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Research Paper

A prototype band-steaming machine: Design and field application

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Soil steaming is a preventive non-chemical weed control method. We designed and studied a new prototype band-steaming machine. Tests were conducted during the growing cycle of organically cultivated carrot in real-field conditions, in order to study the effect of different steam doses on crops and a natural weed seedbank, throughout the whole growth cycle. The prototype has a 3265 MJ h^{-1} steam generator, which applies steam in 12 soil bands, 180 mm wide. The steam was mixed with the soil by mean of an apposite rotary cultivator. Four biological steam doses (0, 1.11, 1.59, and 2.78 kg m^{-2}) were applied in combination with 4000 kg ha^{-1} of CaO prior to sowing the crop. Log-logistic models were used to describe the responses of temperatures, weed density, time required for hand weeding, weed dry biomass at harvest, and carrot yield to the band-steaming application. Based on the experimental data, an economic margin was evaluated to find the optimum application dose. Overall responses were influenced by steam dose. The results showed that a maximum temperature of 63 °C at a 25 mm depth was observed with a steam dose of 2.78 kg m^{-2}. With a 2.78 kg m^{-2} dose, the operative time was approximately 14 h ha^{-1} and total fuel consumption was 768 kg ha^{-1}. An estimated mean steam dose of 2.3 kg m^{-2} could be able to provide similar yield and hand weeding times responses to the highest steam dose applied, thus reducing both the operative time and fuel consumption of the machine.

1. Introduction

Steam is used in agriculture for soil disinfection of pathogens and for weed seed control. Soil steaming prior to cropping destroys a huge number of weed seeds and provides prolonged weed control in the ground (van Loenen et al., 2003; Melander & Jørgensen, 2005; Samtani et al., 2011).

How efficient steam is at heating the soil is strictly related to the steam distribution system used. Sheet steaming

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consists in blowing steam under a sheet, which is left to penetrate the soil. Mean temperatures of 100 °C in the top 10 cm of soil are kept for up to 6–7 h (Minuto, Gilardi, Kejii, Gullino, & Garibaldi, 2005; Runia, 2000). The negative pressure steaming method consists in introducing the steam under a steaming sheet and forcing it into the soil by negative pressure, created in the soil by a fan, which sucks air out of the soil through buried perforated polypropene tubes. The temperatures in the deeper soil layers achieved with negative pressure steaming are higher than with sheet steaming (Runia, 2000). Runia (2000) used negative pressure steaming, and observed a reduction of up to 50% of fuel consumption compared with sheet steaming, and a mean temperature of 60 °C at a 0.45 m depth after a 4 h application.

Improvements in terms of machinery have been achieved by introducing steaming hoods. A steaming hood is a mobile device consisting of corrosion-resistant material connected by a flexible pipe to the steam generator, which is placed onto the area to be steamed. Unlike sheet steaming, it does not involve the cost-intensive working steps such as laying out and weighing the sheets, however, the area steamed per working step is smaller depending on the size of the hood (Echevarría & Rodríguez, 2012). Whole-area treatments using steaming hoods enable temperatures higher that 100 °C to be reached in soil layers of 0–100 mm (Roux-Michollet et al., 2008). However, hood steaming makes extensive use of fossil fuel oil ranging from 2550 to 4250 kg ha^{-1} and the high time consumption of 70–100 h ha^{-1} (Pinel, Bond, White, & de Courcy Williams, 1999).

Steaming hoods can be combined with sub-surface steam injectors (Gay, Piccarolo, Ricauda Aimonino, & Tortia, 2010a). Gay, Piccarolo, Ricauda Aimonino, and Tortia (2010b) developed a custom 2 m × 2.5 m stainless steel hood combined with 99 steam injectors connected to a self-propelled steaming machine powered by a 75 kW engine and carrying a superheated steam generator operating at a relative pressure of 50 kPa with a flow rate of 500 kg h^{-1}. Each injector supplies orthogonal flows of steam via four holes with a diameter of 4 mm buried at a depth of 18 mm. During steaming, the border of the hood remains buried at a depth of 30–40 mm in order to prevent steam leakages. This prototype resulted in a fuel consumption of 8160 kg ha^{-1} of diesel fuel, 66% and 18% lower than sheet and hood steaming without steam injectors (23,885 and 10,030 kg ha^{-1}, respectively). Maximum temperatures ranged from 70 up to 100 °C in soil layers of 0–90 mm and decreased at temperatures ranging from 50 up to 70 °C in two hours after steam application for 6–10 min (Gay et al., 2010b).

