# Managing compost stability and amendment to soil to enhance soil heating during soil solarization

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**Abstract**

Soil solarization is a method of soil heating used to eradicate plant pathogens and weeds that involves passive solar heating of moist soil mulched (covered) with clear plastic tarp. Various types of organic matter may be incorporated into soil prior to solarization to increase biocidal activity of the treatment process. Microbial activity associated with the decomposition of soil organic matter may increase soil temperatures during solarization, potentially enhancing solarization efficacy. However, the level of organic matter decomposition (stability) necessary for increasing soil temperature is not well characterized, nor is it known if various amendments render the soil phytotoxic to crops following solarization. Laboratory studies and a field trial were performed to determine heat generation in soil amended with mature green waste compost and wheat bran during solarization. Respiration was measured in amended soil samples prior to and following solarization as a function of soil depth. Additionally, phytotoxicity was estimated through measurement of germination and early growth of lettuce seedlings in greenhouse assays. Amendment of soil with 10% (g/g) compost (8% green waste + 2% wheat bran) containing 16.9 mg $CO_2$/g dry weight organic carbon resulted in soil temperatures that were 2$^o$C to 4$^o$C higher than soil alone. Approximately 85% of total organic carbon within the amended soil was exhausted during 22 days of solarization. There was no significant difference in residual respiration with soil depth down to 17.4 cm. Although freshly amended soil proved highly inhibitory to lettuce seed germination and seedling growth, phytotoxicity was not detected in solarized amended soil at any depth tested, between 0-17.4 cm, after 22 days of field solarization.

## 1. Introduction

Solarization is a method for inactivating weed and pathogen propagules in soil without chemical treatment. Solarization involves mulching (covering) of moist soil with clear plastic sheeting, resulting in elevated soil temperatures through passive solar heating that promote thermal inactivation of weeds and pathogens (Katan et al., 1976). Biological and chemical changes in soil during solarization, including microbial community alterations, temporary production of biotoxic chemical compounds, and increases in available plant nutrients, can also be involved (Stapleton, 2000). Solarization is generally most effective when performed during the hottest months of the year (Horowitz et al., 1983) in areas with warm climate (Stapleton, 2000). However, this period often conflicts with the growing season. Decreasing solarization duration could avoid such infringement. Since relatively small increases in temperature can have a drastic effect on the time necessary for inactivating microbial pathogens (Pullman et al., 1981) and weed propagules (Egley, 1990), increased soil heating during solarization may lessen the time required. Additionally, elevating soil temperature through non-solar means during solarization may make solarization viable in areas with cooler climates.

Heat generation from biological activity in soil may complement solar heating to raise temperatures during solarization. However, biological activity in soil due to microbes is influenced by a range of factors, including organic matter level (stability), soil oxygen availability, temperature and moisture (Aslam and VanderGheynst, 2008). Destabilizing soil with organic matter can increase soil temperature during solarization as a result of increased soil biological activity (Komariah et al., 2011). However, various aspects of this strategy are not well understood. The relationship between soil stability level and elevated heating during

75 solarization has not been studied. Moreover, it is unknown how such soil destabilization
76 treatments affect microbial activity in soil following solarization.
77 The objectives of this study were to investigate how biological activity in soil amended
78 with compost at varying levels of stability affects heat generation during solarization and to
79 measure the amount of residual biological activity in solarized, amended soil as a function of soil
80 depth. Laboratory studies were conducted in temperature-controlled incubators to determine
81 compost stability and amendment levels needed to achieve elevated soil temperature. These
82 studies were followed by a field experiment to evaluate the laboratory observations. Soil
83 biological activity and compost stability were characterized by measuring respiration.
84 Additionally, phytotoxicity of amended soil was measured prior to and following solarization via
85 germination and seedling growth assays in greenhouses.
86
87 **2. Materials and Methods**
88 *2.1 Soil and compost preparation*
89 Dry topsoil (Hanford sandy loam) was collected on May 15, 2010 from the 0-15 cm
90 depth range at UC Kearney Agricultural Research and Extension Center (KARE) in Parlier, CA
91 (36.6 $^{o}$N; 119.5 $^{o}$W; elevation 97 m a.s.l.), sieved through a 3.18 mm screen and stored at room
92 temperature. Varying levels of compost stability were achieved by preparing compost mixtures
93 containing stable green waste compost and varying amounts of autoclaved wheat bran. This was
94 done to maintain a consistent microbial inoculum associated with the compost while enabling
95 control of organic matter (and the potential for biological activity) added to the soil. Wheat bran
96 was selected because its composition is similar to agricultural residues and municipal solid
97 waste. Green waste compost was collected on January 21, 2010 from Zamora Compost in Yolo

