RFID temperature sensors for monitoring soil solarization with biodegradable films

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Highlight

- RFID sensors are effective for real-time temperature monitoring during solarization.
- Lesions of biodegradable film can be highlighted by RFID temperature assessment.
- Easy-to-use monitoring tools help the farmer to understand the thermal effect.

Abstract

Soil-borne pathogen and weed control can be achieved by soil solarization even if estimation of time treatment is difficult to assess. Thus, due to dependence to environmental conditions and the need to minimize the time of treatments, the implementation of monitoring tools may help in solarization managements, especially when biodegradable films were applied or weather condition are subjected to significant variation. Digitalization of data relative to plants thanks to RFID applications has been used for health or treatment monitoring, sample collecting and retrieving sanitary information: this paper presents the testing of RFID sensor application for soil solarization purposes. Different matrices were selected to assess RFID temperature sensors performances. Sandy, loam and clay soils with different moisture-holding capacity were selected for sensor burial. Sensors were covered by 5 or 10 cm of fresh matrix and read immediately. Reliability was found to be more than 90% in all tested conditions, while higher failure in tag reading was recorded in clay soil at 90 % of moisture-holding capacity (-7 % of tag reliability). Soil solarization treatment was carried out as case of study during a period characterized by changeable weather using a biodegradable film. Data, expressed as thermal addition and temperature classes, collected continuously by sensors permitted to design real-time graphs that help the farmer to understand the thermal effect caused by treatment. Throughout the second and third week of treatments, T_{max} at 5 cm depth is increased by 9-13 °C or 11-14 °C compared to environment, respectively. Otherwise, T_{max} at 10 cm depth is increased by 7-9 °C compared to environment throughout the second and third week, showing as sensors are able to collect temperature during solarization. The soil microbial community of soils treated with solarization exhibited a slight reduction of cumulative carbon metabolic activity compared to control (8.8 % of reduction), while among 31 preselected carbon sources, the soil microbial communities were capable of utilizing up to 23 carbon source without difference between treatments. Unified Modeling Language activity diagrams for solarization management via digital sensors were designed and effects of biodegradable film on microbial population were observed. The integration of information technology solutions with new-generation biodegradable films may offer an interesting revaluation of soil solarization in actual farm organization.

Keywords: heat treatment; soil-borne pathogens; weeds.

1. Introduction

Soil-borne pathogen and weed control can be achieved by soil solarization, a traditional approach to plant protection which effectiveness rely on potentially wide spectrum of action and lack of residues (Katan, 2000; Gill and McSorley, 2011). Solarization consists of trapping solar radiation with plastic films laid on the soil, which allows soil temperature increases of up to 50 °C near the surface. Recently, technological improvements were developed, thanks to novel plastic films able to reduce treatment time and enhance biological effects (Gill et al., 2009). Moreover, novel approach of solarization (e.g. biosolarization, biodegradable films) represent promising sustainable options for plant protection (Bonanomi et al., 2008; Mauromicale et al., 2010; Klein et al., 2012; Dominguez et al., 2014; Kanaan et al., 2015) with beneficial effects on soil microbes (Camprubí et al., 2007). As reported by Collange et al. (2014), the heating intensity, thus the control efficacy, depends on a rapid increase of temperature that must be achieved during the first days of the treatment and maintained during several weeks (Chellemi et al., 1997), and the soil-borne pest localization, because heating effect decreases in deeper soil layers (Stapleton, 1997). As a consequence, in order to control fungi (Patricio et al., 2006; Bonanomi et al., 2008) or viruses (Luvisi et al., 2015), it is recommended to start solarization in the warmer season and make it last for at least 3-4 weeks, even if estimation of time treatment is difficult to assess. Thus, due to dependence to environmental conditions and the need to minimize the time of treatments, the implementation of monitoring tools may help in solarization managements, especially when biodegradable films were applied or weather condition are subjected to significant variation. Generally, biodegradable films are fragile compared to polyethylene one and, after some weeks from soil application, are subjected to micro lesions that lead to break the film, leaving film scraps over the treated soils that are ineffective to control pests and weeds. Thus a pre-established time of treatment may easily lead to useless and expensive prolongation of solarization. Similarly, in countries such as Italy were weather conditions may vary over the short term even in the warmer seasons, a real-time evaluation of temperature achieved in the soil could be useful. Thanks to frequent acquisition of thermal parameter of solarized soils (such as thermal addition or temperature classes), farmers can be supported in decision making process, such as stop the treatment if the thermal values achieved are considered sufficient or extend the treatment over the predicted time. Thus, objectives of research in solarization management may relay in integration of IT solution for real-time monitoring of temperature, evaluation of commercial sensors for application in soils or development of novel one due to signal attenuation, as well as definition of theoretical model for data management via software.

