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Short communication

Mixing steam with soil increases heating rate compared to steam applied to still soil

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ABSTRACT

Before development of a new field steam applicator, this study was done to determine whether the application of steam from a source that is mixed with the soil is more efficient than application from a source that does not mix the soil, to aid in the machines' design. A cement mixer, either in motion or still, was used to contain soil or sand as it was treated with steam, and the heat profile of the soil or sand after the steam application was measured. The results indicated that the soil and sand were heated more thoroughly and rapidly from surface to deeper layers when steam was mixed compared to steam applied to the surface of still soil or sand.

1. Introduction

Lengthy history of field-scale steaming mostly describes stationary methods introducing steam from the surface or below soil for disinfestation (Johnson, 1946). Originally used in the greenhouse for control of weeds, pathogens, nematodes, and arthropods, steam heats the soil as the hot gas and vapors flow through the pores releasing its' heat energy as it condenses on the particle surfaces. In contrast dry heat moves more slowly in soil than steam, by conducting heat from soil particle to particle. A thorough discussion of these factors of moisture, texture, porosity, the energy transfers by conduction, convection, and radiation, and the differences between heat and steam can be found in Baker (1957). Application of steam in the field requires technological advances that allow faster application and low costs. One possible adaptation for increasing application speed is to blend steam with soil. Our hypothesis was that the physical mixing of steam with soil would improve the speed and uniformity of soil heating compared with steam application made to the soil surface or introduced from stationary sources.

Efficiency was limited in our efforts introducing steam for field disinfestation from stationary sources (Samtani et al., 2012). Our trials demonstrated to us costly labor requirements, materials, fuel and insulation. The motivation to develop steam disinfestations for the field was to replace chemical fumigants such as 1, 3-dichloropropene, where they are limited by regulations such as buffer zones and geographical limits on the total fumigant amounts allowed, and by grower practices such as organic farming where fumigants are not used (Carpenter et al., 2001). The limitations encountered using stationary steam sources motivated us to focus on labor and fuel efficiency, which led us to evaluation of automatic steam applicators. While there are many studies of heat dispersion associated with the development of the Celli ECOSTAR 600SC self-propelled machine for steam application (Peruzzi et al., 2011, 2012), the steam applied in that system is introduced at a fixed point above and/or below soil from a source moving over and/or through the soil, and then mixed by rotary hoe. In contrast, the steam applicator we helped design and evaluate delivered the steam through the tips of the hoes as they rotated, thus releasing the steam at all points in the profile of soil with each rotation. Before building such an automatic steam applicator we sought to test the premise that mixing soil with steam heats soil faster than introducing steam from a still source. For evaluation of this effect, a simple system using a cement mixer was built with internal shanks to deliver steam during mixer rotation.

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2. Materials and methods

2.1. Operation of model system

Nearest approximation to a full-scale field applicator suggested rotation of a cement mixer to compare introducing steam either above or into soil. Both soil and sand (100%) were studied. Field soil (57 kg) or dry sand (53 kg) were added to a cement mixer (0.1 m^3 capacity). The sand was mixed grades with particles from 0.05 to 2 mm in diameter. The soil was a Chualar sandy loam (fine-loamy, mixed, superactive, thermic Typic Argixerolls) with a pH of 7.2, and coarse and very coarse sand ranges from 20 to 30% in the tilled horizons from which it was collected. Replications were sequential over time in random order. The time for loading, steaming, cooling, and cleaning was lengthy, so runs began at temperatures ranging from 14 to 25 °C in sand, soil and atmosphere. Temperature was sampled for at least 5 min prior to every run to establish base temperature prior to steaming, by methods described below. Soil or sand was treated with steam for 60 s from a small steam generator (Sussman Model M6, Long Island City, NY). The steam pressure was initially 500–550 kPa decreasing to <100 kPa by the end of the 60 s run, and delivered >1.13 kg steam over this interval. Steam mass was determined by mass added to soil or sand while mixing, and atmospheric loss is acknowledged. Steam temperature during the applications ranged between 110 and 120 °C at the boiler output. The steam was delivered through a central shaft into the mixer chamber with side shanks with eight openings of approximately 2 mm each. The shank was either positioned to deliver the steam approximately 2–4 cm above the surface, or with openings immersed in the tumbling soil or sand if the mixer was in motion as shown in Fig. 1. The shaft was inserted through a sealed hole in the center of the mixer lid. The lid was clamped to the opening of the cement mixer to contain the steam applied to the mixer chamber. While containing the steam in an area above the surface, leakage through the gasket allowed the atmospheric pressure above the surface to remain unaffected, simulating conditions of a free-flowing steam application to field soils. Immediately following 60 s of steam injection into the cement mixer (either on still soil or sand or while in motion), a small port was opened to the still mixer, allowing insertion of a probe using 4 Hobo TMC6-HD temperature sensors monitored using the U12-008 recorder (Onset, Pocasset, MA) to measure the temperature 5 cm above, and at 7, 15, and 23 cm below the soil or sand surface. The sensors recorded temperatures each second for more than an hour. This procedure was replicated twice for each still treatment and each treatment while in motion. Data presented was collected in late August and early September 2012 for sand and April of 2014 for soil. The entire experiments were repeated. Results include means of two experiments in sand, and two in soil. Temperatures recorded above the soil or sand were not presented or used for soil heating analysis. These were recorded only for validation that steam was in fact being delivered into the system.