98 County, CA. Compost was air dried under ambient conditions to a moisture content of 30.2%
99 (dry weight basis), sealed in plastic bags, and stored at room temperature (ca. 21-28 $^{o}$C). Food
100 grade wheat bran ('Giusto's Vita Grain', South San Francisco, CA) was autoclaved dry at 121 ˚C
101 for 20 minutes. The sterile wheat bran (11.7% moisture content, dry basis) was then sealed in
102 plastic bags and stored at room temperature.
103
104 *2.2 Soil mixture and microcosm preparation*
105 For bioreactor experiments, soil mixtures were wetted to 80% of water holding capacity
106 according to Table I. Wetted soil mixtures were equilibrated overnight at 4 ˚C prior to bioreactor
107 loading. To prepare soil for field trial microcosms, soil was wetted to 12% moisture content (wet
108 weight basis) and compost and wheat bran were wetted separately to 50% moisture content (wet
109 weight basis) the day prior to solarization. Wetted soil, compost, and wheat bran were combined
110 to achieve 90% soil, 8% compost, and 2% wheat bran (dry weight basis). Soil mixtures were
111 allowed to equilibrate for approximately 12 hours under ambient conditions. Equilibrated soil
112 mixtures were packed into 3.8 L black plastic Grow Bags with drainage holes to facilitate
113 moisture and gas exchange (neHydro, Southampton, MA) to form microcosms. HOBO
114 thermistors connected to HOBO U12 and H8 data loggers (Onset Computer, Bourne, MA) were
115 embedded in the center of each microcosm at a depth 12.7 cm. The diameter and height of filled
116 microcosms were 17.8 cm and 17.4 cm, respectively.
117
118 *2.3 Solarization*
119 The KARE field site used for soil collection in bioreactor experiments was used for
120 conducting the field experiment. The field site was cropped with sunflower in 2007, left fallow

in 2008, and cropped with a winter forage mix (approximately 50% oats, 25% beardless barley, and 25% beardless wheat). Cool-season weed covers were present during portions of each year. To prepare for the solarization experiment, the field was plowed in May 2011 to incorporate the remains of the forage mix. The field was then irrigated, dried down, disced twice, then rotovated to bring soil to seedbed texture. Finally, an orchard float was passed over the soil to smooth the soil surface sufficiently for plastic film application. Solid-set sprinklers were then placed around the plot and the site was irrigated five, three, and one day prior, as well as immediately before the initiation of the experiment. Pre-experiment water application totaled approximately 6.5 cm, which was sufficient to bring the soil to above field capacity at depths sampled in this study.

The field site was arranged into 5 plots. Each plot contained one microcosm with soil only (not amended) and one microcosm with soil amended with compost and wheat bran. Microcosms were buried within plots such that the top of the microcosm was flush with the soil line. Microcosms were buried 0.6 m apart from each other with a 0.9 m buffer between microcosms and plot borders. Microcosms were arranged randomly within each plot. Plots were covered with 0.7 mil transparent plastic sheets ('Huskey Film Sheeting'; Poly-America, Inc., Grand Prairie, TX) and sheet edges were embedded in soil along plot borders to begin solarization. Temperature was logged every 10 minutes during solarization. After 22 days of solarization, microcosms were exhumed from field plots and stored at 1 ˚C overnight. Microcosms were stored at ambient conditions for approximately 3 hours during transport from the field site to the laboratory. Upon arrival, microcosms were cut into 5.8 cm sections to isolate soil samples from various depths. Soil sections were sealed in plastic bags and stored at -20 ˚C until analysis of residual respiration and phytotoxicity.

144 *2.4 Respiration measurement*

145 Respiration measurements were performed on 100 g samples (dry weight basis) of each
146 soil mixture (Table I). Samples were placed into 250-ml bioreactors as previously described
147 (May and VanderGheynst, 2001) and wrapped with closed-cell foam insulation. Four replicates
148 were examined for each soil mixture. For preliminary respiration experiments, HOBO pendant
149 temperature loggers (Onset Computer, Bourne, MA) were embedded within one bioreactor from
150 each soil mixture treatment. Reactors were supplied with air at a rate of 20 ml/min and subjected
151 to a diurnal temperature cycle of 25 ˚C for 8 hours and 50 ˚C for 16 hours via ambient heating to
152 simulate solarization temperatures. Distilled water was added to reactors weekly to maintain
153 initial moisture contents. Carbon dioxide concentrations in reactor influents and effluents were
154 measured using an infrared $CO_2$ sensor (Vaisala, Suffolk, UK) and mass flow rate through
155 reactors was measured using a mass flow meter (Aalborg, Orangeburg, NY). Carbon dioxide
156 and mass flow measurements were taken approximately every 5 hours for each bioreactor.
157
158 *2.5 Phytotoxicity assay*

159 Phytotoxicity of amended soil prior to and following solarization was assessed using a
160 leaf lettuce germination and seedling growth assay. Freshly wetted, non-amended field soil and
161 freshly prepared field soil mixed with just compost or with compost and wheat bran served as
162 controls. Soil samples were mixed with an equal volume of coarse sand to permit drainage and
163 distributed to plastic seeding trays containing six 2.5×2.3×5.1 cm wells each. Leaf lettuce seeds
164 (*Lactuca sativa* var. Parris Island Cos) (Sustainable Seed Co., Petaluma, CA) were sowed in
165 wells at a depth of 1 cm, and with a density of four seeds spaced equidistantly per well. Four
166 trays were prepared for each soil sample. Trays were placed in a greenhouse and arranged

randomly on germination mats heated to 37 ˚C. Trays were watered via misters for 1 minute hourly spanning 9 hours per day. After 10 days, germination rates were determined by counting the number of seedlings emerged from the soil for each tray. Samples of seedlings were randomly chosen from each treatment, harvested, gently washed, weighed, and photographed. Root and shoot length measurements of seedlings were obtained from photographs using ImageJ (National Institutes of Health, Bethesda, MD) software. Seedlings were oven dried at 100 ˚C for 48 to 96 hours and dry weight measurements were taken on desiccated seedlings.