Commonly, in order to monitor soil temperature during solarization, temperature sensors connected to data loggers had to be deployed in field. Conventional loggers are very effective in order to collect with high precision the soil temperature during solarization period (Luvisi et al., 2006; Peruzzi et al., 2012;) but they are expensive and, due to their professional purpose, they may be not user-friendly by farmers. Moreover, while sensors are buried, loggers are usually leaved on the ground during treatments and they is exposed to risks (i.e. animals or thefts), thus they should be monitored. Thus, up-to-date Information Technology (IT) solutions may be desirable. Digitalization of data relative to plants has been used for health monitoring, sample collecting and retrieving sanitary information (Thrane, 2008; Cunha et al., 2010). To establish a safe link between data and plant-associated samples, radiofrequency identification (RFID) tags have been proposed (Bowman, 2005; Bollen et al. 2007); their use in plant pathology has also been proposed (Kumagai and Miller, 2006; Luvisi et al., 2012a). The importance of hypermedia knowledge and information transfer in agriculture has been investigated since the last decade of the 20th century (Carrascal et al., 1995) and more recently information sharing and collaboration between users via the web have been introduced through the Agricultural Information Management System of FAO (http://aims.fao.org/), forestry information systems (Farcy et al. 2005) or the plant-associated microbe database (Almeida et al. 2010), with useful features for stakeholders. In addition, platforms to share and manage information in agriculture can be implemented by RFID-based technologies (Sørensen et al. 2010), providing a safe and durable link between items and information. Finally, health or treatments data can be integrated with Web 2.0 collaborative workspace, provided for useful data interchange and communications between users: generally, retrieving information from activities, samples or documents is easier when using RFID-labelling with workspace support (Luvisi et al., 2012b). In order to evaluate IT solutions for the management of soil-borne pathogens, this paper presents the testing of an RFID application for soil solarization purposes. Soil depth cause significant effects on signal attenuation, as well as soil water content (Li et al., 2007; Bogena et al., 2009). Thus evaluation of RFID sensor characteristics and tag distribution in soil are investigated in order to overcome obstacle to tag readability. Moreover diagrams were designed to define the workflow of operations necessary to perform a comparison between real-time data collected from sensors and farm historical data, in order to design specific management software. A treatment using a novel biodegradable film was reported as case of study.

2. Materials and Methods

2.1. RFID temperature sensor tests

Semi-passive Ultra-High Frequency (UHF) logger tags (Easy2Log RT0005, Caen RFID, Italy) were used as temperature sensors. Tags are compatible with the EPCGlobal C1G2 and ISO18000-6C standards. Frequency range is 860 MHz - 928 MHz. A handheld reader (qIDmini, Caen RFID, Italy), compliant with UHF tag standards was used. The reader, with an integrated linear antenna, was connected via Bluetooth with a laptop, working at 865.600-867.600 MHz. RF power was programmable from 5dBm e.r.p. (3mW e.r.p.) to 22dBm e.r.p. (150mW e.r.p.). Tags were configured to store temperature samples in intervals of 1 hour in the internal memory. Temperature operating range was -20 to 70 °C with temperature accuracy of ±0.5 °C Different matrices were selected to assess RFID temperature sensors performances. Sandy, loam and clay soils with different moisture-holding capacity (10, 50 and 90%) were selected for sensor burial. Tags were buried to cover the temperature sensors by 5 or 10 cm of soil and read immediately. Thanks to RFID antenna disposition within tag compare to temperature sensors, the antenna is nearer to the soil surface compared to temperature sensor (Fig. 1). Thus, the antenna is at ground level (±0.5 cm) at 5 cm depth temperature sensor, while about 2.4 cm of soil cover the antenna when temperature sensor is 10 cm depth.

To estimate the system reliability in selected environmental conditions, the number of detected tags was divided by the total, with 15 tags for three replications. Replications were necessary because the reliability is essentially a random variable and therefore mean values have to be estimated (Ampatzidis and Vougioukas, 2009).

2.2. Case of study

In order to evaluate the effectiveness of RFID sensors for monitoring soil temperatures, soil solarization was carried out during periods characterized by changeable weather (late May-June). Soil solarization was carried out in San Piero a Grado (PI), central Italy, using a starch based biodegradable film MaterBi (biodegradable film). Biodegradable film is a transparent film (thickness 30 mm) produced from a starch base (Novamont S.p.a., Italy). Films covered the soil for 60 days. Full details regarding field preparation are presented elsewhere (Stapleton, 2000). Tags were buried placing the temperature sensor at 5 and 10 cm depth. Manual reading with a handheld every week in order to assess real-time retrieving of temperature. Measured temperatures were divided into three classes ($T \leq 35$ °C, 35 °C $> T \leq 40$ °C, 40 °C $> T \leq 45$ °C). The length of time each class persisted in the soil was taken into account, along with the temperature measured each hour. The thermal addition parameter ($\sum T$) was calculated as sum of the individual temperatures (measured every hour) for the 8 weeks following treatment. A microbial test was carried out in order to evaluate soil solarization effectiveness. Soil samples were collected to evaluate total fungi, *Trichoderma* spp. and actinomycetes as CFU per gr of soil, using potato dextrose agar, P190 and water–agar medium, respectively (Papavizas and Davey, 1959; Ho and Ko, 1979). Community-level physiological profiles of soil microbial communities, using EcoPlates (Biolog Inc., CA, USA) incubation, were carried out by calculating the average well colour development, richness and Shannon–Weaver index (Chen et al. 2013). Soils were collected following Cheng et al. (2013) immediately before and after treatments, sampling the top 10 cm of soil using a 3.6-cm-diameter soil corer. Five soil cores from random location in each 1x2 m plot were collected and mixed together as a composite sample. Soil samples were stored on ice for transport to the laboratory, where they were homogenized and sieved (2 mm) to remove roots and rocks. Fresh soils were used for soil microbial assay and test with EcoPlates. Activity and functional diversity of the soil microbial communities were measured following procedure described by Winding et al. (1994). Trials were repeated over 2 years, while temperature graphs were reported for one year of case of study.

