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The potential of active and passive infrared thermography for identifying dynamics of soil moisture and microbial activity at high spatial and temporal resolution

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ABSTRACT

Spatio-temporal analyses of soil properties are important for more profound insights into soil processes. Up to now, non-invasive approaches analyzing physical and biological soil properties and dynamics at the microscale are not available due to methodological, instrumental, and analytical challenges. In this study, we evaluate the use of active and passive infrared thermography (IRT), a non-invasive and non-contact technique, for the detection of surface temperature-based parameters on soil surfaces. The potential and possibilities of IRT were analyzed with a focus on the detection and calibration of soil moisture using active IRT and the determination of microbial activity using passive IRT. A pool of 51 soil samples was used to cover a wide range of chemical, physical, and biological soil properties. The samples were rewetted to 16 different moisture contents, filled into vessels, and placed in an air-proof glove box with an adjusted relative humidity of about 92% to reduce soil drying. Immediately after rewetting, the soil surface temperature was determined using active and passive IRT procedures at a high temporal resolution (1 min for passive IRT, hourly for active IRT) and a spatial resolution of 0.283 mm. Soil material was also sterilized by γ-irradiation in order to obtain sterile samples for validating the passive IRT procedure. Active IRT measurements were qualified for the detection of soil surface moisture due to changing specific heat capacity at varying water contents. The mean volumetric water contents explained up to 88% of active IRT values, which were a good approximation for relative differences in the spatial and temporal distribution of moisture contents. Passive IRT measurements are useful for the detection of microbial activity on soil sample surfaces since temperature increases by up to 0.5 K were detected on the surfaces of all non-sterile samples immediately after rewetting. In sterile samples, rewetting did not result in heat production. With regard to the commonly observed “Birch”-CO_2-pulse, these results strongly suggested that the heat evolution on the surface of the non-sterile soils was associated with the rapidly increasing microbial activity from consuming dead and easily available soil biomass. In conclusion, IRT is a promising mapping tool of soil surface processes especially for undisturbed soil samples, since IRT techniques allow studying moisture and microbial activity of intact soil structures.

1. Introduction

The spatial and temporal heterogeneity of soil properties at the microscale have increasingly moved into the focus of many studies, since the microscale has a great potential to reveal new insights into soil processes (Dechesne et al., 2007; Grundmann and Debouzie, 2000; Nunan et al., 2003; Vos et al., 2013; Young and Crawford, 2004). However, while soil physical properties have been intensively studied at the microscale (Heeraman et al., 1997; Heng et al., 2010; Hirmas et al., 2016; Hummel et al., 2001; Lehmann et al., 2008; Moran et al., 2000; Pierret et al., 2003), the soil microbial heterogeneity at this scale is only poorly understood (Kuzyakov and Blagodatskaya, 2015; Tecon and Or, 2017; Vos et al., 2013). This is mainly due to methodical limitations, since it is much more challenging to develop mapping tools that display microbial activities (Kluge et al., 2013; Kuzyakov and Blagodatskaya, 2015; Pausch and Kuzyakov, 2011; Schmidt and Eickhorst, 2014). Especially real-time methods that can simultaneously describe soil physical as well as biological parameters and dynamics are not available at the microscale.

In this context, infrared thermography (IRT) seems to be a promising tool (Kluge et al., 2013). IRT measures thermal energy radiated from object surfaces. The emitted energy detected by an IRT camera is

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mainly a function of surface temperature, which is transformed into a visible image (Meola and Carlomagno, 2004). Passive and active IRT are the two basic approaches of the IRT technique (Bagavathiappan et al., 2013; Theodorakeas et al., 2015). Passive IRT monitors the thermal radiation emitted by the surface of the test body under natural condition whereas, for active IRT, the test body is thermally irradiated by an external energy source to produce an intensive thermal contrast on the test body surface.

During the past decade, both passive and active infrared thermography techniques have become powerful and effective tools in a wide range of applications, since these techniques show numerous advantages. One of the main advantages of IRT is that it only requires an infrared camera with little other instrumentation. Other important advantages are that infrared thermography, as a remote sensing technique, can be used without physical contact to the test objects and their destruction (Bagavathiappan et al., 2013; Usamentiaga et al., 2014). Additionally, IRT provides a real-time temperature map of the test surfaces with a scan speed of up to 1600 Hz in a high thermal and spatial resolution. Modern IRT systems show a thermal sensitivity better than 0.02 K and a spatial image resolution with > 1.5 megapixels (Meola and Carlomagno, 2004).