*2.6 Data analysis*

$CO_2$ evolution rate (CER) was calculated for each reactor based on mass balances of $CO_2$ at each time point:

$$CER = F(CO_{2,out} - CO_{2,in}) \quad (1)$$

where $F$ is the mass flow rate of gas through the reactor (mg/day/g dry weight), and $CO_{2,out}$ and $CO_{2,in}$ are the concentrations of $CO_2$ (%) in the reactor effluent and influent, respectively. Cumulative $CO_2$ evolution (cCER) was determined by integrating CER over time. A saturation model was fitted to cCER versus time data using KaleidaGraph v. 4.1.0 (Synergy Software, Reading, PA) (Aslam and VanderGheynst, 2008):

$$cCER = C_T t(c + t)^{-1} \quad (2)$$

where $C_T$ is the theoretical maximum amount of $CO_2$ that can be evolved (mg $CO_2$/g dry weight), $c$ is a constant describing the length of time needed to achieve half of $C_T$ (days), and $t$ is time (days).

190 Temperature versus time data were integrated to obtain degree-day values. The
191 trapezoidal rule was used to approximate the definite integral between each time point.
192 Cumulative degree-day versus time data were used as an indicator of soil heating.
193 Specific heat capacity values for soil mixes were estimated from the specific heat
194 capacities of mixture components (Table II). Specific heat capacity values for dry soil and
195 compost were estimated from standard values for soil and lignocellulosic material, respectively
196 (Irvine et al., 2010). The specific heat capacity of wheat bran was estimated from that of rice
197 bran (Sreenarayanan, 1986). The specific heat capacity of each mixture was calculated as the
198 sum of products obtained from multiplying each component's specific heat capacity by the mass
199 fraction (fresh weight basis) of the component in the mixture. Soil heating was calculated as
200
$$q = \int_0^t \rho_b c_p \frac{dT}{dt} dt \quad (3)$$
201
202 where $q$ is the heat added to the soil mixture (J/mL), $\rho_b$ is the bulk density of the wetted soil
203 mixture (g/mL), $c_p$ is the specific heat capacity of the mixture (J/g/˚C), and $T$ is the temperature
204 of the soil mixture (˚C). Temperature change with respect to time was calculated using the
205 central difference method. Constant specific heat capacity and soil moisture content were
206 assumed, given the temperature range of solarization, the excess of saturated soil surrounding the
207 microcosms, and the plastic tarp preventing evaporation.
208 Statistical analyses were performed using JMP-IN software (version 8.0, SAS, Cary,
209 NC). Tukey's Honest Significant Difference test (a test for comparing multiple means that
210 adjusts α for each pairwise t-test such that α=0.05 for the entire set of comparisons) was used to
211 compare mean values. Response means were compared using plots as blocks.
212

## 3. Results

### *3.1 Respiration and soil temperature in laboratory incubations*

Respiration experiments performed on soil amended with compost and varying levels of wheat bran showed that soil respiration increased significantly with the level of added wheat bran (Figure 1, Table III). Total potential cumulative $CO_2$ respiration, represented by the estimated value of $C_T$ (equation 2), increased proportionally with the amount of wheat bran added indicating that wheat bran could induce biological activity in the soil and that the majority of the biological activity in the amended soil was associated with the decomposition of the wheat bran. While addition of wheat bran significantly decreased the time needed for cumulative $CO_2$ evolution to reach half the steady-state value (as embodied by c in equation 2) compared to soil amended with compost alone, amendment with 5% wheat bran did not significantly affect the estimated value of c compared to 1% wheat bran.

Temperature data indicated that increasing wheat bran amendment also increased soil heat generation. Temperature differences among the soil mixture treatments were most pronounced 24 hours following the start of diurnal incubation (Figure 2). Moreover, temperature differences were most apparent during the 50 ˚C period of incubation. During this period, soil amended with compost and 5% wheat bran exhibited a peak temperature over 7 ˚C higher than that achieved in soil alone and approximately 5 ˚C higher than that observed in soil amended with compost and 1% wheat bran. Both treatments with wheat bran amendment achieved temperatures above the ambient temperature within the incubator (50 °C). The trend in temperature differences was also apparent during the 25 ˚C period of incubation, but the spread in temperatures among the treatments was considerably smaller. After approximately 3 days of incubation, temperature differences among soil mixture treatments began to decrease and