2.3. Statistical analysis

Differences in tag reliability were determined using analysis of variance (ANOVA). Data expressed in percent were converted in arcsin values. $P < 0.05$ was considered to be significant. In table, same letter following values indicate that values do not differ significantly. Following Chen et al. (2013), the metabolic richness, the number of Ecoplates substrates metabolized, (i.e., total number of wells with absorbance over 0.25), and metabolic diversity (Shannon–Weiner diversity index) were measured as microbial community functional diversity. The absorbance values of microplates measured at 72 h of incubation were used to calculate microbial community functional diversity. The SPSS 16.0 (SPSS INC., Chicago, IL, USA) software package was employed for ANOVA.

3. Results

3.1 RFID temperature sensor tests

RFID tag readings when temperature sensors were covered by 5 or 10 cm of matrices were reported in Table 1. RFID reliability was found to be more than 90% in all tested conditions: soil properties such as tested texture or moisture-holding capacity interfere with signal transmission partially, only at 10 cm depth. Higher failure in tag reading was recorded in clay soil at 90 % of moisture-holding capacity (-7 % of tag reliability).

3.2. Case of study

Temperature measured over 8 weeks after soil solarization treatment by temperature sensors were reported in Fig. 2. Environmental temperatures were also reported in the same graphs. Bad weather conditions happen during the first week (T_{max} 19-22 °C, T_{min} 10-13 °C), while temperatures rise constantly during the second (T_{max} 21-26 °C, T_{min} 10-12 °C) and third week (T_{max} 26-33 °C, T_{min} 13-19 °C). Weather variability affect the fourth week (T_{max} 24-31 °C, T_{min} 16-18 °C), than solarization film broke after 37 days, leaving film scraps over the treated soils. During the first four weeks, the trend of soil temperature follow environmental condition at both depth, even if environmental changes are more effective at 5 cm depth compared to 10 cm (Fig. 2). Throughout the second and third week, T_{max} at 5 cm depth is increased by 9-13 °C or 11-14 °C compared to environment, respectively. Otherwise, T_{max} at 10 cm depth is increased by 7-9 °C compared to environment throughout the second and third week. As reported in Fig. 2, after the breaking point at day 37, soil temperature are quite unaffected by film scraps and soil daytime temperature were similar to environmental temperatures.

Data collected continuously permitted to design real-time graphs (Fig. 3) that help the farmer to understand the thermal effect caused by treatment. Data indicated as the first week was quite ineffective in achieving a thermal condition useful to control pests and weeds. The higher thermal class ($40\ ^{\circ}C > T \leq 45\ ^{\circ}C$) was never reached at both depth, while the lower one ($35\ ^{\circ}C > T \leq 40\ ^{\circ}C$) was maintained for just 16 hours at 5 cm depth. During the second week, soil at 5 cm depth reached the higher temperature class for one hour and the lower class was achieved for 31 hours. Almost no effects were recorder at 10 cm depth, with just four hours at the lower temperature class. Conversely, third and fourth week were the most effective period. At 5 cm depth, soil achieved $40\ ^{\circ}C > T \leq 45\ ^{\circ}C$ for 34 (third week) and 11 hours (fourth week). The lower temperature class was achieved for 33 (third week) and 20 hours (fourth week). At 10 cm depth, even if soil did not achieve the higher temperature class, soil temperature was set at $35\ ^{\circ}C > T \leq 40\ ^{\circ}C$ for 33 and 17 hours during the third and fourth week, respectively. Farmer could use this information ($\sum T$ and, more significantly, temperature classes) to support the decision making process that lead to extend or stop the treatment and start the following cultivation (i.e. during the case of study the T_{max} never exceeded 44 °C, that could be considered a sub-optimal temperature that can lead to extend the treatment). Contribution to heating due to fifth week was weak and the extension of treatment was useless due to film breaking point.

Soil solarization did not induced biological vacuum with regard to the investigated microbial community. The treatment did not significantly alter total fungi (28.8±4.3 cfu) and actinomycetes (58.9±9.6 cfu). The community of *Trichoderma* spp. was slightly increased with solarization (from 14.5±0.5 cfu in untreated soils to 15.4±0.5 cfu in solarized ones, with 5.1 % of increase). Cumulative carbon metabolic activity was the integration of average well color development over incubation time, relatively indicating the total carbon utilized by soil microbial communities. The soil microbial community of soils treated with solarization exhibited a slight reduction of cumulative carbon metabolic activity compared to control (from 268.5±8.3 in untreated control to 245.0±4.5 in solarized soils, with 8.8 % of reduction). This implies the soil microbial community established after solarization was capable of consuming carbon substrates at nearly the same efficiency as untreated soils. Carbon source utilization richness expressed the number of usable substrates by a soil microbial community and reflected the diversity of microbial metabolism. The metabolism of each carbon substrate of Ecoplates was individually evaluated. Among 31 preselected carbon sources, the soil microbial communities were capable of utilizing up to 23 carbon source. This measurement was not significantly affected by solarization (from 20.8±2.2 in untreated control to 20.5±1.6 in treated ones). Shannon's index of carbon source utilization was not influenced by treatment (from 3.00±0.15 in untreated control to 2.93±0.16 in solarized soils), suggesting no effect on functional diversity.

