Soil-Fumigation: Discovery, Application, and Alternatives

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Discovery:

The first well-documented application of the scientific method to agriculture resulted in the discovery of soil-fumigants in 1869 by Baron Paul Thenard (Sagnier 1884, Wilhelm 1966). Carbon disulfide (CS_2) was identified as a candidate fumigant and application was optimized by Thenard to treat grape phylloxera (*Phylloxera vitifoliae*) infestations in wine-grape (*Vitis vinifera*) production systems in France during the late 1800s (Wilhelm 1966). Initial applications of CS_2 were delivered to soil surrounding dormant vines by teams equipped with fumigation guns, or "fumiguns", as seen in Figure 1a (Bolle 1882). As the efficacy of fumigation in reducing pest pressure and enhancing vine performance was demonstrated demand grew to fumigate larger swaths of vineyards (Peligot 1884). Mechanical injectors (Fig. 1b) were developed before the 1880s to satisfy the growing demand to fumigate (Barral 1884). Before 1900, one million acres were fumigated (Thenard 1884), often prophylactically, in areas absent of grape ghylloxera, and despite the availability of resistant root stocks (Wilhelm 1966). Other crops, including potato, were also subjected to CS_2 applications during the late 1800s (Girard 1894 a,b,c) – the benefits of fumigation were observed, interest among growers was aroused, and the era of fumigation commenced.

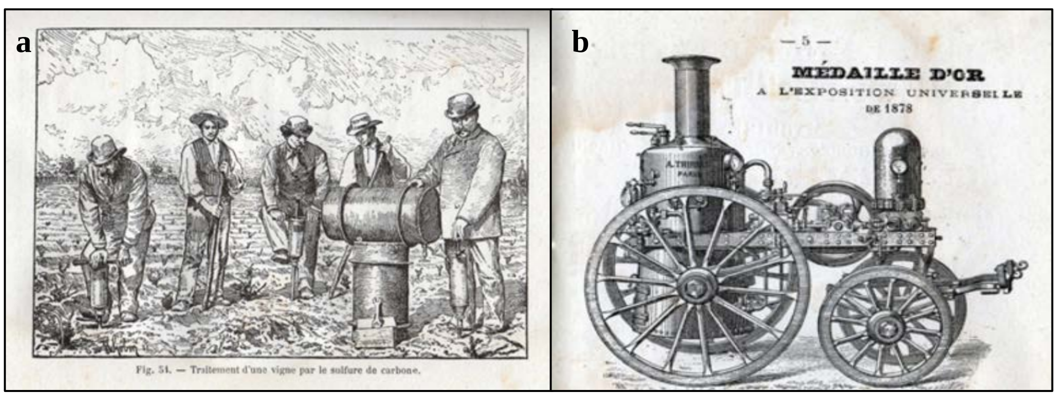

Figure 1. Application of carbon disulfide (CS_2) to dormant wine-grape vines during the late 1800's with fumigation guns (a) and mechanical injector (b). Drawings by J.A. Barral, 1884.

Application:

Since the discovery and optimization of CS_2 as a soil fumigant, various other chemistries were developed or adapted from other applications to treat soilborne pests and plant pathogens. After CS_2 and in chronological order, chloropicrin, methyl bromide, 1,3-dichloropropene, ethylene dibromide, 1,2-dibromo-3-chloropropane, and methyl isothiocynate were discovered (Lembright 1990). Of these fumigants only chloropicrin, methyl bromide, 1,3-dichloropropene and methyl isothiocynate are contemporarily applied while methyl-bromide is applied under critical and quarantine and preshipment use exemptions in accordance with the Montreal Protocol (EPA 2017). Nationally, these fumigants are applied primarily in the Northwest, Southeast, and, to a lesser extent, in the mid-Atlantic and mid-western regions of the United

States (Fig. 2). Potato, strawberries, tomato, and carrot cropping systems demand the most extensive fumigation treatment to manage soilborne pests and pathogens (Blecker and Thomas 2012). The efficacy of fumigants in reducing disease pressure in potato cropping systems has been documented observationally and experimentally (e.g. Easton et al. 1972). Likewise the off-target impacts of fumigants are documented (Sande et al. 2011) and, together with enhanced regulations, have demanded alternative management strategies to control pests and pathogens.

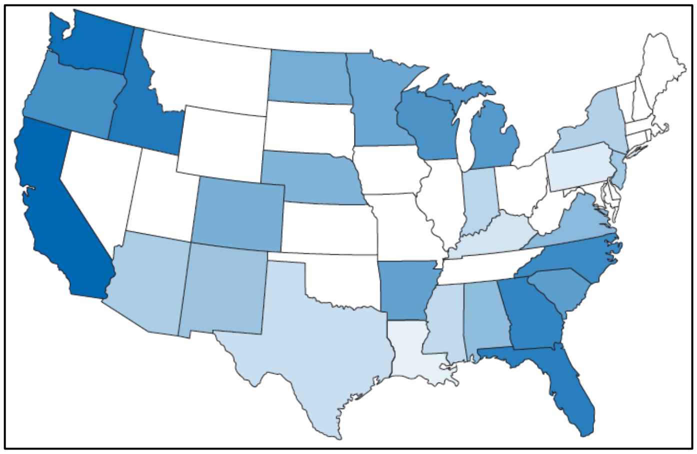

Figure 2. Distribution of fumigation applications in the continental United States. Fumigants are applied more in dark blue states than white states. Map adapted by Blecker and Thomas 2012 from EPA data.