236 temperatures in all treatments converged thereafter. The trend in temperature differences is
237 consistent with biological activity measured by respiration.
238
239 *3.2 Respiration from field solarization soil mixtures*
240 Respiration measurements were performed on soil mixtures used in the field trial (i.e.,
241 non-amended soil and soil amended with 8% compost and 2% wheat bran) prior to solarization.
242 This amendment level was selected based on laboratory results to achieve sufficient biological
243 activity for soil heating. As in the preliminary respiration experiment, amended soil resulted in
244 significantly higher respiration compared to soil alone (Table IV).
245 Respiration was measured in amended soil microcosm depth slices following
246 solarization. Data were used to estimate $C_T$ values for soil sections (Table V). The $C_T$ values did
247 not vary significantly with soil depth ($\alpha$=0.05). Comparing $C_T$ values estimated for freshly
248 amended, non-solarized soil to the greatest average $C_T$ value observed in solarized soil, at least
249 85% of respiration potential was expended in the field during 22 days of solarization.
250
251 *3.3 Heat generation in soil mixtures during field solarization*
252 One thermistor failed in the field and did not yield temperature data. For the remaining
253 thermistors, temperature data obtained during solarization were used to calculate temperature
254 differences between microcosms containing amended soil and microcosms containing soil alone
255 within each plot. At the monitored depth of 12.7 cm, soil amended with compost and wheat bran
256 exhibited higher temperatures compared to soil alone during the first seven days of solarization
257 (Figure 3). Both maximum and minimum temperatures were significantly higher in amended soil
258 ($p$<0.001 for both comparisons). Differences were most pronounced during late evening, night,

and early morning hours, with amended soil reaching temperatures over 2.5 ˚C higher than soil alone within the first seven days of solarization. As the solarization process progressed, differences in temperatures between the two soil treatments became less evident. After approximately 10 days, the maximum temperature elevation of amended soil over soil alone decreased to less than 1 ˚C. The average maximum and minimum temperatures in microcosms containing amended soil during the first seven days of solarization were 44.7 and 30.6 °C, respectively. Alternately, the average maximum and minimum temperatures in microcosms containing non-amended soil were 43.9 and 28.7 °C, respectively. Heating of soil mixtures during solarization was calculated as described in the methods section (equation 3, Figure 4). The data show that amended soil accumulated significantly more heat than non-amended soil during solarization. Likewise, amended soil exhibited significantly higher degree-day values compared to soil alone. However, the difference in degree-days in amended soil versus soil alone did not change significantly between 7 and 22 days of solarization ($p = 0.44$), suggesting that although amended soil experienced greater heating compared to non-amended soil, elevated temperatures in amended soil occurred primarily during the first week of solarization.

*3.4 Phytotoxicity of soil mixtures prior to and following field solarization*

Soil amended with stable compost and wheat bran was phytotoxic immediately following amendment as indicated by significantly reduced lettuce seed germination and seedling growth compared to non-amended soil or soil amended with just compost (Tables VII and VIII). Germination rates did not vary significantly by depth in solarized amended soil samples. For germinated seedlings, none of the seedling growth parameters measured varied significantly with soil depth in solarized, amended soil (Table VIII). Seedling shoot length, fresh weight, and dry

weight for seedlings grown in solarized amended soil either exceeded or did not significantly differ from positive controls containing non-amended soil, in all depth slices tested. Root lengths for seedlings grown in the top 11.6 cm of solarized amended soil did not significantly differ from seedlings grown in non-amended soil. However, seedlings from the greatest depth range tested in solarized, amended soil, 11.7 to 17.4 cm, had significantly shorter root lengths compared to those grown in non-amended soil. Root length, fresh weight, and dry weight values were significantly greater in the control mixture containing soil amended with compost alone (no wheat bran) compared to solarized, amended soil.

## 4. Discussion

Respiration and temperature data obtained from bioreactors showed that biological activity and heat generation in amended soil can be controlled through addition of organic matter. Control reactors containing non-amended soil, or soil amended with green waste compost alone (no wheat bran), exhibited minimal respiration, indicating that field soil and green waste compost were highly stable. On the other hand, the destabilizing addition of wheat bran increased respiration potential in compost-amended soil. Since the wheat bran was sterilized prior to use, increased respiration was a result of bran providing nutrients to soil and compost microbial communities and not from microorganisms present on the bran itself. Heat generation associated with biological activity in amended soil was sufficient to raise temperatures by as much as 5$^{o}$C over non-amended soil during simulated solarization in bioreactors. Temperature increases of this magnitude are agriculturally relevant. For instance, increasing temperature from 46 °C to 50 °C is sufficient for reducing the time needed for thermal inactivation of seeds from several weed species by 44-75% (Dahlquist et al., 2007).