3.3. Activity diagrams for solarization management via digital sensors

In Fig. 4 we repot the Unified Modeling Language (UML) activity diagrams for solarization management via digital sensors. Diagrams were designed to shows the workflow of operations necessary to perform a comparison between real-time data collected from sensors and farm historical data (Fig. 4). Activity diagram of the function 'forecast' show the interaction of the software with the user to calculate $\sum$ T and thermal classes from temperature retrieved by sensors. If available, the user can compare these parameters to data from previously carried out treatments and decide to extend the treatment or stop it. If historical data are not available and the user decided to stop the solarization, parameters have to be stored until following classification of treatment (unconfirmed historical data), via 'management' function. After crop cultivation, the user can estimate the solarization effectiveness and store the treatment parameter within the database (confirmed historical data).

4. Conclusions

Our findings suggest that sensors reliability was generally satisfactory considering matrices involved in soil solarization. Compared to that in air, the underground communication exhibits significant challenges for the development of wireless underground sensor network (Vuran and Akyildiz, 2010). Stuntebeck et al. (2006) indicate that just 6 cm of wet soil cause a significant attenuation in signal, thus we need to orientate the tags along soil profile accurately, in order to avoid a soil layer thicker than 2.4 cm. As shown, limited effects due to matrix parameters such as soil texture or soil moisture-holding capacity were reported considering test conditions. Temperature sensors did not show a reduced reliability when covered by more than 5 cm of matrices. These results confirm readability tests by other workers in agricultural applications (Bowman, 2005; Kumagai and Miller, 2006; Ampatzidis and Vougioukas, 2009), suggesting that RFID microchips can be implemented in soil solarization practices. Anyway, in order to establish a remote measurement of soil temperature (i.e. establishing a remote reading with automated data transmission), the high signal attenuation caused by water-containing products need to be considered, limits the communication range to less than 0.5 m for the commonly used 2.4 GHz radio chips (Jedermann et al., 2014). By theoretical analysis of the dependency of signal attenuation on the operating frequency, Jederman et al. (2014) show that the signal attenuation can be largely reduced by the use of 433 MHz or 866 MHz devices, but forwarding of messages over multiple hops inside a sensor network may represent a difficult task for an automated soil temperature system.

Concluding, RFID temperature sensors represent easy-to-use and cheap tools to support the decision making process during long term treatment such as solarization, when the risk to premature stop of treatment or excessive extension of solarization period may lead to loss of effectiveness or increasing costs. Anyway, thermal sum and temperature classes are not intended as fixed thresholds above that pests or weeds control is assured, but their measurement (and collection) over the years can help the farmer to manage the solarization treatment according to his specific needs and environmental conditions. Even if a similar approach can be achieved via traditional sensors and processor unit, RFID sensors may be leave in the field without monitoring, can be integrated within smartphone applications and allow an easier real-time monitoring for farmers. The integration of IT solutions with new-generation biodegradable films may offer an interesting revaluation of soil solarization in actual farm organization.

References

Almeida, N.F., Yan ,S., Cai, R., Clarke, C.R., Morris, C.E., Schaad, N.W., Schuenzel, E.L., Lacy, G.H., Sun, X., Jones, J.B., Castillo, J.A., Bull, C.T., Leman, S., Guttman, D.S., Setubal, J.C., Vinatzer, B.A., 2010. PAMDB, a multilocus sequence typing and analysis database and website for plant-associated microbes. Phytopathology 100, 208-215.

Ampatzidis, Y.G., Vougioukas, S.G., 2009. Field experiments for evaluating the incorporation of RFID and barcode registration and digital weighing technologies in manual fruit harvesting. Comput. Electron. Agr. 66, 166-172.

Bogena H.R., Huisman J.A., Meier H., Rosenbaum U., Weuthen A., 2009 Hybrid Wireless Underground Sensor Networks: Quantification of Signal Attenuation in Soil. Vadose Zone J. 8(3), 755-761.

Bollen, A.F., Riden, C.P., Cox, N.R., 2007. Agricultural supply system traceability, Part I: Role of packing procedures and effects of fruit mixing. Biosyst. Eng. 98, 391-400.

Bonanomi, G., Chiurazzi, M., Caporaso, S., Del Sorbo, G., Moschetti, G., Felice, S., 2008. Soil solarization with biodegradable materials and its impact on microbial communities. Soil Biol. Biochem. 40, 1989-1998.

Bowman, K.D., 2005. Identification of woody plants with implanted microchips. HortTechnology, 15, 352-354.