2.2. Data analysis

Depth-specific summation of the heat accumulated in excess of starting temperature allowed comparison by Student's *t*-test of the areas under curves that represented soil temperatures as a result of steam application to still or moving soil. Each temperature record from an experimental treatment replication was comprised of the three sub-surface data strings that depicted the heating and cooling curves of soil or sand at each depth as shown in Fig. 2, which shows the means of two replications in the first experiment performed in sand. Using the trapezoidal method of approximating integrals, the first 2 s of each hour-long record was the temperature before heating began, providing the baseline from which heating was measured. The sums of the arbitrary units (Δ°C × s) representing area under the curves of temperatures over time were paired by whether the cement mixer was in motion or not, then compared using a two-tailed *t*-test.

3. Results

3.1. Comparison of heat transfer when steam is introduced either still or in motion

Integration of the areas under the heating curves showed that physical blending of soil or sand with steam raised temperatures more rapidly and thoroughly than only applying steam from the

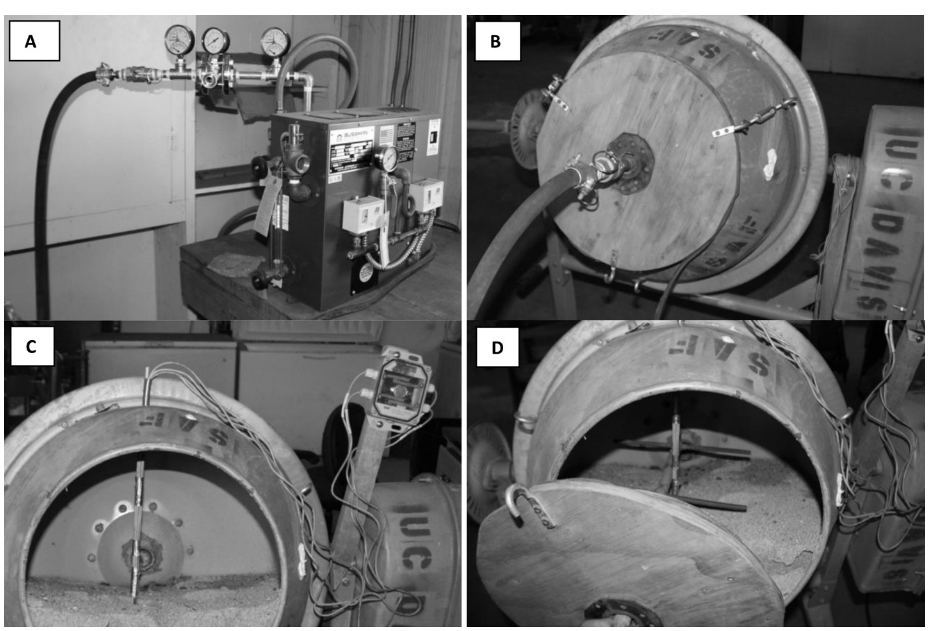

Fig. 1. The system used for testing physical mixing effect on soil steam distribution. A) the steam boiler. B) the cement mixer in closed position ready to be steamed. C) the sand and temperature recording apparatus. D) the internal shanks in place to deliver steam either from the surface or while physically mixing the sand.