The results from simulated solarization in bioreactors motivated a solarization field experiment to examine if increased heat generation in soil amended with destabilizing green waste was reproducible under agricultural conditions. Respiration measurements performed on amended soil mixtures prior to and following field solarization revealed that the majority of potential respiration was exhausted during the 22-day solarization treatment. Differences in soil temperature between non-amended and amended treatments were greatest during the first week of solarization, suggesting that most respiration occurred during this period. This time scale is comparable to that observed in initial bioreactor experiments under aerobic conditions. In addition, earlier work on evolution of biotoxic volatile compounds over time in solarized, cabbage residue-amended soil (Gamliel and Stapleton, 1993) gave similar results.

Following the field experiment, residual respiration in soil did not vary significantly from the surface layer down to 17.4 cm depth, suggesting that oxygen availability did not limit cumulative respiration over this depth range. As a decrease in respiration might be expected deeper in soil, where oxygen concentrations may be lower, it is possible that the 22-day length of solarization treatment was sufficient for measured depths to reach equal cumulative respiration. However, it is possible that amended soil at greater depths took longer to reach steady-state cumulative respiration compared to soil near the surface.

Soil amended with compost achieved higher temperatures during solarization compared to non-amended soil. Temperature differences between amended and non-amended soil reached approximately 2.5 °C daily, at 12.7 cm depth, for the first 5 days of solarization. Depending upon temperatures reached, such temperature differences can have a drastic effect on thermal inactivation of soil microorganisms. For instance, a 2.5 °C increase in temperature reduced the time required to achieve 99% thermal death in spores of the fungal soil pathogen

*Plasmodiophora brassicae* by over 75% (Myers et al., 1983). Interestingly, the greatest temperature differences between microcosms with amended soil and those with soil alone were observed during the late night and early morning hours when ambient temperatures were coolest. This is in contrast to preliminary bioreactor temperature data, where maximum temperature differences occurred during the warmest period of the diurnal incubation cycle. This result may stem from differences in oxygen availability between the two systems. Bioreactors had ambient air continuously flowing through them, whereas buried soil gained oxygen only by diffusion from the surface. Moreover, prior work has shown that soil oxygen concentrations can fall to low levels when excess water at the surface inhibits diffusion (Drew, 1990), a condition similar to that produced by mulching of moist soil with plastic tarp during solarization. In an earlier solarization study (Stapleton and DeVay, 1984), moist soil that was tarped, but shaded to prevent solar heating, exhibited a significantly increased presence of pectolytic enteric bacteria – not found in heated soil – suggesting development of microaerobic or anaerobic conditions. The shaded treatment provided partial control of targeted soilborne pests, but usually considerably less so than solarization. Whereas bioreactors may have had adequate oxygen to support increased respiration at higher temperatures, limited oxygen in microcosms undergoing field solarization may have inhibited respiration as temperature increased. Prior research has shown that amendment with organic matter leads to anaerobic conditions during solarization as a result of increased microbial activity and that such conditions are desirable for control of certain fungal pathogens (Blok et al., 2000). Data presented here suggest that elevated soil heating may be an additional mode of inactivation for other pathogens.

Our experimental soil was found to be initially phytotoxic to lettuce following amendment with both stable compost and wheat bran. The addition of organic matter rendered

the soil mixtures unstable, as indicated by respiration data following amendment. Previous work has shown that phytotoxic, volatile organic acids (VOA) are evolved during composting and that VOA levels increase with compost instability (Manios et al., 1989) and with soil anaerobiosis (Poggi-Varaldo et al., 1999). As a result, soil amended with compost and wheat bran may accumulate more VOA after solarization begins due to the plastic tarp inhibiting oxygen diffusion into the soil (Klein et al., 2007). A period of volatile compound evolution can be desirable, as such compounds are often toxic to soil pathogens (Gamliel and Stapleton, 1993; Ramirez-Villapudua and Munnecke, 1988), provided these compounds dissipate from the soil prior to planting a subsequent crop. In this study, the lack of significant phytotoxicity in solarized amended soil samples suggested that phytotoxic compounds, such as VOA, had dissipated from the soil by end of the 22-day solarization treatment. Although approximately 15% of total respiration potential remained in amended soil following solarization, this level of biological activity did not significantly decrease seedling germination and growth compared to plants grown in soil alone. Residual VOA levels vary with the composition of the materials used for compost, degree of instability, and other factors. These properties need to be considered when combining compost amendment with soil solarization. However, this study suggested that soil organic matter levels can be manipulated to optimize soil heating and other biotoxic effects during solarization while minimizing undesirable phytotoxicity following treatment.

*4.1 Conclusions*

Amendment of soil with mature green waste compost destabilized with wheat bran increased both soil respiration and soil temperature during solarization beyond that generated by solar heating alone. Under the conditions presented in this study, respiration and temperature

elevation could be controlled through the amount of organic matter in soil and its stability. Following 22 days of field solarization, less than 15% of total potential respiration remained in amended soil samples. Residual respiration did not vary significantly with soil depth down to 17.4 cm. Although freshly amended soil was inhibitory to leaf lettuce germination and seedling growth, factors resulting in subsequent phytotoxicity were eliminated during the solarization process at all soil depths examined. Amendments containing green waste compost may be of value in agricultural soil disinfestations operations.

