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Short communication

Multi-study analysis of the added benefits of combining soil solarization with fumigants or non-chemical measures

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ABSTRACT

Soil solarization (SH) is a non-chemical method in which solar heating is used to manage a wide range of soilborne pests. We analyzed several independent studies to assess the efficacy of SH in suppressing a wide range of soilborne pathogens in different agrosystems and under various climatic conditions, and to quantify the added value of combining SH with chemical or non-chemical measures. We analyzed 69 documented experiments and calculated the level of pest management efficacy by SH alone or in combination with either fumigants, organic amendments or biological agents. The analyses were clustered into three groups of soilborne pathogens: (i) various species and formae speciales of *Fusarium;* (ii) root-knot nematodes; (iii) a group consisting of the pathogens *Sclerotium cepivorum*, *Verticillium*, *Pyrenochaeta*, *Rhizoctonia* and *Pythium*. Combining SH with additional measures improved management efficacy, reduced the variance between experimental results, increased the percentage of cases with high management efficacy and reduced the percentage of cases with low management efficacy, compared to SH alone. The efficacy of SH combined with additional measures was not significantly affected by the initial disease pressure. Yield increase in the *Fusarium* group was positively correlated with disease control efficacy, and the combined measures produced the upper values. These results demonstrate the benefit of combining SH with other control measures in managing soilborne pathogens.

1. Introduction

Soil solarization (SH) is a soil disinfestation tool for managing soilborne pests (including pathogens, arthropods and weeds). It consists of solar heating of a wet soil that is covered by transparent plastic film during the hot season for a few weeks (Katan et al., 1976; Gamliel and Katan, 2012). The efficacy of SH in suppressing pest populations in various crops and under diverse climatic conditions and agrosystems was demonstrated in numerous studies since 1976. The phaseout of methyl bromide, the attempts to reduce reliance on conventional pesticides (Lamichhane et al., 2016) and the increasing restrictions on the use of chemical pesticides has boosted the adoption and application of SH. This technique may be implemented alone or in combination with other measures such as soil fumigation, organic amendments or biological agents.

Integrated pest management (IPM) became the major concept for reducing the dosage of pesticides. It is a holistic approach whose goals extend beyond the management of a specific pest or a particular period or site. According to Andrews (1983) integrated management includes, among others, diversified controls coordinated to achieve an additive or, preferably, synergistic effect. One of the definitions of IPM was given by Kogan (1998): IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously, coordinated in management strategies. Gray et al. (2009) too, emphasized the importance of harmonious use of multiple methods. IPM was successfully applied in a variety of crops (Kogan, 1998; Gramaje et al., 2018). SH is a non-chemical soil disinfestation tool which is applied on a large scale and can be a significant component in IPM programs.

Lamichhane et al. (2016) regard IPM as a careful consideration of all available plant protection methods and their subsequent integration. Barzman et al. (2015) reviewed eight principles of IPM required by the European Union which states, among others, that the combination of management strategies generates more effective and sustainable results than single tactics approaches. All these lead to the well-accepted

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conclusion that combining methods of pest management is at the heart of IPM since it enables improved management efficacy and reduced pesticide usage, as well as improved diversity of pest control tools and other benefits (Chellemi et al., 2016; Katan et al., 2012). Replacing methyl bromide, which has a wide spectrum of pest control, further requires the use of a combination of management tools for different pests. Damping-off diseases of seedlings are caused by a variety of pathogens, such as *Pythium* and *Rhizoctonia* spp.. These diseases are increasingly emerging and intensified, and hence integrated management is required to reduce their considerable damage (Lamichhane et al., 2017).

Efforts have been made to further improve SH performance. Combining SH with other management tools, under the IPM approach, has the potential to increase pest management effectiveness and reproducibility due to additive or even synergistic effects (Katan et al., 2012). Being a climate-dependent method, the effectiveness of SH varies in different cases. Therefore, cluster analysis of many studies of SH application can reveal certain trends of efficacy, identify gaps of inefficacy, and suggest ways to optimize the SH effect.

The objectives of the current study were to use a multi-study assessment approach for: (i) assessing the efficacy of SH in suppressing a wide range of pests (oomycetes, fungi and nematodes) under diverse agrosystems and climatic conditions and (ii) quantifying the added value of combining SH with fumigants or non-chemical measures. A portion of the data has been briefly presented previously (Shlevin et al., 2016).