Alternatives:

Various alternative management strategies for fumigation are available and depend on the pathogen or pest in question. For potato production systems in the Pacific Northwest, fumigants are primarily applied to reduce populations of the soilborne plant pathogen *Verticillium dahliae,* the causal pathogen of Verticillium wilt of potato. Alternative management strategies for Verticillium wilt are limited because (i) although moderately resistant cultivars are available completely resistant cultivars have yet to be developed, (ii) efficacious biocides for *V. dahliae*, other than fumigants, have yet to be identified, and (iii) the efficacy of cultural management tactics like crop rotation, cover crops and green manures is often variable. However, cultural management tactics like crop rotation and green manuring merit review here given their popularity, potential to suppress diseases, and impart desirable agronomic qualities to soils.

The effects of crop rotation and green manures on tuber yield, disease and stem incidence, and inoculum density vary from study to study (Fig. 3). Despite the variability observed in Figure 3, tuber yields generally increase, disease incidence generally decreases, stem incidence is either not affected or decreases, and inoculum density generally increases or remains the same after rotation crops are grown or green manure crops are incorporated. Several sources might contribute to the variability observed in published studies including but not limited to (i) the species and genotypes of crops planted, (ii) cultural factors (e.g. the time the crop is planted), (iii) the populations and density of the pathogen(s) present, (iv) the presence or absence of aggressive strains, and (v) environmental differences. Despite this variability, several reproducible trends can be observed in the literature: (a) suppression of wilt can be established in two-three years of green manures (Davis et al. 1996, 1998, and 2010), (b) recurrence of wilt can occur when potatoes are grown for two consecutive years (Davis et al. 2010), and (c) suppression of wilt can be restored after one year of green manures (Davis et al. 2010).

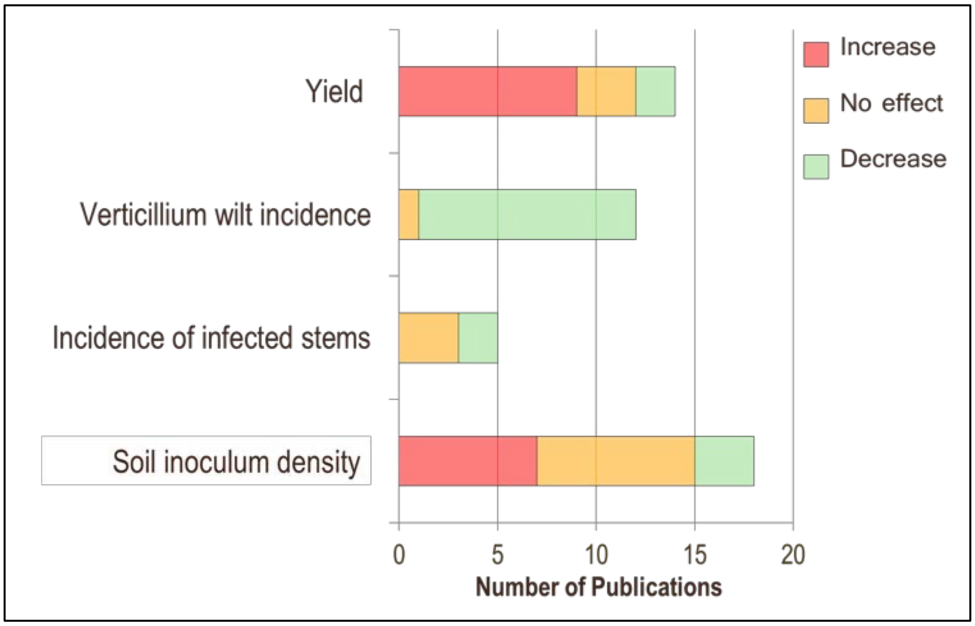

Figure 3. The effects of crop rotation and green manures on potato yield, Verticillium wilt incidence, the incidence of stems infected with *Verticillium dahliae*, and inoculum density compiled from 25 peer-reviewed publications.

Two major mechanisms have been proposed to explain the observed suppression of Verticillium wilt. Suppression may be induced, established, and maintained after a rotation or green manure crop is planted by: (i) competitive exclusion, whereby microbes selected for and propagated in response to a rotation or green manure crop outcompete *V. dahliae* and thereby exclude the pathogen from infecting potato (Qin et al. 2008) and/or (ii) biofumigation, whereby secondary metabolites, called glucosinolates, produced primarily by brassicaceous crops hydrolyze into isothiocyanates and directly inhibit *V. dahliae* or indirectly inhibit *V. dahliae* by promoting anatagonistic microorganisms (Neubauer et al. 2014). These mechanisms are not mutually exclusive or exhaustive and may operate together with other mechanisms to produce a suppressive state. For example, green manure crops can positively contribute to soil properties (Ochiai et al. 2008) and may thereby enable plants to defend against pathogens and pests while producing high-quality yields. Finally, the induction of these mechanisms by crop rotation and or green manuring appears to be specific to the Verticillium wilt pathosystem. Examples of disease suppression in other pathosystems are induced, established, and maintained by sustained monoculture of susceptible hosts which, over time, recruit microorganisms antagonistic to the pathogen and maintain a disease suppressive state despite the presence of pathogen (Raajimakers and Mazzola, 2016).

Conclusions:

Fumigants can enable production of high-quality potatoes in soils infested with plant pathogens like *V. dahliae*; however, the expenses and off-target effects of fumigants necessitate an option for effective alternatives. Resistance, biocides, and cultural management strategies should be used together to achieve optimal short and long term crop performance and profits. More research is needed to elucidate the mechanism(s) responsible for producing wilt suppressive soils. Once identified, practices which induce, establish, and maintain disease suppression can be implemented by growers.

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