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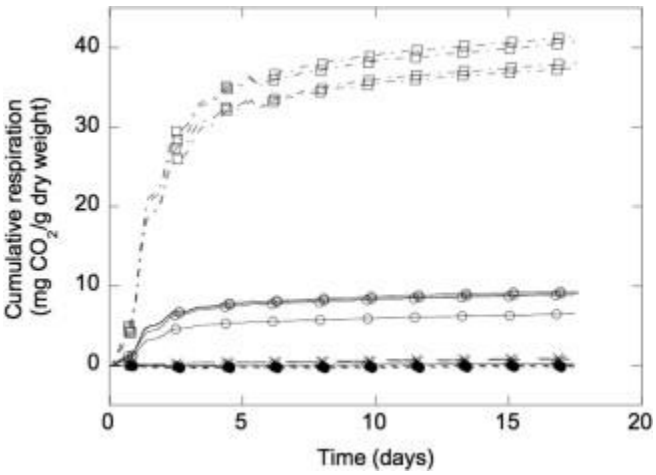
436 **Figures**

437

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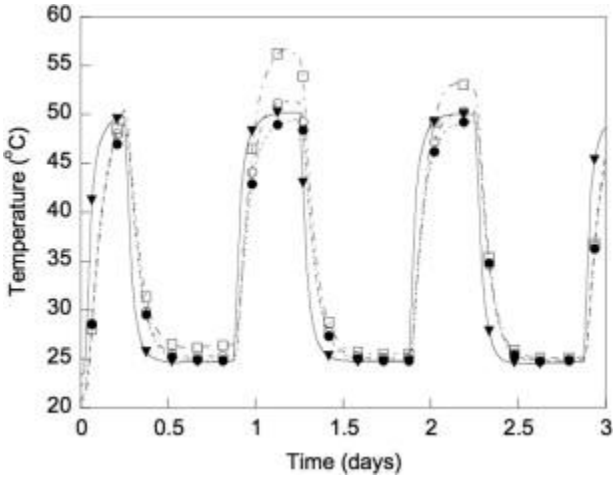
440 Figure 1. Cumulative $CO_2$ respiration in soil mixtures incubated under diurnal conditions.

441 Treatments shown are 87% soil+8% compost+5% wheat bran (□), 91% soil +8% compost +1%

442 wheat bran (o), 92% soil+8% compost (x), and 100% soil (•). Four replicate bioreactors were

443 examined for each mixture.

444




445

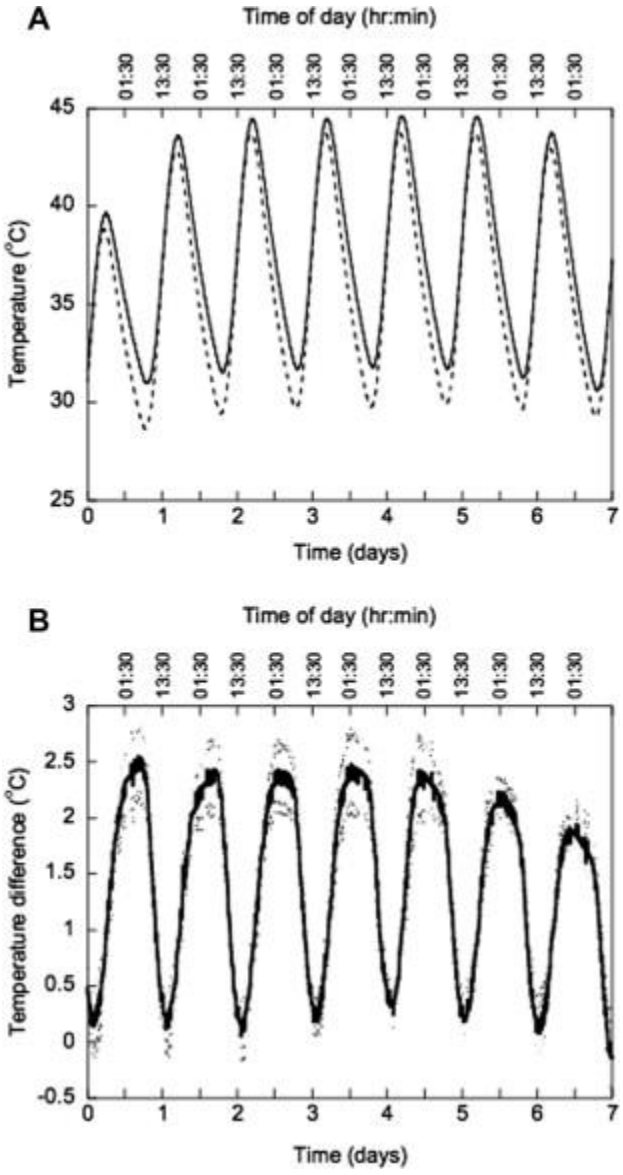
446 Figure 2. Temperature profiles in soil mixtures during the first three days of diurnal incubation.

447 Points represent the incubator temperature (▾), 87% soil+8% compost+5% wheat bran

448 temperature (□), 91% soil +8% compost +1% wheat bran temperature (o), and 100% soil

449 temperature (•).

