This paper reviews the efforts undertaken at our laboratory and elsewhere in Japan to revive the old method of soil solarization. The efforts entail the development of a simplified technique to estimate the greenhouse soil temperature, the examination of microbial and nutrient dynamics as affected by soil solarization, and the improvement of soil management to enhance the effect of soil solarization.

**INTRODUCTION**

Methyl bromide is an odorless, colorless gas. When it is compressed as a liquid and applied as pesticidal formulations, it is extremely effective to control soil-borne diseases, insects, nematodes and other pests in open fields and greenhouses, thus has been widely used. However, methyl bromide is a toxic substance. Because it dissipated rapidly to the atmosphere at the normal temperature and normal pressure, it is most dangerous at the fumigation site. Human exposure to high concentrations of methyl bromide can harm the lungs, eyes, and skin. Moreover, it is recognized as an ozone-depleting substance. The 1992 Montreal Protocol on Substances that Deplete the Ozone Layer set out a mandatory timetable for the phase out of methyl bromide. Japan accomplished the complete phase-out of methyl bromide in 2013. However, finding alternatives is a challenge because methyl bromide sterilizes soil so well.

Katan et al. (1976) first reported about the effectiveness of solar heating of the soil by means of mulching with transparent polyethylene to control soil-borne pathogens. Kodama and Fukui (1978 a & b) reported about the successful control of several soil-borne diseases in the closed polyvinyl houses under summer conditions. After these, many scientists have tried soil solarization for various crops. It has been proven as an environmentally friendly method for controlling soil-borne pathogens using solar power. It is achieved by mulching the soil and covering it with an energy trap. The trap is usually a transparent polyethylene cover. Up to the present, almost all important soil-borne pathogens have been tested. Although the results were not as effective as methyl bromide, the technique in general, has proved acceptable in the greenhouse industry as an alternative to methyl bromide for many areas in Japan.

In the past, the conventional soil management in Japan was as follows: irrigation, mulching, disinfection by soil solarization, fertilization, ridging, and planting; in that order. An attempt was made to maintain the temperature above 40°C at the depth of up to 15 cm. However, the subsurface soil temperature may not reach that level. Under this situation, when plowing, the subsurface soil that contains living pathogens may mix with the surface soil. This would cause ineffective disinfection by the soil solarization. To improve the disinfection effect by soil solarization, the soil management process needs to be modified, that is: irrigation, fertilization, ridging, mulching, disinfection by soil solarization, and planting; in that order (Shiraki et al. 1998). This modified soil management process has been introduced in approximately 10% of the greenhouses in Miyazaki Prefecture.

Since 2013 we endeavor to further improve the modified soil management process. The equipment is setup to collect soil temperature data and the exposure period, and to investigate the impact of high temperature on soil microbial and nutrient dynamics. Our purpose is to provide techniques and data that will convince farmers to utilize the modified soil management process.

**Tools for Measuring Soil Temperature**

In the southwest of Japan, it is empirically known that the period of the three weeks after the rainy season is suitable for soil solarization. An unpopular and old method was used to measure the soil temperature by burying a parafilm that would melt if the temperature reaches a certain level (Kodama 1978). However, this method is not always reliable and the farmer often blames the unstable weather for the failure of soil solarization. Our
research revealed that the root cause for the failure is the improper monitoring of the soil temperature in the field.

The desired disinfection effect can be achieved by monitoring the soil temperature during the soil solarization period. Ochi et al. (2015) reported that in order to reduce the population density of tomato damping-off pathogen, *Haematonecrida ipomoeae*, and eliminate the disease in a greenhouse, using soil solarization, it was necessary to expose the soil to 40°C for a period of 380 hours, or 43°C for a period of 300 hours. The result clearly shows that the effectiveness of soil solarization is a function of exposure temperature (intensity) and duration of exposure. To achieve the desired disinfection effect, the data of intensity and duration of exposure needs to be collected, and the soil solarization adjusted. This gives the farmer a better control of soil-borne diseases.

Based on the aforementioned fact, a better criterion for effective soil solarization has been developed. This involves an integration of exposure temperature and duration of exposure. In the graph of temperature versus time, the area under the curve represents the integral of temperature and time (Figure 1). Our criterion is the area defined by the 40°C line and the curve. This criterion is better than the time above 40°C. The advantages of the area criterion are: a precise estimation of the available nitrogen in the soil following soil solarization, and a good evaluation of soil microbial survivals. Using the area criterion, we may be able to shorten the soil solarization time by developing a quick and useful diagnostic technique for evaluating changes in microbial population following the soil solarization.