Mobile steaming hoods have the disadvantage of performing a discontinuous application of steam because the hood must stay put in the soil for periods ranging from 6 to 15 min (Pinel et al., 1999; Gay et al., 2010a). Peruzzi, Raffaelli, Ginanni, Fontanelli, and Frasconi (2011) improved a self-propelled machine able to apply broad-steaming continuously. The steamer (Celli Ecostar SC 600) was developed in cooperation with the University of Pisa and Celli (Celli SpA, Forlì, Italy) (Celli, 2015). The Celli Ecostar SC 600 also differs from other steamers due to the possibility of injecting exothermic compounds into the soil, in addition to the steam (Bioflash system). CaO is commonly used as an exothermic compound, providing extra heat to the soil (Bàrberi, Moonen, Peruzzi, Fontanelli, & Raffaelli, 2009). Bàrberi et al. (2009) found that soil temperatures were different and lower when steam was applied alone compared with the application of steam in combination with 4000 kg ha^{-1} of CaO. The machine can be equipped with three different injection bars and with ridging-mulching equipment in order to cover the soil with a plastic film after the steam application. The driving speed ranges from 60 to 6000 m h^{-1}. At the common treatment speed of 150 m h^{-1}, the operative time was 53 h ha^{-1} for a total fuel consumption of 2288 kg ha^{-1} and temperatures remained above 60 °C for 30 min in soil layers of 0–10 cm (Peruzzi et al., 2011). Gelsomino, Petrovičová, Zaffina, and Peruzzi (2010) found that the use of combination of CaO with steam did not cause bacterial eradication or compositional shifts in bacterial community structure, and soil steaming stimulated an increased release of soluble nutrients (K^+, Mn^{2+}, NH^{4+}–N). The use of combination of CaO with steam is safe and does not cause hygienic-toxicological and environmental issues (Triolo, Materazzi, & Luvisi, 2004). Fennimore et al. (2014) evaluated a newly designed mobile steam applicator for the efficient soil disinfestation of weeds and pathogens in raised strawberry beds. The tractor-drawn machine physically mixed the steam with the soil as it passed through the shaped planting beds. The steam was produced by a 74 kW propane-fuelled generator. In the study the target temperature of 70 °C was achieved and maintained for 30 min in all the steam treated strawberry beds with an average speed of 161 m h^{-1}. The operative time was 47 h ha^{-1} for a generator fuel consumption of 12,191 kg ha^{-1}.

Extremely high fuel consumption and low operative times are major disadvantages of broad soil steaming (Melander & Kristensen, 2011). In order to save the energy consumption and decrease the operative time, steam could be applied only in bands corresponding to the intra-row area, which is where weeds cause the main problems in terms of weed control (Melander & Jørgensen, 2005). Melander, Jørgensen, and Elsgaard (2004) developed a prototype band steamer able to apply steam in soil bandwidths of 80 mm at a depth of 50 mm. Elsgaard, Jørgensen, and Elmholt (2010) applied band-steaming in a field study using a prototype with steaming tines that injected the steam produced by a 200 kW (720 MJ h^{-1}) steam generator at a depth of 50 mm, and found that the temperature decreased from about 75 °C to 45 °C in 8 min.

Hansson and Svensson (2007) used a band-steaming prototype with a 700 kW (2520 MJ h^{-1}) diesel-driven steam generator in order to apply steam in 105 mm wide soil bands at a depth of 50 mm. The quantity of steam applied per unit area and the temperature in the steamed bands varied with the tractor driving speed (from 200 up to 370 m h^{-1}). A mean labour requirement of about 8 h ha^{-1} which allowed a maximum temperature of 86 °C at a 40 mm depth was needed to obtain 90% weed control within the steamed bands, with an energy use of 485 kg ha^{-1} of diesel fuel (Hansson & Svensson, 2007).

No experiments however have been conducted to evaluate both weed control and crop yields after the application of different steam doses in soil bands. The aim of this research was to design a new prototype band-steaming machine and to study its field application. Tests were conducted during the