450




451

452 Figure 3. Average temperature profiles for amended soil and soil alone during the first seven

453 days of solarization. (A) Average temperatures of microcosms containing soil amended with 8%

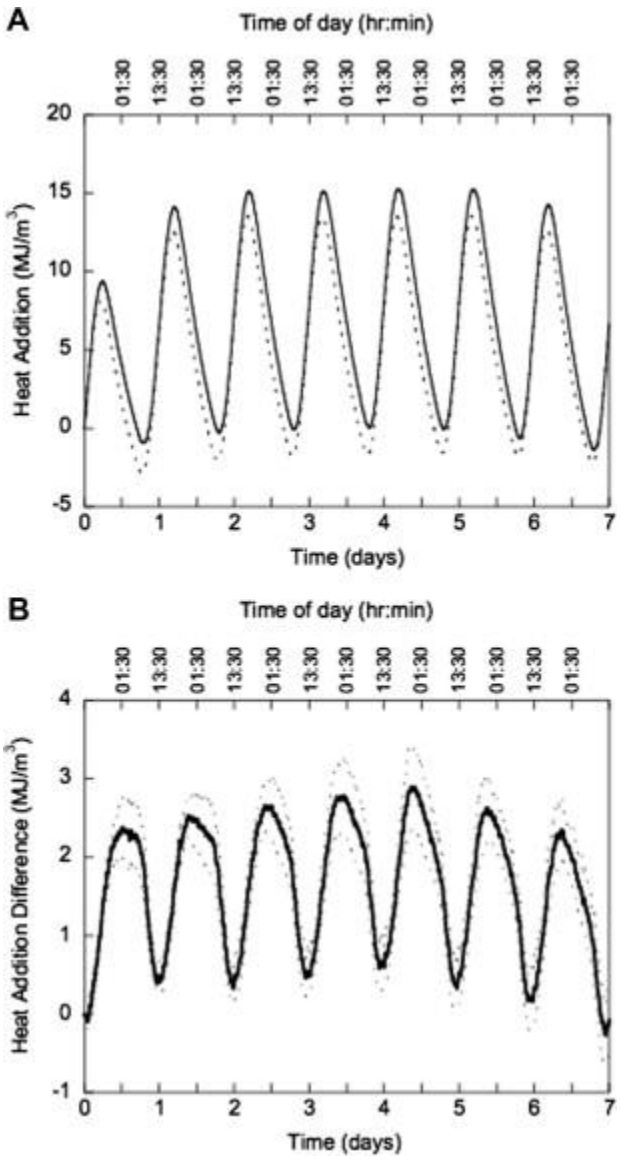
454 compost and 2% wheat bran (dry mass basis) (solid line) and microcosms containing only soil

455 (dashed line). (B) Average temperature difference between microcosms with amended soil and

456 soil alone ($T_{\text{amended soil}} - T_{\text{soil alone}}$). Upper and lower dotted lines represent the average temperature

457 difference plus or minus one standard deviation, respectively. n = 4

458




459

460 Figure 4. Average heat addition for amended soil and soil alone during the first seven days of

461 solarization. (A) Average heat addition of microcosms containing soil amended with 8%

462 compost and 2% wheat bran (dry mass basis) (solid line) and microcosms containing only soil

463 (dashed line). (B) Average heat addition difference between microcosms with amended soil and

soil alone ($q_{\text{amended soil}} - q_{\text{soil alone}}$). Upper and lower dotted lines represent the average difference in addition plus or minus one standard deviation, respectively. n = 4

## Tables

Table I. Soil mixtures used for preliminary respiration experiments to determine the effect of organic matter amendment on soil biological activity and heat generation.

| Treatment | Code | Moisture content* (% dry basis) |
|---|---|---|
| Soil only | 100%S | 12 |
| Soil amended with 8% compost | 92%S + 8%C | 18 |
| Soil amended with 8% compost and 1% wheat bran | 91%S+8%C+1%WB | 20 |
| Soil amended with 8% compost and 5% wheat bran | 87%S+8%C+5%WB | 26 |

* selected to achieve 80% water holding capacity

Table II. Soil properties used for determining heating during solarization.

| Soil mixture | Component | Mass percentage (wet basis) | $c_p$ (J/g-˚C) | Mixture $c_p$ (J/g-˚C) | Bulk density (g/ml) |
|---|---|---|---|---|---|
| Soil | soil | 88.0% | 0.80 | 1.21 | 1.8 |
| | water | 12.0% | 4.18 | | |
| Amended soil | soil | 73.6% | 0.80 | 1.40 | 1.7 |
| | compost | 6.5% | 0.42 | | |
| | wheat bran | 1.6% | 1.30 | | |
| | water | 18.2% | 4.18 | | |

485 Table III. Saturation model (eq. 3) parameter estimates for soil mixtures under diurnal

486 incubation.

| Soil mixture | $C_T$ (mg $CO_2$/g dry weight) | $c$ (days) |
|---|---|---|
| 100%S | n/a | n/a |
| 92%S + 8%C | 2.05 (0.569) a | 26.8 (16.7) a |
| 91%S + 8%C + 1%WB | 9.36 (1.48) b | 1.81 (0.0760) b |
| 87%S + 8%C + 5%WB | 44.3 (2.19) c | 1.72 (0.376) b |

487 Values are given as means with one standard deviation given in parentheses. n = 4, except for

488 100%S, where data did not exhibit sufficient saturation behavior for parameter fitting, and 92%S

489 + 8%C, where only two reactors provided data suitable for parameter fitting. Within each

490 column, values not connected by the same letter are significantly different ($\alpha = 0.05$).

