-CSIC). His main research on microbial plant–microbe interactions is related with the elucidation of the multitrophic interactions that take place on the roots during the biocontrol, using as a model the subtropical avocado tree. Special attention is paid to the bacterial genus *Pseudomonas* and *Bacillus* and its molecular bases of acting against soil borne phytopathogenic fungi.

Jesús Mercado-Blanco is tenured scientist in the Institute for Sustainable Agriculture (Spanish National Research Council, CSIC). His main research interests focus on agricultural microbiology and biotechnology and the development of control tools within integrated disease management strategies, using Verticillium wilt of olive as study model. Specific research topics are the bases underlying plant–microbe interactions by molecular and '-omic' approaches and the identification, characterization and use of microbiological control agents, with emphasis on bacterial endophytes.