Camprubí, A., Estaún, V., El Bakali, M.A., Garcia-Figueres, F., Calvet, C., 2007).Alternative strawberry production using solarization, metham sodium and beneficial soil microbes as plant protection methods. Agron. Sustain. Dev. 27, 179-184.

Carrascal, M.J., Pau, L.F., Reiner, L., 1995. Knowledge and information transfer in agriculture using hypermedia: a system review. Comput. Electron. Agr. 12, 83-119.

Chen, F., Zheng, H., Zhang, K., Ouyang, Z., Wu, Y., Shi, Q., Li, H., 2013. Nonlinear impacts of Eucalyptus plantation stand age on soil microbial metabolic diversity. J. Soil Sediment 13, 887–894.

Chellemi, D.O., Olson, S.M., Mitchell, D.J., Secker, I., McSorley, R., 1997. Adaptation of soil solarization to the integrated management of soilborne pests of tomato under humid conditions. Phytopathology 87, 250-258.

Collange, B., Navarrete, M., Montfort, F., Mateille, T., Tavoillot, J., Martiny, B., Tchamitchian, M., 2014. Alternative cropping systems can have contrasting effects on various soil-borne diseases: Relevance of a systemic analysis in vegetable cropping systems. Crop Prot. 55, 7-15.

Cunha, C.R., Pere,s E., Morais, R., Oliveira, A.A., Matos, S.G., Fernandes, M.A., Ferreira, P.J.S.G., Reis, M.J.C.S., 2010. The use of mobile devices with multi-tag technologies for an overall contextualized vineyard management. Comput. Electron. Agr. 73, 154-164.

Domínguez, P., Miranda, L., Soria, C., de los Santos, B., Chamorro, M., Romero, F., Daugovish, O., López-Aranda, J.M., Medina, J.J., 2014. Soil biosolarization for sustainable strawberry production. Agron. Sustain. Dev. 34, 821-829.

Farcy, C., de Terwangne, B., Blerot, P., 2005. A distributed information system for public forest and wildlife management in the Walloon Region (Belgium) using open GIS standards. Comput. Electron. Agr. 47, 207-220.

Gill, H.K, McSorley, R., Treadwell, D.D., 2009. Comparative Performance of Different Plastic Films for Soil Solarization and Weed Suppression. HortTechnology 19, 769-774.

Gill, H.K., McSorley, R., 2011. Effect of different inorganic/synthetic mulches on weed suppression during soil solarization. Proc. Fl. State Hortic. 124, 310-313.

Ho, W.C., Ko, W.H., 1979. Alkalized water agar as a selective medium for enumerating actinomicetes, Phytopathology 69, 1031.

Kanaan, H., Medina, Sh., Krassnovsky, A., Raviv, M., 2015. Survival of *Macrophomina phaseolina* s.l. and *Verticillium dahlia* during solarization as affected by composts of various maturities. Crop Prot. 76, 108-113.

Katan, J., 2000. Soil and substrate disinfestation as influenced by new technologies and constraints. Acta Hortic. 532, 29-35.

Klein, E., Katan J., Gamliel, A., 2012. Soil suppressiveness to *Meloidogyne javanica* as induced by organic amendments and solarization in greenhouse crops. Crop Prot. 39, 26-32.

Kumagai, M.H., Miller, P., 2006. Development of electronic barcodes for use in plant pathology and functional genomica. Plant Mol. Biol. 61, 515-523.

Mauromicale, G., Lo Monaco, A., Longo, A.M.G., 2010. Improved efficiency of soil solarization for growth and yield of greenhouse tomatoes. Agron. Sustain. Dev. 30, 753-761.

Li, L., Vuran, M.C., Akyildiz, I.F., 2007. Characteristics of underground channel for wireless underground sensor networks. In Proc. Annu. Mediterranean Ad Hoc Networking Workshop, 6th, Corfu, Greece. 12–15 June 2007. Univ. of Athens and Ionian Univ., Corfu, Greece.

Luvisi, A., Materazzi, A., Triolo, E., 2006. Steam and exothermic reactions as alternative techniques to control soil-borne diseases in basil. Agron. Sustain. Dev. 26, 201-207.

Luvisi, A., Panattoni, A., Triolo, E., 2012a. Radio-frequency identification could help reduce the spread of plant pathogens. Calif. Agr. 66, 97-101.

Luvisi, A., Panattoni, A., Triolo, E., 2012b. Electronic identification-based Web 2.0 application for plant pathology purposes. Comput. Electron. Agr. 84, 7-15.

Luvisi, A., Panattoni, A., Materazzi, A., 2015. Heat treatments for sustainable control of soil viruses. Agron. Sustain. Dev. 35, 657-666.

Papavizas, G.C., Davey, C.B., 1959. Evaluation of various media and antimicrobial agents for isolation of soil fungi. Soil Sci. 88, 112-117.

Patricio, F.R.A., Sinigaglia, C., Barros, B.C., Freitas, S.S., Tessarioli Neto, J., Cantarella, H., Ghini, R., 2006. Solarization and fungicides for the control of drop, bottom rot and weeds in lettuce. Crop Prot. 25, 31-38.