2. Materials and methods

2.1. Pooling and selection of data

First, we formulated a comprehensive and reliable dataset for the analyses. We screened electronic databases (Agricola, CAB Abstracts), proceedings of national and international symposia and scientific reports for relevant publications on soil and substrate disinfestation by SH alone or combined with chemical and non-chemical measures. Only reported studies which met the following criteria were included in the dataset and used in our analysis: (i) the reported research included at least the following treatments: untreated control, SH alone, and SH combined with either fumigant, organic amendment or biological agent; (ii) the research provided measurable data on disease incidence or disease severity as affected by the treatments; (iii) adequate statistical analysis was carried out. In total, 51 publications which met these requirements were used, including 69 individual trials (hereafter termed 'records'). These records were included in our multi-study analysis (Table 1). The pathosystems studied in the different reports (i.e., hosts and pests [oomycetes, fungi or nematodes]), and agricultural practices (i.e., open fields, greenhouses, net houses), the experimental design used (i.e., plot size, number of replications), specifics of treatments (i.e., the specific fumigant/s used, biological agent/s or organic amendments used), or the evaluation procedures (i.e., disease rating) were not used as criteria for inclusion or exclusion of records. In 27 of the publications (34 records) dealing with *Fusarium* diseases, treatment effects on harvested yield were included. These data were analyzed as well. References to all records and additional relevant information are presented in Table 1.

2.2. Data analyses

The final dataset included diverse pathosystems (i.e., pests and hosts). Because the experimental designs used by the experimenters differed markedly, as did disease-rating and yield-evaluation procedures, it was necessary to formulate standardized parameters for common analysis of the data. Consequently, data recorded in each of the experiments were used to calculate two parameters exemplifying the contribution of the treatments in suppressing the disease and improving yield (when applicable). The first parameter, disease control efficacy (*DCE*, in %), represented the relative contribution of the SH treatment, alone or in combination with other measures, in suppressing the disease as compared to disease level recorded in the untreated treatment of the same trial. DCE was estimated using the formula: $DCE_i = 100 \times (1\text{-}DT_i/DC_i)$, where: DCE_i = control efficacy; DT_i = % disease in the treated plots; DC_i = % disease in the untreated plots; and $i = 1$ to n = the number of treatments in the trial. Similarly, the relative contribution of the treatments to yield increment (*RYI*, in %) was estimated as: $RYI_i = 100 \times (1\text{-}YT_i/YC_i)$, with RYC_i = relative yield contribution; YT_i = yield in the treated plots; YC_i = yield in the untreated plots; and $i = 1$ to n—the number of treatments in the trial.

For additional analyses, individual records were grouped into three clusters of the major pests prevailing in each of the trials. Each cluster included pests possessing comparable properties with respect to relative sensitivity to solarization. Grouping was based on our long-term experience with solarization and on experimental reports from the literature (e.g., Bollen, 1985; Davis, 1991; McGovern and McSoreley, 2012). The clusters were as follows: (i) various species or formae speciales of *Fusarium*; (ii) root-knot nematodes; (iii) other fungi (*Sclerotium cepivorum*, *Verticillium*, *Pyrenochaeta, Rhizoctonia*) and oomycete (*Pythium*). In addition, data for all records were analyzed concurrently. For each of the treatments (i.e., SH, SH + fumigant, and SH + organic amendment or biological agent) in each of the pest clusters, the following variables were calculated: (i) the average *DCE* value (in %); (ii) the percentage of records with sufficient control; disease control was regarded as sufficient if *DCE* was ≥70%; (iii) the percentage of records with insufficient control; disease control was regarded as insufficient if *DCE* was ≤40%; (iv) the coefficient of variation of the average *DCE* value (in %). These estimates were calculated only for treatments that included at least eight individual records. Mean ± standard error was calculated for each variable and differences between the treatments were compared using χ^2 test and defined as significant at $P \leq 0.05$.

The number of records included in the *Fusarium* cluster significantly exceeded the number of records in the other clusters. This enabled performing further analyses of the data for the *Fusarium* cluster. First, the relationship between disease pressure in the experiment (defined as disease incidence or disease severity in untreated control plots) and *DCE* was plotted. Linear regression analysis was performed and when this relationship was significant, results of the analysis were included in this report. In addition, the relationship between *DCE* and *RYI* was plotted and a linear regression equation was calculated for the data. One record with *RYI* value above 200% was regarded as an outlier and excluded from the analysis because it is possible that other effects, beyond *Fusarium* disease suppression, contributed to the exceptionally high yield increment.

3. Results

3.1. The benefits of combining SH with fumigants or with biological agents and organic amendments

The current analysis validates the efficacy of SH alone in suppressing diseases caused by pathogens and nematodes of the three tested groups. An average of 58–78% *DCE* was found in the surveyed records. However, when solarization was applied alone, the percentage of records with sufficient control (*DCE* ≥ 70%) was relatively low: 22–58% (Figs. 1 and 2). *DCE* and percentages of sufficient control were significantly improved when SH was combined with either fumigants, biocontrol agents or organic amendments. Such combinations resulted, in some cases, in 100% *DCE* (Figs. 1B and 2). In parallel, the percentage of records with insufficient control (*DCE* ≤ 40% control) decreased markedly (0–5%) when combined treatments were applied, as compared to SH alone (19–33%) (Fig. 3). The coefficients of variation for *DCE* of SH alone ranged from 20 to 48%, as compared to significantly lower coefficients of variation for *DCE* of SH combined with either