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Table IV. Cumulative respiration saturation model (eq. 3) parameter estimates for field trial soil mixtures prior to solarization.

| Soil mixture | $C_T$ (mg $CO_2$/g dry weight) | $c$ (days) |
|---|---|---|
| 100%S | 0.220 (0.0388) a | 8.22 (6.33) a |
| 90%S + 8%C + 2%WB | 16.9 (1.78) b | 1.43 (0.0814) b |

Values are given as means with one standard deviation given in parentheses. n = 3 for 100%S due to two reactors not yielding data suitable for parameter estimation. n = 5 for amended soil. Within each column, values not connected by the same letter are significantly different ($\alpha$ = 0.05).

Table V. Estimated values for maximum cumulative $CO_2$ evolution in amended soil samples as a function of depth following solarization.

| Depth (cm) | $C_T$ (mg $CO_2$/g dw) |
|---|---|
| 0 - 5.8 | 1.93 (0.74) |
| 5.9 - 11.6 | 2.02 (0.43) |
| 11.7 - 17.4 | 2.42 (0.99) |

Values are given as means with one standard deviation given in parentheses. n = 5.

509 Table VI. Degree-day differences in microcosms during solarization.

| Solarization time (days) | Soil treatment | Degree-days (˚C·day) |
|---|---|---|
| 7 | 100%S | 250.9 (0.9) a |
| 7 | 90%S + 8%C + 2%WB | 260.9 (0.4) b |
| 22 | 100%S | 821.0 (6.3) c |
| 22 | 90%S + 8%C + 2%WB | 835.7 (1.2) d |

510 Values are given as means with one standard error of the mean given in parentheses. Within
511 columns, values not connected by the same letter are significantly different based on Student's t-
512 tests of the one-tailed hypothesis that microcosms with amended soil experienced greater heating
513 than microcosms with only soil ($\alpha = 0.05$). $n = 4$.

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Table VII. Lettuce seed germination rates in solarized amended soil samples and freshly prepared control soil mixtures.

| Soil mixture | Solarized | Germination (%) |
|---|---|---|
| 90% S + 8% C + 2% WB, 0-5.8 cm depth | + | 94.0 (3.7) a |
| 90% S + 8% C + 2% WB, 5.9-11.6 cm depth | + | 94.0 (4.6) a |
| 90% S + 8% C + 2% WB, 11.7-17.4 cm depth | + | 95.6 (4.2) a |
| 100% S | - | 86.5 (18.2) a |
| 92% S+ 8% C | - | 87.9 (13.1) a |
| 90% S + 8% C + 2% WB | - | 45.0 (39.5) b |

Values are given as means with one standard deviation given in parentheses. Values not connected by the same letter are significantly different ($\alpha = 0.05$). n = 20.

Table VIII. Dimension and weight values for lettuce seedlings grown in solarized amended soil samples and control soil mixtures.

| Soil mixture | Solarized | Root length (cm) | Shoot length (cm) | Fresh weight (mg) | Dry weight (mg) |
|---|---|---|---|---|---|
| 90% S + 8% C + 2% WB, 0-5.8 cm depth | + | 6.20 (1.48) bc | 2.36 (0.31) a | 47.6 (8.1) b | 2.3 (1.1) bc |
| 90% S + 8% C + 2% WB, 5.9-11.6 cm depth | + | 6.04 (1.37) bc | 2.35 (0.37) a | 46.6 (10.2) b | 2.2 (0.7) bc |
| 90% S + 8% C + 2% WB, 11.7-17.4 cm depth | + | 5.65 (1.29) c | 2.33 (0.40) a | 46.3 (9.9) b | 2.4 (0.7) bc |
| 100% S | - | 6.63 (1.74) ab | 2.08 (0.41) b | 44.0 (9.3) b | 2.5 (0.7) ab |
| 92% S+ 8% C | - | 7.08 (1.46) a | 1.96 (0.41) b | 53.7 (12.5) a | 2.9 (0.8) a |
| 90% S + 8% C + 2% WB | - | 2.68 (1.33) d | 1.64 (0.49) c | 35.4 (18.9) c | 2.1 (1.0) c |

Values are given as means with one standard deviation given in parentheses. Values not connected by the same letter are significantly different ($\alpha = 0.05$). n = 75, except for the 90% S + 8% C + 2% WB control mixture, where sample size was limited by some trays containing less than 15 seedlings.