Peruzzi, A., Raffaelli, M., Frasconi, C., Fontanelli, M., Barberi, P., 2012. Influence of an injection system on the effect of activated soil steaming on Brassica juncea and the natural weed seedbank. Weed Res. 52, 140-152.

Sørensen, C.G., Fountas, S., Nash, E., Pesonen, L., Bochtis, D., Pedersen, S.M., Basso, B., Blackmore, S.B., 2010. Conceptual model of a future farm management information system. Comput. Electron. Agr. 72, 37-47.

Stapleton, J.J., 1997. Solarization: an implementable alternative for soil disinfestation, in: Canaday, C. (Ed.), Biological and Cultural Tests for Control of Plant Diseases vol. 12., St. Paul, pp. 1-6.

Stapleton, J.J., 2000. Soil solarization in various agricultural production systems. Crop Prot. 19, 837–841.

Stuntebeck, E.P., Pompili, D., Melodia, T., 2006 Wireless underground sensor networks using commodity terrestrial motes. In 2nd IEEE Workshop on Wireless Mesh Networks (WiMesh 2006), pp. 112-114.

Thrane, C., 2008. Quality assurance in plant health diagnostics – the experience of the Danish Plant Directorate. Eur. J. Plant Pathol. 121, 339–346.,

Vuran, M.C., Akyildiz, I.F., 2010. Channel model and analysis for wireless underground sensor networks in soil medium. Physical Communication 3, 245-254.

Winding, A.K., 1994. Fingerprinting bacterial soil communities using Biolog microtitre plates. In: Ritz, K., Dighton, J., Giller, K.E. (eds) Beyond the biomass: compositional and functional analysis of soil microbial communities. Wiley, Chichester, pp. 85-94.

Table 1

RFID tag reliability (readable tags divided by total, %) using temperature sensors covered by 5 or 10 cm of soil (sandy, loam or clay soils, at 10, 50, 90 % of moisture-holding capacity).

	Tag reliability					
	5 cm* depth moisture-holding capacity			**10 cm** depth moisture-holding capacity**		
Soil	10	50	90	10	50	90
Sandy	100 a[#]a[§]	100 aa	100 aa	100 aa	98 ba	96 ca
Loam	100 aa	100 aa	100 aa	100 aa	98 ba	96 ca
Clay	100 aa	100 aa	100 aa	98 bb	98 ba	93 cb

[*] RFID antenna was at ground level (0±0.5 cm)

[**] RFID antenna was covered by 2.4±0.5 cm of soil

[#] values in the same line followed by the same letter do not differ significantly according to Duncan´s multiple range test ($P \leq 0.05$)

[§] values in the same column followed by the same letter do not differ significantly according to Duncan´s multiple range test ($P \leq 0.05$)

Fig. 1. Distribution of sensors along the soil profile.

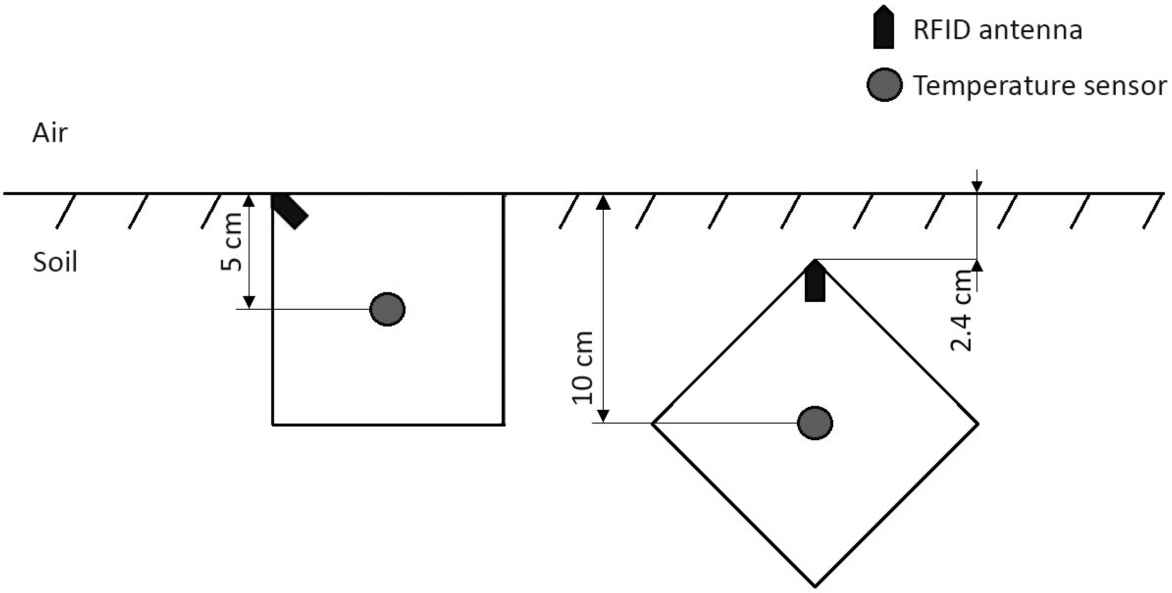


Fig. 2. Temperature measured over 8 weeks after soil solarization treatment by temperature sensors covered by 5 or 10 cm of soil, compared to environmental data. The arrows indicate the solarization film breaking point.