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![Figure 1: A sample of the time above 40°C and the area defined by the 40°C line and the curve](image)

Shimotaka et al. (2016) calculates the area criterion by the solar heating load index (°C ・ hours), which includes the heat capacity of the exposed soil. We developed a simple formula for calculating the solar heating load index.

\[
\text{SHLI} = A \Delta T^B \Delta T = T_{\text{max}} - T_c
\]

where A and B are constants, \(T_{\text{max}}\) is the daily maximum soil temperature (°C), and \(T_c\) is 40°C

To overcome the farmers’ reluctance to use the above criterion because of the cost of soil temperature recorders, we have developed a method of estimating soil temperatures without soil temperature recorders. The estimation is based on the data recorded in a nearby greenhouse in a particular disinfection period and data from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency. AMeDAS provides the weather data collected by more than 840 weather stations throughout Japan since 1974 and supports real-time monitoring of weather conditions with high temporal and spatial resolution. It makes available information on air temperature, but not soil temperature. We estimate the daily maximum soil temperature using the AMeDAS data, and then we calibrate the estimated data using the data of the neighboring greenhouse. This system can be offered to the greenhouse grower.
Impact of Soil Solarization on Nutrient Dynamics

Apart from its disinfection effects, soil heating from solarization also changes the nitrogen and phosphorus dynamics in the soil. It releases soluble nutrients from chemical fertilizers and promotes the mineralization of the native soil organic matter and composts. Ihara et al. (submitted) showed that soils incubated at 45 and 60°C rendered more available nitrogen than those incubated at 30°C. Furthermore, the mineralization of various soils samples was positively correlated with the soil temperature. Because of these facts, the farmers can reduce the application of nitrogen fertilizers. In relation to the measurement of soil nitrogen, Ihara et al. (submitted) have also adapted a rapid and easy-to-use technique (Uezono and Kato 2012) of assessing the available nitrogen in the soil following soil solarization.

On the other hand, Sugito et al. (2017) have conducted a soil incubation experiment, simulating solarization to elucidate the effects of soil solarization on phosphate availability. Results show that phosphate dynamics following soil solarization differed depending on the type of fertilizer or compost applied. Following solarization, the available phosphate increased significantly in soil mixed with a fertilizer containing organic matter as a phosphate source. In soil mixed with phosphate fertilizer or manure compost, the available phosphate remained almost constant. This implies that soil incubation experiments simulating solarization can be used to determine optimal phosphate application rates for cultivation systems in which fertilizer or compost is applied before solarization.

Impact of Soil Solarization on Microbial Communities

Soil solarization is not only an ecologically friendly method of controlling various soil-borne diseases and pests but also affects the overall structure and diversity of non-pathogenic members of the soil microbial community. It has a negative effect on protozoans, which feed on some of pathogenic bacteria and fungi.

A quick tool to forecast nitrification levels and times

Soil bacterial and fungal communities were affected by the soil solarization treatment. Yokoe et al. 2015 showed that the heat treatment at 45°C or solarization caused a significant change in the variety and size of the communities of bacteria and fungi. The positive correlations between the proportion of nitrate in inorganic nitrogen content and the copy number of bacterial and archaeal amoA gene and the viable number of ammonia-oxidizing bacteria were revealed (Yamagata et al. in press). The determination of amoA gene of ammonia-oxidizing bacteria is possibly a quick and useful diagnostic technique for evaluating the suppression and the restoration of nitrification following the soil solarization.

A quick evaluation tool of the protozoa

The ciliates are a group of protozoans. They play an important role in the soil ecosystems and nutrient flow as predators of bacteria and fungi. Murase et al. (2015) demonstrated both the vulnerability and resilience of the ciliate community to soil solarization. Thus, the dynamics of the ciliate population would be excellent bioindicators for the risk of re-emergence of soil-borne pathogens.

Fertilization Before Solarization in the Modified Soil Management

In Wakayama Prefecture, a slow-releasing chemical fertilizer, Hyper-CDU (crotonylidene diurea), was mixed with organic materials and applied to a pea field. In this trial, the modified soil management process was superior to the traditional soil management process because of 15% labor savings (without additional fertilization) and 20% saving of nitrogen. There was no difference in pea yields between the modified soil management and the traditional soil management.

In Miyazaki Prefecture, an organic fertilizer made from Japanese distilled spirit “Shochu” residue was compared with common organic fertilizers. In comparison with the common organic fertilizers, this fertilizer contains much quick-decomposable nitrogen. Tomato growth after transplanting was better with the Shochu residue organic fertilizer than that with common manure. This fertilizer enhances the effect of soil reduction, and demonstrates a stable disinfection effect.

CONCLUSIONS

Through various experiments in our group, soil solarization in combination with the modified soil
management process, prove the following: stable results of soil-borne diseases and pests control, enhancement of nitrogen and phosphorous release from both chemical and organic fertilizers, reduction of labor and fertilizer inputs, rendering the crop profitability human health, and safe environment. A simplified technique for estimating soil temperature by extrapolating the data of AMeDAS and the neighboring greenhouse soil temperature was also developed. It enables estimating the effectiveness of soil solarization, taking in account the exposure temperature and duration of exposure.

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