Based on these benefits, passive and active IRT have a broad range of applications ranging from life sciences and medicine to engineering and industry (Meola and Carlomagno, 2004). Most common industrial applications for passive IRT are building insulation diagnostics as well as mechanical and electrical inspections for locating defects (Bagavathiappan et al., 2013; Fokaides and Kalogirou, 2011; Utne et al., 2012). For example, IRT inspections of buildings can be used to detect heat losses and missing or damaged thermal insulations in walls and roofs (Fokaides and Kalogirou, 2011; Grinzato et al., 1998). The most common application of active IRT is industrial material testing for the detection of defects and fine cracks (Busse et al., 1992; Hain et al., 2009; Huth et al., 2002; Ranjit et al., 2015; Theodorakeas et al., 2015; Wu and Busse, 1998).

Although IRT has been used for many environmental investigations (Antonucci et al., 2013; Grudzielanek and Cermak, 2015; Jones, 1999), it has rarely been used in soil science, especially at the microscale. Generally, all soil properties associated with thermal surface radiation can potentially be assessed with IRT approaches. Thus, especially water content and microbial activity may be detectable using IRT techniques in soils due to increasing volumetric heat capacities with increasing water contents (Abu-Hamdeh, 2003; Antonucci et al., 2011) and to heat production of microorganisms during respiration (Barros et al., 2011; Kluge et al., 2013; Sparling, 1981), respectively.

Concerning the soil water content, there are many studies using passive IRT as a remote sensing tool to identify water content of landscapes at large scales (Bittelli, 2011; Njoku et al., 2003; Verstraeten et al., 2006). So far, only Antonucci et al. (2011) showed that active IRT is also a useful technique for assessing soil water contents at smaller scales. In their laboratory study, they used active IRT to heat various soil samples with different initial temperatures and water contents. Total water contents of the soil samples were calibrated against the temperature variations with correlation coefficients of up to 0.74. However, the study of Antonucci et al. (2011) did not consider the possibility of active IRT to detect the spatial distribution as well as the dynamics of soil water content on the soil surfaces.

The possibility of using IRT approaches for detecting the microbial activity of soil samples has only been assessed by Kluge et al. (2013). The authors used the passive IRT approach to determine the spatial distribution of soil microbial activity on soil sample surfaces after glucose application. They showed that a substrate-induced increase of the surface temperature from the stimulated microbial activity was detectable. However, they did not determine the spatial distribution of soil moisture. Soil moisture will not only influence the measured surface temperatures but also alters the process rates of microbial activity (Baldrian et al., 2010; Barros et al., 1995; Skopp et al., 1990). Thus, for a better understanding of interactions between soil physical properties and biological processes at the microscale, the simultaneous determination of soil moisture and microbial activity dynamics is of special interest.

The present study evaluated the potential of active and passive IRT for the detection of soil surface temperatures with the aim to obtain soil surface properties at high spatial and temporal resolution. The detection and calibration of soil moisture were performed with active IRT and the determination of microbial activity with passive IRT. In the first part of the study, the potential and accuracy of active IRT to determine soil moisture contents and detect structural patterns of the soil surface was investigated. In the second part, the rewetting effect of soil samples and the resulting increase in microbial activity was examined using passive IRT. Finally, active and passive IRT approaches were combined for evaluating the potential of IRT to assess microbiological and microphysical soil properties and for analyzing surface temperature changes from different perspectives.

2. Material and methods

2.1. Soil sampling

For this study, a pool of 48 soil samples was used from different sites across North Rhine-Westphalia (Germany). The top- and subsoil samples (0–30 and 30–60 cm) cover a wide range of chemical, physical, and biological soil properties (Supplementary Material, Table S1). All soils were air-dried after sampling and sieved to < 2 mm.

In addition to this sample set, two samples from agricultural topsoils (A and B) and one from a forest subsoil (C), were selected for the long-term incubation experiments described in detail below. Soil properties of these samples are listed in Table 1. In order to obtain sterile samples of these soils A, B, and C, subsamples were exposed to a total dose of 75 kGy of γ-irradiation during three 24-hour irradiation intervals, which is considered sufficient to achieve sterility (McNamara et al.,

Table 1

Physical and chemical characteristics of the soil samples used for the incubation experiments.

Soil sample	pH[a]	C/N[b]	SOC[b]	WHC[c]	Sand[d]	Silt[d]	Clay[d]	C_{mic}[e]	Basal respiration[f]
					[%]			[$\mu g\ g^{-1}$]	[CO_2 mg h^{-1}]
A	6.1	14	2.5	50.9	38	54	8	126.7	2.18
B	7.1	13	3.0	61.5	7	85	8	171.9	4.10
C	3.7	10	0.4	50.6	12	68	20	32.2	0.29

[a] 0.01 M $CaCl_2$.

[b] Vario EL Elementar Analyser (Elementar Analysesysteme GmbH, Hanau, Germany).

[c] After DIN EN ISO 11267 (2014-07).

[d] Analysette (Fritsch GmbH, Idar-Oberstein, Germany).

[e] After Vance et al. (1987).

[f] Respicond (Nordgren Innovations AB, Bygdeå, Sweden).