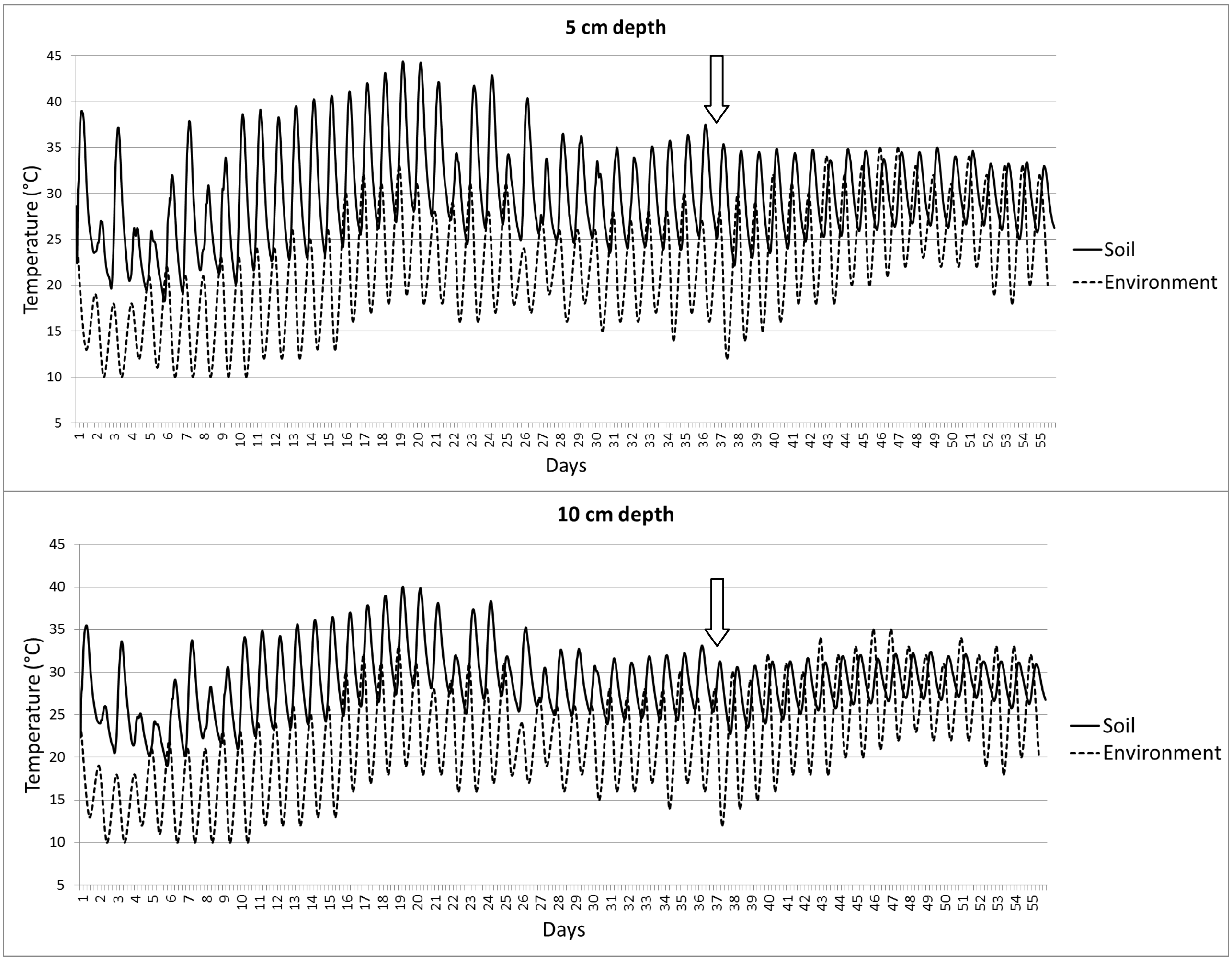
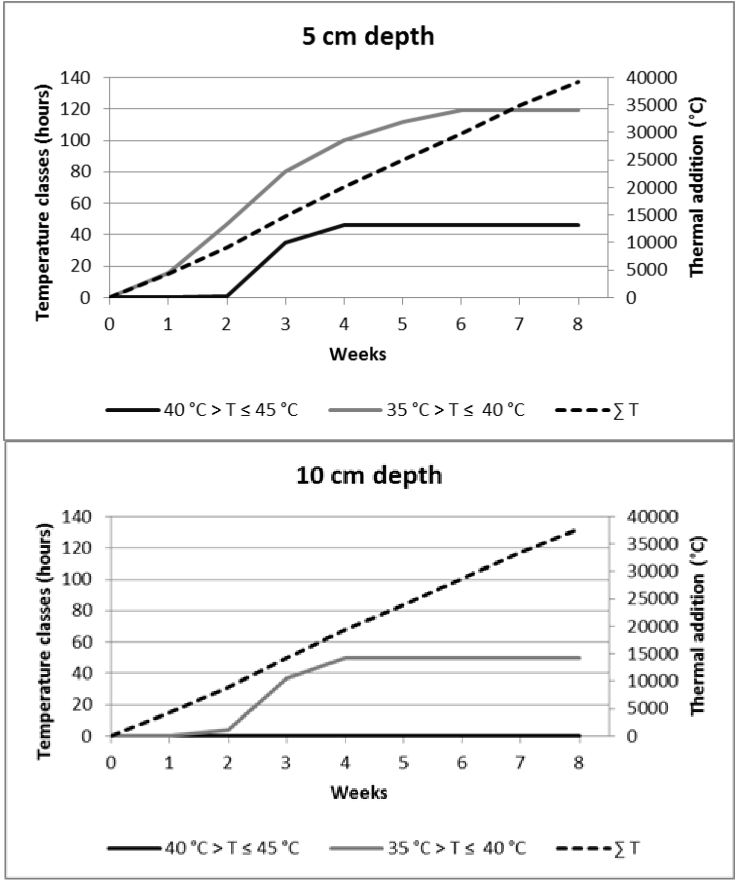
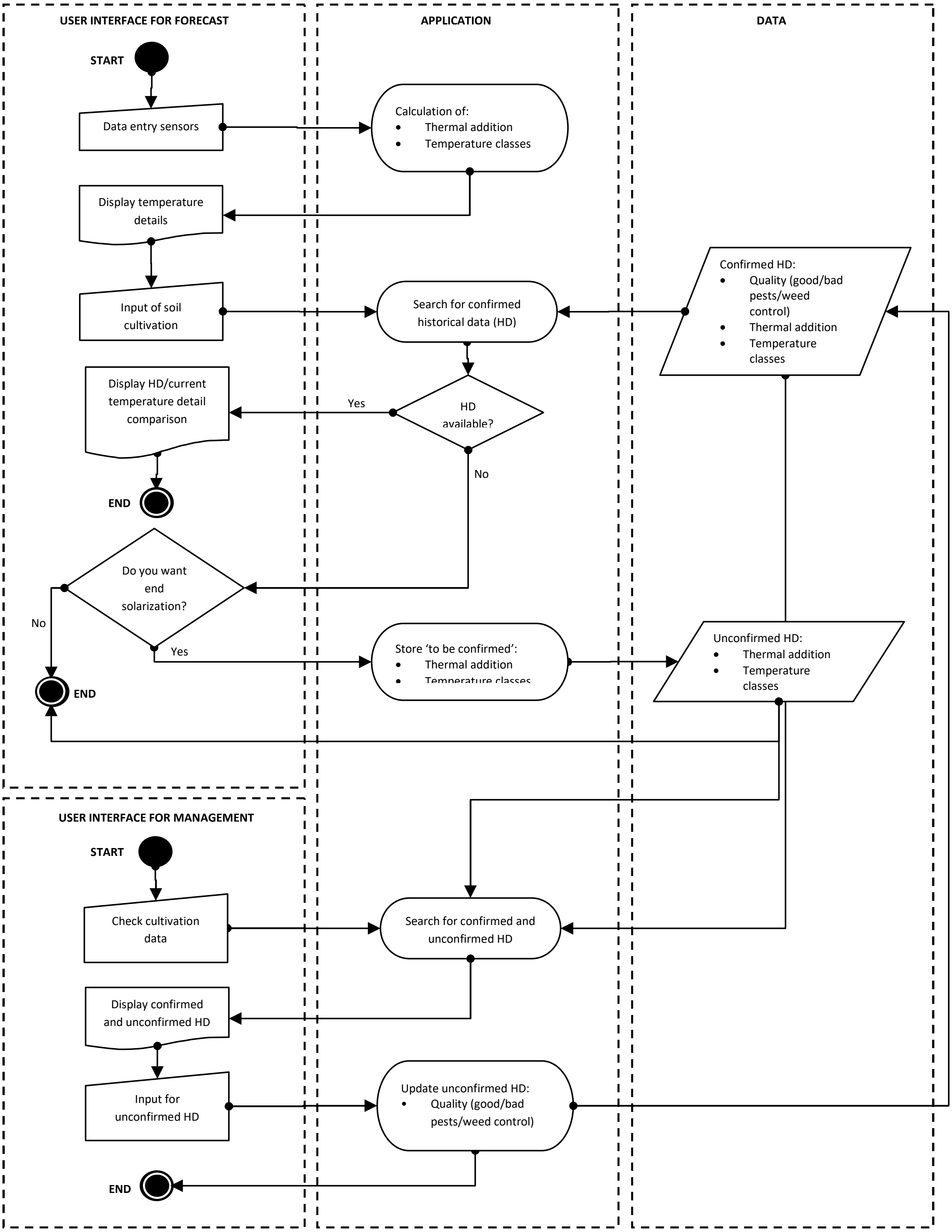


Fig. 3. Higher temperature classes (35 °C > T ≤ 40 °C, 40 °C > T ≤ 45 °C, expressed as hours) and thermal addition (∑ T, calculated as sum of the individual temperatures measured every hour) measured in solarized soil with biodegradable film. Data measured over 8 weeks after treatment by RFID temperature sensors covered by 5 or 10 cm of soil.



549 **Fig. 4.** UML activity diagram of the functions 'forecast' and 'management' to compare current solarization
550 achievement to farm historical data.



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